ANALYSIS OF VENTILATION POSITIONING INFLUENCE ON COOLING EFFICIENCY OF PROTECTIVE CLOTHING

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Abstract. Maintaining thermal comfort in protective clothing is essential in industrial and high-workload environments, where excessive heat accumulation inside the garment can lead to discomfort, fatigue, and heat stress. Proper ventilation design improves airflow between the human body and the clothing, thereby enhancing heat dissipation. The present study investigates the influence of ventilation positioning on the cooling efficiency of protective clothing using Computational Fluid Dynamics (CFD). To simplify the analysis, an elliptical model representing the human body and a protective jacket with a uniform air gap is developed. The jacket is created with 105 ventilation holes of 4.4 mm diameter. Three different ventilation positions are analysed: (1) openings located 95 mm from the top, (2) openings located 95 mm from the bottom, and (3) openings located 145 mm from the top of the model. The simulations are carried out using SolidWorks Flow Simulation with an inlet air velocity of 2 $m \cdot s^{-1}$, ambient temperature of 20 °C, and atmospheric pressure of 101325 Pa. The body temperature is taken as 36.5 °C with a metabolic heat generation of 200 W. The performance of each configuration is evaluated in terms of heat transfer rate, pressure difference, surface temperature difference, total enthalpy rate, and average heat flux.

The results show that the position of ventilation openings significantly affects airflow behaviour and heat removal. When the openings are placed near the top, warm air escapes more easily due to the combined effect of forced and natural convection, resulting in lower pressure difference (211.82 Pa) and higher temperature difference (13.24 °C). As the openings move away from the top, pressure difference increases (≈254 Pa) and cooling efficiency slightly decreases. The study concludes that placing ventilation openings near the upper region of protective clothing improves heat dissipation and overall cooling performance.

Keywords: CFD, heat transfer, ventilation design, SolidWorks Flow Simulation, protective jacket.

Introduction

The use of protective clothing is very common in industrial, firefighting, military and high work environments to help protect workers in such hazardous environments as high temperature, flames, chemicals and mechanical hazards [1; 2]. Although this type of clothing is necessary to protect a person, it can significantly reduce the ability of the human body to release excess heat which causes heat buildup within the clothing microclimate [3]. High heat levels may result in thermal distress, poor performance at work, exhaustion, and finally heat stress or heat-related diseases [4]. Consequently, balancing protection and thermal comfort has also become a research question of relevance to the area of heat transfer, textile engineering, and computational fluid dynamics (CFD).

Ventilation is among the most important characteristics of thermal comfort of protective clothing, along with the characteristics of material fabrics and composite material interlayer used in clothing design [5, 6]. Ventilation openings should be properly designed to enable the movement of air between the body and the clothing layer which improves convective heat transfer and the loss of excess heat and moisture [7]. Nevertheless, the efficiency of ventilation is not only based on the size of the openings but also determined by the way they are placed on the garment. The wrong placement can decrease the capacity to get the hot air out of the clothing, which will decrease the overall cooling effectiveness of the clothing design [8]. CFD tools enable the investigator to study complicated thermal and fluid flow phenomena without incurring the expensive experimental equipment. The software programs like SolidWorks Flow Simulation allow simplified human body shapes and clothing to be modelled to determine temperature fields, patterns of air flows, pressure changes and heat transfer rates under varied design conditions [9]. The concept of simplified models also contributes to the minimization of the complexity of the computations and ensures the credible understanding of the physical behaviour of the system.

It has been demonstrated in the previous studies that the design of ventilation has a considerable impact on the thermal regulation of protective clothing [10], along with the use of different composite materials in clothing design [11], although, little has been achieved on the analysis of the effect of ventilation positioning along the vertical axis of the protective clothing. Because a hot air naturally ascends as a result of upward forces, how the ventilation openings are located, either higher or lower on

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the garment, can affect the movement of the air and the ability to cool the garment. Knowledge of this relationship is critical in enhancing the design of protective jackets to be worn in high-temperature or high-worker situation [12].

