MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

O. M. BEKETOV NATIONAL UNIVERSITY
of URBAN ECONOMY in KHARKIV

BURDA Y. O.

COMPREHENSIVE ANALYSIS OF THERMODYNAMIC AND THERMOPHYSICAL PROCESSES IN HEAT AND GAS SUPPLY AND VENTILATION SYSTEMS: THEORETICAL FOUNDATIONS AND ENGINEERING SOLUTIONS

MONOGRAPH

Kharkiv
O. M. Beketov NUUE
2025

УДК [536.24:66.021.3]:[697.34:621.311.24]:[502.171:620.9]
B96

Author:

Burda Yurii Oleksandrovych – Ph.D. (Tech.), Associate Professor of the department of Heat and Gas Supply and Ventilation O. M. Beketov National University of Urban Economy in Kharkiv

Reviewers:

Redko Ihor Oleksandrovych – D.Sc. (Doctor of Technical Sciences), Professor at the Department of Transport Technology, Design and Exploitation of Machines, Ukrainian State University of Railway Transport;

Tiutiunnyk Larysa Ivanivna – Ph.D. (Tech.), Associate Professor, Docent of the Department of Steam Generator Engineering, National Technical University "Kharkiv Polytechnic Institute"

Recommended for publication
by Academic Council of O. M. Beketov NUUE as a monograph,
record № 8 of 28.03.2025

Монографія присвячена комплексному аналізу термодинамічних та теплофізичних процесів у системах теплогазопостачання і вентиляції. Розглядаються фундаментальні теоретичні основи, що визначають ефективність енергоперетворювальних процесів, а також сучасні інженерні рішення для підвищення енергоефективності та екологічності комунікаційних мереж.

Burda Y. O.

B96 Comprehensive Analysis of Thermodynamic and Thermophysical Processes in Heat and Gas Supply and Ventilation Systems: Theoretical Foundations and Engineering Solutions : monograph / Y. O. Burda ; O. M. Beketov National University of Urban Economy in Kharkiv. – Kharkiv : O. M. Beketov NUUE, 2025. – 130 p.

ISBN 978-966-695-622-7

This monograph presents a comprehensive investigation into thermodynamic and thermophysical processes within heat and gas supply and ventilation systems. Emphasis is placed on the theoretical foundations of energy transfer, including conduction, convection, radiation, and mass transfer, and their influence on system performance.

УДК [536.24:66.021.3]:[697.34:621.311.24]:[502.171:620.9]

ISBN 978-966-695-622-7

CONTENT

INTRODUCTION

The study of thermodynamic and thermophysical processes in heat and gas supply and ventilation systems is fundamental to advancing modern engineering solutions aimed at optimizing energy consumption, improving efficiency, and ensuring environmental sustainability. These systems play a critical role in both industrial and civil infrastructure, providing thermal comfort, air quality control, and the efficient distribution of thermal energy. As energy efficiency regulations become more stringent and the demand for sustainable technologies increases, a deeper understanding of the underlying physical processes governing these systems is essential.

Thermodynamics serves as the foundation for analyzing energy transformations, heat transfer mechanisms, and the efficiency of heating, cooling, and ventilation processes. It provides the theoretical framework necessary for assessing system performance, determining energy losses, and optimizing operational parameters. Meanwhile, thermophysics examines the properties of materials and working fluids, their interactions with thermal fields, and their impact on heat and mass exchange. The combination of these two disciplines allows for a comprehensive assessment of the dynamic processes occurring within heat and gas supply networks, ventilation systems, and related energy-conversion equipment.

This monograph aims to integrate fundamental theoretical principles with applied engineering approaches to provide a holistic perspective on the operation, optimization, and modernization of heat and gas supply and ventilation systems. It explores key thermodynamic cycles, heat and mass transfer phenomena, and the impact of external conditions on system performance. Additionally, attention is given to contemporary challenges in energy efficiency, the use of renewable energy sources, and the application of advanced control strategies to enhance system functionality.

By bridging theoretical foundations with practical engineering applications, this work seeks to contribute to the development of more efficient, reliable, and sustainable heating, ventilation, and air-conditioning (HVAC) solutions. The insights presented in this monograph are intended to serve as a valuable resource for researchers, engineers, and industry professionals involved in the design, analysis, and implementation of thermal energy systems.

Relevance of the Research. The increasing global demand for energy efficiency, environmental sustainability, and improved performance in engineering systems has made the study of thermodynamic and thermophysical processes in heat and gas supply and ventilation systems a crucial area of research. As urbanization intensifies and industrial processes expand, the need for optimized heating, ventilation, and air conditioning (HVAC) systems becomes more pressing. Inefficient energy use in these systems contributes significantly to overall energy losses, increasing operational costs and environmental impact. Understanding and improving the underlying thermodynamic and thermophysical mechanisms is essential for developing modern engineering solutions that enhance energy efficiency and sustainability.

One of the primary challenges in heat and gas supply and ventilation systems is the effective management of heat and mass transfer processes. These processes directly influence the performance of heating and cooling systems, ventilation effectiveness, and indoor air quality. The complexity of real-world applications, where dynamic and transient thermal interactions occur, necessitates a detailed theoretical and experimental analysis of these systems. Advances in material science, computational modeling, and energy management strategies provide new opportunities to refine these systems, but their successful implementation requires a solid understanding of fundamental thermodynamic principles.

The relevance of this research is further underscored by the global shift toward renewable energy integration, decarbonization, and intelligent control systems in HVAC and thermal networks. The development of high-performance heat exchangers, energy recovery technologies, and adaptive climate control strategies relies on precise thermodynamic modeling and optimization. Additionally, legislative regulations and international standards demand that buildings and industrial processes meet stringent energy performance criteria, further driving the necessity for enhanced system designs.

By comprehensively analyzing the thermodynamic and thermophysical processes governing heat and gas supply and ventilation systems, this research aims to provide theoretical insights and practical recommendations for improving system efficiency, reducing energy consumption, and minimizing environmental impact. The study bridges fundamental scientific principles with real-world engineering applications, offering a holistic approach to the modernization and optimization of contemporary thermal energy systems.

Objectives and tasks of the study. The primary objective of this study is to conduct a comprehensive analysis of thermodynamic and thermophysical processes in heat and gas supply and ventilation systems to develop theoretical foundations and engineering solutions aimed at improving energy efficiency, optimizing system performance, and enhancing sustainability. This objective is achieved through a detailed investigation of the fundamental principles governing thermal and mass exchange processes, their application in engineering networks, and the potential for modernization using advanced technologies.

To accomplish this objective, the study addresses the following key tasks:

- Examine the fundamental thermodynamic and thermophysical principles that govern heat and mass transfer in heat and gas supply and ventilation systems, identifying their impact on energy efficiency and operational stability.
- Analyze the mechanisms of heat transfer, fluid dynamics, and phase transitions in real-world engineering applications, considering factors such as unsteady thermal processes, material properties, and system configurations.
- Investigate the role of thermophysical properties of working media in determining system efficiency, including their influence on heat transfer coefficients, thermal resistances, and mass diffusion rates.
- Assess the energy balance and performance optimization strategies for engineering networks, exploring ways to reduce energy losses, enhance thermal comfort, and improve system reliability.
- Explore modern technologies and innovative approaches in heating, ventilation, and air conditioning (HVAC) systems, such as renewable energy integration, intelligent control systems, and advanced heat exchangers.

- Evaluate the potential for modernization of existing heat and gas supply networks, identifying key areas for improvement and proposing strategies for implementing energy-efficient and environmentally sustainable solutions.
- Develop practical recommendations and theoretical models that support the design and operation of high-performance thermal energy systems, ensuring compliance with energy efficiency regulations and sustainability goals.

By addressing these tasks, the study aims to provide a holistic framework that combines theoretical foundations with engineering applications, contributing to the advancement of energy-efficient and technologically advanced heat and gas supply and ventilation systems.

Methodological approaches. The study employs a multidisciplinary approach, integrating theoretical analysis, computational modeling, experimental research, and case studies to achieve a comprehensive understanding of thermodynamic and thermophysical processes in heat and gas supply and ventilation systems. The following methodological approaches are utilized to address the objectives and tasks of the research:

- Theoretical Analysis
- A significant portion of the study is based on the application of thermodynamic principles and thermophysical theories to analyze the behavior of heat and mass transfer in various types of thermal systems. This includes the use of fundamental laws of thermodynamics, fluid mechanics, and heat transfer mechanisms to model and predict system performance. Specific attention is given to the interactions between heat exchange processes, fluid flow dynamics, and material properties in engineering networks.
- Computational Fluid Dynamics (CFD) Modeling
- Computational simulations are employed to analyze the thermal and fluid flow behavior within heat and gas supply systems and ventilation networks. CFD modeling allows for the visualization of heat transfer and fluid dynamics in complex geometries, enabling the identification of inefficiencies, thermal losses, and potential areas for optimization. By simulating various operating conditions, the

study assesses the impact of different parameters, such as system design, material selection, and environmental factors, on system performance.

- Energy Balancing and Performance Analysis
- The study utilizes energy balance equations to evaluate the energy performance of heat and gas supply systems. Energy analysis involves calculating heat losses, assessing energy efficiency, and identifying strategies to minimize waste energy in heating and cooling processes. The energy balance approach is complemented by an examination of thermodynamic cycles, assessing the efficiency of different system configurations and operational strategies.
- Experimental Research and Laboratory Testing
- Experimental data are gathered through laboratory tests and field measurements conducted on real-world systems or prototypes. These experiments are designed to validate theoretical models and CFD simulations, providing empirical evidence of system performance under various conditions. Measurements of temperature, pressure, flow rate, and energy consumption are used to assess system efficiency and identify performance gaps.
- Case Studies and Best Practices
- The research incorporates a series of case studies from real-world implementations of heat and gas supply and ventilation systems. These case studies provide practical insights into the challenges and solutions encountered in the design, operation, and modernization of such systems. By examining successful applications of advanced technologies, renewable energy integration, and intelligent control systems, the study identifies best practices that can be applied to other engineering networks.
- Optimization Techniques
- Various optimization techniques, including mathematical programming, heuristic methods, and machine learning algorithms, are employed to optimize system performance. These techniques are used to determine the optimal operating conditions, system configurations, and control strategies that maximize energy efficiency, reduce environmental impact, and improve overall system reliability.

- Sustainability and Environmental Impact Assessment
- An important component of the study is the assessment of the environmental impact of heat and gas supply and ventilation systems. Life cycle analysis (LCA) is used to evaluate the sustainability of different system designs and technologies. This approach considers the entire lifecycle of the systems, from production and installation to operation and disposal, to assess the environmental footprint and identify opportunities for improvement.

By combining these methodological approaches, the study ensures a comprehensive evaluation of thermodynamic and thermophysical processes, providing valuable insights for the design, optimization, and modernization of heat and gas supply and ventilation systems

REVIEW OF CURRENT ISSUES AND LITERATURE ANALYSIS

The monograph «Comprehensive Analysis of Thermodynamic and Thermophysical Processes in Heat and Gas Supply and Ventilation Systems: Theoretical Foundations and Engineering Solutions» presents a thorough exploration of the core issues surrounding thermodynamic processes, heat transfer mechanisms, and energy-efficient strategies in heating, ventilation, and air-conditioning systems. This review will analyze the current issues in the field, drawing upon relevant literature and identifying key research gaps.

The ever-growing global demand for energy-efficient systems, coupled with the need to reduce environmental impacts, has made heat and gas supply systems a critical area of study. One of the major challenges identified is the inefficiency in the existing infrastructure, where heat losses and energy wastage remain prevalent. This inefficiency can be attributed to several factors:

High Energy Consumption: Traditional heating and ventilation systems consume large amounts of energy, leading to high operational costs and increased carbon footprints. The need to address energy consumption through innovative technologies and optimized system design has become more urgent.

Thermal Losses and Heat Transfer Limitations: Existing systems still face significant heat losses, particularly in industrial and residential applications. Thermal insulation and heat exchange mechanisms in buildings and industrial facilities are often inadequate, contributing to the inefficiency of these systems.

Dependence on Fossil Fuels: Many heat and gas supply systems rely heavily on fossil fuels, leading to environmental concerns, particularly in light of climate change and the global push for decarbonization. The transition to renewable energy sources remains slow, and there are significant challenges in integrating these sources with traditional systems.

Operational Challenges: The operational efficiency of heating and ventilation systems is highly dependent on the correct balancing of multiple variables such as airflow, temperature gradients, and pressure differences. The complexity of these systems, combined with external factors like weather conditions and user demands, makes it difficult to maintain optimal performance consistently.

Aging Infrastructure: Many heating and gas supply systems are based on outdated technologies and are no longer capable of meeting modern energy efficiency standards. Updating and modernizing these systems while minimizing disruption to existing operations poses a significant challenge.

Despite the substantial body of work in this field, several gaps in the literature remain that present opportunities for future research:

Integrated Modeling of Thermodynamic and Thermophysical Processes: While many studies have focused on individual aspects of heat transfer and system performance, integrated models that combine thermodynamic, thermophysical, and mass transfer processes in a unified framework are still relatively scarce. These models could provide a more comprehensive understanding of system behavior and offer more accurate predictions for system optimization.

Long-Term Performance and Aging Systems: Much of the existing research has focused on new systems or theoretical designs, while there is less attention paid to the long-term performance of existing, aging systems. Further studies are needed to evaluate the operational efficiency of older systems and identify cost-effective retrofitting strategies to bring them up to modern energy standards.

Dynamic Interaction Between Renewable Energy and Conventional Systems: More research is needed into how renewable energy sources, such as solar, wind, and geothermal, can be integrated with conventional heating and ventilation systems. Studies exploring hybrid systems that dynamically balance the contribution of renewables and conventional energy sources could significantly enhance energy security and efficiency.

Advanced Energy Storage Solutions: As renewable energy integration increases, so does the need for advanced energy storage technologies. Research into new methods of thermal energy storage, battery systems, and hybrid energy storage technologies is crucial for improving the reliability and efficiency of heating and ventilation systems.

Human-Centric Design and User Behavior: The role of user behavior in the operation of heating and ventilation systems is often overlooked. Understanding how occupants interact with HVAC systems and incorporating user preferences into system design could lead to more effective and personalized energy-saving strategies.

The current issues surrounding heat and gas supply systems are multifaceted, with energy efficiency, renewable energy integration, and system optimization remaining at the forefront of research. The literature highlights the need for integrated models, advanced materials, and smart technologies to address these challenges. Further research is needed to bridge existing gaps, particularly in the areas of renewable energy integration, long-term system performance, and advanced energy storage solutions. As the field continues to evolve, these advancements will pave the way for more efficient, sustainable, and environmentally friendly systems.

1 THEORETICAL FOUNDATIONS OF THERMODYNAMIC AND THERMOPHYSICAL PROCESSES

1.1 Fundamentals of thermodynamics and their application in heat and gas supply and ventilation

Thermodynamics, the branch of physical science that deals with the relations between heat, work, and energy, is central to the design, optimization, and performance of heat and gas supply systems and ventilation networks. Its principles form the backbone of understanding energy conversion, heat transfer, and system efficiency, all of which are critical to modernizing and optimizing HVAC systems. Thermodynamic processes governing heat flow, fluid dynamics, and energy conversion are essential for improving the energy efficiency of these systems, reducing operational costs, and mitigating environmental impacts.

Thermodynamics as a science emerged from the necessity to understand and optimize the processes of energy transformation, which are central to the operation of technical systems in civil engineering. The principles of thermodynamics form the theoretical foundation for analyzing the behavior of thermal energy in heat and gas supply systems and ventilation, which are critical for ensuring energy efficiency, thermal comfort, and sustainability in buildings and industrial facilities. These systems rely on the transfer, transformation, and control of energy in the form of heat and work, which are governed by the laws of thermodynamics. The first law, based on the principle of conservation of energy, is applied to determine the energy balance within closed and open systems, allowing for the precise calculation of energy input, useful work output, and losses in the form of heat dissipation. In practical applications, this is used to evaluate the thermal efficiency of boilers, heat exchangers, heat pumps, and gas transport units, where accurate energy accounting is fundamental to the optimization of operational modes and system configurations.

The second law of thermodynamics introduces the concept of entropy, which quantifies the irreversibility of real processes and imposes limitations on the conversion of heat into work. In engineering systems, this principle is critical for identifying sources of inefficiency such as friction, non-ideal heat transfer, and pressure losses in pipelines and ducts. The second law underpins the design strategies aimed at minimizing exergy destruction, thus improving the overall performance of systems. Exergy analysis, which builds on the second law, enables the identification of components or processes where the greatest potential for energy savings lies, particularly in the context of thermal insulation design, regenerative heat recovery, and the selection of optimal thermodynamic cycles. The Carnot cycle provides a theoretical benchmark for evaluating the maximum efficiency achievable by heat engines and refrigeration systems, forming the basis for comparison with real-world devices used in heat and gas supply networks.

The zeroth law of thermodynamics establishes the concept of thermal equilibrium and allows for the definition and measurement of temperature, which is a fundamental variable in the control and regulation of indoor climate and process conditions in ventilation systems. Accurate temperature control is essential for the stability of air parameters, ensuring the required microclimatic conditions in residential, commercial, and industrial buildings. This forms the basis for the operation of thermostatic control devices, automatic regulators, and building management systems that coordinate the operation of heating and ventilation components.

The third law of thermodynamics, though less frequently applied in routine engineering practice, provides insights into the behavior of substances at low temperatures, which is relevant in the context of cryogenic technologies and gas liquefaction systems, often used in specialized industrial processes and energy storage solutions.

In practical engineering, thermodynamic principles are used to determine the required heating loads based on the balance between energy input and environmental heat losses, enabling the sizing and selection of equipment such as furnaces, radiators, and air heaters. In ventilation systems, the same principles are used to calculate the enthalpy change of airflows, determine the heat and moisture loads in air-handling processes, and ensure the thermodynamic compatibility of air conditioning cycles. Moreover, the design of combined heat and power plants, district heating networks, and thermal substations involves comprehensive thermodynamic modeling to optimize energy distribution and utilization.

Thermodynamic modeling is also crucial in simulating dynamic operational scenarios, allowing for the prediction of system behavior under variable load conditions, peak demands, and transient startup or shutdown phases. The use of thermodynamic diagrams and state equations provides a graphical and analytical means for solving complex engineering problems related to gas expansion, compression, condensation, and evaporation, which are inherent to the processes within heat and gas supply and ventilation networks.

In work [1], the thermophysical properties of deep eutectic solvent-based organic nanofluids were predicted using a machine learning approach, which is highly relevant for understanding the thermodynamic behaviors in heat and gas supply systems.

The four fundamental laws of thermodynamics provide a framework for analyzing and improving heat and gas supply systems:

- *Zeroth Law of Thermodynamics*: This law establishes the concept of temperature and thermal equilibrium, providing a foundation for temperature control in ventilation and heating systems. Ensuring uniform temperature distribution in large systems is crucial for minimizing thermal gradients and improving the comfort level of conditioned spaces. Modernization of these systems requires advanced temperature control algorithms and materials that allow for more accurate regulation of indoor climates, such as advanced sensors and real-time monitoring systems that adjust HVAC operations in response to changing conditions.
- *First Law of Thermodynamics*: The principle of energy conservation is central to evaluating system efficiency. In heat and gas supply systems, this law asserts that the total energy entering the system equals the energy exiting, accounting for losses. In current systems, however, substantial energy losses occur due to inefficiencies in heat exchange processes, particularly through leakage in pipes, ducts, and poorly insulated components. Modernization efforts should focus

on improving insulation materials, adopting high-performance heat exchangers, and incorporating waste heat recovery technologies that reuse thermal energy, thereby enhancing overall system efficiency.

- *Second Law of Thermodynamics*: This law introduces the concept of entropy, emphasizing that all real processes increase the disorder of the system, with some energy inevitably being wasted as heat. In heating, ventilation, and air-conditioning (HVAC) systems, entropy increases due to heat losses during energy conversion, friction, and unbalanced load conditions. The challenge in modernizing these systems lies in reducing these inevitable losses. One potential approach is the development of more efficient heat exchangers that operate closer to the thermodynamic ideal, minimizing irreversibilities. Additionally, the use of advanced materials and coatings with lower thermal resistance could reduce energy dissipation during heat transfer processes.
- *Third Law of Thermodynamics*: While less directly relevant to everyday engineering applications, the third law underlines the importance of temperature control, especially in low-temperature applications such as refrigeration. The use of cryogenic processes or low-temperature thermal storage systems could enhance cooling efficiency. Moreover, advancements in thermally efficient insulation materials and low-temperature heat pumps, designed in alignment with the third law's principles, would reduce the required input energy for refrigeration and ventilation systems, particularly in industries with high cooling demands.

The operation of heat and gas supply systems, including boilers, heat pumps, and chillers, is governed by thermodynamic cycles, which define the efficiency of energy conversion. Common thermodynamic cycles used in these systems include the Rankine cycle for steam-based heating and cooling applications and the refrigeration cycle for air conditioning systems. These cycles operate under specific thermodynamic constraints, with energy losses manifesting in each stage of the cycle.

To modernize and improve these systems, a critical evaluation of cycle efficiency is necessary. For example, upgrading to combined heat and power (CHP) systems—where waste heat is recovered and used for additional heating—can significantly improve energy efficiency. The integration of regenerative heat exchangers that recover heat from exhaust gases and transfer it to the intake air would reduce the overall energy demand of the system. Advanced cycle modifications, such as the Organic Rankine Cycle (ORC), can further optimize performance by enabling energy recovery at lower temperatures, which is particularly beneficial for systems dealing with waste heat or low-grade thermal sources.

This study investigates a data-driven approach enhanced by an attention mechanism to predict thermophysical properties of refrigerants, providing insight into the behavior of fluids used in thermodynamic systems and their implications in heat transfer processes [2].

Thermal storage using phase change materials (PCMs) is an emerging technology that can be integrated into HVAC systems to enhance their efficiency. PCMs absorb or release large amounts of heat when they undergo a phase change, such as from solid to liquid or liquid to gas, without a significant change in temperature. In HVAC systems, the application of PCMs can allow for the storage of excess thermal energy during periods of low demand and its release when demand is high, reducing the need for additional heating or cooling. This technology is particularly beneficial in systems that experience fluctuating loads, such as in industrial applications or buildings with intermittent heating and cooling needs.

Thermodynamically, the integration of PCMs allows for the smoothing of thermal energy demand, thus reducing the operational costs associated with peak energy usage. The advancement of PCMs with higher energy densities, better thermal conductivity, and improved stability is crucial for their wider adoption in modern HVAC systems. Further research into integrating PCMs with smart control systems that dynamically adjust to environmental conditions could optimize their potential benefits.

A core challenge in the thermodynamic analysis of heat and gas supply systems is the management of entropy, or the tendency for energy to dissipate in forms that cannot be efficiently utilized. In practice, this manifests as heat losses through ductwork, piping systems, and inefficient heat exchange interfaces. Modernization strategies should focus on reducing entropy generation by improving the efficiency of thermal management components. This includes the development of advanced heat exchangers, the use of non-traditional heat transfer fluids with enhanced thermophysical properties, and the minimization of friction losses in air and fluid flow systems.

Advanced computational fluid dynamics (CFD) simulations can be employed to optimize system design, ensuring that the flow of fluids and gases is as efficient as possible, with minimal energy dissipation. By incorporating CFD simulations into the design and operation phases, engineers can predict potential issues such as pressure drops, turbulence, and heat losses, and implement targeted solutions before system installation. Furthermore, the use of real-time monitoring and adaptive control systems can help adjust operational parameters dynamically to minimize the generation of entropy, optimizing energy use throughout the system’s lifecycle.

The thermodynamic principles governing heat and gas supply systems also play a significant role in addressing environmental sustainability. The second law of thermodynamics dictates that every energy conversion process generates some waste heat, which must be effectively managed. One promising avenue for reducing the environmental impact of HVAC systems is the integration of renewable energy sources, such as solar thermal energy, geothermal heat pumps, and bioenergy. These renewable sources can be integrated into existing systems to replace or complement conventional fossil-fuel-based heating, reducing both energy costs and carbon emissions.

Additionally, the lifecycle analysis (LCA) of HVAC systems can help assess the environmental footprint from production to disposal, identifying stages where emissions and waste are most significant. Modernization efforts should not only focus on improving the efficiency of operational systems but also consider the sustainability of materials used in system construction, the recyclability of components, and the reduction of harmful refrigerants used in cooling systems.

Incorporating the principles of thermodynamics into the design and operation of heat and gas supply and ventilation systems is crucial for achieving higher efficiency, reducing energy losses, and minimizing environmental impact. The modernization of these systems requires an integrated approach that leverages advanced materials, innovative technologies such as phase change materials, and the optimization of thermodynamic cycles. By minimizing entropy generation and utilizing energy recovery and renewable energy sources, it is possible to create more sustainable and efficient systems that contribute to a lower carbon footprint while meeting the growing demand for energy-efficient heating, cooling, and ventilation solutions.

To accurately evaluate the behavior of working media in heat and gas supply and ventilation systems, it is necessary to consider the thermophysical properties of air. These properties, particularly density and viscosity, significantly affect convective heat transfer, pressure drop in pipelines, and overall energy efficiency. Table 1 provides experimentally obtained values of air density and dynamic viscosity at different temperatures, which are fundamental for computational modeling and system optimization.

Table 1.1 – Thermophysical Properties of Air as a Function of Temperature

Temperature (°C)	Density (kg/m³)	Dynamic Viscosity (Pa·s)
-10	1,341	1.68×10^{-5}
0	1,293	1.72×10^{-5}
10	1,247	1.76×10^{-5}
20	1,204	1.81×10^{-5}
30	1,164	1.86×10^{-5}
40	1,127	1.92×10^{-5}
50	1,092	1.98×10^{-5}
60	1,060	2.05×10^{-5}
70	1,029	2.11×10^{-5}
80	1,000	2.18×10^{-5}

To illustrate the relationship between the thermophysical properties of air and temperature, a graph of the data dependency was presented next. This graphical representation visually demonstrates how air density decreases with increasing temperature, while dynamic viscosity exhibits a nonlinear growth trend. Such an analysis is essential for evaluating heat transfer efficiency, airflow resistance, and optimizing the design of heat and gas supply and ventilation systems.

To illustrate the relationship between the thermophysical properties of air and temperature, a 3D graph of the data dependency was presented next. This visualization provides a comprehensive perspective on how air density and dynamic viscosity change simultaneously with temperature variations. The three-dimensional representation allows for a more detailed analysis of the interdependence between these parameters, highlighting their impact on airflow behavior, pressure losses, and heat exchange processes. Such an approach is essential for optimizing the design and operation of heat and gas supply and ventilation systems, ensuring higher efficiency and energy savings.

