

SELECTION OF APPROPRIATE ESTIMATION CRITERIA IN FLOW SIMULATION STUDY FOR PREDICTING COOLING EFFICIENCY OF VENTILATED PROTECTIVE CLOTHING

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A Computational Fluid Dynamics (CFD) is utilised in various research and engineering areas across multiple fields and industries. The research field of ventilation and indoor air science has experienced a significant surge in scientific articles focused on the utilisation of CFD. With the solution of increasingly complicated ventilation problems, CFD validation and verification are more important than ever. The present study focuses on the crucial task of selecting suitable criteria in a flow simulation analysis aimed at predicting the cooling efficiency of ventilated protective clothing. This study examines three different cases of a simplified elliptical model of the human body with a protective jacket comprising 11, 48, and 105 ventilation elements. SolidWorks Flow Simulation is used to simulate all three models individually to calculate values of eight different criteria. It is assumed that increasing the number of ventilation units would result in an enhancement of cooling efficiency. However, it is crucial to understand how the values of various criteria change in flow simulation studies under different situations, and which criteria are crucial for the analysis. The criteria values for three cases are recorded and compared. The analysis results indicate a gradual increase in values of heat transfer rate, pressure and temperature differences as the number of ventilation units increases. However, certain parameter values like flow pressure difference do not provide sufficient information to predict efficiency of the system, whereas a parameter like average temperature shows low sensitivity. The study suggests that the heat transfer rate and heat flux are the most appropriate criterion to be examined in such a situation. This is due to the fact that an increased heat transfer rate from the body signifies a more effective cooling mechanism.

Keywords: *CFD, heat transfer, protective jacket, SolidWorks flow simulation, ventilation.*

1. INTRODUCTION

The efficient design and management of ventilation systems are crucial for maintaining indoor air quality and improving building energy efficiency [1]. The characteristics of the airflow within a building have a significant impact on the effectiveness of ventilation systems in removing pollutants from that space [2]. The same is true for ventilated protective clothing. Computational Fluid Dynamics (CFD) has been extensively utilised for the design and implementation of building ventilation systems. This approach is also increasingly being adopted in other areas of fluid dynamics research, such as the ventilation of protective clothing [3]. To design systems involving fluid flows, CFD simulations are frequently used as the base. Recent developments in CFD have enabled the creation of precise engineering models that capture the irregular shape of a clothed human body, as well as the significant variations in length and time scales that are typically encountered in computational simulations. These variations include thin layers of clothing covering a relatively large human body and irregular air spaces. Body-fitted coordinates or unstructured grids are employed to simulate intricate structures, such as a clothed human arm covered by a permeable layer of clothes, or simpler geometries like a cylinder covered with fabric [4]. This enhanced functionality can assist researchers in designing protective equipment that is both more comfortable and more effective.

In order to ensure human thermal comfort, it is necessary to maintain a heat balance between the human body and the surrounding environment. This involves regulating the heat generated within the body and the heat transferred to or from the body. The heat dissipation/gain process is influenced

by multiple factors, and it involves different types of heat transport, such as conduction, convection, radiation, and evaporation. When the body absorbs more heat than it can release, it leads to thermal discomfort as the body's core temperature and heat storage grow. Normally, the body's core temperature is around 36.5 °C (+ or - 1 °C) in thermal comfort conditions. Experiencing an excessive increase in body heat may cause a serious threat to one's health and lead to heat stress. In order to alleviate heat stress or attain thermal comfort in such circumstances, it is imperative to implement efficient cooling methods [5]. Utilising personal cooling systems to provide individualised cooling can be an effective method to reduce heat stress or achieve thermal comfort in situations when implementing widespread air conditioning is not possible [6]. Personal cooling systems (PCS) are specifically developed to reduce the risks posed by elevated core body temperatures, while also enhancing the overall job performance of individuals. Various personal cooling systems are available, such as a cooling chair [7], wrist-band devices [8], radiant cooling desk [9], desk fan [10], and personal cooling clothing [11]–[14], and so on. Clothing creates its own atmosphere and is our most personal space, according to Watkins [15].

