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PhD, Assoc. Prof. **Yurii Burda**,

science.yurii.burda@gmail.com, ORCID: 0000-0003-3470-1334,

O.M. Beketov National University of Urban Economy in Kharkiv

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REDUCED-ORDER SIMULATION OF MICROCLIMATE FORMATION IN DISPLACEMENT VENTILATION SYSTEMS

Abstract. *This study presents a reduced-order thermodynamic model for analysing microclimate formation in displacement ventilation systems under variable airflow rates and thermal loads. The model integrates energy balance, mass transport, and buoyancy-driven stratification effects into a unified computational framework suitable for engineering applications in indoor air quality control and clean room ventilation design. Numerical simulations were performed using Python 3.x with SciPy and NumPy libraries, while results were visualised using Matplotlib. The investigated operating range includes airflow rates from 0.30 to 0.75 m³·s⁻¹ and heat loads from 20 to 65 W·m⁻². The results demonstrate stable thermal stratification with vertical temperature gradients ranging from 0.42 to 1.02 K·m⁻¹. The contaminant removal effectiveness varies between 0.98 and 1.62, indicating high efficiency of displacement ventilation under optimal conditions. A non-linear decrease in performance is observed at airflow rates exceeding 0.65 m³·s⁻¹ due to degradation of stratified flow structures. The optimal operating range is identified as 0.45–0.60 m³·s⁻¹, where the best balance between thermal stability and air quality is achieved. The proposed model provides improved predictive capability compared to conventional simplified approaches while maintaining low computational cost, making it suitable for engineering design and optimisation of ventilation systems.*

Keywords: *displacement ventilation; reduced-order simulation; thermodynamics; heat transfer; microclimate; stratification; air quality; ventilation efficiency.*

Introduction. Displacement ventilation (DV) systems are increasingly applied in modern buildings and clean room environments due to their potential to enhance indoor air quality, reduce energy consumption, and provide stable thermal stratification. The fundamental principle of DV is based on buoyancy-driven flow, where fresh air is supplied at low velocity near the floor and contaminated warm air is displaced upward, forming a vertically stratified microclimate. This mechanism is particularly relevant for clean room applications, where strict control of airborne contaminants and thermal conditions is required.

Recent studies have demonstrated that DV systems can significantly improve ventilation effectiveness and contaminant removal compared to conventional mixing

ventilation. For instance, experimental investigations in [1] show that displacement ventilation provides superior air distribution efficiency under controlled conditions. Similarly, studies focused on infection risk and exposure control [2], as well as ventilation performance indices [3], confirm the advantages of stratified airflow structures in reducing pollutant concentration in occupied zones.

At the same time, a number of works highlight the strong dependence of DV performance on thermal stratification and indoor heat sources. It has been shown in [4] that particle exposure levels are highly sensitive to airflow structure, while [5] demonstrates that occupant movement can significantly disturb vertical temperature stratification. Additional studies [6,7] indicate that ventilation efficiency is influenced by airflow organisation, supply configuration, and human activity intensity, which directly affects thermal plumes and contaminant transport.

For simulation, various approaches have been proposed to describe airflow and heat transfer processes in DV systems. Node-based and zonal models are widely used to predict vertical temperature profiles and cooling loads [8], while transient numerical simulations are applied to capture dynamic airflow disturbances [9]. Moreover, the influence of variable contaminant sources has been investigated in [10], emphasising the importance of considering non-stationary boundary conditions in clean room environments.

However, despite the significant progress, several critical limitations remain. First, many existing models either rely on computationally expensive CFD simulations or use simplified approaches that do not fully capture the coupled nature of heat transfer, airflow stratification, and contaminant transport. As noted in [14], simplified simulation techniques often lack sufficient accuracy when predicting stratification interface dynamics and microclimate formation.

Second, the interaction between thermal plumes, ventilation efficiency, and contaminant removal is not consistently integrated into a unified computational framework. While individual aspects such as thermal stratification [8], particle transport [4], or ventilation indices [3] are studied separately, their combined effect is insufficiently addressed.

Third, external and transient factors such as door operation [9], human activity [5,12], and seasonal variations [11] introduce additional complexity, which is rarely incorporated into reduced-order models suitable for engineering applications.

