Synopsis of the thesis to be submitted for the award of the degree of Doctor of Philosophy

# NUMERICAL SIMULATION AND EXPERIMENTAL EVALUATION OF HEAT TRANSFER IN EXTREME COLD CLIMATE CLOTHING

by

**Vikrant Uday Dupade**

**(2017MEZ8601)**

**DEPARTMENT OF MECHANICAL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**NEW DELHI-110016, INDIA**

**MARCH 2023**

## TABLE OF CONTENTS

# 1. INTRODUCTION

## 1.1 Background

At Siachen Glacier-Saltoro Ridge in northern Jammu and Kashmir, ambient temperature can drop up to -60 °C. Snowstorms, low atmospheric pressure, and high wind speeds (up to 60 km/h) worsen the climate. Without proper clothing, extreme cold causes frostnip, frostbite, hypothermia, and heart disease. Over 1000 Indian soldiers, including 35 officers, died in harsh conditions until August 15, 2022. Irrespective of environmental conditions, maintaining a 37 °C body core temperature allows a person to work safely and efficiently. Cold-weather diseases can be avoided by using the appropriate clothing. For extreme cold, multilayer clothing is best. The insulation layer, which provides most of the thermal resistance, should be optimised to be lighter and thinner still providing the necessary thermal insulation and comfort. To develop effective extreme cold weather clothing, fibre denier, cross-section, and structural parameters like areal density and thickness must be optimised. For extreme cold weather clothing insulation, high-bulk nonwoven structures are used. The insulating medium needs to be improved by using multiple layers. Modelling and predicting thermophysical properties and heat transfer through high-bulk nonwovens can predict thermal insulation before production. Sweating thermal manikins can be used to evaluate the performance of extreme cold weather clothing [1].

## 1.2 Construction of Extreme Cold Weather Clothing

A multilayer clothing system is made up of three different levels of fabric, each level must perform a specific task [2, 3].

Level 1: It is a skin-contacting polyester knitted fabric that manages moisture and provides tactile comfort. The skin-contacting layer must be antibacterial to prevent bacterial and fungal infections.

Level 2: A polyester grid fleece middle layer. Fleece fabrics have high insulation and moisture transfer. Fleece fabric insulates and spreads sensible sweat to keep skin comfortable.

Level 3: It has multiple layers of insulation with a wind and waterproof protective nylon layer.

Optional active heating layer: Mountain and military multilayer clothing with external electrical heating are widely used in temperatures down to -40 °C and low metabolic activity. Cold-weather clothing with external heating expands its use.

## 1.3 Heat and moisture transfer through cold weather clothing

Heat and moisture transfer through extreme cold weather clothing is studied to analyse the performance. The fibrous material transfers heat from human skin to the environment via conduction, convection, and radiation. Mobile condensation and freezing can affect the performance and life of extreme cold weather clothing, making moisture transfer more important. When a person is active and generates metabolic heat, sweating glands activate to increase heat loss through perspiration. In extreme cold weather, sweating is only possible if the clothing insulation is too high or the wearer is doing physical activities like mountain climbing, skiing, or carrying heavy loads. Heat transfer through the fabric is a coupled conduction radiation heat transfer problem for porosities below 0.992 due to the lack of free air movement for convection. Fibre diameter, areal density, insulating material thickness, and layering sequence affect heat transfer through multi-layered protective clothing. Fabric thermophysical properties affect heat transfer and can be used to optimise clothing insulation. Several numerical models predict heat transfer through multi-layered cold protective clothing. Extreme cold climate survival depends on clothing insulation, metabolic heat, and environmental temperature. Electrical, phase change material, chemical, and fluid flow heating are external heating methods. External heat extends cold protective clothing's range. A sweating-guarded hot plate tests the thermal and evaporative resistance of developed fabrics. The thermal resistance of high bulk nonwoven can be studied using a custom-made guarded hot plate inside a cold chamber that can reach and maintain -60 °C. Full ensemble extreme cold weather clothing can be tested using a sweating thermal manikin. The thermal manikin can be set to temperature control mode to maintain the manikin surface temperature or heat flux mode to maintain metabolic heat generation to each zone. A nude thermal manikin can evaluate boundary air layer insulation, while a clothed manikin can evaluate total and intrinsic clothing insulation. The sweating rate of the manikin can be fixed at each zone of the manikin to evaluate the evaporative clothing resistance of the clothing [4, 5].

## 2. LITERATURE REVIEW AND RESEARCH OBJECTIVES

### 2.1 Estimation of temperature-dependent effective thermal conductivity and specific heat of thermally bonded high bulk nonwoven exposed to sub-zero temperature

Many studies have examined how fibre fineness, pore size, and areal density affect heat transfer through nonwoven and thermal conductivity [6, 7]. Coupled conduction-radiation heat transfer model is used to determine the fabric temperature profile [7]. The transient fabric temperature profile is plotted at various time steps. Fibrous material's temperature-dependent thermal conductivity [8], specific heat [9], and radiative properties [10] are modelled. These studies show that fire-protective clothing's thermal conductivity and specific heat increase linearly with local temperature. By considering fabric transmittance and refractive index, the diffusion equation can include radiation heat transfer for optically thick fibrous material [11].

Since extreme cold weather clothing uses high bulk nonwovens as insulators, thermal conductivity and specific heat must be studied. The literature does not estimate the thermophysical properties of high bulk nonwoven exposed to sub-zero temperatures. The literature does not examine how fibre hollowness affects thermal conductivity.

### 2.2 Effect of layering sequence and ambient temperature on the thermal resistance of multilayer high bulk nonwoven under extreme cold temperatures

Barker et al. [12] examined how fabric thickness, bulk density, and layering affect thermal insulation. They found that single-layer fabric thermal insulation increases with thickness. Gnanauthayan et al. [13] examined heat transfer through a multilayer nonwoven assembly layering sequence. They found that placing finer fibre nonwoven on the outside (exposed to ambient) and coarser on the inside provided better thermal insulation than the reverse order. Tian et al. [14] examined how layering sequence affects fabric transient thermal performance from 20°C to 30°C. Sequences of multilayer fabrics affect thermal response. The thermal response of multilayer fabric is most affected by the fabric layer in contact with the hot plate (skin). Wu et al. [15] examined how fabric layering sequence affects heat and moisture transfer. Layering sequence affected fabric assembly moisture accumulation and heat and moisture transfer.

The structure and local temperature of nonwoven layers affect heat transfer. The nonwovens' surface area and compressional resiliency depend on porosity, fibre diameter, and cross-section. Each nonwoven layer can be made from a variety of fibres. Thus, the thermal resistance of the multi-layered polyester nonwoven fabric assembly at various sub-zero temperatures was investigated by sequencing the nonwoven layers made of different denier fibres of the same porosity. 1.4 denier solid (1.4 D S), 3 denier hollow (3 D H), 6 denier hollow (6 D H), and 15 denier hollow (15 D H) polyester fibres were used to make nonwovens. The temperature profiles across the layers were recorded and numerically simulated.

