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CFD ANALYSIS OF AIRFLOW AND THERMAL MANAGEMENT IN AN AIR-COOLED DATA CENTER WITH COLD AISLE CONTAINMENT: A HYPOTHETICAL CASE STUDY

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Abstract: With rising computing demands, data centers produce significant heat loads that must be effectively managed to maintain safe server operation and reduce energy consumption. CFD has become essential in analyzing airflow, thermal distribution, and hot-spot formation in such facilities. Previous research shows CFD can identify thermal issues like hot air recirculation and the importance of containment strategies for efficiency improvements. With the rapid growth of cloud computing and data storage, data centers have become critical infrastructure. However, high heat generation from servers poses a major challenge for efficient thermal management. This project focuses on Computational Fluid Dynamics (CFD) modelling of a 12-rack data center with a total heat dissipation of 500 kW. The objective is to analyze airflow and temperature distribution and determine the maximum temperature for a given CRAC airflow rate. A CFD model is developed using turbulence and heat transfer models to simulate real operating conditions.

***Index Terms* -** Computational Fluid Dynamics (CFD), Data Center Cooling, Airflow Management, Computational Thermal Analysis, Cold Aisle Containment (CAC)

I. INTRODUCTION

Modern data centers house high-density server racks that generate large amounts of heat. Efficient cooling is necessary to: Prevent hardware failure, maintain performance, Reduce energy consumption. Cooling systems like CRAC (Computer Room Air Conditioning) units are widely used. Need for Study: Increasing power density (kW per rack), rising cooling costs, Risk of hotspots affecting system reliability. Perform CFD simulation of a 12-rack data center. Analyze temperature distribution. Determine maximum temperature for a given airflow rate. Evaluate cooling performance of CRAC system hypothetical data center hall (40 m × 20 m × 5 m) houses 120 server racks with total IT power of 500 kW. Cooling is provided by four CRAC (Computer Room Air Conditioning) units supplying cold air through a raised floor plenum. Engineering challenge: Predict the airflow and temperature distribution within the hall, identify thermal hot spots, and evaluate the improvement offered by cold aisle containment (CAC) compared to an open aisle arrangement.CFD has been used to numerically assess airflow and temperature in data centers to support cooling optimization and design decisions. Research shows that server rack layout and CRAC arrangements significantly affect cooling performance and hot air recirculation. Containment systems such as cold or hot aisle containment help mitigate bypass airflow and enhance temperature uniformity.