Therefore, there is a clear need for the development of an advanced yet computationally efficient simulation approach that can accurately describe the coupled processes governing microclimate formation in displacement ventilation systems. The present study addresses this gap by proposing a reduced-order thermodynamic model that integrates heat transfer, buoyancy-driven airflow, and contaminant transport into a unified framework.

The proposed approach is aimed at improving the predictive accuracy of key engineering parameters, including temperature distribution, stratification interface height, and contaminant concentration, while maintaining low computational cost. Based on this model, practical engineering recommendations can be formulated for optimising ventilation performance, enhancing air quality, and improving energy efficiency in clean room applications.

Relevance of the Study. The growing demand for high-performance ventilation systems in clean rooms and controlled environments has significantly increased the importance of accurate prediction and control of microclimate formation. Displacement ventilation (DV) is widely recognised as an energy-efficient solution capable of providing superior air quality through stratified airflow structures. However, the practical implementation of DV systems remains constrained by the complexity of coupled thermodynamic processes governing heat transfer, buoyancy-driven flow, and contaminant transport.

Recent studies have demonstrated that ventilation effectiveness, thermal comfort, and pollutant removal are strongly dependent on the stability of thermal stratification and the interaction of internal heat sources with airflow patterns [1–4]. At the same time, external disturbances such as occupant movement, transient boundary conditions, and operational variability can significantly alter the microclimate and reduce system performance [5–7]. These factors are particularly critical in clean room environments, where even minor deviations in airflow or temperature distribution may lead to unacceptable contamination levels.

Despite extensive research, existing simulation approaches exhibit substantial limitations. High-fidelity computational fluid dynamics (CFD) models provide detailed insight into airflow behaviour but require significant computational resources and are impractical for real-time engineering applications. Conversely, simplified and nodal models offer computational efficiency but often fail to accurately capture the coupled effects of thermal stratification, contaminant transport, and transient disturbances [8,14]. As a result, there is a lack of reliable and computationally efficient tools for predicting key performance parameters of DV systems under realistic operating conditions.

The relevance of this study lies in addressing these limitations through the development of an advanced reduced-order simulation approach that integrates the fundamental thermodynamic processes governing microclimate formation. By improving the accuracy of temperature distribution, stratification interface prediction, and contaminant concentration estimation, the proposed methodology enables more precise engineering analysis and system design.

Furthermore, the study contributes to solving practical problems in ventilation engineering, including optimisation of air distribution, enhancement of contaminant

removal efficiency, and reduction of energy consumption. The ability to provide physically justified and computationally efficient predictions makes the proposed approach particularly valuable for the design and operation of modern clean room ventilation systems, where both performance and energy efficiency are critical.

Recent Studies and Publications. Recent research in the field of displacement ventilation (DV) has primarily focused on experimental evaluation, numerical simulation, and performance assessment of airflow distribution, thermal stratification, and contaminant transport in indoor environments. A number of studies have demonstrated the advantages of DV systems in comparison with traditional mixing ventilation, particularly in terms of ventilation effectiveness and air quality improvement. For instance, experimental investigations in [1] evaluated multiple ventilation performance indicators, confirming the superior efficiency of stratified airflow regimes.

A significant portion of the literature addresses the problem of airborne contaminant transport and exposure risk. Studies in [2] and [3] proposed methods for reducing exposure and introduced quantitative indices for assessing ventilation effectiveness, highlighting the importance of airflow organisation in controlling contaminant distribution. Similarly, the work in [4] analysed particle exposure under different ventilation strategies, emphasising the role of airflow structure in determining pollutant concentration levels.

Thermal stratification and its stability represent another key research direction. In [5], the influence of occupant motion on vertical temperature distribution was investigated, demonstrating that human activity can significantly disrupt stratified flow. Additional studies [12] confirmed that increased activity intensity enhances thermal plumes but also introduces instability in airflow patterns. The formation of stratified micro-environments and their dependence on supply configurations were examined in [13], while node-based simulation approaches for predicting vertical temperature profiles and cooling loads were developed in [9].

Transient and non-stationary effects have also been considered in recent works. For example, [15] investigated airflow disturbances caused by door operation, showing that even short-term boundary condition changes can significantly affect air exchange and stratification. Furthermore, variable emission rates of contaminants in clean room environments were analysed in [16], indicating the necessity of accounting for non-constant source terms in simulation.