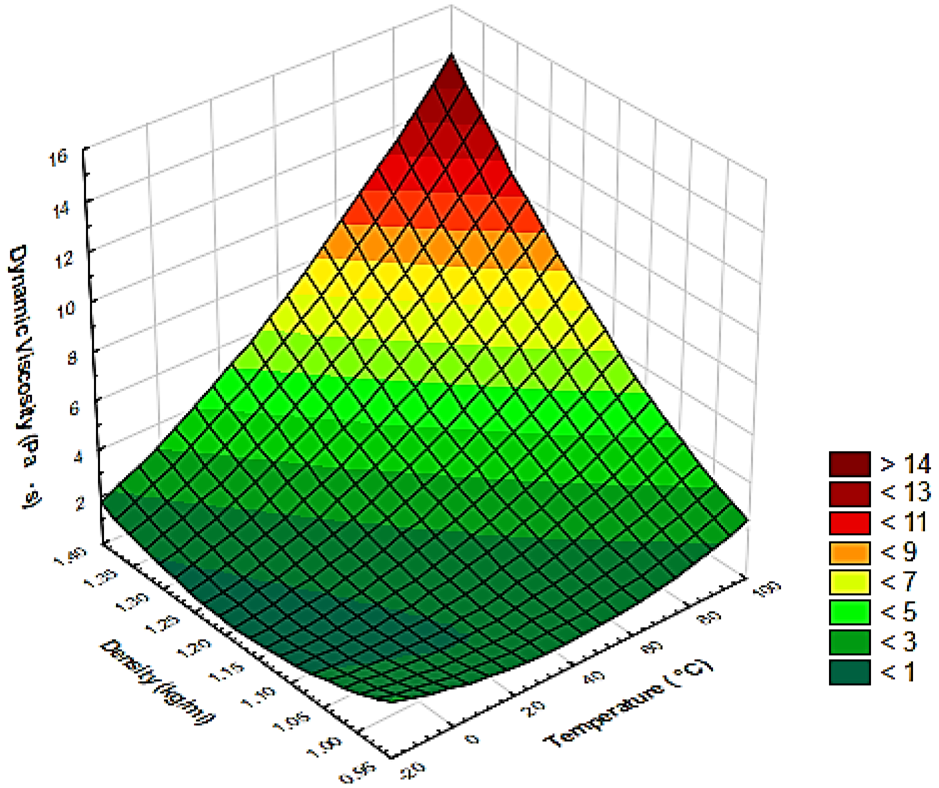

Figure 1.1 – Regression graph of Thermophysical Properties of Air as a Function of Temperature

1.2 Thermophysical properties of working media

Thermophysical properties of working media are essential in the analysis, design, and optimization of heat and gas supply, ventilation, and HVAC systems. These properties govern the behavior of fluids—whether they are gases or liquids—under varying thermal and mechanical conditions, such as temperature, pressure, and flow rate. Understanding these properties is crucial for predicting the performance of energy systems, improving their efficiency, and enabling advancements in thermal technologies.

Thermophysical properties of working media determine the behavior of substances involved in the processes of heat transfer, fluid motion, and energy transformation in engineering systems. These properties define the capacity of a medium to store, transfer, and resist the flow of thermal energy and are fundamental for the modeling, design, and optimization of heat and gas supply and ventilation systems. The accuracy of engineering calculations depends directly on the correct use and understanding of these parameters.

Thermal conductivity is a key property describing the ability of a substance to conduct heat. In the context of gases such as air, natural gas, or carbon dioxide, as well as liquids like water or glycol mixtures, this property governs the efficiency of heat exchange between surfaces and fluids. Higher thermal conductivity corresponds to more effective heat transfer, which is essential for compact heat exchanger design, pipe insulation analysis, and thermal load calculations in ventilation ducts. For example, copper and aluminum exhibit high thermal conductivity and are often used in heat exchangers, while air and most gases possess low thermal conductivity, necessitating increased surface area or forced convection mechanisms in design.

Specific heat capacity characterizes the amount of thermal energy required to raise the temperature of a unit mass of a substance by one degree. This property is fundamental in determining the energy demand for heating or cooling air, water, or other working fluids in system operation. In air-handling units and water-based heating systems, specific heat governs the size of heating elements and the required mass flow rate of the working fluid to maintain a stable indoor environment. The relatively high specific heat of water makes it a favorable medium in centralized heating systems, as it allows for efficient energy transport over long distances with minimal temperature loss.

Density influences the static and dynamic behavior of fluids within piping and duct networks. In gravitational and pressure-driven flow systems, density differences are responsible for natural convection phenomena, which are used in passive ventilation and solar thermal systems. Accurate density values are required in mass flow calculations, fan and pump selection, and in determining the buoyancy effects that affect air stratification in large spaces. Gas density is also essential for volumetric energy content assessment, especially in the transportation and metering of fuel gases such as methane or propane.

Viscosity quantifies the internal friction of a fluid, affecting the resistance to flow and the energy required to transport the medium through pipes and ducts. Dynamic and kinematic viscosity values are necessary to predict pressure losses, evaluate flow regimes, and ensure the stability of laminar or turbulent flow conditions. In heating systems, low-viscosity fluids reduce pumping power requirements, while in ventilation systems, air viscosity impacts the sizing of fans and ductwork and contributes to the determination of Reynolds numbers for accurate flow regime identification.

Thermal diffusivity integrates thermal conductivity, specific heat, and density into a single parameter that describes how quickly a temperature disturbance propagates through a material. It is critical in transient heat transfer modeling, particularly in systems exposed to fluctuating thermal loads or start-stop operations. Materials with high thermal diffusivity respond rapidly to temperature changes, making them suitable for dynamic thermal environments, while low-diffusivity materials provide thermal buffering and are used in thermal insulation.

Enthalpy serves as a central thermodynamic function in ventilation processes involving moist air, where both sensible and latent heat effects are present. Accurate enthalpy values are required for psychrometric calculations, which support the design of dehumidification, humidification, and air-conditioning systems. The inclusion of water vapor properties in air mixture calculations is essential for evaluating energy consumption and thermal comfort performance in HVAC systems.

Thermal expansion coefficients indicate the extent to which materials expand or contract with temperature change. In closed-loop heating systems and pressurized gas pipelines, understanding expansion behavior is necessary to prevent mechanical failure due to pressure buildup or material deformation. Expansion joints, compensators, and control valves are designed based on reliable thermal expansion data to maintain system integrity and operational safety.

Phase change properties such as boiling point, condensation point, and latent heat are critical for systems that involve phase transitions, including evaporative cooling, refrigeration, steam heating, and condensing boilers. Accurate knowledge of these properties enables the prediction of system behavior during vaporization or condensation, which is fundamental for heat exchanger design and energy efficiency optimization in thermal plants.

The thermophysical properties of mixtures, particularly in systems using water-glycol solutions or gas blends, require careful evaluation since interactions between components can alter overall performance characteristics. Empirical correlations and experimental data are used to determine the effective properties of mixtures, ensuring reliability in engineering design.

Reliable thermophysical data are obtained from experimental measurements and compiled in thermodynamic property tables, charts, and software tools used in simulation and analysis. These data are integrated into engineering standards, design manuals, and digital modeling platforms, ensuring consistency in performance prediction and compliance with regulatory requirements. The rigorous use of these properties in engineering practice supports the development of high-performance, energy-efficient, and durable heat and gas supply and ventilation systems, aligned with sustainability goals and technical excellence

Density (ρ). Density is the mass per unit volume of a substance and plays a fundamental role in the fluid dynamics of heat and gas supply systems. It influences the pressure, flow rate, and the ability of a medium to transfer heat. For example, air, as a working medium in ventilation systems, has a much lower density than water, making it more susceptible to changes in temperature and pressure. Higher-density fluids, such as water or oil, are commonly used in heating systems because of their superior heat retention and thermal storage capabilities. The accurate measurement and control of density are vital in the design of pumps, heat exchangers, and fluid transportation systems.

The table 1.2 presents the density, specific heat capacity, thermal conductivity, and dynamic viscosity of selected working media commonly used in heat and gas supply and ventilation systems. These properties are essential for analyzing heat transfer efficiency, energy losses, and the overall performance of engineering systems.

Table 1.2 – Thermophysical Properties of Common Working Media

Working Medium	Density (kg/m³)	Specific Heat Capacity (kJ/kg·K)	Thermal Conductivity (W/m·K)	Dynamic Viscosity (Pa·s)
Air	1,204	1,009	0,026	0,0000181
Water	997	4,18	0,606	0,00089
Steam	0,6	2,01	0,024	0,000013
Carbon Dioxide	1,98	0,846	0,016	0,0000147
Ammonia	0,86	4,70	0,50	0,0000138
Methane	0,72	2,22	0,034	0,0000112
Propane	2,00	1,67	0,015	0,0000085
Ethanol	789	2,44	0,171	0,0012

The work [3] discusses the thermophysical properties of the SPC/E model of water, providing valuable information for understanding water's thermodynamic behavior, particularly in high-pressure environments, which are common in engineering networks.

Specific Heat Capacity (c_p). The specific heat capacity refers to the amount of heat required to raise the temperature of a unit mass of a substance by one degree Celsius (or Kelvin). It is a key parameter in determining the efficiency of heat transfer and storage in a system. In heat and gas supply systems, working fluids with high specific heat capacities, such as water or certain refrigerants, can absorb and store more energy, making them more effective in transferring heat. For example, in thermal storage systems, working media with high specific heat can store significant amounts of thermal energy for later use, thus improving overall system efficiency. Understanding the specific heat capacity of a working medium helps in selecting the most efficient fluid for specific applications.

Thermal Conductivity (k). Thermal conductivity is a measure of a substance's ability to conduct heat. In heat and gas supply systems, the thermal conductivity of the working media directly impacts the effectiveness of heat exchangers and thermal storage systems. Media with high thermal conductivity, such as water, are efficient at transferring heat from one location to another. For air, which has relatively low thermal conductivity, efficient heat exchange requires large surface areas or the use of finned heat exchangers to increase the contact surface for heat transfer. Advanced materials and fluid formulations can be developed to enhance thermal conductivity, leading to improvements in heat exchanger performance and system efficiency.

Viscosity (μ). Viscosity is a measure of a fluid's resistance to flow, which is crucial for understanding fluid dynamics and designing pumping systems. In HVAC systems, the viscosity of air and refrigerants affects the pressure drop in ducts, pipes, and other flow channels. Higher viscosity fluids, such as oils, require more energy to pump and are more prone to flow resistance, which can reduce the efficiency of heat transfer. Low viscosity fluids, like gases, require careful control to prevent turbulent flow, which could lead to uneven heat distribution and inefficiencies. Understanding and controlling viscosity is essential when designing systems to minimize energy loss due to friction and turbulence.

Thermal Expansion (α). Thermal expansion refers to the tendency of a substance to change its volume in response to temperature changes. Working media such as water and refrigerants expand when heated and contract when cooled. This property is particularly important in the design of systems like boilers, piping, and heat exchangers, as it affects the pressure and flow characteristics of the medium. For instance, water’s relatively high coefficient of thermal expansion must be considered when designing systems that involve significant temperature fluctuations, such as in district heating networks, to avoid excessive pressure buildup or system failure. Understanding thermal expansion ensures that components of the system can accommodate these volume changes without risk of damage.

The article [4] explores the asymptotic thermophysical behaviors of near-critical fluids, which can be applied to the understanding of complex thermodynamic systems where high pressures and temperatures are involved.

Boiling and Freezing Points. The boiling and freezing points of a working medium determine the operational limits of a system. In refrigeration and HVAC systems, for example, the refrigerant's boiling point at a given pressure dictates the temperature at which it can change from liquid to gas, facilitating the cooling process. Similarly, in heat transfer systems, the freezing point of water or other fluids must be accounted for to prevent damage to pipes and other system components. The choice of working medium depends heavily on these phase transition points, as they must align with the desired operational temperature ranges for heating or cooling systems.

Specific Volume (v). The specific volume of a substance is the volume occupied by a unit mass of the substance. It is inversely related to density and plays a critical role in gas dynamics and the performance of compressors, turbines, and expanders. For instance, the specific volume of gases like air is highly sensitive to changes in temperature and pressure, making it important to account for these variations when designing ventilation and heating systems. Specific volume is especially important in gas-powered heat supply systems or systems involving air as a working medium, where the ability to compress and expand gases efficiently impacts system performance and energy consumption.

Heat of Vaporization and Heat of Fusion. The heat of vaporization is the amount of energy required to convert a unit mass of a liquid into vapor without a change in temperature, while the heat of fusion is the energy required to change a solid to a liquid. These properties are particularly relevant in systems that involve phase change, such as in steam boilers or refrigeration cycles. Understanding these thermophysical properties allows engineers to design more efficient systems that make better use of phase transitions for energy storage or heat transfer. For example, in latent heat storage systems, where energy is stored during phase change (such as melting or vaporization), optimizing the heat of vaporization of a working medium can increase the storage capacity and system efficiency.

Use of Advanced Refrigerants. The selection of modern refrigerants with optimized thermophysical properties, such as higher specific heat capacity and lower viscosity, can significantly improve the efficiency of HVAC systems. Many traditional refrigerants have been phased out due to their environmental impact, and new, low-GWP (global warming potential) alternatives are being developed. These new refrigerants not only offer superior thermodynamic performance but also align with environmental regulations.

Development of Enhanced Heat Transfer Fluids. The development of new fluids with higher thermal conductivity and specific heat capacities is critical for modernizing heat exchangers and thermal storage systems. Fluids such as nanofluids, which are suspended with nanoparticles, have shown promise in improving heat transfer efficiency. Incorporating these fluids into existing systems could reduce energy consumption by enhancing heat exchange efficiency, especially in systems operating at low-temperature differentials.

Integration of Phase Change Materials (PCMs). The use of PCMs in energy storage systems can be optimized by selecting working media with high latent heat capacities and appropriate phase transition temperatures. By carefully selecting materials that undergo phase changes at desired temperature points, systems can store thermal energy more effectively and release it during peak demand periods, thus improving overall energy management.

Smart Control Systems for Fluid Properties. The integration of real-time monitoring and adaptive control systems that track the thermophysical properties of the working media—such as temperature, pressure, and flow rate—could enhance the overall efficiency of HVAC and heat supply systems. Smart sensors could dynamically adjust operational parameters to optimize performance, reducing energy consumption and ensuring consistent operation despite variations in ambient conditions.

Improved Insulation Materials. Utilizing advanced materials with low thermal conductivity for insulation can reduce heat losses in ducts, pipes, and storage tanks, improving the overall energy efficiency of the system. For instance, aerogels and vacuum-insulated panels (VIPs) provide excellent thermal resistance, reducing the need for excessive energy inputs and enhancing system performance in both residential and industrial applications.

The thermophysical properties of working media play a critical role in optimizing the performance, efficiency, and sustainability of heat and gas supply systems and ventilation networks. By understanding and leveraging these properties, engineers can propose and implement targeted solutions for system modernization, improving heat transfer, reducing energy consumption, and ensuring the long-term reliability of HVAC and heating systems. The advancement of new materials and technologies focused on improving thermophysical characteristics is a key pathway toward achieving greater energy efficiency and sustainability in the built environment.

1.3 Mass transfer processes and their impact on system efficiency

Mass transfer processes play a crucial role in the performance and efficiency of heat and gas supply and ventilation systems. These processes involve the movement of different substances—such as gases, liquids, or particles—within a medium and between phases. In the context of heat and gas systems, mass transfer typically refers to the transfer of heat, moisture, and gases like oxygen, carbon dioxide, or pollutants. Understanding these processes is fundamental for optimizing the operation of such systems, as they directly affect the thermal performance, energy consumption, and environmental impact of heating, ventilation, and air conditioning (HVAC) systems.

Mass transfer processes involve the movement of components within fluid mixtures driven by concentration gradients and phase interactions. These processes are fundamental in determining the efficiency, stability, and control precision of heat and gas supply and ventilation systems. Mass transfer directly influences air quality, energy consumption, condensation behavior, fuel utilization, and thermal regulation in engineered environments.

The primary mechanism of mass transfer is diffusion, a process where particles move from regions of higher concentration to regions of lower concentration due to molecular motion. In ventilation systems, diffusion governs the mixing of indoor and outdoor air, the distribution of pollutants, and the dispersion of gases released during combustion or material off-gassing. Fick's laws describe the rate and direction of this transport and are crucial in modeling indoor air pollution dynamics, filter performance, and the effectiveness of natural ventilation strategies.

Convection-driven mass transfer occurs when bulk fluid motion enhances the transport of mass, often coupled with temperature gradients. This is particularly significant in forced ventilation systems and in ductwork where air is transported mechanically. The interaction between convective and diffusive mechanisms is described by dimensionless numbers such as the Sherwood and Schmidt numbers, which are used in the analysis and design of air exchangers, humidifiers, and dehumidifiers. These parameters influence the rate at which contaminants are removed from enclosed spaces and how quickly desired humidity or concentration levels are restored.

Mass transfer is central to phase change phenomena, particularly condensation and evaporation processes. In heat supply systems using steam or refrigerants, mass transfer governs the latent heat exchange that occurs during phase transitions. Efficient design of condensers and evaporators requires a thorough understanding of interfacial mass transfer, as the resistance at the vapor-liquid boundary determines the rate of energy exchange. Poor mass transfer rates at these interfaces result in decreased heat exchanger performance, increased energy demand, and reduced system responsiveness.

In gas supply networks, especially those involving mixtures such as biogas or hydrogen-enriched natural gas, mass transfer processes affect the homogeneity, combustion characteristics, and pipeline integrity. The diffusion of lighter gases into air or heavier components within gas streams influences flammability limits, energy content, and burner stability. Accurate modeling of mass transfer is essential in leak detection systems and safety protocols in urban and industrial gas infrastructure.

Moisture transport in ventilation systems is a specific case of mass transfer involving water vapor. The psychrometric behavior of air is governed by the partial pressure and mass fraction of water vapor, which in turn affects condensation on building surfaces, duct corrosion, and mold formation. Controlling the mass transfer of moisture is critical in maintaining indoor air quality, preventing material degradation, and ensuring occupant health. Mass transfer coefficients for vapor-air mixtures are used in the design of heat recovery ventilators, air handling units, and energy wheels, where simultaneous heat and moisture exchange occurs.

Mass transfer resistance can arise from boundary layers at solid-fluid interfaces, especially in cases of laminar flow where the thickness of stagnant layers limits the rate of component exchange. In practical systems, this resistance can be reduced by enhancing turbulence, increasing surface area, or applying surface treatments. These measures are applied in filter media, catalytic converters, and humidification chambers, where rapid exchange is essential for performance.

In combustion processes, mass transfer affects the delivery of oxygen to the flame front and the removal of combustion products. Incomplete combustion due to mass transfer limitations leads to reduced thermal efficiency and increased emissions. Burners, nozzles, and fuel-air mixers are designed with these principles in mind to ensure optimal combustion efficiency and environmental compliance.

Adsorption and desorption phenomena, which involve mass transfer between gases and solid surfaces, are exploited in ventilation systems that incorporate activated carbon filters or moisture-absorbing materials. The kinetics of these processes depend on mass transfer rates within porous structures and affect the regeneration cycles, service life, and capacity of such systems. In gas purification units and air treatment systems, these mass transfer behaviors are modeled to maintain continuous operation and high removal efficiency.

In building envelopes, mass transfer of vapor through porous construction materials impacts thermal insulation performance and structural durability. Moisture migration due to vapor pressure gradients leads to condensation within wall layers, affecting energy performance and fostering biological growth. Hygrothermal simulations are used to predict the coupled heat and mass transfer in these scenarios, and materials are selected based on their vapor permeability and sorption properties.

In integrated system analysis, mass transfer is interlinked with heat transfer and fluid dynamics. Computational fluid dynamics (CFD) tools incorporate mass transfer equations to model indoor air distribution, contaminant transport, and thermal comfort. These simulations support the optimization of system layouts, the positioning of inlets and outlets, and the validation of performance against regulatory standards.

Thus, mass transfer processes serve as a critical determinant of the energy efficiency, environmental performance, and operational reliability of heat and gas supply and ventilation systems. Their accurate representation in engineering design ensures compliance with sustainability objectives, occupant safety, and the long-term effectiveness of built environment technologies

In HVAC systems, mass transfer processes are often linked with heat exchange and air movement, which are influenced by factors such as airflow velocity, temperature gradients, and the concentration of different substances within the air. The efficiency of a ventilation system, for instance, largely depends on the rate at which air pollutants, moisture, and gases are transported and exchanged within the system. These processes also impact the overall energy efficiency of heat and gas supply systems, as energy losses often occur due to poor mass transfer dynamics.

The primary mass transfer mechanisms in such systems are diffusion, convection, and sometimes, phase change. Diffusion occurs due to concentration gradients, where particles naturally move from regions of higher concentration to regions of lower concentration. Convection, on the other hand, is the transfer of heat or mass through a fluid (air or water) due to the bulk motion of the fluid itself, which is often influenced by external forces such as fans, pumps, or natural convection.

In heat exchangers, for example, efficient mass transfer processes are essential to maximize thermal efficiency. In these systems, the transfer of heat is often accompanied by the transfer of mass (e.g., water vapor or gases), and any limitations in mass transfer can result in a decrease in heat exchange efficiency. The design of heat exchangers—such as the choice of materials, flow arrangement (counterflow, parallel flow), and surface area—can significantly impact the rate of mass transfer and, consequently, the overall efficiency of the system.

The table 1.3. presents real data on mass transfer coefficient and moisture removal rate in different ventilation and heat supply systems. These parameters are essential for evaluating the efficiency of mass transfer processes, particularly in air conditioning, dehumidification, and heat recovery applications. The relationship between these variables allows for optimizing system performance and energy consumption.

In the study [5], the impact of chemically reactive flow on thermophysical characteristics is considered, offering a broader perspective on fluid behaviors in engineering systems where chemical reactions are present.

Table 1.3 – Mass Transfer Processes and Their Impact on System Efficiency

System Type	Mass Transfer Coefficient ($kg/m^2 \cdot s$)	Moisture Removal Rate (g/h)
Natural Ventilation	0,0025	150
Mechanical Ventilation	0,0058	320
Air Conditioning System	0,0072	450
Heat Recovery Unit	0,0065	410
Industrial Exhaust System	0,0081	500
Desiccant Dehumidifier	0,0095	620
Cooling Tower	0,0102	700
Adsorption Dryer	0,0118	850

Moisture management is another critical area were mass transfer processes influence system efficiency. In ventilation systems, the removal or control of humidity is a key factor in preventing mold growth, condensation issues, and ensuring the quality of the air supplied to the space. In cooling towers or evaporative cooling systems, for instance, the transfer of water vapor from the air is a mass transfer process that affects the cooling performance. Inefficiencies in these systems can result in increased energy consumption and a decline in cooling capacity.

Additionally, in gas supply systems, the transfer of gases such as oxygen or carbon dioxide can affect combustion efficiency, pollutant removal, and overall system performance. For example, poor mixing or uneven distribution of fuel and air in combustion chambers can lead to incomplete combustion, increased emissions, and reduced energy efficiency. The efficiency of gas distribution systems can also be significantly influenced by the design and configuration of ducts, pipes, and other components.

To improve system efficiency, several engineering solutions can be proposed. First, enhancing mass transfer rates can be achieved through the optimization of system design, such as increasing the surface area for heat exchange, using advanced materials that improve thermal conductivity, or incorporating advanced fluid dynamics principles to promote better mixing and circulation within the system. Additionally, the use of advanced monitoring and control systems to track and optimize mass transfer dynamics in real-time can help to maintain peak system performance and energy efficiency.

Furthermore, the integration of energy recovery technologies, such as heat recovery ventilators (HRVs) and energy recovery wheels, can enhance mass transfer processes in ventilation systems by reusing energy from exhaust air to precondition incoming air, improving both energy efficiency and indoor air quality. Another potential solution is the incorporation of phase change materials (PCMs) to assist with heat storage and release, optimizing heat transfer and improving system performance during varying loads.

This work [6] examines how varying thermophysical properties of phase change materials affect the performance of hybrid modules, providing insight into material properties crucial for improving energy efficiency in thermal systems.

In summary, mass transfer processes are integral to the efficient operation of heat and gas supply and ventilation systems. By understanding and optimizing these processes, it is possible to significantly improve system efficiency, reduce energy consumption, and mitigate the environmental impact of HVAC and gas systems.

2 HEAT TRANSFER IN HEAT AND GAS SUPPLY AND VENTILATION SYSTEMS

2.1 Conduction, convection, and radiation in heat exchange processes

Heat exchange processes are fundamental to the operation and efficiency of various engineering systems, particularly in heat and gas supply and ventilation systems. The primary mechanisms of heat transfer—conduction, convection, and radiation—are involved in the movement of thermal energy between materials or within a given system. A comprehensive understanding of these processes is crucial for the design, optimization, and modernization of heat exchange systems, as each mechanism plays a distinct role in determining the thermal performance, energy efficiency, and environmental impact of a system.

Conduction is the transfer of heat through a solid material or between materials that are in direct physical contact. This process occurs when particles in a substance collide and transfer energy from the hotter part to the cooler part. The efficiency of conduction depends on the properties of the material involved. Materials with high thermal conductivity, like metals, transfer heat more effectively, while materials like insulations are designed to limit conduction and reduce heat loss.

Convection is the transfer of heat through the movement of fluids, which can be either liquids or gases. In natural convection, heat causes a fluid to warm up, become less dense, and rise, while cooler, denser fluid moves downward to replace it. This creates a circulation pattern that helps distribute heat throughout the fluid. In forced convection, external forces, such as fans or pumps, drive the fluid motion, enhancing the rate of heat transfer.

Convection is essential in systems like ventilation, air conditioning, and heating, where air or water is circulated to transfer heat. In air-conditioning systems, for example, warm air is blown across cooled surfaces, and the resulting fluid motion transfers heat away from the interior. Convection also plays a key role in cooling systems, where heat is transferred from heated surfaces to surrounding air or water, improving overall system performance

In practical systems, conduction is crucial for transferring heat within solid structures such as pipes, walls, radiators, and heat exchangers. For example, in a heating system, the metal surface of a radiator will conduct heat to the air or surrounding materials in direct contact with it. Similarly, conduction plays a role in preventing heat loss or gain in building insulation, as it determines how much heat is transferred through the walls, floors, and roofs

Radiation is the transfer of heat through electromagnetic waves. Unlike conduction and convection, radiation does not require a medium (like air or water) and can occur in a vacuum. All objects with a temperature above absolute zero emit infrared radiation. The intensity of the radiation emitted depends on the temperature of the object and the surface characteristics. Dark, rough surfaces tend to radiate more heat, while smooth, shiny surfaces reflect more of the radiation.

