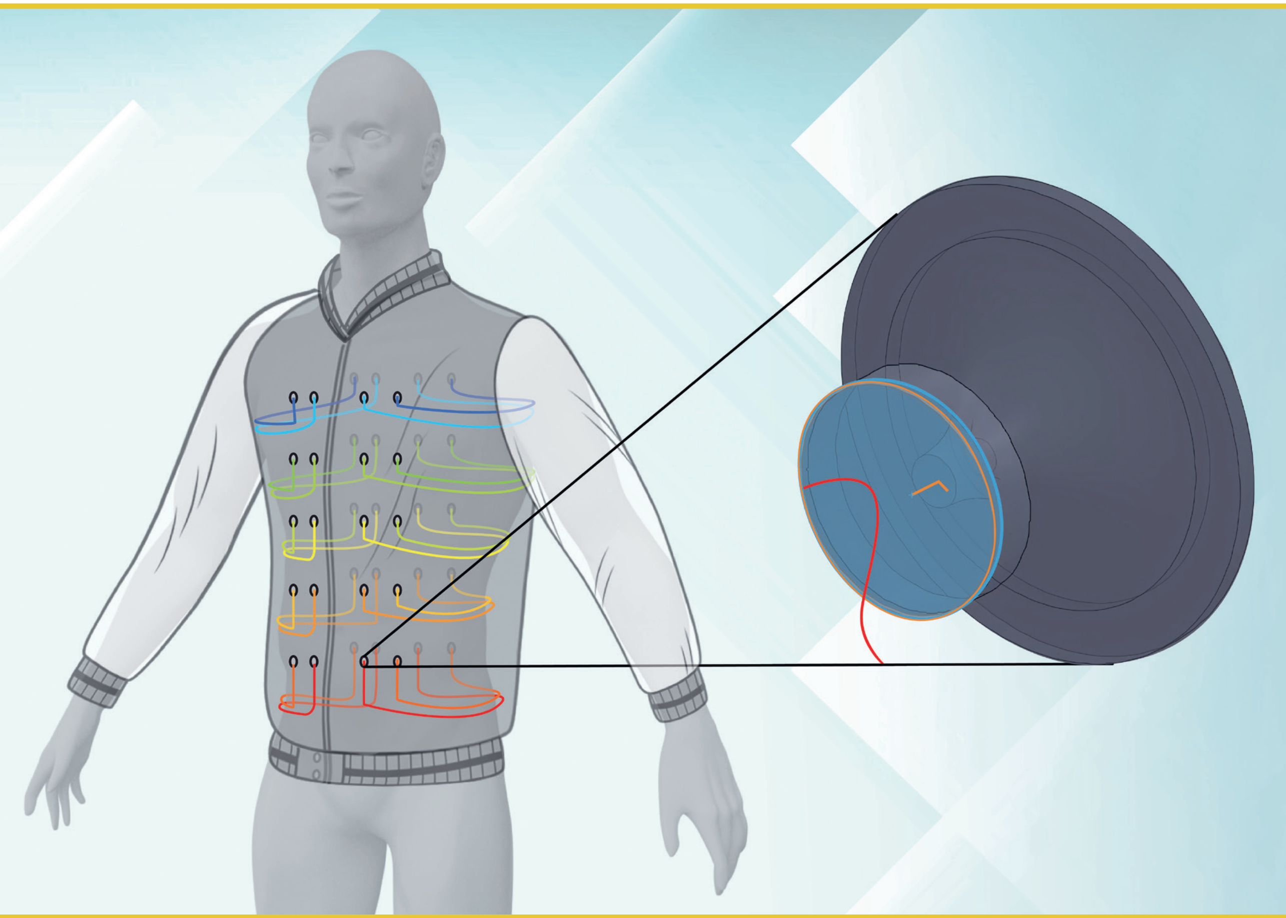
RIGA TECHNICAL UNIVERSITY

Sanjay Rajni Vejanand

OPTIMIZATION OF PROPERTIES OF VENTILATED PROTECTIVE CLOTHING

Summary of the Doctoral Thesis



RTU Press
Riga 2024

RIGA TECHNICAL UNIVERSITY
Faculty of Civil and Mechanical Engineering
Institute of Mechanical and Biomedical Engineering

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Doctoral Student of the Study Programme “Mechanical Engineering and Mechanics (Machine dynamics and design)”

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Summary of the Doctoral Thesis

Scientific supervisor
Professor Dr. sc. ing.
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 12 September 2024 at 14.30 at the Faculty of Civil and Mechanical Engineering of Riga Technical University, Ķīpsalas 6B, Room 420.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Sanjay Rajni Vejanand 
Date: 15.04.2024

The Doctoral Thesis has been written in English. It consists of an Introduction, 5 chapters, Conclusions, 77 figures, and 12 tables; the total number of pages is 144. The Bibliography contains 159 titles.

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ABSTRACT

To protect the human body from external environmental factors like rain, dust, direct sun radiation, insect access, and bites, the outer layer of clothing may lack air permeability, leading to the accumulation of wet and warm air around the body, which can cause discomfort or even overheating. Clothing with closable vents and openings has been designed to enhance air circulation in areas where significant sweating occurs. Yet, this method only enhances air exchange to a limited extent and does not completely fix the issue. The primary advantage of the future design is to provide efficient protection of the human body from different external environmental conditions while also maintaining necessary air circulation and ventilation under clothing to minimize the risk of body overheating. The material's technical and functional features provide a strong competitive edge compared to other air-permeable materials on the market for use in the outer layer of ventilating protective clothing.

The objective of the work is to analyse and optimize the aerodynamic characteristics of the material and ventilation elements that will be developed based on the type of clothing in order to achieve a proper balance of air permeability and mechanical and functional characteristics for protection against external environmental factors. The Thesis is focused on creating ventilation elements that can be fixed at the ventilation holes on the inner side of protective clothing. The attached ventilation elements can improve the structural integrity of the clothing by covering the ventilation holes and restricting dust, direct sunlight, insects, and other contaminants from coming into direct contact with the body; at the same time, it permits proper air circulation between the body and clothing. To achieve the objective, various shapes of ventilation elements are created and evaluated to determine the most effective shape. Furthermore, the shape optimization of a suitable ventilation element is achieved through the use of approximation and optimization techniques. SolidWorks Flow Simulation is used to calculate the pressure, temperature, and heat flow for the simplified elliptical model of the human body with a protective jacket. The aim is to determine the geometric shape of the element that results in the least flow energy losses in the flow channel of the cell, which is demonstrated by the pressure difference (ΔP). Energy losses in the flow rise with higher ΔP, and body cooling reduces when the flow weakens or loses energy. Elements with a higher temperature difference can offer more effective cooling since the heat transfer rate increases with temperature difference. Various criteria, such as heat transfer rate, heat flux, and total enthalpy rate, were analysed in the following studies to evaluate the efficiency of ventilation elements and the overall efficiency of ventilated clothing.

Keywords: CFD, ventilation element, protective clothing, shape optimization, flow simulation.

ACKNOWLEDGEMENT

This Thesis represents the result of my study conducted at Riga Technical University, specifically in the Institute of Mechanics and Mechanical Engineering, from October 2020 to March 2024. During my PhD journey, I became fascinated by scientific discovery and the difficulties that come with conducting research. This prompted me to focus on the study of air-flow analysis of ventilated clothing; this is mainly because of my prior background in CAD, FEM, and Solid Mechanics.

I would like to convey my sincere gratitude to Riga Technical University for offering me the opportunity and necessary resources to pursue my doctoral studies. I would like to express my gratitude to the Doctoral Department for the financial funding and support in my research work. I would also like to extend my gratitude to all individuals who provided assistance, both directly and indirectly, in the development of my Thesis. In particular, I would like to convey my sincere gratitude to my scientific supervisor, Professor Dr. sc. ing. Aleksandrs Januševskis, and Dr. Ivo Vaicis, who helped me with valuable guidance and encouragement. Furthermore, I would like to convey my thanks to Agris Gulevskis for his assistance in providing me with his insightful views and suggestions.

My friends and fellow doctoral candidates provided me with companionship that enhanced and eased my journey. Their strong bond and mutual support greatly helped to smooth my challenging journey of pursuing doctoral studies. In particular, I am grateful to Jaymin Sanchaniya and Umesh Vavaliya for all the help and support they gave me throughout this time.

In closing, my deepest and heartfelt gratitude goes to my parents and family for their continuous support and love. Thanks to their unwavering support, I have successfully navigated through all the various levels of my education, and they have consistently stood by my side through all the challenges and achievements of my life. Without their support, I would not be able to attain the level of success and accomplishments that I have attained today.

Sanjay Vejanand
Riga, March 2024

SUMMARY OF THE THESIS

1. INTRODUCTION

Exposure to extreme temperatures can hinder people's thermoregulation. Therefore, it is essential to take into account the impact of fabric cooling and ventilation on human comfort during the clothing design and development procedure [1]. There is a market demand for improved technical solutions and materials for the exterior part of protective clothing. These solutions should provide good ventilation, especially in warm weather conditions and during heavy physical activities. This is due to the growing interest in the market for efficient protection of the human body against exposure to extreme weather conditions. Many different kinds of protective clothing are readily available to shield the human body from diverse external weather conditions like rain, dust, direct solar radiation, insect access and bites. The danger of body overheating might occur when individuals need to wear protective clothes in warm environments or during times of heavy load conditions [2]. This is due to the insufficient air permeability of the outer layer of cloth, resulting in the collection of warm and wet air on the body, leading to discomfort. To optimize air circulation, a range of adjustable vents and breathable areas have been created in clothes. Nevertheless, this approach only leads to a limited enhancement in air circulation while simultaneously compromising the structural integrity of the garments. Attaching suitable ventilation elements on the inner side of ventilation holes can enhance the mechanical durability of the clothes. This allows for proper air circulation while also preventing dust, raindrops, sun radiation, and insects from directly reaching the body.

This research is associated with analysing and optimizing the aerodynamic properties of the material and ventilation elements that will be created to achieve a balance between air permeability, mechanical strength, and functional features, with the goal of offering protection against external environmental conditions. The work refers to the creation of new techniques for the development of experimental designs, approximations, and optimizations. The Thesis will facilitate the implementation of newly created algorithms and approaches by integrating them into a specific methodology. This will allow the execution of complex tasks, such as optimizing the design of ventilation elements. Gaining an understanding of the interaction of fluid flow with the model is a crucial and complex task. In order to reduce the complexity of the problem, a simplified elliptical model of the human body and jacket is designed and utilized in the study. SolidWorks flow simulation tool is used to compute airflow interaction with the model and analyse the results. The analysis of different shapes of ventilation elements is mentioned in this work. Furthermore, it discusses the metamodeling approach using different order polynomial local and global approximations, as well as Kriging approximations, for the purpose of shape optimization of the ventilation element. The optimization software KEDRO is used to create the design of experiments and further approximation and optimization tasks. Various criteria were used to evaluate the efficiency of ventilation elements. These criteria were also utilized to assess the efficiency of the ventilated model with different numbers of ventilation. Ultimately, numerical simulation and physical experiments are conducted using a realistic model of the human body with a jacket in order to draw conclusions through a comparison of the results.

1.1. Objective of the Thesis

The aim of this research work is to analyze and optimize the aerodynamic properties of the material and ventilation elements that will be designed, depending on the kind of clothing, in order to attain a balance between air permeability, mechanical and functional characteristics for the purpose of providing protection against external environmental conditions. The primary benefit of the newly developed system and ventilation element is that it provides good protection for the human body against the impacts of a variety of external environmental conditions such as rain, dust, direct sun radiation, and insect access and bites. This protection is achieved by ensuring the necessary air circulation or ventilation through the use of under-clothing, which in turn reduces the possibility of the body overheating. The work is associated with the development of new tools for the designs of experiments, approximations, and optimizations. The development of the Thesis will make it possible to put the newly developed algorithms and approaches into practice by incorporating them into a particular methodology and by ensuring that complex tasks, such as the optimization of the ventilation elements' shape, will be conducted. A more effective technical solution and material for the outer layer of protective clothing is needed to ensure the necessary ventilation even in warm climatic conditions and during physical load. This is due to the growing market interest in protecting the human body from environmental hazards.

1.2. Main Tasks of the Thesis

1. The initial task of the study is to examine the flow simulation and analyse airflow interaction of a simplified model of the human body with a protective jacket using the SolidWorks flow simulation tool. The circular model of the body and jacket is considered initially to study airflow interaction and to analyse flow pressure and surface temperature of the body. A simulation study is made with a jacket having three inlets and ten outlets. The same analysis is done in ANSYS fluent to compare the results of SolidWorks and ANSYS to check the reliability of the results. Further, the model is modified into an elliptical shape representing the body and the jacket.
2. Different simple shapes of ventilation elements are studied and analysed by attaching each to the inlet ventilation hole, one by one. The flow pressure and surface temperatures are recorded for each shape of ventilation element to estimate the efficiency of the ventilation element. The analysis is done at different air velocities of 2 m/s, 5 m/s, and 8 m/s to understand the effect of air velocity on the results.

3. Further, the more complex shape of the ventilation element is analysed by varying geometrical dimensions of the model to study the flow variations in the element flow channel with respect to changes in dimensions.
4. Once the efficient shape of the ventilation element is found, the next task is to optimize the design of the element. Shape optimization of the element is achieved by building a metamodel in optimization software KEDRO, where 12 designs of experiments (DOE) were created based on two coordinate values of the geometrical shape of the ventilation element. Twelve geometrical models of the ventilation element were created using these DOE, and each was simulated in SolidWorks flow simulation to obtain values of pressure and temperature differences. The recorded values from SolidWorks were used in KEDRO for further approximation using the Kriging method and optimization.

1.3. Scientific Novelty of the Thesis

The scientific novelty of the Thesis lies in its concept of creating appropriate ventilation elements for the protective clothing, which can be attached to the ventilation holes to provide proper air circulation between the body and clothing to avoid overheating of the body in extreme environmental conditions and during heavy workload conditions. One major drawback of most personal protective clothing with an external cooling system is that they make the structure bulky, which makes garments heavy and uncomfortable to wear. In addition, their cooling efficiency is not steady and reliable for personal clothing cooling devices. These small ventilation elements can be used to overcome these issues as they are very lightweight and do not require any external power to operate.