Computational Fluid Dynamics (CFD) is utilised to analyse the air exchange rates and forecast thermal comfort resulting from fluctuations in air flow. CFD allows us to adequately measure the heat and mass transfer, as well as analyse the airflow pattern within the garment system. The variation in thermal comfort is dependent on the quantity and arrangement of ventilation. Despite being constructed of the same material, the thickness and structure

of the air layer in a garment can vary significantly based on factors such as design, construction, easiness, openness, and slits. As a result, the ventilation impact will also differ significantly. Through the utilisation of CFD, we may include the air layer, openness, and slit as factors and forecast the thermal comfort sensation by establishing a correlation between results and human subject tests [16].

The current research concentrates on the important challenge of selecting appropriate criteria for a flow simulation analysis that is intended to predict the cooling performance of ventilated protective garments. In this study, three distinct cases of a simplified elliptical model of the human body with a protective jacket are investigated. The simplified elliptical model of the body and jacket is selected to reduce the com-

plexity of the problem. The first model consists of eleven ventilation holes where there is a single inlet at the front and 10 outlets at the backside of the jacket. The second model is with 48 ventilation holes, having 24 inlets & 24 outlets, and the third model is with 105 ventilation holes, where there are 48 inlets and 57 outlets. For calculating the values of eight different criteria, Solid-Works Flow Simulation is utilised to simulate each of the three models individually. One can logically hypothesise that increasing the number of ventilation units will result in enhanced efficiency of the cooling. However, it is crucial to fully understand how the values of different parameters in flow simulation studies vary based on specific circumstances, and which parameter is the most appropriate to select in order to achieve a logical conclusion.

2. MODEL DESIGN AND BOUNDARY CONDITIONS

The model design with three distinct cases is depicted in Figs. 1–3, respectively. To reduce the complexity of the problem in this study, we have designed and assembled simple elliptical models of the body and jacket. The body remains centred, and the jacket is positioned over it. The ventilation hole diameter of 4.4 mm is used in all three cases, and toroidal cut out shaped ventilation element [17] is positioned to all the ventilation holes. The ventilation element is positioned at the ventilation hole in a concentric manner, with the front face of the element precisely aligned with the hole. The schematic diagram of ventilation element and its position to ventilation hole is shown in Fig. 4. The ventilation elements are positioned at the internal part of the jacket in the air gap between the body and jacket. This uniform air gap of 3.4 mm is shown in Figs. 1 and 2, with Detail View D. The air gap

remains the same in all three cases stated in this study. All the dimensions presented in Figs. 1–4 are in millimetres.

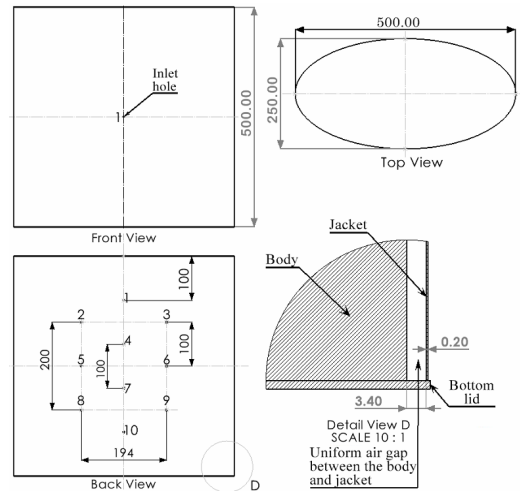


Fig. 1. Case 1: Model design with 11 ventilation holes [3].

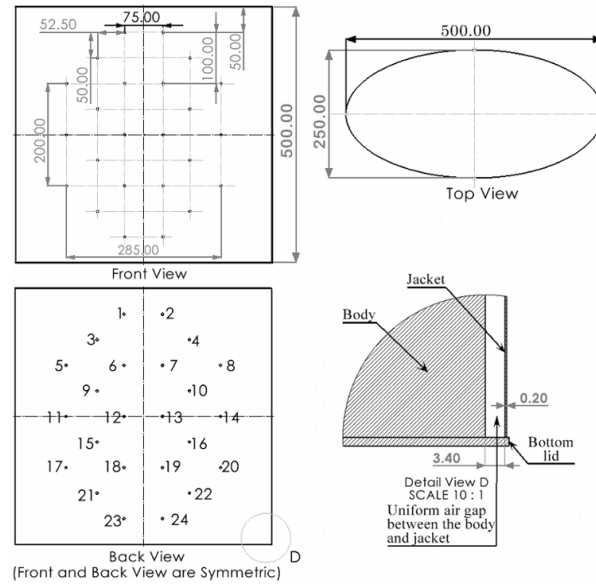


Fig. 2. Case 2: Model design with 48 ventilation holes.