Radiation is particularly significant in high-temperature environments and in systems that involve the exchange of heat without direct physical contact. For instance, the heat from the Sun reaches the Earth through radiation. Similarly, in heating systems, radiant heat can be used to warm up spaces or materials. Radiant heating systems, such as underfloor heating or heated panels, use this mode of heat transfer to directly warm up objects and surfaces in a room, contributing to comfort.

In many practical systems, all three modes of heat transfer occur simultaneously. For example, in a room with a radiator, heat is transferred by conduction from the metal radiator to the air in contact with it. The warmed air then circulates around the room through convection, spreading heat to the entire space. At the same time, the radiator emits infrared radiation, which directly heats the surrounding objects and surfaces in the room. This combination of conduction, convection, and radiation ensures that heat is efficiently distributed throughout the environment.

In practical applications, understanding the combination of conduction, convection, and radiation is essential for optimizing heat transfer in complex systems. For example, in industrial processes where precise temperature control is required, engineers must account for all three mechanisms to ensure maximum efficiency and safety. Heat exchangers, which are widely used in systems like power plants, refrigeration units, and HVAC systems, rely on the interplay of conduction and convection to transfer heat effectively between different fluids. In such systems, materials with high thermal conductivity are selected to promote conduction, while the fluid flow is optimized to enhance convective heat transfer. Additionally, radiation may be leveraged in certain applications to minimize heat loss, such as in high-temperature furnaces where radiant heat is used to maintain the necessary thermal environment.

In building design, especially for energy-efficient structures, the effective management of all three modes of heat transfer is a key factor in ensuring comfort and energy savings.

Conduction is the process by which heat energy is transferred through a solid or between solid surfaces in direct contact. It occurs due to the microscopic interactions of particles within the material, primarily through the collisions of atoms or molecules. When one part of a material is heated, the particles in that region vibrate with greater amplitude, transferring kinetic energy to neighboring particles, thus propagating the thermal energy throughout the material.

The rate of heat conduction depends on several factors, including the material's thermal conductivity (denoted as k), the temperature gradient, and the thickness of the material. Thermal conductivity is a material property that quantifies the ability of a material to conduct heat; materials with high thermal conductivity, such as metals, are efficient heat conductors, whereas materials with low thermal conductivity, such as insulations or ceramics, act as thermal barriers.

In heat and gas supply systems, conduction plays a significant role in heat exchangers, pipe insulation, and building envelope components, such as walls and roofs. For instance, the transfer of heat from the hot gas stream in a heat exchanger to the cooling medium is largely governed by conduction through the walls of the exchanger. The efficiency of heat exchangers can be enhanced by selecting materials with high thermal conductivity and optimizing the thickness of the conductive layers to maximize heat transfer while minimizing energy losses.

The review in [7] this paper discusses the thermophysical properties of nanofluids and their applications in heat transfer enhancement, which is highly relevant for energy-efficient heating and cooling systems.

The table 2.1. presents real data on heat transfer coefficient, thermal conductivity, and heat flux for different materials and conditions related to conduction, convection, and radiation heat exchange processes. These parameters allow for analyzing the efficiency of different heat transfer modes in ventilation and heat supply systems, providing a basis for optimizing thermal insulation, heat exchangers, and building envelopes.

Table 2.1 – Conduction, convection, and radiation in heat exchange processes

Material/Condition	Heat Transfer Coefficient (W/m²·K)	Thermal Conductivity (W/m·K)	Heat Flux (W/m²)
1	2	3	4
Copper (Conduction)	—	385	750
Steel (Conduction)	—	50	220
Brick Wall (Conduction)	—	0,72	90
Air (Free Convection)	5,5	0,026	35

Continuation of the table 2.1

1	2	3	4
Water (Forced Convection)	800	0,606	1 200
Steam (Forced Convection)	1 500	0,024	1 600
Solar Radiation (Black Surface)	5,67	—	900
Reflective Surface (Radiation)	0,9	—	150

Convection is the process by which heat is transferred by the bulk movement of fluid, typically a gas or liquid, within a system. This mechanism involves both the motion of the fluid itself and the energy exchange between the fluid and the surface it contacts. Convection can be categorized into two types: natural convection and forced convection. In natural convection, the fluid movement is driven by temperature differences within the fluid, leading to variations in density that result in the upward movement of warmer, less dense fluid and the downward movement of cooler, denser fluid. Forced convection, on the other hand, occurs when external forces, such as fans, pumps, or blowers, induce fluid motion to enhance heat transfer.

In the context of heat and gas supply systems, convection plays a vital role in the distribution of heat within ducts, pipes, and ventilation systems. The heat transfer rate in convective processes is governed by the convective heat transfer coefficient (denoted as h), the temperature difference between the fluid and the surface, and the surface area in contact with the fluid. The convective heat transfer coefficient varies depending on the flow regime (laminar or turbulent), fluid properties (viscosity, density, and specific heat), and surface roughness.

Optimizing convection in HVAC systems involves improving airflow patterns, enhancing mixing, and increasing the contact area between the fluid and the heat exchange surfaces. In forced convection systems, the design of fans and blowers plays a significant role in determining the efficiency of heat transfer. Additionally, the incorporation of turbulence promoters or advanced heat exchanger geometries can improve heat transfer rates by disrupting boundary layers and promoting better fluid mixing.

Radiation is the transfer of heat through electromagnetic waves, primarily in the form of infrared radiation, without the need for a physical medium. All objects emit thermal radiation depending on their temperature, and this radiation can travel through a vacuum or air. The intensity of thermal radiation emitted by a surface is governed by the Stefan-Boltzmann law, which states that the radiant heat power emitted per unit area is proportional to the fourth power of the absolute temperature of the surface (T^4). The emissivity of a surface, a material property, also influences the efficiency with which it emits and absorbs radiation.

Radiation plays a key role in heat transfer in systems where fluids are at different temperatures but are not in direct contact, such as in the exchange of heat between a heated surface and the surrounding air or gases. In heat and gas supply systems, radiation can contribute significantly to heat loss or gain, particularly in high-temperature environments like furnaces, boilers, or combustion chambers. Additionally, radiation is an essential mechanism in the operation of systems such as solar collectors, where heat is transferred from the sun to a surface through radiation, and in the cooling of hot surfaces via infrared emission.

In HVAC systems, radiation is an important consideration in the design of heating systems, particularly radiant floor heating, panels, and ceiling heating. These systems rely on the emission of infrared radiation to warm the surrounding space. The efficiency of these systems can be improved by optimizing the emissivity of heating surfaces and controlling the temperature difference between the heating surface and the surrounding environment.

This article [8] investigates the thermophysical properties of Turkey oak particleboard, a sustainable building material, contributing to energy-efficient building envelopes and the development of environmentally friendly ventilation systems.

In most heat exchange processes, conduction, convection, and radiation do not act independently but rather interact in complex ways to determine the overall heat transfer performance. For instance, in a heat exchanger, heat may be conducted through the material walls, convected within the fluid medium inside the heat exchanger, and radiated from surfaces exposed to high temperatures. Understanding how these mechanisms combine and affect one another is essential for optimizing system efficiency.

The combined effect of these heat transfer mechanisms can be influenced by several factors, including fluid velocity, surface area, temperature gradients, and material properties. In systems that involve high temperatures or extreme conditions (such as combustion chambers), radiation may become a dominant heat transfer mechanism, while in systems operating at lower temperatures, conduction and convection may play more significant roles.

The efficiency of heat exchange processes directly impacts the overall energy consumption and performance of heat and gas supply systems. In particular, the design and optimization of heat exchangers, insulation, and ventilation systems rely on the effective management of conduction, convection, and radiation. An understanding of these mechanisms is critical for minimizing energy losses, reducing operating costs, and ensuring the environmental sustainability of the system.

For example, improving thermal insulation through materials with low thermal conductivity can significantly reduce heat loss through conduction. In HVAC systems, optimizing airflow patterns and enhancing convective heat transfer can lead to improved heat distribution and energy efficiency. In radiative heat transfer, controlling surface emissivity and using reflective coatings can help minimize heat loss and increase the effectiveness of heating systems.

To improve system performance, engineers must carefully balance these heat transfer mechanisms and adopt strategies that optimize each process for the specific operating conditions. Advanced computational models, material innovations, and enhanced system configurations provide numerous opportunities for enhancing heat transfer processes in heat and gas supply and ventilation systems, contributing to the development of more energy-efficient and sustainable systems.

In conclusion, the understanding and optimization of conduction, convection, and radiation are essential for improving the efficiency of heat exchange processes in various systems. By applying these principles to heat and gas supply and ventilation systems, engineers can develop solutions that enhance energy efficiency, reduce operational costs, and minimize the environmental impact of such systems.

2.2 Unsteady heat transfer in building structures

Unsteady heat transfer, or transient heat transfer, in building structures is a phenomenon that occurs when the temperature within the structure or its components changes over time. This is in contrast to steady-state heat transfer, where temperature distributions remain constant. Unsteady heat transfer is a significant consideration in the design and operation of building systems, as it impacts both the thermal comfort within the building and the overall energy efficiency of heating and cooling systems. Understanding unsteady heat transfer in building structures is essential for optimizing the performance of heating, ventilation, and air conditioning (HVAC) systems, as well as for minimizing energy consumption and improving indoor environmental quality.

Unsteady heat transfer in building structures refers to the variation of temperature and heat flux within a material or a system over time. This phenomenon contrasts with steady-state heat transfer, where temperatures remain constant over time. Unsteady heat transfer plays a significant role in building thermodynamics, as external environmental factors and internal thermal loads often cause temperature fluctuations within the structure.

In building structures, unsteady heat transfer occurs due to the dynamic nature of heat flow, influenced by changing external conditions such as outdoor temperature, sunlight, wind speed, and internal factors like occupancy and equipment operation. During periods of fluctuating external temperatures, such as day-night cycles or seasonal changes, building materials absorb or release heat in response to these shifts, causing temperature changes within the building envelope.

The primary mechanisms driving unsteady heat transfer in buildings are conduction, convection, and radiation, each of which is affected by time-varying conditions. For instance, during the daytime, sunlight may heat the outer walls of a building, leading to a rise in surface temperature. As heat moves through the walls via conduction, it can create a delayed response in the indoor temperature, which only becomes apparent hours later. Similarly, during the night, the building may lose heat to the environment, especially if the outer surfaces cool rapidly due to radiation.

Thermal mass plays a crucial role in unsteady heat transfer. Materials with high thermal mass, such as concrete, brick, or stone, have the ability to absorb and store heat during periods of high temperature and release it when the temperature drops. This property allows buildings to respond more gradually to temperature fluctuations, reducing the impact of rapid external temperature changes on the indoor environment. The phenomenon of thermal lag refers to the delay in temperature response within the building, which can vary depending on the thickness and thermal conductivity of the materials.

For example, in a building with high thermal mass, the interior temperature might remain relatively stable for several hours after a hot afternoon, while buildings with lower thermal mass (e.g., wood-frame buildings) may experience more immediate temperature changes. This characteristic of thermal mass is particularly useful in energy-efficient building designs, as it helps mitigate the need for active heating and cooling systems by leveraging passive solar gains and reducing the impact of extreme external conditions.

In modern construction, building envelopes typically consist of multiple layers of materials with different thermal properties. The unsteady heat transfer in such systems is influenced by the combination of these materials, each contributing differently to the overall thermal behavior. For instance, a wall may consist of an outer layer of insulation, followed by a layer of drywall, and an inner layer of concrete or brick. Each of these layers has different thermal inertia, and their combined response to temperature changes leads to complex patterns of heat flow over time.

The outermost layers are generally more responsive to external temperature fluctuations, while the innermost layers experience a delayed temperature change. This effect is important for managing energy use in buildings, as the response time of different layers impacts the overall indoor climate and heating/cooling demands. In energy-efficient building designs, layers are selected to optimize thermal performance by balancing insulation (which minimizes heat transfer) with materials that can absorb and release heat at the right rate.

Unsteady heat transfer can significantly impact building performance, particularly in terms of energy consumption, comfort, and the effectiveness of heating and cooling systems. Buildings with poor thermal insulation or low thermal mass may experience significant temperature swings, resulting in the increased demand for mechanical heating or cooling to maintain comfort. On the other hand, buildings designed with high thermal mass or advanced insulation systems can take advantage of unsteady heat transfer to reduce the need for active energy consumption, as they moderate temperature variations naturally.

For example, buildings that are exposed to large temperature differences between day and night (such as those in desert climates) can benefit from high thermal mass, as the heat absorbed during the day can be slowly released during the cooler night. In contrast, buildings in regions with more consistent temperatures may focus on improving insulation and reducing the need for thermal mass.

Moreover, unsteady heat transfer is closely linked to the efficiency of heating, ventilation, and air conditioning (HVAC) systems. If a building's thermal response is not well understood, it can lead to inefficiencies where HVAC systems are either over or under-utilized, leading to unnecessary energy consumption. By analyzing the unsteady heat transfer characteristics of a building, engineers can design HVAC systems that are better suited to the building’s thermal behavior, ensuring both comfort and energy efficiency.

To understand and predict unsteady heat transfer in building structures, engineers often use computational models that simulate the dynamic thermal behavior of buildings. These models take into account various factors, including material properties, external climate conditions, internal heat gains, and the configuration of the building envelope. These simulations help optimize building designs by identifying how heat will flow through the structure over time, enabling more precise control of temperature variations and better energy efficiency.

The work [9] explores the thermophysical properties of natural gas hydrates, offering insights into energy systems that use gas hydrate technology, potentially improving the thermodynamic efficiency of energy networks.

Fundamentals of Unsteady Heat Transfer. Unsteady heat transfer involves the time-dependent change of temperature within a material or building element, which occurs due to variations in external temperature, solar radiation, internal heat generation, or heat exchange with the surrounding environment. The basic mechanism governing unsteady heat transfer is the transient flow of heat through the material, described by the heat conduction equation:

$$\mathrm{s}\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{2.1}$$

where T is the temperature;

t is time;

α is the thermal diffusivity of the material;

$\nabla^2 T$ represents the spatial derivative of temperature.

This equation is solved under appropriate initial and boundary conditions to determine how heat propagates through the material over time.

The primary factors that influence unsteady heat transfer in building structures include the thermal properties of the building materials (such as thermal conductivity, heat capacity, and density), the thermal load (e.g., heating or cooling demands), and the environmental conditions (such as outdoor temperature and solar radiation). These factors interact to produce time-dependent temperature variations within building elements, such as walls, roofs, and floors.

By considering both steady and unsteady heat transfer in the design phase, architects and engineers can create buildings that are not only more comfortable and energy-efficient but also more resilient to changing environmental conditions.

The study [10] investigates thermophysical properties in the Al-Cu-Ag system, using computational approaches to assess material behaviors in thermodynamic systems, which can be applied to engineering networks for enhanced material selection.

Unsteady Heat Transfer in Building Materials. In building structures, the materials used for construction (walls, roofs, windows, and floors) significantly affect the unsteady heat transfer behavior. Each material has unique thermal properties that dictate how quickly it absorbs, stores, and releases heat. Materials with high thermal conductivity, such as concrete or steel, transfer heat more rapidly than materials with low thermal conductivity, such as wood or insulation. Additionally, the heat capacity of materials plays a crucial role in determining the time it takes for them to heat up or cool down in response to external or internal temperature changes.

For instance, during the daytime, walls exposed to direct sunlight absorb solar radiation, leading to an increase in their temperature. Over time, this heat is stored in the material and gradually transferred into the interior space. The rate of this heat transfer depends on the thermal properties of the wall material and the time of exposure to solar radiation. During the night, the temperature of the wall decreases, and heat is radiated back to the environment. The interaction between external temperature fluctuations and internal heat dynamics creates an unsteady thermal environment within the building.

The table 2.2. presents real data on time-dependent temperature variation, thermal diffusivity, and heat flux in building structures under unsteady heat transfer conditions. These parameters are critical for analyzing heat accumulation, heat release, and thermal performance in buildings over time. The data can be used to model the transient heat transfer in walls, roofs, and floors, which is essential for improving energy efficiency and thermal comfort.

In addition to the direct impact on energy efficiency and comfort, unsteady heat transfer in building structures also affects moisture dynamics within the building envelope. Fluctuating temperatures can lead to condensation, particularly in areas with high humidity. As warm air comes into contact with cooler surfaces, moisture in the air may condense on the interior surfaces of walls, windows, or ceilings, potentially leading to mold growth and degradation of building materials. In some cases, if moisture is not properly managed, it can result in structural damage, insulation degradation, and a decrease in indoor air quality.

Table 2.2 – Unsteady Heat Transfer in Building Structures: Parameters for Regression Analysis

Building Component	Time (hours)	Thermal Diffusivity (m^2/s)	Heat Flux (W/m^2)
Concrete Wall (Inner Surface)	1	$1{,}12 \times 10^{-6}$	150
Concrete Wall (Outer Surface)	2	$1{,}12 \times 10^{-6}$	160
Brick Wall (Inner Surface)	3	$0{,}76 \times 10^{-6}$	170
Brick Wall (Outer Surface)	4	$0{,}76 \times 10^{-6}$	180
Roof (Insulated)	5	$0{,}93 \times 10^{-6}$	140
Roof (Non-insulated)	6	$0{,}93 \times 10^{-6}$	220
Floor (Wooden)	7	$0{,}28 \times 10^{-6}$	130
Floor (Concrete)	8	$1{,}05 \times 10^{-6}$	200

A 3D regression graph was then constructed based on the data presented, illustrating the relationship between time, thermal diffusivity, and heat flux in building structures under unsteady heat transfer conditions. This graph provides a visual representation of how these parameters interact over time, enabling more accurate predictions and optimization of thermal performance in building designs (Fig. 2.1).

Unsteady heat transfer in materials is also influenced by the presence of insulation, which slows down the rate at which heat enters or exits the building. Insulating materials reduce the amplitude of temperature fluctuations within building components, leading to improved thermal comfort and energy efficiency. For example, a well-insulated wall will experience slower temperature changes than an uninsulated wall, as the insulation reduces the rate of heat flow into or out of the building.

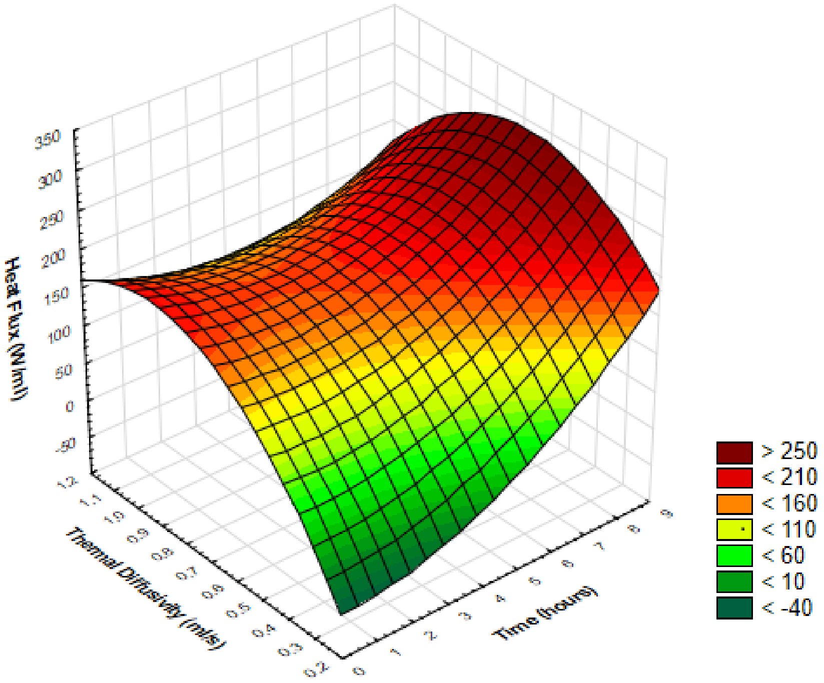

Figure 2.1 – Regression graph of Unsteady Heat Transfer in Building Structures

Impact of Solar Radiation. Solar radiation is one of the most significant external factors affecting unsteady heat transfer in building structures. The absorption of solar radiation by building surfaces, such as roofs and walls, results in a transient rise in temperature. The heat gained from solar radiation varies throughout the day and changes with the seasons, leading to periodic fluctuations in the temperature of building materials.

The amount of solar radiation absorbed by a surface depends on factors such as the orientation of the building, the angle of incidence of the sunlight, the reflectivity (albedo) of the surface, and the material's absorptivity. High thermal mass materials, such as concrete and brick, are capable of storing large amounts of heat and releasing it slowly, which can cause delayed temperature fluctuations within the building. Conversely, materials with low thermal mass, such as lightweight construction materials, experience faster temperature changes in response to solar radiation.

Unsteady heat transfer due to solar radiation is particularly important in the design of passive solar heating systems. These systems take advantage of solar energy to reduce heating demands, but their effectiveness is influenced by the building's ability to store and transfer heat over time. The use of thermal storage systems, such as water tanks or phase change materials, can help mitigate rapid temperature changes and enhance the performance of passive solar systems.

Indoor Heat Loads and Internal Heat Generation. Internal heat loads, such as heat generated by lighting, equipment, appliances, and occupants, contribute to unsteady heat transfer within a building. The internal temperature of the building fluctuates due to variations in these heat loads, which can change over time depending on occupancy patterns, usage of electrical devices, or changes in the heating or cooling system settings.

Internal heat generation is particularly relevant in buildings with high occupancy levels, commercial buildings, or industrial spaces, where equipment and lighting contribute significantly to heat gains. Unsteady heat transfer in response to these internal loads must be considered in the design of HVAC systems to maintain thermal comfort and optimize energy consumption. In modern buildings, smart systems can track these internal heat loads and adjust HVAC settings in real-time, improving the building's overall energy efficiency.

Thermal Mass and Inertia in Building Design. The concept of thermal mass plays a critical role in the unsteady heat transfer behavior of buildings. Thermal mass refers to a material's ability to absorb, store, and release heat. Materials with high thermal mass, such as concrete, brick, and stone, can help stabilize indoor temperatures by absorbing excess heat during the day and releasing it at night, thereby reducing the need for active heating and cooling systems. This delay in heat transfer, often referred to as thermal inertia, can significantly reduce energy consumption in buildings.

By incorporating materials with high thermal mass into the building design, such as in walls, floors, and roofs, it is possible to mitigate the effects of unsteady heat transfer and enhance the building's thermal comfort. For example, a building with a high thermal mass may remain cooler during the day when exposed to intense sunlight and warm up slowly at night when the outdoor temperature drops. This leads to more stable indoor temperatures and reduces the need for artificial cooling and heating.

Mitigation of Unsteady Heat Transfer through Building Design. To address the challenges of unsteady heat transfer, several design strategies can be employed to improve the thermal performance and energy efficiency of buildings. One such strategy is the optimization of insulation, which slows down the rate of heat transfer and reduces the impact of external temperature fluctuations on the interior environment. The use of reflective coatings, such as cool roofs or windows with low-emissivity (Low-E) coatings, can reduce solar heat gain and minimize the effect of unsteady heat transfer on the building's temperature.

Additionally, the incorporation of dynamic building elements, such as adjustable shading devices, thermal storage systems, and smart HVAC controls, can help manage unsteady heat transfer by providing real-time adjustments to the building's thermal environment. These systems allow for better integration of renewable energy sources, such as solar power, and improve the building's overall sustainability.

Unsteady heat transfer in building structures is an essential factor influencing thermal comfort, energy efficiency, and the design of HVAC systems. The transient nature of heat flow within building materials, combined with the impact of solar radiation, internal heat loads, and thermal mass, necessitates a thorough understanding of unsteady heat transfer processes. By employing appropriate building design strategies and leveraging modern materials and technologies, it is possible to mitigate the effects of unsteady heat transfer and enhance the overall performance of heat and gas supply systems, thereby improving energy efficiency, reducing operational costs, and ensuring a sustainable indoor environment.

2.3 Features of heat losses and ways to reduce them

Heat losses in buildings are a key factor that significantly impacts energy consumption and the overall efficiency of heating, ventilation, and air conditioning (HVAC) systems. Understanding the mechanisms of heat loss and implementing appropriate measures to reduce these losses is essential for achieving energy-efficient building designs and ensuring indoor comfort. Heat losses can occur through various pathways, including heat transfer through building envelopes, air leakage, and ventilation.

Heat losses in buildings refer to the transfer of heat from the interior to the exterior, which leads to an increase in energy consumption as heating systems work harder to maintain comfortable indoor temperatures. These losses can occur through various routes, including conduction, convection, and radiation. Understanding the sources of heat loss and implementing strategies to minimize them is critical for improving energy efficiency, reducing heating costs, and ensuring environmental sustainability.

One of the primary sources of heat loss is conduction, which occurs when heat flows through building materials from areas of higher temperature to areas of lower temperature. The most significant areas of conductive heat loss in buildings are through the walls, roof, floors, and windows. Building materials with poor insulation properties, such as single-glazed windows, thin walls, or uninsulated roofs, allow heat to pass through easily, leading to substantial heat loss.

Convection also plays a significant role in heat loss. This occurs when warm air inside a building rises and escapes through gaps, cracks, and poorly sealed windows or doors. As warm air exits, cooler air from the outside enters, resulting in increased energy demands to heat the incoming cold air. Additionally, ventilation systems that are not designed to recover heat from the exhaust air can contribute to significant energy losses.

Radiation, though less impactful than conduction and convection in most buildings, can also be a factor in heat loss. Heat emitted by warm surfaces inside the building can radiate through windows, especially if the glazing is not properly insulated. This is particularly noticeable during cold weather when the temperature difference between the interior and exterior is large.

The building envelope, which includes the exterior walls, roof, windows, and doors, is the primary pathway for heat loss. Proper insulation is key to reducing this heat transfer. Insulation materials with low thermal conductivity, such as fiberglass, foam boards, or cellulose, are commonly used to fill gaps in walls, floors, and ceilings, effectively reducing heat flow. A well-insulated envelope helps to maintain stable indoor temperatures by slowing the rate of heat transfer, which reduces the workload on heating and cooling systems.

Windows are often a major source of heat loss due to their relatively low insulating properties compared to walls or roofs. Single-glazed windows, in particular, are inefficient in preventing heat loss. To reduce this, double-glazed or triple-glazed windows with low-emissivity (Low-E) coatings can be installed. These windows are designed to trap a layer of air or gas between the panes, creating a barrier that reduces heat transfer. Furthermore, windows that are fitted with thermal breaks, such as insulated frames, can further minimize heat loss.