1.4. Practical Value of the Thesis

The Thesis has practical value in the context of developing ventilated protective clothing that incorporates ventilation elements. Considering the increasing interest in the market for effective protection of the human body against exposure to the 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 environmental conditions and during physical load. Such solutions have a very wide range of practical applications and demand on the global market. Furthermore, the study also offers a comprehensive understanding of solving complex practical tasks, such as shape optimization of ventilation elements. The concept can be useful in many firms for solving practical problems, such as optimizing the design of different products.

1.5. Example of Ventilation Setup on a Model

The execution of the experiment with a thermal manikin model wearing a jacket is taking place at the Personal Protective Equipment (PPE) laboratory at Riga Technical University (RTU). This experiment is carried out using two separate jackets: 1) a normal jacket without ventilation features, and 2) a jacket with the attached ventilation elements.

Figure 1 shows a manikin model wearing a ventilated jacket. The detail view 'A' in Fig. 1 provides an enlarged view of four ventilation holes in the jacket that make up a single ventilation unit, while the detail view 'B' is the backside view of detail 'A', displaying the ventilation element attached to the holes.

This experiment shows the significant advantages of a ventilated jacket. These results are currently not attached and will be published as soon as possible after the data declassification procedure, i.e. after the acceptance of the patent application of the industrial partner (European Patent Application No. 21816861.5 by Agris Guļevskis).

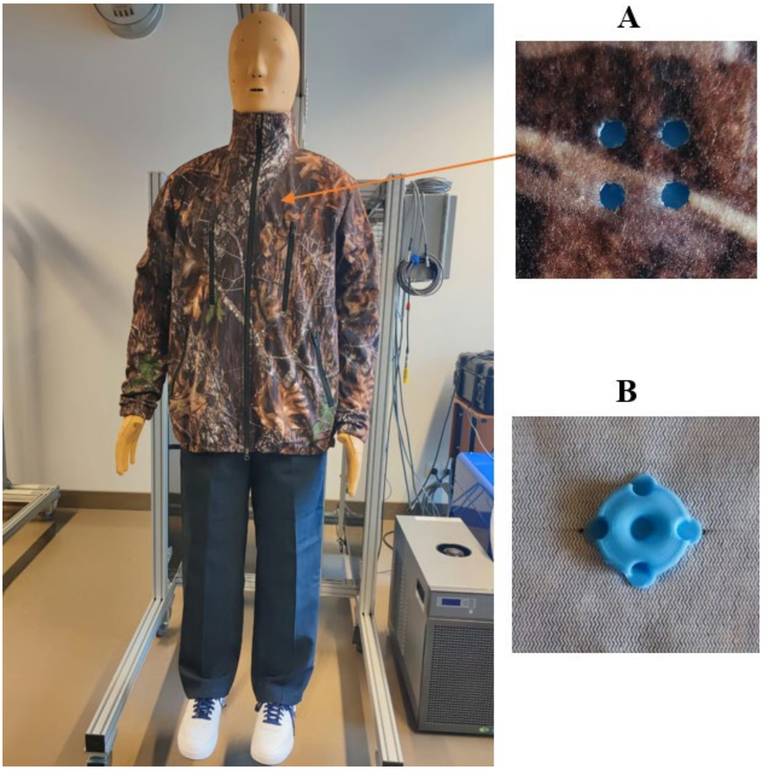


Fig 1. Manikin model with the ventilated jacket: (A) enlarged view of ventilation holes; (B) ventilation element attached to the ventilation holes.

1.6. Research Methods

The following methods were used to obtain the necessary results:

1) CAD modelling with the computer software;
2) CFD (numerical simulation);
3) metamodeling;
4) physical experiment.

1.7. Approbation

The results of the Doctoral Thesis have been presented and discussed at the following international conferences and scientific seminars.

1. 61st International Scientific Conference, Riga Technical University. 12–14 October 2020, Riga.
2. 20th International Scientific Conference “Engineering for Rural Development”, Latvia University of Life Sciences and Technologies. 26–28 May 2021, Jelgava.
3. 62nd International Scientific Conference, Riga Technical University. 12–14 October 2021, Riga.
4. 21st International Scientific Conference “Engineering for Rural Development”, Latvia University of Life Sciences and Technologies. 25–27 May 2022, Jelgava.
5. 63rd International Scientific Conference, Riga Technical University. 12–14 October 2022, Riga.
6. 22nd International Scientific Conference “Engineering for Rural Development”, Latvia University of Life Sciences and Technologies. 24–26 May 2023, Jelgava.
7. 63rd International Scientific Conference, Riga Technical University. 11–13 October 2023, Riga.

1.8. Publications

1. A. Janushevskis, J. V. Sanchaniya, S. R. Vejanand. Designing of Catamaran Hull Spine Beam. 20th International Scientific Conference “Engineering for Rural Development”. ISSN 1691-5976, Volume 20, pp. 1685–5976, Jelgava, 2021. https://www.tf.llu.lv/conference/proceedings2021/Papers/TF365.pdf
2. A. Janushevskis, S. R. Vejanand, A. Gulevskis. Comparative Analysis of Different Shape Ventilation Elements for Protective Clothing. 21st International Scientific Conference Engineering for Rural Development. ISSN 1691-5976. Volume 21, pp. 179–186. Jelgava, 2022. https://www.tf.llu.lv/conference/proceedings2022/Papers/TF052.pdf

3. A. Janushevskis, S. R. Vejanand, A. Gulevskis. Analysis of Different Shape Ventilation Elements for Protective Clothing. WSEAS Transactions on Fluid Mechanics, Volume 17, ISSN: 1790-5087, E-ISSN: 2225-347X, DOI: 10.37394/232013.2022.17.14, 2022. pp. 140–146. https://wseas.com/journals/fluids/2022/a285113-338.pdf
4. A. Janushevskis, S. R. Vejanand, A. Gulevskis. Air Flow Analysis for Protective Clothing Ventilation Elements with and without Constant Cross-section Area Opening. Latvian Journal of Physics and Technical Sciences. 60 (2), DOI: 10.2478/lpts-2023-0012, pp. 63–73, 2023. Published Online: 15 April 2023 Volume 60, Issue 2. https://sciendo.com/article/10.2478/lpts-2023-0012
5. A. Janushevskis, S. R. Vejanand, A. Gulevskis. Shape Optimization of Ventilation Elements for Protective Clothing by Using Metamodeling Approach. 22nd International Scientific Conference Engineering for Rural Development. ISSN 1691-5976, Vol. 22, pp. 164–172, Jelgava, 2023. https://www.tf.llu.lv/conference/proceedings2023/Papers/TF032.pdf
6. Sanchaniya, J. V., Rana, V., & Vejanand, S. R. (2024). Optimization of Electrospinning Parameters for High-Strength Oriented Pan Nanofiber Mats. Latvian Journal of Physics and Technical Sciences. (Accepted for publishing).
7. S. R. Vejanand, A. Janushevskis, I. Vaicis. Selection of Appropriate Criteria for Optimization of Ventilation Element for Protective Clothing Using a Numerical Approach. Computation 2024, 12, 90. https://doi.org/10.3390/computation12050090
8. S. R. Vejanand, A. Janushevskis, I. Vaicis. 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

2. LITERATURE REVIEW

Chapter 2 is devoted to a brief literature review starting with the historical development of clothing ventilation and on to modern technological advancements. It also highlights several limitations and disadvantages associated with the field of clothing ventilation. Advancements in technology and materials science have led to the creation of new ventilation features in clothing with the goal to improve comfort and regulate body temperature in a variety of conditions in the modern era. Here are a few noteworthy examples.

Mesh panels and venting systems

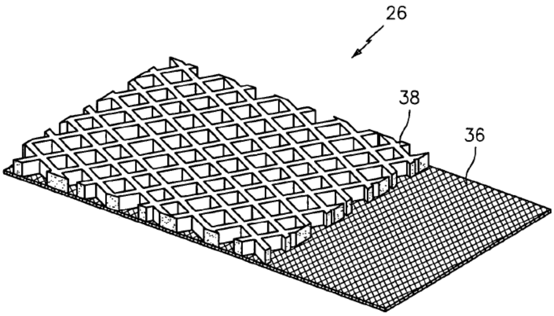


Fig. 2.1. A three-dimensional, partly sectioned representation of the spacer mesh fabric used in accordance with the invention: 26 – spacer material design, 36 – thin fabric layer, 38 – thick mesh structure layer [3].

Figure 2.2 depicts additional potential versions of the ventilation system in accordance with the invention. For example, a variation in the width of ventilation systems US 7,043,767 B2 5 is shown here in a sports jacket (10) with multi-slit-like ventilation systems (40) arranged next to one another, which can be arranged as multiple ventilations, for example, under arms, in the upper body region, or in the shoulder region. A perpendicular variant (42) is illustrated with the spacer material created in an approximate wedge shape. An alternative ventilation system (44) is depicted on the left side of the sports jacket (10) in Fig. 2.2. The flexible, three-dimensionally cross-linked spacer material is incorporated as an areal, for example, a strip-like element (46) into the garment surface. This indicates that element 46 is sewn to the remaining clothing material at the edges in each case. A flap (48) is positioned above this areal part (46) and can cover it [3].

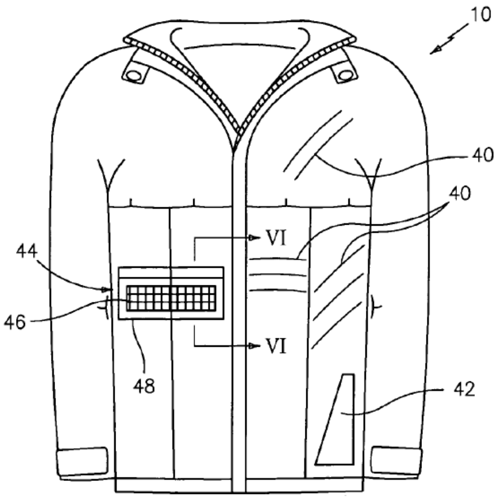


Fig. 2.2. A jacket with a ventilation system containing spacer mesh fabric [3].

Moisture-wicking fabrics

The garment engineering has come a long way, and one of the most exciting discoveries was the development of moisture-wicking materials, which are now widely used in sportswear and outdoor clothes where sweating is a big discomfort [4].

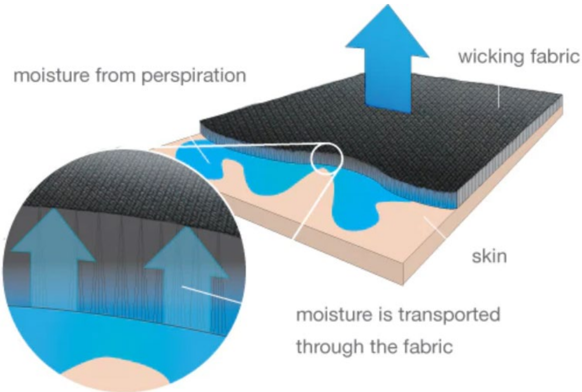


Fig 2.3. Moisture-wicking fabric [5].

Active Cooling techniques

Some innovations go beyond natural ventilation to include active cooling solutions. Certain specialized clothes, for example, include built-in fans (air cooling), cooling packs, or liquid cooling systems that actively circulate cool air or fluids around the body to cool the skin [6].

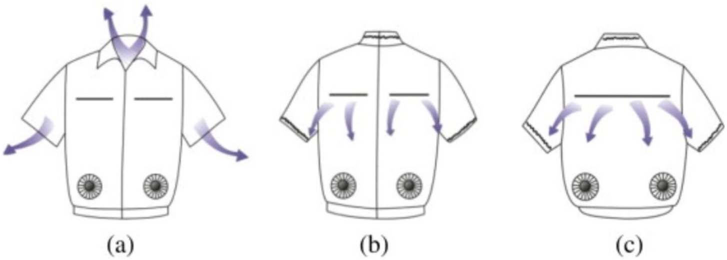


Fig. 2.4. Ventilated jackets with fans and different openings: (a) normal opening; (b) front opening; (c) back opening [6].

As illustrated in Fig. 2.5, liquid cooling garments usually come with circulating water tubes filled with a cold liquid resource and a micro water pump device at the inner layer to drive the liquid flowing in the tube to reduce the temperature [8], [9]. Liquid cooling garments (LCG) have been demonstrated to be one of the most promising technologies in the clothing cooling arena after multiple investigations and is employed in a variety of fields, including military [10], mining [11], and sports [12].

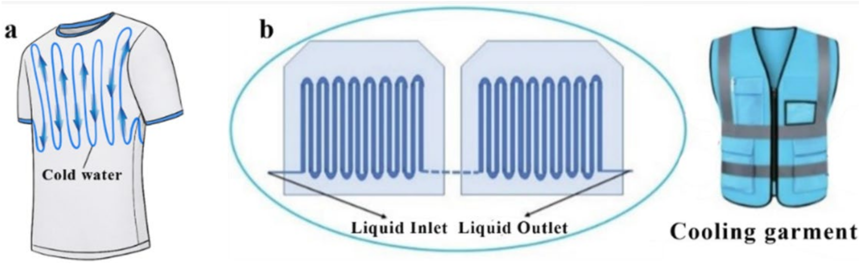


Fig. 2.5. Liquid cooling system: **a** – schematic diagrams of a liquid cooling garment; **b** – liquid cooling garment with a thermoelectric (TE) device [7], [13].

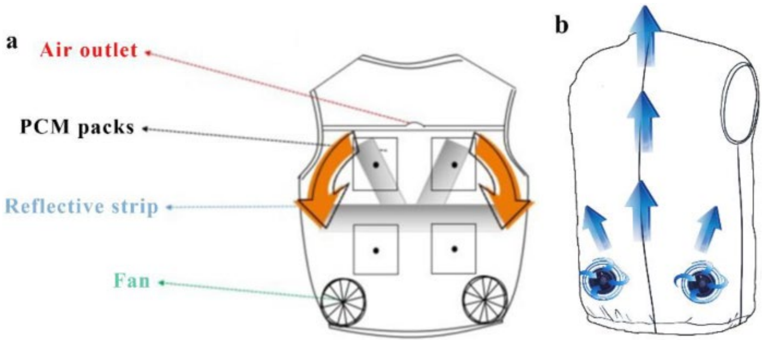


Fig. 2.6. Air cooling technique: a – air cooling with a PCM cooling vest (PCV) [14]; b – an air cooling garment's schematic illustrations [13].

Figure 2.6 a shows a novel hybrid personal cooling vest (PCV) designed by Ni et al. [15]. Their unique PCV was combined with PCMs and ventilation fans, demonstrating the adaptability and reliability of this hybrid cooling garment. Phase change materials (PCMs) cooling can use latent heat from the body or the environment directly to reduce the temperature of the microclimate between the clothing and the body without additional energy usage [16]. Based on an air tubing network and TE cooling plates, Lou et al. examined the relationship between the cooling effect and different body positions, which is useful for improving the combination of the cooling system and the clothing in an efficient and easy way in daily life [17].