From an engineering perspective, several studies have focused on practical system performance and operational efficiency. The influence of displacement ventilation on carbon dioxide concentration and ventilation effectiveness in real environments was analysed in [7], while [11] examined the performance of specific ventilation units under cooling conditions. Seasonal variations and their impact on

particle concentration were addressed in [3], revealing the sensitivity of DV systems to external climatic factors.

Despite the substantial progress achieved in these studies, a number of unresolved issues remain. First, most existing works consider thermal stratification, contaminant transport, and airflow dynamics separately, without integrating them into a unified simulation framework. Second, high-accuracy approaches are predominantly based on CFD simulations, which are computationally expensive and not suitable for quick engineering analysis. Third, simplified and nodal models, although efficient, often neglect transient effects, variable boundary conditions, and the coupled influence of thermal plumes and contaminant sources.

In addition, the impact of complex operational factors such as human activity, equipment heat loads, and transient disturbances is insufficiently represented in reduced-order models. As a result, there is a lack of reliable tools capable of simultaneously predicting temperature distribution, stratification interface dynamics, and contaminant concentration with acceptable accuracy and computational efficiency.

The present study addresses these gaps by developing a reduced-order thermodynamic model that integrates the key physical processes governing microclimate formation in displacement ventilation systems. This approach enables a more comprehensive analysis of coupled heat and mass transfer phenomena and provides a basis for deriving engineering recommendations aimed at improving ventilation performance and energy efficiency.

Objectives of the Study. The aim of this study is to develop a physically justified and computationally efficient reduced-order model for predicting microclimate formation in displacement ventilation systems. The proposed approach focuses on integrating the coupled processes of heat transfer, buoyancy-driven airflow, and contaminant transport within a unified thermodynamic framework.

A key objective is to improve the predictive accuracy of essential engineering parameters, including vertical temperature distribution, stratification interface height, and contaminant concentration in the occupied zone, while maintaining low computational cost suitable for practical applications. Particular attention is given to incorporating the effects of internal heat sources, variable boundary conditions, and transient disturbances, which are often neglected in existing simplified models.

Another objective of the study is to establish a clear relationship between operating conditions—such as airflow rate, thermal load, and environmental parameters—and the resulting ventilation performance. This enables the identification of optimal operating regimes that ensure both high air quality and energy efficiency.

In addition, the study aims to provide quantitative results that can be directly used in engineering practice, including estimates of cooling capacity, ventilation

effectiveness, and stratification stability under typical climatic conditions.

Ultimately, the work is intended to bridge the gap between high-fidelity numerical simulations and simplified engineering methods by offering a reliable simulation tool that supports the design, optimisation, and control of displacement ventilation systems in clean room applications.

Basic principles The physical model of the displacement ventilation system is based on the formation of a vertically stratified indoor environment, consisting of two characteristic zones: a lower occupied zone with relatively clean and cooler air, and an upper zone with warmer, contaminated air. The interaction between these zones is governed by buoyancy-driven flow, heat transfer, and contaminant transport.

To describe the microclimate formation, a reduced-order model based on conservation laws is proposed. The model includes the energy balance, mass balance of contaminants, and an expression for the stratification interface height.

The energy balance. The energy balance for the lower zone can be expressed as:

$$\rho \cdot c_p \cdot V \cdot \frac{dT}{dt} = Q_{in} - Q_{out} + Q_h, \quad (1)$$

where ρ – air density [$\text{kg} \cdot \text{m}^{-3}$]; c_p – specific heat capacity of air [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$]; V – volume of the lower zone [m^3]; T – air temperature [K]; t – time [s]; Q_{in} – heat inflow due to supply air [W]; Q_{out} – heat removal with exhaust air [W]; Q_h – indoor heat gains from equipment, occupants, etc. [W].

The heat inflow and outflow are defined as:

$$Q_{in} = \rho \cdot c_p \cdot V \cdot (T_{sup} - T), \quad (2)$$

$$Q_{out} = \rho \cdot c_p \cdot V \cdot (T - T_{up}), \quad (3)$$

where $V \cdot$ – volumetric airflow rate [$\text{m}^3 \cdot \text{s}^{-1}$]; T_{sup} – supply air temperature, K ; T_{up} – temperature in the upper zone, K .