II. LITERATURE

Traditional CFD models accurately characterize data center thermodynamics but require hours-long computations. Wang et al. (2020). A high-performance electronic system has accelerated the development of advanced cooling techniques (Ahmed et al., 2025). The rapid growth of AI and high-performance computing has increased thermal management challenges in modern data centres, driving the adoption of liquid, hybrid, and intelligent cooling technologies for improved efficiency and sustainability (Al Kez et al., 2025). Amorim et al. (2024) reviewed recent advancements in thermal management technologies for data centres, focusing on multilevel cooling approaches including active, passive, liquid, and two-phase cooling systems. The study emphasized the role of advanced cooling methods, waste heat recovery, and energy-efficient strategies in reducing power consumption and improving the sustainability of data centre operations. Cao et al. (2025) investigated the optimization of server inlet areas for improving thermal management in high-density data centres using CFD-based analysis. The study demonstrated that adjusting inlet configurations can enhance airflow distribution, reduce temperature gradients, prevent server overheating, and improve thermal uniformity without requiring additional cooling infrastructure. Chu and Wang (2019) numerically investigated airflow management in a small container data centre using CFD simulations. The study demonstrated that optimization of plenum depth, installation of baffles, and improved perforated tile arrangements can significantly enhance airflow uniformity. The implementation of cold aisle containment and optimized airflow distribution strategies improved cooling performance by increasing rack cooling efficiency and reducing thermal imbalance. Cui et al. (2025) investigated the influence of tilted server arrangements on airflow distribution and thermal management in air-cooled data centres using a validated CFD–experimental approach. The study found that a server tilt angle of 30° significantly reduced cold–hot air mixing, improved airflow uniformity, minimized hotspot formation, and enhanced cooling efficiency compared with conventional horizontal server configurations. Deng et al. (2026) developed a CFD-based data-driven machine learning framework for rapid temperature prediction in large-scale data centres. The study compared individual and ensemble ML models with conventional CFD simulations and demonstrated that ML approaches can significantly reduce computational time while maintaining prediction accuracy. However, the authors highlighted that prediction performance depends on airflow complexity and the spatial characteristics of the thermal environment. Hu et al. (2024) reviewed the ASHRAE RP-1675 guidelines for computational fluid dynamics (CFD) applications in data centres, focusing on improving the reliability and accuracy of CFD-based thermal analysis. The study emphasized best-practice modelling approaches through validation with experimental measurements, including the effects of CRAH units, raised-floor plenums, perforated tiles, and airflow distribution components for sustainable data centre design and operation. Jiang (2024) investigated the impact of different airflow organization strategies on the thermal environment of data centres using numerical simulations. The study compared under-floor precision air conditioning, inter-column air conditioning, and rack backplane cooling configurations, demonstrating that cold aisle containment (CAC) and hot aisle containment (HAC) significantly improve airflow efficiency, reduce cold–hot air mixing, minimize hotspots, and enhance energy utilization. Among the evaluated methods, HAC showed superior performance in optimizing thermal conditions and cooling efficiency. Kargar and Moran (2025) proposed a dual-loop free cooling approach for data centres by transforming the building structure into a large-scale heat exchanger. Using CFD simulations and analytical models, the authors showed that the proposed system can achieve low PUE values across different climatic conditions, providing a sustainable and scalable solution for future data centre thermal management. Strategies such as airflow isolation and hot aisle optimization have been shown to enhance airflow management and improve cooling effectiveness (Lyu et al., 2026). Recent studies integrating CFD simulations, experimental validation, and optimization techniques have shown significant improvements in coolant selection, heat sink design, and flow distribution control (Zhang et al., 2026). The selection of appropriate turbulence models and consideration of buoyancy effects are essential for reliable thermal and airflow management studies (Wibron et al., 2018). CFD-based airflow analysis has been widely applied to optimize airflow (Sarella and Patel, 2026). CFD-based thermal assessments and heat transfer correlations help optimize cold plate designs, coolant flow conditions, and energy-efficient operation of DLC systems (Moon and Cho, 2025). Hybrid approaches combining CFD simulations with machine learning and evolutionary algorithms enable faster optimization of airflow and cooling system parameters (Omrani and Ghassemi, 2025). Automated CFD frameworks are being developed to overcome the limitations of conventional CFD approaches (Szeliga et al., 2025). Understanding airflow patterns and particle transport mechanisms is essential for maintaining equipment reliability while adopting energy-efficient cooling approaches (Saini et al., 2022). CFD-based evaluation of airflow management, containment solutions, and thermal optimization strategies enables significant improvements in cooling performance and operational efficiency (Sarikaya et al., 2025). CFD-based analysis and performance evaluation indices show that localized cooling approaches can reduce bypass airflow, improve temperature uniformity, and enhance overall cooling efficiency compared with traditional room-based systems (Singh et al., 2025). CFD-based evaluations have demonstrated improvements in airflow control, reduction of thermal inefficiencies, and better utilization of cooling capacity after retrofit implementation (Singh et al., 2025).

III. RESEARCH METHODOLOGY

The methodology section outline the CFD simulation of a 12-rack data centre with 500 kW heat load to: Predict airflow behavior Determine maximum temperature zones. Data Centre Dimensions: Length: 40 m; Width: 14 m; Height: 11.9 m; Rack height: 2.47 m. System Components: Server racks (12 units); CRAC unit; Cold air inlet; Hot air outlet; Room enclosure. Layout Description: Cold air enters from CRAC; Passes through racks; Absorbs heat; Exits as hot air Presented in Table 1 and Figure. 1 to Figure. 8.

