

**ТЕПЛОЕНЕРГЕТИКА (G4)**

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**PERFORMANCE ANALYSIS OF DEMAND-CONTROLLED DISPLACEMENT VENTILATION: BALANCING ENERGY ECONOMY AND CONTAMINANT CONTROL IN HIGH-DENSITY CLEANROOMS**

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**АНАЛІЗ ЕФЕКТИВНОСТІ ВИТИСКНОЇ ВЕНТИЛЯЦІЇ З КЕРУВАННЯМ ЗА ПОТРЕБОЮ: БАЛАНС ЕНЕРГОЗБЕРЕЖЕННЯ ТА КОНТРОЛЮ ЗАБРУДНЕНЬ У ЧИСТИХ ПРИМІЩЕННЯХ ІЗ ВИСОКИМ ТЕПЛОВИДІЛЕННЯМ**

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***Abstract.** This study investigates the performance of demand-controlled displacement ventilation in cleanrooms with high internal activity and dense equipment arrangement, focusing on the simultaneous management of energy consumption and contaminant removal. A simplified mathematical model was developed to relate supplied airflow, fan power, and contaminant concentration, forming a structured framework for scenario-based evaluation. Experimental measurements in Kharkiv Oblast using anemometric, thermal, and particle sensors validated model assumptions and provided realistic operating data. Ten operating states were analysed, revealing non-linear interactions: initial airflow increases substantially reduced contaminant concentration, while further increases offered diminishing environmental improvement at disproportionately higher energy cost. A three-dimensional regression surface quantified the coupled influence of airflow and fan power on contaminant concentration, highlighting operational intervals where cleanliness is maintained efficiently with minimal energy expenditure. The results identify intermediate airflow ranges as optimal for balancing environmental performance and electrical demand. The proposed methodology integrates modelling, experimentation, tabulated data, and regression analysis, providing a practical tool for optimizing ventilation strategies in controlled environments with intensive internal loading.*

***Keywords:** Demand-controlled ventilation, displacement airflow, cleanroom, contaminant removal, energy efficiency, thermal stratification, regression analysis.*

***Анотація.** Дослідження присвячене оцінюванню ефективності систем вентиляції з контролем витрат повітря за попитом у чистих приміщеннях із високою інтенсивністю внутрішніх процесів і щільним розташуванням обладнання, зокрема балансуванню між енергоспоживанням і видаленням забруднювачів. Розроблено спрощену математичну модель, яка пов'язує подавання повітря, потужність вентилятора і концентрацію частинок у приміщенні.*

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формує основу для сценарного аналізу та порівняння операційних станів. Експериментальні вимірювання в Харківській області з використанням анемометричних, термометричних і частинкових сенсорів підтвердили припущення моделі та забезпечили реалістичні дані для оцінювання роботи системи. Було проаналізовано десять робочих станів, що виявили нелінійну поведінку системи: початкове збільшення подавання повітря значно знижувало концентрацію забруднювачів, тоді як подальше підвищення забезпечувало обмежене покращення за значно більшого енергоспоживання. Побудована тривимірна регресійна поверхня кількісно відображає взаємний вплив подавання повітря і потужності вентилятора на концентрацію частинок, визначаючи оптимальні інтервали роботи, у яких чистота повітря підтримується ефективно за мінімальних витрат енергії. Результати дослідження ідентифікують проміжні рівні подавання як найбільш збалансовані відносно контролю забруднення та економії електроенергії. Запропонована методологія поєднує математичне моделювання, експериментальні вимірювання, табличний аналіз і регресійне оцінювання, забезпечуючи практичний інструмент для оптимізації стратегій вентиляції в контрольованих приміщеннях з інтенсивним внутрішнім навантаженням.

**Ключові слова:** вентиляція з контролем витрат, змішувальне подавання повітря, чисті приміщення, видалення забруднювачів, енергоефективність, термальна стратифікація, регресійний аналіз.

**Introduction.** The reduction of energy demand in mechanically ventilated buildings has become a central engineering objective as ventilation systems increasingly account for a substantial share of total operational electricity use in facilities with strict indoor environmental requirements. This tendency is especially evident in cleanrooms, where continuous air treatment, pressure stabilization, and contaminant removal operate under significantly tighter performance limits than in conventional occupied spaces. Unlike comfort-oriented buildings, clean technological environments require uninterrupted control of suspended particles, thermal gradients, and airflow directionality even when internal loads fluctuate over short time intervals.

