COMPARATIVE ANALYSIS OF DIFFERENT SHAPE VENTILATION ELEMENTS FOR PROTECTIVE CLOTHING

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Abstract. The rise in average temperatures caused by climate change in recent decades has contributed to an even greater need for increased outdoor cooling of the human body, even in the temperate climate zone. In this paper three different ventilation element types E1, E2 and E3 are designed to study the effectivity of ventilation at two different wind inlet velocities. These ventilation elements have different geometric dimensions, the main difference is in the dimensions of the outlet of the element from where the inlet air moves to the system and the height of the element. The aim is to see which geometrical shape of the element causes the smallest flow energy losses in the cell flow channel from the inlet to outlet, characterized by the pressure difference (ΔP). The higher ΔP, the higher flow energy losses. If the flow has lost energy (weakened), the body cooling decreases. SolidWorks Flow Simulation is used to calculate the pressure, temperature, and heat flux for the simplified elliptical model of the human body with a protective jacket. The obtained results are compared and analysed to propose the optimum geometric shape of the ventilation element. The pressure and temperature difference for each ventilation element are calculated for the comparison and the obtained results show that element E1 provides lower pressure difference than E3, while E2 gives the lowest pressure difference than both E1 and E3. The results also depict that the element E3 provides less temperature difference than E1 and E2, while in terms of heat transfer all three-ventilation elements show quite close results, since there is a unit ventilation system in the study.

Keywords: flow simulation, ventilation element, protective jacket, heat transfer.

Introduction

Increased ambient temperatures and/or physical exertion cause the human body to release a significant amount of heat, which needs to be removed from the body to prevent health-threatening overheating [1]. When the body temperature rises to a certain level, sweating starts, which is the most effective mechanism of the body’s natural thermoregulation [2], as the heat released by the body is absorbed (used) by evaporation of the liquid. The evaporative intensity depends on the movement of air (circulation) and the relative humidity of the air at the surface of the body. Moist air or even saturated vapour should be removed from the body to improve evaporation of sweat in the interlayer of air between the body and clothing [3]. Various venting solutions are known in clothing [4], such as different vents, the use of mesh fabric in different parts of clothing and others, but they do not fully provide effective air exchange and at the same time protection against different conditions of the external environment. For example, the mesh fabric provides good body ventilation and cooling but does not protect against sun radiation, insect access and other mechanical effects, which can be particularly important for different garments in hot climates. Breathable fabrics commonly used provide sufficient vapour permeability but often insufficient body ventilation and mechanical protection, for example, against some insect species, mainly mosquitoes, which are carriers of many dangerous diseases (e.g., malaria). On the other hand, the risk of overheating is significantly increased by wearing clothing made of dense fabrics that provide reliable protection against insects. Air permeability and mechanical protection are essentially inverse requirements. The main aim is to develop composite materials for use in protective clothing [5] that provide mechanical protection to the body and improve air circulation between the body and the clothing [6].

By combining the indispensable properties of fabric (e.g., elasticity, optimum weight to strength ratio) [7] with the properties of polymer materials, the weight of the protective clothing is not significantly increased, and the necessary ergonomic properties and visual appearance are maintained. Protective clothing is especially intended for use in warm and hot climatic conditions in travelling, expeditions, hunting, fishing, forestry, agriculture, military and other areas, where maximum body ventilation and cooling is required. In order to protect a human body against exposure to external environmental conditions such as rain, dust, direct sun radiation, insect access and their bites, the outer layer of clothing may have insufficient air permeability, resulting in the accumulation of warm and wet air at the body, causing discomfort or even risk of overheating. Various closable vents and open parts of clothing have been created to improve the air exchange [8].

However, in this way, air exchange is only partially improved, and the problem is not fully resolved. The main advantage of the developed approach is effective protection of human body against the effects of various external environmental conditions, ensuring the required air circulation and under clothing ventilation, thereby reducing the risk of overheating of the body [9]. To achieve the goal, a complex task, such as form optimization of the ventilation elements, is performed. A set of technical and functional characteristics of material gives a significant competitive advantage over the available air-permeable materials on the market for use in the outer layer of ventilating protective clothing. Due to the increasing interest in the market for effective protection of human body against exposure to external environment, there is a need for more efficient technical solutions and materials to be used in the outer layer of protective clothing, while also ensuring the necessary ventilation even in warm climatic conditions and during physical load.