The following assumptions are considered:

Airflow is steady and turbulent: Air inlet temperature = 8°C; Uniform airflow to all racks; Each rack receives 0.6 kg/s air mass flow; Heat load uniformly distributed; Server racks modeled as porous media; Walls are adiabatic; Heat source equally distributed (~400–500 kW total);

Governing Equations:

Continuity Equation Mass conservation: $\nabla\cdot(\rho V)=0$;

Momentum Equation $\rho(V\cdot\nabla V)=-\nabla P+\mu\nabla 2V$;

Energy Equation $\rho Cp\ (V\cdot\nabla T)=k\nabla 2T+Q$.

Geometry & Domain: 3D model of hall including server racks, raised floor plenum, CRAC units, and containment barriers. Mesh refinement around rack inlets and outlets. CFD Settings: Turbulence: k-ε model (common choice for indoor airflow simulations); Air properties: treated as incompressible ideal gas Steady state simulations (sufficient for average cooling performance study).

Table 1: Boundary conditions

Boundary	Condition
CRAC supply	12 °C, 1.2 m/s airflow
Rack heat load	Uniform 4.2 kW per rack
Walls	Adiabatic
Return vents	Pressure outlet

Table 1 displayed Boundary conditions.

3.1 CFD simulation of 12 Rack Data centre

This section provides CFD simulation of 12 Rack Data centre.

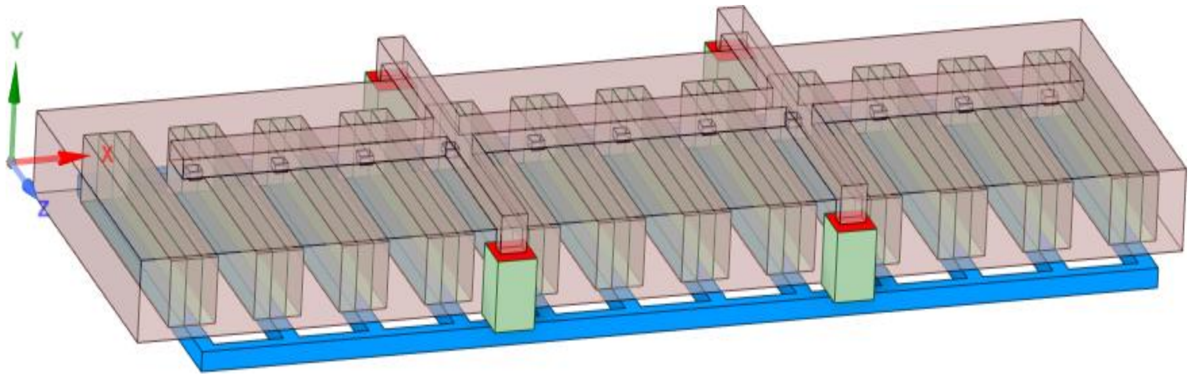

Figure. 1 CFD simulation of 12 Rack Data centre with 500 KW heat dissipation rate to find maximums temperature for given flow rate of CRAC unit.