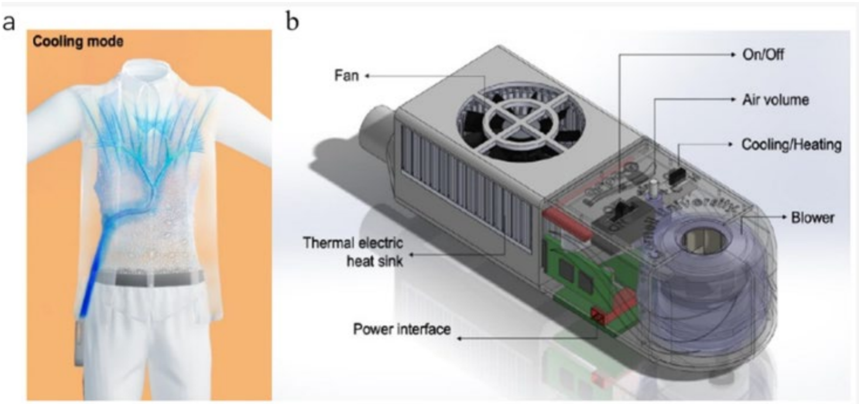


Fig. 2.7. Thermoelectric (TE) cooling: a – TE cooling undergarment; b – illustration of a TE cooling module [18], [13].

Air cooling and liquid cooling garments are uncomfortable and heavy, with bulky air or fluidic pathways, and their cooling efficiency is not steady and reliable for personal clothing cooling devices [19].

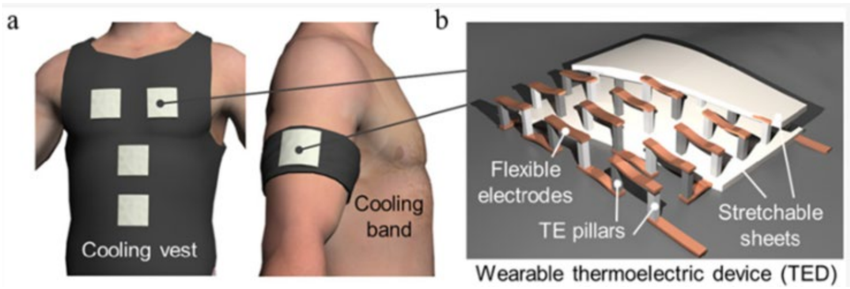


Fig. 2.8. Thermoelectric device (TED): a – cooling garments with wearable TE devices (TEDs); b – the structure of a TED [20], [13].

As shown in Fig. 2.8, Hong et al. created a flexible and portable thermoelectric cooler with scalable application [21]. To boost thermal conductivity, inorganic semiconductor thermoelectric pillars were mounted on two elastic, flexible Ecoflex films that were filled with thermally conductive filler aluminium nitride. This device can run continuously for 8 hours without a heatsink and provides more than 7.6 °C cooling effects [13]. Zhang et al. presented a wearable TEC based on a two-layer flexible heatsink [22] made of hydrogel and nickel foam as phase change material to absorb heat and thermally conductive material to conduct heat, respectively.

The main disadvantage of most personal protective clothing with an external cooling system is that they make the structure bulky, which makes garments heavy and uncomfortable to wear. In addition, their cooling efficiency is not steady and reliable for personal clothing cooling devices. This demands the need for more advanced technological solutions in this field.

Furthermore, this chapter provides a detailed classification of protective clothing, describing the different types of clothing designed for specific purposes. The main purpose of every clothing is to shield the human body from harmful weather conditions. However, the term "protective clothing" is employed when clothing is specifically designed to provide proper protection against hazards such as fire, wind, microorganisms, chemicals, gas, radiation, electricity, and so on [23]. Protective clothing items provide a practical purpose, such as personal protective clothing, which primarily aims to shield the human body from unfavourable environmental factors, including physical, chemical, biological, and thermal hazards [24].

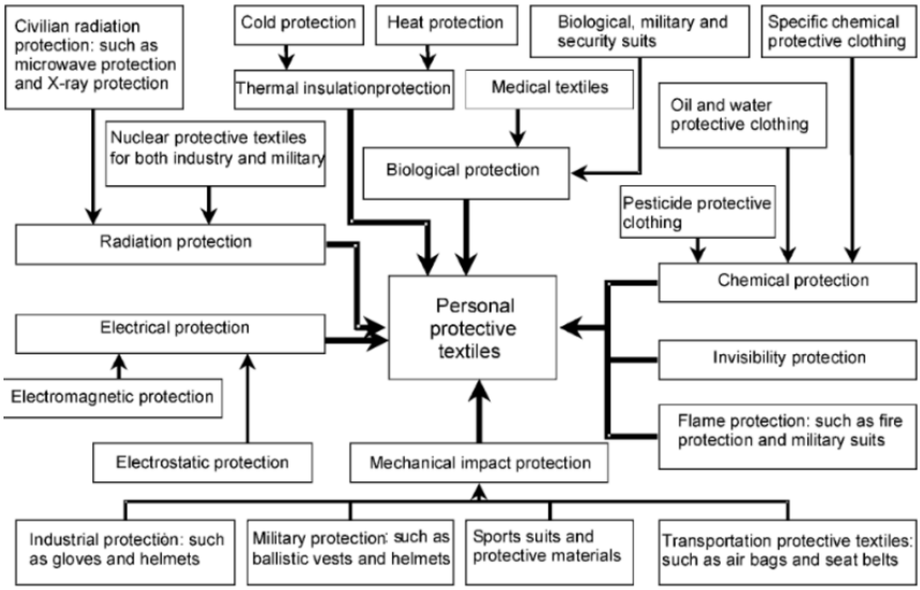


Fig. 2.9. Classification of protective clothing [25].

Choosing suitable protective clothing based on the type of danger is essential to safeguard oneself from potential hazards [26]. Nevertheless, the issue with the majority of personal protective equipment (PPE) lies in the fact that enhanced safety can only be guaranteed at the expense of increased expenditures and physical discomfort, which includes reduced flexibility, accuracy, comfort, and vision [27]. Additional inherent risks associated with traditional PPE include heat-induced strain, restricted movement, risk of accidents, seizures, physiological problems, and anxiety [28].

Fig. 2.10. Examples of protective clothing [24].

Graphene is a two-dimensional sheet made up of carbon atoms connected in a planar arrangement. It has been widely recognized as a revolutionary material in various technological fields due to its outstanding mechanical, thermal, chemical, electrical, and antibacterial characteristics [29]. Its outstanding characteristics make it an appealing material with potential for various technical applications, giving it an edge over other similar materials [30]. The integration of graphene or its derivatives into polymers/textiles can enhance the characteristics of fabrics for particular usage [31].

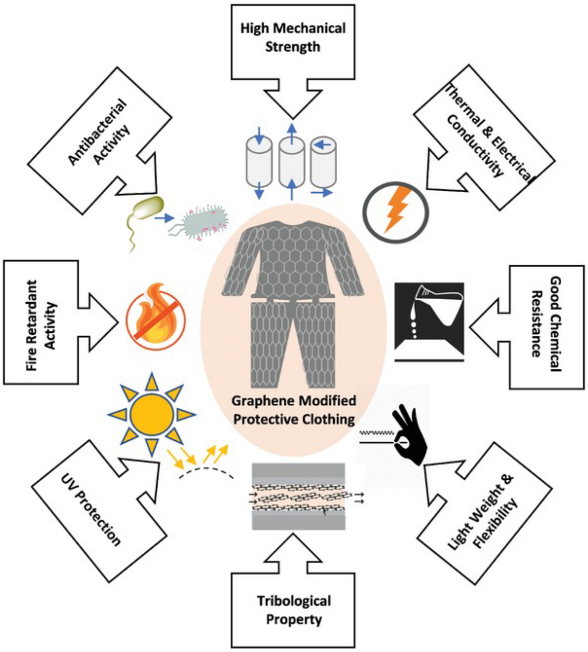


Fig. 2.11. Graphene-enhanced protective clothing with multifunctional characteristics [29].

2.1. Conclusions of Literature Review

1. The main disadvantage of most personal protective clothing with an external cooling system is that they make the structure bulky, which makes garments heavy and uncomfortable to wear.
2. In addition, their cooling efficiency is not steady and reliable for personal clothing cooling devices. This demands the need for more advanced technological solutions in this field.
3. This necessitates the development of novel technical solutions to enhance clothing ventilation and comfort.
4. This chapter provides comprehensive information on subjects such as clothing insulation and the thermal comfort of the human body. It also discusses the use of computational fluid dynamics (CFD) for numerical simulation, as well as techniques for approximation and optimization of the results.

3. ANALYSIS OF THE STUDIED OBJECT (CLOTHING) AND FLUID FLOW MODEL: SOLIDWORKS FLOW SIMULATION

In order to analyse and understand the interaction of fluid flow, a simple cylindrical model of a solid body and jacket is being utilized. The model's schematic diagram is shown in Fig. 3. The dimensions of the model are selected randomly in this study since the main aim is to understand the flow simulation process and study fluid interaction with the model. For the numerical analysis, the SolidWorks flow simulation tool is used.

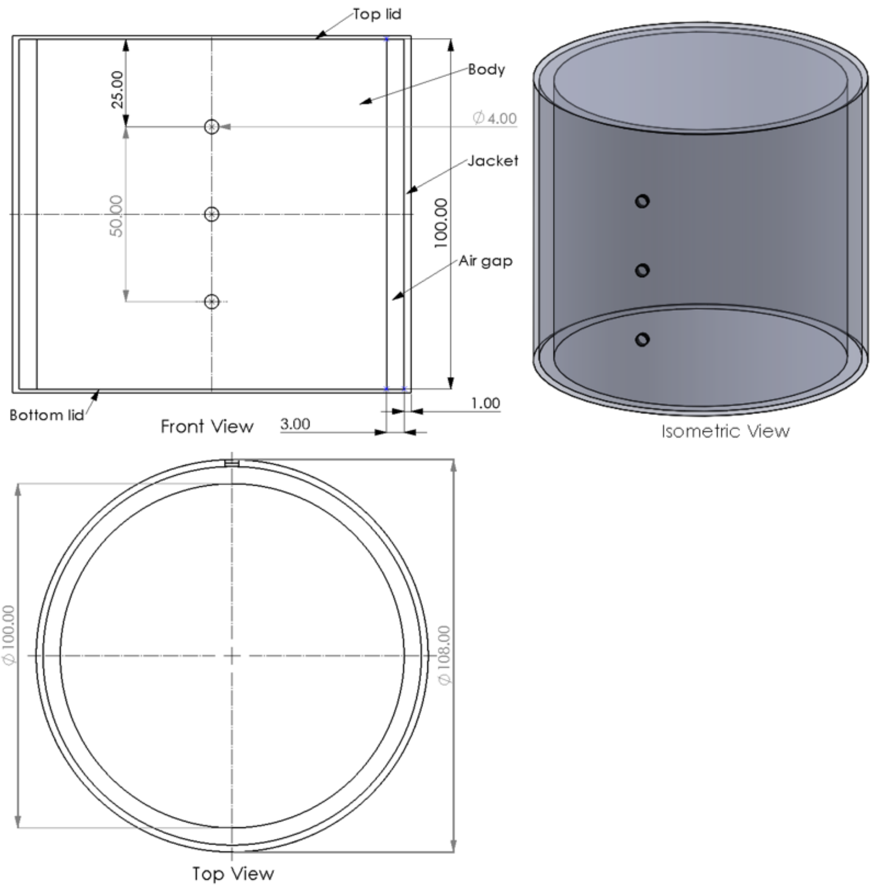


Fig. 3. Schematic diagram of cylindrical model.

3.1. Boundary Conditions of Ventilation Model

This is a transient study. In the simulation study, heat conduction and convection are considered with a physical time of 1 second. The physical time is selected smaller to save computation time.

Furthermore, gravity is taken into consideration. The study fluid is the air with laminar and turbulent characteristics. The next step is to select the initial boundary condition of the study. Here the inlet air velocity of 5 m/s is set for the study. Inlets are three ventilation holes of 4 mm diameters in this study, while outlet is assigned at the bottom lid with environmental pressure condition (Fig. 3.1). The air temperature of 20 °C and pressure of 101325 Pa is considered. The top part of the model is considered air-tight, which means air can only pass through the bottom part of the model. Inlet velocity at the ventilation holes is shown with red arrows, and outlet boundary condition with environment pressure is shown with blue arrow in Fig. 3.1. The heat generation rate of the body is considered 200 W, under normal walking conditions [32]. The normal average body temperature is taken as 36.5 °C.

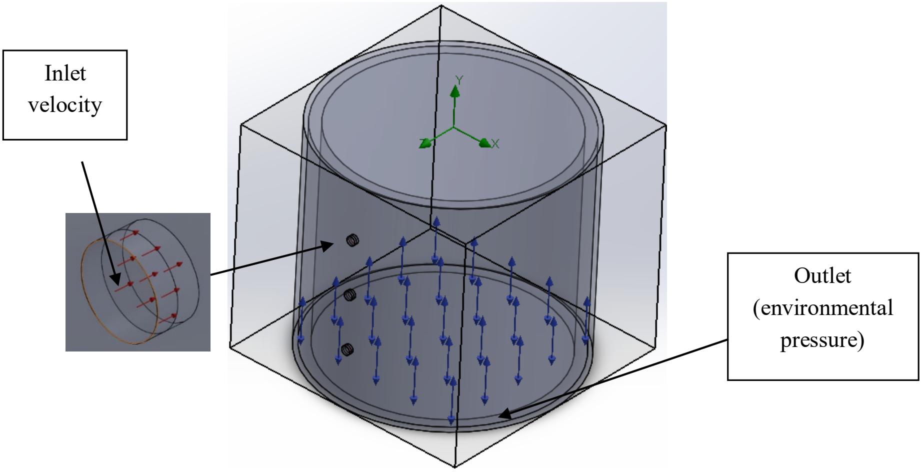


Fig. 3.1. Computational domain with initial conditions (cylindrical model).

In the present study mesh size (N_x = 28, N_y = 24, N_z = 28) is employed in the flow simulation study as using fine mesh extensively increases computational time. The model is simulated to obtain results for the flow pressure and the surface temperature of the body. Flow pressure is calculated in the air gap between the jacket and body once air enters through the ventilation holes. The second parameter of the study is the surface temperature of the body to see the effect of ventilations on the surface temperature.