### 2.3 Effect of ambient temperature, metabolic heat, and clothing insulation on the required external active heating for the survival of humans exposed to sub-zero temperatures

The electrically heated fabric uses polyester yarns coated with silver, chromium, and zirconium [16]. Shin et al. [17] tested graphene-heated clothing in cold weather and concluded that intermediate heating conserved more energy than continuous heating, and back heating was more effective than chest heating. Hao et al. [18] created a flexible heated fabric from metal filament yarns and found that for constant electrical resistance, with power fabric temperature increases linearly. Bai et al. [19] investigated temperature perception in flexible heating fabrics. They found that electrical wire density increases the power density at same voltage. Udayraj et al. [20] compared human thermal comfort in low ambient temperatures using electrically heated clothing, a radiant heating panel, and a heated chair and mattress. Electrically heated clothing was more comfortable than the other two body heating methods and used less energy. Song et al. [21] found that partial body heating improves thermal comfort and sleep quality in cold ambient temperatures. Ambient temperature, clothing insulation, metabolic heat, and external active heating affect extreme cold weather performance. Active heating in extremely cold weather clothing helps low-metabolism wearers.

It is important to study the external heat needed for the comfortable and prolonged working of humans with low metabolic heat in sub-zero temperatures under different clothing insulation. A fully dressed thermal manikin will help evaluate the active heating garment. Thermal manikin tests on clothing ensembles are time-consuming. Thus, a guarded hot plate in a cold chamber is used to study the effect of various parameters on required active heating.

### 2.4 Survival time of humans in an extreme cold climate: Experimental, numerical and parametric study on ambient temperature, fabric insulation and metabolic heat

Haigh [22] examined human survival in extreme cold. He found that physiological responses (shivering and vasoconstriction), clothing (thermal insulation), exercise, external heat, and food nutrition (metabolic heat generation) affect cold-climate survival. Cold weather causes shivering and vasoconstriction. Peak shivering quadruples basal metabolic heat [23]. Vasoconstriction reduces local skin blood flow from 17% to 50% to maintain heat balance and reduce core-to-skin heat loss. Vasoconstriction maintains core temperature and prolongs life [24]. Respiratory heat loss was 25–30% of the metabolic rate at rest but only 15–20% during work [25]. Ducharme et al. [26] examined how clothing insulation affected survival time at -30°C, 20 km/h, and 70% relative humidity. They found that clothing insulation increases survival time. Due to body shape, still air entraps males and females differently, affecting survival time. Tikuisis [27] examined how ambient temperature and clothing insulation affect cold-weather survival and found that the survival time increases with ambient temperature for the same clothing insulation. For the same ambient temperature, he found that clothing insulation increases survival time. Humans in cold water survive longer as ambient temperature, metabolic heat, and clothing insulation rise. Kinetic processes delay body core cooling during tissue regeneration [28].

Extreme cold weather clothing design should prioritise survival time. Survival may depend on ambient temperature, fabric insulation, and metabolic heat. Designing a fabric ensemble requires knowledge of the survival time of a person wearing extreme cold-weather clothing. Extreme cold weather clothing can be optimised by studying survival time. In-house developed guarded hot plate instrument inside a cold chamber with an ambient temperature of 210 K to 310 K is used to study how different parameters affect human survival time.

### 2.5 Performance evaluation of developed extreme cold weather clothing using a thermal manikin

Nakagawa and Nakaya [29] examined the effect of ambient temperature on cold protective clothing insulation. They found that clothing insulation increases when the ambient temperature drops from 20.8 to 9.6 °C and upper body clothing insulation are more affected by ambient temperature than lower body insulation. A thermal manikin was used by Luo et al. [30] to study convective heat transfer's effects on walking speed, wind speed, and temperature difference between the manikin surface and the environment. Wind and walking speed increase convective heat loss, which is directly proportional to the temperature difference between the manikin surface and the environment. Havenith [31] found that for any wind speed, walking speed decreases clothing thermal insulation. They found that clothing insulation decreased with wind speed regardless of walking speed. The same ensemble's thermal insulation varies greatly depending on fit. The tight fit zones of the shoulder and upper chest provide the most clothing insulation, followed by the stomach and lower back and calf [32]. The loose fit ensemble traps still air in fabric structures and between garment layers, reducing conduction heat losses. The same ensemble with a loose fit has 33–48% more clothing insulation than the normal fit. [33]. Kang [34] computed clothing heat transfer at various air gap thicknesses. Air escaping from the outfit insulates it. Peak insulation is 15 mm at the closed ends of the ensemble openings at the leg, hand, and neck, and 4 mm at the open end.

Human survival in extreme cold climates depends on clothing, environment, and activity. Extreme cold weather clothing must withstand extreme wind and temperature. To assess the ensemble's performance under various operating conditions, a thermal manikin or field trial is recommended. Extreme cold weather clothing performance depends most on intrinsic thermal insulation. Performance evaluations can optimise clothing ensembles. Thus, studying how ambient temperature, walking speed, and wind speed affect intrinsic clothing thermal insulation is crucial.

### 2.6 Objectives of the research

After thoroughly inspecting and understanding the published literature on heat transfer through cold weather clothing and the research gaps discussed above, the present study proposes the following objectives to bridge the gap between existing literature and the expected treatment efficacies.

1. Estimation of temperature-dependent effective thermal conductivity and specific heat of thermally bonded high bulk nonwoven exposed to sub-zero temperature.
2. To understand the effect of layering sequence and ambient temperature on the thermal resistance of multilayer high bulk nonwoven under extreme cold temperatures
3. To examine the requirement of active heating for the survival of humans exposed to sub-zero temperatures for different ambient temperature, metabolic heat and fabric insulation
4. Estimation of survival time of humans in an extreme cold climate for different ambient temperature, fabric insulation and metabolic heat
5. Experimental study to evaluate the performance of developed extreme cold weather clothing using a thermal manikin

## 3. ESTIMATION OF EFFECTIVE THERMAL CONDUCTIVITY AND SPECIFIC HEAT OF NONWOVEN EXPOSED TO SUB-ZERO TEMPERATURE

### 3.1 Introduction

In this chapter, temperature-dependent effective thermal conductivity and specific heat of high bulk thermal bonded polyester nonwoven composed of 1.4 D S fibre is obtained. In the numerical technique, conductivity and specific heats were calculated using available theoretical relations along with the measurement of transmittance. Using these properties data, coupled conduction-radiation problem was solved to determine the temperature distribution inside the nonwoven web. Experiments were conducted to measure the temperature distribution inside the nonwoven web and an excellent matching of the numerical and experimental data of temperature has been achieved proving that the determination of the conductivity and specific heat by the numerical method was reasonably accurate.

### 3.2 Material and methods

To estimate nonwoven temperature-dependent thermophysical properties, thermally bonded high bulk fibre webs are prepared. 1.4 denier solid staple polyester fibres of 35 mm length were used to make thermally bonded nonwovens. A multi-layered nonwoven sample of areal density 600 g/m$^2$ with a thickness of 24 mm was used for experimentation. Experiments were performed using a guarded hot plate shown in Fig. 1. Sub-zero climatic conditions were maintained using a climatic chamber.