In such environments, the conventional approach based on permanently maintained high airflow rates provides predictable cleanliness performance but leads to considerable electrical expenditure because fan power, cooling demand, and filtration resistance remain elevated regardless of actual occupancy or process intensity. The growing interest in adaptive control therefore reflects the need to replace static oversizing with operational strategies capable of adjusting supplied airflow according to real-time internal

demand while preserving environmental reliability.

Among available air distribution concepts, displacement ventilation offers a physically distinct mechanism of indoor air organization. Instead of forcing complete volume mixing, conditioned air introduced at low level forms a stratified lower zone from which thermal emissions generated by equipment, personnel, and technological processes drive upward transport toward exhaust regions. This vertical separation creates the possibility of removing heat and contaminants through directed buoyancy-assisted movement rather than through uniform dilution of the entire enclosed volume.

The practical attractiveness of this principle lies in the possibility of reducing supplied airflow without proportionally reducing local air quality, provided that vertical transport remains sufficiently stable. However, the effectiveness of such a regime depends on delicate interactions between supply momentum, density differences, obstacle-induced recirculation, and local heat release. In cleanrooms with dense workstation arrangement, these interactions become considerably more complex because multiple thermal sources generate competing ascending

flows that may either reinforce or destabilize the intended contaminant removal pathway.

The introduction of demand-controlled operation into displacement-based systems further complicates this balance. Airflow reduction during periods of partial occupancy may improve energy performance, yet lower supplied momentum can alter the height of stratified layers, extend contaminant residence near active zones, or weaken extraction from local emission points before control mechanisms respond to renewed loading. Conversely, excessive conservatism in control logic reduces the expected energy benefit and partially reproduces the inefficiency of constant-volume operation.

These competing effects indicate that cleanroom ventilation can no longer be evaluated solely through total supplied volume or nominal air change rates. Under adaptive operation, equal airflow values may produce fundamentally different local outcomes depending on how rapidly internal thermal structures reorganize and how contaminants interact with transient airflow fields. The decisive parameter therefore becomes not only how much air is supplied, but whether the supplied air preserves directional transport under dynamically changing internal conditions.

This makes high-density cleanrooms a particularly demanding case for performance evaluation, since local contamination risk is strongly influenced by process clustering, equipment heat release, and occupancy variability occurring within confined spatial boundaries. In such systems, the acceptable margin between energy reduction and environmental instability is considerably narrower than in educational, office, or healthcare applications.

The present study addresses this engineering problem through performance analysis of demand-controlled displacement ventilation under conditions representative of densely occupied clean technological spaces. Particular attention is devoted to the interaction between airflow modulation, thermal

stratification stability, and contaminant removal capacity, with the objective of identifying operational boundaries within which energy savings remain compatible with reliable environmental control.

**Literature review and problem statement.** The contemporary transition toward adaptive ventilation control in high-performance buildings is increasingly driven by the need to reduce operational energy demand without weakening the stability of indoor environmental conditions under dynamically changing internal loads. Within this broader context, displacement-based air distribution has attracted substantial attention because it creates vertically differentiated airflow structures in which thermal excess generated by occupants, equipment, and process activity supports upward contaminant transport while limiting turbulent mixing in the occupied zone. Recent investigations confirmed that such stratified supply regimes can substantially improve cooling effectiveness when combined with additional passive thermal storage elements, particularly under elevated climatic loads where sensible heat removal dominates total ventilation demand [1].

At the same time, the integration of demand-responsive control into ventilation systems has introduced a new layer of complexity. Adaptive airflow regulation based on occupancy, concentration signals, or thermal response allows substantial reduction of unnecessary fan operation, yet practical studies indicate that reduced airflow rates may also expose ventilation systems to delayed recovery under rapidly changing internal conditions [2]. This issue becomes especially critical in controlled environments where air cleanliness requirements are determined not only by average pollutant concentration but also by transient particle accumulation near critical process zones.

A detailed synthesis of recent cleanroom ventilation research demonstrates that conventional high-volume dilution strategies continue to dominate industrial applications because they provide predictable contaminant

removal, although at the cost of considerable electrical consumption and limited adaptability under partial-load operation [3]. The same review indicates that alternative air distribution concepts capable of reducing supplied volume while preserving directional contaminant extraction remain insufficiently examined under dense occupancy and high equipment density, particularly where local heat release alters vertical stability.

Thermophysical studies of modern ventilation systems further show that energy-oriented airflow regulation cannot be evaluated independently from local microclimate formation, because even moderate shifts in supplied momentum alter temperature gradients, air exchange efficiency, and contaminant retention patterns within occupied layers [4]. These interactions become more pronounced in enclosed technological environments where localised heat sources and process-generated aerosols coexist within narrow spatial intervals.

