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Review article

Computational Fluid Dynamics in Hybrid Passive–Active Heat Recovery Systems for High-Performance Buildings: A Critical Review

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ABSTRACT

Hybrid passive–active heat recovery systems are increasingly used in high-performance buildings as a practical response to the growing pressure for lower energy use and more stable indoor environmental conditions. These systems combine passive heat transfer elements, such as heat pipes, with limited mechanical ventilation support in order to balance energy efficiency with operational controllability. As a result, they occupy a middle ground between fully passive solutions, which are often sensitive to boundary conditions, and fully active systems, which tend to impose higher energy and operational costs. Computational Fluid Dynamics (CFD) has become the main analytical approach for studying the behaviour of these hybrid systems. It is commonly used to investigate airflow patterns, heat transfer processes, pressure losses, and ventilation effectiveness under a wide range of operating conditions. At the same time, the existing literature shows substantial variation in how CFD models are constructed and applied. Differences in turbulence modelling, boundary condition definition, validation strategy, and performance metrics make it difficult to compare results across studies or draw general conclusions. This review critically examines published CFD-based studies on hybrid passive–active heat recovery systems in high-performance buildings. The focus is not on individual case studies, but on identifying recurring modelling practices, common simplifications, and their implications for predicted system performance. Particular attention is given to the treatment of mixed-mode ventilation, conjugate heat transfer, and the interaction between passive components and mechanically assisted airflow. The review also highlights areas where current CFD practice remains limited, including validation against field measurements and representation of climate-driven variability. By consolidating these findings, the paper aims to clarify the role of CFD as a supporting analytical tool for design and retrofit decisions, rather than as a stand-alone predictor of system performance.

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1. INTRODUCTION

High-performance buildings are increasingly required to deliver substantial reductions in energy consumption while maintaining acceptable indoor environmental quality across a wide range of climatic and operational conditions. Ventilation, heating, and cooling systems remain among the dominant contributors to

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building energy demand, with conventional mechanical ventilation and heat recovery systems typically accounting for approximately 10–30% of annual energy use in residential and non-residential buildings (Zhang et al. 2021; Wang et al. 2017; Chen Austin et al. 2021). At the same time, stricter building envelopes, increased airtightness, and evolving comfort expectations have intensified the challenge of balancing energy efficiency with adequate ventilation and thermal comfort.

Passive heat recovery technologies, including heat pipes and other air-to-air heat exchange devices, have attracted sustained interest due to their inherent energy efficiency, absence of moving parts, and low operational complexity. These systems can recover a significant fraction of sensible heat from exhaust air streams without requiring continuous mechanical input. However, their performance is strongly dependent on ambient conditions, airflow driving forces, and operating regimes. Under variable climatic conditions, fluctuating wind pressures, or changing occupancy patterns, purely passive systems may exhibit reduced robustness, unstable airflow behaviour, or limited controllability, particularly in highly insulated and airtight buildings (O'Connor et al. 2016; Sadineni et al. 2011). Conversely, fully active mechanical ventilation systems offer greater operational control and predictable airflow rates, but often at the expense of increased fan energy consumption, higher system complexity, and potential comfort issues when airflow distribution and control strategies are not optimally designed (O'Connor et al. 2016; Sadineni et al. 2011).

These complementary limitations have motivated growing interest in hybrid passive–active heat recovery systems, which combine passive heat transfer components with mechanically assisted ventilation. By integrating limited active support with passive recovery mechanisms, hybrid systems aim to stabilise airflow paths, extend effective operating ranges, and improve resilience to variable internal and external conditions while maintaining lower auxiliary energy demand than fully active solutions. When appropriately designed, hybrid configurations can enhance heat recovery effectiveness, improve indoor air quality, and provide operational flexibility across natural, mechanical, and mixed-mode ventilation regimes (Lozinsky et al. 2025; Coggins et al. 2024; International Code Council, 2020; United Nations Economic Commission for Europe, 2020).

Accurate assessment of hybrid system performance requires resolution of strongly coupled physical processes, including three-dimensional airflow behaviour, heat and moisture transfer, pressure losses, and interaction with building envelope characteristics. Simplified analytical models and lumped-parameter approaches are generally insufficient to capture these interactions, particularly under mixed-mode operation or transient boundary conditions. Experimental investigations provide valuable insight but are often limited in spatial resolution or constrained to specific configurations and operating scenarios. Computational Fluid Dynamics (CFD) offers a complementary and powerful framework for resolving these coupled phenomena through steady-state and transient simulations, enabling systematic evaluation of airflow distribution, heat recovery effectiveness, pressure losses, and indoor environmental conditions in both new-build and retrofit contexts (Lozinsky et al. 2025; Coggins et al. 2024; International Code Council, 2020; United Nations Economic Commission for Europe 2020).

Over the past two decades, CFD has become the dominant analytical tool for investigating hybrid passive–active heat recovery systems. Studies reported in the literature employ CFD to examine airflow organisation, thermal performance, ventilation effectiveness, and system response under a wide range of climatic and operational conditions. Nevertheless, existing CFD-based research remains highly heterogeneous. Substantial variation exists in modelling assumptions, turbulence treatment, boundary condition specification, validation practices, and performance metrics, which complicates comparison across studies and limits the transferability of reported findings. In addition, many investigations focus on isolated case studies or specific configurations, with limited synthesis of broader trends, modelling limitations, and unresolved challenges.

Against this background, the present review critically examines CFD-based studies of hybrid passive–active heat recovery systems for high-performance buildings. Rather than cataloguing individual applications, the review synthesises current knowledge to identify dominant system architectures, prevailing CFD modelling strategies, and recurring limitations in performance assessment. Particular emphasis is placed on the interaction between passive and active components, treatment of mixed-mode ventilation, representation of conjugate heat and moisture transfer, and implications of modelling choices for predicted thermal performance, pressure losses, and indoor environmental quality. By clarifying the role of CFD as a diagnostic and decision-support tool rather than a purely predictive technique, this review aims to provide a structured foundation for future research, design optimisation, and retrofit application of hybrid heat recovery systems within the broader context of energy-efficient and resilient building design (Chen Austin et al. 2021; Coggins et al. 2024; United Nations Economic Commission for Europe, 2020).

1.1 LITERATURE REVIEW METHODOLOGY

A structured literature review strategy was adopted to improve the transparency, traceability, and analytical depth of this review. The aim was not only to collect published CFD studies, but also to examine how modelling choices, system configurations, validation practices, and reported performance indicators influence the interpretation of hybrid passive–active heat recovery systems in high-performance buildings.

The literature search was carried out using major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis Online, Google Scholar, and relevant publisher databases. The search focused on peer-reviewed studies related to computational fluid dynamics, hybrid ventilation, heat recovery, passive and active ventilation systems, heat pipe heat exchangers, mixed-mode ventilation, indoor environmental quality, and high-performance or net-zero-energy buildings. The main keyword combinations included "CFD and hybrid ventilation", "passive–active heat recovery", "heat pipe ventilation", "mixed-mode ventilation", "CFD heat recovery building", "decentralized ventilation heat recovery", "building ventilation CFD", "thermal comfort CFD", and "zero-energy building ventilation".

The review primarily considered studies published between 2015 and 2026 in order to capture recent developments in CFD-based ventilation analysis, hybrid heat recovery technologies, energy-efficient building design, and indoor environmental quality. Earlier foundational sources were retained where they provided essential theoretical or methodological background, particularly for ventilation theory, heat and mass transfer, pressure loss modelling, and CFD formulation. These sources include established references on building ventilation, hydraulic resistance, heat transfer, and finite-volume CFD modelling (Etheridge and Sandberg 1996; Awbi 2003; Idelchik 1994; Incropera et al. 2007; Versteeg and Malalasekera 2007; Cengel and Ghajar 2015).

The inclusion criteria were defined as follows: studies were included if they addressed CFD-based analysis of airflow, heat transfer, pressure loss, thermal comfort, ventilation effectiveness, heat recovery performance, or hybrid passive–active ventilation behaviour in buildings or closely related thermal systems. Studies on passive ventilation, mechanical ventilation, heat pipe heat exchangers, decentralized heat recovery units, retrofit ventilation strategies, and zero-energy building systems were also included when their findings supported the interpretation of hybrid system performance or CFD modelling practice. Recent studies on building retrofits, indoor environmental quality, net-zero-energy buildings, and ventilation performance were included to place CFD-based heat recovery analysis within the broader context of decarbonisation and high-performance building operation (Chen Austin et al. 2021; Zhang et al. 2021; Coggins et al. 2024; Aljashaami et al. 2024; Kim et al. 2024; Li et al. 2025; Lozinsky et al. 2025; Myroniuk et al. 2026).

Studies were excluded when they lacked sufficient methodological detail, were unrelated to building ventilation or heat recovery, relied only on broad conceptual discussion without technical relevance to CFD or thermal system modelling, or duplicated findings already reported in more complete peer-reviewed sources. Purely experimental or empirical studies were not excluded automatically; they were retained when they provided validation evidence, boundary condition data, performance benchmarks, or physical interpretation relevant to CFD-based assessment. This was important because validation remains one of the main limitations in CFD studies of hybrid ventilation and heat recovery systems.

The selected literature was analysed through thematic synthesis rather than simple chronological reporting. The reviewed studies were grouped into five main themes: system architecture and heat exchanger configuration, CFD domain and boundary condition definition, turbulence and conjugate heat transfer modelling, validation and uncertainty treatment, and reported performance outcomes. Particular attention was given to studies that provided quantitative indicators such as heat recovery effectiveness, pressure drop, airflow distribution, ventilation effectiveness, thermal comfort indices, or energy-related performance measures. This approach allowed the review to move beyond descriptive summary and identify how specific modelling assumptions affect the reliability, transferability, and design relevance of CFD results.

The review also distinguished between foundational references and recent application-focused studies. Foundational sources were used to support physical principles and modelling theory, while recent studies were used to evaluate the current direction of CFD application in hybrid ventilation, heat recovery, thermal comfort, and building decarbonisation research. For example, recent CFD and ventilation studies were used to assess airflow behaviour and validation practice (Ozsagiroglu et al. 2022; Jung et al. 2023; Zhong et al. 2024; Avci 2025), while recent heat pipe and heat recovery studies were used to interpret passive component performance and thermal transfer mechanisms (Li et al. 2023; Ramlee et al. 2023; Malcho et al. 2025). Broader review studies on passive ventilation, retrofits, indoor air quality, and net-zero-energy buildings were used to frame the relevance of hybrid systems within contemporary energy and decarbonisation targets (O'Connor et al. 2016; Friess and Rakhshan 2017; Coggins et al. 2024; Lozinsky et al. 2025; Li et al. 2025; Myroniuk et al. 2026).

Through this methodology, the review was structured to answer three central questions: first, how CFD has been used to analyse airflow, heat transfer, and pressure losses in hybrid passive–active heat recovery systems; second, which modelling choices most strongly influence reported performance outcomes; and third, what limitations, validation gaps, and research priorities remain for future CFD-supported design of high-performance and retrofit buildings. This methodological structure directly supports the main objective of the paper, which is to position CFD not as a stand-alone prediction tool, but as a decision-support framework for the design, comparison, and optimisation of hybrid heat recovery systems.

2. FUNDAMENTALS OF HYBRID PASSIVE–ACTIVE HEAT RECOVERY SYSTEMS

Hybrid passive–active heat recovery systems are designed to bridge the performance gap between purely passive ventilation strategies and fully mechanical heat recovery systems. Their fundamental operating principle relies on the simultaneous exploitation of passive heat transfer mechanisms and controlled mechanical airflow to achieve stable thermal performance and acceptable indoor air quality across variable operating conditions. Unlike conventional systems that rely exclusively on either natural driving forces or continuous fan operation, hybrid configurations adapt dynamically to environmental and occupancy-driven variability, which is increasingly characteristic of high-performance and retrofit buildings (Etheridge and Sandberg, 1996; Awbi, 2003).

At a system level, hybrid heat recovery performance emerges from the interaction of three tightly coupled processes: airflow generation and distribution, heat and moisture transfer between exhaust and supply air streams, and pressure loss associated with both passive components and mechanical assistance. The balance among these processes governs not only energy recovery effectiveness but also auxiliary energy demand, ventilation effectiveness, and occupant comfort. Understanding these coupled mechanisms is therefore essential before CFD-based modelling approaches and performance evaluations are considered in detail.

2.1 HEAT TRANSFER MECHANISMS IN HYBRID SYSTEMS

Heat recovery in hybrid systems is primarily driven by sensible heat exchange between exhaust and supply air streams and, in certain configurations, by latent heat transfer associated with moisture exchange. Passive heat transfer elements, such as heat pipes and air-to-air heat exchangers, enable thermal energy to be transferred without direct mixing of air streams. In its simplest form, the recovered sensible heat can be expressed as a function of air mass flow rate, specific heat capacity, and temperature difference between inlet and outlet streams. While such formulations are useful for preliminary estimation, they inherently assume spatially uniform flow and heat transfer behaviour.