This paper evaluates the effect of ventilation placement in terms of cooling effectiveness of protective jacket on the basis of the CFD simulation. To simplify analysis, an elliptical model of the human body is developed with a protective jacket on it. Three cases are taken, with the ventilation openings lying under varying distances on the top and bottom of the model. The rate of heat transfer, the behaviour of airflow, the temperature and pressure difference are evaluated using SolidWorks Flow Simulation in consideration of every set of configurations. The results obtained are compared in order to define the influence of the location of ventilation openings on cooling performances and fluid flow energy losses in protective clothing systems. The primary objective of this study is to understand the effect of ventilation positioning on the thermal performance of protective clothing. The results can be used to design improved experiments for optimizing the placement of ventilation openings in garments, which may improve thermal comfort for workers in demanding environments.

Model components and boundary conditions

Fig. 1 shows the base geometric model used in the present CFD investigation. In order to reduce the complexity of the real human-clothing system, a simplified elliptical representation of the human body and protective jacket is created. The body model is placed concentrically inside the jacket model such that a uniform air gap is maintained between the body and the clothing layer. This simplification allows the study to focus mainly on airflow and heat transfer behaviour without introducing unnecessary geometric complexity. All the dimensions provided in the figures are in millimetres (mm).

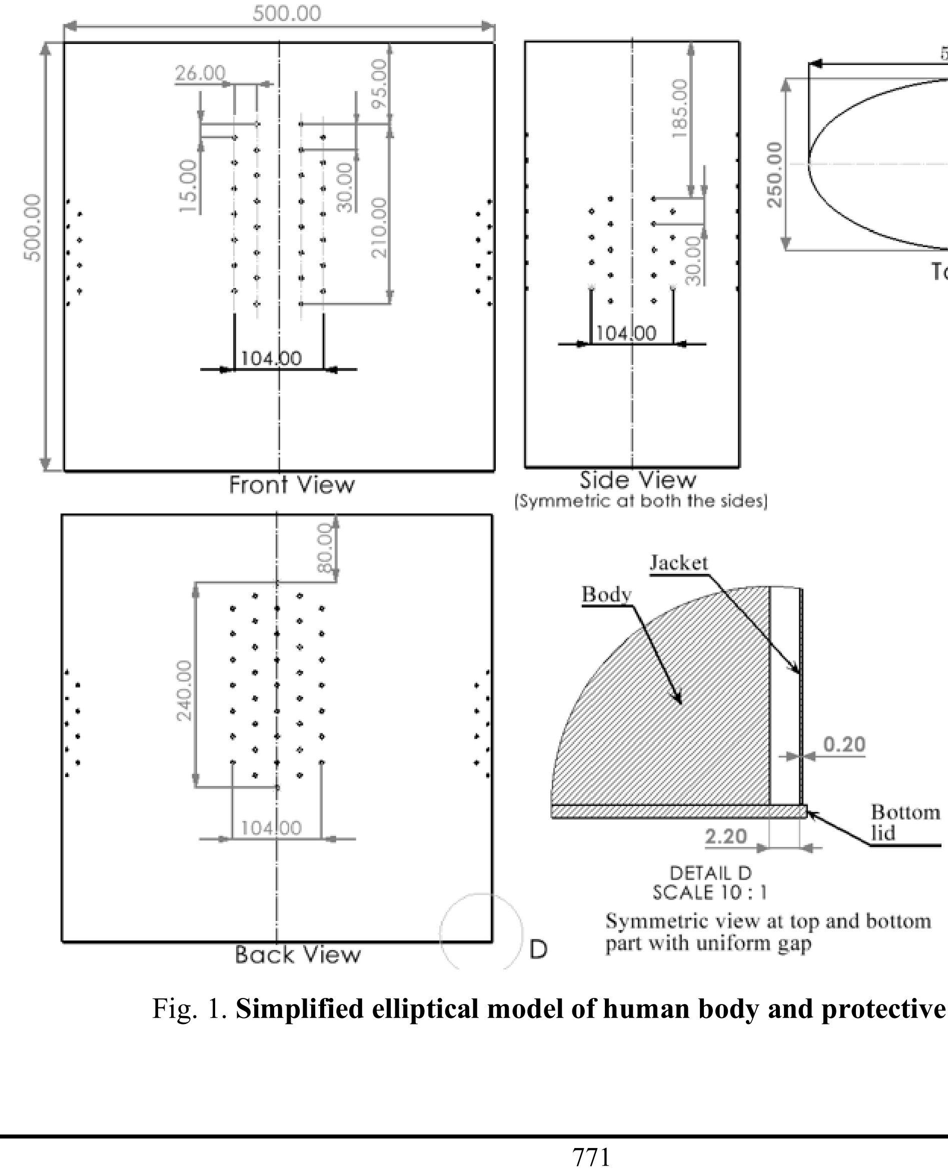
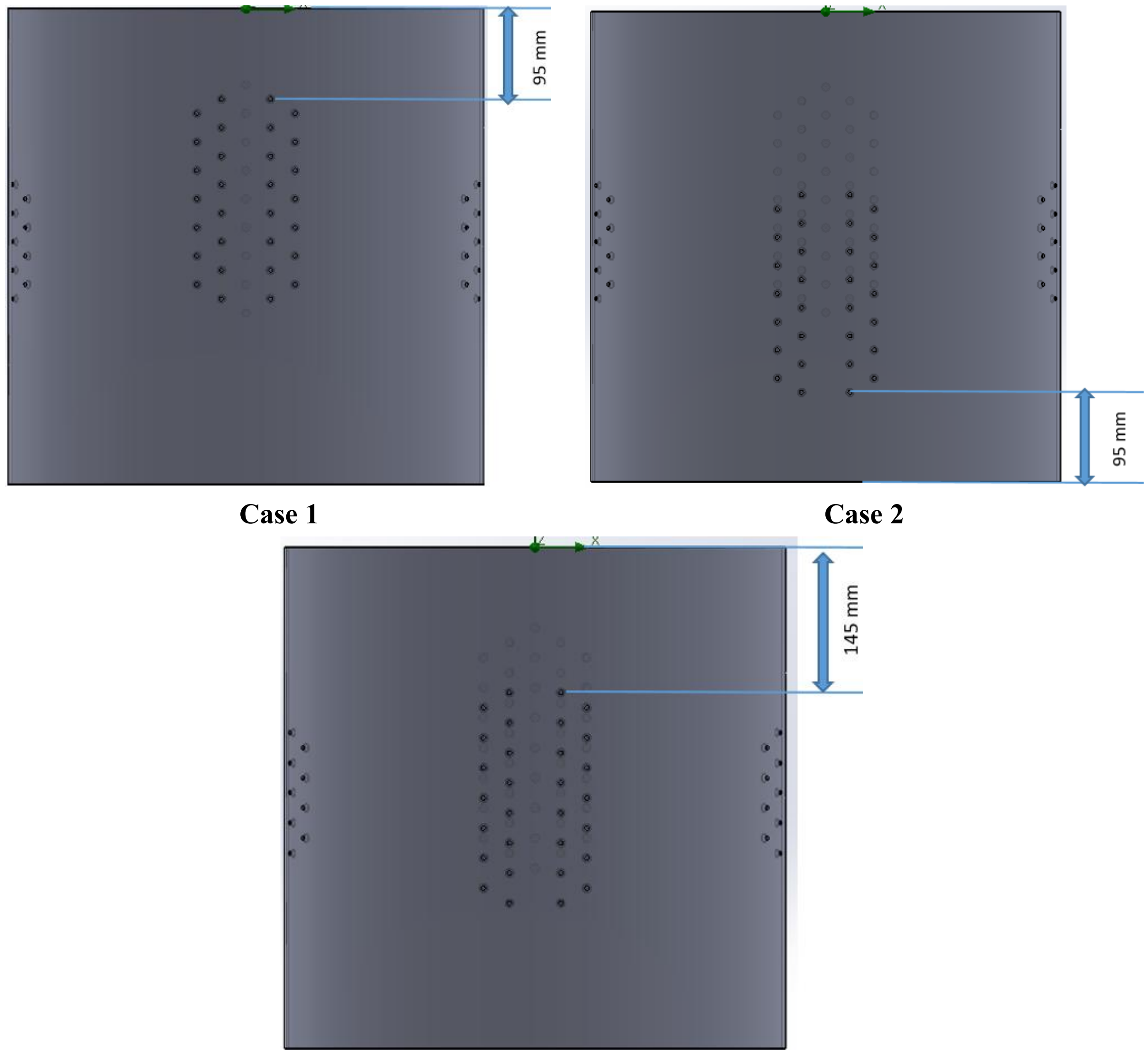