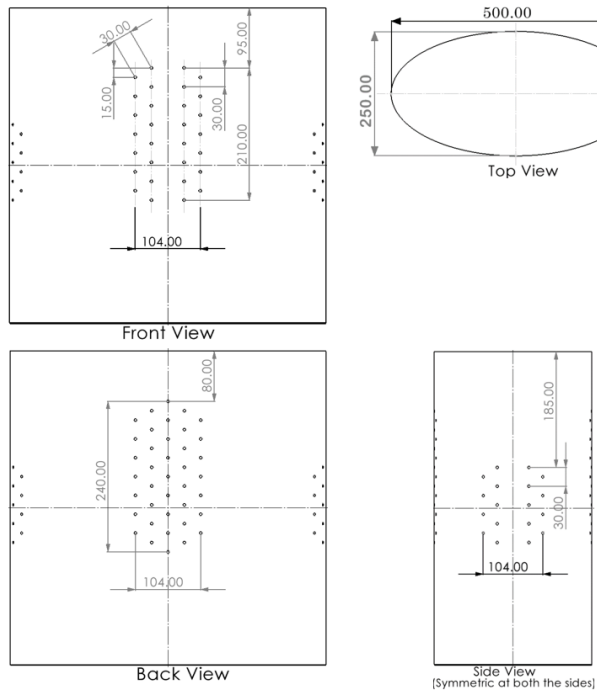


Fig. 3. Case 3: Model design with 105 ventilation holes.

For Cases 1 and 2, the model does not have any ventilation holes on the sides. However, in Case 3, there are a total of 18

ventilation holes on each side, as depicted in Fig. 3. The first 9 ventilations on each side are assigned as inlet boundary con-

ditions, while the remaining 9 on each side are designated as outlet boundary conditions. These nine elements on each side

are also visible in the front and back views of Fig. 3.

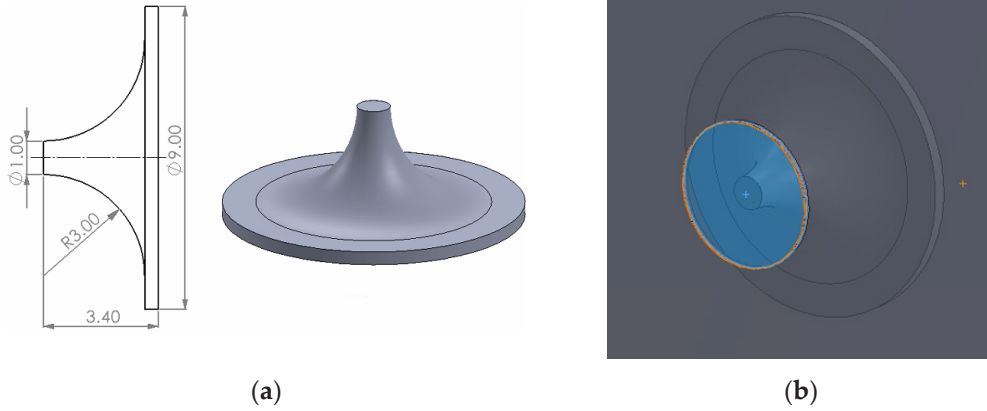


Fig. 4. Ventilation element: (a) geometric dimensions of element; (b) position of ventilation element (highlighted orange circle shows ventilation hole).

The results are calculated using SolidWorks internal flow simulation tool. This study is transient, and the results are calculated for the physical time of 5 seconds. The flow simulation study uses standard settings, with an initial air temperature of 20 °C and an air pressure of 101325 Pa. The experiments are performed with an air velocity of 4 m/s, which is established as the inlet boundary condition. The airflow is perpendicular to the front surface of the model. The outlets located on the backside of the jacket are assigned to environmental

pressure condition, which are designated as outlet boundary conditions. The average normal human body temperature is taken as 36.5 °C, while the amount of heat generated by the body during regular walking is considered to be 200 W [18], which is assigned to the body. Figure 5 shows the computational domain of the model, with the specified boundary conditions. In the simulation study, different materials with distinct properties are assigned to both the jacket and the body. Table 1 displays the material properties.