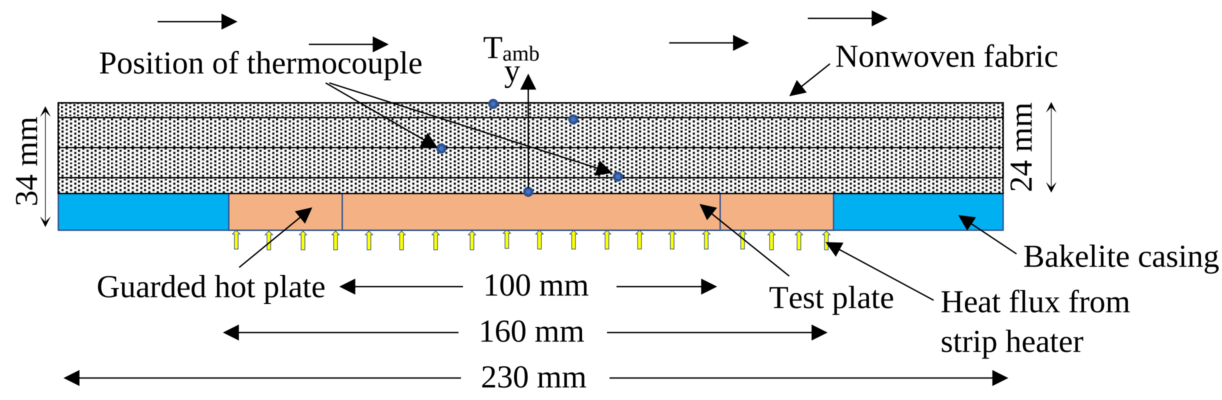



Fig. 1 Schematic of the experimental setup

### 3.3 Numerical modelling

The heat transfer through the high bulk nonwoven fibre web sample exposed to sub-zero temperature is a one-dimensional coupled conduction and radiation problem. The area (or projected surface area normal to the heat flow) of thermocouples is negligible compared to fabric surface area, so one-dimensional coupled conduction and radiation calculation is not affected. The constant temperature boundary condition at one face (y = 0) and convective-radiative boundary condition at the other face (y = 24 mm) is imposed. The governing energy equation and boundary conditions for heat transfer through the fabric are given by [10]

$$\frac{\partial}{\partial y}\left(k_{e,nw}(T)\frac{\partial T}{\partial y}\right) = \rho_{nw}(T)C_{p,nw}(T)\frac{\partial T}{\partial t} \quad (1)$$

Initial and Boundary conditions:

$$T(y,0) = \text{Specified value } (T_{simulated}) \quad (2)$$

$$T(0,t) = \text{Set value in the experiments } (306 \pm 1 \text{ K}) \quad (3)$$

$$-k_{e,nw}(T)\left.\frac{\partial T}{\partial y}\right|_{y=L} = [h_c\{T(L,t) - T_{amb}\}] + [\varepsilon\,\sigma\,\{T(L,t)^4 - T_{amb}{}^4\}] \quad (4)$$

### 3.4 Determination of properties using theoretical relations and radiation measurements

In this study, the thermophysical properties of fabric i.e., thermal conductivity and specific heat are considered temperature dependent. These properties are first calculated using theoretical relations and some measurement data of radiation transmittance. Effective thermal conductivity is calculated from diffusive thermal conductivity and radiative thermal conductivity, which is given by

$$k_{e,nw}(T) = k_{c,nw}(T) + k_{r,nw}(T) \quad (5)$$

The diffusive thermal conductivity of nonwoven is consisting of the diffusive thermal conductivity of solid (polyester) and gas (air), which is given by [10]

$$k_{c,nw}(T) = k_{c,s}(T) + \frac{k_{c,a}(T) - k_{c,s}(T)}{1 + \frac{\mathrm{K}}{1+\mathrm{K}}\left[1 + z\frac{k_{c,a}(T) - k_{c,s}(T)}{k_{c,a}(T) + k_{c,s}(T)}\right]} \quad (6)$$

To calculate the radiative thermal conductivity, the optical thickness of all prepared nonwoven samples is measured using transmittance experimentation. From transmittance, it is straightforward to get an exponential relation for all nonwoven samples as given by Eq. (7) with an $R^2$ value of 0.99.

$$\tau(L) = \exp(-241.1L) \quad (7)$$

$$O_t = -\ln\tau(L) \quad (8)$$

where, $O_t$ is the optical thickness and which is (>>1) for all the used samples, therefore the fabric sample can be assumed to be optically thick. The radiative conductivity can be defined as [10],

$$k_{r,nw} = \frac{16\sigma {n_{nw}}^2 T^3}{3\beta} \quad (9)$$

The specific heat and density of the nonwoven sample are calculated as a weighted average of polyester and air.

$$C_{p,nw}(T) = (1-p)C_{p,PET}(T) + pC_{p,a}(T) \quad (10)$$

### 3.5 Results and discussion

The numerical and experimental temperature profile inside the nonwoven made up of 1.4 D S polyester fibre at various ambient temperatures are shown in Fig. 2. The hotter side of the fabric is maintained at 306$\pm$1 K for all these experiments and numerical simulations. It is seen from the figure that for every ambient temperature, temperature profiles at different locations match well. A maximum percentage error of 1.66% and a maximum absolute error of 4.2 K is observed at 20 mm from the test plate.

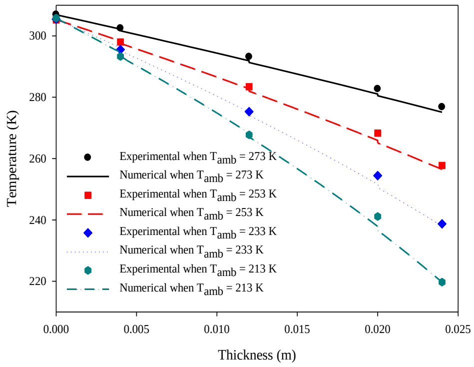
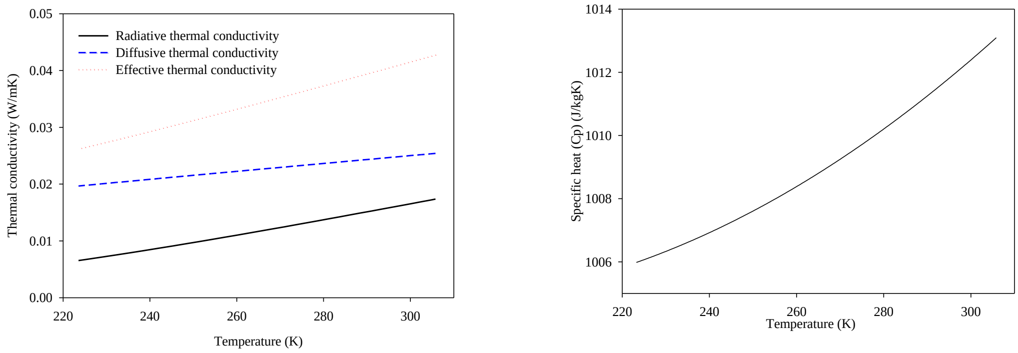



Fig. 2 Measured and simulated temperature profiles inside nonwoven made up of 1.4 D S

### 3.6 Thermal conductivity and specific heat

The temperature-dependent diffusive thermal conductivity, radiative thermal conductivity and effective thermal conductivity and specific heat of nonwoven made up of 1.4 D S polyester fibre is plotted in Fig. 3. It is observed that with an increase in local temperature of the nonwoven web, diffusive thermal conductivity, radiative thermal conductivity and effective thermal conductivity and specific heat increases linearly. It is also interesting to see that the specific heat of nonwoven is not a function of fibre structure.