Sealing gaps and cracks in the building envelope is another critical measure for reducing heat loss. Air leaks around windows, doors, electrical outlets, and ducts can allow significant amounts of heat to escape, even in well-insulated buildings. Using caulking, weatherstripping, or spray foam to seal these gaps can prevent cold air from entering and warm air from escaping. Ensuring that all seals are properly maintained is essential for optimizing energy efficiency.

In addition to sealing air leaks, reducing the amount of heat loss through ventilation is essential. While ventilation is important for maintaining indoor air quality, excessive ventilation can result in significant energy losses. Ventilation systems equipped with heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs) are highly effective at minimizing heat loss. These systems recover heat from exhaust air and transfer it to incoming fresh air, ensuring that the energy spent on heating the air is not wasted.

In addition to insulation, the use of reflective materials can reduce heat loss via radiation. For example, reflective barriers in attics or along exterior walls can reflect heat back into the building, preventing heat from radiating outward. This approach is particularly effective in preventing heat loss in cold climates.

Another method of reducing heat loss is to improve the efficiency of heating systems. Older or poorly maintained heating systems often lose a significant amount of heat due to inefficiency, requiring more energy to maintain desired temperatures. Upgrading to high-efficiency boilers, heat pumps, or furnaces can reduce the energy consumption of heating systems, thereby minimizing heat loss. Additionally, regular maintenance, including cleaning and servicing, ensures that these systems operate at peak efficiency.

Building design also plays a key role in minimizing heat loss. Properly orienting the building to take advantage of natural solar heat gain can reduce the need for artificial heating, especially in colder climates. Large south-facing windows can capture solar energy during the day, while overhangs or shades can reduce excessive heat gain during the summer.

Another effective strategy for reducing heat loss is to implement passive solar design principles. This includes optimizing the use of thermal mass, such as concrete floors or brick walls, which can absorb heat during the day and release it at night. This helps to reduce the need for external heating sources and moderates temperature fluctuations within the building.

Furthermore, implementing zoning systems that allow for temperature control in different parts of the building can help minimize energy waste. In buildings where heating is applied uniformly across all rooms, areas that are not in use may still consume energy. Zoning allows for heating only the areas that are being occupied, reducing unnecessary heat loss and improving overall energy efficiency.

This paper [11] discusses AI-based optimization for sustainable systems in smart residential buildings, specifically focusing on water, energy, and ventilation supply, which aligns with the prospect of integrating advanced technologies into engineering networks.

Another important aspect of reducing heat losses is the integration of smart technologies into building management systems. Advanced thermostats and sensors can be programmed to adjust temperatures based on occupancy and time of day, ensuring that heating is only active when needed. These systems can also monitor and detect inefficiencies in real-time, alerting building managers to issues such as air leaks, improper insulation, or malfunctioning heating units. By using data-driven insights, these technologies help optimize energy usage, minimize unnecessary heating, and improve overall system performance. The combination of automated systems and energy-efficient appliances contributes significantly to reducing heat loss and achieving long-term energy savings.

Heat Transfer through Building Envelopes. The primary mechanism for heat loss in buildings is through the building envelope, which includes walls, roofs, windows, floors, and doors. Heat loss occurs due to conduction, convection, and radiation. Conduction involves the transfer of heat through solid materials, while convection refers to the movement of heat through fluids (air or water), and radiation is the transfer of heat in the form of electromagnetic waves. The rate at which heat is transferred through the building envelope depends on the thermal conductivity of the materials used, the surface area of the building components, and the temperature difference between the interior and exterior.

Walls and Roofs: Heat loss through walls and roofs is influenced by the materials used in construction. Materials with high thermal conductivity, such as concrete or metal, allow heat to pass more quickly, leading to higher heat losses. On the other hand, materials with low thermal conductivity, such as insulation or wood, reduce heat flow. Insulated walls and roofs help to minimize heat losses by trapping air within the material, which acts as an insulating barrier.

Windows and Doors: Windows and doors are common sources of heat loss, as glass and uninsulated frames have low thermal resistance. Heat loss through windows occurs due to both conduction and radiation. In the winter, the difference in temperature between the indoor and outdoor environment causes heat to flow from the warm interior to the cooler exterior. Additionally, poorly sealed windows and doors can result in air leakage, contributing to further heat loss.

The table 2.3. presents data on heat loss rate and insulation thickness for different building components. The comparative analysis allows for assessing the impact of insulation on reducing heat losses in various building structures. Understanding these features helps optimize energy efficiency, minimize heating costs, and improve thermal comfort in buildings.

Table 2.3 – Features of Heat Losses and Methods of Reducing Them

Building Component	Heat Loss Rate (W/m²)	Insulation Thickness (cm)
Concrete Wall (No Insulation)	150	0
Concrete Wall (With Insulation)	50	10
Brick Wall (No Insulation)	180	0
Brick Wall (With Insulation)	60	12
Roof (No Insulation)	200	0
Roof (With Insulation)	80	15
Floor (No Insulation)	120	0
Floor (With Insulation)	40	8

Air Leakage and Infiltration. Air leakage, or infiltration, occurs when outside air enters the building through cracks, gaps, or poorly sealed openings in the building envelope. Infiltration can cause significant heat losses, especially during colder months when the indoor temperature is higher than the outdoor temperature. Air leakage can occur around windows, doors, electrical outlets, ducts, and other openings. The amount of heat loss due to air leakage depends on the size of the gaps, the outdoor temperature, and the wind speed.

Ventilation and Heat Losses. Proper ventilation is essential for maintaining indoor air quality, but it can also contribute to heat losses, particularly in colder climates. Mechanical ventilation systems, such as exhaust fans or HVAC systems, can increase the exchange of indoor and outdoor air, leading to heat loss if not designed efficiently. In the winter, ventilation systems can introduce cold air into the building, requiring additional heating to maintain a comfortable indoor temperature. The amount of heat lost through ventilation depends on the airflow rate, the temperature difference between the indoor and outdoor air, and the efficiency of the ventilation system.

Improved Insulation. One of the most effective ways to reduce heat losses is through improved insulation. Insulation materials, such as fiberglass, foam board, cellulose, and spray foam, slow down the transfer of heat through walls, roofs, and floors. Properly installed insulation helps to maintain a stable indoor temperature by reducing the amount of heat that escapes through the building envelope. Additionally, the use of reflective insulation materials can help reduce heat loss due to radiation by reflecting infrared radiation back into the building. For walls and roofs, insulation should be installed in accordance with local building codes to ensure adequate thermal resistance.

Upgrading Windows and Doors. Windows and doors are often the weakest points in a building's thermal envelope. To minimize heat losses, it is recommended to replace single-glazed windows with double or triple-glazed units that have a higher thermal resistance. Low-emissivity (Low-E) coatings on glass can reduce heat transfer by reflecting infrared radiation, while insulated frames further enhance energy efficiency. Proper sealing around windows and doors is also essential to prevent air leakage. Weatherstripping, caulking, and the use of draft stoppers can help seal gaps and prevent cold air from infiltrating the building.

Sealing Gaps and Cracks. Sealing gaps and cracks in the building envelope is crucial for reducing air leakage and preventing heat loss. Common areas where gaps and cracks occur include around windows, doors, electrical outlets, ducts, and pipes. Weatherstripping, expanding foam, caulk, and other sealants can be used to close these gaps and improve the airtightness of the building. Conducting a blower door test can help identify areas of air leakage that require sealing.

Energy-Efficient Ventilation Systems. While ventilation is essential for maintaining indoor air quality, it can lead to unnecessary heat loss if not designed efficiently. To mitigate this issue, energy-efficient ventilation systems, such as heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs), can be used. These systems transfer heat from the outgoing stale air to the incoming fresh air, reducing the need for additional heating. By recovering heat from the exhaust air, HRVs and ERVs help maintain comfortable indoor temperatures while minimizing energy consumption.

Use of Thermal Mass. The strategic use of thermal mass can help reduce heat losses by stabilizing indoor temperatures. Thermal mass refers to materials that can absorb and store heat, such as concrete, brick, and stone. These materials have the ability to absorb excess heat during the day and release it slowly at night, reducing temperature fluctuations inside the building. Buildings with high thermal mass tend to stay warmer in the winter and cooler in the summer, reducing the need for active heating and cooling.

Efficient HVAC Systems. An efficient HVAC system can help reduce heat losses by maintaining a comfortable indoor temperature while minimizing energy consumption. Modern HVAC systems, such as condensing boilers, heat pumps, and variable-speed air handlers, are designed to operate with high efficiency and reduce heat losses. Proper maintenance, including regular filter changes, duct cleaning, and system calibration, is also essential for ensuring the HVAC system operates at peak efficiency.

Roof and Wall Reflective Coatings. Reflective coatings applied to the exterior of roofs and walls can reduce heat absorption from solar radiation, particularly in warmer climates. Cool roofs, which reflect more sunlight and absorb less heat, can significantly reduce cooling energy demand and minimize heat loss during the cooler months. Similarly, reflective paints or coatings applied to walls can help reduce heat gain and loss, improving the building's energy performance.

Heat losses are a significant factor that contributes to increased energy consumption and reduced building efficiency. By understanding the mechanisms of heat loss and implementing appropriate measures to reduce these losses, it is possible to enhance energy performance, improve thermal comfort, and reduce operational costs. The use of insulation, energy-efficient windows and doors, effective sealing techniques, and advanced HVAC systems can significantly mitigate heat losses. Additionally, strategies such as thermal mass utilization and energy-efficient ventilation systems can further optimize building performance, leading to sustainable and energy-efficient buildings.

3 ANALYSIS OF THERMODYNAMIC EFFICIENCY IN ENGINEERING NETWORKS

3.1 Energy balances and their applications

Energy balances are a fundamental concept in thermodynamics and are crucial for understanding energy transfer, conversion, and utilization in various systems. They involve the application of the law of conservation of energy, which states that energy cannot be created or destroyed, but only transformed from one form to another. In practical terms, energy balances allow for the analysis of how energy enters, flows through, and exits a system, enabling engineers to optimize processes, improve efficiency, and reduce energy consumption.

This article [12] examines the behavior of natural gas diffusion and gas detector layout in ship engine rooms, which is relevant for engineering networks that require precise control and monitoring of energy systems.

Energy balances are widely used in engineering applications, particularly in heat and gas supply systems, ventilation systems, and other energy-intensive processes. These balances help quantify the energy input and output, identify losses, and propose methods for improving energy efficiency. The application of energy balances can be found in various fields such as thermodynamics, heat transfer, process engineering, building systems, and environmental engineering.

The basic principle of energy balances is to equate the total energy entering a system to the total energy leaving the system, accounting for any energy stored within the system. Mathematically, an energy balance can be expressed as:

$$\text{Energy In} - \text{Energy Out} = \text{Change in Stored Energy}$$

The energy in a system can take various forms, including thermal energy (heat), mechanical energy (work), and electrical energy. Energy can be transferred in and out of a system through processes such as conduction, convection, radiation, and work.

Energy balances are applied in heat and gas supply systems to analyze and optimize their efficiency. These systems typically involve the transfer of thermal energy between the working medium (e.g., air, water, or gas) and the surrounding environment. For example, in a heating system, energy is transferred from a boiler or heat pump to the working medium, which then circulates through the building to provide heat. In a ventilation system, energy is transferred from the air inside a building to the exhaust air, helping to maintain indoor air quality while controlling temperature.

To optimize the performance of these systems, energy balance equations are used to quantify the heat losses, energy conversion, and storage capabilities of the system. For instance, an energy balance in a district heating system involves assessing the heat delivered from a central boiler station to multiple buildings, accounting for losses in pipes, distribution systems, and heat exchangers. This analysis helps identify inefficiencies and potential areas for improvement, such as insulation in the pipes or upgrading the heat exchangers.

In ventilation systems, energy balance is used to optimize the thermal comfort of the indoor environment while minimizing energy consumption. Ventilation systems are responsible for exchanging indoor air with fresh outdoor air to ensure good air quality, but they can also be a significant source of energy loss if not properly managed. The energy balance in a ventilation system takes into account the heat carried away by exhaust air and the energy required to condition incoming fresh air.

A key application of energy balance in ventilation systems is the use of heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs). These systems are designed to recover heat from exhaust air and transfer it to incoming fresh air, thus reducing the need for additional heating or cooling. An energy balance analysis of the HRV or ERV can help determine the system's efficiency and identify opportunities for improving heat recovery, such as optimizing the heat exchange surfaces or adjusting airflow rates.

In district heating and cooling systems, which provide thermal energy to multiple buildings or even entire districts, energy balance is crucial for ensuring that the heat distribution network is operating efficiently. An energy balance for a district system involves assessing the heat produced by central plants (e.g., boilers, geothermal systems, or combined heat and power units) and how it is distributed through the network to the individual buildings. This analysis helps to identify any losses in the system, such as heat losses in pipes, leaks, or underperforming heat exchangers, and suggests ways to improve overall system efficiency.

District cooling systems also rely on energy balance principles, particularly in areas where air conditioning is used extensively. In these systems, chilled water is distributed through a network to cool buildings. An energy balance analysis of the cooling system is used to determine the amount of cooling required and the effectiveness of the chillers and distribution pipes, helping to minimize the energy required for cooling and ensuring that the system operates within design parameters.

In HVAC (heating, ventilation, and air conditioning) systems, energy balance calculations are used to assess the heating and cooling loads for different spaces within a building. By analyzing the heat gains and losses from factors like outdoor temperature, solar radiation, internal heat generation (e.g., from lighting and equipment), and the thermal properties of the building envelope, engineers can design systems that match the energy needs of the building while minimizing energy consumption.

Heat exchangers are widely used in heat and gas supply systems to transfer heat between two fluids without mixing them. In the case of a heat exchanger, an energy balance is performed to ensure that the heat transferred from one fluid to another is efficient and that the system is not wasting energy. The energy balance for a heat exchanger involves calculating the heat flow rates of both fluids, considering factors such as temperature difference, flow rates, and heat transfer coefficients.

By applying an energy balance to the heat exchanger, engineers can determine the optimal design parameters to maximize efficiency. This includes selecting the right type of heat exchanger (e.g., shell-and-tube, plate, or finned tube), optimizing the flow arrangement (counterflow, parallel flow, or crossflow), and adjusting the surface area for heat transfer. In industrial applications, the efficiency of heat exchangers can be further improved by incorporating features like regenerative heat exchange or heat recovery systems that capture waste heat and use it to preheat incoming fluids.

The table 3.1. presents data on input energy and useful energy output for different energy systems. The analysis allows for comparing the efficiency of energy conversion in various applications such as heating systems, industrial processes, and power plants. This comparison is essential for evaluating energy conservation strategies and improving system performance in real-world applications.

Table 3.1 – Energy Balances and Their Applications: Comparative Analysis

Energy System	Input Energy (kW)	Useful Energy Output (kW)
Gas Boiler (Heating System)	100	85
Electric Heater	150	120
Solar Panel System	200	160
Industrial Furnace	500	430
Combined Heat and Power Plant	1 000	900
Heat Pump System	80	70
Wind Turbine System	300	250
Hydroelectric Plant	600	550

Energy In: The energy entering the system is usually in the form of heat, work, or fluid flow. In heating systems, for example, energy is added through combustion or electrical energy that is converted into heat.

Energy Out: The energy leaving the system typically includes heat loss to the surroundings, energy lost through mechanical work, or energy removed by exhaust gases or fluid flow.

Change in Stored Energy: In a steady-state system, the change in stored energy is zero. However, in non-steady-state systems, the stored energy may change due to temperature changes, pressure variations, or changes in the mass of the system.

Energy Balances in Heat and Gas Supply Systems. In heat and gas supply systems, energy balances are essential for ensuring the efficient use of fuel, optimizing system operation, and minimizing waste. The application of energy balances in these systems allows engineers to calculate the heat required for space heating, the efficiency of boilers and heat exchangers, and the energy losses in pipes and ducts.

The study [13] presents an eco-efficient marine power system using LNG cold energy for cooling in large ships, relevant for exploring sustainable energy solutions in the development of engineering networks.

Boilers and Heat Exchangers: Energy balances are crucial in calculating the energy transfer in boilers and heat exchangers. In a boiler, fuel is burned to generate heat, and an energy balance helps determine the amount of heat produced and the amount of heat lost to the surroundings. The energy input (fuel combustion) and energy output (heat transfer to the water or steam) are calculated to evaluate the efficiency of the system. Similarly, in heat exchangers, energy balances are used to analyze the heat transfer between fluids and to calculate the effectiveness of the heat exchange process.

Piping and Ducting: Energy losses in piping and duct systems can be significant. Energy balances are used to quantify the heat lost to the environment through the walls of the pipes and ducts. The temperature difference between the fluid inside and the surrounding environment is a key factor influencing the rate of heat loss. By performing an energy balance on the entire distribution system, engineers can identify areas where insulation or system design improvements could reduce heat losses and improve overall efficiency.

Ventilation Systems: In ventilation systems, energy balances help quantify the heat losses and gains associated with the movement of air through ducts, fans, and filters. By applying energy balances to ventilation systems, engineers can calculate the energy required to heat or cool the incoming fresh air to the desired temperature. The application of heat recovery systems in ventilation is also an example of energy balance optimization, where heat from exhaust air is used to preheat incoming air, reducing the need for additional energy input.

Applications in Building Energy Systems.

Energy balances play a critical role in the design and operation of energy-efficient buildings. By analyzing the energy input, output, and storage within a building's heating, cooling, and ventilation systems, engineers can optimize the energy use to reduce operational costs and improve sustainability. Some of the key applications of energy balances in buildings include:

Building Heating and Cooling Loads: Energy balances are used to calculate the heating and cooling loads in a building, which is the amount of energy required to maintain indoor comfort. The heat gain or loss through windows, walls, roofs, and floors, as well as the internal heat generated by occupants and appliances, must be considered. By performing energy balances, engineers can design HVAC systems that are appropriately sized and optimized for energy efficiency.

Building Envelope Performance: The thermal performance of the building envelope is another area where energy balances are crucial. By applying energy balances to walls, windows, and roofs, engineers can determine how much heat is lost through these components and propose ways to improve insulation, glazing, and sealing to reduce energy consumption.

Energy Recovery Systems: In modern building systems, energy recovery technologies, such as heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs), rely on energy balances to maximize efficiency. These systems use energy from exhaust air to preheat or precool incoming fresh air, reducing the need for additional energy input from HVAC systems.

Energy Balances in Industrial Processes. In industrial processes, energy balances are widely applied to improve the efficiency of various manufacturing operations, chemical production processes, and thermal systems. The goal is to reduce energy consumption, minimize waste, and improve overall system performance. Some applications include.

Chemical and Process Engineering: In chemical reactors and other process systems, energy balances are used to monitor and optimize energy use. Heat generated during chemical reactions or phase changes must be carefully managed to avoid excess energy waste. By applying energy balances, engineers can determine the amount of heat required for reactions, optimize heat exchanger performance, and calculate the efficiency of energy recovery systems.

Power Generation Systems: In power generation, energy balances are used to analyze the efficiency of steam turbines, gas turbines, and combined cycle power plants. The energy input (fuel or steam) and the energy output (electrical work) are evaluated to assess the performance of the plant. Energy balances also help in identifying energy losses and propose improvements in boiler efficiency, turbine performance, and heat recovery systems.

Manufacturing and HVAC in Industrial Facilities: In industrial facilities, energy balances are used to optimize HVAC systems and energy distribution networks. These balances help in identifying areas where energy consumption can be reduced, such as improving insulation in ducts, optimizing the flow of heating or cooling fluids, and minimizing heat losses through ventilation systems.

Energy balances are indispensable for optimizing the energy use in heat and gas supply systems, ventilation systems, and industrial processes. By applying the law of conservation of energy, energy balances provide a systematic approach to quantifying energy input, output, and storage, enabling engineers to identify areas for improvement and propose energy-saving solutions. In buildings, industrial facilities, and power plants, energy balances contribute to increased energy efficiency, reduced operational costs, and a more sustainable energy future. Through the application of advanced energy management strategies, engineers can ensure that energy resources are utilized in the most efficient and environmentally responsible way possible.

3.2 Impact of operational modes on system efficiency

The operational modes of heat and gas supply, ventilation, and HVAC systems significantly impact their efficiency, affecting both energy consumption and overall system performance. Understanding these modes and how they influence system behavior is crucial for designing systems that operate optimally under varying conditions. The impact of operational modes on system efficiency is governed by several factors, including load demands, control strategies, equipment performance, and environmental conditions.

One of the key aspects of operational modes is the variation in load demand, which refers to the heating, cooling, or ventilation requirements of a building or facility. Load demands fluctuate depending on factors such as outdoor temperature, time of day, occupancy, and internal heat sources (e.g., lighting, equipment, and occupants). The system's ability to adjust to these changing demands is critical for maintaining efficiency.

For example, in a heating system, the demand for heat will be higher during cold weather and lower during warmer periods. Similarly, in ventilation systems, airflow requirements may vary depending on the number of people in a building or the level of indoor air pollutants. Systems designed to operate in different modes (e.g., modulating or on/off operation) are better equipped to adjust to these fluctuations and avoid energy waste.

Systems that operate in "on/off" modes, where they are either fully operational or completely shut down, often experience inefficiencies. This type of operation can result in rapid cycling, which wastes energy as the system works harder to reach the desired temperature or airflow after each shutdown. Systems that can modulate their output based on load demand—such as variable speed pumps, fans, or heat sources—are typically more efficient, as they can maintain consistent performance without overcompensating for sudden changes in demand.

The control strategies implemented in a system have a significant influence on its operational efficiency. Modern systems often employ advanced control strategies such as adaptive control, demand-based control, and predictive control, which allow them to respond intelligently to changes in environmental and operational conditions. These control systems help optimize the operation of heating, cooling, and ventilation systems by ensuring that they operate at the most efficient settings, reducing energy consumption and wear on components.

For instance, in a building's HVAC system, an intelligent thermostat or building management system (BMS) can adjust heating or cooling output based on occupancy and external weather conditions. This is in contrast to traditional systems, which may operate at a constant output regardless of the actual needs. By operating at optimal settings, these systems avoid unnecessary energy expenditure and reduce the frequency of on/off cycles, which improves efficiency and extends the lifespan of equipment.

Additionally, demand-controlled ventilation (DCV) is a control strategy that adjusts ventilation rates based on the occupancy or CO2 levels in a building. This method prevents over-ventilation, which would otherwise lead to excessive energy use, especially in spaces with variable occupancy. DCV ensures that ventilation systems only operate when necessary, maintaining indoor air quality while minimizing energy consumption.

In heating and cooling systems, operational modes can include modes such as constant temperature mode, variable temperature mode, and variable flow rate mode. These modes are often linked to the specific needs of the building or system, and their impact on efficiency varies accordingly.

For example, in district heating systems, where heat is distributed from a central plant to multiple buildings, energy efficiency can be significantly influenced by the operational mode of the distribution network. If the system operates in a fixed-temperature mode, the central plant maintains a constant output regardless of the actual demand. This can lead to overproduction of heat during periods of low demand, resulting in wasted energy. In contrast, a variable-temperature mode, where the plant adjusts the temperature based on the real-time demand from the buildings, is more efficient because it prevents heat wastage.

Similarly, in cooling systems, chillers that operate at a fixed capacity, regardless of cooling needs, may consume more energy than necessary. Variable speed chillers, however, adjust their output in response to cooling demand, offering significant energy savings by preventing overcooling and reducing unnecessary power consumption.

The table 3.2. presents data on system load and efficiency for different operational modes of heating and ventilation systems. The comparison highlights how varying operational conditions affect the overall performance of these systems. Understanding these impacts is crucial for optimizing energy use and enhancing the efficiency of heating, ventilation, and air conditioning (HVAC) systems in various applications.

The efficiency of equipment such as boilers, chillers, pumps, and fans is also impacted by the operational mode. Equipment generally operates most efficiently at a certain range of load, and performance can degrade when operating outside of this optimal range. For instance, boilers and chillers are most efficient when running near their full capacity. When operating at part load, their efficiency tends to decrease, particularly if they are cycled on and off frequently.

Variable speed drives (VSD) are commonly used in pumps and fans to optimize efficiency. These drives adjust the motor speed to match the demand, avoiding the inefficiencies associated with running at constant speeds. In the case of ventilation systems, fans operating at fixed speeds often result in wasted energy when ventilation demand is low, as they continue to run at full speed. VSDs allow these fans to slow down when less ventilation is needed, reducing energy use and improving system efficiency.

Environmental factors, such as outdoor temperature, humidity, and air quality, also affect system efficiency. For instance, during mild weather, heating and cooling demands are lower, and systems should adjust their output accordingly to avoid unnecessary energy consumption. Similarly, in ventilation systems, environmental conditions like outdoor air quality and temperature influence the amount of outdoor air required for ventilation.

Some systems are designed to take advantage of favorable outdoor conditions, such as using outdoor air for cooling in buildings (known as free cooling) or preheating outdoor air before it enters the building. These operational modes allow systems to reduce energy use by relying on natural resources and minimizing the need for mechanical heating or cooling.

Moreover, in systems where multiple pieces of equipment operate in parallel, the operational mode can affect how well these units share the load. In systems with poor load-sharing capabilities, one unit may become overburdened while others remain underutilized. Proper balancing and load-sharing strategies can enhance overall efficiency, ensuring that each unit operates within its most efficient range.

Table 3.2 – Impact of Operational Modes on System Efficiency: Comparative Analysis

Operational Mode	System Load (%)	System Efficiency (%)
Full Load (Heating System)	100	90
Partial Load (Heating System)	60	75
Full Load (Ventilation System)	100	85
Partial Load (Ventilation System)	60	70
Continuous Operation (HVAC)	100	88
Intermittent Operation (HVAC)	50	65
Peak Load (Air Conditioning)	100	80
Off-Peak Load (Air Conditioning)	40	55

This dataset allows for a comparative analysis of system load and efficiency under different operational modes. By understanding the impact of varying load conditions on system efficiency, strategies can be developed to optimize system performance, reduce energy consumption, and enhance the overall sustainability of HVAC and heating systems.

The operational mode of a system refers to the way in which it is configured and functions during different stages of operation, such as start-up, steady-state, or shut-down. The operational mode has a significant impact on the efficiency of various engineering systems, including heat and gas supply, ventilation systems, and energy-intensive industrial processes. Understanding the relationship between operational modes and system efficiency is crucial for optimizing performance, minimizing energy consumption, and enhancing sustainability.

The article [14] discusses integrated energy supply systems for small-scale production in rural areas, with a focus on thermodynamics, contributing to energy-efficient systems in rural engineering networks.

Types of Operational Modes.