Table 1. Material Properties [19], [20]

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

Assumptions considered in the simulation study are as follows:

- jacket is considered as air-tight, meaning that no air passes through the top and bottom parts;
- study does not take radiation into consideration, as the amount of heat lost

through radiation will be equal in all circumstances;

- thermal energy transfers via conduction and convection from the body to jacket and then to the surrounding environment.

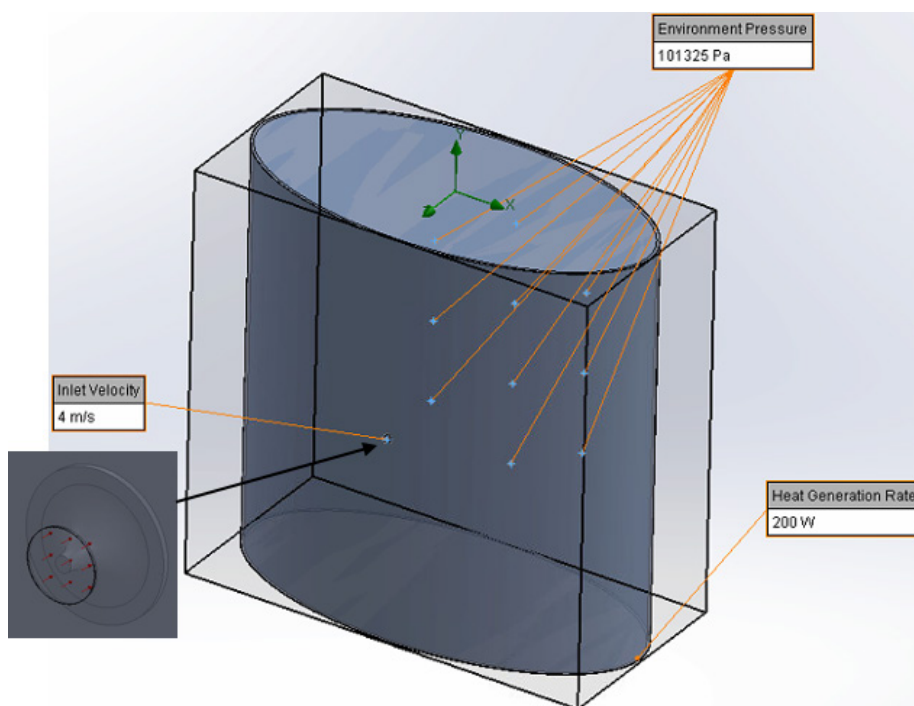


Fig. 5. Computational domain and boundary conditions in Case 1.

Figure 5 shows computational domain with set boundary conditions in Case 1. Inlet air of 4 m/s is visible at the front side, which enters into the air gap between the body and jacket and moves out through backside ventilations, which are assigned to environmental pressure. The heat generation rate of the body is set to 200 W. The same boundary conditions are assigned to model in Cases 2 and 3, the only difference is the numbers of inlet and outlet ventila-

tion holes in each case. In this study basic mesh of size ($N_x = 36$, $N_y = 36$, $N_z = 18$) is utilised for the numerical simulation, as using fine mesh highly increases computational time. However, in this particular study, using fine mesh will not significantly impact the final outcome of finding appropriate criteria for cooling efficiency of protective clothing, as this study represents comparison of different criteria, using the same set of values in all three cases.

3. RESULTS AND DISCUSSION

The flow simulation study is set in SolidWorks for 5 seconds of physical time to obtain values of eight criteria mentioned in Table 2 below. Figure 6 shows the flow pressure and surface temperature plots for all three cases. The given pressure difference is measured in the air gap between the

body and jacket. Air enters into this air gap through front inlet ventilations and moves out through outlet ventilations at the backside of jacket. The detail values of all the criteria obtained from the simulation studies are mentioned in Table 2.