(a) (b)

Fig. 3 Temperature-dependent (a) thermal conductivities and (b) specific heat of nonwoven

## 4. EFFECT OF LAYERING SEQUENCE AND AMBIENT TEMPERATURE ON THE THERMAL RESISTANCE UNDER EXTREME COLD TEMPERATURES

### 4.1 Introduction

In the present study, the effect of the sequence of layers and ambient temperature in an optically thick multilayer high bulk thermal bonded polyester nonwoven on thermal resistance is investigated at sub-zero temperatures. The temperature profiles across the layers, both measured and numerically simulated match well. One dimensional coupled conduction-radiation heat transfer model is used to solve the governing equation. Radiative thermal conductivity is calculated using the mathematical equations for optically thick medium available in the literature. The mathematical model is solved by using temperature-dependent thermophysical properties.

**4.2 Material and methods**

Four polyester thermal bonded nonwovens (A, B, C and D) were produced, all having the same 8 mm thickness, 200 g/$m^2$ areal density and 0.982 porosity but with different fibre deniers. Polyester fibres of 1.4 D S, 3 D H, 6 D H and 15 D H are used to prepare nonwoven samples A, B, C and D respectively. All the fibres have different hollowness.

**4.3 Construction of multi-layered assembly from nonwovens**

Two sets of multi-layered assemblies were prepared. The first set has combinations of nonwovens A, C and D and the second one has nonwovens, B, C and D. The arrangement of nonwoven layers in the first set are: A-C-D, A-D-C, C-A-D, C-D-A, D-C-A and D-A-C and in the second set: B-C-D, B-D-C, C-B-D, C-D-B, D-C-B and D-B-C. In the case of A-C-D, the $1^{st}$ layer is nonwoven A (contacting the hot plate), the $2^{nd}$ layer is C (sandwiched between A and D) and the $3^{rd}$ layer is D (one face of D is in contact with the $2^{nd}$ layer and another face is exposed to the ambient. All the layered assemblies follow the same rule.

**4.4 Experimentation**

After mounting the wrapped sample over the plates, the test and guard plate were brought to a temperature of 307$\pm$1 K (representing the human skin temperature) using strip heaters provided at a guarded hot plate. The test and guard plate temperature replicate the human skin temperature. Then the climatic chamber was set to a temperature of 273 K. After reaching the steady-state conditions (set temperatures of the plates and climatic chamber remain constant), the current and voltage supplied separately to the test and guard plate were recorded. The electrical power supplied to maintain the test and guard plate at the set temperature is calculated. The heat flux from the test plate was used to calculate the thermal resistance (($m^2$.K)/W) of the multilayered nonwoven assembly. The experiments were performed at the ambient temperatures of 273 K, 253 K, 233 K and 213 K for all the combinations of multi-layered nonwovens.

**4.5 Numerical modelling**

The numerical model was developed based on the conservation of energy and mathematical relation available in the literature. The actual experimental condition is simulated. One face of the fabric is in contact with a test plate maintained at a constant skin temperature. The other face exposed to ambient temperature dissipates heat to the ambient by convection and radiation heat transfer. Thermal contact resistance (0.01 ($m^2$.K)/W) between two layers of fabrics is also considered in the numerical model.

**4.6 Results and discussions**

The thermal resistance ($I_{res}$) of fabric assembly is calculated as

$$I_{res} = \frac{T_{(0)} - T_{(l_1+l_2+l_3)}}{q^{"}} \quad (11)$$

For every layering sequence, the observed heat flux at the test plate at 307$\pm$1 K with different ambient temperatures increases with a decrease in ambient temperature. The observed heat flux at the test plate at 307$\pm$1 K for constant ambient temperature is independent of the layering sequence. It is seen that the thermal resistance of multi-layer assembly increase with a decrease in ambient temperature. The thermal resistance for every ambient temperature is independent of the layering sequence.

# 5. EFFECT OF AMBIENT TEMPERATURE, METABOLIC HEAT, AND CLOTHING INSULATION ON THE REQUIRED EXTERNAL ACTIVE HEATING

## 5.1 Introduction

In the current work, the effect of ambient temperature, metabolic heat and nonwoven fabric thermal insulation on the required active heating under sub-zero ambient temperatures to maintain skin temperature at 307 K (34 °C) has been investigated numerically and experimentally. The active heated fabric is sandwiched between knitted and high bulk nonwoven and mounted on the guarded hot plate exposed to sub-zero temperatures. The temperature profile inside the fabric assembly was plotted numerically and authenticated with experimental data. The study on active heating fabrics of three different patterns made of stainless steel yarn indicated the importance of the arrangement of conductive yarns. This will be useful in selecting the yarn pattern as per the wearers' requirements and an available electrical power source. The validated numerical results by the experimental measurements will be helpful in the optimization of the required active heating.

## 5.2 Material and method

Three fabrics, single jersey polyester (knitted), woven fabric incorporated with steel yarns and thermal bonded high bulk nonwoven were chosen for the experimentation. The knitted fabric made from twist-less multifilament yarns has an areal density of 130 g/m$^2$ and a thickness of 0.52 mm. Stainless steel multifilament yarn of 1010 tex with 800 filaments, each of diameter 12 µm along with multifilament polyester base yarn was plain-woven to develop an active heated fabric using an Ashford loom. An external DC supply is used to provide electrical power for heating the fabric. Three different configurations are considered. The purpose of different arrangements of stainless steel filament yarn in the active heating layer is to study the heating provided by the fabrics at a different voltages. The best possible arrangement can be used as per the requirement and availability of the electric power supply. The high bulk thermal bonded 1.4 denier solid polyester nonwoven fabric of 98.2 % porosity was used to provide thermal insulation.