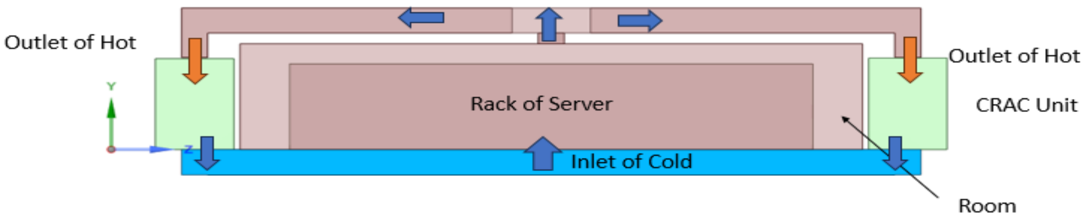

Figure. 2 Inlet and outlet

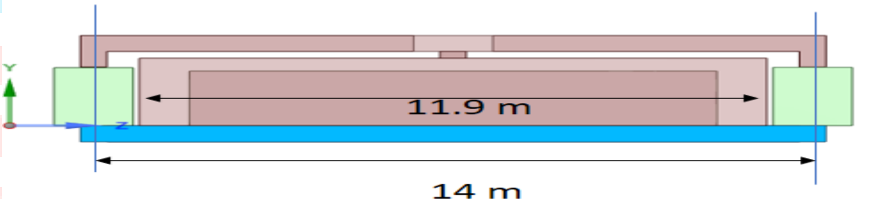

Figure. 3 Room width dimensions

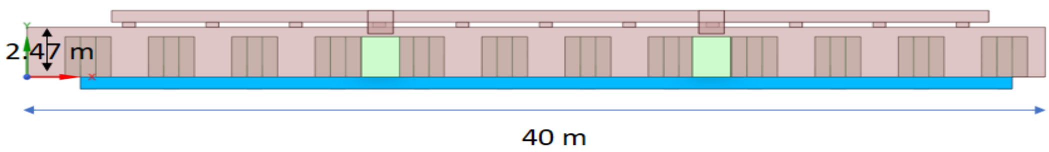

Figure. 4 Room Length dimensions

3.2 Modelling Assumptions

The following assumptions are considered in CFD simulation:

CFD domain starts from cold air inlet to cold passage to suction duct of CRAC units

Air inlet to 12 racks is assumed to be uniform with fixed temperature of cold air which equally flows to both side of racks

Heat dissipation rate is assumed to be uniform to each server rack

Server rack is modelled as porous medium with volumetric heat source

Adiabatic walls of rooms

Total air mass flow rate to each rack: 0.6kg/s with inlet temperature 8°C

CFD Model:

Turbulent K-e model

Convective Heat transfer model

Porous model to server racks, 80% fluid zone

Heat source (400 KW) is equally distributed to all server racks

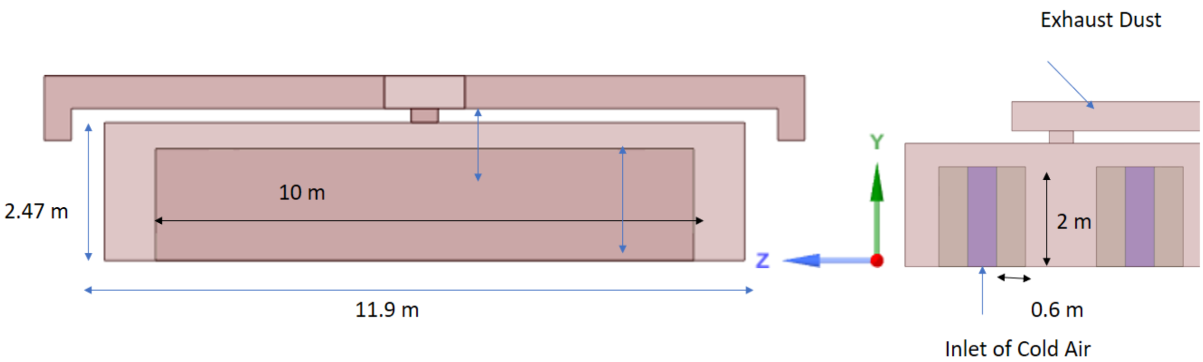

Figure. 5 CFD model of data centre dimensions

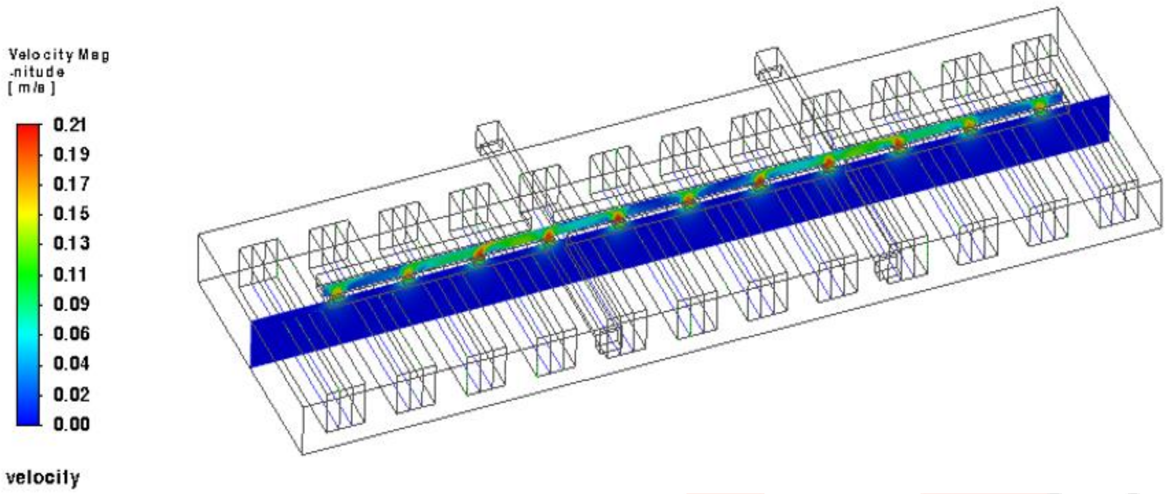

Figure. 6 CFD model of data centre at cold temperature

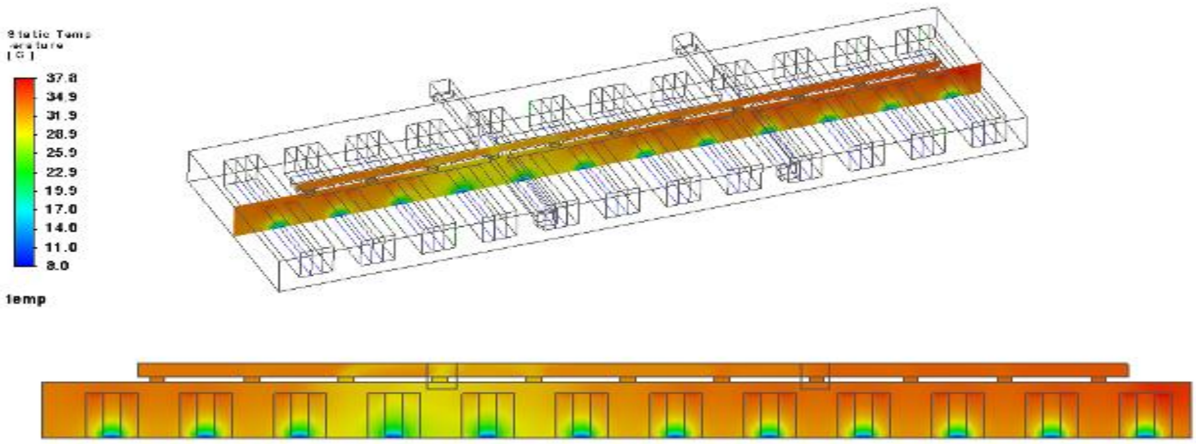

Figure. 7 CFD model of data centre at temperature rise

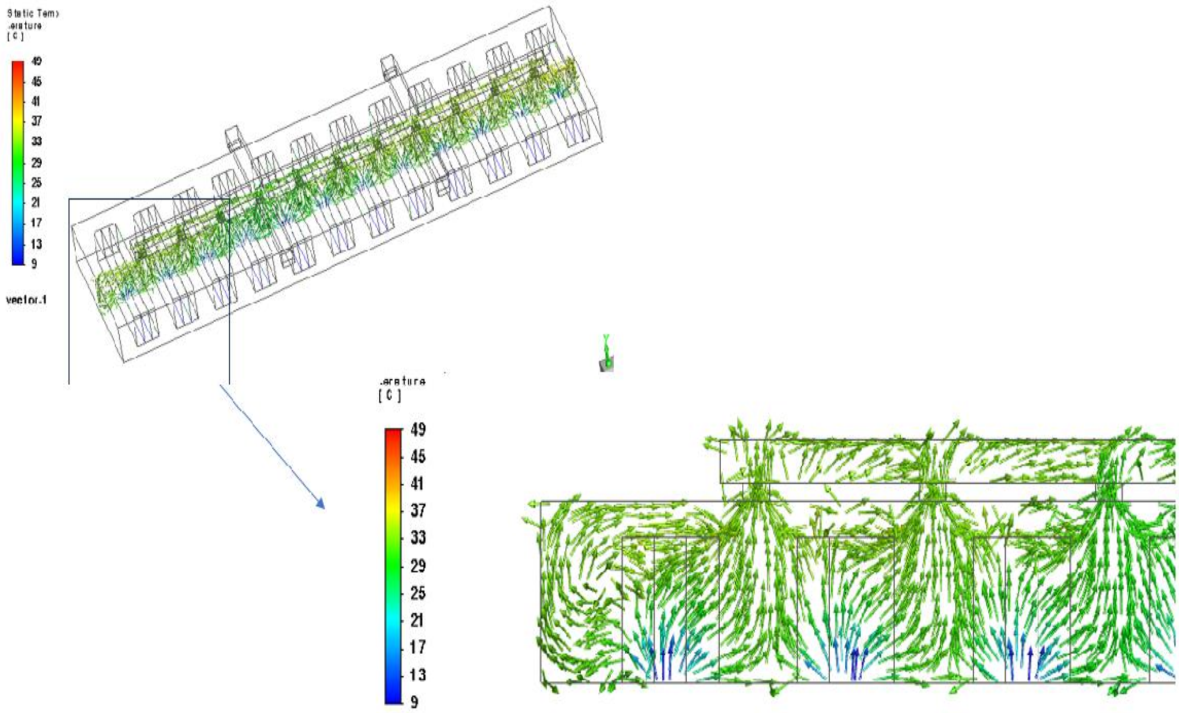

Figure. 8 CFD model of data centre air flow

IV. RESULTS AND DISCUSSION

4.1 Results of Descriptive Statics of Study Variables

Case A: Baseline without Containment
Significant recirculation zones found near aisle entrances.
Temperature gradients show maximum interior temperatures up to ~37°C at server intakes.
Non-uniform cooling leading to hot spots in rack rows.
Interpretation: Poor separation of cold and hot streams resulting in higher return temperatures and inefficiencies.
Containment effect: CAC successfully prevents mixing of cold supply and hot exhaust air, reducing hot spots.
CFD insights: Helps visualize critical dead zones and pressure imbalances within raised floor plenum.
Design implication: Containment and optimized CRAC placement reduce required fan power and extend equipment life.

Case B: Cold Aisle Containment
Recirculation reduced and airflow directed through cold aisle. Temperature uniformity improved: max inlet temps ~30°C. Improved performance indices compared to baseline.