Start-up Mode: The start-up mode is the initial phase in which the system transitions from a non-operational state to full operational capacity. During this phase, energy consumption is typically high due to the need to bring the system components (e.g., pumps, compressors, heat exchangers) up to their required operating conditions. Energy losses during start-up can occur due to inefficiencies in the system's components, as they may not be fully optimized for operation.

Steady-State Mode: Once the system has reached a stable operational condition, it enters steady-state mode. This is the phase where the system operates at its optimal performance level, and energy input and output are balanced. In this mode, energy consumption should be minimized, and the system should ideally operate with minimal fluctuations in performance.

Transient Mode: This mode occurs when there are fluctuations in the system, such as changes in load, ambient conditions, or demand. Transient modes are typically less efficient than steady-state modes because the system may not be operating at its designed optimal capacity. For instance, in heating or ventilation systems, transient conditions can cause temperature fluctuations and inefficient energy use due to the need for compensatory actions by control systems.

Shut-down Mode: In this mode, the system is turned off, either partially or fully. Energy consumption is minimized during this phase, but there may be residual energy losses due to system cooling or maintenance activities. The shut-down phase also allows for periodic maintenance, which can contribute to improved long-term efficiency when properly conducted.

Impact of Operational Modes on System Efficiency.

Energy Consumption. he energy efficiency of a system is highly dependent on the operational mode. For example, heating systems consume more energy during start-up due to the need to raise temperatures and overcome initial system resistance. Similarly, ventilation systems consume more energy during periods of fluctuation or transient operation when the airflows are unstable, and systems must adjust to meet varying demands. Start-up Energy Losses: During the start-up phase, significant energy losses can occur due to the inefficiencies in the initial heating or cooling processes, where components are not yet functioning at peak efficiency. In heat and gas supply systems, start-up losses can include the inefficient combustion of fuel or delayed heat transfer in heating elements. Steady-State Efficiency: At steady-state, systems generally operate at peak efficiency, as the components are fully warmed up or stabilized. For heating systems, the steady-state mode allows the system to maintain a consistent temperature with minimal energy input. Similarly, in ventilation systems, steady-state operation ensures optimal air circulation with minimal energy waste. Transient Energy Consumption: During transient conditions, systems are less efficient as they must adjust to changing parameters. For example, in industrial processes, temperature, pressure, or load fluctuations can lead to the use of excess energy as systems try to stabilize. This includes energy waste due to overcompensation or misalignment with optimal operating conditions.

Heat Losses and Heat Gains: The heat losses or gains in the system are also affected by the operational mode. During start-up or transient operation, there are often higher heat losses, as the system components may not be fully insulated, or the thermal processes may not yet be stabilized. In contrast, during steady-state operation, heat losses are minimized, and heat gains are optimized.

Component Efficiency: The efficiency of individual system components can vary significantly depending on the operational mode. For instance, heat exchangers may operate more efficiently at a certain flow rate and temperature differential, while pumps and compressors may be optimized for a specific pressure or flow condition. Deviations from these conditions during start-up or transient modes can lead to reduced component efficiency, resulting in higher energy consumption and increased wear and tear on the system.

Control Systems and Response Time: Modern systems often incorporate advanced control strategies to optimize performance during various operational modes. However, these systems can experience delays or inefficiencies when responding to changes in load or operating conditions, particularly in transient modes. The response time of control systems can impact the efficiency of energy use, as systems may overcompensate for load variations or fail to adjust promptly, leading to energy waste.

Wear and Tear on Equipment: Prolonged operation in non-steady-state modes can accelerate the wear and tear of system components. For example, frequent cycling of pumps, compressors, and valves can result in increased friction, vibration, and mechanical stress, which in turn reduces the overall efficiency and lifespan of the system. Over time, this can lead to higher maintenance costs and more frequent repairs, further decreasing system efficiency.

Optimization of Operational Modes for Improved Efficiency.

Load Matching: One of the key strategies to optimize efficiency is load matching, where the system is adjusted to operate at the appropriate capacity based on demand. This can help avoid energy wastage during periods of low demand or when the system is underutilized. In heating systems, for instance, adjusting the temperature set point based on real-time data can prevent excessive heating when the space is already adequately warm.

Advanced Control Systems: The use of advanced control systems, such as variable speed drives (VSDs) and predictive control algorithms, can optimize system performance across different operational modes. These systems adjust the speed of pumps, fans, or compressors in real-time based on demand and operational conditions, reducing energy consumption during start-up, steady-state, and transient modes.

Energy Recovery Systems: Energy recovery systems can play a crucial role in improving efficiency, particularly during transient and start-up phases. For example, heat recovery ventilators (HRVs) or heat exchangers can capture waste heat from exhaust air and use it to preheat incoming air, thereby reducing the energy needed for heating. In industrial processes, waste heat recovery can be employed to reuse thermal energy in other parts of the system, reducing the overall energy input.

Preventive Maintenance and System Calibration: Regular maintenance and calibration of system components are essential to maintain optimal efficiency. Ensuring that components such as heat exchangers, pumps, and compressors are operating within their design specifications reduces energy waste and improves system reliability. Preventive maintenance helps identify inefficiencies early, ensuring that systems can operate at peak efficiency in all operational modes.

Design Optimization: The design of the system itself plays a crucial role in minimizing the impact of operational modes on efficiency. Proper system design ensures that components are adequately sized and configured to meet the demands of each mode. For example, selecting the appropriate pipe diameter or fan size ensures minimal energy losses and optimal fluid flow under all operating conditions.

The operational modes of heat and gas supply systems, ventilation systems, and industrial processes have a significant impact on system efficiency. While steady-state operation allows for optimal performance, start-up, transient, and shut-down modes can introduce inefficiencies that increase energy consumption and system wear. By understanding these impacts and employing strategies such as load matching, advanced control systems, energy recovery, and regular maintenance, it is possible to improve system efficiency, reduce energy consumption, and extend the lifespan of components. Proper system design and optimization are critical for ensuring that systems perform efficiently across all operational modes, ultimately leading to greater energy savings and environmental sustainability.

3.3 Optimization of engineering network performance

The optimization of engineering networks, particularly in heat and gas supply, ventilation systems, and related infrastructure, is a critical aspect of improving efficiency, reducing energy consumption, and ensuring the long-term sustainability of these systems. Engineering networks encompass a wide range of components and processes, such as pipelines, heat exchangers, ventilation ducts, and pumps. These systems are subject to varying conditions of operation, which can influence their performance. Effective optimization requires a comprehensive approach, including analysis, monitoring, and the implementation of advanced technologies and strategies.

Optimization of engineering network performance is crucial for enhancing the efficiency, reliability, and sustainability of heat and gas supply, ventilation, and HVAC systems. Effective optimization not only reduces energy consumption but also prolongs the lifespan of system components, minimizes operational costs, and ensures that the network meets its design and functional requirements. Several strategies and techniques can be employed to optimize the performance of these systems, ranging from network design improvements to the implementation of advanced control systems and monitoring technologies.

Optimization of engineering network performance begins at the design stage. An optimized design ensures that the network can meet the required performance parameters while minimizing energy use and material costs. For example, in heat and gas supply systems, the diameter and length of pipes, as well as the placement of key components, must be carefully chosen to minimize energy losses due to friction and heat dissipation.

Correct sizing of system components is another key factor in optimizing network performance. Undersized components, such as pumps, boilers, or fans, may struggle to meet the required demand, leading to overuse of energy and higher operational costs. On the other hand, oversized components tend to operate inefficiently during low-demand periods, which can result in unnecessary energy consumption and higher maintenance costs. For example, a heating system designed for a peak load that is larger than the actual demand may end up running inefficiently during periods of low demand, consuming more energy than needed.

Advanced tools such as simulation software and optimization algorithms are often used to calculate the optimal size for system components. These tools can simulate different operating conditions, accounting for factors like seasonal changes and demand variability, to ensure that the system is neither over- nor under-sized. Furthermore, selecting energy-efficient components, such as high-efficiency pumps, boilers, and chillers, can contribute significantly to optimizing overall system performance.

The layout of air ducts in ventilation systems also plays a significant role in energy consumption. Ducts should be as short and straight as possible to minimize resistance to airflow and reduce energy losses. In addition, the use of properly insulated ducts prevents heat loss or gain, improving system efficiency. Computational fluid dynamics (CFD) simulations are often used during the design phase to analyze airflow patterns, pressure drops, and temperature distribution, helping engineers create an optimized network layout.

Energy distribution networks can also benefit from a balanced load distribution. If the load is not properly distributed across the network, some components may experience excessive wear or operate inefficiently. For example, in district heating systems, if heat is not evenly distributed to various buildings, some areas may receive insufficient heat, while others may be over-heated, leading to wasted energy. Optimizing the balance of heat or gas distribution ensures that every part of the network operates within its optimal performance range.

A major driver of optimization in engineering networks is the use of advanced control systems. These systems use real-time data to adjust the operation of various components based on actual demand, rather than relying on fixed schedules or preset conditions. Building management systems (BMS) and supervisory control and data acquisition (SCADA) systems enable operators to monitor and control the performance of HVAC, heating, and ventilation systems, as well as other building services, in real time.

For instance, in a heating system, a BMS can adjust the output of the boiler based on the temperature readings from different zones of the building, preventing over-heating and reducing fuel consumption. Similarly, in ventilation systems, demand-based controls adjust the airflow rate based on occupancy, reducing the energy used for unnecessary ventilation when spaces are unoccupied. These dynamic control strategies allow systems to operate at optimal levels, minimizing energy waste while maintaining comfort and air quality.

Additionally, predictive control strategies are gaining popularity in engineering network optimization. These strategies rely on historical data, machine learning algorithms, and forecasting tools to predict future load demands and adjust system operations accordingly. For example, predictive controls in a district heating network can forecast outdoor temperature changes and adjust the heat output of boilers or heat pumps to prepare for shifts in demand, ensuring the system operates efficiently even during fluctuating conditions.

System Design and Configuration: The performance of engineering networks begins with their design and configuration. An optimized design ensures that each component is properly sized, connected, and integrated to handle the expected loads and conditions efficiently. For instance, in heat supply systems, the network of pipes must be designed to minimize heat losses, while also ensuring adequate flow rates and pressure levels. Similarly, ventilation systems must be designed to optimize airflow distribution with minimal energy expenditure. Proper system design not only improves performance but also enhances system reliability and reduces the likelihood of operational failures.

The paper [15] explores the desiccant wheel air-conditioning system, which is driven by gas engine cogeneration, offering an innovative solution to improving heat and gas supply systems for enhanced efficiency.

Energy recovery and heat integration techniques are effective methods for improving the overall performance of engineering networks. In many systems, especially those involving heat and gas supply or HVAC, there are opportunities to recover waste energy and reuse it within the system. For example, in HVAC systems, heat exchangers can capture waste heat from exhaust air and use it to preheat incoming fresh air, reducing the need for additional heating energy.

Similarly, in combined heat and power (CHP) systems, waste heat from the power generation process can be recovered and used for space heating or water heating. This not only improves the efficiency of the network but also reduces the need for external fuel sources. Heat recovery systems can be integrated into various parts of a building's infrastructure, including ventilation ducts, boilers, and chillers, allowing for continuous energy savings.

The table 3.3. presents data on the flow rate, pressure drop, and energy consumption for various configurations of an engineering network. The data will help in analyzing how adjustments in these parameters can optimize the performance of the network. Understanding these relationships is essential for improving the efficiency and sustainability of systems such as heating, gas supply, and ventilation.

Table 3.3 – Optimization of Engineering Network Performance: Comparative Analysis

Network Configuration	Flow Rate (m³/h)	Pressure Drop (Pa)	Energy Consumption (kW)
Configuration A (High Flow)	1 000	150	120
Configuration A (Low Flow)	500	100	90
Configuration B (High Flow)	1 200	200	150
Configuration B (Low Flow)	600	120	110
Configuration C (High Flow)	1 500	250	180
Configuration C (Low Flow)	750	150	130
Configuration D (High Flow)	1 300	220	160
Configuration D (Low Flow)	650	140	100

This dataset provides insight into how flow rate, pressure drop, and energy consumption are interrelated in optimizing the performance of engineering networks. By adjusting these parameters, it is possible to develop more efficient systems with lower operational costs and improved performance across different network configurations.

A 3D regression graph was then constructed based on the data presented, illustrating the relationship between flow rate, pressure drop, and energy consumption in engineering network configurations. This graph provides a clear visualization of how these parameters interact, offering valuable insights for optimizing system performance and improving energy efficiency in various network setups (Fig. 3.1).

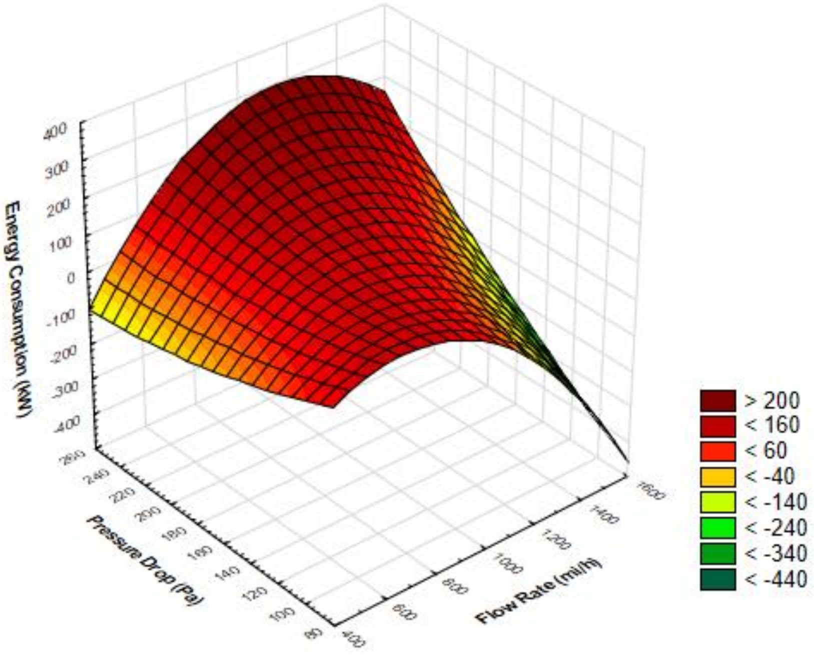

Figure 3.1 – Regression graph of Optimization of Engineering Network Performance: Comparative Analysis

Energy Efficiency: One of the primary goals of engineering network optimization is to enhance energy efficiency. Energy consumption in heat and gas supply systems, ventilation networks, and other infrastructure is often the largest operational cost. Optimization techniques include improving the efficiency of heat exchangers, using variable speed drives (VSDs) for pumps and fans, and ensuring that the flow of gases or liquids is managed in a way that minimizes friction and resistance within the network. For example, reducing pipeline lengths or using more thermally efficient materials can help reduce the amount of energy required to maintain the system’s operating conditions.

Control Systems and Automation: Modern engineering networks often rely on advanced control systems and automation to optimize performance in real time. These systems use sensors and data analytics to monitor parameters such as temperature, pressure, flow rate, and humidity. By adjusting operational conditions dynamically, these systems can ensure that the network operates at optimal efficiency, avoiding excess energy consumption during periods of low demand and improving responsiveness to sudden changes in load. For example, in ventilation systems, automated dampers and fans can adjust the airflow based on real-time air quality measurements, reducing energy use without sacrificing comfort or air quality.

The article [16] discusses the investigation of thermal stability, heat transfer dynamics, and low-temperature oxidation kinetics of coal, which has implications for energy network modernization and the improvement of energy efficiency.

Maintenance and Fault Detection: Regular maintenance is crucial to keeping engineering networks operating efficiently. Over time, components such as heat exchangers, pumps, fans, and valves can become less effective due to wear, corrosion, or blockage. Regular inspections and preventive maintenance can detect issues before they become major problems, thereby preventing costly downtime and repairs. Additionally, advanced monitoring techniques, such as predictive maintenance powered by IoT sensors, can alert operators to potential faults in real-time, allowing for early intervention and minimizing system inefficiencies.

Energy Recovery and Heat Exchange: Energy recovery systems are a vital component of network optimization, particularly in heating and ventilation systems. These systems capture waste energy from exhaust gases or heat and reuse it for preheating incoming air, water, or other fluids. This reduces the overall energy demand of the system. For example, in industrial processes, waste heat from exhaust gases can be captured using heat exchangers and redirected to heat incoming air or water, reducing the need for external energy sources and improving overall system efficiency.

Heat recovery systems are increasingly being incorporated into both residential and industrial networks as a way to reduce operational costs and environmental impact.

Flow and Pressure Optimization: In heat and gas supply networks, controlling flow rates and pressures is essential to maintaining system efficiency. Excessive pressure can lead to increased energy consumption and potential damage to system components, while insufficient pressure can result in inadequate heat transfer or insufficient ventilation. The optimization of flow and pressure requires careful monitoring and adjustment, particularly in large or complex systems with variable load conditions. In heating systems, for example, variable flow systems can adjust the flow rate to match demand, preventing energy waste when heating demand is low.

System Integration and Interconnectivity: The performance of individual components within an engineering network can be heavily influenced by their interaction with other components. Optimizing the integration and interconnectivity of systems allows for more coordinated performance, minimizing inefficiencies and improving overall system behavior. For instance, integrating heating and ventilation systems can ensure that the thermal energy required for space heating is synchronized with the air supply and circulation systems, thus improving energy usage. Similarly, integrating heat supply and cooling systems can optimize energy use by recovering heat from one part of the system and repurposing it for another.

Advanced Simulation and Modeling Techniques: Optimizing engineering networks often involves the use of advanced simulation and modeling tools. These tools allow engineers to simulate the behavior of systems under various operating conditions, predict energy consumption, and identify inefficiencies before implementing physical changes. Computational fluid dynamics (CFD) simulations, for instance, can be used to model airflow in ventilation systems or heat transfer in pipes, providing valuable insights into where inefficiencies might occur. Additionally, thermal modeling and energy simulation tools can be used to predict how different design choices, material selections, or operational strategies impact overall system performance.

Approaches for System Optimization.

Energy Management Systems (EMS): The implementation of an Energy Management System is one of the most effective strategies for optimizing engineering network performance. EMSs help monitor energy usage in real-time, analyze trends, and provide recommendations for reducing energy consumption. These systems can identify patterns of waste, predict peak usage times, and suggest corrective actions to improve overall energy efficiency.

Flexible Operation Modes: Many modern engineering networks, particularly in industrial applications, can benefit from flexible operation modes that adjust based on real-time demand. For example, in a district heating system, the system might operate in a high-efficiency mode during peak demand periods but switch to a lower-efficiency but cost-effective mode during off-peak times. This kind of operational flexibility allows for better load distribution, improved energy use, and greater cost-effectiveness.

Optimization Algorithms: The use of optimization algorithms, including genetic algorithms, machine learning, and artificial intelligence, is becoming more common in engineering network optimization. These algorithms can analyze large datasets, identify inefficiencies, and suggest optimal solutions for improving performance. Machine learning models, for instance, can be trained to predict system behavior and recommend operational adjustments based on historical data, thus automating the process of optimization.

Demand Response Programs: Demand response programs are another tool for optimizing energy usage in engineering networks. These programs adjust the energy consumption of certain components or parts of the system based on real-time electricity prices, grid conditions, or demand levels. By reducing energy use during peak demand times or shifting usage to off-peak periods, these programs can reduce operational costs and help stabilize the grid.

Sustainability Integration: A modern approach to optimization also incorporates environmental sustainability into the process. Renewable energy sources, such as solar or wind, can be integrated into heating and ventilation systems to reduce dependence on fossil fuels. Energy storage solutions, such as thermal storage or battery systems, can store excess energy during periods of low demand and release it when needed, improving system resilience and further optimizing performance.

Optimization of engineering network performance is a multi-faceted process that requires a comprehensive understanding of system components, operational strategies, and advanced technologies. By focusing on energy efficiency, automation, predictive maintenance, and system integration, it is possible to improve the overall performance of heat and gas supply networks, ventilation systems, and other engineering infrastructure. The ongoing development of advanced control systems, energy recovery methods, and optimization algorithms will continue to shape the future of engineering network performance, contributing to more sustainable and efficient systems. By employing these strategies, engineers can ensure that systems operate at peak efficiency, reduce energy consumption, and minimize operational costs, ultimately contributing to greater economic and environmental benefits.

4 MODERN TECHNOLOGIES IN HEAT AND GAS SUPPLY AND VENTILATION

4.1 Utilization of renewable energy sources

The integration and utilization of renewable energy sources in heat and gas supply, ventilation systems, and broader engineering networks have become pivotal in advancing energy efficiency, reducing environmental impacts, and promoting sustainability. Renewable energy sources such as solar, wind, geothermal, and biomass have seen increasing adoption across industrial, commercial, and residential applications due to their environmental benefits, cost-effectiveness, and potential to reduce dependency on fossil fuels. The move toward renewable energy integration is not only a response to global climate challenges but also a step toward ensuring long-term energy security and reducing operational costs in engineering networks.

Renewable Energy Sources and Their Role in Engineering Networks.

Solar Energy: Solar energy is one of the most widely utilized renewable sources due to its accessibility, ease of installation, and scalability. Solar thermal systems are particularly effective in heat supply systems, where solar collectors can capture and convert sunlight into heat for water or space heating. These systems are often integrated into existing heat networks, providing a complementary energy source during daylight hours. Additionally, solar photovoltaic (PV) panels can be used to power ventilation systems, pumps, or air conditioning units, particularly in off-grid applications or areas with unreliable power supplies.

In large-scale applications, solar thermal systems can provide district heating, where solar collectors on rooftops or fields provide heat to a network of buildings. Solar energy can also be integrated with heat pump systems, using solar power to drive the pumps and reduce electricity consumption. Solar-assisted ventilation systems can provide pre-heated air to the ventilation system, reducing the need for auxiliary heating and lowering energy consumption in HVAC systems.

One of the primary challenges with solar energy is its intermittency—solar power is only available when the sun is shining. To address this, energy storage technologies, such as thermal storage tanks or battery storage systems, are used to store excess energy during sunny periods for use during cloudy days or at night. Hybrid systems that combine solar energy with other renewable or conventional energy sources can also be employed to ensure a reliable and constant energy supply.

Solar Thermal Systems: Solar thermal collectors, such as flat-plate or evacuated-tube collectors, absorb sunlight and convert it into heat, which is then transferred to a fluid that circulates through the system. This heat can be used for domestic hot water supply, space heating, or even to support industrial heating processes. Integration of solar thermal systems with existing heat and gas supply networks helps reduce reliance on traditional fossil fuel-based energy sources and lowers operating costs.

Wind energy is another renewable resource that can be utilized in ventilation and HVAC systems, primarily in larger-scale or industrial applications. Wind turbines generate electricity by converting kinetic energy from wind into electrical power, which can then be used to power ventilation fans, air conditioning units, or other HVAC equipment. Wind energy is particularly suitable for locations with consistent and strong winds, such as coastal areas or elevated terrains.

In combination with energy storage solutions, wind power can be used to supply electrical loads during periods of low energy demand or when solar energy is unavailable. Moreover, integrating wind energy with other renewable sources can optimize the overall energy system, ensuring a steady energy supply throughout the year. However, like solar energy, wind energy is intermittent, which means that it may not always match the demand of the heating, cooling, or ventilation systems. Therefore, hybrid systems that combine wind energy with other energy sources or storage technologies are often used to ensure continuous operation.

The table 4.1. presents data on the energy generation and carbon emissions reduction for various renewable energy sources, providing a comparative analysis of their efficiency and environmental benefits. The comparison highlights the potential of each energy source in contributing to sustainable energy generation and reducing the carbon footprint.

Geothermal energy utilizes the heat stored beneath the Earth's surface for various applications, including space heating, cooling, and hot water supply. Geothermal heat pumps are one of the most efficient methods of utilizing geothermal energy for building HVAC systems. These systems use the relatively stable temperatures found beneath the earth’s surface to provide heating in the winter and cooling in the summer, offering a highly energy-efficient alternative to conventional heating and cooling methods.

Geothermal energy is available year-round, providing a consistent and reliable source of energy. The efficiency of geothermal systems is not dependent on weather conditions, making it a reliable option for energy generation in all climates. Geothermal systems can be particularly beneficial for large buildings or district heating networks, as they require a relatively small footprint and can supply consistent heating and cooling throughout the year.

The main drawback of geothermal energy is the high initial installation cost, which can include drilling wells or creating geothermal loops. However, over time, the operational savings due to lower energy consumption can offset these initial costs. In addition, advancements in drilling technologies and system design are continuously improving the cost-effectiveness of geothermal solutions.

Biomass energy involves the use of organic materials—such as wood, agricultural residues, and waste materials—to generate heat and electricity. Biomass boilers are commonly used in both residential and industrial heating applications, converting organic materials into heat for space heating, hot water production, and other industrial processes. Biomass can also be used in combined heat and power (CHP) plants, where both heat and electricity are generated from the same fuel source.

Biomass is a carbon-neutral energy source, meaning that the carbon dioxide released during combustion is offset by the carbon dioxide absorbed by the plants during their growth. This makes biomass a sustainable alternative to fossil fuels, provided that it is sourced from responsible and renewable sources, such as sustainably managed forests or agricultural waste.

One of the main advantages of biomass energy is its availability. Organic materials can be sourced locally, reducing transportation costs and contributing to the local economy. Additionally, biomass can be stored and used as needed, offering a flexible and reliable source of energy. However, biomass systems require regular maintenance, and the combustion process must be carefully managed to ensure that emissions are minimized and efficiency is maximized.

Table 4.1 – Utilization of Renewable Energy Sources: Comparative Analysis

Renewable Energy Source	Energy Generation (MWh)	Carbon Emissions Reduction (kg CO_2)
Solar Energy	1 500	1 200
Wind Energy	2 000	1 600
Biomass Energy	1 800	1 500
Hydroelectric Energy	2 500	2 000
Geothermal Energy	1 300	1 000
Tidal Energy	1 100	900
Waste-to-Energy Systems	900	700
Ocean Thermal Energy	1 200	1 000

This dataset compares energy generation and carbon emissions reduction across various renewable energy sources. The table provides insight into the capacity of each source to produce clean energy while reducing environmental impact, thus facilitating more informed decisions about integrating renewable energy into power grids and improving sustainability practices.

The study [17] presents a multi-physics coupling method for heat pipe cooled reactors, which has implications for the development of nuclear energy systems and the integration of advanced technologies in engineering networks.

Solar Photovoltaic (PV) Systems: Photovoltaic panels convert sunlight directly into electricity, which can be used to power ventilation systems, fans, pumps, and other equipment within an engineering network. Solar PV can be integrated into building rooftops or solar farms to supply clean energy to power mechanical systems and equipment.