## 5.3 Numerical modelling

A one-dimensional steady-state energy equation with energy generation is solved to simulate the actual experimental conditions. Constant heat flux is imposed at the face of the knitted fabric in contact with the plates while the face of the ensemble is exposed to sub-zero temperatures, dissipating heat to the ambient by both convection and radiation heat transfer. The temperature-dependent effective thermal conductivity of fabrics is given by

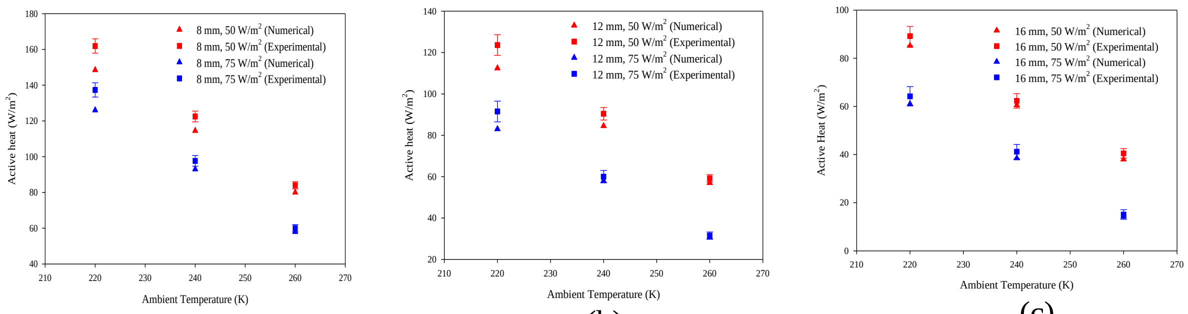
$$k_{e,1} = (0.0001088T) + 0.001655; \text{ for knitted fabric} \quad (12)$$

$$k_{e,2} = (0.00009T) + 0.018; \text{ for active heating fabric} \quad (13)$$

$$k_{e,3} = (0.0002394T) - 0.02675; \text{ for nonwoven fabric} \quad (14)$$

## 5.4 Results and discussions

The experimental and numerical heat supplied to the active heating fabric at different fabric assembly and testing conditions are noted. The effect of ambient temperature and metabolic heat flux on the required active heating for fabric assembly with the nonwovens having a thickness of 8 mm, 12 mm and 16 mm are plotted in Fig. 4.




(a) (b) (c)

Fig. 4 Effect of various factors on the required active heating

The required heat flux to the active heating fabric increases linearly with the decrease in ambient temperature, metabolic heat and nonwoven insulation. The experimental heat flux is 5 to 10 % more than the numerical values due to the convective air current inside the nonwoven fabric and the heat loss through the sideways of the fabric assembly during experiments. The validated numerical results using experimental measurements will be helpful in optimization of the required active heating and deciding the heating fabric as per the wearers' requirement and available electrical power source. It is possible to use the numerical model for any insulating fabric made of different fibres, provided the temperature-dependent thermophysical properties of the fibres are known.

## 6. SURVIVAL TIME OF HUMANS IN EXTREME COLD CLIMATE: EXPERIMENTAL AND NUMERICAL STUDY

### 6.1 Introduction

In extreme cold weather clothing design, wearer survival time is crucial. Designing extreme cold weather clothing requires knowledge of a person's survival time in various combinations of ambient temperature, metabolic heat, and fabric thermal insulation. A fully dressed thermal manikin helps evaluate extreme cold-weather ensembles. Creating many clothing ensembles for thermal manikin tests takes time. We used a guarded hot plate instrument in a climatic chamber to measure the survival time of a person under various ambient temperatures, metabolic heat, and fabric insulation on a set of layers of extreme cold weather clothing. One-dimensional numerical heat transfer through fabric layers is also considered. The model also considers each clothing layer's temperature-dependent thermophysical properties. Measured and numerically simulated transient temperature profiles across the fabric assembly match well. Thus, a guarded hot plate inside a cold chamber could be used to study human survival under different ambient temperature, fabric insulation, and metabolic heat conditions.

### 6.2 Material and methods

Artificial skin (thickness $l_1$ = 12 mm) is placed over the test plate and guard plate. A single jersey knitted fabric (thickness $l_2$ = 0.52 mm) is placed over the artificial skin, over which a high loft nonwoven as single or double or triple layers (thickness $l_3$ = 4 mm to 12 mm) were placed to vary the thermal insulation. The whole assembly of fabrics and the artificial skin were wrapped around (top and sideways) by a very thin (0.1 mm) impermeable membrane to avoid disturbance due to air currents on the top and side surfaces. The sub-zero temperature achieved in the cold chamber refers to the surrounding temperature for the experimental setup.

In the first set of experiments, the nonwoven with 4 mm thickness with thermal insulation of 0.67 clo was placed over the knitted fabric with thermal insulation of 0.53 clo. The total thermal insulation of the ensemble (1.2 clo) is the sum of the thermal insulation of the knitted fabric and nonwoven. The temperatures of the hot and guard plate were set at 310.1

K. Initially, the chamber temperature is at room temperature of 293 K (20°C). Sufficient time was given to achieve the steady-state. Then the chamber temperature was set at 253 K (-20°C) and at the same time the heat flux supplied to the hot and guard plate was set to 40 W/m$^2$ corresponding to the metabolic heat of a sleeping person. The cold chamber temperature starts decreasing from 293 K (20°C) and it took 840 s to reach 253 K (-20°C). After reaching 253 K (-20°C), the chamber is maintained at a constant temperature of 253 K (-20°C). Since the set power representing the metabolic heat supplied to the hot and guard plate is much lower compared to the rate of heat loss from the hot plate, the hot plate could not be maintained at a temperature of 310 K, and gradually the temperatures of both the plates start to drop. The additional shivering heat was supplied to the plates at an interval of one minute as per the equation that relates the core (test plate) and skin (above the skin) temperatures to the shivering heat. The shivering heat generation as a function of body core temperature, skin temperature and body fat is given by [35]

$$q''_{shv} = \frac{155.5(310 - T_{core}) + 47(306 - T_{skin}) - 1.57(306 - T_{skin})^2}{\sqrt{BF\%}}$$
$$for\ 305\ K < T_{core} < 310\ K \qquad (15)$$
$$q''_{shv,max} = 200\ (W/m^2)$$
$$q''_{shv} = q''_{shv,max}\, sech[2(T_{core} - 305)^{1.4}]\ if\ T_{core} \le 305\ K$$

Where, $T_{core}$ is the core temperature and $T_{skin}$ is the skin temperature and *BF%* is the body fat percentage. The body fat percentage for a healthy human being is 20 which is considered in this study.

The precise time duration for the hot plate to reach the temperature of 300 K (27 °C) (the onset of severe hypothermia) from 310 K (37 °C) is obtained from ADAM. The ADAM records temperature to an accuracy of 0.1 °C at an interval of one second. This is the survival time. One dimensional numerical model is developed depicting the experimental conditions

### 6.3 Results and discussions

The effect of ambient temperature on the survival time with different fabric insulation for a constant metabolic heat flux of 60 W/m$^2$ is plotted in Fig. 5. It is observed that for given fabric insulation and metabolic heat, the survival time increases with an increase in the ambient temperature. The observed survival time increases by 23372 s (6.49 hrs), 70345 s (19.54 hrs) and 141067 s (39.18 hrs) respectively for the fabric insulations of 1.2 clo, 1.88 clo and 2.56 clo, when the ambient temperature increased from 213 K to 253 K. It is also observed that for constant ambient temperature and metabolic heat, survival time increases with increase in fabric insulation. The observed survival time increases by 18138 s (5.04 hrs), 53285 s (14.8 hrs) and 135833 s (37.73 hrs) respectively for the ambient temperatures of 213 K, 233 K and 253 K, when the fabric insulation is increased from 1.2 clo to 2.56 clo.