It is also important at the initial stage to understand and check the reliability of the obtained results. To check the reliability of the results, the ANSYS software is used to perform the same analysis using the same model and boundary conditions. The results comparison is shown in Table 3.1.

Table 3.1

Numerical Results Comparison. SolidWorks v/s ANSYS

	Pressure [Pa]			**Body surface temperature [°C]**		
	Minimum	Maximum	ΔP	Minimum	Maximum	ΔT
ANSYS	101323.29	101340.14	16.85	31.13	36.74	5.61
SolidWorks	101324.47	101341.11	16.64	31.39	36.76	5.37

In Table 3.1, ΔP and ΔT refer to the pressure difference and temperature difference, respectively. The achieved pressure range is very close with minor variation. The range of surface temperature values obtained in ANSYS is also close to that in SolidWorks. The difference in the results obtained for ΔP is 1.25 %, and for ΔT it is 4.37 %, which is within an acceptable tolerance as the difference is less than 5 %. This difference can be due to the method of discretization as it has higher impact on the simulation results. SolidWorks and ANSYS use different element types for the process of meshing. The element used in ANSYS is a 20-node hexahedral solid element, while the element in SolidWorks is cubic.

3.2. Analysis of Different Simple Shapes of Ventilation Elements

Chapter 3.2 includes the detailed analysis of different simple and complex shapes of ventilation elements. In order to simplify the problem in this study, a basic elliptical shape model of the jacket and body is created. The body is positioned at the centre, with the jacket placed over it, maintaining a consistent gap of 2.2 mm between them. Figure 3.2.1 displays the schematic illustration of the model. The jacket has one inlet ventilation hole with a diameter of 2 mm on the front side and 10 outlet holes with a diameter of 4 mm on the back side.

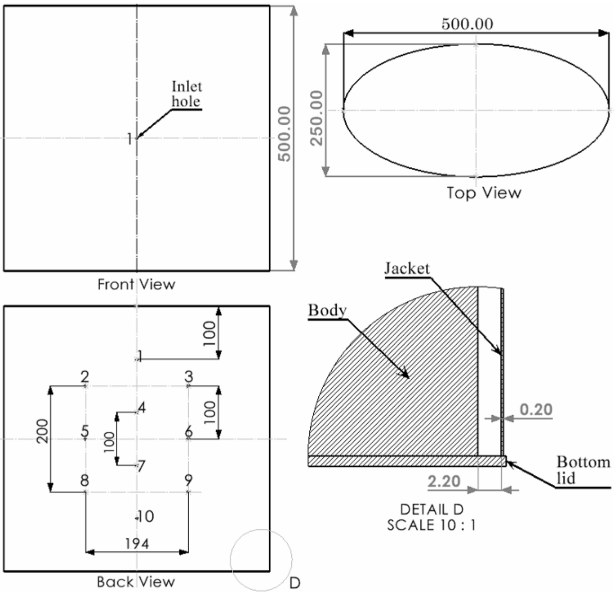


Fig. 3.2.1. Elliptical model of body and jacket.

In this study, five different ventilation elements are utilized to examine and compare the efficiency of each shape. Figure 3.2.2 illustrates the shape and nomenclature of each ventilation component. The position of the ventilation element relative to the jacket's inlet hole is denoted by a circular symbol in Fig. 3.2.2. The shapes of elements E4 and E5 are circular, but they have different curvatures. The main difference is that E4 is attached tangent to the intake hole, whereas E5 is attached concentrically to the inlet hole.

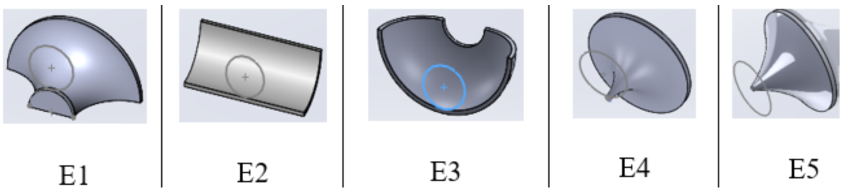


Fig. 3.2.2. Different simple shapes of ventilation elements.

The study is conducted at intake air velocities of 2 m/s, 5 m/s, and 8 m/s. In the simulation study, the jacket and body are assigned separate materials with specific material properties. The analysis considers the same material properties as the jacket for all ventilation elements. The properties of these materials are presented in Table 3.2. The boundary conditions in the study are the same as described in Section 3.1.

Table 3.2

Material Properties [33], [34]

Material property	Human body	Jacket
Average density [kg/m^3]	985	1420
Specific heat [J/ kg·K]	3600	1140
Thermal conductivity [W/m·K]	0.21	0.261

Results and Discussion

The results are presented for the physical time of 5 seconds. Moreover, the difference in the obtained results for each element would be almost the same at any specific time; hence, to reduce computational time, a smaller physical time of 5 seconds is selected for the study. Here, the basic mesh is employed to save computational time. This study involves a comparative analysis of five different elements that share the same set of values in the numerical simulation. Thus, the difference in the results at a given mesh level would be almost the same as we are using the same values and boundary conditions in each case. Therefore, the final outcome of the study will not be significantly influenced by it.

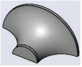
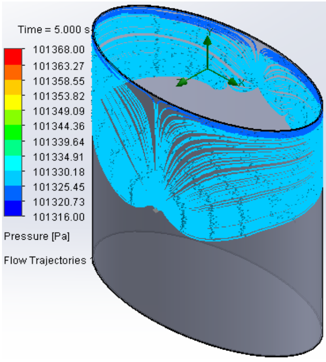
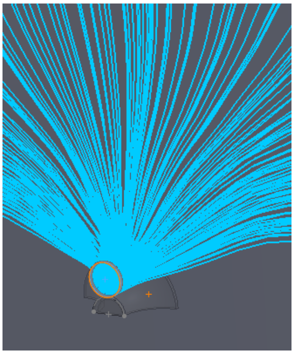
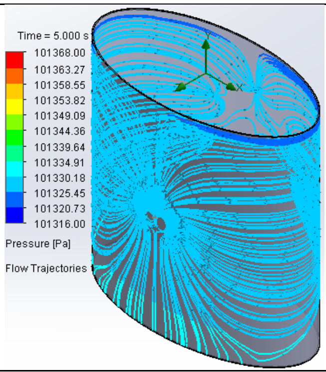
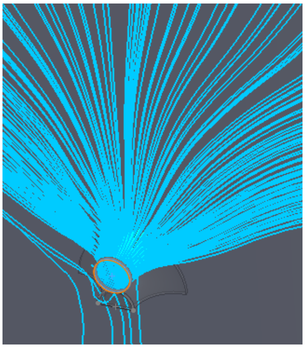
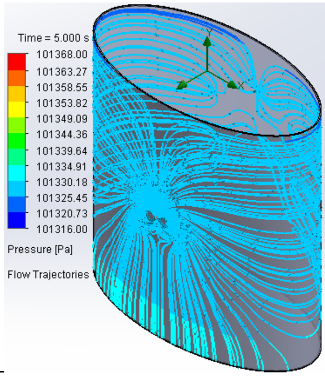
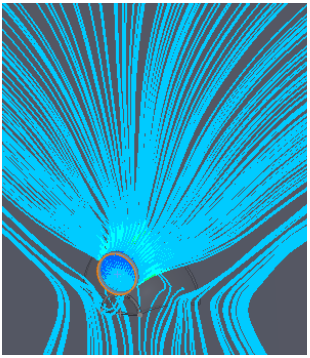
<table>
<tr><th>Element</th><th>Velocity [m/s]</th><th colspan="2">Pressure plots [Pa]</th></tr>
<tr><td rowspan="3">E1
</td><td>2</td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td></tr>
<tr><td>8</td><td></td><td></td></tr>
</table>

Fig. 3.2.3. Flow pressure trajectories for E1.

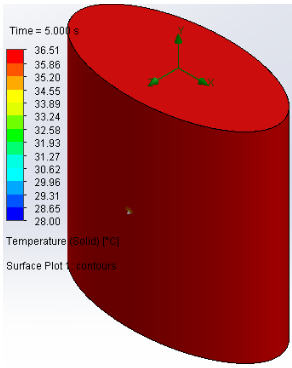
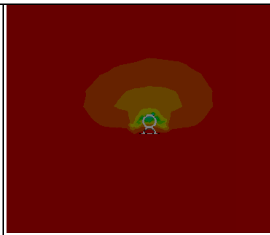
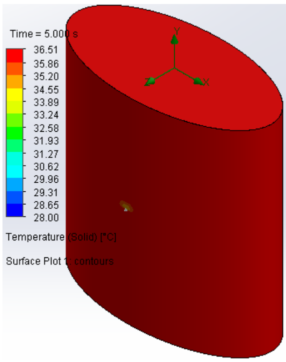
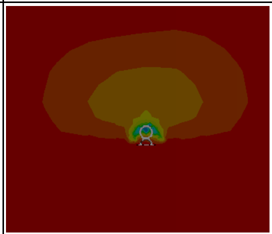
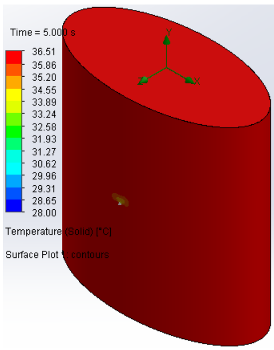
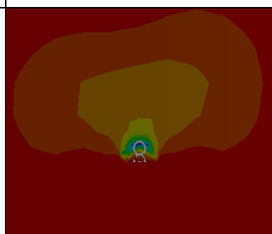
<table>
<tr><th>Velocity [m/s]</th><th colspan="2">Surface temperature plots [°C]</th></tr>
<tr><td>2</td><td>
</td><td></td></tr>
<tr><td>5</td><td>
</td><td></td></tr>
<tr><td>8</td><td>
</td><td></td></tr>
</table>

Fig. 3.2.4. The surface temperature of the body for E1.

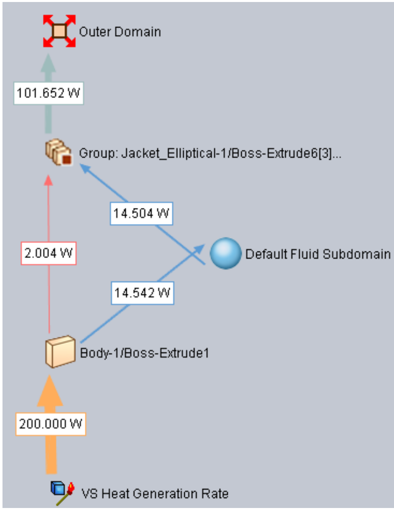


Fig. 3.2.5. Flux plot for E1 at 2 m/s.

As shown in Fig. 3.2.5, the flux plots are used to compute the rate of heat transfer in each case. As illustrated in Figs. 3.2.3 to 3.2.5, the values of flow pressure, surface temperature and heat flux are obtained for each of the five ventilation elements, and results are compared. The result comparison is shown in Figs. 3.2.6 to 3.2.8.

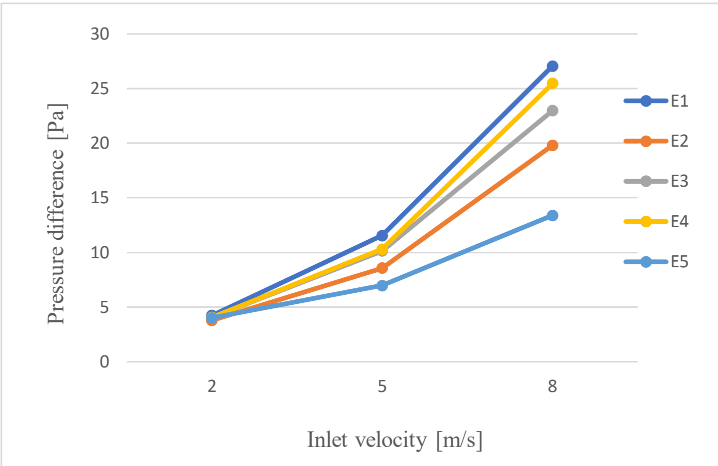


Fig. 3.2.6. Pressure difference v/s velocity.

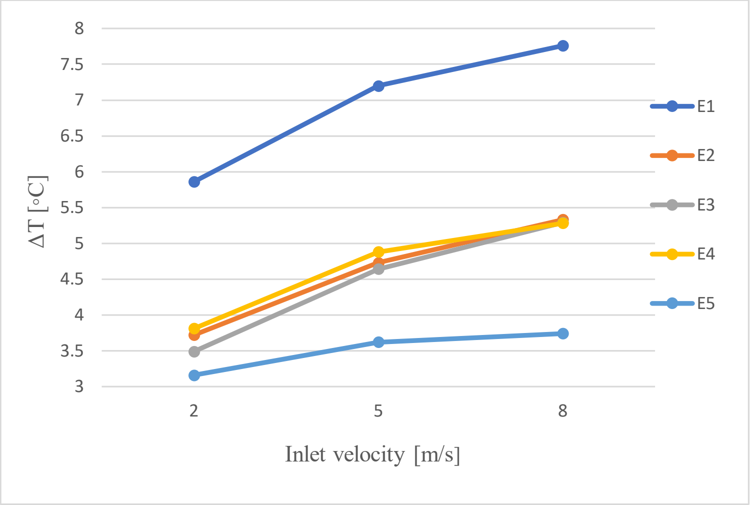


Fig. 3.2.7. Surface temperature difference (ΔT) v/s velocity.

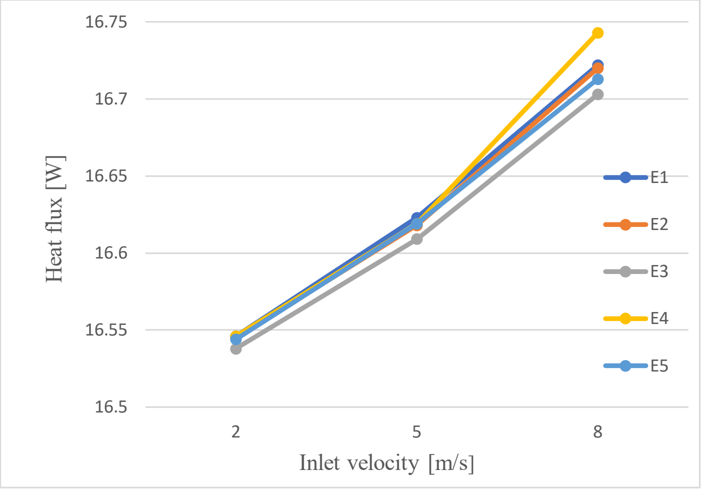


Fig. 3.2.8. Heat flux v/s velocity.

