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Wind Chill Effect & Thermal Insulation

Study of Wind Chill Effect and Thermal Insulation using Infrared Imaging

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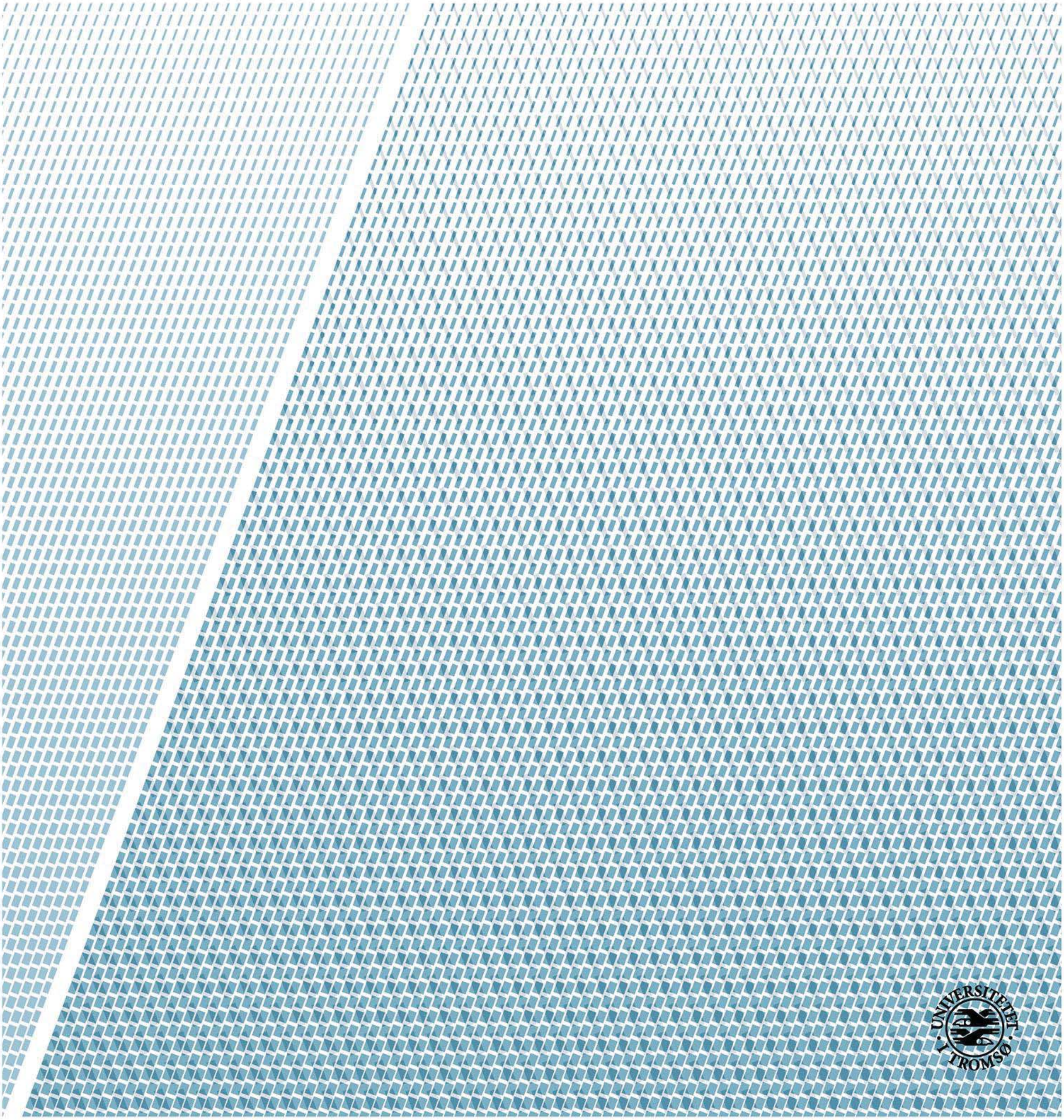
Master in Technology and Safety in High North, May 2017



Preface

This report is submitted in the course TEK-3901 (Master thesis – 30 stp) that is part of the Masters in Technology and Safety at UiT The Arctic University of Norway, Tromsø, Norway. The work described in this report was carried out at the Department of Engineering and Safety in 2016-17. It is the original and independent work of author except where specially acknowledged in the text. Neither the present report nor any part thereof has been previously submitted at any other university. This report contains approximately 11445 words, 35 figures, and 10 tables.