Model components and boundary conditions

To reduce the complexity of the problem in this study, simple elliptical shape models of the jacket and body are designed and assembled so that the body remains in the center and the jacket over it with a uniform gap of 2.2 mm in between. The schematic drawing of the model is shown in the Fig. 1. There are four inlet ventilation holes of 2 mm diameter in the front side comprising in a single ventilation element and ten outlet holes of 4 mm diameter at the back side of the jacket.

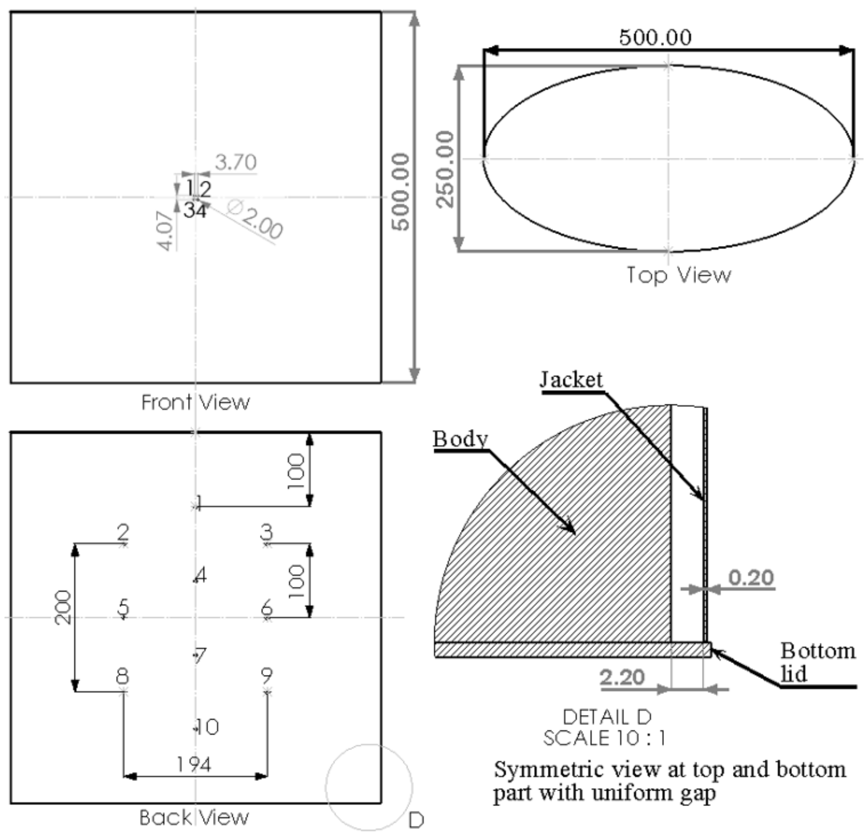
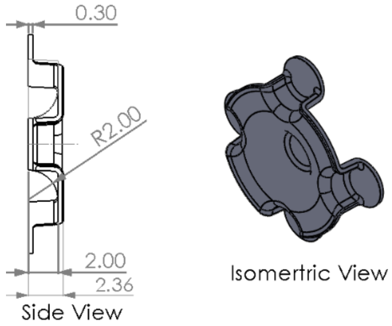
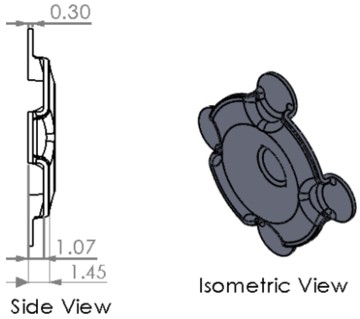