It is evident from the results analysis that element E5 provides the lowest pressure difference and smaller energy losses at the inlet flow channel than other mentioned elements in the study. A smaller pressure difference results in more uniform flow throughout the system and fewer flow fluctuations, and when you have fewer fluctuations in the flow, energy losses are also small, which ultimately provides better cooling of the system. Moreover, E5 offers more gradual temperature differences at different inlet velocities, resulting in fewer variations of temperature due to air fluctuation. As a person moves in different directions, the air intake through the protective jacket's vents may come from various sides and angles, which may result in flow fluctuations. If there are higher temperature variations at different air velocities, it may cause higher temperature at one point and lower at another, which may create discomfort in the body. Considering all the results and analysis points, element E5 is the most suitable out of all the mentioned ventilation elements in the present study, which could provide better cooling and comfort of the body.

3.3. Comparative Analysis of Complex Shape Ventilation Elements

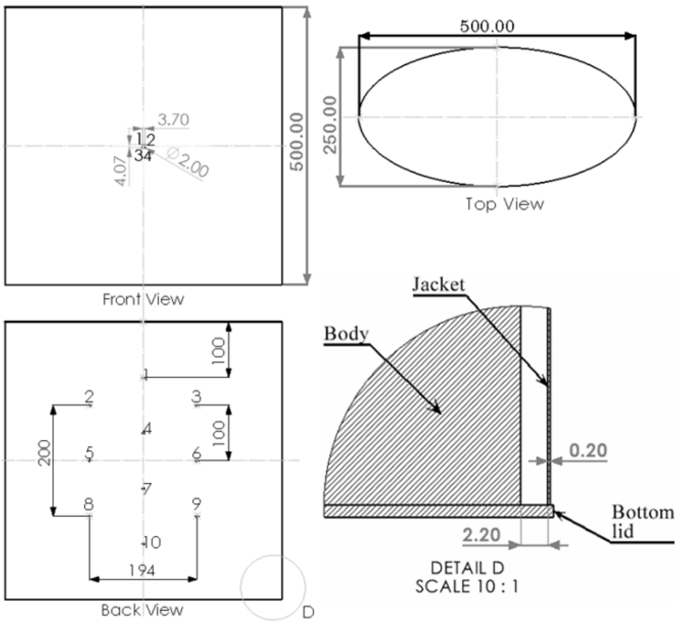
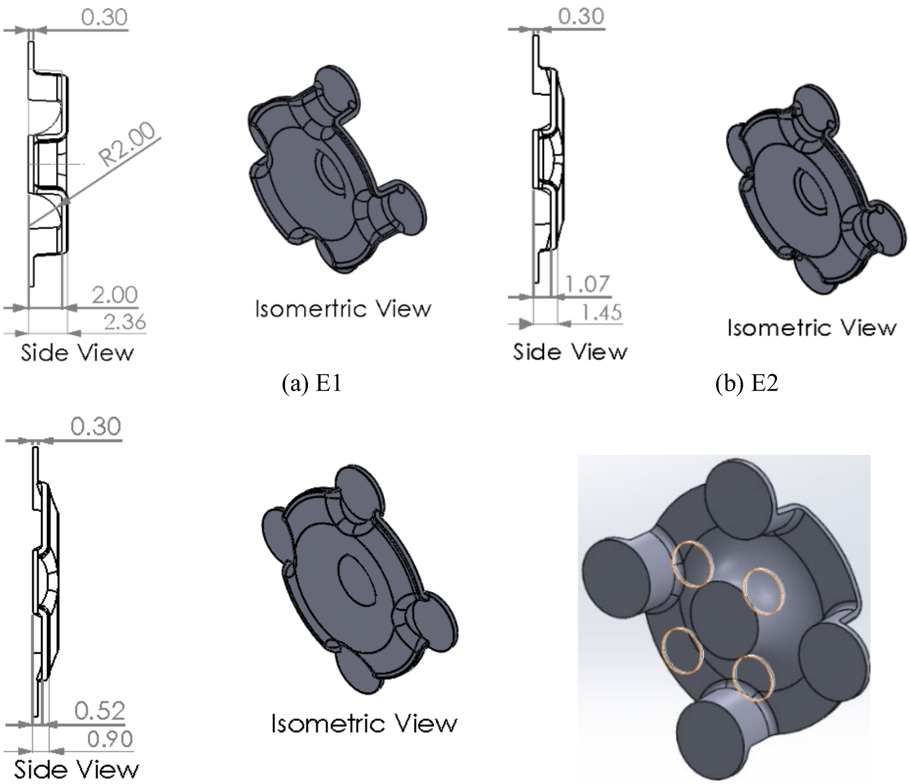


Fig. 3.3.1. Elliptical model design with single ventilation element comprising four ventilation holes.

The same elliptical model design is used in the study as it is mentioned in the previous study, the main difference here is that there are four inlet ventilation holes of 2 mm diameter on the front side comprising a single ventilation element and ten outlet holes of 4 mm diameter at the back side of the jacket. The schematic drawing of the model is shown in Fig. 3.3.1.



(a) E1 (b) E2

(c) E3 (d) Position of ventilation holes

Fig. 3.3.2. Three different geometric dimensions of ventilation element.

The simulation study is made with the same boundary conditions and material properties as mentioned in the previous study by positioning each ventilation element shown in Fig. 3.3.2. These ventilation elements are positioned simultaneously, and results are recorded for comparison. From the obtained results, it can be concluded that for a smaller inlet velocity of 2 m/s, element E1 is more appropriate, but it shows higher pressure difference and energy losses in the cell flow channel at a higher inlet velocity of 5 m/s. This is an important point to notice because some elements may work well at smaller velocities but may not provide good performance at higher velocities. Hence, it is important to choose the proper element according to working parameters. Considering overall performance at smaller and higher inlet velocities, 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 proceeding with further investigations, for example, optimization of the location points of the multiple ventilation elements on protective clothing.

3.4. Conclusions of the Analysis of Different Shape Ventilation Elements

1. It is evident from the analysis of the results in Section 3.2 that element E5 provides the lowest pressure difference and smaller energy losses at the inlet flow channel than other mentioned elements in the study. A smaller pressure difference results in more uniform flow throughout the system and fewer flow fluctuations, and when you have fewer fluctuations in the flow, energy losses are also small, which ultimately provides better cooling of the system.
2. From the obtained results in Section 3.3, it can be concluded that for a smaller inlet velocity of 2 m/s, element E1 is more appropriate, but it shows higher pressure difference and energy losses in the cell flow channel at a higher inlet velocity of 5 m/s. This is an important point to notice because some elements may work well at smaller velocities but may not provide good performance at higher velocities. Hence, it is important to choose the proper element according to working parameters.
3. 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.
4. Based on the analysis of the results in Section 3.4, it can be concluded that element E1 provides overall better results both at lower and higher air velocities. Moreover, E1 provides the smallest energy losses in the element flow channel and shows fewer fluctuations in pressure and temperature difference with the change in air velocity than other mentioned elements. This makes element E1 more suitable than the other mentioned elements, which could provide better cooling at different inlet air velocities.

4. FORMATION OF THE INPUT DATA FOR THE MODELING OF THE RESEARCH OBJECT (CLOTHING) MODEL

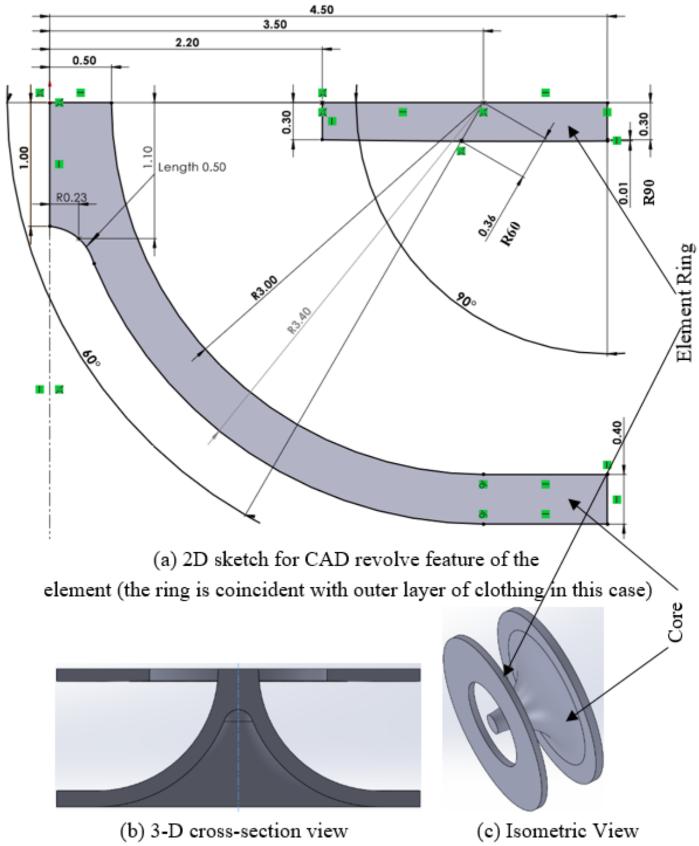
4.1. Formulation of Task of Shape Optimization of Ventilation Element

The primary objective of Section 4.1 is to determine the geometric shape of the element that minimizes flow energy losses in the cell flow channel, as shown by the pressure difference. A multistep approach was implemented to attain optimal results.

1. Strategizing the placement of control points for non-uniform rational B-splines (NURBS) to achieve elements with a smooth shape.
2. Constructing geometric models using SolidWorks in accordance with the design of experiments.
3. Calculating responses for a comprehensive model utilizing (CAE) software (SolidWorks Flow Simulation).
4. Creating metamodels for responses derived from the computer experiment.
5. Employing metamodel for optimizing the shape of elements.
6. Validating the optimal design of the entire model using (CAE) software.

Two design variables, the length of straight lines R60 and R90, are presented with specified lower and higher bounds, as shown in Figs. 4.1.1 and 4.1.2.

The lower endpoints of these lines ($0.36 \leq R60 \leq 2$; $0.01 \leq R90 \leq 2.5$) serve as control points for NURBS that determine the smooth shape of the outer ring of the ventilation element. Metamodel construction utilizes the mean square distance Latin hypercube (MSDLH) design of the experiment with two components, as shown in Fig. 4.1.3.

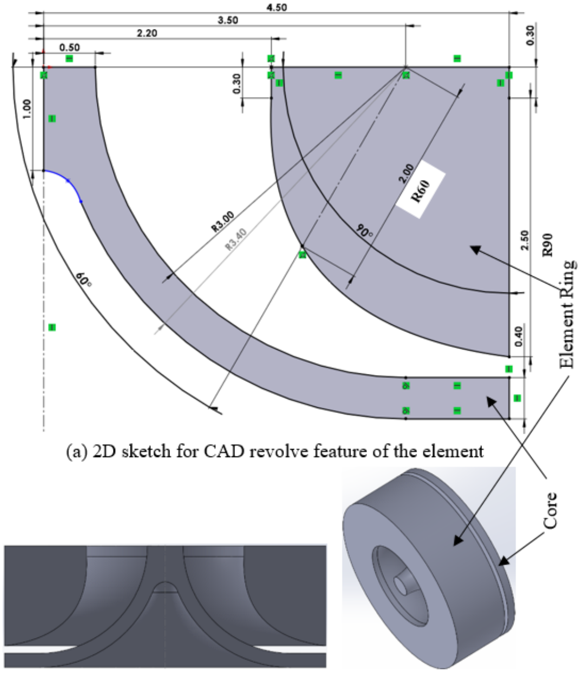


(a) 2D sketch for CAD revolve feature of the element (the ring is coincident with outer layer of clothing in this case)

(b) 3-D cross-section view (c) Isometric View

Fig. 4.1.1. CAD model of ventilation element with lower bounds of design variables.

Figures 4.1.1 and 4.1.2 display the smallest and largest dimensions of the element ring. Figure 4.1.3 (a) illustrates the design of experiment (DOE) with 12 numerical design values within a specified range. In this DOE, factors X1 = R60 and X2 = R90 represent the coordinates of the element ring, where R60 corresponds to points at 60°, and R90 corresponds to points at 90° with the horizontal axis in the 2D sketch.

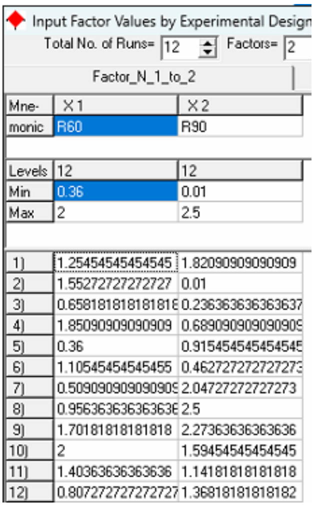


(a) 2D sketch for CAD revolve feature of the element

(b) 3-D cross-section view

(c) Isometric view

Fig. 4.1.2. CAD model of ventilation element CAD model with upper bounds of design variables.


Input Factor Values by Experimental Design

Total No. of Runs= 12 Factors= 2

Factor_N_1_to_2

Mne-monic	X1	X2
	R60	R90
Levels	12	12
Min	0.36	0.01
Max	2	2.5
1)	1.25454545454545	1.82090909090909
2)	1.55272727272727	0.01
3)	0.65818181818181818	0.236363636363637
4)	1.85090909090909	0.68909090909090909
5)	0.36	0.915454545454545
6)	1.10545454545455	0.462727272727273
7)	0.50909090909090909	2.04727272727273
8)	0.95636363636363636	2.5
9)	1.70181818181818	2.27363636363636
10)	2	1.59454545454545
11)	1.40363636363636	1.14181818181818
12)	0.807272727272727	1.36818181818182

Fig. 4.1.3. MSDLH DOE with 12 trials for two factors generated by KEDRO.

Using KEDRO, this design of experiment (DOE) is constructed, resulting in the generation of 12 geometric models of elements by SolidWorks. The model used in the simulation is the same as the one employed in Section 3.2, with the only difference being an increase in the air gap between the body and jacket from 2.2 mm to 3.4 mm. This is because the length of the used ventilation element is 3.4 mm in this study.