This CFD successfully predicts thermal behavior of data center. Temperature distribution depends on airflow rate, Porous modelling effectively represents server racks, Hotspots can be minimized with better airflow design, CFD can robustly predict airflow and temperature distributions in a data center environment., Cold aisle containment significantly improves thermal performance over open configurations., Optimization using CFD offers valuable support for energy-efficient design strategies.

IV. ACKNOWLEDGMENT

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REFERENCES

[1] Ali Wang, R., Zhou, X., Dong, L., Wen, Y., Tan, R., Chen, L., Wang, G. and Zeng, F., 2020. Kalibre: Knowledge-based neural surrogate model calibration for data center digital twins. In Proceedings of the 7th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, pp. 200-209.

[2] Ahmed, K.R.A., Kumar, J.P.N., Shyam, A., Perumal, D.A. and Velraj, R., 2025. Effective heat transfer enhancement for high-efficient electronic cooling: a review. Journal of Thermal Analysis and Calorimetry, 150(21), pp. 16991-17022.

[3] Al Kez, D., Foley, A., Wong, F.W., BM, H., Dolfi, A. and Srinivasan, G., 2025. AI-driven cooling technologies for high-performance data centers: State-of-the-art review and future directions. Energy and AI, p. 100412.

Amorim, G.S., Belman-Flores, J.M., de Paoli Mendes, R., Sandoval, O.R., Khosravi, A. and Garcia-Pabon, J.J., 2024. Recent advancements in thermal management technologies for cooling of data centers. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 46(8), p. 472.