Fig. 1. **Simplified elliptical model of human body and protective jacket**

The ventilation hole diameter is fixed at 4.4 mm, and a total of 105 holes are distributed on the jacket surface. The top view shows the elliptical cross-section of the body and jacket, while the detail (D) section view indicates the air gap (2.20 mm) between the body and the clothing, which plays an important role in convective heat transfer.

The variable parameter in this study is the vertical position of the ventilation openings, measured consistently from the top reference plane of the jacket model. This reference is used for all cases to ensure clarity and consistency in comparison. The simplified geometry is created in SolidWorks and SolidWorks Flow Simulation tool is used to analyse the airflow pattern, pressure distribution, and heat transfer characteristics inside the clothing system.



Case 1 **Case 2**

Case 3

Fig. 2. **Different positions of ventilation openings on clothing model (Front views)**

Fig. 2 illustrates the three configurations analyzed in this study. The ventilation position is defined as the vertical distance from the top of the jacket in all cases, eliminating ambiguity in comparison:

- Case 1: 95 mm from the top;
- Case 2: 95 mm from bottom;
- Case 3: 145 mm from the top.

This unified reference system allows a clear interpretation of trends in airflow and heat transfer behaviour.

In all cases, the number of holes and their diameter remain the same, while only the vertical position of the ventilation openings is changed. Changing the vertical location of the holes allows the investigation of how buoyancy-driven airflow and natural convection affect heat removal from the body. The position of ventilation openings can significantly influence cooling performance and pressure loss inside the clothing.

Boundary conditions and simulation parameters

The CFD analysis is carried out using SolidWorks Flow Simulation under standard atmospheric air as the working fluid with a pressure of 101325 Pa and a temperature of 20 °C, which are taken as the reference environmental conditions. An inlet air velocity of 2 $m \cdot s^{-1}$ is assigned to represent moderate airflow in the air gap between the body and jacket model.

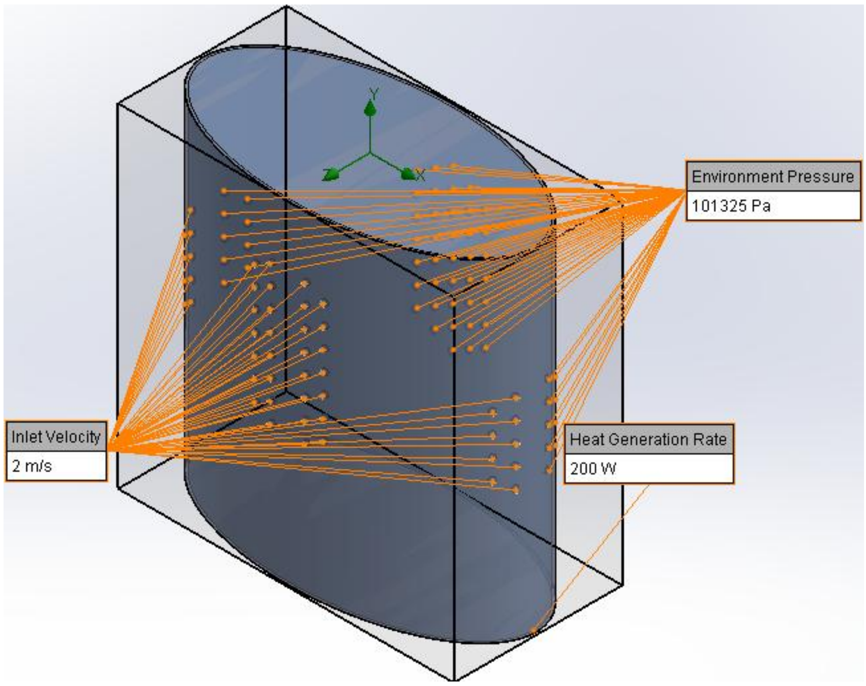


Fig. 3. **Computational domain and boundary conditions**

Different materials are assigned to the body and the jacket model in the simulation to represent realistic thermal behaviour. The thermal conductivity, density, and specific heat of these materials are defined according to the values listed in Table 1. The human body temperature is taken as 36.5 °C, which corresponds to normal physiological conditions. In addition, the metabolic heat generation of the body during normal walking activity is taken as 200 W [13, 14], and this heat is applied as a heat source inside the body model.