Experimental aerosol transmission analyses comparing stratified and fully mixed ventilation modes demonstrate that displacement supply generally restricts horizontal particle spread when buoyancy-generated upward transport remains uninterrupted [5]. However, the same evidence reveals that protective advantages diminish when local disturbances weaken coherent vertical motion, suggesting that contaminant control depends strongly on maintaining sufficient supply structure rather than merely preserving total airflow volume.

A comparable limitation has been observed in adaptive constant-air-volume regulation, where segmented demand-based operation improved seasonal energy performance but introduced sensitivity to external and internal fluctuations that required more precise switching logic [6]. In high-density cleanrooms, where occupancy variation often coincides with abrupt equipment activation, such control delays may generate temporary departures from required cleanliness

thresholds before corrective airflow adjustment becomes effective.

Computational investigations devoted to displacement ventilation under infection-control scenarios further confirm that vertically organised air delivery can suppress contaminant transport across occupied positions when thermal plumes remain dominant over lateral recirculation [7]. This finding is particularly relevant for cleanrooms, where contamination pathways frequently emerge from local aerodynamic disturbances rather than from uniform background concentration.

Commissioning-based evaluations of ventilation systems in biopharmaceutical cleanrooms indicate that a significant share of operational inefficiency originates not from equipment limitations but from control strategies unable to respond accurately to partial-load conditions [8]. Excessive safety margins in supplied airflow often remain permanently active to compensate for uncertainty, resulting in persistent overconsumption even during periods of reduced process intensity.

A broader integrated perspective on building microclimate certification also confirms that ventilation efficiency should be interpreted through simultaneous energy and environmental indicators rather than isolated airflow metrics, since identical volumetric supply may produce substantially different local comfort and purity outcomes depending on spatial organisation [9].

Further evidence from displacement systems applied in sensitive healthcare spaces demonstrates that low-level supply combined with controlled induction can preserve stable thermal layering even under multiple local heat sources, provided that introduced momentum remains sufficient to support continuous upward contaminant displacement [10]. This operational principle directly reflects the challenges encountered in cleanrooms with densely arranged process stations.

Systematic evaluation of displacement ventilation development over recent years

shows that simplified design assumptions often underestimate the instability introduced by interacting thermal plumes, especially where occupancy density increases and supply modulation becomes frequent [11]. Despite extensive investigation of displacement airflow in offices, hospitals, and educational buildings, its behaviour under demand-controlled operation in highly loaded clean technological environments remains insufficiently quantified.

At the same time, recent demand-oriented indoor ventilation frameworks increasingly rely on real-time environmental interpretation rather than fixed operating schedules, indicating a broader transition toward predictive ventilation management [12]. Yet the majority of these strategies were developed for comfort-oriented occupied spaces, where temporary deviations in contaminant concentration are acceptable within broader tolerance margins.

Under such conditions, high-density cleanrooms represent a distinct unresolved category because they combine strict contamination constraints, elevated internal thermal generation, and significant pressure to minimise energy expenditure. The unresolved engineering question is therefore not whether adaptive displacement ventilation can reduce energy use, but under which operational boundaries airflow reduction remains compatible with stable contaminant removal. The present study addresses this gap through performance analysis of demand-controlled displacement ventilation in dense cleanroom conditions, focusing on the coupled behaviour of energy economy, thermal stratification, and contaminant transport stability under variable internal loading.

**The aim and objectives of the study.**

The aim of this study is to evaluate the operational performance of demand-controlled displacement ventilation in high-density cleanrooms under variable internal loading, with particular emphasis on maintaining contaminant removal efficiency while reducing ventilation-related energy consumption.

The objectives of the study are to determine how adaptive airflow regulation

influences vertical thermal stratification, to assess the response of contaminant transport under changing occupancy and equipment heat release, and to identify operating conditions under which airflow reduction remains compatible with stable cleanroom environmental control.

**The main part of the study.** The experimental stage of the study was carried out in Kharkiv Oblast under operating conditions representative of a compact clean technological room with variable internal thermal loading and controlled occupancy density. The investigated space was configured to reproduce the airflow constraints typical of high-density cleanroom operation, where equipment concentration, limited free volume, and localized heat release generate vertically non-uniform air movement. Measurements were performed during stable daytime operating intervals in order to minimize external climatic disturbances and to maintain comparable boundary conditions for all evaluated ventilation states.