[4] Cao, S., Wu, T., Ling, J. and Wu, L., 2025. Optimizing server inlet areas for enhanced thermal management in data centers: A CFD-based investigation. International Communications in Heat and Mass Transfer, 168, p. 109432.

[5] Chu, W.X. and Wang, C.M., 2019. CFD investigation of airflow management in a small container data center. IEEE Transactions on Components, Packaging and Manufacturing Technology, 9(11), pp. 2177-2188.

[6] Cui, W., Zhao, W., Yin, H., Ma, Z., Tian, X., Lv, W. and Wang, Z., 2025. Study on the characteristics of tilted server arrangement for air distribution optimization in data centers. SSRN Electronic Journal, DOI:10.2139/ssrn.6108712.

[7] Deng, P., Xu, Q., Zhu, X. and Dong, W., 2026. CFD-based data-driven machine learning temperature prediction: case study on a 180-rack server room within a large-scale data center. International Journal of Thermal Sciences, 221, p. 110465.

[8] Hu, B., Vangilder, J., Seymour, M., Patel, D., Joshi, Y. and Lin, C.X., 2024. Guidance for data-center CFD (RP-1675). Science and Technology for the Built Environment, 30(5), pp. 468-486.

[9] Jiang, D., 2024. Effects and optimization of airflow on the thermal environment in a data center. Frontiers in Built Environment, 10, p. 1362861.

[10] Kargar, S. and Moran, J.L., 2025. Combining direct and indirect free cooling for data centers via transformation into a building-scale heat exchanger. Applied Energy, 392, p. 125973.

[11] Lyu, Y., Bai, X., Wang, L., Wang, Y. and Jin, C., 2026. Improvement strategies based on airflow characteristic in a row-based cooling data center. Energy and Buildings, 357, p. 117136.

[12] Moon, J.H. and Cho, J., 2025. Total thermal assessment and Nusselt number correlation for 2U servers with direct liquid cooling. Thermal Science and Engineering Progress, 58, p. 104278.

[13] Omrani, M. and Ghassemi, M., 2025. AI-driven optimization of fan-wall cooling system in a medium-density data center. International Journal of Heat and Mass Transfer, 247, p. 127159.

[14] Saini, S., Shahi, P., Bansode, P., Shah, J.M. and Agonafer, D., 2022. Simplified and detailed analysis of data center particulate contamination at server and room level using Computational Fluid Dynamics. Journal of Electronic Packaging, 144(2), p. 024501.

[15] Sarikaya, O.M., Kuzay, M., Demirel, E., Melgaard, S.P., Nielsen, J.E., Jensen, R.L. and Szeliga, W., 2025. Energy efficiency enhancement in two European data centers through CFD modeling. Scientific Reports, 15(1), p. 24952.

[16] Sarella, G. and Patel, A.K., 2026. Impact of air flow pattern and distribution on indoor air quality using computational fluid dynamics. Air Quality, Atmosphere & Health, 19(5), p. 103.

[17] Singh, N., Permana, I., Agharid, A.P. and Wang, F.J., 2025. Innovative retrofits for enhanced thermal performance in data centers using independent row-based cooling systems. Thermal Science and Engineering Progress, 57, p. 103101.

[18] Singh, N., Permana, I., Helal, H.H., Wei, C.C. and Wang, F.J., 2025. Performance improvement approach for retrofitting a data center. Journal of Building Engineering, 111, p. 113238.

[19] Szeliga, W., Oleksiak, A., Roszak, R. and Górzeński, R., 2025. CFD4DC: Automated CFD framework for heat transfer analysis of data centers. Applied Thermal Engineering, 259, p. 128982.

[20] Wibron, E., Ljung, A.L. and Lundström, T.S., 2018. Computational fluid dynamics modeling and validating experiments of airflow in a data center. Energies, 11(3), p. 644.

[21] Zhang, B., Li, H., Xu, T., Wang, L., Chen, L. and Li, Z., 2026. Integrated CFD modeling and experimental validation of single-phase immersion cooling for data center thermal management. Energy, 320, p. 140315.