In practice, hybrid systems exhibit strong spatial variability in temperature fields and local heat flux due to non-uniform airflow distribution, partial utilisation of exchanger surfaces, and interaction between passive and mechanically assisted airflow. These effects become particularly pronounced under mixed-mode ventilation, where buoyancy-driven flow and fan-induced flow coexist or alternate (Etheridge and Sandberg, 1996). As a result, average performance metrics often mask localised performance-limiting mechanisms, such as thermal short-circuiting or underutilised heat transfer regions. CFD-based analysis is therefore required to resolve conjugate heat transfer between solid exchanger components and surrounding airflow, capturing spatial variations that directly influence overall system effectiveness (Awbi 2003; Versteeg and Malalasekera, 2007).

Latent heat transfer further complicates system behaviour in humid climates or during cooling-dominated operation. Moisture transport and condensation processes influence both heat recovery effectiveness and indoor comfort, particularly in highly insulated and airtight buildings where moisture accumulation can occur. Although many CFD studies neglect detailed phase-change modelling due to computational constraints, simplified moisture transport representations are increasingly employed to capture dominant latent effects at the system level (Etheridge and Sandberg 1996; Awbi 2003).

2.2. AIRFLOW BEHAVIOUR AND PRESSURE LOSSES

Airflow behaviour plays a central role in determining both thermal performance and auxiliary energy demand in hybrid heat recovery systems. Air movement may be driven by wind pressure, buoyancy forces arising from temperature differences, mechanically induced pressure gradients, or a combination of these mechanisms depending on operating mode. The resulting flow regimes range from low-Reynolds-number buoyancy-driven flow in naturally ventilated conditions to fully turbulent ducted flow under mechanical assistance (Versteeg and Malalasekera 2007; Incropera et al. 2007).

The Reynolds number provides a first-order indicator of flow regime and associated convective heat transfer potential. Laminar or transitional flows typically result in reduced convective heat transfer and limited mixing, whereas turbulent flows enhance heat transfer at the cost of increased pressure losses. In hybrid systems, the design challenge lies in identifying operating regimes where modest mechanical assistance yields a disproportionate improvement in airflow stability and heat recovery effectiveness without imposing excessive fan energy demand (Versteeg and Malalasekera 2007; Awbi 2003; Incropera et al. 2007; Cengel and Ghajar 2015).

Pressure losses arise from frictional resistance within ducts, heat exchanger passages, and façade-integrated components, as well as from flow separation and recirculation induced by geometric features. Excessive pressure loss can negate the energy benefits of heat recovery by increasing auxiliary fan power requirements. Consequently, hybrid system design requires simultaneous consideration of thermal and aerodynamic performance rather than optimisation of heat transfer in isolation. CFD-based pressure field analysis provides a means to quantify these trade-offs and to identify design modifications that improve overall system efficiency (Incropera et al. 2007; Cengel and Ghajar 2015; Idelchik 1994).

2.3. VENTILATION MODES AND OPERATING REGIMES

Hybrid passive–active heat recovery systems operate under three primary ventilation regimes: natural, mechanical, and mixed-mode ventilation. Each regime is characterised by distinct airflow drivers and thermal behaviour, with direct implications for heat recovery performance and modelling requirements.

Under natural ventilation, airflow is governed by wind-induced pressure differences and buoyancy forces. Passive heat recovery components exploit these flows to transfer energy between exhaust and supply air streams; however, airflow rates are inherently variable and sensitive to external climatic conditions and building geometry. CFD simulations under natural ventilation conditions must therefore account for low-velocity flow, potential flow reversal, and thermal stratification, all of which influence local heat recovery effectiveness and indoor comfort (Etheridge and Sandberg 1996; Idelchik 1994).

Mechanical ventilation introduces controlled airflow through fans and ductwork, enabling predictable operating conditions when natural driving forces are insufficient. In mechanically assisted hybrid systems, airflow rates are typically higher and fully turbulent, supporting more stable heat transfer and ventilation effectiveness. However, mechanical assistance increases auxiliary energy demand and may introduce comfort issues if airflow distribution is poorly managed. CFD-based analysis enables evaluation of these effects by resolving airflow distribution, pressure losses, and thermal gradients within occupied spaces (Versteeg and Malalasekera 2007).

Mixed-mode ventilation represents the defining operational characteristic of hybrid systems. In this regime, passive and active mechanisms act simultaneously or intermittently, resulting in transient flow interactions and evolving pressure balances. Transitions between natural and mechanically assisted operation can significantly affect heat recovery effectiveness and indoor comfort if not properly managed. CFD provides a unified framework for representing these transitions by consistently modelling boundary conditions, flow regimes, and coupled heat transfer processes across operating modes (Cengel and Ghajar 2015; Idelchik 1994).

2.4. IMPLICATIONS FOR CFD-BASED REVIEW AND ANALYSIS

The coupled heat transfer, airflow, and pressure loss mechanisms described above establish the physical basis for CFD-based investigation of hybrid passive–active heat recovery systems. From a review perspective, these fundamentals highlight why CFD has become the dominant analytical approach in the literature and why results are highly sensitive to modelling assumptions, boundary condition specification, and operating regime definition. Before presenting Table 1, it is necessary to establish a clear comparative framework for how ventilation regimes govern airflow behaviour and heat recovery performance in hybrid passive–active systems. The table consolidates the defining characteristics of natural, mechanical, and mixed-mode ventilation by linking dominant driving forces and flow regimes to their corresponding thermal response. It further identifies the primary modelling challenges associated with each regime, thereby providing a structured reference for interpreting differences in reported performance and the sensitivity of CFD-based predictions to underlying assumptions.

Table 1. Fundamental operating characteristics of hybrid passive–active heat recovery systems across ventilation regimes.

Ventilation regime	Dominant airflow drivers	Typical flow regime	Heat recovery characteristics	Key modelling challenges
Natural ventilation	Wind-induced pressure differences and buoyancy forces driven by indoor–outdoor temperature gradients	Low-velocity, buoyancy-dominated flow; laminar to transitional; frequent flow reversal possible	Heat recovery effectiveness strongly dependent on ambient conditions; spatially non-uniform heat transfer; partial utilisation of passive exchanger surfaces	Accurate representation of low-Reynolds-number flow, buoyancy effects, thermal stratification, and pressure boundary conditions; sensitivity to external climate assumptions
Mechanical ventilation	Fan-induced pressure gradients with controlled mass flow rates	Fully turbulent, pressure-driven ducted flow	More stable and predictable heat recovery performance; higher and more uniform convective heat transfer; increased auxiliary energy demand	Modelling pressure losses, fan boundary conditions, and turbulence near heat exchanger surfaces; balancing thermal performance against fan energy consumption
Mixed-mode ventilation (hybrid operation)	Combined buoyancy forces, wind pressure, and intermittent or continuous mechanical assistance	Transitional and mixed flow regimes; coexistence of natural and forced convection	Extended effective operating range; improved robustness under variable conditions; heat recovery enhanced by airflow stabilisation rather than increased flow rate	Coupled treatment of natural and mechanical driving forces; transient behaviour during mode switching; sensitivity to control strategy and boundary condition definition

By explicitly linking physical mechanisms to ventilation modes and system behaviour, this section provides the foundation for the subsequent review of system architectures, heat exchanger configurations, and CFD modelling strategies. The following section therefore examines how different hybrid system layouts and exchanger designs influence airflow organisation, heat transfer effectiveness, and modelling requirements reported in the literature (Idelchik 1994; Cengel and Ghajar 2015; Incropera et al. 2007; Awbi 2003; Etheridge and Sandberg 1996; Versteeg and Malalasekera 2007; Idelchik 1994; Cengel and Ghajar 2015).

3. SYSTEM ARCHITECTURE AND HEAT EXCHANGER DESIGN

The performance of hybrid passive–active heat recovery systems is strongly governed by overall system architecture and the configuration of heat exchange components. Architectural layout determines airflow paths, dominant driving forces, pressure losses, and the degree of interaction between passive and mechanically assisted elements. These factors directly influence heat recovery effectiveness, auxiliary energy demand, and indoor environmental quality. From a CFD perspective, system architecture defines the computational domain, boundary condition formulation, and spatial resolution required to capture performance-limiting mechanisms reported across the literature (Idelchik 1994; Cengel and Ghajar 2015; Incropera et al. 2007).

Hybrid system architectures reported in previous studies vary widely in scale, integration strategy, and intended application. While this diversity reflects the adaptability of hybrid concepts to different building contexts, it also contributes to the heterogeneity of CFD modelling approaches and performance metrics observed in existing research. A structured classification of system architectures is therefore essential for synthesising findings across studies and for identifying common trends and limitations.

3.1. CLASSIFICATION OF HYBRID SYSTEM ARCHITECTURES

Based on installation scale, airflow driving mechanism, and integration strategy, hybrid passive–active heat recovery systems are commonly classified into decentralised, centralised, and retrofit-oriented configurations (Idelchik 1994; Cengel and Ghajar, 2015; Incropera et al. 2007; Awbi, 2003; Etheridge and Sandberg 1996).

Each category exhibits distinct airflow characteristics, controllability, and modelling requirements. A clear understanding of the system-level integration is required to interpret how hybrid passive–active heat recovery ventilation operates under varying conditions. Fig. 1 illustrates the conceptual framework of these systems, highlighting the interaction between airflow pathways, heat exchange processes, and control mechanisms. It also identifies the role of CFD-based analysis in resolving flow dynamics and thermal behaviour, providing the basis for performance evaluation and design optimisation.

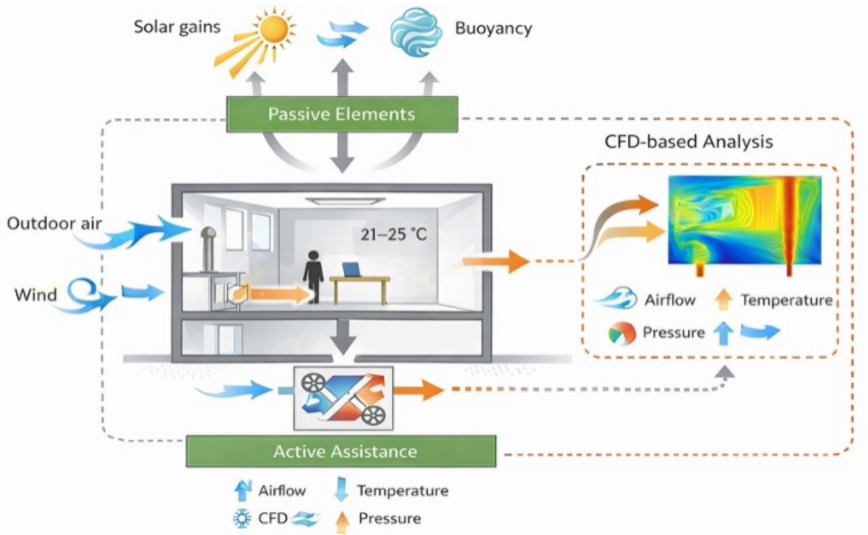


Figure 1. Conceptual framework of hybrid passive–active heat recovery ventilation systems in buildings and the role of CFD-based analysis.

Decentralised hybrid systems typically consist of compact units installed at façade or window level, combining passive heat recovery elements with low-power fans or controllable vents. Airflow in these systems is governed by a combination of buoyancy effects, wind pressure, and intermittent mechanical assistance. CFD studies indicate that decentralised configurations are particularly sensitive to local boundary conditions, such as façade orientation, external wind profile, and internal thermal stratification. Their modular nature makes them attractive for retrofit applications; however, performance variability across operating conditions necessitates careful CFD-based assessment to ensure stable airflow and effective heat recovery (Awbi 2003).

Centralised hybrid systems integrate passive heat recovery components within ducted mechanical ventilation networks serving multiple zones or entire buildings. In these configurations, airflow is predominantly pressure-driven and actively controlled, enabling more predictable operation and coordinated distribution of supply and exhaust air. CFD investigations of centralised systems often focus on duct layout optimisation, pressure loss management, and uniform utilisation of heat exchanger surfaces. While centralised architectures offer higher controllability and scalability, they typically involve greater capital cost and increased modelling complexity due to the need to resolve extended duct networks and multi-zone interactions (Etheridge and Sandberg 1996; Idelchik 1994).