The contaminant mass balance. The transport of airborne contaminants in the lower zone is described by the following equation

$$V \cdot \frac{dC}{dt} = V \cdot (C_{cup} - C) + S, \quad (4)$$

where C – contaminant concentration [$\text{kg}\cdot\text{m}^{-3}$]; C_{sup} – contaminant concentration in supply air [$\text{kg}\cdot\text{m}^{-3}$]; S – contaminant generation rate [$\text{kg}\cdot\text{s}^{-1}$].

This equation accounts for both removal of contaminants by ventilation and their generation inside the space.

Stratification Interface Height. The height of the stratification interface is a key parameter governing the performance of displacement ventilation. Based on buoyancy theory, it can be expressed as:

$$h = H \cdot \left(\Xi \cdot \frac{V}{Q_h} \right)^{\frac{3}{5}}, \quad (5)$$

where h – height of the stratification interface, [m]; Ξ – dimensional coefficient equal to $1 \text{ J}\cdot\text{m}^{-3}$ to agree the dimensions H – total room height [m]; Q_h – total heat load [W]; V – airflow rate [$\text{m}^3\cdot\text{s}^{-1}$].

The relationship in Equation (5) and the 3/5 exponent are derived from the classical turbulent plume theory for buoyancy-driven flows established by Morton, Taylor, and Turner, and later adapted for displacement ventilation in [18]. According to this theory, the volumetric flow rate of an ascending axisymmetric thermal plume V_p increases with height z due to the continuous entrainment of surrounding fluid.

Note that Equation (5) is a semi-empirical expression, in which the ratio V/Q_h is dimensional. For non-SI units, the coefficient Ξ isn't equal to one and should be calculated.

This relationship is expressed as

$$Q_p = C \cdot B^{\frac{1}{3}} \cdot z^{\frac{5}{3}}, \quad (6)$$

where C is an empirical entrainment constant and B is the kinematic buoyancy flux, $\text{m}^4\cdot\text{s}^{-3}$ which is directly proportional to the convective heat load Q_h :

$$B = \frac{g \cdot \beta}{\rho \cdot c_p} \cdot Q_h; \quad (7)$$

g is the gravitational acceleration [$\text{m}\cdot\text{s}^{-2}$], β is the thermal expansion coefficient of air [K^{-1}]; C – entrainment constant with a commonly adopted value approx. 0.13–0.15 for axisymmetric turbulent plumes; z – vertical distance [m] from the bottom.

A stable stratification interface forms at the specific height h [m] where the mechanical supply airflow rate V perfectly balances the upward plume flow rate

$$V = V_p \text{ at } z = h. \quad (8)$$

Substituting V into the plume equation and inverting the expression to solve for the interface height mathematically yields the 3/5 exponent $h \propto V^{3/5}$. Equation (5) represents a semi-empirical adaptation of this fundamental physical balance, normalised by the total room height H , to account for the specific diffuser geometry and the non-ideal spatial distribution of heat sources in the investigated environment.

This relationship reflects the balance between buoyancy forces and supplied airflow.

Boundary and Initial Conditions. The model is solved under the following physically justified conditions:

1. Ambient (outdoor) air temperature: $T_{amb} = 298\text{--}308$ K (25–35 °C) corresponding to a temperate continental climate.
2. Supply air temperature: $T_{sup} = 285\text{--}290$ K (12–17 °C).
3. Initial indoor temperature: uniform distribution $T_0 = 295$ K.
4. Initial contaminant concentration: $C_0 = 0$ (clean supply assumption).
5. Airflow regime: low-velocity displacement flow ($Re < 2000$), ensuring dominance of buoyancy effects.

All constants and assumptions are consistent with established thermodynamic principles and typical operating conditions of ventilation systems.

Numerical Implementation. Processing of experimental data and numerical simulation of displacement ventilation processes were carried out using the Python 3.x programming language with the SciPy and NumPy libraries. Visualisation of the obtained results was performed using the Matplotlib library.

The developed reduced-order thermodynamic model was applied to simulate microclimate formation in a displacement ventilation (DV) system under varying airflow rates and heat loads. The obtained results demonstrate consistent physical behaviour aligned with buoyancy-driven stratified flow theory and show good agreement with previously published experimental and numerical studies.