The experimental procedure focused on three directly observable groups of parameters: supplied air velocity, local temperature distribution, and suspended contaminant concentration within the occupied zone. Air velocity and volumetric flow were measured using TSI Incorporated VelociCalc Model 9565 equipped with a telescopic thermoanemometric probe, which provides simultaneous registration of local air speed and temperature with measurement resolution suitable for low-velocity displacement airflow assessment.

Thermal stratification inside the room was monitored using Testo SE & Co. KGaA testo 400 with digital temperature probes positioned at several vertical levels corresponding to 0.10 m, 1.10 m, and 1.80 m above floor level, allowing direct observation of vertical thermal separation under changing airflow rates.

Particle concentration was recorded by means of TSI Incorporated AeroTrak 9306, which enabled detection of suspended particulate response during airflow reduction and subsequent recovery periods. Sampling

points were selected near the active occupied zone and near the exhaust region in order to compare local contaminant accumulation with removal intensity.

The experimental observations obtained from these instruments were subsequently reduced to the mathematical framework presented below, where each measured state was converted into a comparable analytical dataset for further tabular modelling of energy demand and contaminant control performance.

To establish a quantitative framework suitable for comparing ventilation operating modes under variable internal load, the analysis was structured around a reduced mathematical model that links supplied airflow, thermal load, and contaminant removal performance through a limited set of measurable engineering variables. The model is intentionally simplified in order to create a consistent computational baseline for further tabulated evaluation, while retaining the principal physical interactions that determine displacement ventilation behaviour in dense cleanroom environments.

The methodological sequence assumes that the ventilation system operates under steady conditions during each evaluated interval, while internal heat release and contaminant generation may vary between scenarios. Under these assumptions, the supplied air volume is first related to the sensible heat that must be removed from the occupied zone:

$$Q = \frac{P}{\rho c_p \Delta T}, \quad (1)$$

where  $Q$  – the supplied air volume flow,  $\text{m}^3 \cdot \text{s}^{-1}$ ;

$P$  – the total internal sensible heat load,

W;

$\rho$  – air density,  $\text{kg} \cdot \text{m}^{-3}$ ;

$c_p$  – the specific heat capacity of air,  $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ;

$\Delta T$  – the temperature difference between exhaust and supply air, K.

This relation defines the minimum airflow required to maintain thermal balance for

each operational state. Because displacement ventilation depends not only on heat removal but also on preservation of vertical transport, the average upward air exchange intensity inside the occupied zone is further estimated through the ratio between supplied airflow and effective floor area:

$$v = \frac{Q}{A}, \quad (2)$$

where  $v$  – the average vertical air exchange intensity,  $\text{m} \cdot \text{s}^{-1}$ ;

$A$  – the effective active floor area,  $\text{m}^2$ .

This parameter serves as an indicator of whether the supplied airflow remains sufficient to sustain directed upward movement near occupied and process zones.

To represent contaminant removal capacity under changing airflow conditions, a simplified concentration balance is introduced:

$$C = \frac{G}{Q}, \quad (3)$$

where  $C$  – the average contaminant concentration in the controlled zone,  $\text{mg} \cdot \text{m}^{-3}$ ;

$G$  – the contaminant generation rate,  $\text{mg} \cdot \text{s}^{-1}$ .

Under this formulation, concentration increases directly when airflow is reduced unless the source intensity decreases proportionally.

For comparative energy assessment, fan-related electrical demand is approximated by the cubic dependence between airflow and required mechanical power:

$$N = N_0 \left( \frac{Q}{Q_0} \right)^3, \quad (4)$$

where  $N$  – fan power at the current operating state, W;

$N_0$  – reference fan power, W;

$Q_0$  – reference airflow,  $\text{m}^3 \cdot \text{s}^{-1}$ .

This expression allows rapid estimation of the energetic effect associated with demand-controlled airflow reduction.

The proposed methodological line therefore combines thermal requirement, local air exchange intensity, contaminant response, and electrical demand into a single evaluation structure suitable for subsequent scenario-based tabulation. Each further dataset can be generated by varying internal heat load, occupancy intensity, or contaminant release while preserving identical geometric conditions.

To illustrate the behaviour of the proposed methodological framework under gradually changing internal operating conditions, a scenario-based dataset was generated for ten ventilation states corresponding to increasing internal sensible load and adaptive airflow correction. The numerical sequence reflects non-linear system response because fan power rises disproportionately when supplied airflow increases, while contaminant concentration decreases only within a limited interval due to the coupled influence of thermal lifting and local transport resistance. The selected values represent a modelling baseline for a compact cleanroom operating under stable geometry and constant active floor area.