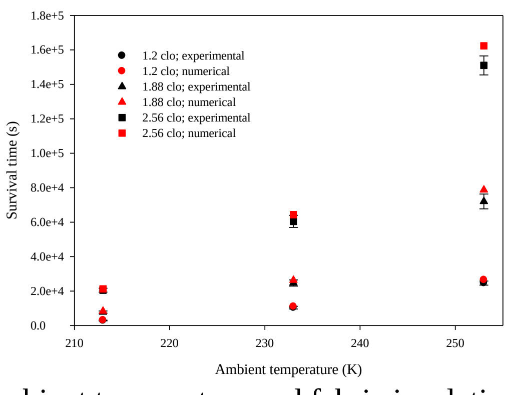



Fig. 5 Effect of ambient temperature and fabric insulation on survival time

# 7. PERFORMANCE EVALUATION OF DEVELOPED EXTREME COLD WEATHER CLOTHING USING A THERMAL MANIKIN

## 7.1 Introduction

In the present work, the effect of ambient temperature, wind speed and walking speed on intrinsic clothing thermal insulation of the developed extreme cold weather clothing (ECWC) has been studied. The experiments were performed using a 34-zone thermal manikin under a controlled environment inside a climatic chamber. Five different ambient temperatures (20, 10, 0, -10, -20 and -30 °C), three walking speeds of the manikin (0, 1.26 and 2.1 km/h) and three different wind speeds (0.8, 1.3 and 1.8 m/s) were selected for the study.

## 7.2 Material and methods

The experiments were carried out inside a climatic chamber using a full-body Asian male medium-size Newton thermal manikin having 34 zones (Fig. 6). To study the performance evaluation of ECWC under different environmental conditions, two sets of ensembles were developed. Ensemble-1 consists of level 1 (skin contacting single jersey knitted fabric), level 2 (grid fleece fabric) and level 3 with high bulk thermal bonded nonwoven of areal density 150 g/m$^2$. The total fabric insulation of ensemble-1 is 0.4605 m$^2$K/W. The ensemble-2 consists of one additional insulating jacket and trousers having the construction same as level 3 but with a high bulk thermal bonded nonwoven of areal density 100 g/m$^2$ with the fabric thermal resistance of 0.262 m$^2$K/W. The additional insulating jacket and trousers are worn over ensemble-1 to form ensemble-2. The total fabric insulation of ensemble-2 is 0.7225 m$^2$K/W. The performance of the developed ECWC ensemble-1 and 2 is evaluated under different environmental conditions for a constant manikin surface temperature of 35 °C. For the first study, ensemble-1 is selected, and it is worn over the manikin. The heat flux $(q'')$ required to maintain the skin temperature $(T_{sk})$ at 35 °C at different environmental conditions is recorded using Thermdac data acquisition software.

Fig. 6. Thermal manikin

The total clothing insulation $(I_T)$ is calculated as:

$$I_T = \frac{T_{sk} - T_{amb}}{q''} \quad (16)$$

The total clothing insulation $(I_T)$ consists of intrinsic clothing insulation $(I_{cl})$ and boundary air layer insulation $(I_a)$ which is calculated for each zone and the weighted average is used to calculate the total clothing insulation of the ensemble. The intrinsic clothing insulation $(I_{cl})$ is calculated as:

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \quad (17)$$

To calculate the boundary air layer insulation the procedure followed is the same as is followed to calculate the total clothing thermal insulation but instead of clothed, the nude manikin is used. The $f_{cl}$ is the clothing area factor which is given by

$$f_{cl} = \frac{A_{cl}}{A_{Du}} \tag{18}$$

where $A_{cl}$ is the outer surface area of the clothed manikin and $A_{Du}$ is the surface area of the nude manikin. The clothing area factor of ensemble-1 and 2 are 1.37 and 1.62 respectively.

**7.3 Results and discussions**

The intrinsic clothing insulation of ensemble-1 at different ambient temperatures is plotted in Fig. 7. To study the effect of ambient temperature on the intrinsic clothing insulation, experiments were performed at different ambient temperatures and constant wind speed with manikin at simply standing conditions. For the respective ambient temperature and wind speed, when the ambient temperature is decreased from 20 to 10 °C, 20 to 0 °C, 20 to -10 °C, 20 to -20 °C and 20 to -30 °C; the intrinsic clothing insulation increases by 5.78, 12.62, 19.23, 21.22 and 24.35 % respectively.

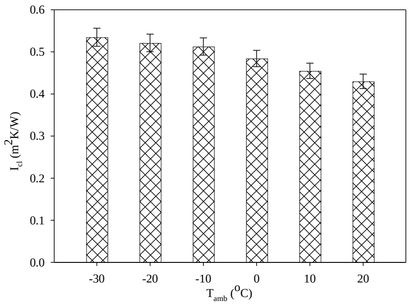



Fig. 7 Intrinsic clothing insulation of ensemble-1 at different ambient temperatures

The effect of the walking speed of the thermal manikin and wind speed on the intrinsic clothing insulation of ensemble-1 at an ambient temperature of -10 °C is shown in Fig. 8.

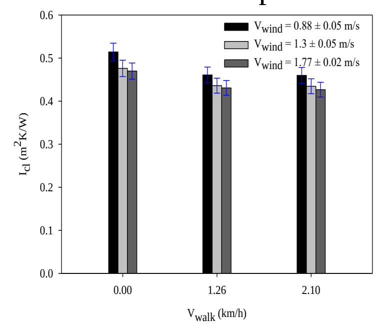



Fig. 8 Effect of walking and wind speed on the intrinsic clothing insulation of ensemble-1

## 8. CONCLUSIONS

The scope of the present work is to study heat transfer through extreme cold weather clothing. Initially, temperature-dependent thermophysical properties of high bulk nonwovens exposed to extreme cold climatic conditions were estimated numerically and validated experimentally. In a multi-layered nonwoven assembly, the effect of layering sequence and temperature on thermal insulation is studied for various combinations. An electrically heated woven structure is made using Ashford loom to study the effect of various parameters on required external active heating. The survival time of humans with lower metabolic activity and low fabric insulation exposed to extreme cold weather conditions is estimated numerically and validated experimentally. The performance of the developed extreme cold weather clothing is evaluated experimentally using the 34-zone sweating thermal manikin under a controlled environment created using a climatic chamber.