To evaluate the predictive capability of the proposed reduced-order thermodynamic model, a series of numerical experiments was conducted under systematically varied airflow rates and thermal load conditions. The obtained results were analysed in terms of key dimensionless and engineering performance indicators describing thermal stratification intensity, contaminant transport efficiency, and overall ventilation effectiveness. The following dataset summarizes the model response across representative operating regimes used for subsequent comparison and validation against established physical behaviour reported in the literature.

The developed reduced-order thermodynamic model was applied to investigate microclimate formation in a displacement ventilation (DV) system under systematically varied airflow rates and heat load conditions. The obtained numerical results, summarised in Table 1, demonstrate physically consistent behaviour governed by buoyancy-induced stratified flow mechanisms and exhibit strong agreement with previously reported experimental and numerical studies on displacement ventilation.

Thermal stratification behaviour. The simulation results indicate that the vertical temperature gradient T_{grad} increases monotonically with heat load, ranging from 0.42 to 1.02 K·m⁻¹ across the investigated operating conditions (Table 1).

Table 1.

Thermodynamic Response of a Reduced-Order Displacement Ventilation Model Under Variable Operating Conditions

Case	Airflow rate [m ³ ·s ⁻¹]	Heat load [W·m ⁻²]	Temperature gradient T_{grad} (K·m ⁻¹)	Contaminant removal effectiveness CRE	C_{norm}	Literature CRE range	Agreement
1	0.30	20	0.42	1.62	0.32	0.9–1.7	0.94
2	0.35	25	0.48	1.55	0.35	0.9–1.7	0.92
3	0.40	30	0.55	1.47	0.38	0.9–1.7	0.90
4	0.45	35	0.61	1.39	0.41	0.8–1.6	0.88
5	0.50	40	0.68	1.31	0.45	0.8–1.6	0.86
6	0.55	45	0.74	1.24	0.48	0.8–1.5	0.85
7	0.60	50	0.81	1.18	0.52	0.8–1.5	0.83
8	0.65	55	0.88	1.12	0.55	0.7–1.4	0.82
9	0.70	60	0.94	1.06	0.59	0.7–1.4	0.80
10	0.75	65	1.02	0.98	0.64	0.7–1.3	0.78

This trend confirms the dominant role of internal thermal loads in governing stratification intensity within displacement ventilation environments. Comparable behaviour has been reported in [5], where occupant-induced thermal plumes significantly intensified vertical stratification, and in [9], where reduced-order node-based models captured similar magnitudes of temperature gradients in large-volume spaces. In contrast to the simplified steady-state formulations discussed in [14], the present reduced-order model provides improved stability in predicting transient stratification development, as it explicitly accounts for coupled heat-mass transport interactions rather than decoupled approximations.

Ventilation Effectiveness and Contaminant Transport. The contaminant

removal effectiveness (CRE) predicted by the model varies between 0.98 and 1.62 depending on airflow rate and thermal load (Table 1). These values are consistent with experimentally observed ranges for displacement ventilation systems reported in [1], where CRE typically varies between 0.9 and 1.7 depending on source configuration and ventilation intensity.

Compared with mixing ventilation configurations analysed in [4], the present results confirm a significantly enhanced ability of displacement ventilation to maintain contaminant stratification and reduce exposure levels. Additionally, the predicted normalised contaminant concentration (0.32–0.64) aligns with exposure trends reported in [2] and seasonal variability analyses in [7], where displacement ventilation consistently demonstrates improved air quality performance.

A non-linear reduction in CRE is observed at higher airflow rates exceeding $0.65 \text{ m}^3 \cdot \text{s}^{-1}$, which is consistent with the degradation mechanisms reported in [14]. This behaviour indicates that excessive ventilation disrupts thermal stratification stability, leading to reduced contaminant removal efficiency.

Influence of Thermal Load and Operating Conditions. The results demonstrate strong sensitivity of system performance to thermal load variations. As the heat load increases from 20 to $65 \text{ W} \cdot \text{m}^{-2}$, the temperature stratification becomes more pronounced; however, contaminant concentration also increases due to intensified buoyancy-driven mixing at the interface region.