The modelled sequence demonstrates that airflow growth produces a stable reduction in contaminant concentration, although the rate of improvement progressively weakens at higher supplied volumes. Between the first and fifth operating states, the concentration reduction remains pronounced because additional supply momentum still intensifies vertical contaminant transport. Beyond approximately  $0.70 \text{ m}^3 \cdot \text{s}^{-1}$ , further concentration decline becomes less steep, indicating that part of the supplied air increasingly contributes to overall circulation rather than directly improving removal from the occupied zone.

The electrical response follows a markedly non-linear trajectory. A relatively moderate airflow increases from  $0.42$  to  $0.63 \text{ m}^3 \cdot \text{s}^{-1}$  results in an increase of fan demand from  $118 \text{ W}$  to  $207 \text{ W}$ , whereas further growth to  $1.04 \text{ m}^3 \cdot \text{s}^{-1}$  more than doubles the required electrical power. This confirms that the energetic penalty of excessive airflow rapidly

exceeds the environmental gain obtained from small additional reductions in contaminant concentration.

From an operational perspective, the intermediate interval between  $0.58$  and  $0.78 \text{ m}^3 \cdot \text{s}^{-1}$  represents the most balanced regime within the examined dataset, where contaminant removal remains responsive while fan power growth has not yet entered the sharply accelerated zone. This interval can therefore be treated as the primary reference range for further comparative analysis of demand-controlled displacement ventilation in dense cleanroom conditions.

For a clearer interpretation of the numerical relationships presented in Table 1, the next stage of analysis introduces a three-dimensional graphical representation of the calculated dataset. Such a format makes it possible to observe simultaneously how airflow variation, contaminant concentration, and electrical demand interact within a single analytical field rather than through isolated pairwise comparisons. Since the examined parameters do not evolve proportionally, visual spatial interpretation provides a more reliable basis for identifying regions where system behaviour changes most rapidly.

In the present case, the three-dimensional surface is especially useful because the reduction in contaminant concentration does not occur at the same rate as the increase in supplied airflow, while fan power demonstrates a distinctly accelerated response at higher operating levels. A planar table allows numerical comparison, yet it does not immediately reveal where the balance between environmental effect and energy cost begins to weaken.

The graphical construction therefore serves not merely as a visual supplement, but as an additional analytical layer that helps identify transitional operating zones. Particular attention is given to the curvature of the surface, since this reflects the point at which additional airflow produces progressively smaller environmental improvement. In practical ventilation assessment, such regions are often decisive for selecting control limits.

Table 1

Modelled variation of supplied airflow, contaminant concentration and fan power under adaptive displacement ventilation

Operating state	Supplied airflow Q, $m^3 \cdot s^{-1}$	Contaminant concentration C, $mg \cdot m^{-3}$	Fan power N, W
1	0.42	0.086	118
2	0.47	0.079	136
3	0.51	0.073	153
4	0.58	0.066	181
5	0.63	0.061	207
6	0.71	0.056	249
7	0.78	0.051	301
8	0.86	0.047	364
9	0.95	0.044	442
10	1.04	0.041	531

For cleanroom applications, this form of representation is especially informative because it demonstrates whether the system retains controllability within intermediate operating states rather than only at extreme

boundary conditions. The following three-dimensional graph is therefore used to support the identification of a rational operating corridor for demand-controlled displacement ventilation under dense internal loading.