1. It can be concluded from the results that with the increase in the local temperature of the nonwoven web, the percentage of heat transfer by radiation increases linearly. For nonwoven composed of 1.4 D S, it varies from 25% at a local temperature of 223 K to 40% at a local temperature of 305 K. At constant local temperature, the percentage of radiative heat transfer through nonwoven increases with an increase in fibre denier. For the same areal density ($g/m^2$) and porosity, the pore size and surface area of the fibre affect the radiation heat transfer through the nonwoven fibre web. With increases in the outer diameter of the fibre, the pore size of the nonwoven web increases and the surface area decreases which increases radiation transmittance and heat transfer through the nonwoven fabric. Therefore, the nonwoven fabric made up of 1.4 D S fibre has the lowest radiative thermal conductivity followed by 3 D H, 6 D H and 15 D H. Still air entrapment in hollow fibre nonwoven decreases the diffusive thermal conductivity of nonwoven. Therefore, the nonwoven fabric made up of 6 D H fibre has the lowest diffusive thermal conductivity followed by 3 D H and 15 D H. For every nonwoven sample, the effective thermal conductivity and specific heat decrease with a decrease in temperature which provides a favourable effect in providing more insulation in an extremely cold climate.
2. The thermal resistance of multi-layer nonwoven assembly increases with a decrease in ambient temperature. The thermal conductivity of nonwoven layers is found to decrease from the inner- to outer layers at a given ambient temperature. The heat flux through nonwoven layers and the thermal resistance of multi-layer nonwoven are independent of the layering sequence if the convective heat transfer is extremely low. The numerical model has been validated with experiments; hence it can be further used for polyester nonwovens made of any denier.
3. For active heating fabric, the voltage required for the supply of a current increases with an increase in the electrical resistance. The power output of the active heated fabric is directly proportional to the electrical resistance of the conductive yarn. The results show that the external active heating required to maintain the test plate (or skin) temperature within a comfortable range depends on the ambient temperature, metabolic heat flux and insulation of nonwoven fabric. For constant nonwoven thermal insulation and metabolic heat flux, the heat flux required at the active heating fabric increases linearly with the decrease in ambient temperature. For the same nonwoven thermal insulation and ambient temperature, active heating decreases with an increase in metabolic heat flux. For constant metabolic heat flux and ambient temperature, the heat flux supplied to the active heating fabric decreases linearly with an increase in nonwoven insulation. However, in active heating garments, external heat is provided around the heart, liver and kidney. In that case, the heat transfer in the human-fabric domain will also be one-dimensional. Therefore, the model will work for the actual human-fabric heat transfer domain. The power required will depend on the patch size, ambient temperature, clothing insulation and metabolic heat. Therefore, depending upon the area of active heating fabric patch provided at that location will not consume the high power.
4. It is observed that the survival time for given environmental conditions depends on the ambient temperature, metabolic heat generation and fabric thermal insulation. The survival time of the human exposed to extreme cold weather conditions increases with an increase in ambient temperature, metabolic heat and fabric thermal insulation. The parametric analysis suggests that the ambient temperature is the predominant parameter affecting the survival time, followed by the fabric insulation. The metabolic heat does not have a significant effect on survival time. For the studied ambient temperature, survival time is increased by 204 % and 744 % for an increase in ambient temperature by 9.4 % and 18.8 %

respectively. For the studied fabric insulation, survival time is increased by 190 % and 512 % for an increase in fabric insulation by 56 % and 113 % respectively. Whereas, for the studied metabolic heat, survival time is increased by 6 % and 9 % for an increase in metabolic heat by 50 % and 75 % respectively. The human thermoregulatory response to vasoconstriction is not considered in this study. Therefore, the survival times in practice would be more than the observed values in this study.

5. The experimental results show that the intrinsic clothing thermal insulation of the developed ECWC increases with a decrease in the ambient temperature and the effect of the temperature is proportional to the ensemble thickness. The clothing thermal insulation decreases with an increase in the walking speed and wind speed. The walking speed has a significant impact on the zones of the arm and the leg while the torso zones remained unaffected. The wind speed significantly reduces the clothing thermal insulation in torso zones while having relatively less influence on the clothing insulation at the arm and leg. For constant ambient temperature, the percentage reduction in clothing insulation is proportional to the walking and wind speed.

**References**


1. Ducharme, M. B., Brajkovic, D., & Frim, J. (1999). The effect of direct and indirect hand heating on finger blood flow and dexterity during cold exposure. *Journal of Thermal Biology*, 24(5-6), 391-396.
2. Harirchi, I., Arvin, A., Vash, J. H., & Zafarmand, V. (2005). Frostbite: incidence and predisposing factors in mountaineers. *British journal of sports medicine*, *39*(12), 898-901.
3. Xin, B., Hu, J., & Yan, H. (2002). Objective evaluation of Polar fleece fabric appearance. *Textile Asia*, *33*(6), 36-40.
4. Cheng, X., & Fan, J. (2004). Simulation of heat and moisture transfer with phase change and mobile condensates in fibrous insulation. *International Journal of Thermal Sciences*, *43*(7), 665-676.
5. Richards, M. G., Rossi, R., Meinander, H., Broede, P., Candas, V., den Hartog, E., ... & Havenith, G. (2008). Dry and wet heat transfer through clothing dependent on the clothing properties under cold conditions. *International Journal of Occupational Safety and Ergonomics*, *14*(1), 69-76.
6. Karamanos, A., Hadiarakou, S., & Papadopoulos, A. M. (2008). The impact of temperature and moisture on the thermal performance of stone wool. *Energy and Buildings*, *40*(8), 1402-1411.
7. Asllanaj, F., Jeandel, G., Roche, J. R., & Lacroix, D. (2004). Transient combined radiation and conduction heat transfer in fibrous media with temperature and flux boundary conditions. *International Journal of Thermal Sciences*, *43*(10), 939-950.
8. Zhao, S. Y., Zhang, B. M., & He, X. D. (2009). Temperature and pressure dependent effective thermal conductivity of fibrous insulation. *International journal of thermal sciences*, *48*(2), 440-448.
9. Talukdar, P., Das, A., & Alagirusamy, R. (2016). Simultaneous estimation of thermal conductivity and specific heat of thermal protective fabrics using experimental data of high heat flux exposure. *Applied Thermal Engineering*, *107*, 785-796.
10. Tilioua, A., Libessart, L., Jeandel, G., & Lassue, S. (2016). Determination of radiative properties of polyester batting insulation material from hemispherical transmittance and reflectance measurements. *Applied Thermal Engineering*, *105*, 594-604.
11. Chen, J. C., & Churchill, S. W. (1963). Radiant heat transfer in packed beds. *AIChE Journal*, *9*(1), 35-41.
12. Barker, R. L., & Heniford, R. C. (2011). Factors affecting the thermal insulation and abrasion resistance of heat resistant hydro-entangled nonwoven batting materials for use