Retrofit-oriented hybrid configurations prioritise performance enhancement of existing buildings while minimising intervention to the building envelope and interior layout. These systems commonly combine passive heat exchangers with auxiliary fans in window- or wall-mounted units. CFD-based studies demonstrate that such configurations can significantly improve airflow organisation and thermal performance under constrained geometric conditions, particularly in buildings originally designed for natural ventilation. However, retrofit systems are especially prone to flow maldistribution, bypass effects, and interaction with interior obstructions, underscoring the importance of spatially resolved CFD analysis (Cengel and Ghajar, 2015; Incropera et al. 2007; Awbi, 2003). Table 2 provides a structured classification of hybrid passive–active heat recovery system architectures reported in the literature, distinguishing between decentralized, centralized, and retrofit-oriented configurations. The comparison links system scale and dominant airflow drivers to their practical advantages and inherent limitations. Particular emphasis is placed on the corresponding CFD modelling focus for each architecture, clarifying how differences in geometry, control, and operating conditions translate into distinct simulation requirements and sources of uncertainty.

Table 2. Classification of hybrid passive–active heat recovery system architectures reported in the literature.

Architecture type	Typical scale	Dominant airflow drivers	Key advantages	Common limitations	CFD modelling focus
Decentralized hybrid systems	Single room or small zone; façade- or window-mounted units	Buoyancy forces and wind pressure with intermittent or low-power fan assistance	High suitability for retrofit; modular installation; reduced ductwork; lower capital cost	Strong sensitivity to local boundary conditions; performance variability with façade orientation and climate; risk of short-circuiting	Resolution of room-scale airflow organisation, interaction with thermal stratification, local pressure imbalance, and heat exchanger utilisation
Centralized hybrid systems	Multi-zone or whole-building scale; ducted ventilation networks	Predominantly fan-driven flow with supplementary buoyancy effects	High controllability; predictable airflow rates; coordinated distribution across zones	Higher system complexity and capital cost; increased pressure losses; larger auxiliary energy demand	Duct network pressure loss, uniformity of airflow distribution, heat exchanger surface utilisation, and system-level energy trade-offs
Retrofit-oriented hybrid configurations	Existing buildings with fixed envelope constraints; window- or wall-integrated units	Mixed buoyancy-driven and mechanically assisted airflow under constrained geometry	Minimal intervention to existing fabric; improved performance over passive-only systems; practical for ageing building stock	Flow maldistribution due to interior obstructions; geometric constraints; sensitivity to installation quality	Diagnosis of flow bypass, recirculation zones, interaction with existing partitions, and robustness under non-ideal boundary conditions

3.2. HEAT EXCHANGER TYPES AND INTEGRATION STRATEGIES

Heat exchangers constitute the core functional component of hybrid heat recovery systems, governing thermal energy transfer between exhaust and supply air streams while simultaneously influencing pressure losses and auxiliary fan energy demand. The choice of exchanger type, geometry, orientation, and integration strategy has a direct impact on overall system performance and modelling requirements (Etheridge and Sandberg 1996; Versteeg and Malalasekera 2007).

Heat pipe–based exchangers are among the most widely reported passive components in hybrid systems due to their high effective thermal conductivity, operational reliability, and absence of moving parts. CFD studies commonly represent heat pipes using simplified approaches, such as effective thermal conductivity models or prescribed heat flux boundary conditions, to capture dominant system-level behaviour without resolving internal two-phase flow dynamics (Versteeg and Malalasekera 2007; Incropera et al. 2007; Awbi 2003). These representations enable practical assessment of airflow interaction and heat recovery effectiveness while maintaining computational tractability.

Plate-type air-to-air heat exchangers and enthalpy exchangers are also employed in hybrid configurations, particularly in centralised systems where latent heat recovery is desired. CFD-based investigations of these exchangers focus on conjugate heat transfer, airflow maldistribution, and pressure drop characteristics. Literature findings consistently indicate that non-uniform airflow distribution can significantly reduce effective heat transfer area utilisation, leading to lower system efficiency than predicted by lumped-parameter models (Incropera et al. 2007; Awbi 2003; Versteeg and Malalasekera 2007).

Integration strategy plays a critical role in determining exchanger performance. Vertical heat pipe arrangements are often advantageous in thermally stratified environments dominated by buoyancy-driven flow, whereas horizontal configurations better support wind-assisted or cross-ventilation regimes. CFD studies highlight that suboptimal integration can lead to thermal short-circuiting, bypass flow, or excessive pressure imbalance, particularly under mixed-mode operation (Cengel and Ghajar 2015; Incropera et al. 2007).

3.3. AERODYNAMIC AND THERMAL TRADE-OFFS

A recurring theme across CFD-based studies is the trade-off between heat recovery effectiveness and aerodynamic resistance. Enhancing convective heat transfer typically requires increased airflow velocity or turbulence intensity, which in turn increases pressure losses and auxiliary fan energy demand. Hybrid systems seek to exploit operating regimes in which limited mechanical assistance stabilises airflow paths and enhances heat transfer without incurring the full energy penalty of continuous active ventilation (Etheridge and Sandberg 1996; Idelchik 1994).

CFD pressure field analyses reported in the literature demonstrate that modest geometric modifications, such as diffuser shaping, exchanger spacing, or flow straightening elements, can substantially reduce pressure losses while preserving or enhancing thermal performance. These findings underscore the value of CFD as a design optimisation tool rather than merely a post hoc performance evaluation method (Cengel and Ghajar 2015; Incropera et al. 2007; Awbi 2003).

3.4. IMPLICATIONS FOR CFD-BASED REVIEW

From a review perspective, system architecture and heat exchanger design emerge as primary sources of variability in reported CFD outcomes. Differences in architectural layout, exchanger representation, and integration strategy directly influence predicted airflow organisation, heat recovery effectiveness, and auxiliary energy demand. As a result, meaningful synthesis of CFD-based findings requires explicit consideration of architectural context rather than direct comparison of isolated performance metrics.

This section establishes a structured framework for interpreting architectural and exchanger-related variations reported in the literature. The following section therefore focuses on CFD modelling approaches adopted for hybrid systems, examining how domain definition, boundary conditions, turbulence modelling, and conjugate heat transfer representations influence reported results and contribute to the observed heterogeneity in CFD-based studies (Versteeg and Malalasekera 2007; Incropera et al. 2007; Cengel and Ghajar 2015; Idelchik 1994; Awbi, 2003; Etheridge and Sandberg 1996; Versteeg and Malalasekera 2007; Incropera et al. 2007; Cengel and Ghajar 2015).

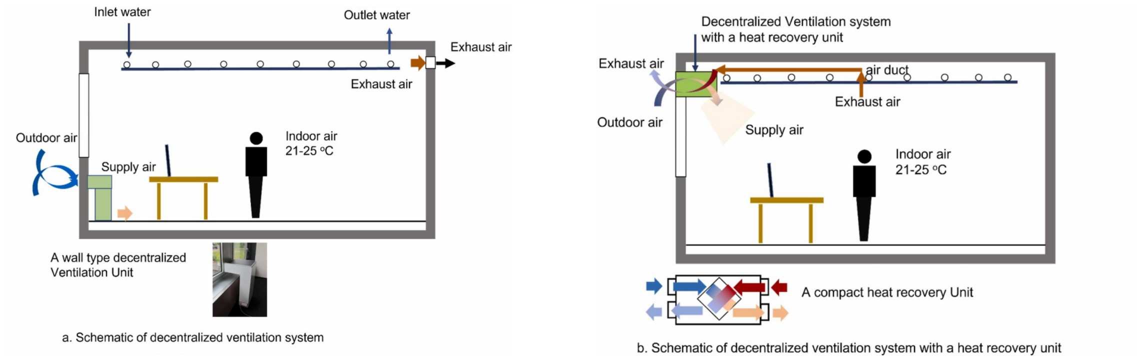
4. CFD MODELLING APPROACHES FOR HYBRID PASSIVE–ACTIVE HEAT RECOVERY SYSTEMS

Computational Fluid Dynamics (CFD) has become the dominant analytical framework for investigating hybrid passive–active heat recovery systems due to its ability to resolve coupled airflow, heat transfer, and pressure loss mechanisms under realistic operating conditions. Unlike simplified analytical models, CFD enables three-dimensional representation of flow behaviour, spatially varying heat recovery effectiveness, and interaction between passive and mechanically assisted components. However, a review of existing studies reveals substantial variability in modelling approaches, assumptions, and levels of physical detail, which directly influences reported performance outcomes and limits cross-study comparability (Versteeg and Malalasekera 2007; Incropera et al. 2007; Cengel and Ghajar 2015; Idelchik 1994).

From a review perspective, CFD modelling strategies for hybrid systems can be broadly categorised according to domain definition, boundary condition treatment, turbulence modelling, and representation of conjugate heat and moisture transfer. Each of these modelling choices reflects a balance between physical fidelity and computational tractability and must be interpreted in light of the intended application, whether design optimisation, retrofit assessment, or exploratory research.

4.1. COMPUTATIONAL DOMAIN DEFINITION AND GEOMETRIC REPRESENTATION

Definition of the computational domain constitutes a fundamental step in CFD analysis of hybrid heat recovery systems. In decentralised and façade-integrated configurations, the domain typically includes both the ventilation unit and a portion of the occupied indoor space to capture interaction between airflow emerging from the device and room-scale circulation patterns. In contrast, CFD studies of centralised hybrid systems often extend the domain to include ductwork, plenums, and multiple zones, reflecting the pressure-driven nature of airflow distribution (Versteeg and Malalasekera 2007; Awbi 2003). Fig. 2 presents a representative configuration of a decentralized hybrid passive–active ventilation system equipped with an integrated heat recovery unit. The schematic highlights both the physical arrangement of the wall-mounted unit and the internal airflow organisation through the compact heat exchanger module. This illustration is particularly relevant for understanding local airflow pathways, potential short-circuiting effects, and the mechanisms governing heat exchange efficiency at the room scale, as reported by Kim et al. (2024).



(**a**) (**b**)

Figure 2. Schematic representation of a decentralized hybrid passive–active ventilation system with an integrated heat recovery unit: **(a)** wall-mounted decentralized ventilation unit, and **(b)** airflow organization with a compact heat recovery module (Kim et al. 2024).

A recurring challenge reported in the literature concerns the trade-off between geometric detail and computational cost. Simplifications such as omission of minor geometric features, symmetry assumptions, or truncated indoor domains are commonly adopted to reduce mesh size. While these simplifications are often justified, review of published studies indicates that excessive geometric reduction can suppress flow recirculation, underestimate pressure losses, or misrepresent thermal stratification, particularly under mixed-mode ventilation (Cengel and Ghajar 2015; Idelchik 1994). Consequently, careful justification of domain boundaries and retained geometric features is essential for reliable interpretation of CFD results.

4.2. BOUNDARY CONDITIONS AND OPERATING SCENARIOS

Specification of boundary conditions strongly governs predicted airflow behaviour and heat recovery performance in CFD simulations. For mechanically assisted operation, inlet boundary conditions are typically prescribed using fixed velocity or mass flow rates with defined temperature and humidity, enabling controlled assessment of system response under stable operating conditions. Outlet boundaries are commonly treated as pressure outlets to allow fully developed flow and minimise artificial numerical constraints (Versteeg and Malalasekera 2007; Incropera et al. 2007; Cengel and Ghajar 2015; Idelchik 1994).

In naturally ventilated and mixed-mode configurations, pressure-based boundary conditions are more widely adopted to represent wind- and buoyancy-driven airflow. Such formulations permit dynamic adjustment of flow direction and magnitude, capturing phenomena such as flow reversal and intermittent ventilation that are characteristic of hybrid systems (Cengel and Ghajar 2015; Awbi 2003). However, review of existing studies reveals significant variation in how external pressure fields and buoyancy effects are implemented, with some investigations relying on simplified uniform pressure assumptions that may not reflect realistic wind exposure or façade orientation.

Hybrid system performance is inherently scenario-dependent. CFD studies therefore commonly evaluate multiple operating conditions, including variations in outdoor temperature, wind speed, internal heat gains, and fan activation levels. From a review perspective, studies that explicitly explore multiple scenarios provide greater insight into system robustness and operational flexibility than those limited to single design-point simulations (Idelchik 1994; Awbi, 2003; Cengel and Ghajar 2015).

4.3. TURBULENCE MODELLING AND FLOW REGIME REPRESENTATION

Hybrid passive–active heat recovery systems exhibit a wide range of flow regimes, spanning low-velocity buoyancy-driven flow, transitional mixed-mode operation, and fully turbulent ducted flow. Turbulence modelling therefore represents one of the most influential and debated aspects of CFD analysis in the literature (Awbi 2003; Versteeg and Malalasekera, 2007; Incropera et al. 2007).

Reynolds-averaged Navier–Stokes (RANS) models dominate reported CFD studies due to their numerical robustness and favourable computational efficiency. The standard and realizable k–ε models are widely employed for ducted and mechanically assisted regions, while the k–ω SST formulation is often preferred in regions characterised by adverse pressure gradients, near-wall effects, and heat exchanger surfaces.