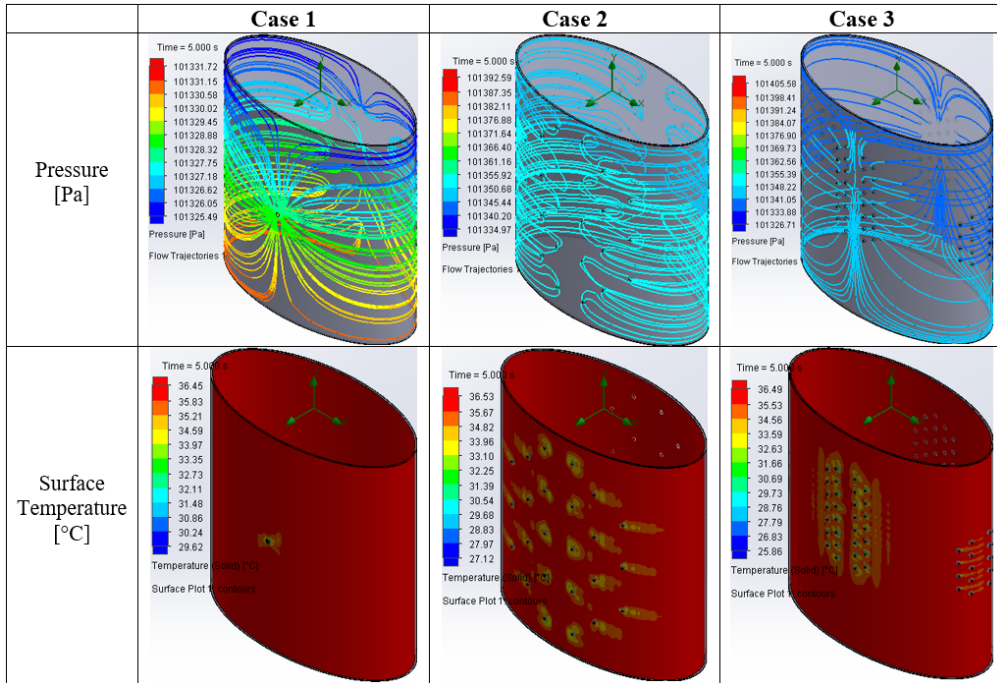


Fig. 6. Flow pressure and surface temperature plots in each case.

The surface temperature is determined by selecting surface of the body to observe how ventilation affects the temperature of body surface. The impact of ventilations on the surface body temperature for all three

scenarios is shown in Fig. 6. The relative values of ΔP and ΔT are calculated based on the acquired results. The detail values of these parameters are provided in Table 2.

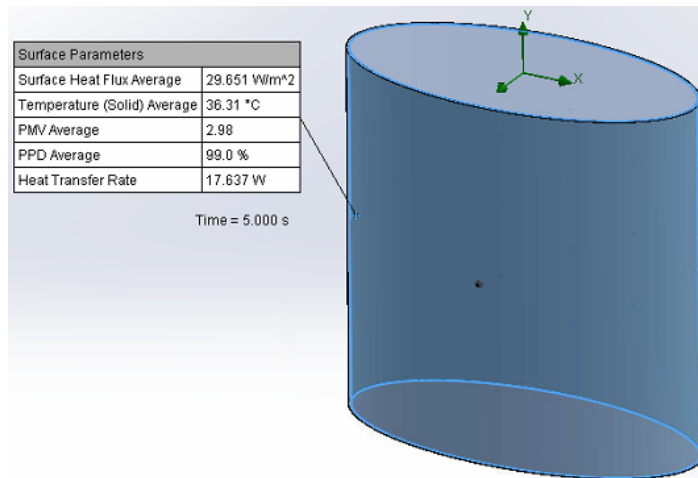


Fig. 7. Numerical values of criteria: HTR, HF, T (avg.), PMV and PPD in Case 1.