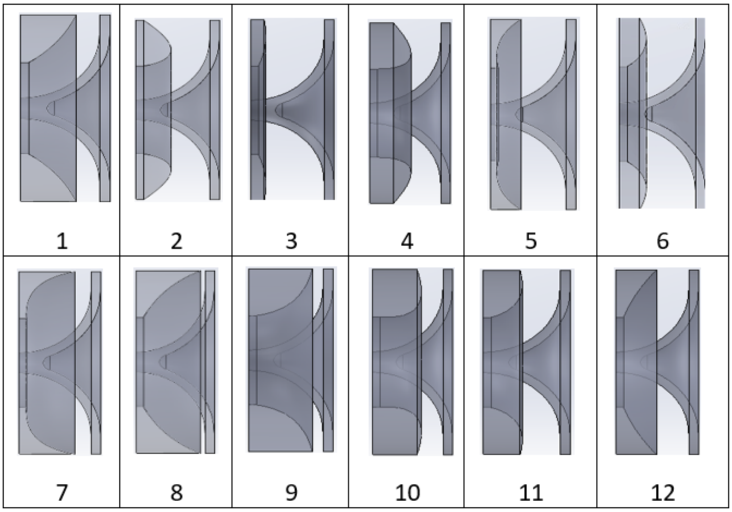


Fig. 4.1.4. Twelve geometrical models of elements constructed using DOE.

Results and Discussion

After setting all the input parameters and boundary conditions mentioned in the previous section, a flow simulation study is conducted for a physical time of 5 seconds. The results are then assessed in terms of flow pressure and surface temperature. From the obtained results, pressure difference (ΔP) and temperature difference (ΔT) are calculated for all twelve elements shown in Fig. 4.1.4. The estimated values of ΔP and ΔT are utilized as data inputs in KEDRO for further approximation and optimization. In Figs. 4.1.5 to 4.1.8, the symbol dP refers to ΔP, and dT refers to ΔT.

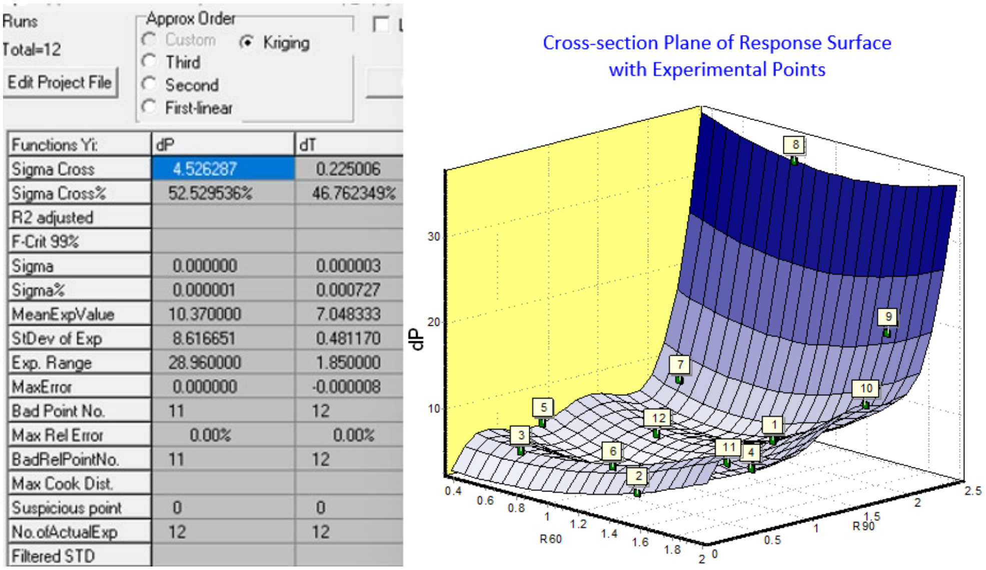


Fig. 4.1.5. Response surface d$P = f\,(R60, R90)$ using an experiment with 12 trials for Kriging approximation for the case of wind velocity of 4 m/s.

Figure 4.1.5 shows Kriging approximation by response surface with experimental points. There are two main indicators to check the quality of approximation: Sigma Cross% and Max Rel Error. Here, Sigma Cross is the leave-one-out-cross-validation error, and Max Rel Error is the maximum relative error (in relation to the experimental values). Your approximation's quality will be severely lacking if the value of Sigma Cross% is closer to or greater than 100 %. A smaller value of Sigma Cross% will result in a better approximation. The approximation is also considered better when the value of the Max Rel Error percentage is smaller or close to zero. A Sigma Cross% of 52.52 % and a Max Rel Error of 0.001 % are indicative of an acceptable level of approximation in this case.

Set Range for Xj, Yi, Fi and Click ColorBox to Visualize Active Constraint!

Indices No	Opt	Min	Max
1)X1: R60	0.501114	0.36	2
2)X2: R90	0.01	0.01	2.5
3)Y1: dP	2.88669	0	0
4)Y2: dT	8.79647	0	0
5)F1	0.501114	0	0
6)F2	0.01	0	0

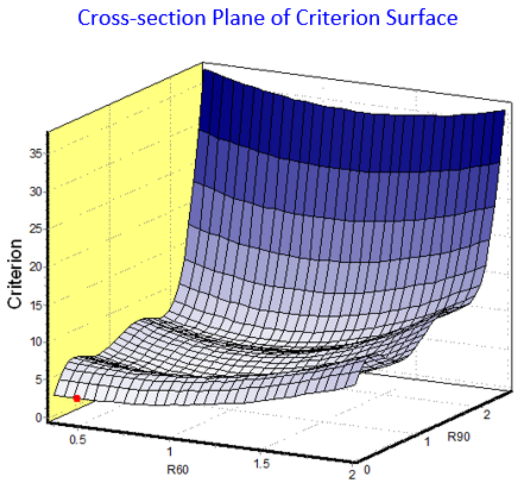


Fig. 4.1.6. Optimization results for the case of wind velocity of 4 m/s (the red point indicates a global minimum of d*P*).

The optimization results according to the minimal pressure difference as a criterion are displayed in Fig. 4.1.6. The obtained results are verified using a flow simulation study conducted at an inlet velocity of 8 m/s. The results are then utilized for approximation and optimization by repeating the same process.

Specific optimal design points for the element ring were determined based on the criteria of minimum pressure difference at wind velocities of 4 m/s and 8 m/s. A very small difference was also observed in the obtained values of optimum design points at 4 m/s and 8 m/s. The coordinate value for R90 remains the same in both cases, with a slight variation for R60. The metamodel's quality for the approximation of results at 8 m/s was better based on the obtained values of Sigma Cross%. It can be concluded from the obtained results that optimum design variables for the element ring can provide minimum pressure difference and, ultimately, better cooling. The ring is practically non-existent at the optimal design points, suggesting that the element without an outside ring will provide the best results. The study demonstrates that employing a metamodeling approach with CFD simulation can significantly decrease the computing time required for optimization.

4.2. Analysis of Ventilation Element with and without Constant Cross-Section Area Opening

Section 4.2 presents the design of a ventilation element with a constant cross-sectional area of 3.14 mm^2, including an outside ring. The paper analyses five distinct scenarios, four of which involve varying coordinate values for the outer ring and core, while the fifth scenario consists of the ventilation element without an outer ring. The efficiency of the ventilation element design is assessed by analysing and comparing the outcomes of all five scenarios. These ventilation elements are attached to the ventilation hole on the inner side of the protective jacket. The goal is to identify the element's geometric configuration that leads to the lowest energy losses in the flow channel of the cell, which are shown by the pressure difference. The energy losses in the flow increase as the pressure difference (ΔP) increases, and the cooling of the body decreases when the flow is weakened or loses energy. In this study, the same elliptical model of the body and jacket is used, as it is described in Section 3.2. Also, the same boundary condition is utilized to obtain results. A simulation study is carried out at three different inlet air velocities of 2 m/s, 5 m/s and 8 m/s.

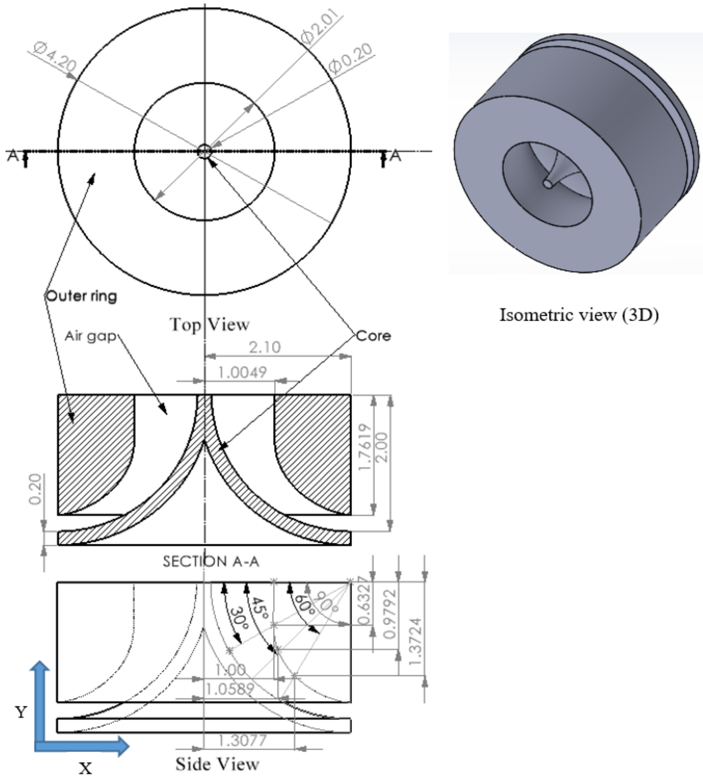


Fig. 4.2.1. Design of element E0-90.

There are four ventilation element designs with outer rings named E0-30, E0-45, E0-60, and E0-90, while the fifth case consists of a core without an outer ring, which is named E1. Figure 4.2.1 presents the design of element E0-90 with core and outer rings. The coordinate values used in all cases of ventilation element design are mentioned in Table 4.2. All mentioned dimensions are in millimetres.

Table 4.2

Coordinate Values of Elements Design

α	X1	Y1	X2	Y2	S
0°	1.0049	0	0.1	0	3.14
30°	1	0.6327	0.3679	1	
45°	1.0589	0.9792	0.6857	1.4140	
60°	1.3077	1.3724	1.1	1.7320	
90°	2.10	1.7619	2.1	2	

In Table 4.2, the symbol α indicates the reference coordinate angle ranging from 0° to 90°. The coordinates for the ring are denoted by X1 and Y1, while the coordinates for the core are denoted by X2 and Y2. Letter S denotes the constant cross-sectional area of the air gap in the element. Therefore, the cross-sectional area between the core and outer ring remains constant at all specified angles. The intricate details of the element's design are shown in Fig. 4.2.1.

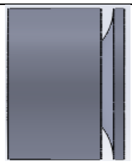
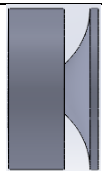
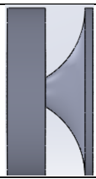
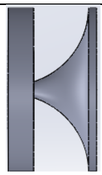
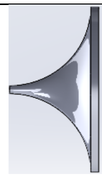
				
E0-90	E0-60	E0-45	E0-30	E1

Fig. 4.2.2. Ventilation elements.

Results Analysis and Discussion

The result analysis is based on the same concept as it is described in Section 3.2.

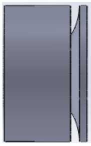
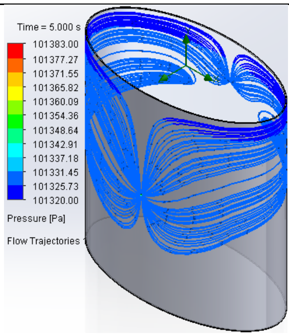
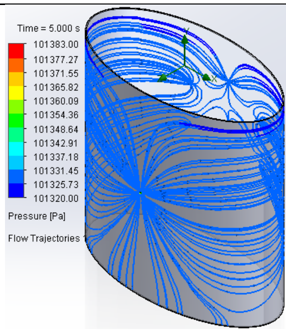
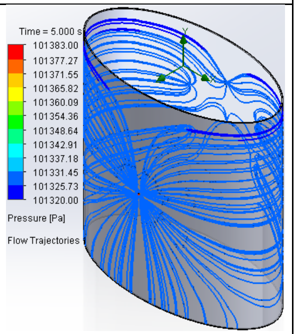
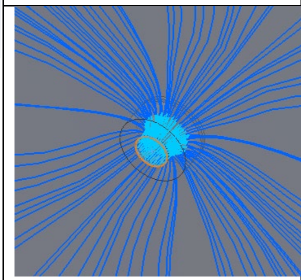
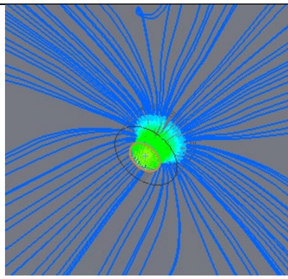
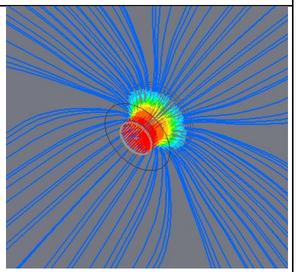
<table>
<tr><td rowspan="3">Element</td><td colspan="3">Pressure plots [Pa]</td></tr>
<tr><td colspan="3">Inlet velocity [m/s]</td></tr>
<tr><td>2 m/s</td><td>5 m/s</td><td>8 m/s</td></tr>
<tr><td rowspan="2">E0-90
</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

Fig. 4.2.3. Flow pressure plots for E0-90.

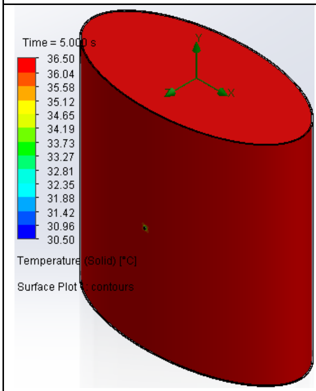
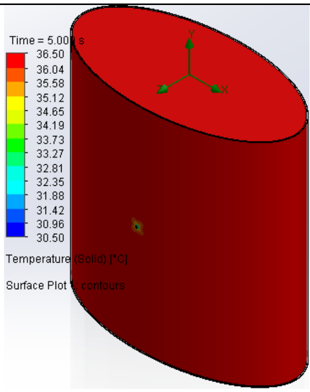
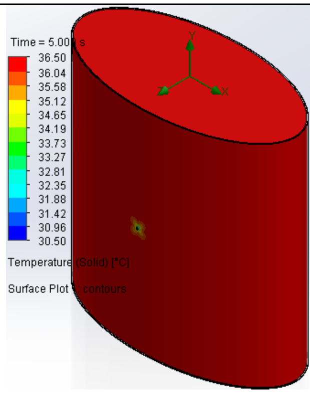
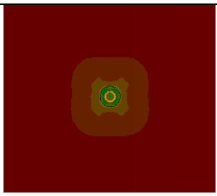
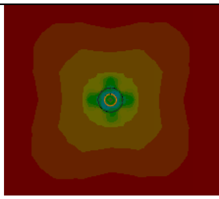
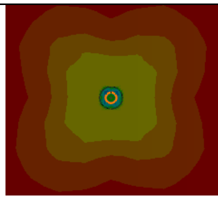
Surface temperature of body [°C]		
Velocity [m/s]		
2	5	8
		
		

Fig. 3.4.4. Surface temperature plots for element E0-90.