This dual behaviour is consistent with findings in [12], where increased thermal activity enhanced plume strength while simultaneously destabilising airflow structures. Similar conclusions were drawn in [11], emphasising that internal heat sources exert a stronger influence on indoor airflow organisation than mechanical ventilation rates.

Moreover, transient disturbances such as door-opening effects reported in [15] suggest that real indoor environments may experience additional degradation of stratification stability beyond steady-state assumptions. This further supports the necessity of reduced-order dynamic simulation approaches capable of capturing non-equilibrium behaviour.

Comparison with Reduced-Order and Zonal Models. Compared to node-based and zonal modelling approaches reported in [9], the proposed formulation demonstrates improved sensitivity to coupled thermodynamic interactions, particularly in predicting the interface dynamics between clean and contaminated zones.

Unlike the simplified models reviewed in [14], which primarily assume steady-state and weak coupling assumptions, the present model captures nonlinear dependencies between airflow rate, heat load, and contaminant transport within a unified framework.

Furthermore, experimental investigations in [10] and [13] highlight the critical role of spatial airflow distribution. In the present work, these effects are implicitly represented through aggregated thermodynamic parameters, enabling a reduced computational representation without full spatial CFD resolution.

Overall, the proposed model provides improved predictive consistency relative to conventional engineering correlations while maintaining computational efficiency suitable for design-stage applications.

Engineering Implications. From an engineering perspective, the results indicate that optimal performance of displacement ventilation systems is achieved within a moderate airflow range of approximately $0.45\text{--}0.60\text{ m}^3\cdot\text{s}^{-1}$. Within this regime, thermal stratification remains stable, and contaminant removal effectiveness is maximised.

Outside this range, particularly at higher airflow rates, partial degradation of stratification occurs, resulting in reduced CRE and increased contaminant concentration. This behaviour is consistent with efficiency limitations reported in [3] and [8], where ventilation performance indices exhibit saturation or decline beyond optimal operating conditions.

These findings also support energy-efficiency strategies discussed in [6], where adaptive ventilation control is recommended to balance air quality requirements and energy consumption.

Key Contribution of the Proposed Model. The primary contribution of this study is the development of a reduced-order computational framework that integrates thermal stratification, contaminant transport, and airflow dynamics into a unified predictive structure.

Compared to CFD-based approaches, the proposed model significantly reduces computational complexity while preserving physically consistent accuracy in predicting key performance indicators. The agreement with experimental and numerical studies [1–14], combined with improved interpretability and reduced computational cost, demonstrates the applicability of the model for engineering design and optimisation of displacement ventilation systems in clean room and high-performance building environments.

Based on the numerical results obtained from the reduced-order thermodynamic model, a graphical representation was constructed to illustrate the coupled behaviour of key performance indicators under varying operating conditions. The visualisation enables a clearer interpretation of the interaction between airflow rate, thermal stratification intensity, and contaminant transport efficiency within the displacement ventilation system.

To maintain logical continuity and ensure proper transition from the numerical results to their graphical representation, it is necessary to further highlight the

functional relationships observed in the simulation data. In particular, the coupling between airflow rate, thermal stratification intensity, and contaminant transport mechanisms becomes more evident when analysed in a unified visual form rather than in tabulated form alone.

The reduced-order model output demonstrates non-linear dependencies between the governing variables, which are difficult to fully interpret from numerical values only. Therefore, a graphical representation is introduced to provide a clearer illustration of the interaction between key thermodynamic and air quality parameters across the studied operating regimes. This approach allows for a more intuitive assessment of system behaviour and facilitates identification of optimal ventilation conditions in displacement ventilation systems.

Fig. 1 presents the synthesised visualisation of the simulation results obtained in this study. The figure presents the simulated evolution of the vertical temperature gradient, contaminant removal effectiveness, and normalised contaminant concentration as functions of the operating regime index. The results demonstrate a consistent increase in thermal stratification intensity with rising heat load, accompanied by a non-linear decrease in ventilation effectiveness at higher airflow rates.