The values of the remaining criteria can be obtained using the surface parameter tool,

which is available in the results section of SolidWorks flow simulation, as depicted in

Fig. 7. All these values are acquired in relation to surface of the body, except the criterion ΔH , which represents the heat transfer through ventilation holes rather than the body surface. This difference sets apart the HTR from ΔH . Thermal comfort in individuals can be assessed using the PMV and PPD. The PMV is a scale used to evaluate

the thermal comfort experienced by individuals, indicating their perception of cold or warm temperatures. The 7-point thermal sensation scale used ranges from +3 (indicating hot) to -3 (indicating cold), with 0 representing a neutral temperature. The obtained specific values of these criteria for all three cases are indicated in Table 2.

Table 2. Numerical Values of the Analysed Criteria

Criteria	Case 1	Case 2	Case 3
HTR [W]	17.637	32.288	43.714
ΔH [W]	-1.021	-23.490	-43.140
HF (avg.) [W/m ²]	29.651	54.284	73.491
ΔP [Pa]	6.23	57.62	78.87
ΔT [°C]	6.83	9.41	10.63
T (avg.) [°C]	36.31	36.15	36.03
PMV (avg.)	2.98	2.95	2.93
PPD (avg.) [%]	99	98.8	98.5

From the examination of the results presented in Table 2, it is noticeable that all the criteria values show a gradual rise as the number of ventilations increases, with the exception of T (avg.), PMV, and PPD, which display an inverse trend. Moreover, these three criteria exhibit the least amount of variation when comparing the values of all three cases,

as it can be noted from Table 2. This makes PVM, PPD, and T (avg.) less effective to accurately anticipate the system's efficiency, since the sensitivity of their values may further decrease when comparing two systems with a small number of ventilation difference. The comparison of results for other criteria in all three cases is illustrated in Figs. 8–12.

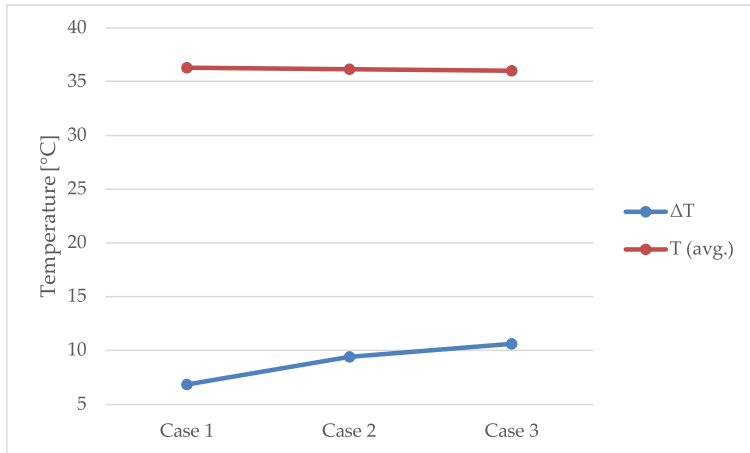


Fig. 8. Surface temperature of body in three cases.

The value of average temperature decreases with the increase in number of

ventilations, which makes sense as with higher number of ventilation more heat can

transfer from the body that lowers body temperature. Moreover, with higher temperature difference, the value of average temperature decreases as the heat transfer rate increases with higher temperature difference. Though the sensitivity of average

temperature obtained is very low as there is very small difference in the values, which may not be very useful in the analysis when there is a small difference in the number of ventilations. The same is true for PMV and PPD.

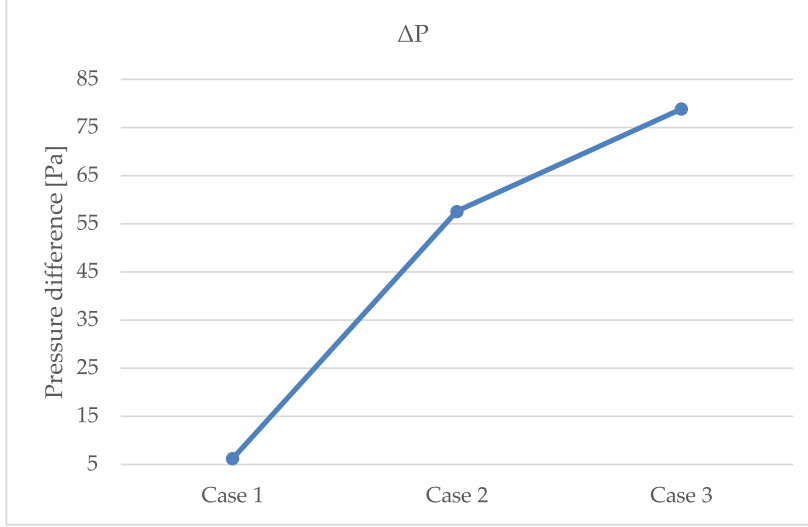


Fig. 9. Flow pressure in gap between the body and jacket in three cases.