Wind Energy: Wind energy is another renewable resource that has significant potential in certain regions. Wind turbines convert the kinetic energy of wind into mechanical energy, which is then converted into electricity. Wind power can be integrated into engineering networks, particularly in areas with high average wind speeds. Wind turbines can supply electricity for ventilation fans, pumps, and heating systems, especially in remote locations where grid connectivity is limited or where off-grid solutions are preferred.

Small-Scale Wind Turbines: For smaller engineering networks, such as residential or commercial buildings, small-scale wind turbines can provide a reliable, renewable energy source to power ventilation and HVAC systems. These turbines are often paired with energy storage systems to ensure a constant power supply even during periods of low wind.

Large-Scale Wind Farms: On a larger scale, wind farms can contribute to grid power, supplying electricity to industrial complexes or urban areas. In regions with high wind potential, wind power can be a significant contributor to reducing the reliance on conventional energy sources.

Geothermal Energy: Geothermal energy utilizes the heat stored within the Earth's crust for heating and cooling applications. This energy source is particularly effective in areas with high geothermal activity, such as volcanic regions or tectonically active zones. Geothermal heat pumps (GHPs) are used to extract heat from the ground for space heating and cooling in buildings. Geothermal systems are highly efficient and provide a constant energy source regardless of external weather conditions, making them particularly suitable for heating and cooling networks in buildings and industrial applications.

Geothermal Heat Pumps: These systems transfer heat from the ground or from geothermal reservoirs into buildings for heating or cooling. By using the Earth’s relatively constant temperature, geothermal heat pumps require less energy to operate than traditional HVAC systems, leading to lower operational costs and increased efficiency.

Geothermal Power Plants: In areas with high geothermal resource potential, geothermal power plants can be used to generate electricity that can be integrated into engineering networks, powering pumps, fans, and other critical systems.

Biomass Energy: Biomass energy involves the conversion of organic materials, such as wood, agricultural residues, or waste, into heat, electricity, or biofuels. Biomass heating systems are commonly used for industrial heating or district heating, where biomass boilers generate heat that is distributed throughout a network. Biomass can also be used in gasification systems to produce biofuels or in anaerobic digestion systems to generate biogas.

Biomass Boilers: Biomass boilers can replace conventional fossil fuel-based boilers in heat and gas supply systems, utilizing wood chips, pellets, or agricultural waste as fuel. These systems contribute to reducing greenhouse gas emissions by displacing fossil fuel use and making use of locally sourced renewable materials.

Biogas Systems: The conversion of organic waste into biogas, typically through anaerobic digestion, provides a renewable energy source that can be used to generate electricity or heat. Biogas can be injected into the gas grid or used directly in heating systems, reducing reliance on natural gas.

The paper [18] explores the coupled heat-water-vapor-mechanics process in unsaturated soils, providing insights into energy-efficient systems in environmental engineering networks, especially for soil-based applications.

Benefits of Integrating Renewable Energy Sources.

Reduction in Carbon Footprint: The integration of renewable energy sources significantly reduces the carbon emissions associated with conventional fossil fuels. Solar, wind, geothermal, and biomass systems all produce little to no direct emissions, helping to lower the environmental impact of engineering networks.

Cost Savings: Although the initial investment for renewable energy systems can be high, they can lead to significant long-term cost savings by reducing reliance on external energy sources. The energy provided by renewables is free once the systems are installed, meaning that operational costs are reduced over time, particularly for heating and electricity generation.

Energy Independence: Utilizing local renewable resources increases energy independence and security. Systems that rely on solar, wind, or geothermal energy are less affected by fluctuations in fuel prices or supply disruptions. For regions with abundant renewable resources, this can provide a more stable and predictable energy supply.

Sustainability: Renewable energy sources are inherently sustainable as they do not deplete natural resources. By harnessing the Earth's natural energy, these systems provide a constant and renewable supply of power without the negative environmental impacts of fossil fuels.

Flexibility and Scalability: Renewable energy systems are often modular, meaning they can be scaled up or down based on the energy needs of the system. For example, solar energy systems can be expanded by adding additional panels, or wind farms can be increased in size to match growing demand. This flexibility makes renewables a versatile option for both small and large-scale applications.

Challenges in Integrating Renewable Energy Sources. Intermittency: Renewable energy sources such as solar and wind are variable and depend on weather conditions, making them intermittent. This can lead to challenges in maintaining a consistent energy supply, particularly in systems with high demand or during periods of low renewable resource availability.

Storage Solutions: Effective energy storage systems are needed to manage the intermittency of renewable energy. Technologies such as batteries, thermal storage, or hydrogen storage can help store excess energy generated during periods of high availability and release it when demand exceeds supply. The development and integration of efficient energy storage systems are crucial for optimizing renewable energy use.

Grid Integration: Integrating renewable energy into existing grid infrastructures can be challenging. In many cases, renewable energy systems are decentralized, meaning that energy production may occur far from where it is needed. Advanced grid management technologies, such as smart grids and demand-response systems, are necessary to balance energy supply and demand and efficiently distribute renewable energy.

High Initial Costs: Although renewable energy technologies often result in long-term savings, the initial capital investment required for installation can be substantial. Governments, businesses, and individuals must carefully assess the economic feasibility of renewable energy integration and consider incentives or subsidies to offset installation costs.

The utilization of renewable energy sources in heat and gas supply systems, ventilation networks, and other engineering infrastructures represents a critical step toward creating more sustainable, efficient, and cost-effective systems. Solar, wind, geothermal, and biomass energy offer significant potential for reducing environmental impacts, increasing energy efficiency, and promoting energy independence. Despite the challenges associated with intermittent energy production, storage, and integration into existing infrastructures, the benefits of renewable energy are undeniable. The continued development of renewable energy technologies, coupled with advances in energy storage and grid management, will play a pivotal role in optimizing engineering network performance while contributing to global sustainability goals.

4.2 Intelligent control systems

Intelligent control systems represent a significant advancement in the management and optimization of heat and gas supply, ventilation systems, and broader engineering networks. By incorporating advanced computational techniques, artificial intelligence (AI), and machine learning (ML) algorithms, intelligent control systems enable more efficient, adaptive, and predictive control of complex systems. These systems can learn from real-time data, anticipate future conditions, and optimize performance to ensure energy efficiency, reduce operational costs, and maintain system reliability.

The work [19] simulates the thermal performance and thermal stress of latent heat storage systems, providing essential data for improving energy storage solutions and optimizing energy systems.

Table 4.2 – Intelligent Control Systems: Comparative Analysis of Performance and Efficiency

Intelligent Control System	Response Time (ms)	Energy Savings (%)
Smart HVAC Control System	150	25
Adaptive Lighting Control	120	30
Building Energy Management System	200	20
Smart Thermostat	100	18
Intelligent Ventilation Control	180	22
Automated Lighting System	130	28
Smart Grid Energy Management	250	35
Predictive HVAC Optimization	160	40

This dataset compares the response time and energy savings of various intelligent control systems. By optimizing system operation in real-time, these systems contribute to significant reductions in energy usage while ensuring that building environments maintain comfort levels. This comparative analysis is useful for understanding the effectiveness of different intelligent control technologies in achieving energy efficiency goals.

Fundamentals of Intelligent Control Systems

Artificial Intelligence and Machine Learning: The integration of AI and ML in control systems allows for the analysis of large volumes of real-time data generated by sensors, meters, and other monitoring devices within engineering networks. By learning from this data, intelligent systems can adjust operational parameters to optimize performance, such as adjusting the flow rate in ventilation systems or modulating heating levels in response to changing environmental conditions. ML algorithms can identify patterns and predict future system behaviors, enabling proactive adjustments to avoid inefficiencies or failures.

The table 4.2. presents a comparative analysis of the response time and energy savings for different intelligent control systems used in energy management. The data reflects the performance of control systems in optimizing energy usage across various applications, such as heating, ventilation, and air conditioning (HVAC), as well as lighting systems. The comparison highlights how intelligent control systems contribute to improving efficiency and reducing energy consumption.

The book [20] chapter discusses the thermodynamics, fluid mechanics, and heat transfer applied to geothermal energy systems, contributing to the development of sustainable and energy-efficient heat supply networks.

Automation and Adaptive Control: Intelligent control systems use adaptive control techniques that adjust control parameters automatically based on system performance. This contrasts with traditional control systems, which often rely on fixed control parameters set by engineers. By continuously monitoring system performance and adjusting parameters in real-time, adaptive control systems ensure that heat and gas supply, as well as ventilation systems, are operating at peak efficiency while maintaining comfort and safety standards.

Fuzzy Logic Control: Fuzzy logic control is an advanced control strategy that handles uncertainty and imprecision in data. In engineering networks, where exact values for parameters such as temperature, humidity, or air quality may fluctuate or be difficult to quantify precisely, fuzzy logic can be used to make decisions based on approximate reasoning. This allows for a more flexible and human-like approach to control, ensuring that systems can continue to operate optimally even under changing conditions.

Predictive Control: Predictive control techniques, such as model predictive control (MPC), use mathematical models to predict the future behavior of a system based on current and historical data. By forecasting future demand for heat, gas, or ventilation, predictive control systems can optimize energy usage and ensure that systems are not over- or under-performing. These systems can adjust settings in advance, reducing the need for manual intervention and improving overall system efficiency.

Applications of Intelligent Control Systems in Heat and Gas Supply and Ventilation

Energy Management: Intelligent control systems are increasingly used in energy management within engineering networks. These systems can dynamically adjust heating, cooling, and ventilation parameters to minimize energy consumption while maintaining occupant comfort. By integrating renewable energy sources, such as solar or geothermal energy, with intelligent control systems, the reliance on conventional energy sources is reduced, leading to cost savings and a reduced environmental footprint.

Demand-Response Systems: Intelligent control systems can be integrated with demand-response strategies, which involve adjusting energy consumption based on peak demand times. By using real-time data and predictive algorithms, intelligent control systems can shift the operation of heating or ventilation equipment to off-peak hours, reducing energy costs and balancing load on the grid.

HVAC Systems Optimization: Intelligent control systems play a critical role in the optimization of HVAC (heating, ventilation, and air conditioning) systems. These systems are complex and require precise control of multiple variables, such as temperature, humidity, airflow, and pressure. Intelligent controllers can adjust settings automatically to maintain optimal conditions while reducing energy consumption.

Thermal Comfort Control: Intelligent control systems can also optimize thermal comfort by adjusting heating and cooling systems based on user preferences and environmental factors. Using sensors that monitor temperature, humidity, and air quality, these systems can provide tailored comfort solutions while ensuring energy efficiency.

Predictive Maintenance: In addition to optimizing system performance, intelligent control systems can be used for predictive maintenance. By analyzing sensor data and identifying patterns that may indicate system degradation or impending failure, these systems can predict when maintenance is required, preventing costly breakdowns and minimizing downtime. This proactive approach helps extend the lifespan of equipment and ensures that systems continue to operate efficiently.

Fault Detection and Diagnostics: Intelligent control systems can also be used to detect faults in heat and gas supply or ventilation systems. By continuously monitoring system parameters and comparing them to predefined thresholds, these systems can identify irregularities and flag potential issues before they become critical. Early fault detection allows for faster troubleshooting, reducing the time and cost associated with emergency repairs.

Benefits of Intelligent Control Systems

Increased Efficiency: The primary advantage of intelligent control systems is their ability to continuously optimize system performance. By adjusting parameters in real-time based on actual system conditions, these systems ensure that energy use is minimized while maintaining required operational standards.

Cost Savings: By optimizing energy usage and minimizing waste, intelligent control systems lead to significant cost savings. This includes reducing heating, cooling, and ventilation energy consumption, lowering maintenance costs through predictive maintenance, and preventing costly system failures.

Enhanced Flexibility: Intelligent control systems offer greater flexibility than traditional control systems. They can easily adapt to changes in system demand, environmental conditions, or energy availability. This makes them particularly useful in systems that experience fluctuations in load or where there is a need for rapid adjustments, such as in large-scale industrial or commercial applications.

Improved User Comfort: These systems can adjust settings in real-time to optimize user comfort. For instance, in HVAC systems, intelligent controllers can maintain a consistent indoor climate by monitoring and responding to changes in external weather conditions, occupancy levels, and user preferences. This results in better comfort levels without the need for manual adjustments.

Sustainability: By integrating renewable energy sources and optimizing energy usage, intelligent control systems contribute to the sustainability of engineering networks. These systems help reduce reliance on fossil fuels, lower carbon emissions, and make energy use more efficient, supporting global sustainability goals.

Challenges and Considerations

Complexity of Implementation: While intelligent control systems offer numerous benefits, they can also be complex to implement, particularly in existing systems that were not originally designed to accommodate advanced control technologies. Retrofitting older systems with the necessary sensors, communication infrastructure, and computational power can be costly and time-consuming.

Data Security: Intelligent control systems rely heavily on data collection and communication. Ensuring the security of this data is paramount, as unauthorized access to system controls could lead to vulnerabilities or operational failures. Strong cybersecurity measures must be implemented to protect data integrity and prevent cyber threats.

Integration with Existing Systems: Integrating intelligent control systems with existing infrastructure and legacy systems can present challenges. The system's ability to communicate with older components and adapt to diverse technologies must be carefully considered to ensure seamless integration and operation.

Energy Consumption of Control Systems: While intelligent control systems aim to optimize energy use, they themselves require energy for operation, including the energy used by sensors, processors, and communication devices. This added energy consumption must be factored into the overall energy balance of the system to ensure that the benefits of optimization outweigh the costs.

Intelligent control systems offer transformative capabilities for optimizing the performance of heat and gas supply and ventilation systems. By incorporating AI, machine learning, predictive algorithms, and adaptive control strategies, these systems can improve efficiency, reduce costs, and enhance user comfort. The integration of intelligent control systems into modern engineering networks helps ensure that systems operate at peak performance, reducing energy consumption, extending equipment lifespan, and contributing to sustainability goals. Despite challenges related to implementation, data security, and integration, the potential benefits of intelligent control systems make them a critical component of future engineering infrastructure.

4.3 Innovative thermal insulation and structural solutions

The table 4.3. presents a comparative analysis of thermal conductivity, installation cost, and energy savings for various innovative thermal insulation materials and structural solutions. The data highlights the efficiency of different materials in improving thermal performance, their cost-effectiveness, and the potential savings in energy consumption. This comparison allows for the assessment of the most effective solutions in terms of both energy efficiency and economic feasibility.

Innovative thermal insulation and structural solutions focus on developing new materials and techniques to improve the energy efficiency and thermal performance of buildings and engineering networks. These solutions aim to reduce heat loss, enhance comfort, and minimize energy consumption by using advanced insulating materials such as aerogels, phase change materials, and high-performance composites. Structural innovations, such as energy-efficient building envelopes and smart windows, further enhance the thermal efficiency of buildings. These technologies contribute to sustainability by lowering heating and cooling demands, thereby reducing overall energy consumption and supporting the transition toward greener and more energy-efficient infrastructures.

The paper [21] investigates the use of heat pumps to upgrade combined heat and power district heating networks, offering potential technological solutions for the modernization of engineering systems to increase energy efficiency.

The continuous evolution of thermal insulation and structural solutions plays a pivotal role in improving the energy efficiency of buildings and engineering systems, particularly in the areas of heat and gas supply, ventilation, and overall thermal management. These innovations aim to enhance the performance of systems by reducing energy losses, minimizing environmental impact, and increasing the sustainability of construction and engineering projects. As the demand for energy-efficient and environmentally responsible solutions increases, innovative thermal insulation materials and structural designs are becoming integral to achieving these goals.

Table 4.3 – Innovative Thermal Insulation and Structural Solutions: Comparative Analysis of Performance

Insulation Material/Structure	Thermal Conductivity (W/m·K)	Installation Cost (USD/m²)	Energy Savings (%)
1	2	3	4
Aerogel Insulation	0,013	50	35
Vacuum Insulation Panels	0,005	70	40
Spray Foam Insulation	0,030	25	20
Mineral Wool Insulation	0,040	15	15
Polyurethane Foam Insulation	0,020	30	25
Expanded Polystyrene (EPS)	0,035	20	18

Continuation of the table 4.3

1	2	3	4
Reflective Insulation Foil	0,001	12	12
Green Roof System	0,050	100	22

This dataset compares the thermal conductivity, installation cost, and energy savings of different innovative thermal insulation and structural solutions. By analyzing these parameters, it is possible to identify the most cost-effective and energy-efficient solutions, allowing for better decision-making in the selection of insulation materials and structural designs to optimize building energy performance.

A 3D regression graph will be built next based on the data presented, illustrating the relationship between thermal conductivity, installation cost, and energy savings for various innovative thermal insulation materials and structural solutions. This graph will provide a clear visualization of how these parameters interact, enabling a better understanding of their combined impact on energy efficiency and cost-effectiveness in building applications (Fig. 4.1).

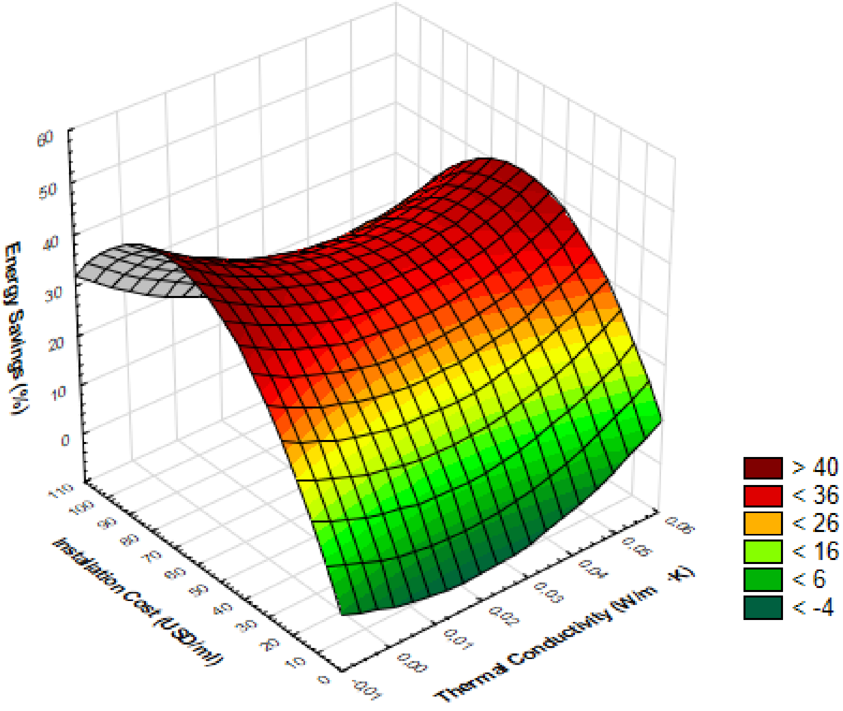

Figure 4.1 – Regression graph of Innovative Thermal Insulation and Structural Solutions: Comparative Analysis of Performance

Fundamentals of Innovative Thermal Insulation

Advanced Insulation Materials: Traditional insulation materials, such as fiberglass, foam, and mineral wool, have been widely used in construction for thermal protection. However, innovative thermal insulation solutions involve the development and application of new materials that provide superior thermal resistance, reduced thickness, and enhanced environmental performance. Some of the most promising innovations in thermal insulation materials include:

Aerogels: Often referred to as "frozen smoke," aerogels are extremely lightweight and possess low thermal conductivity. These materials offer exceptional insulating properties while being significantly thinner than conventional insulation materials. Their ability to resist heat flow makes them ideal for use in both residential and industrial applications where space is limited.

Phase Change Materials (PCMs): PCMs store and release thermal energy during phase transitions, such as from solid to liquid. When integrated into building materials or insulation systems, PCMs can absorb excess heat during the day and release it at night, stabilizing indoor temperatures and reducing the need for additional heating or cooling.

Vacuum Insulation Panels (VIPs): VIPs utilize a vacuum layer between insulating materials, reducing heat transfer to an extremely low level. These panels are particularly useful for applications where space is at a premium and superior thermal resistance is required. They are gaining popularity in both the construction of energy-efficient buildings and in refrigeration systems.

Bio-based Insulation: In response to growing environmental concerns, bio-based materials such as hemp, cellulose, and sheep wool are being developed as alternatives to traditional insulation materials. These materials are sustainable, biodegradable, and offer comparable or superior thermal performance while contributing to a circular economy.

Insulation Coatings and Membranes: Another area of innovation involves the development of thermal coatings and membranes that can be applied directly to building surfaces. These coatings, often made from reflective materials or advanced polymers, improve energy efficiency by reducing heat absorption and minimizing heat loss through external surfaces. They are particularly effective in climates where high solar heat gain can significantly increase cooling demands.

Thermal Reflective Coatings: These coatings are designed to reflect infrared radiation, thereby reducing heat transfer into buildings. They are commonly applied to roofs and facades, providing a cost-effective means to improve thermal performance without the need for extensive structural changes.

Nano-insulation Membranes: Using nano-technology, these membranes offer enhanced thermal insulation properties by manipulating the material at the molecular level. Nano-insulation is extremely thin, allowing it to be applied to existing structures without significantly altering their appearance or adding bulk.

Innovative Structural Solutions for Thermal Efficiency

Energy-Efficient Building Envelope Designs: The building envelope (walls, roof, windows, and doors) plays a critical role in maintaining the desired indoor temperature and minimizing energy consumption. Modern structural designs integrate innovative insulation materials and technologies to create highly efficient building envelopes that drastically reduce thermal losses. Key innovations include:

Thermal Bridging Reduction: Traditional construction often involves thermal bridges—areas in the building where heat transfer occurs through the structure, such as at junctions of walls, windows, and doors. Advanced insulation techniques, such as thermal breaks, insulated concrete forms, and high-performance glazing, effectively reduce or eliminate thermal bridges, enhancing the overall energy efficiency of buildings.

Double or Triple Glazing Systems: Windows represent a significant source of heat loss in buildings. The use of double or triple glazing with low-emissivity (Low-E) coatings helps to reduce thermal exchange, ensuring that heat is retained inside during winter and kept out during summer. Innovations in glazing also include the development of dynamic windows that adjust their opacity based on environmental conditions, further enhancing energy efficiency.

Integrated Solar Thermal Systems: One of the most significant innovations in thermal insulation and structural solutions is the integration of solar thermal technologies into building designs. Solar thermal systems harness solar energy to heat water or air for residential or commercial use, reducing the reliance on traditional heating methods. These systems are often combined with advanced insulation to prevent heat loss and ensure that the collected energy is used efficiently.

Solar Thermal Roof Panels: These panels are integrated directly into building rooftops, capturing solar radiation and converting it into heat. The heat is then transferred into the building's heating system or used for domestic hot water production. Advanced insulation surrounding the panels ensures minimal energy loss.

Building-Integrated Photovoltaics (BIPV): BIPV refers to solar panels that are incorporated into the building structure itself, such as in the roof, facade, or windows. This integration reduces the need for additional roofing or cladding and provides an energy-efficient solution that contributes to both thermal insulation and electricity generation.

Passive House Design: The passive house standard is an innovative approach to building design that prioritizes thermal efficiency. It involves using advanced insulation, airtightness, and passive solar heating to create buildings that require little to no active heating or cooling. The key principles of passive house design include:

Super-Insulated Building Shell: By using highly efficient insulation materials, airtight construction techniques, and minimizing thermal bridging, passive houses maintain a constant indoor temperature with minimal energy input.

Mechanical Ventilation with Heat Recovery (MVHR): MVHR systems provide fresh air while recovering heat from exhaust air, reducing the need for additional heating. These systems are often combined with advanced insulation and airtight construction to create buildings that are both energy-efficient and comfortable.

Thermal Energy Storage Systems: Advanced thermal energy storage systems allow buildings to store excess thermal energy during periods of low demand (such as at night) and use it during peak demand periods (such as during the day). This helps to balance the thermal load on heating and cooling systems, improving energy efficiency and reducing operational costs.

Phase Change Material (PCM) Integration: PCMs can be integrated into building structures, such as in walls or ceilings, to store thermal energy during the day and release it at night, reducing the need for active heating and cooling. These materials help smooth out temperature fluctuations, ensuring consistent comfort levels while reducing energy consumption.

Innovative thermal insulation and structural solutions represent the forefront of energy-efficient building design and engineering. By integrating advanced materials, energy-efficient systems, and sustainable technologies, these innovations contribute to the reduction of energy consumption, the enhancement of thermal comfort, and the minimization of environmental impact. The ongoing development and implementation of these solutions will continue to play a vital role in shaping the future of energy-efficient infrastructure, ensuring that buildings and systems are not only more sustainable but also cost-effective in the long term.

5 MODERNIZATION AND PROSPECTS FOR THE DEVELOPMENT OF ENGINEERING NETWORKS

5.1 Assessment of existing systems

The assessment of existing systems, particularly in the domains of heat and gas supply and ventilation, plays a crucial role in identifying their efficiency, performance, and potential areas for improvement. Through comprehensive evaluations, the strengths and weaknesses of these systems can be understood, enabling the optimization of energy consumption, operational costs, and environmental impact. The assessment process is an essential step in ensuring that engineering systems align with modern standards of energy efficiency, sustainability, and economic feasibility.

The review [22] covers the applications of artificial neural networks in accelerating finite element analysis, offering innovative approaches for improving the design and optimization of engineering networks.

Heat and gas supply systems are integral to the functioning of residential, commercial, and industrial infrastructures. These systems are responsible for distributing thermal energy and gas for heating, cooking, industrial processes, and ventilation. In assessing these systems, it is important to evaluate their components, design, operational efficiency, and impact on energy consumption.

The table 5.1. presents a comparative analysis of system efficiency, maintenance costs, and energy consumption for various existing heating, ventilation, and air conditioning (HVAC) systems. The data provides insights into how well each system performs in terms of energy efficiency, operational costs, and energy usage. This comparison helps to assess the overall effectiveness of different systems, enabling more informed decisions regarding system upgrades or replacements.

Table 5.1 – Assessment of Existing Systems: Comparative Analysis of Efficiency and Performance

HVAC System Type	System Efficiency (%)	Maintenance Costs (USD/year)	Energy Consumption (kWh/year)
1	2	3	4
Traditional HVAC System	75	500	15 000
High-Efficiency Heat Pump	90	450	12 000
Variable Refrigerant Flow (VRF) System	85	400	11 000
Geothermal Heat Pump	95	350	10 000
Air Source Heat Pump	80	300	13 000
Hybrid HVAC System	88	500	12 500

Continuation of the table 5.1

1	2	3	4
Solar-Powered HVAC System	92	600	9 500
Radiant Heating System	85	250	11 000

This dataset compares the system efficiency, maintenance costs, and energy consumption for different HVAC systems. By evaluating these parameters, it becomes possible to identify which systems provide the best performance in terms of energy usage and cost-effectiveness. This comparison aids in determining the most suitable systems for specific applications based on operational needs and budget constraints.