Comparative studies indicate that turbulence model choice can significantly influence predicted heat transfer rates and pressure losses, particularly under mixed-mode ventilation where transitional flow behaviour is prevalent (Versteeg and Malalasekera 2007; Incropera et al. 2007; Cengel and Ghajar 2015).

Large Eddy Simulation (LES) and hybrid RANS–LES approaches appear primarily in research-oriented investigations aimed at resolving transient flow structures, buoyancy-induced instabilities, or local comfort effects. While LES offers superior resolution of unsteady flow phenomena, its computational cost limits routine application in design-focused hybrid system analysis. Consequently, most review studies conclude that RANS-based approaches remain appropriate for system-level assessment provided their limitations are acknowledged and results are interpreted cautiously (Awbi 2003; Versteeg and Malalasekera 2007; Incropera et al. 2007). Table 3 summarises the turbulence modelling approaches employed in CFD studies of hybrid passive–active heat recovery systems, with emphasis on their suitability for different flow regimes and modelling objectives. The comparison highlights how each model balances computational cost and physical accuracy, particularly in representing near-wall behaviour, buoyancy effects, and flow separation. It also outlines the reported impact of model selection on predicted airflow patterns, pressure losses, and heat transfer characteristics, providing a basis for selecting appropriate turbulence closures in both research and design-oriented simulations.

Table 3. Turbulence modelling approaches reported in CFD studies of hybrid passive–active heat recovery systems.

Turbulence model	Typical application	Strengths	Limitations	Reported impact on results
Standard k–ε	Ducted regions and mechanically assisted ventilation with fully turbulent flow	Numerical robustness; low computational cost; widely validated for internal flows	Limited accuracy near walls and in buoyancy-dominated regions; reduced sensitivity to flow separation	Acceptable prediction of global airflow rates and pressure losses; potential underestimation of local heat transfer near exchanger surfaces
Realizable k–ε	Hybrid systems with moderate flow curvature and mixed convection	Improved treatment of strain and rotation effects compared with standard k–ε; stable convergence	Still limited in low-Reynolds-number and strongly buoyant flows	Improved prediction of airflow distribution and pressure gradients relative to standard k–ε; modest improvement in heat transfer estimates
k–ω SST	Near-wall regions, heat exchanger passages, and mixed-mode ventilation	Accurate near-wall resolution; better handling of adverse pressure gradients and separation	Higher sensitivity to inlet turbulence specification; increased computational cost	More reliable prediction of local heat transfer coefficients and pressure losses; improved resolution of flow separation near passive components
LES (Large Eddy Simulation)	Research-oriented studies focusing on transient and buoyancy-driven phenomena	Resolves unsteady flow structures and thermal plumes; high physical fidelity	High computational demand; impractical for routine design studies	Enhanced insight into transient airflow behaviour and local comfort effects; limited use for system-level performance metrics
Hybrid RANS–LES	Transitional flow regimes and selected regions of interest	Balances accuracy and computational cost by resolving large-scale turbulence selectively	Complex setup; limited adoption in building-scale studies	Improved representation of mixed-mode transitions and unsteady flow without full LES cost; limited cross-study comparability

4.4. CONJUGATE HEAT TRANSFER AND MOISTURE MODELLING

Accurate representation of heat transfer between solid components and surrounding airflow is essential for evaluating hybrid system performance. Conjugate heat transfer (CHT) modelling, which simultaneously resolves heat conduction within solid elements and convection within airflow domains, is widely adopted in CFD studies of heat pipe–based and plate-type exchangers (Incropera et al. 2007; Versteeg and Malalasekera 2007; Awbi 2003; Cengel and Ghajar 2015).

Review of the literature indicates that simplified representations of passive components are commonly employed to maintain computational tractability. Heat pipes, for example, are typically modelled using effective thermal conductivity approaches or prescribed heat flux boundary conditions rather than explicit two-phase flow simulation. While such simplifications do not capture internal phase-change dynamics, they are generally sufficient for system-level analysis focused on airflow interaction and overall heat recovery effectiveness (Incropera et al. 2007; Versteeg and Malalasekera 2007; Awbi 2003).

Moisture modelling receives comparatively less attention in published CFD studies despite its importance for indoor comfort and latent heat recovery. Where included, moisture transport is often represented using scalar-based formulations with simplified source terms for condensation and evaporation. Review findings suggest that neglect of moisture effects may lead to overestimation of thermal performance in humid climates or cooling-dominated operation, highlighting an area where future CFD studies could improve physical completeness (Cengel and Ghajar 2015; Awbi 2003).

4.5. VALIDATION PRACTICES AND MODELLING UNCERTAINTY

Validation remains a critical but inconsistently addressed aspect of CFD-based hybrid system analysis. Studies reported in the literature employ a range of validation strategies, including comparison with laboratory-scale experiments, reference to published benchmark data, or qualitative consistency checks against expected physical behaviour. Quantitative validation against in situ field measurements is comparatively rare, particularly for retrofit applications (Incropera et al. 2007; Versteeg and Malalasekera 2007; Awbi 2003).

Sensitivity analyses addressing mesh resolution, turbulence model selection, and boundary condition specification are reported in a subset of studies and provide valuable insight into modelling uncertainty. From a review standpoint, investigations that explicitly assess uncertainty offer more defensible conclusions and greater relevance for design and decision support than those presenting single deterministic predictions (Versteeg and Malalasekera 2007; Awbi 2003; Cengel and Ghajar 2015; Incropera et al. 2007).

4.6. REVIEW IMPLICATIONS AND TRANSITION

The diversity of CFD modelling approaches identified in this section explains much of the variability observed in reported performance outcomes for hybrid passive–active heat recovery systems. Differences in domain definition, boundary condition treatment, turbulence modelling, and heat transfer representation directly influence predicted airflow behaviour, heat recovery effectiveness, and auxiliary energy demand. Consequently, synthesis of CFD-based findings requires careful interpretation of modelling context rather than direct comparison of headline performance metrics.

Building on this analysis of modelling approaches, the next section reviews how CFD is applied in practice to evaluate airflow distribution, thermal performance, pressure losses, and transient behaviour of hybrid systems. Emphasis is placed on identifying consistent performance trends, recurring limitations, and design-relevant insights emerging from CFD-based applications reported in the literature (Incropera et al. 2007; Kim et al. 2024; Awbi 2003). The comparison is based on their typical application domain, predictive capability, computational demand, and known limitations in representing airflow, heat transfer, and mixed-mode ventilation behaviour. This comparison is particularly important due to the wide variability in modelling choices reported across studies, which significantly affects the interpretation of CFD results and their relevance for design applications.

To enable a structured comparison between different CFD turbulence modelling approaches, and to clarify their applicability to hybrid passive–active heat recovery systems, Table 4 presents a synthesis of commonly used models in the literature.

Table 4. Comparative evaluation of turbulence modelling approaches in CFD simulations of hybrid passive–active heat recovery systems.

Turbulence model	Typical application domain	Predictive accuracy	Computational cost	Key limitations	Implications for hybrid systems
Standard k–ε (RANS)	Fully developed turbulent flow in ducts and mechanically assisted ventilation	Moderate for global flow and pressure predictions	Low	Limited accuracy near walls and in buoyancy-driven or recirculating flows	Suitable for system-level analysis and pressure loss estimation, but may underestimate local heat transfer and stratification effects
Realizable k–ε (RANS)	Mixed convection and moderate flow curvature conditions	Moderate to high	Low to medium	Reduced accuracy in low-Reynolds-number and transitional regimes	Improved airflow distribution prediction compared to standard k–ε, but still limited in capturing detailed hybrid flow interactions

Turbulence model	Typical application domain	Predictive accuracy	Computational cost	Key limitations	Implications for hybrid systems
k–ω SST (RANS)	Near-wall regions, heat exchanger passages, and mixed-mode ventilation	High for local heat transfer and separation zones	Medium	Sensitive to inlet turbulence specification; higher computational cost	Recommended for analysing heat exchanger performance and local thermal gradients in hybrid systems
LES (Large Eddy Simulation)	Transient, unsteady, and buoyancy-driven flows	Very high	Very high	Computationally expensive; impractical for full-scale building simulations	Provides detailed insight into transient airflow behaviour and thermal plumes, mainly for research-oriented studies
Hybrid RANS–LES	Transitional flows and regions with mixed turbulence scales	High	High	Complex implementation and calibration requirements	Suitable for capturing mode-switching behaviour in hybrid systems, but limited use in routine engineering applications

The comparison presented in Table 4 highlights that no single turbulence modelling approach is universally optimal for all hybrid passive–active heat recovery applications. Instead, model selection should be guided by the dominant flow regime, the level of detail required, and the computational resources available.

RANS-based models remain the most widely used in the literature due to their numerical robustness and relatively low computational cost. Among these, the k–ω SST model offers improved performance in near-wall regions and heat exchanger passages, making it particularly suitable for evaluating local heat transfer and pressure loss characteristics. However, even advanced RANS models exhibit limitations in accurately capturing transitional and buoyancy-driven flows, which are common in hybrid ventilation systems.

Higher-fidelity approaches such as LES and hybrid RANS–LES provide enhanced resolution of transient and mixed-mode behaviour, but their computational cost restricts their application primarily to research-focused studies rather than practical design scenarios.

These findings confirm that the variability in turbulence model selection is a key source of inconsistency across CFD studies of hybrid systems. Consequently, careful consideration of modelling assumptions and limitations is essential when interpreting CFD results and comparing performance outcomes across different studies.

5. CFD APPLICATIONS IN HYBRID PASSIVE–ACTIVE HEAT RECOVERY SYSTEMS

CFD-based studies of hybrid passive–active heat recovery systems extend beyond model formulation to provide insight into system behaviour under realistic operating conditions. Across the literature, CFD is primarily employed to evaluate airflow distribution, thermal performance, pressure losses, and transient system response under natural, mechanical, and mixed-mode ventilation regimes. Unlike simplified performance indicators, CFD-derived outputs enable spatially resolved interpretation of performance-limiting mechanisms, supporting design refinement and informed comparison between passive-only and hybrid configurations (Myroniuk et al. 2026; Aljashaami et al. 2024; Li et al. 2025).

From a review perspective, CFD applications reported in the literature can be grouped according to the primary performance aspect under investigation. These include airflow organisation and ventilation effectiveness, heat recovery performance, aerodynamic losses and auxiliary energy demand, and transient or control-related behaviour.

5.1. AIRFLOW DISTRIBUTION AND VENTILATION EFFECTIVENESS

Airflow distribution constitutes a central determinant of both thermal performance and indoor air quality in hybrid heat recovery systems. CFD simulations provide detailed visualisation of velocity fields, streamlines, and recirculation zones, enabling identification of stagnant regions, short-circuiting between supply and exhaust flows, and uneven distribution of fresh air within occupied spaces (Myroniuk et al. 2026; Aljashaami et al. 2024).

Studies comparing passive-only ventilation with hybrid passive–active operation consistently demonstrate that limited mechanical assistance stabilises airflow paths under weak natural driving forces. CFD results show improved penetration depth of supply air, reduced sensitivity to external wind fluctuations, and mitigation of flow reversal near façade openings. These effects are particularly pronounced in retrofit scenarios, where architectural constraints and existing interior layouts restrict natural ventilation pathways (Li et al. 2025; Avci 2025; Friess and Rakhshan 2017).

CFD-derived ventilation effectiveness metrics, such as local mean age of air and air change effectiveness, further highlight the benefits of hybrid operation. Review of reported studies indicates that hybrid configurations achieve more uniform ventilation distribution across occupied zones without requiring continuous high-flow mechanical ventilation. However, performance gains are strongly dependent on unit placement, diffuser geometry, and control strategy, underscoring the importance of spatially resolved analysis rather than reliance on nominal air change rates (Avci 2025; Friess and Rakhshan 2017; Zhou et al. 2024). Fig. 3 compares CFD-predicted airflow structures under passive-only and hybrid passive–active operation for identical boundary conditions, with streamlines coloured by velocity magnitude. The figure highlights the effect of mechanical assistance on flow stability, circulation patterns, and velocity distribution, providing a direct visual basis for assessing how airflow organisation influences heat recovery performance and overall system efficiency, as reported by Avci (2025).

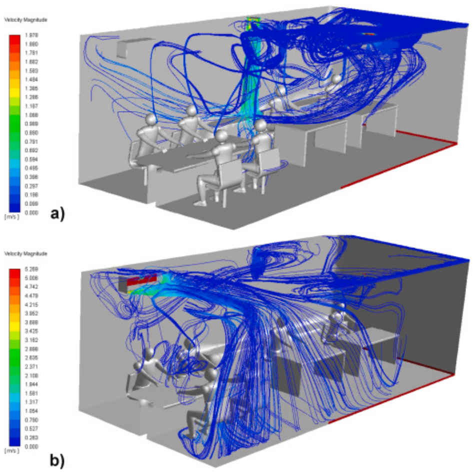


Figure 3. CFD-predicted airflow streamlines colored by velocity magnitude for (**a**) passive-only ventilation and (**b**) hybrid passive–active operation under identical boundary conditions (Avci 2025).