in firefighter turnout suit thermal liner systems. *Journal of Engineered Fibers and Fabrics*, *6*(1), 155892501100600101.
13. Gnanauthayan, G., Rengasamy, R. S., & Kothari, V. K. (2017). Heat insulation characteristics of high bulk nonwovens. *The Journal of the Textile Institute*, *108*(12), 2173-2179.
14. Tian, M., Zhu, S., Pan, N., Qu, L., Han, G., & Pan, F. (2012). Effects of layering sequence on thermal response of multilayer fibrous materials: Unsteady-state cases. *Experimental thermal and fluid science*, *41*, 143-148.
15. Wu, H., & Fan, J. (2008). Study of heat and moisture transfer within multi-layer clothing assemblies consisting of different types of battings. *International Journal of Thermal Sciences*, *47*(5), 641-647.
16. Hamdani, S. T. A., Potluri, P., & Fernando, A. (2013). Thermo-mechanical behaviour of textile heating fabric based on silver coated polymeric yarn. *Materials*, 6, 1072–1089.
17. Shin, S., Choi, H.-H., Kim, Y.B., Hong, B.-H., & Lee, J.-Y. (2017). Evaluation of body heating protocols with graphene heated clothing in a cold environment. *International Journal of Clothing Science and Technology*, 29, 830-844.
18. Hao, L., Yi, Z., Li, C., Li, X., Yuxiu, W., & Yan, G. (2012). Development and characterization of flexible heating fabric based on conductive filaments. *Measurement*, 45, 1855-1865.
19. Bai, Y., Li, H., Gan, S., Li, Y., Liu, H., & Chen, L. (2018). Flexible heating fabrics with temperature perception based on fine copper wire and fusible interlining fabrics. *Measurement*, 122, 192–200.
20. Udayraj, Li, Z., Ke, Y., Wang, F., & Yang, B. (2018). A study of thermal comfort enhancement using three energy-efficient personalized heating strategies at two low indoor temperatures. *Building and Environment*, 143, 1-14.
21. Song, W., Lu, Y., Liu, Y., Yang, Y., & Jiang, X. (2020). Effect of partial-body heating on thermal comfort and sleep quality of young female adults in a cold indoor environment. *Building and Environment*, 169, 106585.
22. Haigh, J. C. (2013). Fieldwork in a cold climate. *Journal of Exotic Pet Medicine*, *22*(1), 51-57.
23. Kang, Z., & Wang, F. (2019). An advanced three-dimensional thermoregulation model of the human body: development and validation. *International Communications in Heat and Mass Transfer*, *107*, 34-43.
24. Xu, X., & Tikuisis, P. (2014). Thermoregulatory modeling for cold stress. *Compr Physiol*, *4*(3), 1057-1081.
25. Cain, J. B., Livingstone, S. D., Nolan, R. W., & Keefe, A. A. (1990). Respiratory heat loss during work at various ambient temperatures. *Respiration physiology*, *79*(2), 145-150.
26. Ducharme, M. B., Tikuisis, P., & Potter, P. (2004). Selection of military survival gears using thermal manikin and computer survival model data. *European journal of applied physiology*, *92*(6), 658-662.
27. Tikuisis, P., 1994. Prediction of survival time for cold exposure. *Sixth Int.* Gmf. *on Envir. Ergon. Montebello, Gmada, Sept. 25-30, I994*
28. Dombrovsky, L. A. (2022). Laser-induced thermal treatment of superficial human tumors: An advanced heating strategy and non-Arrhenius law for living tissues. *Frontiers in Thermal Engineering*, 1.
29. Nakagawa, A., & Nakaya, T. (2021). A survey of clothing insulation for university students in Japan: Effect of clothing insulation distribution between the upper and lower body in the winter. *Journal of Building Engineering*, *44*, 103287.

30. Luo, N., Weng, W. G., Fu, M., Yang, J., & Han, Z. Y. (2014). Experimental study of the effects of human movement on the convective heat transfer coefficient. *Experimental thermal and fluid science*, *57*, 40-56.
31. Havenith, G. (1999). Heat balance when wearing protective clothing. *Annals of occupational Hygiene*, *43*(5), 289-296.
32. Burton, A. C., & Edholm, O. G. (1955). " Man in a Cold Environment," London, Edward Arnold (Publishers).
33. McCullough, E. A., Jones, B. W., & Huck, J. (1985). A comprehensive data base for estimating clothing insulation. *ASHRAE Trans*, *91*(2), 29-47.
34. Kang, Z., Shou, D., & Fan, J. (2020). Numerical modeling of body heat dissipation through static and dynamic clothing air gaps. *International Journal of Heat and Mass Transfer*, *157*, 119833.
35. Chen, W. A. N. G., Xu-Hong, H., Zhang, M. L., Yu-Qian, B., Yu-Hua, Z., Zhong, W. H., & Wei-Ping, J. (2010). Comparison of body mass index with body fat percentage in the evaluation of obesity in Chinese. *Biomedical and environmental sciences*, *23*(3), 173-179.

**ORGANIZATION OF THE THESIS**

Abstract
Table of contents
List of figures
List of tables
Nomenclatures
1. Introduction
2. Literature Review
3. Estimation of temperature-dependent thermal conductivity and specific heat of high bulk nonwoven
4. Effect of layering sequence and ambient temperature on the thermal insulation of multi-layered high bulk nonwoven
5. Effect of fabric insulation, metabolic heat and ambient temperature on the required active heating for the comfortable survival of humans exposed to sub-zero temperatures
6. Estimation of survival time of humans in extreme cold climates at different ambient temperatures, metabolic heat and fabric insulation
7. Performance of developed extreme cold weather clothing using thermal manikin
8. Conclusions, final remarks and outlook

Bibliography

**List of Publications**

1. Dupade, V., Premachandran, B., Rengasamy, R. S., & Talukdar, P. (2022). Estimation of temperature-dependent effective thermal conductivity and specific heat of thermally bonded high bulk nonwoven exposed to sub-zero temperature. *Journal of Thermal Science and Engineering Applications*, *14*(6), 061014.
2. Dupade, V., Kumari, R., Premachandran, B., Rengasamy, R. S., & Talukdar, P. (2022). Effect of layering sequence and ambient temperature on thermal insulation of multilayer high bulk nonwoven under extreme cold temperatures. *Journal of Industrial Textiles*, 15280837221097284.
3. Dupade, V., Premachandran, B., Rengasamy, R. S., & Talukdar, P. (2022). Effect of ambient temperature, metabolic heat and clothing insulation on the required external active heating for the survival of humans exposed to sub-zero temperatures. *The Journal of The Textile Institute*, 1-10.

4. Dupade, V., Premachandran, B., Rengasamy, R. S., & Talukdar, P. (2022). Survival Time of Humans in Extreme Cold Climate: Experimental, Numerical and Parametric Study on Ambient Temperature, Fabric Insulation and Metabolic Heat. *Journal of Heat Transfer*, 1-31.
5. Dupade, V., Kumari, R., Premachandran, B., Rengasamy, R. S., & Talukdar, P Study on the Effect of Ambient Temperature on the Thermal Insulation of the Nonwoven Fabric Exposed to Sub-zero Temperatures: Numerical. AUTEX World Textile Conference, Portugal, September 6-8, 2021.
6. Dupade, V., Premachandran, B., Rengasamy, R. S., & Talukdar, P., Study on thermal conductivity of thermal bonded high bulk hollow fibre nonwoven under the extreme cold weather condition. Fluid Mechanics and Fluid Power (FMFP) 2022, IIT Roorkee, December 12-14, 2022.
7. Dupade, V., Premachandran, B., Rengasamy, R. S., & Talukdar, P, Effect of ambient temperature and wind speed on the survival time of humans exposed to extreme cold weather conditions. 3rd International Conference on Functional Textiles & Clothing, IIT Delhi, New Delhi, India, 10th - 12th February 2023.
8. Dupade, V., Premachandran, B., Rengasamy, R. S., & Talukdar, P, Study on thermal insulation of thermal bonded high bulk hollow fibre nonwoven under the extreme cold weather condition. International Conference on Polymers for Advanced Technology, Goa, India, February 23-25, 2023.
9. Kumari, R., Dupade, V., Rengasamy, R. S., & Chattopadhyay. R., Experimental study on the effect of ambient temperature on the thermal insulation of the bonded nonwoven exposed to sub-zero temperatures, AUTEX World Textile Conference, Portugal, September 6-8, 2021.