Table 1

Material properties [13; 15]

Material property	Human body	Jacket
Average density, $kg \cdot m^{-3}$	985	1420
Specific heat, $J \cdot kg^{-1} \cdot K^{-1}$	3500	1140
Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$	0.21	0.261

Assumptions considered in the simulation study

The following assumptions are made in order to simplify the computational model and to focus on the effect of ventilation positioning on the cooling performance of the protective clothing.

- The jacket is assumed to be air-tight at the top and bottom boundaries, meaning that no air flow is allowed to pass through these regions. This assumption is applied to ensure that the airflow occurs only through the designed ventilation openings, allowing a clear evaluation of the effectiveness of the ventilation holes.
- Thermal radiation is neglected in the present study. The heat loss due to radiation is assumed to be the same for all cases because the external conditions and surface properties remain

unchanged. Therefore, excluding radiation does not affect the comparative analysis of different ventilation positions.

- Heat transfer from the human body to the surrounding environment is assumed to occur only through conduction and convection.

These assumptions reduce the computational complexity while maintaining sufficient accuracy for comparing the thermal performance of different ventilation configurations.

Parameters analysed in the flow simulation study

The following parameters are obtained from the SolidWorks Flow Simulation results to evaluate the thermal and flow performance of the clothing model:

1. **H.T.R. – Heat Transfer Rate (W):** Represents the total rate of heat transferred from the (body-jacket) system to the surroundings.
2. **ΔH – Absolute Total Enthalpy Rate (W):** Indicates the total energy carried by the airflow, including internal energy and flow work, which reflects the overall energy exchange in the system.
3. **H.F. (avg.) – Average Surface Heat Flux (W·m^{-2}):** Shows the average rate of heat transfer per unit area on the surface of the body.
4. **dP – Flow Pressure Difference (Pa):** Represents the pressure loss between inlet and outlet regions, which indicates the resistance to airflow caused by the ventilation configuration.
5. **dT – Surface Temperature Difference (°C):** Denotes the temperature difference on the body surface, used to evaluate the effectiveness of cooling.

Results and discussion

The CFD simulation results obtained from SolidWorks Flow Simulation for the three ventilation configurations are presented in Fig. 4 and Table 2 below. The comparison of the results helps understand the influence of ventilation positioning on the airflow pattern, pressure loss, and heat transfer performance of the protective clothing model.

1. Pressure distribution and airflow behaviour

From the pressure plots and flow trajectories, it can be observed that the airflow enters the clothing region through the ventilation holes and circulates inside the air gap between the body and the jacket before exiting through the openings. In all three cases, the airflow pattern is mainly governed by forced convection due to the inlet velocity and natural convection due to buoyancy.

In **Case 1**, where the ventilation openings are located closer to the top (95 mm from the top), the airflow shows relatively smoother circulation with lower resistance. The pressure difference obtained is 211.82 Pa, which is the lowest among the three cases. This indicates that the airflow encounters less obstruction, allowing easier movement of air inside the clothing.

In **Case 2**, where the ventilation openings are positioned near the bottom (95 mm from the bottom), the airflow must travel upward against the clothing geometry before leaving the system. As a result, stronger recirculation zones are observed, and the pressure difference increases to 254.28 Pa. This indicates higher flow resistance and greater energy loss.

In **Case 3**, where the ventilation openings are located further from the top (145 mm from the top), the airflow path becomes longer compared to Case 1. The pressure difference further increases to 253.99 Pa, which is similar to Case 2, confirming that increasing the distance of the ventilation openings from the top increases flow losses.

2. Surface temperature distribution

The surface temperature contours show that the highest temperatures occur near the body surface, while lower temperatures are observed around the ventilation holes due to incoming cooler air.