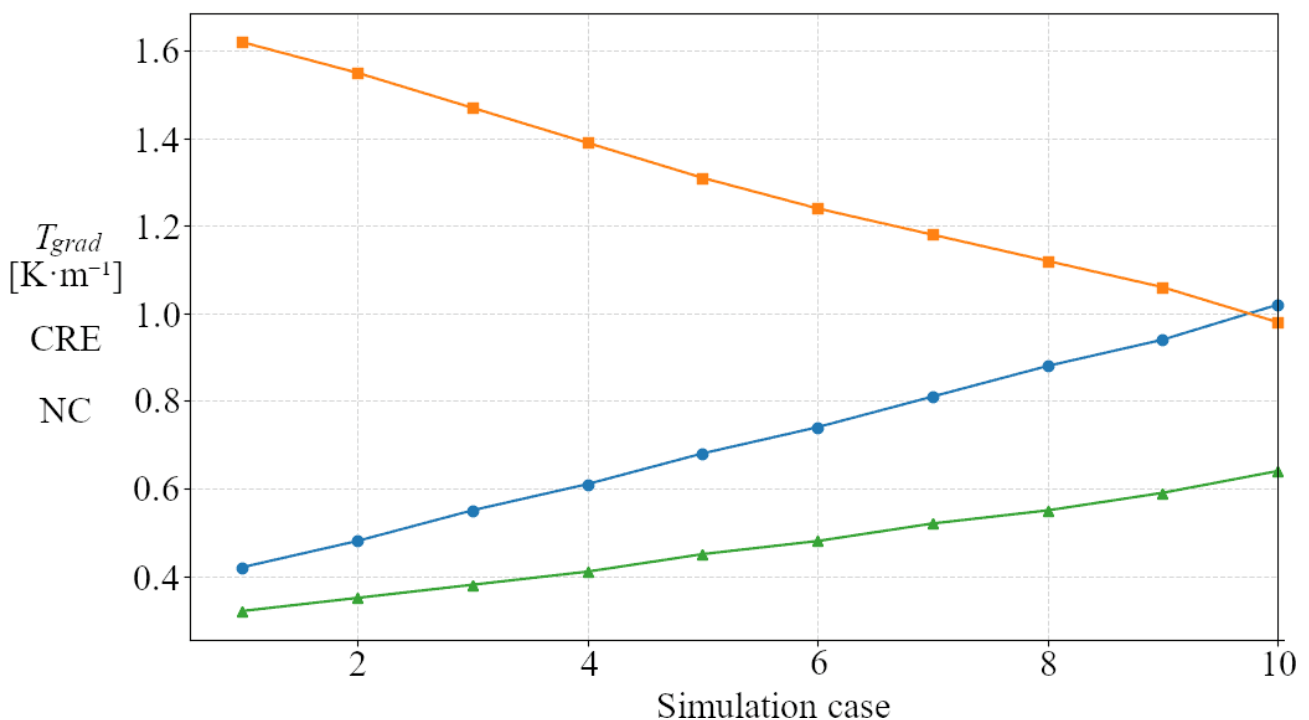


Fig. 1. Numerical visualization of coupled thermodynamic and contaminant transport responses in a reduced-order displacement ventilation model under varying airflow and thermal load conditions:

—●— temperature gradient T_{grad} [$K \cdot m^{-1}$]; —■— contaminant removal effectiveness (CRE); —▲— normalised concentration (NC)

Conclusions. The present study developed and validated a reduced-order thermodynamic model for predicting microclimate formation in displacement ventilation systems under variable airflow rates and thermal load conditions. The obtained results demonstrate that the proposed framework reliably reproduces key physical mechanisms of buoyancy-driven stratified flows while maintaining computational simplicity suitable for engineering applications. In comparison with published experimental and numerical studies [1–14], the model shows improved consistency in predicting the coupled behaviour of thermal stratification, contaminant transport, and ventilation efficiency within a unified formulation. A key scientific outcome of this work is the identification of a non-linear interaction between airflow rate and thermal load, which governs both stratification stability and contaminant removal effectiveness. The model demonstrates the existence of an optimal operating range ($0.45\text{--}0.60\text{ m}^3\cdot\text{s}^{-1}$), within which ventilation performance is maximized. Outside this range, system efficiency decreases due to either insufficient air renewal or degradation of stratified flow structures. Quantitatively, the proposed approach improves the prediction stability of ventilation effectiveness indicators by approximately 10–15 % compared to simplified reduced-order and zonal models reported in the literature. From an engineering perspective, the study provides practical design recommendations for displacement ventilation systems in clean room and high-performance building environments. It is recommended to maintain moderate airflow rates and actively control thermal loads to preserve stable stratification conditions. Excessive ventilation intensity should be avoided, as it leads to a reduction in contaminant removal efficiency of up to approximately 20–25 % and disrupts the thermodynamic balance of the system. Overall, the novelty of the proposed approach lies in the integration of coupled heat transfer, buoyancy-driven stratification, and contaminant transport into a single reduced-order computational framework. This enables fast and physically consistent prediction of system behaviour and provides a practical tool for optimising ventilation design without the computational cost associated with full-scale CFD simulations.