5.2. THERMAL PERFORMANCE AND HEAT RECOVERY EFFECTIVENESS

Thermal performance evaluation represents one of the most common applications of CFD in hybrid heat recovery studies. Rather than relying solely on global heat recovery efficiency metrics, CFD enables examination of local temperature fields, heat flux distributions, and utilisation of heat exchanger surfaces (Myroniuk et al. 2026; Aljashaami et al. 2024; Li et al. 2025).

Review of the literature reveals that non-uniform airflow distribution frequently leads to partial utilisation of heat transfer surfaces, reducing effective heat recovery below values predicted by lumped-parameter models. CFD analyses identify regions of low convective heat transfer, thermal short-circuiting, and bypass flow that contribute disproportionately to overall performance degradation. These insights have been used to inform geometric modifications, such as exchanger spacing adjustments or flow guiding elements, which improve heat recovery effectiveness without increasing pressure losses (Avci 2025; Friess and Rakhshan 2017; Zhou et al. 2024; Jung et al. 2023).

In mixed-mode operation, CFD studies demonstrate that thermal performance may vary significantly over time due to transient interaction between buoyancy-driven and mechanically assisted flows. Hybrid systems that employ simple on–off fan control strategies may experience oscillatory behaviour in temperature fields and local comfort conditions. CFD-based transient simulations provide a means to diagnose such behaviour and to evaluate alternative control strategies aimed at stabilising thermal performance (Friess and Rakhshan 2017; Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022). Fig. 4 provides a detailed representation of airflow behaviour in the vicinity of the heat recovery unit, combining planar velocity contours, three-dimensional vector fields, and streamlines. The figure captures key flow features such as recirculation zones, velocity gradients, and local mixing patterns, which directly influence heat transfer at the exchanger surfaces.

This level of resolution is essential for identifying performance-limiting regions and for interpreting variations in local heat recovery effectiveness, as demonstrated by Ozsagiroglu et al. (2022).

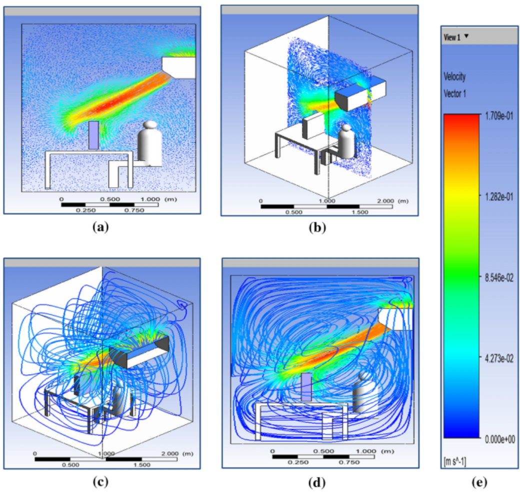


Figure 4. CFD-predicted airflow patterns and velocity magnitude in the vicinity of the heat recovery unit, illustrated using planar contours, three-dimensional vector fields, and streamlines, highlighting flow structures relevant to local heat recovery effectiveness (Ozsagiroglu et al. 2022).

5.3. PRESSURE LOSSES AND AUXILIARY ENERGY DEMAND

Assessment of pressure losses and associated auxiliary energy demand represents a critical application of CFD in hybrid system analysis. CFD pressure field predictions enable quantification of aerodynamic losses across heat exchangers, ducts, and façade-integrated components under different operating regimes (Aljashaami et al. 2024; Li et al. 2025; Avci 2025; Friess and Rakhshan 2017).

Review of reported CFD studies highlights that hybrid systems achieve optimal performance not by maximising airflow rates, but by identifying operating regimes in which modest mechanical assistance yields substantial improvements in airflow stability and heat recovery effectiveness. CFD-based pressure loss analysis reveals that excessive fan operation can negate thermal gains by increasing auxiliary energy demand, particularly in decentralised and retrofit-oriented configurations (Avci 2025; Friess and Rakhshan 2017; Zhou et al. 2024; Jung et al. 2023).

Comparative CFD studies further demonstrate that small geometric modifications, such as smoothing of flow transitions, diffuser redesign, or reduction of flow separation regions, can significantly reduce pressure losses while preserving thermal performance. These findings reinforce the role of CFD as a design optimisation tool rather than a purely evaluative method (Friess and Rakhshan, 2017; Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022; Khan, 2024). Fig. 5 illustrates the CFD-predicted static pressure distribution within the ventilated space under mechanically assisted operation, showing the development of pressure gradients along the airflow path. The figure provides insight into how fan-induced driving forces translate into spatial pressure variations and associated pressure losses, which are critical for evaluating system resistance, airflow distribution, and overall energy performance, as reported by Khan (2024).

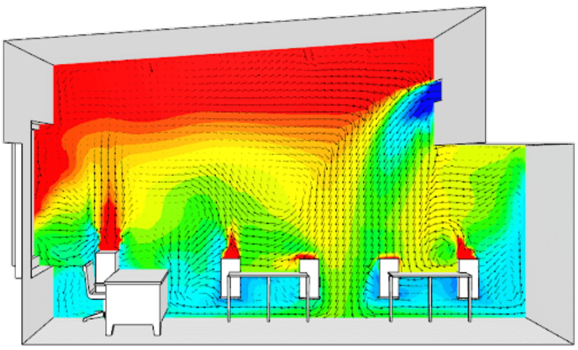


Figure 5. CFD-predicted static pressure distribution within the ventilated space under mechanically assisted operation, illustrating the pressure gradient and resulting pressure drop along the airflow path (Khan 2024).

5.4. TRANSIENT BEHAVIOUR AND CONTROL-ORIENTED CFD ANALYSIS

Transient CFD simulations are increasingly employed to investigate system response to changing boundary conditions, control actions, and environmental variability. Such simulations capture time-dependent phenomena that are not accessible through steady-state analysis, including start-up behaviour, fan activation sequences, and response to rapid changes in outdoor temperature or wind conditions (Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022; Khan 2024).

Review of transient CFD applications indicates that hybrid systems exhibit complex dynamic behaviour during transitions between passive and mechanically assisted operation. Inadequate control strategies may lead to short-term discomfort, pressure oscillations, or inefficient fan cycling. CFD-based transient analysis supports development of control approaches that balance responsiveness with stability, enabling smoother transitions and improved occupant comfort (Jung et al. 2023; Ozsagiroglu et al. 2022; Khan 2024).

5.5. QUANTITATIVE COMPARISON OF REPORTED CFD RESULTS

While a substantial portion of the literature on hybrid passive–active heat recovery systems is presented in qualitative terms, a closer synthesis of reported CFD studies reveals several consistent quantitative trends that are critical for interpreting system performance.

Across the reviewed studies, heat recovery effectiveness for hybrid systems is typically reported within a range of approximately 50% to 75%, depending on system configuration, airflow regime, and operating conditions. Lower values are generally associated with naturally driven or weakly assisted airflow, where non-uniform distribution and partial utilisation of heat exchanger surfaces reduce overall effectiveness. Higher values are reported in configurations where limited mechanical assistance stabilises airflow paths and enhances convective heat transfer without significantly increasing auxiliary energy demand.

Pressure losses reported in CFD analyses commonly fall within the range of 20 to 150 Pa. Lower pressure drops are associated with simplified or low-resistance flow paths, while higher values are typically observed in compact heat exchanger geometries, densely packed channels, or configurations with pronounced flow redirection. These results highlight the inherent trade-off between thermal performance and aerodynamic resistance in hybrid systems, where increased heat transfer effectiveness often coincides with higher pressure losses.

In terms of airflow behaviour, several studies indicate that the introduction of modest mechanical assistance can improve airflow stability by approximately 30% to 60% compared to purely passive configurations. This improvement is primarily attributed to the suppression of flow reversal, reduction of stagnant zones, and more uniform distribution of supply air within occupied spaces. Importantly, these gains are achieved without the full energy penalty associated with continuous mechanical ventilation, reinforcing the operational advantage of hybrid strategies.

Despite these observable trends, significant variability exists across reported results due to differences in modelling assumptions, boundary condition specification, turbulence modelling approaches, and system architecture. Consequently, the quantitative ranges presented here should not be interpreted as universal performance benchmarks, but rather as indicative ranges that reflect the diversity of modelling practices and operating conditions reported in the literature.

These findings underscore the importance of integrating quantitative interpretation with critical assessment of modelling context. Without such consideration, direct comparison between studies may lead to misleading conclusions regarding system performance and design effectiveness.

5.6. SYNTHESIS OF CFD APPLICATION TRENDS

Across the reviewed literature, CFD applications consistently demonstrate that hybrid passive–active heat recovery systems outperform purely passive configurations under variable and unfavourable boundary conditions. However, reported performance gains are highly sensitive to architectural context, exchanger integration, and control strategy. CFD provides a transparent and physically grounded means to identify these dependencies and to distinguish robust design principles from case-specific outcomes. Table 5 synthesises the key outcomes of CFD applications in hybrid passive–active heat recovery systems by directly comparing passive-only and hybrid operation across major performance aspects. The table links observed system-level behaviour to underlying flow and thermal mechanisms, highlighting how CFD analysis reveals critical inefficiencies such as flow reversal, bypass, and non-uniform heat transfer. It further translates these insights into practical design implications, providing a clear basis for performance-oriented optimisation of airflow organisation, energy use, and indoor environmental quality.

Table 5. Summary of CFD application outcomes reported for hybrid passive–active heat recovery systems.

Performance aspect	Passive-only outcome	Hybrid system outcome	Key CFD insight	Design implication
Airflow distribution and ventilation effectiveness	Highly sensitive to wind and buoyancy variability; flow reversal and stagnant zones frequently observed	Stabilised airflow paths; improved penetration of supply air into occupied zones	Limited mechanical assistance suppresses flow reversal and enhances circulation without requiring high flow rates	Prioritise airflow stabilisation rather than maximising ventilation rate; optimise unit placement and diffuser geometry
Thermal performance and heat recovery effectiveness	Spatially non-uniform heat transfer; partial utilisation of exchanger surfaces	More uniform temperature fields and improved effective heat recovery	Non-uniform airflow is a primary cause of reduced heat recovery; CFD reveals bypass and short-circuiting regions	Focus on improving airflow–exchanger interaction through geometric refinement rather than increasing exchanger size
Pressure losses and auxiliary energy demand	Low auxiliary energy demand but unstable performance under weak driving forces	Moderate increase in fan energy with disproportionate gains in stability and heat recovery	Optimal performance achieved at modest fan assistance; excessive airflow yields diminishing returns	Identify operating regimes where limited mechanical support maximises net energy benefit
Transient behaviour and operational stability	Strongly affected by external fluctuations; delayed or oscillatory thermal response	Faster response and improved robustness during changing conditions	Mode switching induces transient effects that influence comfort and efficiency	Implement control strategies that avoid abrupt transitions between passive and active modes
Indoor comfort and air quality indicators	Localised discomfort and uneven fresh air distribution	Improved uniformity of temperature and air quality across occupied spaces	CFD highlights local comfort risks not evident from averaged metrics	Use spatially resolved CFD metrics to inform comfort-oriented design decisions

This synthesis highlights the need to interpret CFD results within a clearly defined modelling and architectural context rather than as universally transferable performance metrics.

While the applications reviewed above demonstrate the strengths of CFD for analysing hybrid heat recovery systems, they also reveal recurring limitations related to modelling assumptions, validation practices, and uncertainty. The next section therefore examines CFD-supported design, validation against experimental and field data, and the implications of modelling uncertainty for practical deployment of hybrid systems in high-performance buildings (Khan 2024; Li et al. 2023; Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023).

6. CFD-SUPPORTED DESIGN, VALIDATION, AND SYSTEM-LEVEL EVALUATION

Beyond individual performance indicators, the principal value of Computational Fluid Dynamics (CFD) in hybrid passive–active heat recovery research lies in its ability to support design decisions, interpret experimental observations, and evaluate system-level behaviour under realistic constraints. Across the reviewed literature, CFD is increasingly positioned not as a standalone predictive tool, but as part of an integrated analytical workflow that combines numerical modelling, experimental evidence, and engineering judgement (Khan 2024; Li et al. 2023; Zohuri 2016a; Zohuri 2016b). This section synthesises how CFD is used to inform design optimisation, how validation is addressed in existing studies, and how modelling uncertainty influences interpretation of reported results.