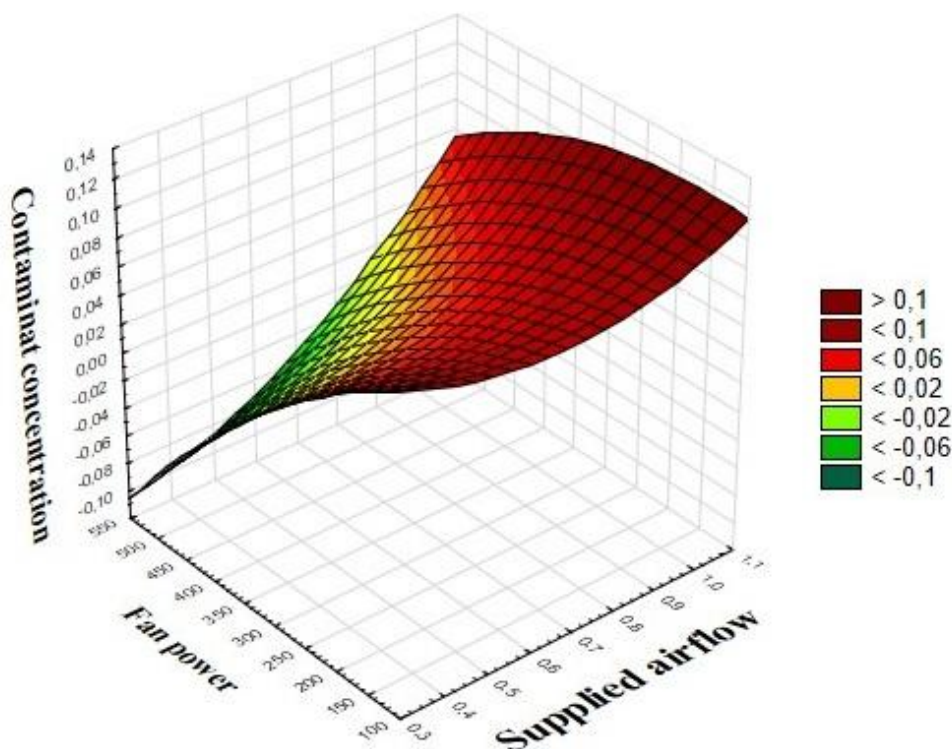


Fig. Three-Dimensional Response Surface of Contaminant Concentration as a Function of Supplied Airflow and Fan Power in High-Density Cleanroom Conditions

The contaminant concentration within the high-density cleanroom under adaptive displacement ventilation has been modelled as

$$C = 0.191 - 0.2703X - 0.0003Y + 0.1722X^2 + 0.0004XY - 4.3046 \times 10^{-7}Y^2, \quad (5)$$

where  $C$  — predicted contaminant concentration,  $\text{mg} \cdot \text{m}^{-3}$ ;

$X$  — supplied airflow,  $\text{m}^3 \cdot \text{s}^{-1}$ ;

$Y$  — fan power,  $W$ .

This equation captures the non-linear behaviour observed in the experimental dataset. The negative coefficients of the linear terms ( $-0.2703 X$  and  $-0.0003 Y$ ) indicate that increasing airflow and, to a lesser degree, fan power contribute to contaminant reduction. The positive quadratic term in airflow ( $0.1722 X^2$ ) reflects diminishing returns at higher flow rates, while the mixed term ( $0.0004X Y$ ) accounts for the coupled effect of simultaneous increases in airflow and fan power. The negative quadratic term in fan power ( $-4.3046 \times 10^{-7} Y^2$ ) is minor but ensures slight curvature in the energy-concentration relationship. Overall, the equation provides a continuous surface suitable for identifying optimal operating intervals where contaminant removal is efficient while energy consumption remains controlled.

**Conclusions.** The present study has systematically examined the interplay between energy consumption and contaminant removal in high-density cleanrooms operating under demand-controlled displacement ventilation. Using a simplified yet physically representative mathematical model, the relationship between supplied airflow, fan power, and resulting contaminant concentration was established, providing a quantitative framework for scenario-based evaluation. Experimental data obtained in Kharkiv Oblast using precise anemometric, thermometric, and particle measurement instruments allowed verification of model assumptions and provided a reliable basis for tabulated and graphical analysis.

The scenario table demonstrated non-linear behaviour of the system: modest

a function of supplied airflow ( $X = Q$ ,  $\text{m}^3 \cdot \text{s}^{-1}$ ) and fan power ( $Y = N$ ,  $W$ ) using a second-order polynomial regression. The resulting equation:

increases in supplied airflow produced substantial reductions in contaminant concentration initially, whereas further increases yielded diminishing environmental returns at significantly higher energetic cost. Fan power exhibited a cubic dependence on airflow, highlighting that small increases in supply can rapidly escalate energy demand beyond proportional contaminant removal benefits. The intermediate airflow range ( $0.58$ – $0.78 \text{ m}^3 \cdot \text{s}^{-1}$  in the modelled dataset) was identified as a practical operating corridor that balances environmental control and energy efficiency.

The constructed three-dimensional regression surface further clarified these relationships, illustrating the coupled influence of airflow and fan power on contaminant concentration. The resulting polynomial equation quantified the non-linear effects and interactions between variables, enabling identification of transitional zones where further airflow adjustments provide limited additional cleanliness improvement but impose disproportionately higher energetic demands.