In **Case 1**, the temperature reduction near the ventilation region is more noticeable, and the temperature difference is 13.24 °C, which is the highest among the three cases. This indicates better cooling performance.

In **Case 2**, the temperature difference decreases to 12.38 °C, which suggests reduced cooling efficiency. This occurs because the ventilation openings are placed near the bottom, and hot air tends to rise, making it more difficult for the warm air to escape effectively.

In **Case 3**, the temperature difference increases slightly to 13 °C, but it is still lower than Case 1. This shows that moving the ventilation openings away from the top reduces the effectiveness of heat removal.

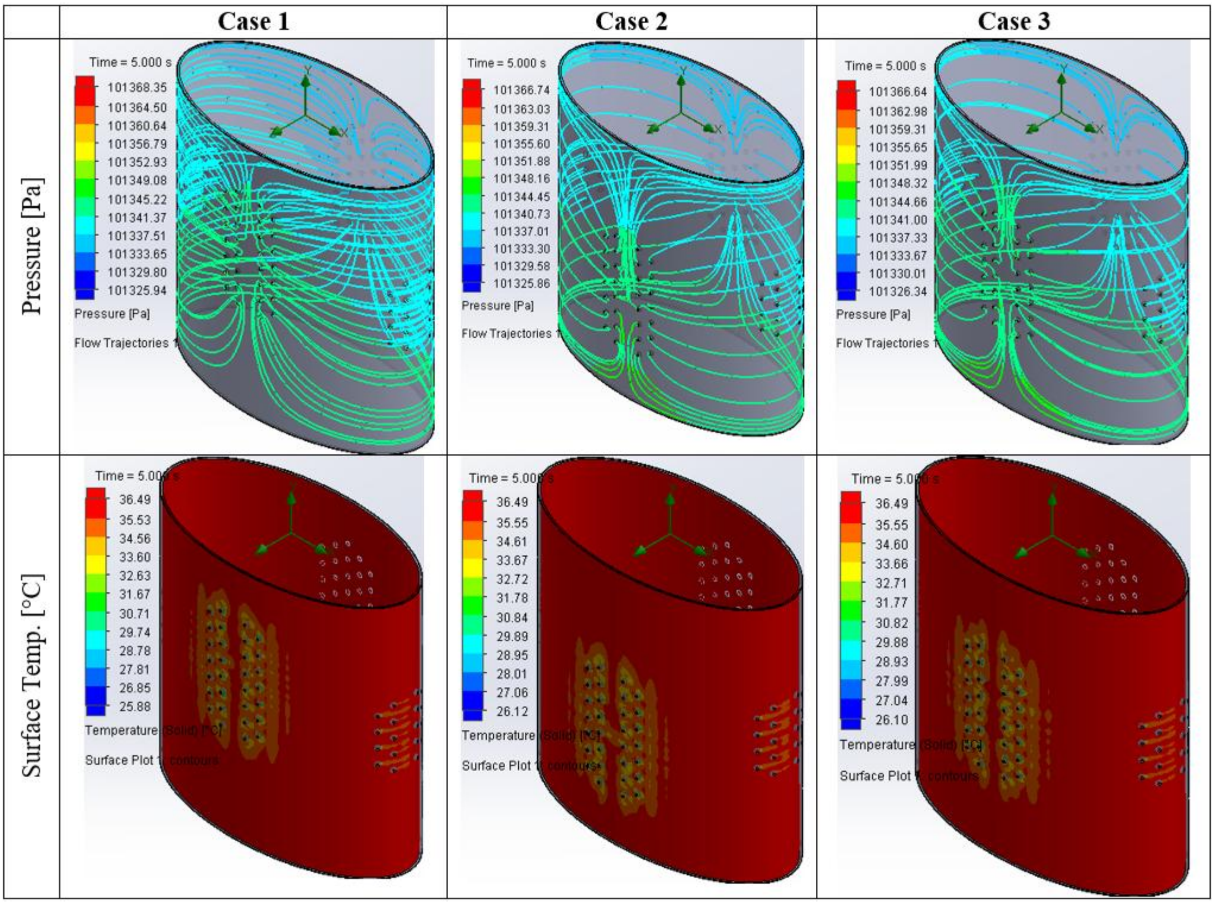


Fig. 4. **Flow pressure and surface temperature plots**

Table 2

Numerical values of studied parameters

Parameters	Case 1	Case 2	Case 3
H.T.R, W	37.889	37.613	37.918
ΔH, W	-37.951	-37.742	-38.053
dP, Pa	211.82	254.28	253.99
dT, °C	13.24	12.38	13.00
H.F. (avg.), W·m^{-2}	11.767	11.681	11.776