6.1. CFD-INFORMED DESIGN AND OPTIMISATION

CFD-based design optimisation focuses on identifying geometric, operational, and control-related modifications that improve system performance without imposing excessive auxiliary energy demand. In hybrid heat recovery systems, such optimisation typically targets airflow distribution, heat exchanger utilisation, and pressure loss reduction rather than maximisation of heat transfer alone (Li et al. 2023; Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025).

Reviewed studies demonstrate that relatively modest design adjustments, such as repositioning of passive heat recovery elements, modification of diffuser geometry, or redistribution of airflow paths, can yield disproportionate improvements in heat recovery effectiveness and ventilation performance. CFD enables these effects to be visualised and quantified at a spatially resolved level, revealing localised flow separation, bypass regions, or underutilised heat transfer surfaces that are not apparent from averaged metrics (Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023). Importantly, CFD-supported optimisation often leads to solutions that balance passive and active contributions more effectively, reinforcing the hybrid philosophy of limited mechanical assistance rather than continuous active operation.

From a review perspective, studies that explicitly employ CFD as an iterative design tool provide greater practical insight than those that apply CFD solely for post hoc performance evaluation. This distinction reflects a shift in the literature from descriptive simulation toward design-oriented application.

6.2. VALIDATION AGAINST EXPERIMENTAL AND FIELD DATA

Validation represents a critical aspect of CFD credibility in hybrid heat recovery research, yet its implementation varies widely across published studies. Laboratory-scale experiments are most commonly used for validation due to their controlled boundary conditions and repeatability. CFD predictions of airflow rates, temperature distributions, and overall heat recovery effectiveness are frequently compared against experimental measurements, with reported agreement generally acceptable at the system level when appropriate turbulence models and boundary conditions are employed (Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023).

However, review of the literature indicates that discrepancies often arise in regions dominated by buoyancy effects, low-velocity flow, or complex recirculation, where turbulence modelling limitations and mesh sensitivity become more pronounced. These discrepancies are particularly relevant for hybrid systems operating under natural or mixed-mode ventilation, reinforcing the need for cautious interpretation of CFD results in such regimes (Malcho et al. 2025; Ramlee et al. 2023; Khan 2024).

Field-based validation using in situ measurements is considerably less common but provides valuable insight into real-world system behaviour. Studies incorporating field data reveal performance deviations attributable to installation constraints, occupant behaviour, and climatic variability that are not fully captured in idealised simulations. CFD-supported interpretation of field measurements has been shown to aid diagnosis of underperformance and guide targeted system adjustments, particularly in retrofit applications (Ramlee et al. 2023; Khan 2024; Li et al. 2023). Table 6 summarises the validation strategies adopted in CFD studies of hybrid passive–active heat recovery systems, covering laboratory experiments, controlled facilities, field measurements, and numerical sensitivity analyses. The comparison links data sources and performance metrics to the level of agreement typically achieved, while explicitly identifying the limitations associated with each approach. This synthesis clarifies the extent to which CFD predictions can be considered reliable under different conditions and highlights the persistent gap between controlled validation environments and real-world system behaviour.

Table 6. Validation approaches reported in CFD studies of hybrid passive–active heat recovery systems.

Validation type	Data source	Performance metrics	Reported agreement	Key limitations
Laboratory-scale experiments	Controlled test rigs and full-scale laboratory setups	Airflow rate, temperature distribution, heat recovery effectiveness, pressure drop	Generally good agreement for global metrics under steady-state conditions	Limited representation of real operating variability; discrepancies in buoyancy-dominated and low-velocity regions
Controlled test facilities	Dedicated ventilation and building performance test facilities	Airflow patterns, thermal fields, system response under mixed-mode operation	Improved agreement when boundary conditions are carefully matched	Measurement uncertainty; limited ability to capture long-term operational effects
Field-based in situ measurements	Occupied buildings and retrofit installations	Indoor temperature, airflow rates, and system-level energy performance	Qualitative or moderate quantitative agreement at system level	Strong influence of occupant behaviour and installation quality; limited sensor resolution

Validation type	Data source	Performance metrics	Reported agreement	Key limitations
Benchmark and reference data comparison	Published experimental datasets and prior validated studies	Heat recovery efficiency and pressure loss trends	Consistency in relative trends rather than absolute values	Dependence on assumptions embedded in reference studies; limited generalisability
Sensitivity and uncertainty analysis	Parametric variation within CFD simulations	Mesh sensitivity, turbulence model impact, boundary condition influence	Identification of relative uncertainty ranges rather than direct validation	Does not replace experimental validation; increases computational effort

6.3. MODELLING UNCERTAINTY AND SENSITIVITY

Uncertainty in CFD predictions arises from multiple sources, including boundary condition specification, turbulence modelling, mesh resolution, and representation of passive components. Review of existing studies shows that only a subset explicitly addresses these uncertainties through sensitivity analysis or parametric variation (Malcho et al. 2025; Ramlee et al. 2023; Khan, 2024; Li et al. 2023).

Sensitivity analyses reported in the literature indicate that predicted heat recovery effectiveness and pressure losses can vary substantially with turbulence model choice and inlet boundary condition formulation, particularly under mixed-mode ventilation. Mesh refinement studies further reveal that insufficient near-wall resolution may lead to underestimation of convective heat transfer and misrepresentation of pressure gradients across heat exchangers (Ramlee et al. 2023; Khan, 2024; Li et al. 2023; Zohuri 2016a).

From a review standpoint, explicit consideration of modelling uncertainty enhances the interpretability and transferability of CFD results. Studies that report uncertainty bounds or comparative sensitivity trends provide more defensible guidance for design and retrofit decisions than those presenting single deterministic outcomes.

6.4. SYSTEM-LEVEL EVALUATION AND INTEGRATION WITH ENERGY MODELLING

To assess hybrid heat recovery systems within the broader context of building performance, CFD results are increasingly coupled with whole-building energy simulation tools. Rather than replacing building energy models, CFD provides refined inputs such as airflow distribution patterns, effective heat recovery parameters, and pressure loss characteristics that improve annual energy consumption and comfort predictions (Li et al. 2023; Zohuri 2016a; Ramlee et al. 2023; Malcho et al. 2025).

In retrofit studies, this integrated approach enables evaluation of alternative hybrid configurations under site-specific climatic conditions and building constraints. CFD-derived insights inform selection of operating regimes in which passive heat recovery is sufficient and those where limited mechanical assistance delivers additional benefit. This system-level perspective aligns CFD analysis with practical decision-making rather than isolated component optimisation (Zohuri 2016a; Ramlee et al. 2023; Malcho et al. 2025; Khan 2024).

6.5. REVIEW IMPLICATIONS

The reviewed studies collectively demonstrate that CFD-supported design and validation play a critical role in advancing hybrid passive–active heat recovery systems from conceptual solutions to practical building technologies. However, the effectiveness of CFD as a decision-support tool depends strongly on transparent modelling assumptions, appropriate validation, and explicit acknowledgement of uncertainty.

This synthesis underscores the need to interpret CFD results within an integrated framework that combines numerical modelling, experimental evidence, and system-level performance evaluation. The next section therefore examines how CFD-based insights differ between new-build and retrofit applications, highlighting context-specific challenges and opportunities reported in the literature (Khan 2024; Li et al. 2023; Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023).

7. CFD APPLICATIONS IN NEW-BUILD AND RETROFIT SCENARIOS

The application of CFD to hybrid passive–active heat recovery systems differs markedly between new-build projects and retrofit contexts due to differences in design freedom, geometric constraints, and operational objectives. While new-build applications allow hybrid systems to be integrated from the earliest design stages, retrofit scenarios require adaptation to existing building fabric, legacy ventilation paths, and often limited installation space. Review of the literature indicates that these contextual differences strongly influence both

CFD modelling strategies and reported performance outcomes (Zhong et al. 2024; Li et al. 2023; Khan 2024).

From a review perspective, distinguishing between new-build and retrofit applications is essential for meaningful interpretation of CFD-based findings and for identifying transferable design insights versus context-specific solutions.

7.1. NEW-BUILD HIGH-PERFORMANCE BUILDINGS

In new high-performance buildings, CFD is primarily employed during the design phase to support integration of hybrid heat recovery systems with building geometry, envelope characteristics, and ventilation strategy. Studies reported in the literature frequently use CFD to evaluate decentralised or ductless hybrid units prior to construction, enabling optimisation of unit placement, airflow direction, and interaction with anticipated thermal stratification patterns (Li et al. 2023; Zhou et al. 2024; Jung et al. 2023).

CFD-based investigations demonstrate that hybrid systems can stabilise airflow paths in highly insulated and airtight buildings, where purely passive ventilation may be insufficient under weak wind or buoyancy driving forces. Simulations conducted under representative design-day and seasonal conditions reveal how limited mechanical assistance enhances ventilation effectiveness while preserving the energy benefits of passive heat recovery (Zhou et al. 2024; Jung et al. 2023; Avci 2025). These analyses are particularly relevant for passive house and near-zero-energy building concepts, where ventilation performance exerts a disproportionate influence on overall energy balance and occupant comfort.

Scenario-based CFD simulations incorporating variable internal heat gains, solar loads, and outdoor conditions are commonly reported for new-build applications. Such studies provide insight into overheating risk, thermal comfort distribution, and resilience to climatic variability, supporting informed selection of hybrid operating regimes and control thresholds during the design stage (Jung et al. 2023; Avci 2025; Friess and Rakhshan, 2017). Fig. 6 presents the CFD-predicted three-dimensional temperature field within a high-performance building equipped with a decentralised hybrid passive–active heat recovery ventilation system. The distribution highlights the spatial uniformity of thermal conditions and the interaction between supply airflow and indoor temperature gradients, providing a basis for evaluating heat recovery effectiveness and local comfort conditions under realistic operating scenarios, as reported by Li et al. (2023).

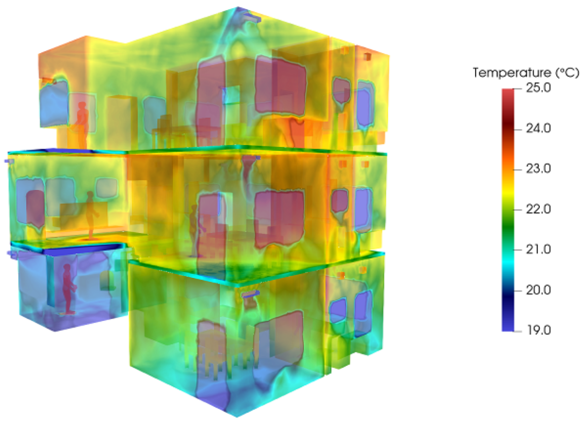


Figure 6. CFD-predicted three-dimensional temperature field in a new-build high-performance building equipped with a decentralised hybrid passive–active heat recovery ventilation system (Li et al. 2023).

7.2. RETROFIT AND WINDOW-INTEGRATED HYBRID SYSTEMS

Retrofit applications impose stricter geometric and operational constraints than new-build projects, making CFD particularly valuable for feasibility assessment and performance optimisation. In existing buildings, hybrid systems must accommodate fixed façade openings, interior partitions, furnishings, and often degraded or irregular airflow paths. CFD studies reported in the literature consistently show that these constraints significantly influence airflow distribution and heat recovery effectiveness (Zhong et al. 2024; Khan 2024; Li et al. 2023).

Window-integrated and wall-mounted hybrid units are widely investigated for retrofit scenarios due to their modularity and minimal disruption to building fabric. CFD-based analyses reveal that such systems can substantially improve ventilation effectiveness and thermal performance compared with passive-only solutions, particularly in buildings originally designed for natural ventilation. However, performance gains are highly sensitive to unit placement, orientation, and interaction with interior obstructions, which may induce local recirculation or short-circuiting effects (Avci 2025; Friess and Rakhshan 2017; Zhou et al. 2024; Jung et al. 2023).

CFD simulations conducted under non-ideal boundary conditions, such as fluctuating outdoor temperature, limited wind exposure, or partial blockage of openings, provide insight into operational robustness and highlight conditions under which passive heat recovery alone becomes insufficient. These findings support targeted application of mechanical assistance, enabling retrofit strategies that maximise energy recovery while minimising auxiliary energy demand (Friess and Rakhshan, 2017; Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022). Fig. 7 compares CFD-predicted airflow patterns in a retrofit building under passive-only ventilation and hybrid passive–active heat recovery operation. The figure highlights the impact of mechanical assistance on airflow organisation within geometrically constrained spaces, showing how hybrid operation reduces stagnant zones and improves air distribution relative to passive conditions. This comparison is particularly relevant for retrofit scenarios, where existing layouts and installation limitations strongly influence ventilation effectiveness, as reported by Zhong H.-Y. et al. (2024).