Fig. 1. **Elliptical model design**

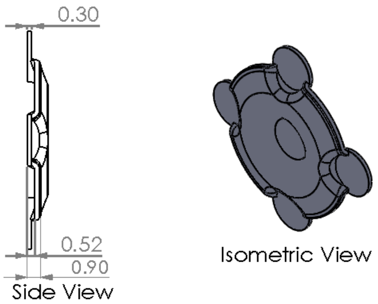
Three different designs of the ventilation element are used in the study which can be seen in the Fig. 2a, 2b and 2c. The shapes of the element are similar with different geometric dimensions to study the optimum geometric shape of the ventilation element. A single ventilation element is comprising of four inlet ventilation holes forming a unit ventilation system. Fig. 2d shows the position of the ventilation element with respect to the ventilation holes. The element is attached at the inner side of the jacket. The initial air temperature of 20 °C and environmental pressure of 101325 Pa are taken as standard values in the internal flow simulation study. The study is made at two different inlet air velocities of 2 and 5 $m \cdot s^{-1}$. Different materials with specific material properties are assigned to the jacket and body at the initial stage of simulation which are mentioned in Table 1. The average human body temperature is taken as 36.5 °C and the heat generation rate of the body (normal walking condition) as 200 W [10].



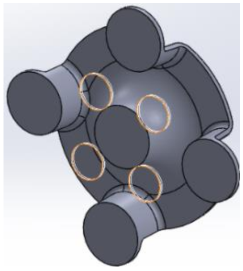
2a. E1



2b. E2



2c. E3



2d. Position of the ventilation element

Fig. 2. **Design of ventilation elements**

Table 1

Material Properties [11; 12]

Material property	Human body	Jacket
Average density, kg·m^{-3}	985	1420
Specific heat, J·kg^{-1} K^{-1}	3600	1140
Thermal conductivity, W·m^{-1}·K^{-1}	0.21	0.261

Assumptions/consideration taken in the Flow Simulation

- The top and bottom part of the jacket are closed to study the effectiveness of the ventilation.
- The top and bottom part in simulation is assigned as the outer wall which have outer environmental effects.
- Radiation is not considered as the heat loss by radiation will be the same in all cases.
- Heat transfer through conduction and convection from the body to the jacket and to outer environment.

Results and discussion

The same initial parameters are set in the SolidWorks Flow Simulation for all three elements and results are obtained for the physical time of 5 seconds. This is a transient process and specifying higher physical time for the study will take higher computational time to complete the solution, again the difference in the results of the elements will remain the same at any specific time. Hence, smaller physical time is selected for the study and results are obtained in form of pressure, surface temperature (body) and heat flux.

In Fig. 3, the first raw pictures show axonometric view of the pressure distribution over the complete model with the same color scale for all columns, while the second and third raw pictures are the zoom view near the ventilation hole to visualize how the ventilation elements affect the flow path and pressure distribution at different velocities. Here, equal scale is taken for all the plots to compare the pressure distribution in each case, and respective values of the obtained pressure are given in Table 2. It is observed from the pressure plots that element E2 shows the lowest energy losses than E1 and E3 specifically at a higher velocity of 5 m·s^{-1}. This means that element E2 may provide better cooling with less pressure variations.