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Abstract

Wind chill factor is explained as the cooling sensation due to the exposure of wind temperature environment. The wind chill factor depends on air temperature, wind velocity, and humidity. Wind chill poses serious health risks. Various wind chill index models are given in the literature. In order to understand the wind chill effect, it is important to understand the phenomenon of heat transfer. There are three modes of heat transfer namely conduction, convection and radiation. The convective mode of heat transfer is most dominant in the case of wind chill. BS-EN 342 and ISO 11079:2007 (E) defines the clothing insulation requirements. Preliminary experiments using infrared thermography in cold room at The Arctic University of Norway demonstrates higher heat transfer under wind chill conditions with the means of infrared imaging. The experiments were also conducted to measure the relative required insulation of winter jackets, summer jackets and sweaters via infrared imaging.

“The sun was warm but the wind was chill.
You know how it is with an April day.
When the sun is out and the wind is still,
You're one month on in the middle of May.
But if you so much as dare to speak,
a cloud come over the sunlit arch,
And wind comes off a frozen peak,
And you're two months back in the middle of March.”

Robert Frost

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Nomenclature

Symbols

h_{wc}	$[kCal/m^2h^oC]$	Heat transfer coefficient
V	$[m/s]$	Wind Velocity
V_s	$[km/h]$	Wind Velocity
T_{air}	[°C]	Temperature of the surroundings
$\bar{T}$	[°C]	Mean air temperature
T_s	$[K\ ]$	Surface Temperature
T_{s1}	$[K\ ]$	Surface Temperature of wall on one side
T_{s2}	$[K\ ]$	Surface Temperature of wall on other side
$T_{\infty 1}$	$[K\ ]$	Hot fluid Temperature
$T_{\infty 2}$	$[K\ ]$	Cold fluid Temperature
T_{∞}	$[K\ ]$	Room (fluid/air) Temperature
h_{head}	$[W/m^2K]$	Heat transfer coefficient for head
h_{face}	$[W/m^2K]$	Heat transfer coefficient for face
h_r	$[W/m^2K]$	Radiative heat transfer coefficient
h_c	$[W/m^2K]$	Convective Heat transfer coefficient
h	$[W/m^2K]$	Convective heat transfer coefficient
h_1	$[W/m^2K]$	Convective heat transfer coefficient of hot fluid
h_2	$[W/m^2K]$	Convective heat transfer coefficient of cold fluid
Q	$[W/m^2]$	Heat flow per unit area
T_{cheek}	[°C]	Cheek skin temperature
R_{cheek}	$[m^2K/W]$	Thermal resistance of skin
q''	$[W/m^2]$	Heat transfer per unit area
q''_x	$[W/m^2]$	Heat transfer per unit area in x-direction
q''_n	$[W/m^2]$	Multi-directional heat transfer per unit area
k	$[W/(m.K]$	Thermal conductivity
x	$[m\ ]$	Unit direction
y	$[m\ ]$	Unit direction

z	$[m]$	Unit direction
L	$[m]$	Characteristics Length
Nu	$[dimensionless]$	Nusselt number
Nu_x	$[dimensionless]$	Local Nusselt number
$\overline{Nu_x}$	$[dimensionless]$	Average Nusselt number
Re_x	$[dimensionless]$	Local Reynold number
Pr	$[dimensionless]$	Prandtl number
$IREQ$	$[m^2K/W]$	Required Clothing Insulation
$IREQ^*$	$[m^2K/W]$	Relative Required Clothing Insulation
M	$[W/m^2]$	Metabolic rate
W	$[W/m^2]$	Effective mechanical power
E_{res}	$[W/m^2]$	Respiratory evaporative heat loss
C_{res}	$[W/m^2]$	Respiratory convective heat loss
E	$[W/m^2]$	Evaporative heat exchange
K	$[W/m^2]$	Conductive heat exchange
R	$[W/m^2]$	Radiative heat exchange
C	$[W/m^2]$	Convective heat exchange
S	$[W/m^2]$	Body heat storage rate
T_{sk}	$[°C]$	Mean skin temperature
T_C	$[°C]$	Mean clothing surface temperature
$I_{cl,r}$	$[m^2K/W]$	Resultant clothing insulation
Clo	$[m^2K/W]$	Clothing insulation unit