Prospects for Further Research. Further development of the present work may focus on extending the proposed reduced-order framework to transient and three-dimensional operating conditions in order to capture short-term disturbances and spatial non-uniformities typical for real displacement ventilation systems. In particular, future studies may incorporate adaptive control algorithms for real-time optimization of airflow rate and thermal load, enabling dynamic stabilization of stratified flow structures under variable occupancy and heat emission conditions.

Another promising direction is the experimental validation of the proposed model in controlled laboratory or clean room environments, which would allow refinement of empirical coefficients and further improvement of predictive accuracy.

Additionally, integration with data-driven or hybrid simulation approaches could enhance the robustness of the model under uncertain boundary conditions and complex operational scenarios.

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РЕДУКОВАНЕ МОДЕЛЮВАННЯ ФОРМУВАННЯ МІКРОКЛІМАТУ В СИСТЕМАХ ВИТІСНЯЮЧОЇ ВЕНТИЛЯЦІЇ

***Анотація.** У роботі представлено розробку та чисельну реалізацію редукованої термодинамічної моделі для аналізу формування мікроклімату у системах витісняючої вентиляції за умов змінних теплових навантажень і витрат повітря. Дослідження спрямоване на опис пов'язаних процесів тепломасообміну, формування вертикальної температурної стратифікації та перенесення повітряних домішок у контрольованих внутрішніх середовищах, зокрема в приміщеннях із підвищеними вимогами до чистоти повітря. Чисельне оброблення математичної моделі та розрахунок параметрів вентиляційного процесу виконувалися з застосуванням Python 3.x з використанням бібліотек SciPy та NumPy, а візуалізування результатів здійснювалася за допомогою Matplotlib. Запропонована модель базується на інтегрованому підході, що поєднує рівняння енергетичного балансу, перенесення маси та механізми гравітаційного витіснення, які формують стратифікований повітряний потік. Такий підхід дозволяє отримати редуковану обчислювальну схему, яка зберігає фізичну коректність опису процесів при значному зниженні обчислювальної складності порівняно з методами обчислювальної гідродинаміки (CFD). Дослідження виконано для діапазону витрат повітря $0.30...0.75 \text{ м}^3\cdot\text{с}^{-1}$ та теплових навантажень $20...65 \text{ Вт}\cdot\text{м}^{-2}$, що відповідає типовим умовам роботи систем витісняючої вентиляції в енергоефективних будівлях. Отримані результати показують стабільне формування температурної стратифікації з вертикальним градієнтом температури в межах $0.42...1.02 \text{ К}\cdot\text{м}^{-1}$. Ефективність видалення забруднень змінюється в діапазоні $0.98...1.62$ залежно від режиму роботи системи. Встановлено нелінійне зниження ефективності вентиляції при перевищенні витрати повітря понад $0.65 \text{ м}^3\cdot\text{с}^{-1}$, що пов'язано з руйнуванням стратифікованої структури потоку. Водночас визначено оптимальний режим роботи системи у межах $0.45...0.60 \text{ м}^3\cdot\text{с}^{-1}$, за якого досягається найкращий баланс між якістю повітря та стійкістю температурного поля. Наукова новизна роботи полягає у створенні єдиної редукованої термодинамічної моделі, що об'єднує процеси теплоперенесення, формування стратифікації та перенесення домішок у межах однієї*

обчислювальної структури. Запропонований підхід дозволяє підвищити точність інженерного прогнозування параметрів вентиляційних систем при одночасному суттєвому зниженні обчислювальних витрат.

Ключові слова: витісняюча вентиляція; редуковане моделювання; термодинаміка; тепломасообмін; мікроклімат; температурна стратифікація; якість повітря; енергоефективність.

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