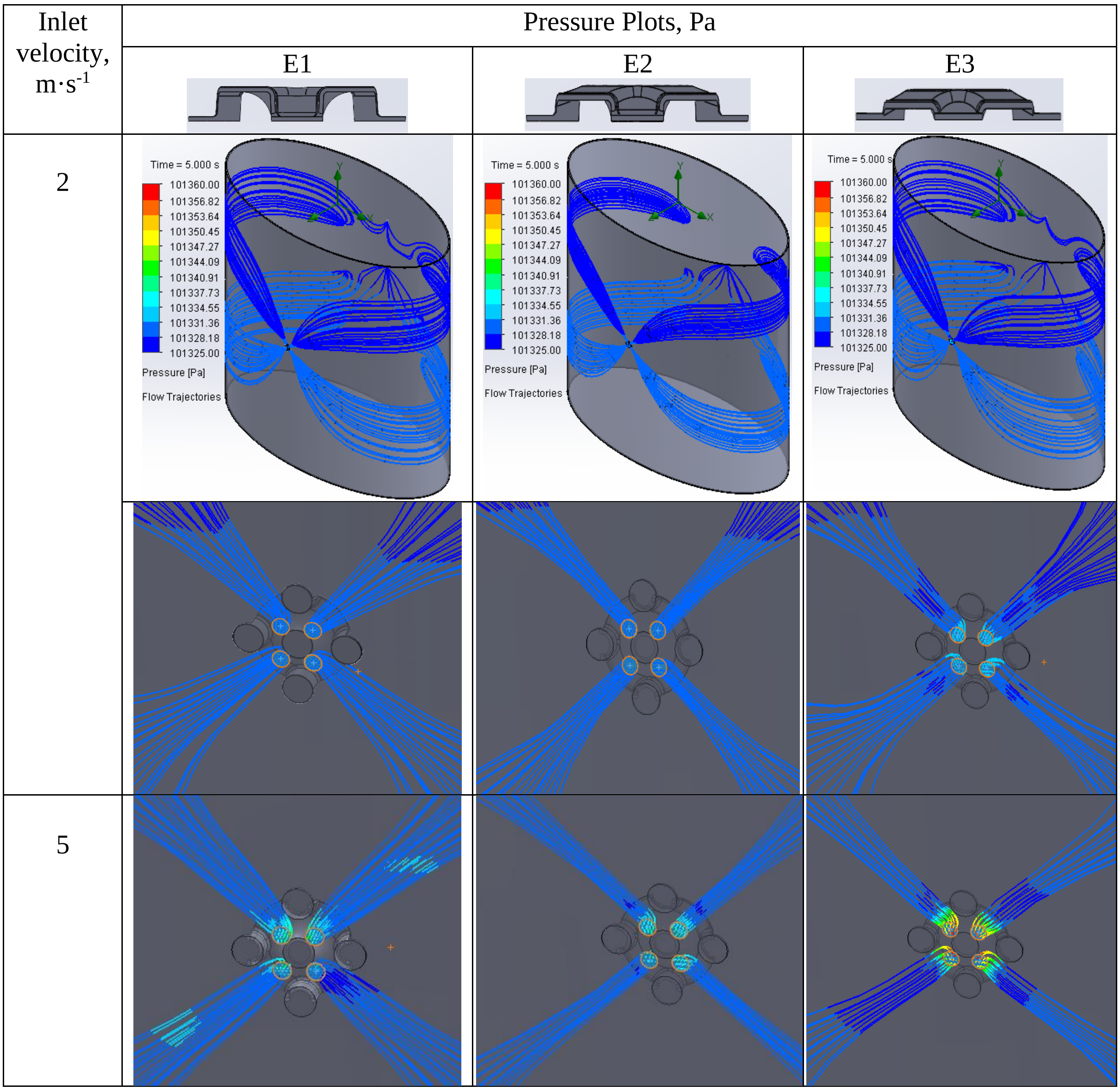


Fig. 3. **Pressure plots**

In Fig. 4, the first row shows pictures of temperature distribution over the complete model, while the next rows show pictures with the zoom view near the ventilation holes to visualize the cooling effect. Detailed values of the obtained temperatures in all three cases are shown in Table 2. It is clearly seen from the temperature plots that the cooling coverage area extends near the ventilation with the increasing inlet velocity from 2 to 5 m·s^{-1} in all cases. Here, equal scale is taken for easy comparison and visualization.

In the flux plot, Body_5P-1/Boss-Extrude1 refers to the human body model, jacket_elliptical-5P1 to the jacket and default fluid subdomain is air. The amount of heat released to the atmosphere is represented by Outer Domain in the plot. The rate of heat transfer in all cases is calculated from the flux plots as shown in Fig. 5, similarly the values of heat fluxes are calculated for other ventilation elements at different velocities, which are mentioned in Table 2.