Figure 9 shows that the pressure difference rises as the number of ventilations increases, and this provides a noticeable change in the values for three cases. While considering the pressure plots in Fig. 6, it does not offer significant insights into the cooling efficiency because the majority of pressure fluctuations occur at the ventilation openings in a very small area, particularly for Cases 2 and 3. Figure 10 (a) clearly illustrates that the maximum pressure, indicated by the red line, act in a very tiny region near the inlet, which may have a negligible effect or can be neglected. Moreover, the pressure difference values provided here are expressed in Pa, and according to the unit the difference between the measured values in all three cases are small to make any definitive conclusions on the cooling efficiency of the model based on these values. The same can also apply to tem-

perature differences, where lower temperature occurs in a very small region that can be considered unimportant to provide any precise conclusion. This region is depicted by the dark blue colour in Fig. 10 (b). Consequently, relying on this small region may not yield an accurate measurement of the temperature difference, which may lead to incorrect conclusions.

In general, an increased temperature difference leads to higher heat transfer rate, which in turn enhances the efficacy of cooling. However, there are specific circumstances (such as discussed above) in which the region with the lowest temperature is negligible and thus cannot be regarded significant. Hence, it is critical to consider additional appropriate criteria in such circumstances to ensure the reliability of the results before making a final conclusion.

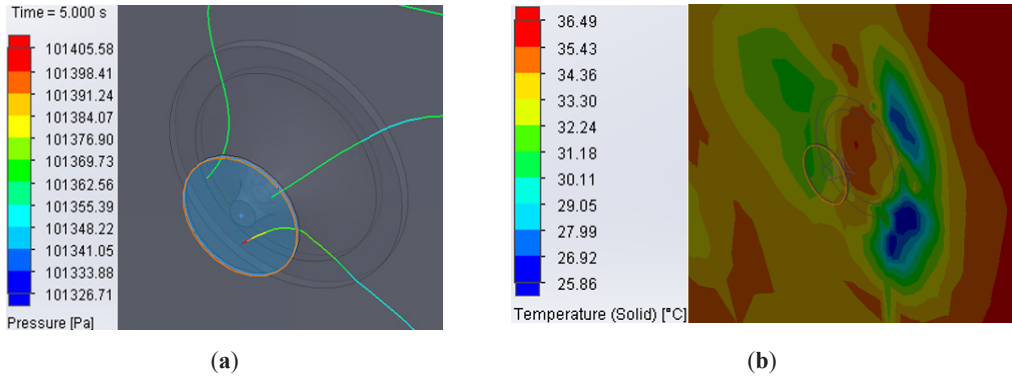


Fig. 10. Pressure and surface temperature variation near ventilation hole:
 (a) Flow pressure variation; (b) Surface temperature variation near ventilation hole.

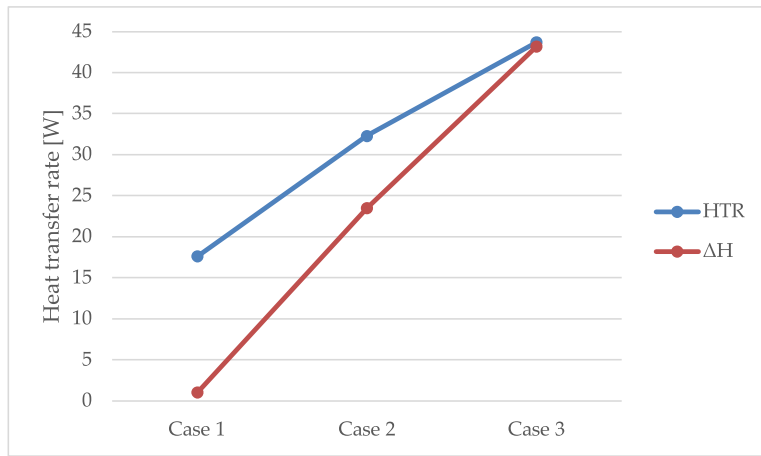


Fig. 11. Heat transfer rate in three cases.