3. Heat transfer rate and heat flux

The values of total heat transfer rate (H.T.R.) for the three cases are close to each other, but a slight reduction is observed in Case 2, indicating that placing the ventilation openings near the bottom reduces the overall heat transfer capability.The variation in average surface heat flux is small, but Case 2 again shows the lowest value, confirming weaker cooling performance. The absolute total enthalpy rate (ΔH) also follows a similar trend, with Case 3 having the highest magnitude (-38.053 W), indicating slightly higher energy transfer due to increased airflow path.

4. Overall comparison of 3 cases

From both graphical results and numerical data, the following observations can be made.

- Increasing the distance of ventilation openings from the top increases pressure loss inside the clothing.
- Ventilation openings placed closer to the top provide better natural convection assistance, allowing hot air to escape more easily.
- Positioning the openings near the bottom reduces cooling efficiency because warm air accumulates near the upper region.
- The heat transfer rate changes only slightly, but the flow pressure difference and temperature difference clearly indicate the effect of ventilation positioning.

Design implications for protective clothing

Based on the CFD analysis, the following design guidelines can be proposed for ventilated protective garments.

- Ventilation openings should be positioned near the upper region of the garment to enhance natural convection-driven heat removal.
- Avoid placing ventilation openings exclusively near the lower region, as this leads to heat accumulation in the upper zone.
- Maintain a balanced distribution of openings to reduce pressure losses and improve airflow uniformity.
- Minimize airflow resistance by ensuring shorter flow paths between inlet and outlet regions.
- Consider combining forced airflow with buoyancy effects in ventilation design for optimal performance.

These guidelines can assist designers in improving thermal comfort and reducing heat stress in real-world applications.

Limitations and future work

The present study is based on numerical simulations and has not been experimentally validated. While CFD provides reliable insight into airflow and heat transfer behaviour, future work should include experimental testing using thermal manikins or wearable sensor systems to validate the numerical findings. Additionally, real fabric permeability, sweating effects, and transient environmental conditions should be considered for more comprehensive analysis.

Conclusions

Among the three configurations analyzed, Case 1 (95 mm from the top) demonstrates the best overall performance. It yields the lowest pressure difference (211.82 Pa) and the highest surface temperature difference (13.24 °C), indicating more efficient heat removal. In comparison, Cases 2 and 3 exhibit significantly higher pressure losses (254.28 Pa and 253.99 Pa) and lower cooling effectiveness. Although the heat transfer rate varies only slightly (≈37.6-37.9 W), the differences in pressure loss and temperature distribution clearly demonstrate the impact of ventilation positioning. The results confirm that locating ventilation openings closer to the top enhances airflow circulation and supports natural convection, thereby improving cooling efficiency.

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Author contributions

Conceptualization, S.R.V. and A.J.; methodology, S.R.V. and A.J.; software, S.R.V.; validation, S.R.V. and A.J; formal analysis, S.R.V.; investigation, S.R.V.; data curation, S.R.V.; writing – original draft preparation, S.R.V.; writing – review and editing, S.R.V. and A.J.; visualization, S.R.V. and A.J.;

project administration, S.R.V.; funding acquisition, S.R.V. All authors have read and agreed to the published version of the manuscript.