Similar to that in Figs. 4.2.3 and 4.2.4, the values of flow pressure and surface temperature of remaining ventilation elements are calculated, and results are compared. The results comparison is shown in Figs. 4.2.5 and 4.2.6.

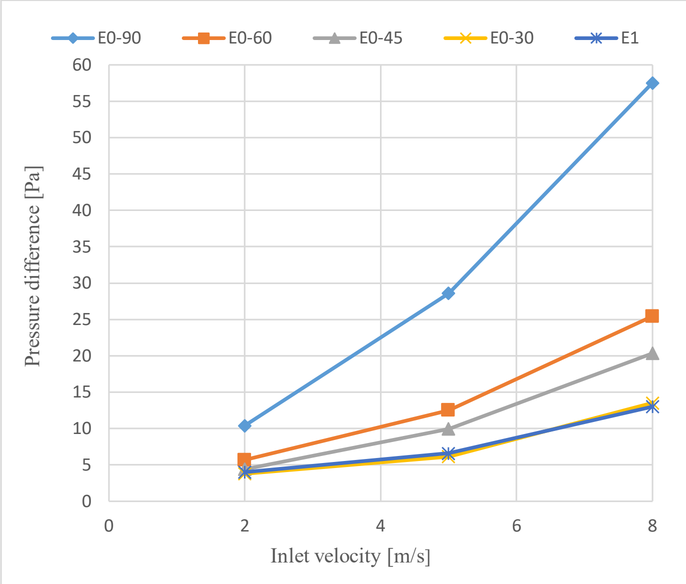


Fig. 4.2.5. Pressure difference at different air velocities.

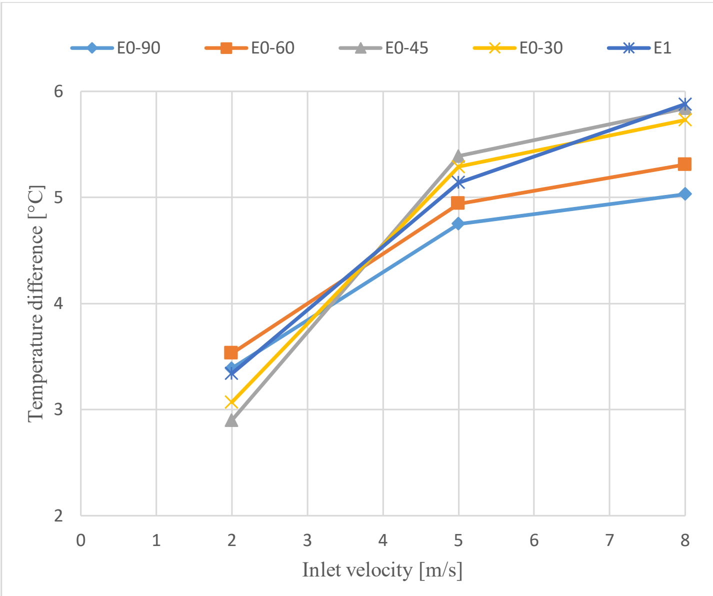


Fig. 4.2.6. Temperature difference at different air velocities.

Upon observing Fig. 4.2.6, it is evident that at a velocity of 2 m/s, elements E0-60 and E0-90 exhibit the highest difference in temperature. However, with velocities of 5 m/s and 8 m/s, both elements display the smallest temperature difference. The elements E0-60 and E0-90 exhibit higher energy losses and pressure differences, which increase with the increase in velocity. This indicates the low efficiency of these elements. Regarding elements E0-45 and E0-30, both exhibit the smallest temperature difference at a velocity of 2 m/s but the largest difference at 5 m/s. This suggests that they may not be particularly efficient at lower speeds but can deliver better results at higher air velocities. E1 is the element that exhibits consistent and better performance at both lower and higher input velocities. This is due to the fact that E1 exhibits the lowest energy losses in the flow channel at all mentioned velocities. Considering all the mentioned points in the Results and Discussion, it can be concluded that element E1 provides overall better results both at lower and higher air velocities.

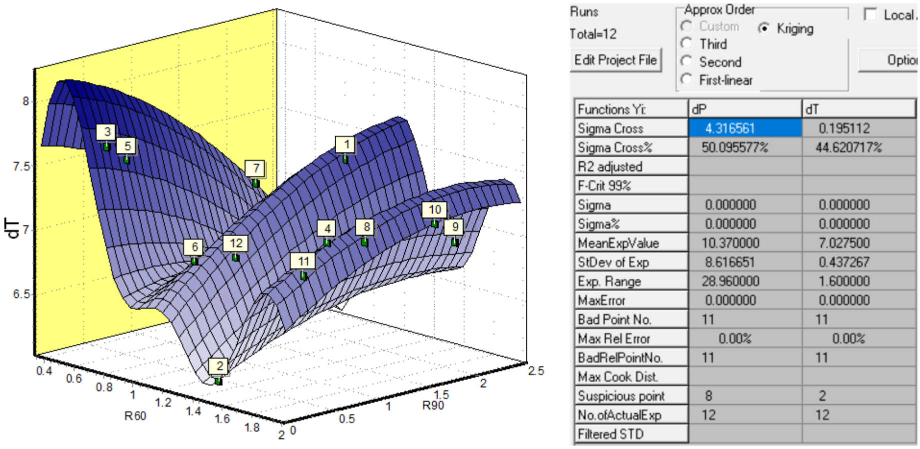
4.3. Selection of Appropriate Criteria for Optimization of Ventilation Element

Section 4.3 aims to determine suitable criteria for optimizing the shape of ventilation elements in protective garments using a metamodeling approach. Complex models generally need computationally demanding algorithms; hence metamodels, sometimes called approximations, response surfaces, or surrogate models, are utilized to expedite the optimization process. The approach is the same as described in Section 4.1, but here six different criteria are used for the analysis.

The different criteria considered in the flow simulation study are:

1) HTR – heat transfer rate [W];
2) H – absolute total enthalpy (average) [J/kg];
3) ΔH – absolute total enthalpy rate [W];
4) HF – surface heat flux (average) [W/m^2];
5) dP – pressure difference (from flow trajectories) [Pa];
6) dT – surface temperature difference (body) [°C].

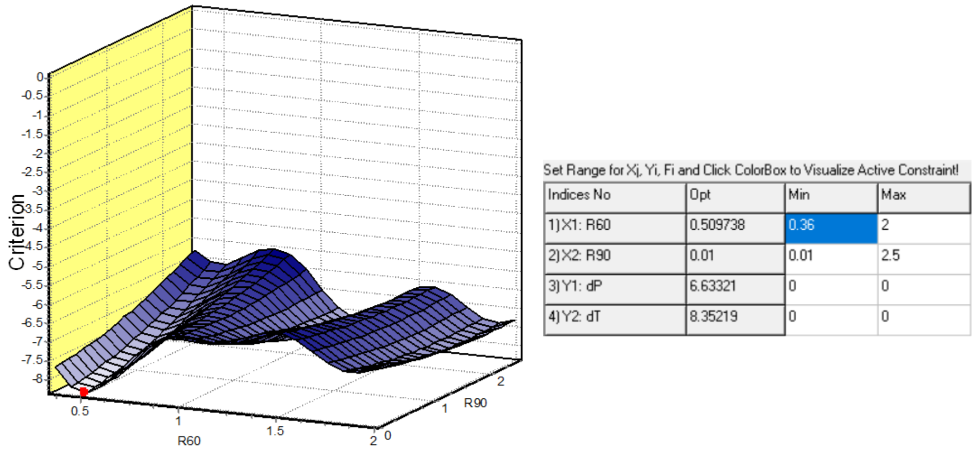
Results and Discussion



Functions Yi:	dP	dT
Sigma Cross	4.316561	0.195112
Sigma Cross%	50.095577%	44.620717%
R2 adjusted		
F-Crit 99%		
Sigma	0.000000	0.000000
Sigma%	0.000000	0.000000
MeanExpValue	10.370000	7.027500
StDev of Exp	8.616651	0.437267
Exp. Range	28.960000	1.600000
MaxError	0.000000	0.000000
Bad Point No.	11	11
Max Rel Error	0.00%	0.00%
BadRelPointNo.	11	11
Max Cook Dist.		
Suspicious point	8	2
No.ofActualExp	12	12
Filtered STD		

(a) **(b)**

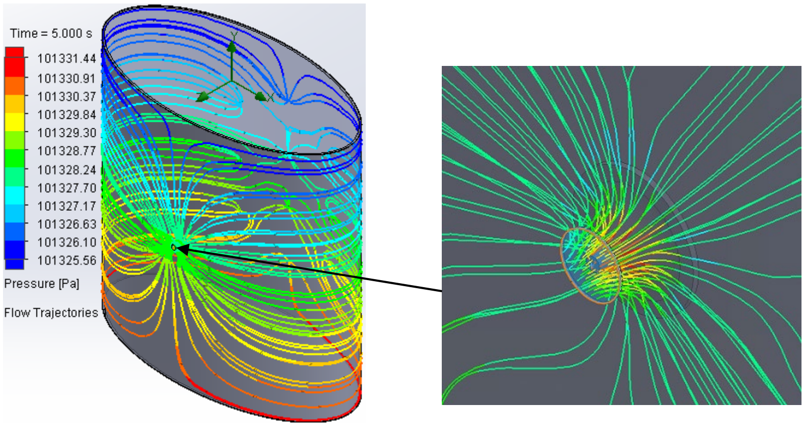
Fig. 4.3.1. Response surface d$T = f\,(R60,\ R90)$ using 12 DOE for Kriging approximation: (a) cross-section plane of response surface; (b) indices of the approximation quality.



Indices No	Opt	Min	Max
1) X1: R60	0.509738	0.36	2
2) X2: R90	0.01	0.01	2.5
3) Y1: dP	6.63321	0	0
4) Y2: dT	8.35219	0	0

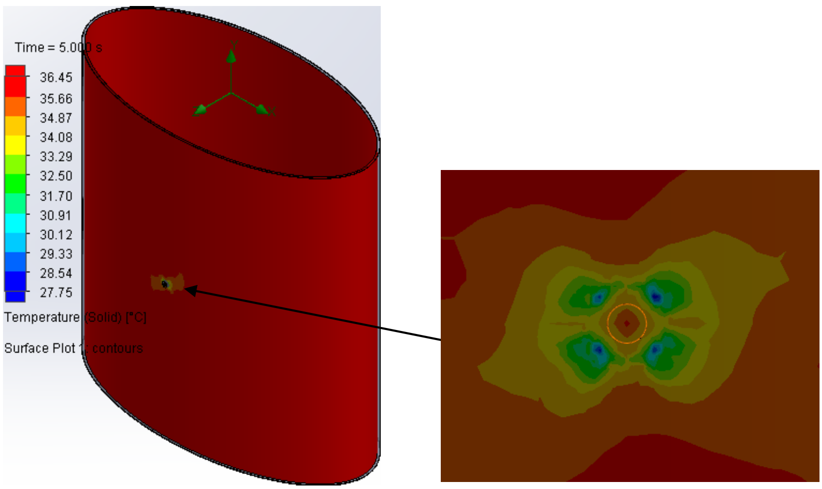
(a) **(b)**

Fig. 4.3.2. Optimization result (the red dot indicates a global minimum of -dT): (a) cross-section plane of the criterion surface; (b) optimum values.



(**a**) (**b**)

Fig. 4.3.3. Flow pressure plots for optimum element design: (a) flow pressure over the entire model; (b) zoomed view near the ventilation hole.

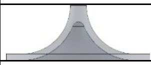
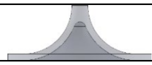


(**a**) (**b**)

Fig. 4.3.4. Surface temperature of body: (a) surface temperature plot of the whole model; (b) enlarged view near the ventilation hole.

Table 4.3

Obtained Results

Indices	**d*P* [Pa]**	**d*T* [°C]**
The optimum shape of the element	R60 = 0.50	R60 = 0.50
	R90 = 0.01	R90 = 0.01
		
Sigma Cross%	50.09	44.62
Optimum values from KEDRO	6.63 (Min)	8.35 (Max)
Value from flow simulation results	6.75	8.55

The values obtained for the optimal design through optimization using KEDRO and SolidWorks flow simulation are close with a minor deviation of 0.12 Pa for dP and 0.2 °C for dT. The percentage difference between the obtained values is 1.7 % for dP and 2.34 % for dT. The error falls within the permissible tolerance as it is less than 5 %.

4.4. Conclusions on Shape Optimization of Ventilation Element

1. It can be concluded from the obtained results in Section 4.1 that the ring is practically non-existent at the optimal design points, suggesting that the element without an outside ring will provide the best results. The study demonstrates that employing a metamodeling approach with CFD simulation can significantly decrease the computing time required for optimization.
2. In Section 4.3, different criteria were considered for the optimization of the ventilation element, and the results indicate that not all parameter values will show enough sensitivity for the approximation and optimization of the element.
3. From the results, it is clear that dP and dT are the most appropriate and sensitive criteria for the optimization of the ventilation element out of all the mentioned criteria in this study. Moreover, both these parameters provide the same optimal shape of the ventilation element.
4. However, dT shows slightly better approximation quality than dP, which makes dT the most appropriate parameter for the optimization of the ventilation element. This is also true as the ventilation elements are to be used in protective clothing to provide efficient cooling of the human body in case of warm environments or heavy work-load conditions, and temperature is the best indicator to predict the efficiency of cooling.