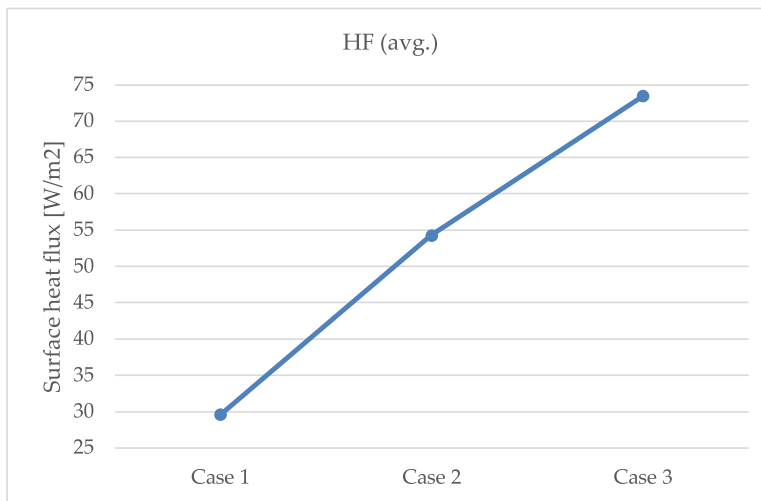


Fig. 12. Average surface heat flux of body in three cases.

The values of HTR, ΔH , and HF increase as the number of ventilation units increases. These values provide sufficient sensitivity for the analyses. However, ΔH only takes into account the area of heat transfer through ventilation holes and not the entire body surface. Thus, ΔH may not be the most suitable criterion compared to HTR and HF, which consider the overall

heat transfer of the entire body surface. The main difference between HF and HTR is that HF provides surface heat flux per meter square area, whereas HTR provides the overall heat transfer rate of the body surface. Both of these criteria are very useful for predicting the cooling efficiency of the system and can be utilised based on specific requirements.

4. CONCLUSIONS

Based on the result analysis, it can be concluded that HTR (heat transfer rate) and HF (heat flux) are the most appropriate criteria for analysing the heat removal from the ventilated system (body with ventilated jacket) in the study. Since the goal is to predict cooling efficiency, either of the criteria can be helpful because cooling efficiency increases with an increase in heat transfer rate. While temperature difference can be following criteria for the analysis but in certain cases it might not provide enough sensitivity for the analyses, which is why it is better to use it in combination with other relevant criteria such as HTR or HF in this case to ensure the reliability of the results.

This study demonstrates variations in parameter values in CFD simulations in three different cases and identifies criteria that are helpful for forecasting cooling efficiency in the analysis. It is evident that certain criteria, such as flow pressure, may not be very useful in predicting cooling efficiency of the system. Moreover, parameters like average temperature, PMV and PPD can show less sensitivity in certain scenarios. In the future, it allows for the formulation of more realistic and complex CFD problems for ventilated protective clothing, taking into consideration uncertainty introduced, for instance, by varying wind direction and ventilation positions.

AUTHORS' CONTRIBUTIONS

Conceptualisation, S.R.V. and A.J.; methodology, S.R.V. and A.J.; software, S.R.V.; validation, I.V., and S.R.V.; 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, I.V., S.R.V., A.J and I.V.; visualization, S.R.V. and I.V.; project administration, S.R.V.; funding acquisition, S.R.V., A.J., and I.V. All authors have read and agreed to the published version of the manuscript.

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NOMENCLATURE

1. HTR – Heat Transfer Rate of the body [W].
2. ΔH – Absolute Total Enthalpy Rate [W].
3. HF (avg.) – Surface Heat Flux of the body (average) [W/m²].
4. ΔP – Flow Pressure Difference [Pa].
5. ΔT – Surface Temperature Difference of the body [°C].
6. T (avg.) – Average Surface Temperature of the body [°C].
7. PMV (avg.) – Predicted Mean Vote (average).
8. PPD (avg.) – Predicted Percentage Dissatisfied (average) [%].

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