References

[1] Krzemińska S.M., Szewczyńska M. Hazard of Chemical Substances Contamination of Protective Clothing for Firefighters – A Survey on Use and Maintenance. Int J Occup Med Environ Health. March 1, 35(2), 2022, pp. 235-248. DOI: 10.13075/ijomeh.1896.01868

[2] Alvarado-Ibarra J. , Burrola-Núñez H. 23 - Protective clothing for civilian and specialist industrial workers. Protective Textiles from Natural Resources. The Textile Institute Book Series; 2022, pp. 751-770. DOI: 10.1016/B978-0-323-90477-3.00024-9

[3] R. Li, Islam Md R., Xia Y., Huang J., Gholamreza F. , Dolez P. I. , Lai A. , Gathercole R. , Li R. Heat and moisture transfer through skin-clothing microclimate. International Journal of Heat and Mass Transfer. Volume 231, October 2024, 125867. DOI: 10.1016/j.ijheatmasstransfer.2024.125867

[4] Cheveldayoff P., Chowdhury F., Shah N., Burow C., Figueiredo M., Nguyen N., et al. Considerations for occupational heat exposure: A scoping review. PLOS Clim 2(9), 2023, e0000202. DOI: 10.1371/journal.pclm.0000202

[5] Sanchaniya J. V, Smogor H., Gobins V., Noël V., Lasenko I., Rackauskas S. Layer-by-Layer Integration of Electrospun Nanofibers in FDM 3D Printing for Hierarchical Composite Fabrication, Polymers (Basel)., vol. 18, no. 1, 2026. DOI: 10.3390/polym18010078

[6] Song G. Improving Comfort in Clothing. Woodhead Publishing Series in Textiles: Number 106. Woodhead Publishing limited (2011).

[7] Choudhary B., Raj. U. Local and overall convective heat transfer coefficients for human body with air ventilation clothing: Parametric study and correlations. Building and Environment. Volume 229, 1 February 2023, 109953. DOI: 10.1016/j.buildenv.2022.109953

[8] Yang J., Wang F., Song G., Li R., Raj U. Effects of clothing size and air ventilation rate on cooling performance of air ventilation clothing in a warm condition. International Journal of Occupational Safety and Ergonomics. Volume 28, 2022 - Issue 1. 02 July, 2020. pp. 354-363. DOI: 10.1080/10803548.2020.1762316

[9] Vejanand S. R., Janushevskis A., Vaicis I. Selection of Appropriate Estimation Criteria in Flow Simulation Study for Predicting Cooling Efficiency of Ventilated Protective Clothing. Latvian Journal of Physics and Technical Sciences. Volume 62: Issue 2 (April 2025). DOI: DOI: 10.2478/lpts-2025-0010

[10] Ferraro S. D., Falcone Ti. , Morabito M. , Messeri A. , Bonafede M. , et al. Cooling garments against environmental heat conditions in occupational fields: measurements of the effect of a ventilation jacket on the total thermal insulation. International Journal of Industrial Ergonomics. Volume 86, November 2021, 103230. DOI: 10.1016/j.ergon.2021.103230

[11] Sanchaniya J. V, Kannathasan K. R., Vejanand S. R., Joshi J., Lasenko I. Effect of Infill Pattern Design on Tensile Strength of Fused Deposition Modelled Specimens, Environment Technology Resources - Proceedings of the 16th International Scientific and Practical Conference, 2025, vol. 4, pp. 375–382. DOI: DOI: 10.17770/etr2025vol4.8409

[12] Vejanand S. R., Janushevskis A., Vaicis I. Selection of Appropriate Criteria for Optimization of Ventilation Element for Protective Clothing Using a Numerical Approach. Computation 2024, 12, 90. DOI: 10.3390/computation12050090

[13] Vejanand S. R., Janushevskis A., Vaicis I. Analyzing the Efficiency of Ventilation Elements Used in Protective Clothing with Simplified Model. 23rd International Scientific Conference "Engineering for Rural Development", Jelgava, 2024. DOI: 10.22616/ERDev.2024.23.TF036

[14] Kumar R., Aggarwal R. K., Sharma J. D., Pathania S. Predicting Energy Requirement for Cooling the Building Using Artificial Neural Network. Journal of Technology Innovations in Renewable Energy, 1(2), 2013, pp. 113-121. DOI: 10.6000/1929-6002.2012.01.02.6

[15] Giering K., Lamprecht I., Minet O. Specific heat capacities of human and animal tissues. Proceedings of SPIE – The International Society for Optical Engineering, January 1996, 2624, pp. 188-197.