5. ANALYSIS OF THE EFFICIENCY OF THE STUDIED OBJECT (CLOTHING) AND VENTILATION ELEMENT BY SOLIDWORKS FLOW SIMULATION

5.1. Analysis of Efficiency of Ventilation Element with Simplified Model

This study aims to assess the efficacy of ventilation elements E1 and E2 with a focus on reducing computation time. The ventilation elements are designed for use in protective clothing to provide effective cooling and prevent insects, rain, and dust from directly reaching the human body. Therefore, selecting the correct element is crucial. Using a fine mesh in simulations is crucial for obtaining accurate findings, but it significantly increases computing time. On the other hand, a coarse mesh may not provide precise values but might be useful for comparing results when using the same parameters to estimate efficiency. This study compares ventilation elements E1 and E2 in two separate scenarios to determine the most efficient element with respect to optimal computational time. The first scenario uses a simplified elliptical model of the human body and jacket. In the second case, the model is simplified into two square plates, where one plate refers to the jacket surface and the other represents the body. This study utilizes SolidWorks flow simulation to provide results with an inlet air velocity of 2 m/s. The specific model dimensions and boundary conditions are explained in the next section.

5.2. Simplified Model Design and Boundary Conditions

This study compares ventilation elements E1 and E2 to determine the most efficient element with respect to optimal computational time. The model is simplified into two square plates, where one plate refers to the jacket surface and the other represents the body. The boundary conditions and material properties are kept the same as in previous studies (Section 3.2).

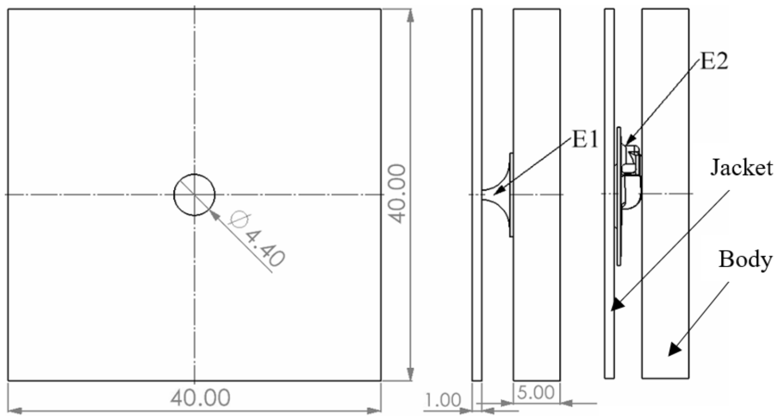


Fig. 5.2.1. Simplified model with two square plates.

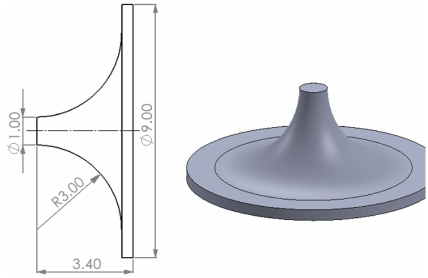


Fig. 5.2.2. Ventilation element E1.

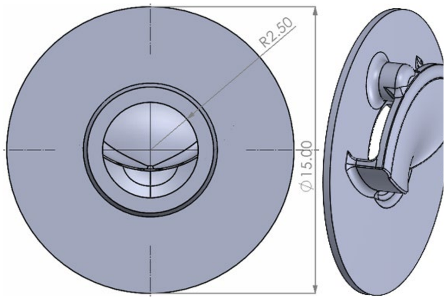


Fig. 5.2.3. Ventilation element E2.

The criteria that were considered in the analysis of the flow simulation study are:

1) HTR – heat transfer rate [W];
2) HF (avg.) – surface heat flux (average) [W/m^2];
3) dP - pressure difference [Pa];
4) dT – surface temperature difference (body) [°C];
5) T (avg.) – average surface temperature (body) [°C].

Results and Discussion

All the results mentioned here are simulated for the physical time of 10 seconds. The values of criteria dP and dT are calculated from the results presented in Figs. 5.2.4 and 5.2.5, respectively, while the values of the remaining parameters are obtained from the surface parameter option available in the results section of the SolidWorks flow simulation. All the obtained values are illustrated in Table 5.2. In Table 5.2, Δ refers to the difference in value between E1 and E2.

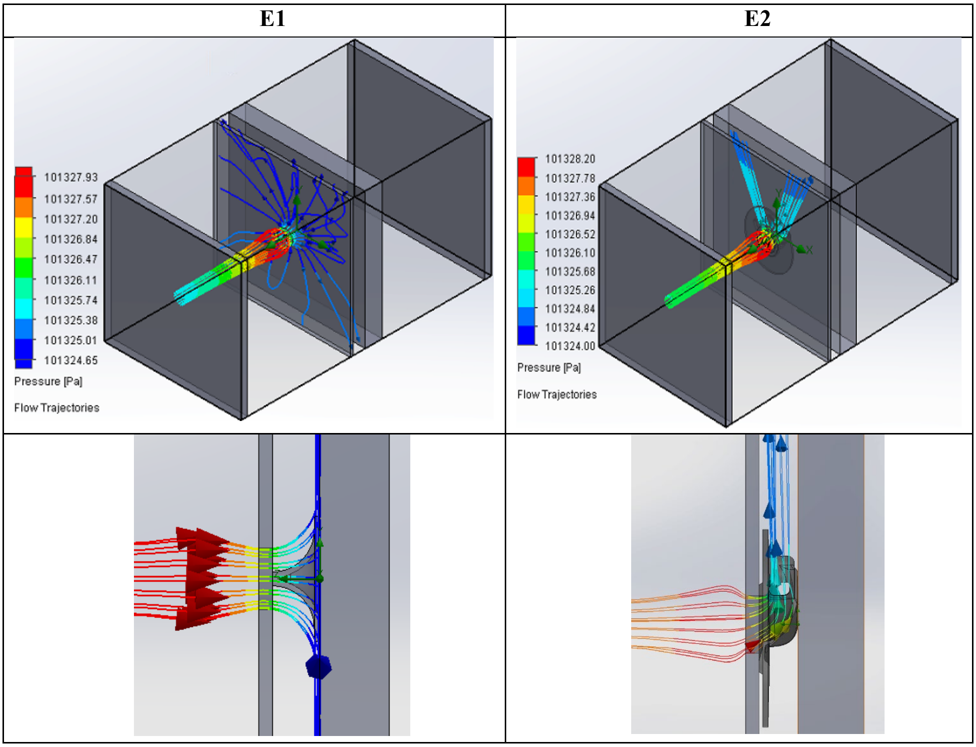
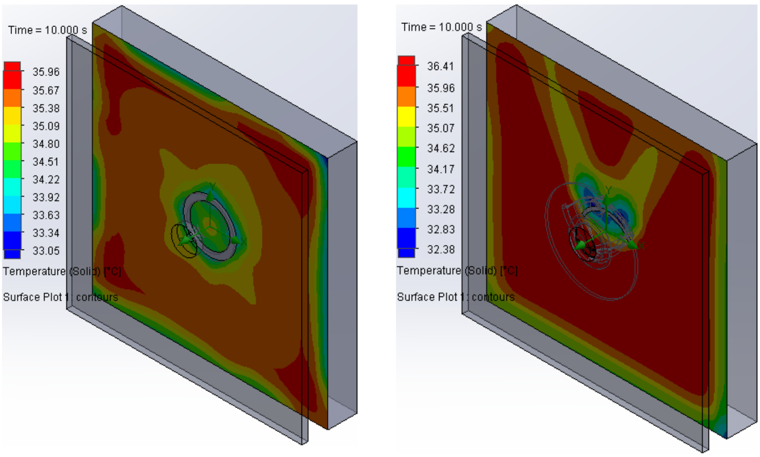


Fig. 5.2.4. Flow pressure trajectories.



E1 E2

Fig. 5.2.5. Surface temperature plots in Case 2.

Table 5.2

Numerical Values of Results for Case 2

Parameters	E1	E2	Δ
HTR [W]	0.328	0.196	0.132
HF (avg.) [W/m²]	207.097	124.507	82.59
dP [Pa]	3.28	4.2	0.92
dT [°C]	2.91	4.03	1.12
T (avg.) [°C]	35.34	35.90	0.56

Table 5.2 shows that the sensitivity of the HF and dT is higher than other criteria. Element E1 provides higher value of HF compared to E2, indicating that the heat transfer rate of E1 is better. A higher heat transfer rate refers to a higher cooling efficiency. Therefore, the average body temperature for E1 (35.34 °C) is lower than that of E2 (35.90 °C). Based on this analysis, it can be concluded that element E1 offers better cooling efficiency compared to E2.

5.3. Selection of Appropriate Criteria for Analysing Efficiency of Ventilated Clothing

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.

The criteria analysed in the flow simulation study are:

1) HTR – heat transfer rate [W];
2) ΔH – absolute total enthalpy rate [W];
3) HF (avg.) – surface heat flux (average) [W/m^2];
4) dP – pressure difference [Pa];
5) dT – surface temperature difference [°C];
6) T (avg.) – average surface temperature [°C];
7) PMV (avg.) – predicted mean vote;
8) PPD (avg.) – predicted percentage dissatisfied (average) [%].

Results and Discussion

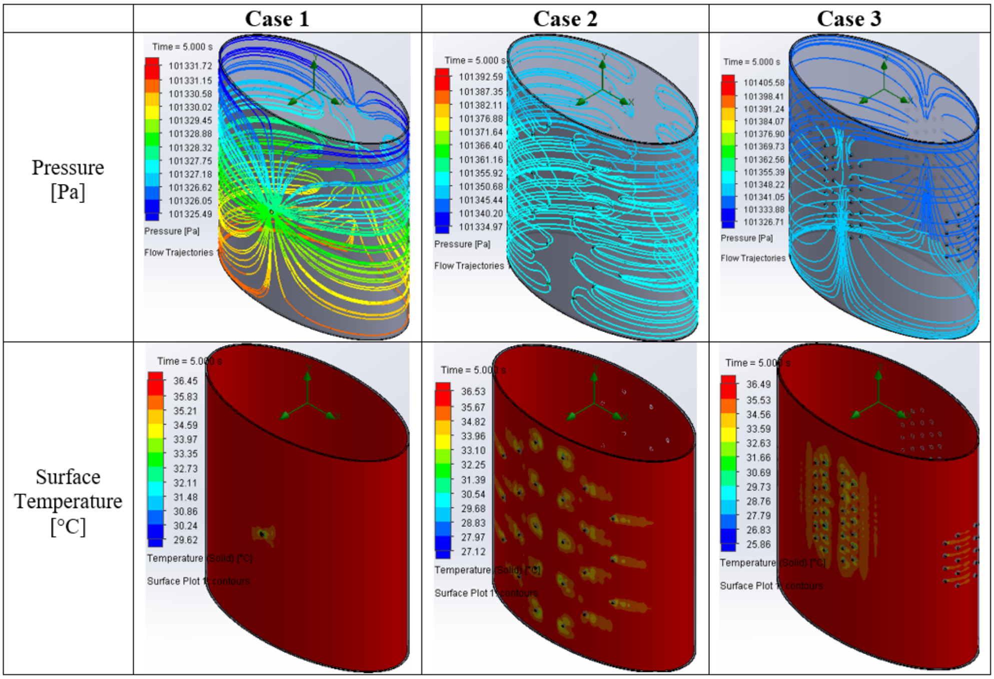


Fig. 5.3. Flow pressure and surface temperature plots in each case.

Table 5.3

Numerical Values of 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
dP [Pa]	6.23	57.62	78.87
dT [°C]	6.83	9.41	10.63
T (avg.) [°C]	36.31	36.15	36.03
PMV (avg.)	3.05	2.95	2.93
PPD (avg.) [%]	99	98.8	98.5

The analysis of the results suggests that the most suitable criteria for evaluating the heat dissipation from the system (body) in this study are HTR and HF. Given that the objective is to forecast cooling efficiency, either of the criteria can be advantageous, as cooling efficiency rises in accordance with an increase in heat transfer rate.

5.4. Conclusions of Appropriate Criteria for Analysing the Efficiency of Ventilated Clothing

1. Based on the result analysis, it can be concluded that HTR and HF are the most appropriate criteria for analysing the heat removal from the system (body) in this 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.
2. While the temperature difference can follow criteria for the analysis, 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 results.
3. This study demonstrates variations in parameter values in CFD simulations in different instances and identifies criteria that are helpful for forecasting cooling efficiency in the analysis. It is evident that certain criteria, such as pressure, may not be very useful in predicting the cooling efficiency of the system. Moreover, parameters like average temperature can show less sensitivity in certain scenarios.
4. In the future, it allows 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 position.

CONCLUSIONS

1. This Thesis provides a detailed analysis of the flow simulation study using a simplified model of the human body with a protective jacket. SolidWorks flow simulation is utilized for numerical simulation, offering a concise understanding of simulation studies and the interaction of fluid flow with the ventilated model.
2. Furthermore, various ventilation elements of simple and complex shapes are created and analysed in detail by positioning each element at the corresponding ventilation hole in the ventilated jacket. The conducted numerical analysis provides insights into the impact of different shapes of ventilation elements on fluid flow and identifies that the toroidal cut-out shape of the element is the most efficient out of the others presented in the study.
3. A methodology was developed to optimize the shape of a toroidal cut-out ventilation element. In order to accomplish the objective, a metamodeling technique was employed, using different order polynomial local and global approximations, as well as Kriging approximations. Numerical simulation results were approximated and optimized to obtain optimum values of element design.
4. Numerical simulation was conducted using the optimized ventilation element to check the reliability of the method and optimization results. The difference between the numerical and optimization results is 2.34 %. The error is within acceptable tolerance since it is below 5%.
5. The optimization study effectively demonstrates that combining the metamodeling approach with CFD simulation can greatly reduce the computational time required for the optimization. It takes about 4 hours of processing time on a multicore computer with i9 processor to conduct a CFD simulation for calculating a single criterion point for the stated problem. However, by utilizing metamodels, the entire optimization process may be completed in just a few minutes.
6. In the future, it will allow for the development of a more accurate shape optimization problem for ventilation elements, taking into account numerous positions of inlets and uncertainty caused by factors such as varying wind direction. Also, this technique is useful in solving other similar optimization problems.
7. Furthermore, various criteria are analysed to predict the most suitable one for the shape optimization of ventilation elements and predict the cooling efficiency of ventilated clothing in the numerical simulation. The results indicate that the flow pressure (dP) and temperature difference (dT) are the most sensitive criteria for optimizing ventilation elements, while the heat transfer rate (HTR) is the most appropriate for predicting cooling efficiency. This enables the selection of the right criteria for future studies.

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