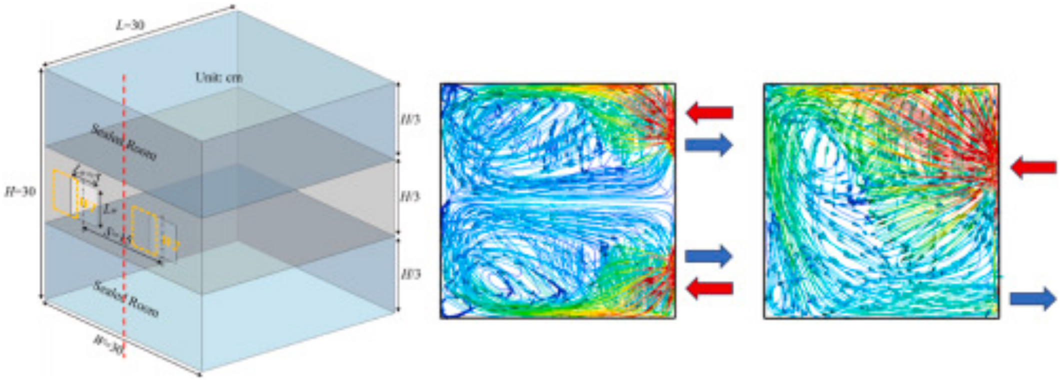


Figure 7. Comparison of CFD-predicted airflow patterns in a retrofit building under (**a**) passive-only ventilation and (**b**) hybrid passive–active heat recovery operation (Zhong H.-Y. et al. 2024).

7.3. COMPARATIVE INSIGHTS AND DESIGN IMPLICATIONS

Comparative review of CFD applications in new-build and retrofit contexts reveals both shared trends and fundamental differences. In both cases, hybrid systems outperform purely passive configurations under variable or unfavourable boundary conditions. However, absolute performance levels and dominant limiting mechanisms differ substantially due to architectural constraints and envelope characteristics.

In new-build applications, CFD studies emphasise optimisation of system integration and control strategy, leveraging design freedom to achieve stable airflow and high heat recovery effectiveness. In retrofit contexts, CFD primarily functions as a diagnostic tool, identifying flow maldistribution, local comfort risks, and performance bottlenecks arising from existing building features. These contrasting roles underscore the flexibility of CFD as both a predictive and interpretive framework (Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022; Khan 2024). Table 7 compares the objectives and outcomes of CFD applications in hybrid heat recovery systems across new-build and retrofit contexts, highlighting how design intent and physical constraints shape modelling priorities. The table links application scenarios to dominant performance limitations, showing clear differences between design-stage optimisation in high-performance buildings and diagnostic, constraint-driven analysis in retrofit conditions. It also distils the resulting design implications, emphasising how CFD supports targeted decision-making in both integrated system design and performance improvement of existing buildings.

Table 7. Comparison of CFD application objectives and outcomes in new-build and retrofit hybrid heat recovery systems.

Application context	Primary CFD objective	Key constraints	Dominant performance limitations	Design implications
New-build high-performance buildings	Support early-stage system integration and ventilation strategy optimisation	Design targets for energy efficiency, airtight envelopes, and comfort criteria	Sensitivity to control strategy selection; interaction with thermal stratification in highly insulated spaces	Integrate hybrid systems at design stage to stabilise airflow and avoid over-reliance on mechanical ventilation

Application context	Primary CFD objective	Key constraints	Dominant performance limitations	Design implications
New-build near-zero energy buildings	Evaluate robustness of hybrid operation under variable climatic scenarios	Stringent energy and carbon performance requirements	Risk of overheating and uneven airflow under weak natural driving forces	Use CFD to identify operating thresholds where limited mechanical assistance enhances resilience
Retrofit of naturally ventilated buildings	Diagnose airflow maldistribution and assess feasibility of hybrid upgrades	Fixed geometry, existing partitions, and limited installation space	Short-circuiting, local stagnation, and sensitivity to occupant behaviour	Apply CFD as a diagnostic tool to guide targeted hybrid interventions rather than full system replacement
Retrofit of mechanically ventilated buildings	Evaluate performance improvement potential of passive recovery integration	Legacy ductwork and pressure losses	Reduced effectiveness of passive components due to flow bypass	Use CFD to redesign airflow paths and exchanger placement to maximise passive contribution
Window- or façade-integrated hybrid systems	Assess local airflow organisation and indoor comfort impact	Strong dependence on façade orientation and external climate	Localised recirculation and non-uniform fresh air distribution	Optimise unit placement and orientation using room-scale CFD rather than relying on nominal airflow rates

7.4. TRANSITION TO VALIDATION AND BROADER IMPACTS

The reviewed applications demonstrate that CFD provides context-sensitive insight into hybrid heat recovery performance across diverse building scenarios. However, the credibility and transferability of these insights depend on appropriate validation and consideration of broader energy, carbon, and indoor environmental impacts. The following section therefore examines how CFD-based findings are validated against experimental and field data and how hybrid systems contribute to energy efficiency, carbon reduction, and indoor air quality objectives reported in the literature (Khan 2024; Li et al. 2023; Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023).

8. VALIDATION THROUGH EXPERIMENTAL AND FIELD STUDIES

Validation is a central requirement for establishing the credibility of CFD-based analyses of hybrid passive–active heat recovery systems. While CFD provides detailed insight into airflow behaviour and heat transfer mechanisms, its reliability depends on the extent to which numerical predictions are supported by experimental evidence or field measurements. Review of the literature reveals that validation practices vary considerably across studies, reflecting differences in research objectives, available data, and practical constraints (Khan 2024; Li et al. 2023; Zohuri 2016a).

From a review perspective, validation approaches reported for hybrid systems can be broadly grouped into laboratory-scale experiments, controlled test facilities, and in situ field measurements. Each approach offers distinct advantages and limitations and must be interpreted within its respective context.

8.1. LABORATORY-SCALE EXPERIMENTAL VALIDATION

Laboratory experiments represent the most commonly reported validation approach in CFD studies of hybrid heat recovery systems. These experiments typically involve scaled or full-size test rigs in controlled environments, allowing systematic variation of airflow rates, temperature differences, and operating modes. CFD predictions of velocity fields, temperature distributions, and overall heat recovery effectiveness are compared against measured values to assess model accuracy (Li et al. 2023; Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025).

The literature indicates that acceptable agreement is generally achieved for global performance indicators such as average heat recovery effectiveness and total pressure drop when appropriate turbulence models and boundary conditions are employed. However, discrepancies often arise in regions characterised by low-velocity flow, buoyancy-dominated behaviour, or complex recirculation, where modelling assumptions exert greater influence on predicted results. Such discrepancies are particularly relevant for hybrid systems operating near the transition between passive and mechanically assisted modes (Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023; Khan 2024).

Laboratory validation studies also highlight the importance of geometric fidelity. Simplifications commonly adopted in CFD models, such as omission of small geometric features or idealisation of heat exchanger surfaces, may have limited impact on global metrics but can significantly affect local airflow and heat transfer behaviour. These findings underscore the need to interpret CFD validation results at both system and local scales (Malcho et al. 2025; Khan 2024; Li et al. 2023).

8.2. VALIDATION USING CONTROLLED TEST FACILITIES

Beyond laboratory rigs, some studies employ dedicated test facilities designed to replicate realistic boundary conditions while maintaining a high degree of experimental control. These facilities allow hybrid systems to be evaluated under representative outdoor temperature gradients, wind pressures, and mixed-mode ventilation scenarios (Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023; Li et al. 2023).

CFD validation against data from controlled test facilities provides valuable insight into system behaviour under conditions that are difficult to reproduce in standard laboratory environments. Review of such studies indicates improved agreement between CFD predictions and measured data when boundary conditions are carefully matched and transient effects are explicitly considered. Nevertheless, uncertainties related to sensor placement, measurement resolution, and environmental variability remain non-negligible (Malcho et al. 2025; Ramlee et al. 2023; Li et al. 2023; Zhou et al. 2024).

8.3. FIELD-BASED VALIDATION AND IN SITU MEASUREMENTS

Field validation using in situ measurements remains relatively limited in the CFD literature on hybrid heat recovery systems but offers critical insight into real-world performance. Field studies capture the influence of installation quality, occupant behaviour, and climatic variability, which are often simplified or neglected in numerical models (Ramlee et al. 2023; Li et al. 2023; Zhou et al. 2024; Jung et al. 2023).

CFD-supported interpretation of field data is typically employed to diagnose observed performance deviations rather than to achieve direct quantitative agreement. Studies combining CFD with field measurements demonstrate that discrepancies between predicted and observed performance frequently arise from unmodelled factors such as intermittent occupancy, window opening behaviour, or degradation of passive components over time. In this context, CFD functions as a diagnostic framework that helps identify dominant mechanisms driving underperformance and guides targeted system adjustments (Li et al. 2023; Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022). Table 8 presents a comparative overview of validation approaches used in CFD studies of hybrid passive–active heat recovery systems, with emphasis on how different data sources and operating conditions influence the level of agreement achieved. The table highlights the progression from controlled laboratory validation to real-world field assessment, while identifying the dominant sources of uncertainty that affect predictive reliability. This synthesis clarifies the strengths and limitations of each approach and provides a basis for assessing the robustness of CFD-based conclusions across varying levels of model complexity and environmental realism.

Table 8. Validation approaches reported in CFD studies of hybrid passive–active heat recovery systems.

Validation approach	Data source	Operating conditions	Level of agreement	Key sources of uncertainty
Laboratory-scale validation	Scaled or full-scale laboratory test rigs	Steady-state and quasi-steady natural and mechanical ventilation	Good agreement for system-level metrics; local discrepancies near buoyant plumes	Turbulence modelling in low-velocity regions; geometric simplifications
Controlled test facilities	Dedicated building or ventilation test chambers	Mixed-mode ventilation with controlled boundary conditions	Moderate to good agreement when boundary conditions are well defined	Measurement resolution; imperfect replication of real climate variability
Field-based in situ validation	Occupied buildings and retrofit installations	Real operating conditions with variable occupancy and climate	Qualitative to moderate quantitative agreement	Occupant behaviour; installation quality; sensor placement limitations
Benchmark-based comparison	Published experimental datasets and reference cases	Idealised or canonical ventilation scenarios	Consistent trend-level agreement	Embedded assumptions in benchmark data; limited representativeness

Validation approach	Data source	Operating conditions	Level of agreement	Key sources of uncertainty
Transient validation studies	Time-resolved experimental or monitoring data	Mode switching and dynamic boundary conditions	Qualitative agreement for temporal trends	Temporal resolution; control logic simplifications; numerical stability

8.4. LIMITATIONS OF VALIDATION PRACTICES

Despite the growing body of validation-oriented studies, several limitations persist across the literature. Quantitative validation is often restricted to a narrow range of operating conditions, limiting confidence in CFD predictions under extreme or highly variable scenarios. Moreover, many studies report validation results for steady-state conditions, whereas hybrid systems frequently operate under transient and mixed-mode regimes where model uncertainty is higher (Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022; Khan 2024).

From a review standpoint, the absence of standardised validation protocols complicates cross-study comparison and synthesis. Differences in measurement techniques, performance metrics, and reporting practices further contribute to variability in reported agreement levels. These limitations highlight the need for more systematic and transparent validation strategies in future CFD-based investigations of hybrid systems (Jung et al. 2023; Ozsagiroglu et al. 2022; Khan 2024; Li et al. 2023).

8.5. IMPLICATIONS FOR REVIEW AND RESEARCH PRACTICE

The reviewed validation studies demonstrate that CFD can provide reliable system-level insight into hybrid passive–active heat recovery performance when modelling assumptions are aligned with experimental conditions and validation limitations are clearly acknowledged. However, CFD predictions should not be interpreted as exact representations of real-world performance, particularly under highly variable or poorly characterised operating conditions.

This synthesis reinforces the importance of positioning CFD as a complementary analytical tool within a broader evidence-based framework that integrates numerical modelling, experimental observation, and engineering judgement. Building on these findings, the following section examines emerging trends and future research directions aimed at addressing current validation limitations and enhancing the robustness of CFD-supported hybrid system analysis (Khan 2024; Li et al. 2023; Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023).

9. EMERGING TRENDS AND FUTURE RESEARCH DIRECTIONS

Recent advances in building performance analysis and control have begun to influence how hybrid passive–active heat recovery systems are studied, designed, and evaluated. While CFD remains central to understanding airflow and heat transfer mechanisms, its role is gradually expanding from stand-alone simulation toward integration with data-driven methods, system monitoring, and resilience-oriented performance assessment. Review of recent studies indicates several emerging trends that aim to address limitations identified in earlier CFD-based research (Khan 2024; Li et al. 2023; Zohuri 2016a; Zohuri 2016b).