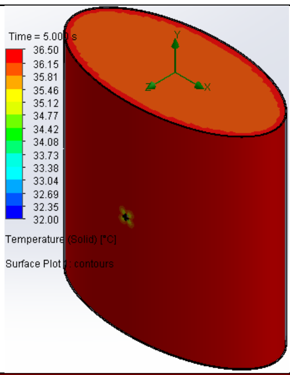
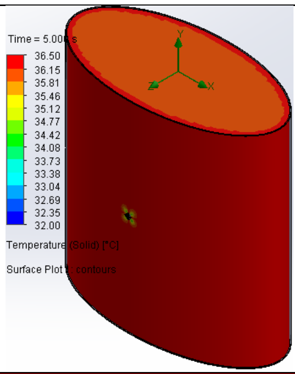
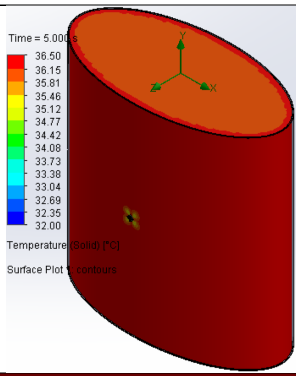
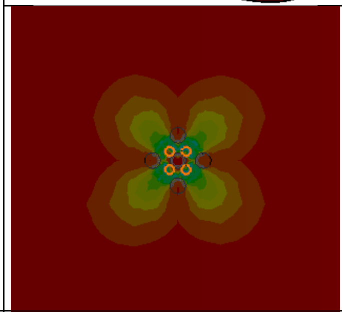
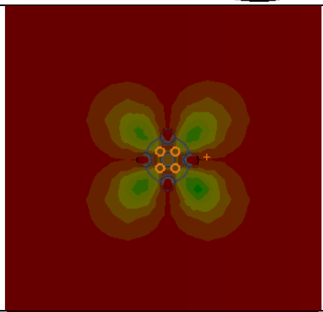
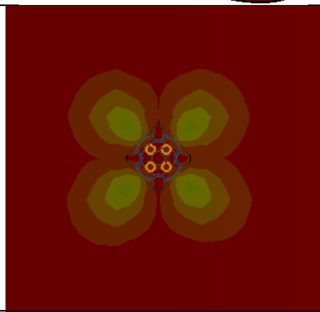
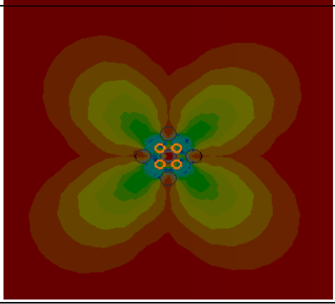
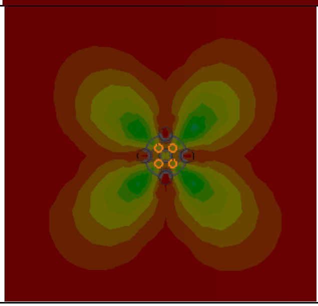
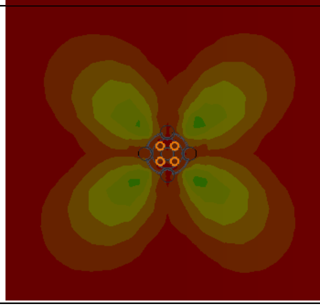
Inlet velocity, $m \cdot s^{-1}$	Temperature, °C		
	E1	E2	E3
2			
			