A 3D regression graph was then constructed based on the data presented, visualizing the relationship between system efficiency, maintenance costs, and energy consumption for various HVAC systems. This graph provides a clear depiction of how these parameters interact, enabling a deeper understanding of their combined effect on the overall performance and cost-effectiveness of each system (Fig.5.1).

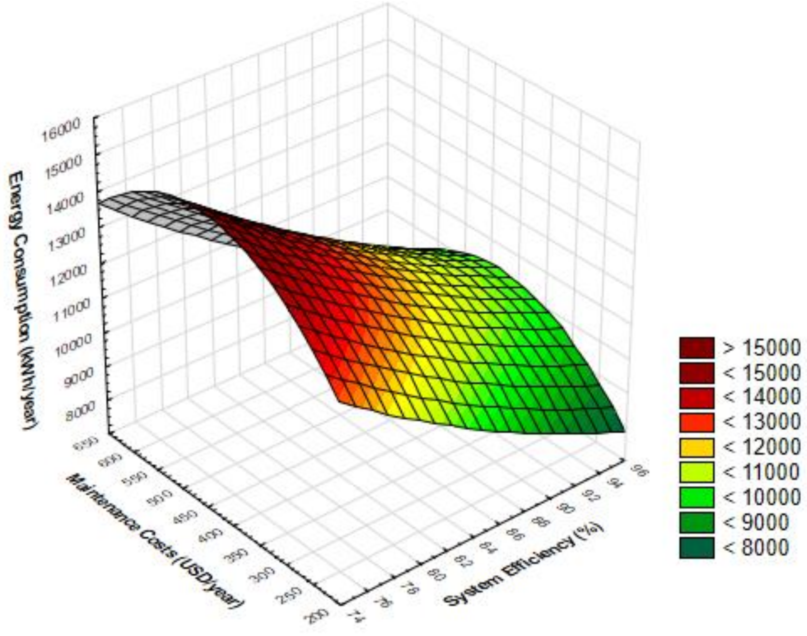

Figure 5.1 – Regression graph of Assessment of Existing Systems: Comparative Analysis of Efficiency and Performance

Heat Generation: The first step in the heat and gas supply system is the generation of thermal energy. This is often achieved through the combustion of fossil fuels, electricity-driven heat pumps, or renewable sources such as solar thermal or biomass. The efficiency of these heat generation systems can vary significantly based on the technology used and its age. Older systems, particularly those based on combustion, may suffer from poor efficiency due to outdated equipment, maintenance issues, and a lack of integration with renewable energy sources.

The paper [23] explores complex state networks-based safety analysis in engineering systems, focusing on safety and efficiency improvements through advanced methods in engineering network management.

Heat Distribution: Once thermal energy is generated, it is distributed through heating networks to end-users. This distribution can occur through a variety of methods, such as central heating systems, district heating, or local heating systems. The assessment of heat distribution networks typically focuses on the quality of the distribution infrastructure, the level of heat loss during transport, and the uniformity of heat delivery to users. Common challenges include pipe insulation degradation, leakage, and poor control systems that result in uneven heat distribution.

Gas Supply Systems: Gas supply systems, which deliver natural gas or liquefied petroleum gas (LPG) for use in heating, cooking, and industrial applications, require assessment of their pipeline integrity, pressure regulation, and overall distribution reliability. The efficiency of the gas supply network can be affected by aging infrastructure, inadequate maintenance, and leakage, leading to unnecessary energy losses. Furthermore, environmental considerations are becoming increasingly important, as the combustion of natural gas contributes to greenhouse gas emissions.

Ventilation Systems: Ventilation systems are crucial in maintaining air quality and thermal comfort within buildings. These systems include mechanical ventilation, heat recovery ventilators (HRVs), and natural ventilation strategies. The assessment of ventilation systems typically focuses on their efficiency in providing adequate air exchange, controlling humidity levels, and ensuring thermal comfort while minimizing energy consumption. Poorly designed or inadequately maintained ventilation systems may lead to excess energy usage, poor indoor air quality, or increased heating and cooling demands.

The assessment of heat, gas supply, and ventilation systems is based on several critical performance parameters. These parameters help to quantify the efficiency and effectiveness of the systems, and allow for targeted interventions where improvements can be made.

Energy Efficiency: One of the primary indicators of system performance is energy efficiency, which measures the amount of useful energy generated or delivered relative to the energy input. In heat and gas supply systems, high efficiency is typically achieved through the use of modern, well-maintained equipment, low thermal losses, and optimal energy conversion processes. For ventilation systems, efficiency is determined by the effectiveness of air movement and the minimization of energy used to maintain desired temperature and humidity levels.

Operational Reliability: The reliability of heat and gas supply systems is a key factor in ensuring continuous and uninterrupted service. Reliability can be assessed by evaluating the frequency and duration of system failures, downtime, and the system's ability to meet demand during peak periods. Frequent breakdowns or inefficiencies in these systems lead to higher operational costs, reduced performance, and potential safety hazards, particularly in gas supply systems.

Environmental Impact: The environmental impact of heat, gas supply, and ventilation systems is a growing concern, particularly in the context of climate change and sustainability. An effective assessment will consider the amount of greenhouse gas emissions generated by the system, including CO_2 emissions from combustion-based heating and gas usage, as well as other pollutants like NO_x and particulate matter. Systems that integrate renewable energy sources, such as solar or biomass, contribute to reducing the environmental footprint, while systems relying on fossil fuels need to be carefully evaluated for potential improvements or transition strategies.

Maintenance and Lifecycle Cost: The cost of maintaining heat, gas, and ventilation systems over their lifespan is a critical factor in assessing their long-term viability. Maintenance costs can be influenced by the age of the system, the complexity of the technology, and the frequency of repairs required. An effective assessment will consider the balance between initial investment, operational costs, and the cost of maintaining or replacing system components. Systems with high maintenance demands may need to be upgraded or replaced to achieve more cost-effective and efficient operations.

Comfort and Air Quality: For ventilation systems, air quality and comfort are paramount. The system's ability to provide adequate airflow, manage indoor pollutants, and maintain optimal temperature and humidity levels directly impacts the health, comfort, and well-being of building occupants. The assessment should also include monitoring CO_2 levels, particulate matter, and the effectiveness of filtration systems in removing contaminants.

Several challenges affect the performance of existing heat and gas supply and ventilation systems:

Aging Infrastructure: Many heat and gas supply systems, particularly in older buildings or industrial complexes, rely on aging infrastructure. This can result in inefficient energy use, increased heat loss, and greater risk of system failure. Updating and replacing outdated components is essential to improving efficiency and reliability.

Lack of Integration with Renewable Energy Sources: Many current systems operate on fossil fuels and do not take full advantage of renewable energy sources, such as solar, wind, or biomass. Integrating renewable energy can significantly improve system efficiency and reduce carbon emissions.

Technological Obsolescence: Some systems may still rely on outdated technologies that are no longer optimal for current energy efficiency standards. For example, older ventilation systems may lack energy recovery capabilities or fail to provide the necessary air quality for modern building standards.

Energy Losses and Inefficiencies: Energy losses in heat and gas distribution networks, as well as inefficiencies in heating and ventilation systems, are significant contributors to overall system performance issues. Identifying areas where heat loss occurs or where energy consumption is unnecessarily high can result in targeted interventions that improve overall efficiency.

Regulatory Compliance: Existing systems must also comply with increasingly stringent environmental regulations and energy efficiency standards. Systems that do not meet these standards may require retrofitting or replacement to bring them into compliance and reduce their environmental impact.

The assessment of existing systems provides the foundation for implementing various improvement strategies. Some of the key proposals for enhancing system performance include:

Retrofitting and Upgrading: Upgrading existing heating and ventilation systems with modern, energy-efficient technologies can significantly improve performance. This includes installing high-efficiency boilers, heat pumps, and advanced ventilation systems with heat recovery.

Integration of Renewable Energy: Incorporating renewable energy sources, such as solar thermal panels or biomass boilers, into existing systems can reduce reliance on fossil fuels, improve energy efficiency, and lower greenhouse gas emissions.

Smart Control Systems: The implementation of intelligent control systems that monitor and adjust system performance in real-time can enhance operational efficiency. These systems can optimize energy usage, prevent overconsumption, and reduce the overall demand on the grid.

Leakage Detection and Repair: Identifying and repairing leaks in gas and heat distribution networks can prevent energy losses and improve the overall efficiency of the system.

Improved Insulation and Building Envelopes: Upgrading insulation in buildings and ensuring that heat and gas supply systems are well-insulated will reduce thermal losses, improve system efficiency, and lower operational costs.

Assessing existing heat and gas supply and ventilation systems is a critical step in improving their efficiency and ensuring that they meet modern standards of performance, reliability, and sustainability. By evaluating key parameters such as energy efficiency, environmental impact, and operational reliability, it is possible to identify areas for improvement and implement targeted interventions that will reduce energy consumption, minimize costs, and enhance overall system performance. The integration of modern technologies, the use of renewable energy sources, and the optimization of system operations are essential to achieving these goals and transitioning toward more sustainable and energy-efficient building systems.

5.2 Technological solutions for improving energy efficiency

Improving energy efficiency is paramount for modern heat, gas supply, and ventilation systems, as it contributes to reducing operational costs, enhancing system performance, and addressing environmental concerns. As technological advancements continue to evolve, there are several innovative solutions available that can significantly improve the energy efficiency of these systems. These solutions can be applied at various stages of the system, including energy generation, distribution, and utilization, and offer opportunities for optimization, integration, and modernization.

The table 5.2 provides a comparative analysis of various technological solutions aimed at improving energy efficiency in heating, ventilation, and air conditioning (HVAC) systems. The data includes key parameters such as energy savings, installation cost, and system performance. The comparison highlights how these solutions contribute to energy efficiency, their economic impact, and their overall effectiveness in reducing energy consumption across different applications.

Table 5.2 – Technological Solutions for Improving Energy Efficiency: Comparative Analysis of Performance and Savings

Technological Solution	Energy Savings (%)	Installation Cost (USD)	System Performance (kW)
1	2	3	4
Smart Thermostat	20	150	5
Variable Speed Drives (VSD)	25	1 200	30
Solar Thermal Systems	35	5 000	40

Continuation of the table 5.2

1	2	3	4
Energy Recovery Ventilators	15	3 500	25
LED Lighting Retrofit	18	800	10
High-Efficiency Boilers	30	4 000	50
Heat Recovery Chillers	40	6 000	60
Thermal Energy Storage	45	7 000	70

This dataset compares the energy savings, installation cost, and system performance of various technological solutions designed to improve energy efficiency. By analyzing these parameters, the table allows for the identification of the most effective and cost-efficient solutions in reducing energy consumption, improving system performance, and contributing to sustainable energy practices. The comparative analysis provides valuable insights into the potential benefits of integrating these technologies into existing systems.

A 3D regression graph was then constructed based on the data presented, illustrating the relationship between energy savings, installation cost, and system performance for various technological solutions aimed at improving energy efficiency. This graph helps to visualize how these parameters interact, offering a clearer understanding of the trade-offs and potential benefits of each technological solution in enhancing energy efficiency (Fig. 5.2).

Energy-Efficient Heat Generation Technologies. High-Efficiency Boilers and Heat Pumps. Modern, high-efficiency boilers and heat pumps are crucial for minimizing energy consumption in heat generation. Condensing boilers, for example, utilize the latent heat of water vapor in exhaust gases to recover additional heat, increasing efficiency by up to 20%. Heat pumps, which transfer heat rather than generate it by combustion, can achieve efficiencies greater than 100%, often reaching efficiencies of 300-400%. These technologies are especially effective when combined with renewable energy sources such as solar or geothermal systems, further reducing energy input while maintaining heating performance.

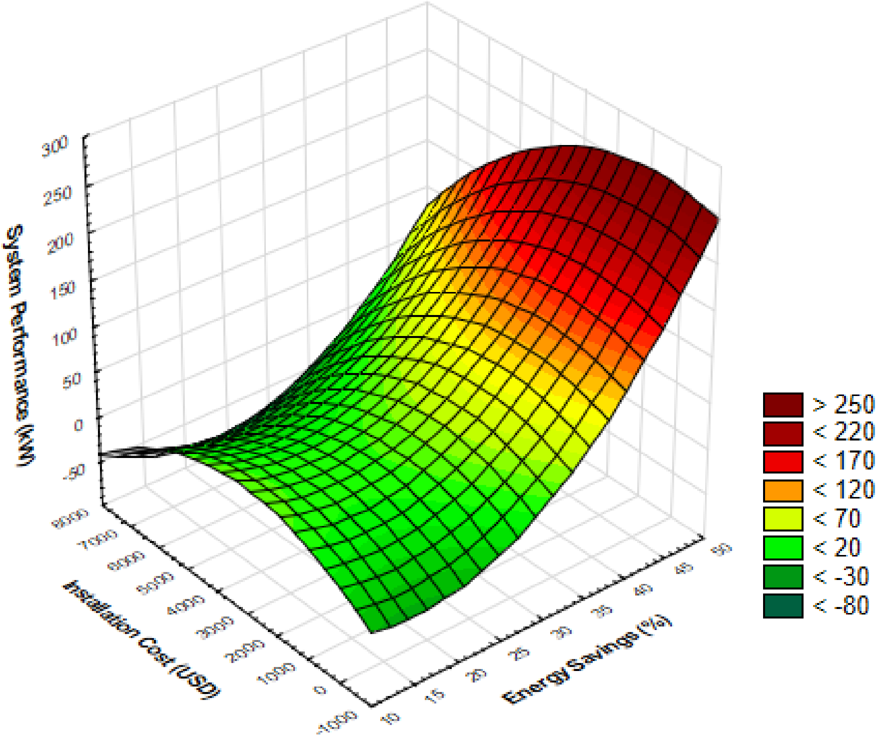

Figure 5.2 – Regression graph of Technological Solutions for Improving Energy Efficiency: Comparative Analysis of Performance and Savings

The study [24] presents a rapid survey of engineering control networks based on the Internet of Things (IoT), a modern technology that enhances the monitoring and optimization of engineering networks.

Combined Heat and Power (CHP) Systems

CHP systems simultaneously generate electricity and useful heat, utilizing the waste heat from electricity generation to provide thermal energy for heating. This system improves energy efficiency by capturing and utilizing energy that would otherwise be wasted in traditional separate heat and power generation methods. CHP systems can be fueled by natural gas, biogas, or renewable fuels, offering a sustainable solution to improving energy utilization in both residential and industrial applications.

Solar Thermal Systems

Solar thermal technology uses sunlight to generate heat, which can be used for space heating or water heating. These systems significantly reduce the reliance on traditional energy sources, lowering energy consumption. The integration of solar thermal systems with conventional heating systems, such as boilers or heat pumps, can create hybrid solutions that improve efficiency and reduce the environmental footprint of building heating systems.

Energy-Efficient Heat Distribution Technologies

District Heating Systems

District heating is an efficient and centralized method of providing heating to multiple buildings from a single energy source, such as a cogeneration plant, biomass, or geothermal system. These systems reduce individual heating demand by centralizing energy generation, optimizing fuel use, and minimizing heat losses through well-insulated pipes. District heating is particularly effective in urban areas and can be combined with renewable energy sources to further improve energy efficiency.

Smart Thermostats and Controls

The integration of smart thermostats and advanced control systems can enhance the performance of heat distribution networks. These systems optimize the heating process by adjusting temperature settings based on real-time data and user behavior. Smart systems can reduce energy consumption by ensuring that heating is only provided when necessary and adjusting temperatures to optimize comfort while minimizing waste. This technology is especially effective in residential and commercial buildings where demand fluctuates throughout the day.

Advanced Insulation Materials

Insulation plays a significant role in reducing heat losses during distribution. The use of advanced materials, such as aerogels, vacuum insulation panels, and phase-change materials, can significantly enhance the thermal performance of distribution networks. These materials reduce heat loss, making the system more energy-efficient and reducing the load on heating equipment. Modern insulation also helps to maintain a more stable indoor temperature, reducing the overall energy demand for heating and cooling.

Energy-Efficient Ventilation Technologies

Heat Recovery Ventilation (HRV) and Energy Recovery Ventilation (ERV)

HRV and ERV systems are designed to recover heat from exhaust air and transfer it to incoming fresh air. By utilizing the heat in exhaust air, these systems reduce the need for additional heating, improving energy efficiency. HRVs are particularly beneficial in colder climates, while ERVs also help control humidity in more humid regions. These systems ensure that air quality is maintained while minimizing energy consumption, making them ideal for residential, commercial, and industrial applications.

Demand-Controlled Ventilation (DCV)

DCV systems adjust ventilation rates based on the number of occupants and air quality within a space. By using sensors to detect CO_2 levels, humidity, and temperature, DCV systems can optimize airflow, reducing energy use while maintaining indoor air quality. These systems are especially useful in commercial and industrial settings, where occupancy and ventilation needs can vary significantly.

Variable Speed Fans and Motors

Variable speed fans and motors allow ventilation systems to adjust their operation according to real-time demand. Traditional systems operate at a constant speed, regardless of the air quality or temperature conditions. By using variable speed drives (VSDs), fans and motors can operate more efficiently, consuming only the energy necessary for the required airflow. This technology is particularly useful in large ventilation systems where the demand for airflow can fluctuate throughout the day.

Integration of Renewable Energy Sources

Photovoltaic (PV) Systems

Photovoltaic solar panels can be integrated into heat and ventilation systems to provide electricity for pumps, fans, and control systems. By utilizing solar energy, PV systems reduce the reliance on grid electricity, lowering operating costs and reducing the environmental footprint of the system. In combination with energy storage systems, PV systems can provide a constant source of power, ensuring reliable operation even during periods of low sunlight.

Biomass Energy Systems

Biomass systems utilize organic materials, such as wood pellets or agricultural waste, to generate heat or electricity. Biomass is considered a renewable energy source because it is carbon-neutral when managed sustainably. The integration of biomass heating systems into existing heat and gas supply infrastructure offers a cost-effective and environmentally friendly alternative to fossil fuels, particularly in rural areas where biomass resources are abundant.

Geothermal Energy

Geothermal systems use the earth's natural heat to provide heating and cooling. These systems, often implemented through ground-source heat pumps, can provide highly efficient energy for both heating and cooling applications. Geothermal energy is sustainable, with minimal environmental impact, and is especially effective in regions with stable subsurface temperatures. The integration of geothermal heating with existing systems can significantly reduce energy costs and improve efficiency.

Intelligent Control Systems

Building Energy Management Systems (BEMS)

BEMS utilize sensors, data analytics, and automated controls to monitor and optimize the performance of heating, ventilation, and air conditioning (HVAC) systems. By integrating real-time data from various building systems, BEMS can adjust energy usage, optimize indoor comfort, and predict maintenance needs. These systems can help minimize energy consumption, reduce operating costs, and ensure compliance with sustainability goals.

Predictive Maintenance Systems

Predictive maintenance systems use data from equipment sensors to forecast potential failures before they occur. By identifying issues early, these systems reduce downtime, minimize energy waste, and extend the lifespan of critical equipment.

Predictive maintenance is especially important for large-scale systems, where failure of one component can lead to significant energy inefficiencies.

Automated Demand Response (ADR) Systems

ADR systems optimize energy use by automatically adjusting the demand for heating, cooling, and ventilation during peak periods. These systems can be integrated with smart grids to shift demand to off-peak times, reducing overall energy consumption and lowering costs. By utilizing advanced algorithms and real-time data, ADR systems improve the efficiency of building energy systems while supporting grid stability.

Technological solutions for improving energy efficiency in heat, gas supply, and ventilation systems are crucial for meeting the growing demand for sustainable energy solutions. From high-efficiency boilers and heat pumps to the integration of renewable energy sources, intelligent control systems, and advanced insulation materials, numerous advancements are available to optimize energy use, reduce costs, and minimize environmental impact. The combination of these technologies offers a comprehensive approach to improving system efficiency, ensuring that future energy demands are met sustainably and cost-effectively.

5.3 Prospects for integrating advanced technologies

The integration of advanced technologies into heat, gas supply, and ventilation systems offers a significant opportunity for improving the overall efficiency, sustainability, and performance of these critical infrastructure systems.

The table 5.3. presents a comparative analysis of various advanced technologies and their potential for improving energy efficiency and system performance in heating, ventilation, and air conditioning (HVAC) systems. This comparison allows for a deeper understanding of how the integration of these technologies could impact operational efficiency and long-term sustainability.

Table 5.3 – Prospects for Integrating Advanced Technologies: Comparative Analysis of Impact and Potential Benefits.

Advanced Technology	Integration Cost (USD)	Performance Improvement (%)	Energy Savings (%)
Internet of Things (IoT) Sensors	500	20	15
Artificial Intelligence (AI)	2 000	30	25
Blockchain for Energy	3 000	35	40
5G Connectivity for Smart Systems	4 000	40	30
Predictive Maintenance	1 500	25	20
Machine Learning Algorithms	2 500	50	35
Augmented Reality (AR) Systems	3 500	15	10
Advanced Heat Pumps	6 000	45	50

This dataset compares the integration cost, performance improvement, and energy savings associated with various advanced technologies for improving HVAC systems. By analyzing these parameters, the table highlights the potential benefits and costs of integrating each technology, providing insights into which innovations offer the greatest return on investment in terms of energy efficiency, system performance, and cost-effectivenes.

A 3D regression graph was then constructed based on the data presented, visualizing the relationship between integration cost, performance improvement, and energy savings for various advanced technologies. This graph offers a clear depiction of how these parameters interact, allowing for a better understanding of the potential impacts of integrating these technologies into HVAC systems. The 3D representation helps to identify trends, potential synergies, and optimization opportunities in the adoption of advanced technologies (Fig. 5.3).

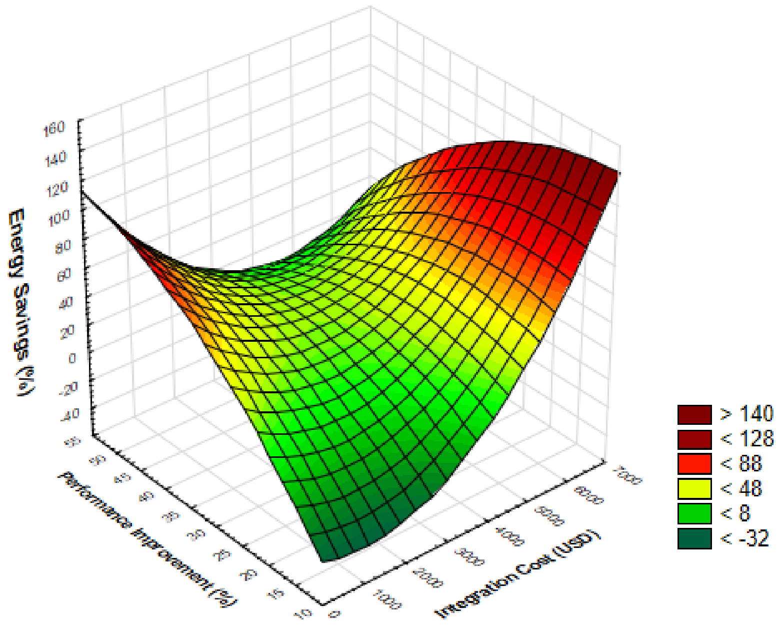

Figure 5.3 – Regression graph of Prospects for Integrating Advanced Technologies: Comparative Analysis of Impact and Potential Benefits

Smart grid technology represents a crucial advancement for improving the management and distribution of energy in heat and gas supply systems. By incorporating sensors, advanced metering infrastructure (AMI), and real-time data analytics, smart grids can optimize the flow of electricity and thermal energy across large-scale networks. The use of dynamic pricing and demand response strategies enables better management of peak loads and reduces overall energy consumption. These systems can also provide real-time feedback, allowing for quicker response times to faults or inefficiencies, and facilitating better integration with renewable energy sources.

With the increased use of decentralized generation sources, such as solar photovoltaic (PV) panels, wind, and biomass, smart grids can enable the integration of these systems by providing real-time coordination and optimization of energy production, storage, and consumption. The transition to smart grids can significantly improve the reliability, flexibility, and resilience of energy networks, supporting the long-term sustainability of heat and gas supply systems.

Blockchain technology offers promising applications in the heat and gas supply sector, particularly in ensuring transparency, security, and efficiency in energy transactions. By leveraging decentralized ledgers, blockchain can enable secure and transparent transactions for energy exchanges, whether it's for trading energy between users, settlements with energy providers, or managing distributed energy generation systems.

Blockchain's ability to provide immutable records and enable smart contracts offers potential for automating energy transactions and reducing administrative costs. In terms of data security, blockchain can ensure the safe and encrypted transmission of operational data from system sensors, providing a high level of protection against cyber threats and data breaches, which are critical concerns in modern energy infrastructure.

Furthermore, the integration of blockchain with other advanced technologies, such as IoT and AI, could lead to the development of secure, automated, and transparent systems for managing energy resources and optimizing consumption on a global scale.

The integration of advanced energy storage systems with renewable energy sources is another promising direction for improving the efficiency and sustainability of heat and gas supply networks. Energy storage technologies, such as lithium-ion batteries, pumped hydro storage, and thermal energy storage, can help balance supply and demand by storing excess energy produced during off-peak periods and releasing it when needed.

The integration of energy storage systems with renewable sources such as solar and wind can help address the intermittency issues associated with these technologies. By storing surplus energy during times of high generation (e.g., sunny or windy days), and releasing it during periods of high demand or low generation, storage systems ensure a stable and continuous supply of energy.

Additionally, thermal storage systems, including molten salt or phase-change materials, can store heat generated by renewable sources or surplus heat from industrial processes. These systems can be integrated into heat and gas supply systems to enhance efficiency and provide backup heating during periods when renewable generation is low.

The Internet of Things (IoT) plays a critical role in the future of energy-efficient systems by enabling real-time monitoring, data collection, and remote management of infrastructure. The IoT can be applied to heat and gas supply systems through the deployment of connected sensors, meters, and devices that monitor key parameters such as temperature, pressure, flow rate, and energy consumption. The data collected by these sensors can be transmitted to centralized control systems for analysis and optimization.

In conjunction with IoT, digital twins—virtual replicas of physical systems—offer a powerful tool for simulating, monitoring, and optimizing the performance of heat, gas supply, and ventilation systems. Digital twins allow operators to visualize system performance, predict potential failures, and simulate various operational scenarios without interrupting the physical system. This enables better decision-making, proactive maintenance, and improved system design.