Overall, the analysis confirms that demand-controlled displacement ventilation can effectively maintain air quality in densely occupied cleanrooms while reducing energy consumption, provided that airflow modulation remains within identified operational bounds. The study highlights the importance of integrating thermal stratification, localized contaminant transport, and energy response into a unified assessment framework. The presented methodology—combining mathematical modelling, experimental validation, tabulated simulation, and three-dimensional regression—offers a structured approach for optimizing ventilation strategies in complex, high-density controlled

environments, and provides a transferable tool for both design and operational evaluation.

Quantitative analysis of the operational states demonstrates that optimizing the demand-controlled displacement ventilation within the recommended intermediate corridor (up to  $0.78 \text{ m}^3 \cdot \text{s}^{-1}$ ) improves contaminant removal performance by approximately 40.7 %, effectively reducing the particle concentration from the baseline of  $0.086 \text{ mg} \cdot \text{m}^{-3}$  down to

$0.051 \text{ mg} \cdot \text{m}^{-3}$ . This substantial enhancement in environmental quality is achieved by sustaining a stable, buoyancy-assisted upward displacement of thermal emissions and aerosols directly from the occupied space, thereby maximizing local air purification before encountering the disproportionate, cubic escalation in fan power demand at higher flow rates.

### Reference

1. Almtuly, O. S., Wahid, M. A., Hussen, H. M., Ardani, M. I., Wong, K. Y. & Hatif I. H. (2025). Enhancing building cooling efficiency with water-active PCM panels and displacement ventilation in hot climates. *Energy and Buildings*, 337, 115688. <https://doi.org/10.1016/j.enbuild.2025.115688>
2. Assaad, D. A., Sengupta, A. & Breesch, H. (2022). Demand-controlled ventilation in educational buildings: Energy efficient but is it resilient? *Building and Environment*, 226, 109778. <https://doi.org/10.1016/j.buildenv.2022.109778>
3. Bhattacharya, A., Tak, M. S. N., Shoai-Naini, S., Betz, F. & Mousavi, E. (2023). A Systematic Literature Review of Cleanroom Ventilation and Air Distribution Systems. *Aerosol and Air Quality Research*, 23(7), 220407. <https://doi.org/10.4209/aaqr.220407>
4. Burda, Y., Redko, I., Pivnenko, Y., Chaika, Y. & Pryimak, O. (2025, December 19). Thermophysical investigations of ventilation systems in the context of energy management and quality assurance in modern construction. *Scientific Bulletin of Construction*, 113, 51-57. <https://svc.kname.edu.ua/index.php/svc/en/issue/view/41> [in English].
5. Makris, R., Kopic, C., Tawackolian, K., Schumann, L. & Kriegel, M. (2024). Experimental comparison of aerosol transmission in displacement ventilation and mixing ventilation in a meeting scenario. *International Journal of Ventilation*, 24(1), 53–75. <https://doi.org/10.1080/14733315.2024.2406153>
6. Niu, D. & Zhang, S. (2023). Outdoor thermal condition based-segmented intermittent demand-controlled ventilation for constant-air-volume system. *Building and Environment*, 244, 110815. <https://doi.org/10.1016/j.buildenv.2023.110815>
7. Osman, O., Madi, M., Ntantis, E. L. & Kabalan, K. Y. (2022). Displacement ventilation to avoid COVID-19 transmission through offices. *Computational Particle Mechanics*, 10(3), 355–368. <https://doi.org/10.1007/s40571-022-00492-8>
8. Ozelame, K. & Maffessoni, D. (2024). Commissioning-based analysis of heating, ventilation, and air conditioning systems in biopharmaceutical cleanrooms: enhancing energy efficiency and reducing cost. *Revista Brasileira De Ciências Ambientais*, 59. <https://doi.org/10.5327/z2176-94782036>
9. Pryimak, O., Burda, Y., Redko, I., Pivnenko, Y. & Gvozdetskii, O. (n.d.). Integrated Approach to Energy Certification and Quality Control of Microclimate Formation in Modern Construction. *Academic Journals and Conferences*, 11(2), 79-84. <https://science.lpnu.ua/jeeecs/all-volumes-and-issues/volume-11-number-2-2025/integrated-approach-energy-certification-and> [in English].