5			

Fig. 4. **Surface temperature of the body**

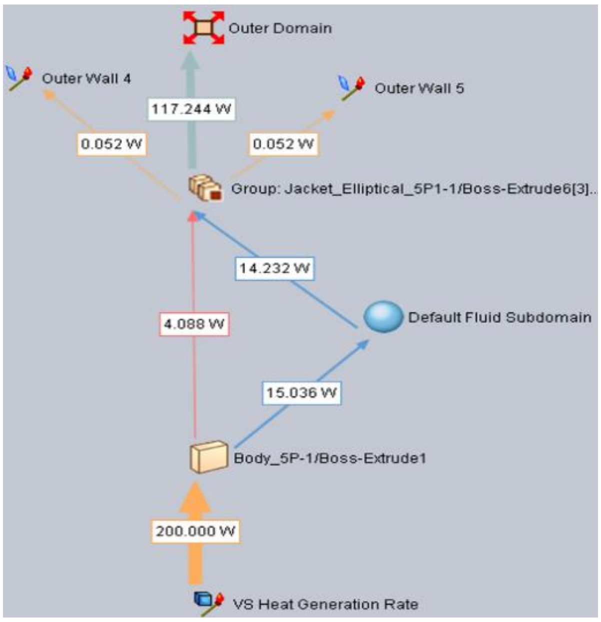


Fig. 5. **Flux plot for E1 at 2 $m \cdot s^{-1}$**

Table 2

Numerical values of the results

Element	Inlet velocity, $m \cdot s^{-1}$	Values	Pressure, Pa	ΔP, Pa	Temperature, °C	ΔT	Heat transfer from body to fluid, W
E1	2	Max	101330.12	4.2	36.50	3.87	18.64
		Min	101325.92		32.63		14.563
		Ave	101328.03		36.50		-
	5	Max	101344.28	18.41	36.50	4.45	19.124
		Min	101325.87		32.05		15.036
		Ave	101328.08		36.50		-
E2	2	Max	101330.36	4.18	36.50	2.28	18.612
		Min	101326.18		34.22		14.586
		Ave	101328.06		36.50		-
	5	Max	101339.31	12.84	36.50	2.6	19.087
		Min	101326.47		33.90		15.061
		Ave	101328.06		36.50		-
E3	2	Max	101333.97	8.18	36.50	1.53	18.616
		Min	101325.79		34.97		14.590
		Ave	101328.05		36.50		-
	5	Max	101359.92	34.04	36.50	1.88	19.103
		Min	101325.88		34.62		15.077
		Ave	101328.04		36.50		-

The results are compared in terms of the pressure difference, temperature difference and heat transfer as below. Fig. 6 clearly depicts that element E2 provides the lowest pressure difference. The obtained results show that element E2 provides 5.57 Pa less pressure difference than element E1 at the wind velocity of 5 $m \cdot s^{-1}$, which is 30.26% less than E1. Moreover, E2 provides 4 Pa less pressure difference than element E3 at the wind velocity of 2 $m \cdot s^{-1}$, which is about 48.90% reduction, while at 5 $m \cdot s^{-1}$ it gives 21.2 Pa less pressure difference, which is 62.28% less than E3. The change in the temperature difference with respect to the velocity is also more gradual in E2 that can be seen in Fig. 7, which means less variations in the temperature with air fluctuation. Since there is a single ventilation element in the present study, heat transfer is almost the same in all three elements. Once there will be a higher number of elements, this difference will be greater, as there will be differences in the effectiveness of the elements at different inlet angles and directions. This is an important parameter, as higher rate of the heat transfer provides higher cooling of the body.