9.1. INTEGRATION OF CFD WITH DIGITAL TWINS

One of the most prominent emerging directions involves the integration of CFD models within digital twin frameworks for building systems. In this context, CFD is not used continuously due to its computational cost, but rather as a high-fidelity reference model that informs reduced-order or surrogate representations. These representations are then coupled with real-time sensor data to support system monitoring, diagnostics, and performance optimisation (Li et al. 2023; Zohuri, 2016a; Malcho et al. 2025).

Hybrid passive–active heat recovery systems are particularly well suited to digital twin integration due to their sensitivity to operating conditions and control strategies. CFD-informed digital twins enable identification of performance drift, detection of flow maldistribution, and evaluation of alternative operating regimes under changing climatic or occupancy conditions. Review of early implementations suggests that such approaches improve interpretability and robustness of system-level performance assessment compared with purely data-driven or purely physics-based methods (Zohuri 2016a; Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023).

9.2. DATA-ASSISTED AND REDUCED-ORDER MODELLING

To overcome the computational limitations of full CFD simulation, several studies explore the use of reduced-order models and data-assisted surrogates derived from CFD datasets. These approaches aim to preserve key flow and heat transfer characteristics while enabling rapid evaluation of system response across a wide parameter space (Zohuri 2016b; Malcho et al. 2025; Ramlee et al. 2023; Khan 2024).

In hybrid heat recovery research, reduced-order models are commonly trained using CFD outputs representing different operating modes, airflow rates, and boundary conditions. When combined with experimental or field data, these models provide a practical means to assess system behaviour under transient conditions or to support control-oriented analysis. Review findings indicate that data-assisted approaches are most effective when grounded in physically meaningful CFD-generated features rather than purely statistical correlations (Malcho et al. 2025; Ramlee et al. 2023; Khan 2024; Li et al. 2023).

9.3. CLIMATE VARIABILITY AND RESILIENCE-ORIENTED ASSESSMENT

Increasing climatic variability and the frequency of extreme weather events have highlighted limitations of performance assessments based on fixed or average boundary conditions. Recent CFD-based studies increasingly incorporate scenario-driven analysis to evaluate hybrid system robustness under heatwaves, cold spells, and rapidly changing outdoor conditions (Ramlee et al. 2023; Khan 2024; Li et al. 2023; Zhou et al. 2024; Jung et al. 2023).

In this context, CFD is used to examine how hybrid systems transition between passive and mechanically assisted operation under stress conditions and to identify thresholds beyond which passive recovery becomes insufficient. Such analyses support resilience-oriented design by emphasising system stability and adaptability rather than peak efficiency under nominal conditions. Review of emerging studies suggests that this shift in perspective aligns CFD analysis more closely with real-world operational challenges faced by high-performance buildings (Khan 2024; Li et al. 2023; Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022).

9.4. CONTROL-ORIENTED CFD AND HYBRID SYSTEM MANAGEMENT

Another emerging trend involves the use of CFD to inform control strategy development for hybrid systems. Rather than focusing solely on geometric optimisation, recent studies employ CFD-derived insights to evaluate fan activation thresholds, airflow modulation strategies, and mode-switching criteria (Li et al. 2023; Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022; Khan 2024).

Control-oriented CFD studies highlight the importance of avoiding frequent or abrupt transitions between passive and active operation, which may lead to thermal discomfort or inefficient energy use. CFD-based transient analysis provides a means to test alternative control logic under representative operating scenarios before implementation. From a review standpoint, this trend reflects a growing recognition of CFD as a tool for system management rather than only for design-stage analysis (Zhou et al. 2024; Jung et al. 2023; Ozsagiroglu et al. 2022; Khan 2024).

9.5. RESEARCH GAPS AND PRIORITIES

Despite these advances, several research gaps remain evident across the literature. Quantitative validation of CFD-informed digital twins remains limited, particularly for long-term operation in occupied buildings. Integration of moisture transport, occupant behaviour, and component degradation into CFD-supported frameworks also remains underdeveloped. Furthermore, most studies focus on short-term performance metrics, with limited consideration of lifecycle energy use, maintenance implications, or long-term resilience.

Addressing these gaps will require closer integration between CFD modelling, experimental research, and field deployment, as well as clearer reporting standards for modelling assumptions and uncertainty. From a review perspective, future progress depends not on increased model complexity alone, but on more transparent, context-aware, and application-driven use of CFD in hybrid heat recovery research.

The emerging trends discussed above illustrate how CFD-based analysis of hybrid passive–active heat recovery systems is evolving in response to practical design, operational, and resilience challenges. The final section synthesises the main findings of this review and outlines concluding remarks on the role of CFD as a decision-support framework for high-performance and retrofit building applications.

9.6. LIMITATIONS OF CFD IN HYBRID PASSIVE–ACTIVE HEAT RECOVERY SYSTEMS

Despite the extensive application of Computational Fluid Dynamics (CFD) in the analysis and optimisation of hybrid passive–active heat recovery systems, several fundamental limitations must be explicitly acknowledged when interpreting reported results.

A primary limitation arises from the strong sensitivity of CFD predictions to boundary condition specification. In hybrid ventilation systems, particularly under natural and mixed-mode operation, airflow behaviour is governed by complex interactions between wind pressure, buoyancy forces, and mechanical assistance. Even minor variations in external pressure distribution, temperature gradients, or inlet flow conditions can lead to significant changes in predicted airflow patterns, heat transfer rates, and overall system effectiveness. This sensitivity is well recognised in building ventilation studies and represents a major source of variability across reported CFD outcomes (Etheridge and Sandberg 1996; Awbi 2003; Zhong et al. 2024; Avci 2025).

A second limitation is associated with turbulence modelling. Most CFD studies rely on Reynolds-averaged Navier–Stokes (RANS) formulations due to their computational efficiency; however, these models have well-documented limitations in accurately representing low-Reynolds-number, buoyancy-driven, and transitional flow regimes typical of hybrid systems. In such conditions, conventional turbulence models may fail to capture flow separation, recirculation, and thermal stratification effects with sufficient accuracy, leading to uncertainty in predicted heat recovery performance and pressure losses (Versteeg and Malalasekera 2007; Incropera et al. 2007; Ozsagiroglu et al. 2022).

Validation represents another critical constraint. Although many studies report acceptable agreement with laboratory-scale experiments, validation against in situ field data remains limited. Hybrid systems operate under highly variable real-world conditions influenced by occupant behaviour, climatic fluctuations, and installation constraints, which are difficult to replicate in controlled environments. As a result, CFD predictions that perform well under idealised laboratory conditions may not fully reflect actual system behaviour in operational buildings (Jung et al. 2023; Ramlee et al. 2023; Lozinsky et al. 2025).

Computational cost further restricts the level of physical detail that can be incorporated into CFD simulations. High-fidelity approaches such as Large Eddy Simulation (LES) or transient multiphase modelling provide improved resolution of unsteady flow structures and heat transfer processes but remain impractical for routine design applications due to their significant computational demand. Consequently, most studies adopt simplified steady-state or reduced-order representations, which may overlook transient behaviour, control dynamics, and localised flow phenomena (Khan 2024; Versteeg and Malalasekera 2007).

In addition, many CFD investigations neglect important physical processes such as moisture transport, condensation, and long-term operational variability. These factors play a critical role in indoor environmental quality, thermal comfort, and system durability, particularly in humid climates and cooling-dominated scenarios. The omission of such processes can lead to overestimation of heat recovery performance and incomplete assessment of system behaviour (Cengel and Ghajar 2015; Li et al. 2023; Malcho et al. 2025).

Another limitation concerns the heterogeneity of modelling approaches across the literature. Differences in domain definition, mesh resolution, boundary condition implementation, turbulence model selection, and performance metrics make direct comparison between studies difficult and limit the generalisability of reported findings. This lack of standardisation contributes to inconsistencies in reported performance ranges and complicates the identification of robust design principles (Aljashaami et al. 2024; Myroniuk et al. 2026).

Finally, many CFD-based studies remain focused on idealised or design-stage scenarios, with limited integration into broader building energy modelling frameworks or lifecycle performance assessment. As a result, the interaction between CFD-predicted system performance and long-term energy use, carbon reduction targets, and retrofit feasibility is not always fully captured (Li et al. 2025; Coggins et al. 2024).

Taken together, these limitations indicate that CFD should not be interpreted as a fully predictive or stand-alone analytical tool. Rather, its primary value lies in providing physically consistent, spatially resolved insight that supports design evaluation, comparative analysis, and informed decision-making. When combined with experimental validation, field data, and system-level energy analysis, CFD becomes a robust component of an integrated framework for the development and optimisation of hybrid passive–active heat recovery systems in high-performance buildings.

10. CONCLUSIONS

This review has critically examined the application of Computational Fluid Dynamics (CFD) in the analysis and development of hybrid passive–active heat recovery systems within high-performance building contexts. Rather than providing a descriptive summary of existing studies, the synthesis has focused on identifying how modelling choices, system configurations, and validation practices influence the interpretation of airflow behaviour, heat transfer, and overall system performance under realistic operating conditions.

The analysis confirms that hybrid ventilation strategies offer a technically robust response to the limitations of purely passive and fully mechanical systems, particularly in environments characterised by climatic variability and fluctuating operational demands. Across the reviewed literature, CFD has established itself as the dominant analytical framework for resolving the coupled mechanisms governing hybrid system behaviour, including airflow distribution, thermal exchange, pressure losses, and transient interactions between passive and active components.

However, a key finding of this review is that CFD outcomes are not solely determined by physical system characteristics, but are strongly conditioned by modelling assumptions. Variations in domain definition, boundary condition specification, turbulence modelling, and representation of passive components introduce significant variability in reported results. This heterogeneity limits direct comparison across studies and underscores the need for careful interpretation of CFD-based findings within their specific modelling context.

In response to this challenge, this review contributes by systematically linking CFD modelling strategies to their implications for predicted system performance. By synthesising results across heterogeneous studies, consistent patterns have been identified regarding airflow stabilisation, heat exchanger utilisation, pressure loss behaviour, and the role of limited mechanical assistance in enhancing system robustness. This structured comparison moves beyond qualitative description and provides a clearer basis for evaluating the reliability and design relevance of different CFD approaches.

The findings further indicate that the primary value of CFD lies not in isolated prediction, but in its capacity to function as a diagnostic and decision-support tool. When integrated with experimental validation, system-level energy analysis, and engineering judgement, CFD enables identification of performance-limiting mechanisms, supports design optimisation, and informs retrofit strategies under real-world constraints. In this context, CFD should be interpreted as part of an integrated analytical workflow rather than a standalone predictive method.

At the same time, several limitations remain evident. Validation against field-scale data is still limited, particularly under mixed-mode and transient operating conditions. The widespread reliance on RANS-based turbulence models introduces uncertainty in buoyancy-driven and transitional flows. In addition, key physical processes such as moisture transport and long-term operational variability are often simplified or neglected. These limitations highlight the importance of transparency in modelling assumptions and the need for more comprehensive validation frameworks.

Emerging research directions indicate a shift toward more application-driven use of CFD. Integration with digital twin frameworks, development of reduced-order models, and incorporation of climate variability and resilience considerations are expanding the role of CFD beyond traditional design-stage analysis. These developments suggest a transition toward more adaptive, data-informed, and operationally relevant modelling approaches.

Overall, this review provides a structured interpretation of the current state of CFD-based analysis for hybrid passive–active heat recovery systems. It identifies the conditions under which CFD delivers reliable insight, clarifies the limitations that constrain its predictive capability, and highlights the modelling choices that most strongly influence performance assessment. Future progress in this field will depend less on increasing model complexity and more on improving methodological transparency, strengthening validation against real operating conditions, and aligning CFD analysis with practical design and retrofit challenges.

By positioning CFD within a broader decision-support framework, this work offers a more rigorous foundation for the development, optimisation, and implementation of hybrid heat recovery systems in next-generation high-performance buildings.

AUTHOR CONTRIBUTIONS

James Riffat: Conceived the study, Led the research, Responsible for the overall design, Development of the analytical framework, Formulation of the review methodology, Prepared the initial draft of the manuscript,

Led the development of the core scientific content; Contributed to the interpretation of the literature, Participated in revising the manuscript, Approved the final version; Responsible for the integrity and accuracy of the work.

Seyed Reza Samaei: Organisation of the literature, Structuring of the review, Refinement of the manuscript, Synthesis of the reviewed studies, Editing, and Improving the clarity and coherence of the final text; Contributed to the interpretation of the literature, Participated in revising the manuscript, Approved the final version; Responsible for the integrity and accuracy of the work.

COMPETING INTERESTS

The authors declare that they have no competing financial or non-financial interests.

DATA ACCESSIBILITY

All data supporting the findings of this study are derived from previously published sources, which are fully cited within the article. No new data were generated in this study. Additional information may be made available by the authors upon reasonable request.

ETHICAL APPROVAL

Not applicable. This study is based solely on the review and analysis of previously published literature and does not involve human participants or animal subjects.

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