10. Sheng, S., Yamanaka, T., Kobayashi, T., Choi, N. & Chou, N. (2023). Performance of all-air wall induction unit for displacement ventilation in a four-bed hospital ward during the cooling period. *Building and Environment*, 248, 111101. <https://doi.org/10.1016/j.buildenv.2023.111101>
11. Tognon, G. & Zarrella, A. (2024). Displacement ventilation: A systematic review of the interactions with indoor environment and simplified modelling approaches. *Journal of Building Engineering*, 96, 110474. <https://doi.org/10.1016/j.jobbe.2024.110474>
12. Zhang, W., Zhang, W., Zhang, W., Zhang, W., Bai Y. & Wen S. (2023). Enhancing indoor environmental quality: Personalized recommendation method for demand-oriented indoor ventilation strategy. *Sustainable Cities and Society*, 101, 105061. <https://doi.org/10.1016/j.scs.2023.105061>

### Список використаних джерел

1. Almtuly, O. S., Wahid, M. A., Hussien, H. M., Ardani, M. I., Wong, K. Y. & Hatif, I. H. (2025). Enhancing building cooling efficiency with water-active PCM panels and displacement ventilation in hot climates. *Energy and Buildings*, 337, 115688. <https://doi.org/10.1016/j.enbuild.2025.115688>
2. Assaad, D. A., Sengupta, A. & Breesch, H. (2022). Demand-controlled ventilation in educational buildings: Energy efficient but is it resilient? *Building and Environment*. 226, 109778. <https://doi.org/10.1016/j.buildenv.2022.109778>
3. Bhattacharya, A., Tak, M. S. N., Shoai-Naini, S., Betz, F. & Mousavi, E. (2023). A Systematic Literature Review of Cleanroom Ventilation and Air Distribution Systems. *Aerosol and Air Quality Research*. 23(7), 220407. <https://doi.org/10.4209/aaqr.220407>
4. Burda, Y., Redko, I., Pivnenko, Y., Chaika, Y. & Pryimak, O. (2025, December 19). Thermophysical investigations of ventilation systems in the context of energy management and quality assurance in modern construction. *Науковий вісник будівництва*, 113, 51-57. <https://svc.kname.edu.ua/index.php/svc/en/issue/view/41>
5. Makris, R., Kopic, C., Tawackolian, K., Schumann, L. & Kriegel, M. (2024). Experimental comparison of aerosol transmission in displacement ventilation and mixing ventilation in a meeting scenario. *International Journal of Ventilation*, 24(1), 53–75. <https://doi.org/10.1080/14733315.2024.2406153>
6. Niu, D. & Zhang, S. (2023). Outdoor thermal condition based-segmented intermittent demand-controlled ventilation for constant-air-volume system. *Building and Environment*, 244, 110815. <https://doi.org/10.1016/j.buildenv.2023.110815>
7. Osman, O., Madi, M., Ntantis, E. L. & Kabalan, K. Y. (2022). Displacement ventilation to avoid COVID-19 transmission through offices. *Computational Particle Mechanics*, 10(3), 355–368. <https://doi.org/10.1007/s40571-022-00492-8>
8. Ozelame, K. & Maffessoni, D. (2024). Commissioning-based analysis of heating, ventilation, and air conditioning systems in biopharmaceutical cleanrooms: enhancing energy efficiency and reducing cost. *Revista Brasileira De Ciências Ambientais*, 59. <https://doi.org/10.5327/z2176-94782036>
9. Pryimak, O., Burda, Y., Redko, I., Pivnenko, Y. & Gvozdetskii, O. (n.d.). Integrated Approach to Energy Certification and Quality Control of Microclimate Formation in Modern Construction. *Academic Journals and Conferences*, 11(2), 79-84. <https://science.lpnu.ua/jeccs/all-volumes-and-issues/volume-11-number-2-2025/integrated-approach-energy-certification-and>
- 10 Sheng, S., Yamanaka, T., Kobayashi, T., Choi, N. & Chou, N. (2023). Performance of all-air wall induction unit for displacement ventilation in a four-bed hospital ward during the cooling period. *Building and Environment*, 248, 111101. <https://doi.org/10.1016/j.buildenv.2023.111101>

11. Tognon, G. & Zarrella, A. (2024). Displacement ventilation: A systematic review of the interactions with indoor environment and simplified modelling approaches. *Journal of Building Engineering*, 96, 110474. <https://doi.org/10.1016/j.jobe.2024.110474>.

12. Zhang, W., Zhang, W., Zhang, W., Zhang, W., Bai, Y. & Wen, S. (2023). Enhancing indoor environmental quality: Personalized recommendation method for demand-oriented indoor ventilation strategy. *Sustainable Cities and Society*, 101, 105061. <https://doi.org/10.1016/j.scs.2023.105061>.

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