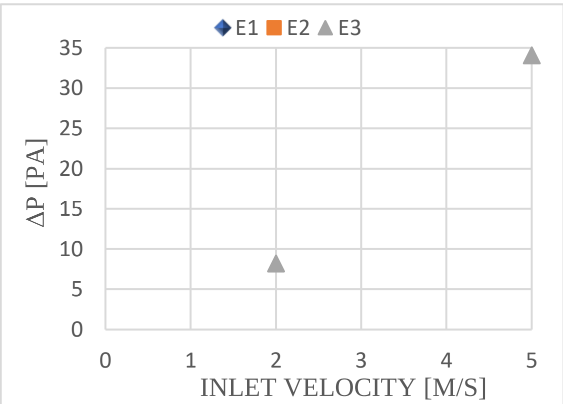


Fig. 6. **Pressure difference (ΔP) v/s velocity**

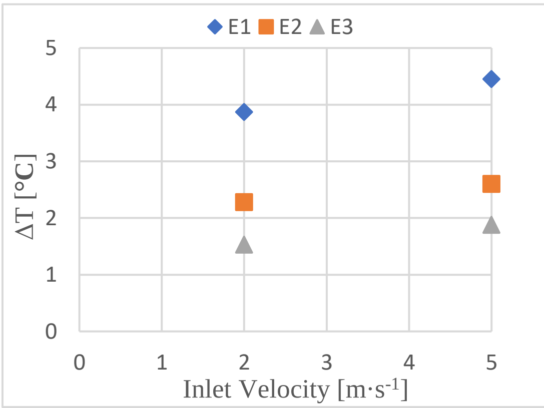


Fig. 7. **Temperature difference (ΔT) v/s velocity**

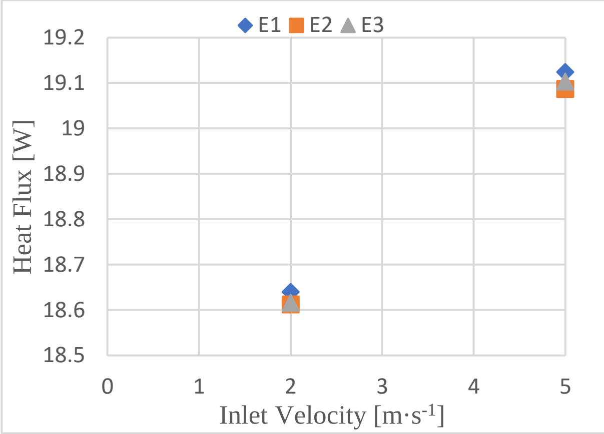


Fig. 8. **Heat flux v/s velocity**

The following are the important points concluded from the obtained results.

- From the obtained results it can be seen that the pressure difference increases gradually from lower to higher inlet velocities in all ventilation elements. Initially at a lower velocity of 2 m·s^{-1}, elements E1 and E2 show almost the same pressure difference, but E3 shows more pressure variations at the inlet, which is an indication of poor performance. This pressure difference increases gradually at 5 m·s^{-1} in all elements. This is an important point to notice, because some elements may work well at a smaller velocity but may show poor performance at a higher velocity. Hence, it is important to know the working parameters of the system and choose the right element accordingly.
- Element E2 gives the lowest pressure difference amongst the three elements at both 2 and 5 m·s^{-1}, which can be seen in Fig. 6. Lower pressure difference means less flow variations and a more uniform flow inside the system which will provide better performance.
- Moreover, E2 shows the smallest flow energy losses in the cell flow channel than the other two designs, specifically at a higher velocity of 5 m·s^{-1}. This means that element E2 may provide better cooling as it causes less flow energy losses.
- Element E2 also provides more gradual temperature difference with increased velocity, which means less variations in the temperature with respect to the air fluctuation (inlet velocities). The air intake through the openings in the protective jacket may be from different sides and at different angles as a person moves.

Conclusions

The main motivation of this study was to see which geometrical shape of ventilation elements causes the smallest flow energy losses in the cell flow channel and could possibly provide higher cooling. These energy losses in the ventilation elements can be known through proper air flow simulation study with any powerful CAE software as employed in this study with the help of SolidWorks Flow Simulation. The pressure difference (ΔP) is an important parameter to determine the effectivity of the element, as the element with a lower pressure difference will have lower energy losses and could provide better cooling. As per the mentioned results in the study, E3 is the least efficient out of the three ventilation element designs, as it shows a higher pressure difference, followed by the lowest temperature difference. This means the cooling efficiency of element E3 is lower than that of E1 and E2.

From the obtained results, it can be concluded that for smaller inlet velocity of 2 ms^{-1} element E1 is more appropriate but it shows higher pressure difference and energy losses in the cell flow channel at higher inlet velocity of 5 ms^{-1}. This is an important point to notice because some element may work well at smaller velocity but may not provide good performance at higher velocities, hence it is important to choose proper element according to working parameters. Considering overall performance at smaller and higher inlet velocity, element E2 is more appropriate than the other mentioned element designs in the study, which provides the lowest pressure difference and the smallest flow energy losses in the cell flow channel that could provide better cooling. This study shows that it is important to choose proper dimensions of the element opening, as very small dimensions may provide higher pressure difference and a larger opening size may provide higher temperature difference, while selecting a proper dimension in between may improve the performance. Selecting proper dimensions can be a difficult task, but it can be achieved through proper optimization and simulation study. At the same time the developed models are usable for the comparative ventilation effectivity analysis that will allow proceed with further investigations, for example, optimization of the location points of the multiple ventilation elements on protective clothing.

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Author contributions

Conceptualization, A.J. and S.R.V.; methodology, A.J. and S.R.V.; software, A.J. and S.R.V.; validation, S.R.V. and A.G.; formal analysis, A.G. and S.R.V.; investigation, S.R.V. and A.G.; data curation, S.R.V. and A.G.; writing – original draft preparation, S.R.V. and A.G.; writing – review and editing, A.J. and S.R.V.; visualization, S.R.V. and A.G; project administration, S.R.V.; funding acquisition, A.J., S.R.V. and A.G. All authors have read and agreed to the published version of the manuscript.

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