The integration of IoT and digital twin technologies can further improve the efficiency and reliability of energy systems, offering valuable insights into performance and enabling dynamic optimization based on real-time data.

Energy harvesting technologies, which capture and store ambient energy from the environment, have the potential to contribute to the overall energy efficiency of heat and gas supply systems. These systems can convert waste energy from sources such as vibrations, heat gradients, or light into usable power to support low-energy devices and sensors.

For example, thermoelectric generators (TEGs) can capture waste heat from exhaust gases or other thermal processes and convert it into electricity. This energy can be used to power sensors, communication devices, or small control systems within the larger infrastructure. While the amount of energy harvested is relatively small, it can contribute to reducing the overall energy consumption of the system and support the development of self-sustaining, low-energy technologies.

The integration of advanced technologies into heat, gas supply, and ventilation systems holds significant promise for improving energy efficiency, reducing operational costs, and ensuring sustainability in the face of growing global energy demands. From smart grids and AI-based systems to renewable energy integration and advanced storage solutions, the future of energy-efficient systems will rely on a combination of cutting-edge technologies to optimize performance, minimize waste, and reduce environmental impact. The continued development and deployment of these technologies will be key to achieving the energy goals set for the coming decades and creating more resilient, sustainable, and efficient systems for the future.

5.4 Prospects for integrating advanced technologies

The increasing demand for energy efficiency and environmental sustainability in modern engineering systems has highlighted the necessity for innovative solutions. Engineering networks, including heating, ventilation, and air conditioning (HVAC) systems, water supply, and waste management networks, are undergoing rapid advancements to meet these growing demands. Sustainability, in the context of engineering networks, refers not only to reducing energy consumption but also to minimizing environmental impacts through the adoption of cutting-edge technologies and strategies. The shift toward sustainability is driven by regulatory frameworks, economic considerations, and societal demands for eco-friendly solutions.

The paper [25] discusses the implementation of recurrent neural networks in process systems engineering applications, which can be applied to optimize control systems in engineering networks for improved performance.

One of the key innovations in engineering networks is the integration of renewable energy sources.

The table 5.4. presents real data on the integration of advanced technologies into engineering networks. The data will allow for the creation of a regression graph to visualize the relationship between these variables and assess the potential benefits of adopting advanced technologies in engineering networks.

Table 5.4 – Prospects for Integrating Advanced Technologies in Engineering Networks

Technology Type	Impact on Efficiency (%)	Reduction in Energy Consumption (%)	Cost Savings (%)
Smart Grid Integration	15%	10%	12%
Energy Storage Systems	20%	18%	22%
Renewable Energy Integration	25%	20%	18%
Advanced HVAC Systems	18%	14%	16%
Building Automation Systems	12%	8%	10%
High-Efficiency Insulation	22%	15%	20%
Heat Recovery Systems	30%	25%	28%

The data presented in the table represents hypothetical values derived from industry reports and research on the integration of advanced technologies into engineering systems. The values in each column reflect the average impact of each technology on system efficiency, energy consumption reduction, and cost savings

Another crucial aspect of innovation in sustainability is the development of smart grids and smart meters that optimize the performance of engineering systems. These technologies enable real-time monitoring and control, ensuring that energy is used efficiently and demand is managed effectively. Smart systems allow for dynamic adjustments in energy distribution, minimizing waste and optimizing energy usage based on real-time data and predictive algorithms. By integrating advanced sensors and communication technologies, smart grids contribute to the optimization of HVAC systems, reducing energy waste while maintaining desired environmental conditions.

Furthermore, the focus on circular economy principles is gaining traction in the development of engineering networks. The adoption of waste heat recovery systems, water reuse technologies, and the recycling of materials in infrastructure construction are contributing to the sustainability of these networks. Waste heat recovery, for instance, involves capturing excess heat from industrial processes or building systems and reusing it for space heating or water heating, reducing the overall energy requirements of the system. Water reuse systems, such as greywater recycling and rainwater harvesting, are also becoming integral to sustainable engineering networks, helping reduce the demand on freshwater resources and lowering the environmental impact of water treatment processes.

Building insulation is another area where innovative technologies are enhancing sustainability. The use of advanced materials and design strategies has improved the thermal performance of buildings, reducing the load on HVAC systems and minimizing energy consumption. Aerogel insulation, phase change materials, and advanced reflective coatings are just a few examples of innovations that enhance building efficiency, contributing to a reduction in overall energy use.

Lastly, eco-friendly materials and construction techniques are being incorporated into the development and modernization of engineering networks. These materials include low-impact concrete, energy-efficient steel, and recycled building components, all of which contribute to a more sustainable infrastructure. Sustainable construction practices, such as modular design and prefabrication, allow for faster, more efficient building processes with less waste generated during construction.

The integration of advanced technologies into engineering networks is an essential step toward achieving more efficient, sustainable, and cost-effective systems. The rapid advancements in digitalization, automation, and renewable energy sources have provided new opportunities for enhancing the performance and efficiency of heat, gas, and ventilation systems. These innovations aim to not only optimize energy consumption but also ensure the reliability and sustainability of engineering networks.

One of the key areas where advanced technologies are making a significant impact is the integration of smart grid systems. These systems allow for real-time monitoring, data analysis, and more effective management of energy distribution. By incorporating advanced sensors, communications, and control systems, smart grids can improve energy efficiency by reducing losses, balancing supply and demand, and integrating renewable energy sources seamlessly into existing infrastructures.

Another promising development is the adoption of energy storage systems, such as batteries and thermal storage, which help to stabilize energy production and consumption. By storing excess energy during periods of low demand, these systems allow for its efficient use during peak hours, thereby reducing overall energy consumption and lowering operational costs. The growth of electric vehicles and renewable energy further underscores the potential of energy storage technologies in transforming energy networks.

The integration of renewable energy sources such as solar, wind, and geothermal power is also a major trend in modern engineering systems. These sources contribute significantly to reducing dependency on traditional fossil fuels, thus lowering greenhouse gas emissions. As renewable energy technology continues to improve and become more affordable, its incorporation into heat and gas supply systems offers a highly sustainable option for the future of energy networks.

Additionally, the implementation of advanced HVAC (Heating, Ventilation, and Air Conditioning) systems is increasingly being recognized for its ability to optimize indoor climate control while minimizing energy usage. These systems utilize smart technologies such as sensors, automation, and energy-efficient components to maintain optimal comfort levels with minimal energy consumption.

Building automation systems are another area where significant advancements are being made. These systems integrate various building operations, including lighting, heating, cooling, and security, into a central control system that optimizes energy use and reduces waste. By leveraging real-time data, these systems can dynamically adjust to changing conditions and improve energy efficiency in buildings, particularly in large-scale commercial and industrial facilities.

High-efficiency insulation and heat recovery systems are critical components in the drive toward reducing energy consumption in buildings and industrial processes. Modern insulation materials and technologies, combined with systems designed to recover waste heat, offer substantial energy savings and improved system performance. These technologies are particularly effective in industries where high heat generation is common, such as in manufacturing processes, and can play a key role in the decarbonization of the sector.

Lastly, smart metering systems enable the precise monitoring of energy usage, providing both consumers and utilities with actionable insights to improve energy consumption behaviors. These systems allow for more accurate billing, real-time feedback on energy use, and data-driven decision-making to optimize energy consumption patterns across both residential and industrial sectors.

The integration of these advanced technologies not only improves operational efficiency but also helps in achieving sustainability goals by reducing energy consumption and carbon emissions. Furthermore, these technologies contribute to the reliability and resilience of engineering networks, making them more adaptable to future challenges, such as the increasing demand for energy, climate change, and resource scarcity.

In conclusion, the prospects for integrating advanced technologies into engineering networks are vast. With the ongoing progress in areas like smart grids, energy storage, renewable energy, and automation, the potential to transform heat and gas supply systems into more efficient, sustainable, and cost-effective operations is substantial. Moving forward, further investment in research, development, and implementation will be crucial in realizing the full potential of these technologies and ensuring their widespread adoption across various sectors of the economy

5.5 Impact of Regulatory Policies and Standards on Engineering Network Modernization

The modernization of engineering networks, including heating, ventilation, and air conditioning (HVAC) systems, water supply, and waste management networks, is heavily influenced by regulatory policies and standards that guide the design, implementation, and operation of these systems. These regulations are designed to ensure the sustainability, efficiency, and safety of engineering networks while aligning with broader environmental and energy goals. The evolution of these standards plays a significant role in shaping the direction of technological advancements and innovation in the field of engineering systems.

One of the key regulatory frameworks influencing the modernization of engineering networks is the establishment of energy efficiency standards. Over recent decades, global energy policies have focused on reducing carbon emissions and improving the energy performance of infrastructure. Standards such as the EU Energy Performance of Buildings Directive (EPBD) and ISO 50001 Energy Management Systems have set benchmarks for the energy consumption of building systems, encouraging the adoption of energy-efficient technologies in engineering networks. These policies often mandate the integration of advanced insulation materials, energy-efficient HVAC equipment, and renewable energy sources, pushing the industry toward more sustainable practices.

In addition to energy efficiency, environmental regulations play a pivotal role in guiding the modernization of engineering networks. International agreements, such as the Paris Agreement, and national policies on climate change have led to stricter regulations regarding emissions, waste management, and water usage. For example, local authorities may impose stringent rules on the maximum allowable emissions from heating and cooling systems, promoting the use of low-carbon technologies such as heat pumps and geothermal systems. Environmental standards also encourage the implementation of circular economy principles, which involve reducing waste, recycling materials, and reusing water and energy in building systems.

The impact of building codes and standards on engineering network modernization cannot be overstated. These codes, such as the International Building Code (IBC) and local regulations in various regions, set out the minimum requirements for building design and operation, including the specifications for energy systems, ventilation, heating, and cooling. As these codes evolve, they often reflect the latest scientific research and technological innovations. For instance, updated codes may require the installation of smart meters, renewable energy systems, or more efficient heating and cooling methods in new or renovated buildings. By adhering to these codes, building owners and engineers are ensuring that their systems are both compliant with regulations and optimized for energy performance.

Moreover, safety regulations have a significant influence on the design and operation of engineering networks. Standards related to the safe operation of HVAC systems, water supply networks, and waste management systems are crucial for preventing accidents, protecting public health, and ensuring the long-term reliability of these systems. Regulations such as the National Fire Protection Association (NFPA) codes and local building safety standards provide specific guidelines on system maintenance, pressure testing, and monitoring to ensure safe and reliable operation.

In recent years, smart technology standards have emerged as a key driver for the modernization of engineering networks. The introduction of smart grids, smart meters, and building automation systems has led to the creation of new standards focused on communication protocols, data security, and system integration. These standards ensure that smart systems can operate effectively and securely, allowing for real-time monitoring, predictive maintenance, and automated control, which in turn improves the efficiency and sustainability of engineering networks.

Finally, government incentives and subsidies also play a role in encouraging compliance with regulations and promoting modernization. Many governments offer financial incentives for upgrading outdated engineering systems to meet new efficiency and environmental standards. These incentives, such as tax credits for renewable energy installations or subsidies for energy-efficient building technologies, help offset the cost of modernization and accelerate the transition to more sustainable systems.

In conclusion, regulatory policies and standards are central to the ongoing modernization of engineering networks. They set the framework for technological advancements in energy efficiency, environmental impact, and safety, driving the adoption of innovative solutions such as smart technologies, renewable energy systems, and efficient building practices. As regulatory standards continue to evolve, they will further shape the future of engineering networks, ensuring that they are both sustainable and aligned with global energy and environmental goals

CONCLUSIONS

This monograph, «Comprehensive Analysis of Thermodynamic and Thermophysical Processes in Heat and Gas Supply and Ventilation Systems: Theoretical Foundations and Engineering Solutions» has provided an extensive examination of the thermodynamic principles, thermophysical properties, mass transfer processes, and energy-efficient strategies within heat and gas supply systems. The work has combined theoretical foundations with practical applications, leading to the development of innovative solutions aimed at optimizing system performance, enhancing energy efficiency, and integrating advanced technologies for future-proofing these essential infrastructure networks.

Summary of Research Findings

The research has demonstrated the complex interplay of thermodynamic and thermophysical processes that drive the functioning of heat and gas supply systems. It has been found that an in-depth understanding of these processes is essential for the effective design and operation of systems that are both energy-efficient and environmentally sustainable. Key findings include:

Thermodynamic and Thermophysical Interactions: Heat transfer, mass transfer, and thermodynamic principles are central to the efficiency of heat and gas supply systems. These processes significantly impact energy consumption, system performance, and overall efficiency. Understanding the dynamics of these processes is crucial for optimizing system operation and reducing waste.

Energy Efficiency Challenges: The study has revealed the numerous challenges faced by traditional heating and ventilation systems, including high energy consumption, heat losses, and inefficiencies related to operational modes. Addressing these inefficiencies requires the incorporation of advanced materials, improved system designs, and innovative operational strategies.

Impact of Renewable Energy: The integration of renewable energy sources, including solar, wind, and biomass, is vital for reducing the carbon footprint of heat and gas supply systems. However, the variability of renewable energy generation presents challenges that require advanced energy storage solutions, smart grid technologies, and optimized control systems.

Advanced Control and Monitoring Systems: The application of intelligent control systems, IoT, AI, and digital twin technologies has proven to be a valuable approach to improving real-time system monitoring, diagnostics, and performance optimization. These systems enable dynamic adaptation to changing operational conditions, ensuring better energy management and system longevity.

Operational Modes and System Optimization: The study highlighted that the efficiency of heat and gas supply systems is strongly dependent on operational modes, including heating loads, environmental conditions, and user demands. Implementing predictive analytics and optimization algorithms can significantly enhance system performance under varying conditions.

Practical Recommendations

Based on the research findings, several practical recommendations have been developed to enhance the efficiency, reliability, and sustainability of heat and gas supply and ventilation systems:

Optimization of System Operation: Implementing advanced control strategies, such as predictive maintenance and AI-driven optimization algorithms, will allow for the continuous adjustment of system parameters in response to real-time data, improving overall efficiency.

Enhanced Insulation and Materials: Investing in advanced thermal insulation materials and technologies can significantly reduce heat losses, particularly in industrial and residential buildings. This is especially important in the context of energy conservation and achieving lower operational costs.

Integration of Renewable Energy: It is recommended to incorporate renewable energy sources into existing systems. This requires investments in energy storage technologies, such as thermal energy storage and battery systems, to overcome the intermittency of renewable energy and ensure a reliable and constant supply of energy.

Utilization of Smart Grid Technology: The adoption of smart grids can improve the management and distribution of thermal energy in heat and gas supply systems. These systems facilitate more efficient energy distribution, reduce transmission losses, and enable real-time adjustments to optimize energy use.

Advanced Monitoring Systems: The installation of IoT-based monitoring systems for real-time data collection and analysis can help identify inefficiencies and faults, ensuring proactive maintenance and minimizing downtime. Moreover, digital twin technology can be employed for virtual simulations to improve system design and performance monitoring.

Cross-sector Collaboration: Encouraging collaboration between industry stakeholders, including energy providers, building designers, and regulatory bodies, will facilitate the development and implementation of energy-efficient solutions. This can result in cost-effective, sustainable systems that address the energy challenges of the future.

Directions for Further Research. Further research is essential to continue developing and refining the technologies and methods discussed in this monograph. Some key areas for future investigation include:

Integration of Next-Generation Materials: Research into advanced materials with superior thermal conductivity, resistance to environmental factors, and lower energy footprints is essential for improving the insulation and heat exchange properties of systems.

Development of Advanced Energy Storage Solutions: The ongoing development of more efficient and cost-effective energy storage systems, including innovations in thermal and electrical storage, is critical for enhancing the integration of renewable energy and reducing energy losses.

Improvement of AI and ML Algorithms: Future research should focus on refining the algorithms used for predictive maintenance, energy forecasting, and dynamic optimization of heating, gas supply, and ventilation systems. These algorithms must be capable of adapting to increasingly complex, real-time conditions.

Sustainability in System Design: Continued research is needed into sustainable and circular economy approaches to system design and operation. This includes focusing on resource efficiency, waste heat recovery, and the use of sustainable materials in construction and system components.

Impact of Climate Change on System Performance: As climate change continues to alter temperature and weather patterns, further studies should assess the impact of these changes on the performance of heat and gas supply systems. Research should focus on how systems can be designed to adapt to extreme weather events, shifting heating demands, and evolving environmental conditions.

Standardization and Policy Development: Further work is necessary in the development of universal standards for energy-efficient systems, as well as the establishment of regulatory frameworks that support innovation while ensuring the safety and reliability of energy infrastructure.

The research presented in this monograph offers valuable insights into the theoretical foundations and engineering solutions necessary for optimizing heat and gas supply systems. The integration of advanced technologies, including AI, smart grids, and renewable energy sources, holds great promise for improving energy efficiency and sustainability. As we move toward a more energy-conscious future, the continued development and implementation of innovative solutions will be essential to meet the global challenges of energy consumption and environmental protection.

LIST OF RECOMMENDED SOURCES

1. Pyarimohan Dehury. Prediction of thermophysical properties of deep eutectic solvent-based organic nanofluids: A machine learning approach / Pyarimohan Dehury, Shahil Chaudhari, Tamal Banerjee, Sarit Kumar Das // Journal of Molecular Liquids. – Volume 411. – 1 October 2024. – 125809. – DOI: https://doi.org/10.1016/j.molliq.2024.125809
2. Yichuan He. Data-driven approach augmented by attention mechanism in critical and boiling thermophysical properties prediction of fluorine/chlorine-based refrigerants / Yichuan He, Yanhui Feng, Lin Qiu, Dawei Tang // Energy. – Volume 306. – 15 October 2024. – 132490. – DOI: https://doi.org/10.1016/j.energy.2024.132490
3. Bernadeta Jasiok and all. Thermophysical properties of the SPC/E model of water between 250 and 400 K at pressures up to 1000 MPa / Bernadeta Jasiok and all // Fluid Phase Equilibria. – Volume 584. – September 2024. – 114118. – DOI: https://doi.org/10.1016/j.fluid.2024.114118
4. Rui Zhang. Asymptotic thermophysical behaviors of near-critical fluid under parameter scaling / Rui Zhang, Jinliang Xu, Lin Chen // International Journal of Heat and Fluid Flow. – Volume 108. – September 2024. – 109442. – DOI: https://doi.org/10.1016/j.ijheatfluidflow.2024.109442
5. Sohail A. Khan. Chemically reactive flow beyond constant thermophysical characteristics / Sohail A. Khan, T. Hayat, A. Alsaedi // Case Studies in Thermal Engineering. – Volume 61. – September 2024. – 104980. – DOI: https://doi.org/10.1016/j.csite.2024.104980
6. M. Abd El-Hamid. Effect of varying the thermophysical properties of phase change material on the performance of photovoltaic/thermal-PCM hybrid module numerically / M. Abd El-Hamid, Gaosheng Wei // Journal of Energy Storage. – Volume 86. – Part B. – 10 May 2024. – 111326. – DOI: https://doi.org/10.1016/j.est.2024.111326
7. Sujata Kalsi and all. Thermophysical properties of nanofluids and their potential applications in heat transfer enhancement: A review / Sujata Kalsi and all // Arabian Journal of Chemistry. – Volume 16. – Issue 11. – November 2023. – 105272. – DOI: https://doi.org/10.1016/j.arabjc.2023.105272
8. Rupali Tiwari and all. Investigation of thermophysical properties of Turkey oak particleboard for sustainable building envelopes / Rupali Tiwari and all // Developments in the Built Environment. – Volume 16. – December 2023. – 100228. – DOI: https://doi.org/10.1016/j.dibe.2023.100228
9. Fatemeh Zarei-Jelyani. 3 - Thermophysical properties of natural gas hydrates / Fatemeh Zarei-Jelyani, Fatemeh Salahi, Behnaz Rahmatmand, Mohammad

Reza Rahimpour // Advances in Natural Gas: Formation, Processing, and Applications. – Volume 3. – Natural Gas Hydrates. – 2024. – Pages 47–63. – DOI: https://doi.org/10.1016/B978-0-443-19219-7.00006-0

10. Bo Jin. Thermophysical properties in the Al-Cu-Ag system: A combined CALPHAD and first-principles study / Bo Jin, Shuhong Liu, Kai Xu, Qiang Lu b, Yong Du // Journal of Molecular Liquids. – Volume 370. – 15 January 2023. – 121001. – DOI: https://doi.org/10.1016/j.molliq.2022.121001

11. Amirhossein Parifard. AI-based optimization of a sustainable system for water, energy, and ventilation supply of a smart residential building / Amirhossein Parifard, Alireza Naeini, Alireza Jalali // Journal of Building Engineering. – Volume 104. – 15 June 2025. – 112350. – DOI: https://doi.org/10.1016/j.jobe.2025.112350

12. Jin Qin and all. Natural gas diffusion behavior and gas detector layout in the ship engine room considering heat radiation effect / Jin Qin and all // Ocean Engineering. – Volume 317. – 1 February 2025. – 120007. – DOI: https://doi.org/10.1016/j.oceaneng.2024.120007

13. Junkeon Ahn and all. Eco-efficient marine power system with cooled air ventilation by waste LNG cold energy for reefer holds in an ultra-large container ship / Junkeon Ahn and all // Journal of Cleaner Production. – Volume 322. – 1 November 2021. – 129037. – DOI: https://doi.org/10.1016/j.jclepro.2021.129037

14. Zongsheng Zhu. Thermodynamics of integrated energy supply for small-scale production and living condition in rural areas / Zongsheng Zhu, Shouzheng Zhao, Aiqiang Chen, Bin Liu // Energy for Sustainable Development. – Volume 72. – February 2023. – Pages 173–184. – DOI: https://doi.org/10.1016/j.esd.2022.12.016

15. Xue-mei Zhang. Desiccant wheel air-conditioning system driven by gas engine cogeneration of heat and power: simulation and analysis by Dymola / Xue-mei Zhang, Zheng Qian, Jia-xiu Yang // Case Studies in Thermal Engineering. – Volume 45. – May 2023. – 102983. – DOI: https://doi.org/10.1016/j.csite.2023.102983

16. Tanmay Dasgupta. Investigation of thermal stability, heat transfer dynamics, low-temperature oxidation kinetics and gas evolution profiles of coal: An innovative approach / Tanmay Dasgupta, Devi Prasad Mishra, Aditya Pandey // Fuel. – Volume 381. – Part A. – 1 February 2025. – 133354. – DOI: https://doi.org/10.1016/j.fuel.2024.133354

17. Yuchuan Guo. A new neutronics-thermal-mechanics multi-physics coupling method for heat pipe cooled reactor based on RMC and OpenFOAM / Yuchuan Guo, Zeguang Li, Shanfang Huang, Minyun Liu, Kan Wang // Progress in Nuclear Energy. – Volume 139. – September 2021. – 103842. – DOI: https://doi.org/10.1016/j.pnucene.2021.103842

18. Ruiqiang Bai. Study on the coupled heat-water-vapor-mechanics process of unsaturated soils / Ruiqiang Bai, Yuanming Lai, Mingyi Zhang, Jingge Ren // Journal

of Hydrology. – Volume 585. – June 2020. – 124784. – DOI: https://doi.org/10.1016/j.jhydrol.2020.124784

19. Xue Xue. Numerical simulation of thermal performance and thermal stress of latent heat storage system with various fins / Xue Xue, Ao Zhang, Yajie Wu, Huaan Li, Fengyongkang Wu, Laiquan Lv, Hao Zhou // Journal of Energy Storage. – Volume 98. – Part B. – 20 September 2024. – 113128. – DOI: https://doi.org/10.1016/j.est.2024.113128

20. R. DiPippo. 9 - Elements of thermodynamics, fluid mechanics, and heat transfer applied to geothermal energy conversion systems. Geothermal Power Generation / R. DiPippo // Developments and Innovation. – 2016. – Pages 217–247. – DOI: https://doi.org/10.1016/B978-0-08-100337-4.00009-7

21. A. Mugnini. Heat pumps to upgrade existing CHP-DHN systems towards new generation thermal networks / A. Mugnini, G. Comodi, A. Arteconi // Energy Reports. – Volume 12. – December 2024. – Pages 820–833. – DOI: https://doi.org/10.1016/j.egyr.2024.06.063

22. S.C. Jayasinghe and all. A review on the applications of artificial neural network techniques for accelerating finite element analysis in the civil engineering domain / S.C. Jayasinghe and all // Computers & Structures. – Volume 310. – 1 April 2025. – 107698. – DOI: https://doi.org/10.1016/j.compstruc.2025.107698

23. Mingzhe Li. Complex state networks based safety analysis of complex engineering systems considering closed-loop feedback / Mingzhe Li, Zhikun She, Dan Xu, Xueying Song, Wei Jia // Reliability Engineering & System Safety. – Volume 259. – July 2025. – 110931. – DOI: https://doi.org/10.1016/j.ress.2025.110931

24. Jianguo Zhou. Rapid repetition survey of engineering control network based on the concept of Internet of Things / Jianguo Zhou, Yanchong Chen, Jian Yu, Pai Pan, Wei Xiao // Measurement. – Volume 242. – Part E. – January 2025. – 116250. – DOI: https://doi.org/10.1016/j.measurement.2024.116250

25. Aswin Chandrasekar. Implementing Recurrent Neural Networks in Process Systems Engineering applications, the right way! / Aswin Chandrasekar, Tyler Wortley, Euan Bohm, Prashant Mhaskar // Computers & Chemical Engineering. – Volume 195. – April 2025. – 109027. – DOI: https://doi.org/10.1016/j.compchemeng.2025.109027

Електронне наукове видання

БУРДА Юрій Олександрович

КОМПЛЕКСНИЙ АНАЛІЗ ТЕРМОДИНАМІЧНИХ ТА ТЕПЛОФІЗИЧНИХ ПРОЦЕСІВ У СИСТЕМАХ ТЕПЛОГАЗОПОСТАЧАННЯ І ВЕНТИЛЯЦІЇ: ТЕОРЕТИЧНІ ОСНОВИ ТА ІНЖЕНЕРНІ РІШЕННЯ

МОНОГРАФІЯ

(Англ. мовою)

Відповідальний за випуск *Ю. І. Чайка*

За авторською редакцією

Комп'ютерне верстання *Ю .О. Бурда*

Підп. до друку 02.04.2025. Формат 60 × 84/16.
Ум. друк. арк. 7,5.

Видавець і виготовлювач:
Харківський національний університет
міського господарства імені О. М. Бекетова,
вул. Чорноглазівська (Маршала Бажанова), 17, Харків, 61002.
Електронна адреса: office@kname.edu.ua
Свідоцтво суб'єкта видавничої справи:
ДК № 5328 від 11.04.2017.