Greek Symbols

ε	$[dimensionless]$	Thermal Emissivity
σ	$\left[\frac{W}{m^2K^4}\right]$	Stefan-Boltzmann Constant

Abbreviations

WCI	Wind Chill Index
IR	Infrared (Electromagnetic Infrared Wave)
FPA	Focal Plane Array
FOV	Field of View
NIR	Near Infrared (Wavelength ranges in 0.75-1μm)
SIR	Short Infrared (Wavelength ranges in 1-2.5μm)
MWIR	Middle Wave (Wavelength ranges in 3-5μm)
LWIR	Long Wave Infrared (Wavelength ranges in 8-14μm)
IREQ	Required Clothing Insulation (m^2K/W)
IREQ*	Relative Required Clothing Insulation (m^2K/W)
WP	Water Penetration

Chapter 1. Introduction

1.1 Wind Chill Factor

Wind chill factor is explained as the cooling sensation due to the exposure of wind-temperature environment. Excessive wind chill factor can be a health hazards since excessive heat loss from the body may result into hypothermia / frostbite.

A human body is normally at 37°C. The heat is generated in the body via metabolic reaction. If heat is withdrawn at a higher rate than it is generated then hypothermia / frostbite may happen. The same is true otherwise, if heat is not withdrawn at appropriate rate, it may result in hyperthermia / heat stroke.

In cold climate, our body creates a thin film of heat to keep ourselves warm. This heat film is swept away in windy conditions hence creating the wind chill factor. This is demonstrated in Figure 1.1.

Wind chill factor depends on air temperature, wind velocity and humidity.

The wind chill factor is directly influenced by the phenomenon of heat transfer. The heat transfer is process of transfer of heat energy from one system to another. Generally, the rate of heat transfer is higher if there is higher temperature difference between the systems. In physics, heat transfer is associated with three different modes namely conduction, convection and radiation.

Conduction is a process of heat transfer in solids. In this case, heat is transferred by the microscopic vibration in the molecules. A good example is a cooking pot. Generally metals have better thermal conductivity than wood and ceramics.

Convection is a process of heat transfer within the fluids. The rate of heat transfer in convection is dependent on the fluid velocity. A good example of convection is heating in a room via a heater. The wind chill factor is mainly connected with the convective mode of heat transfer.

Radiation is a process of heat transfer through electromagnetic waves. This mode of heat transfer does not require any physical medium. A good example of such is our planet earth being warmed by the sun. In this case, heat energy is transported via solar radiation through space.

The wind chill factor also depends on the humidity. For example a wet skin will result in increased heat loss. This is due to the fact that not only heat is transferred due to the temperature difference but also due to the phenomenon of evaporation. The same can be related to opposite scenario. Once we are feeling too hot, our bodies have mechanism of producing sweat which result in evaporation hence enhancing heat loss.

Figure 1.1: Wind draws heat from human body creating the wind chill factor.

1.2 Objective of Report

The overall objective of the project is to prove the wind chill factor, which causes the heat loss from human body (body cooling) at different wind velocity by observing the thermal image of the human body using IR camera. There will be approach to understand the risks associated with cold climate. It also includes the protective measures to provide the safety and reliability for human being. For this purpose, thermal image of human being, using IR camera is observed for the assessment of the important thermal insulation property of cold protective clothing. A limited number of winter jacket, summer jackets, and sweaters are tested in cold room under specified condition to calculate the relative required thermal insulation (IREQ*).

1.3 Effects of Cold Weather on Human Body

It has been observed that working conditions are more difficult in cold environment than in a warmer environment. The decreased body temperature due to heat loss affects the physical, manual and perceptive performance of the individuals. The efficiency of the physiological function diminishes in cold. There are many other problems faced by the individuals such as depression, dissatisfaction, insomnia and lack of motivation because of cold and darkness during winter. It is important to provide the special safety precautions, prevention means and risk management to minimize the health hazards in cold weather [1-4].

The wind velocity induces wind chill factor, hence increasing the heat loss from a human body. This may result in a challenge for a human body to maintain its core temperature (37°C or 98.6 °F) which may cause hypothermia, frostbite, pneumonia or influenza. Infection disease such as influenza is more common during winter because of higher air pollution. Physiological function and performance of individuals are slower in cold due to body cooling (heat loss) [4-6].

The influences of cold environment on the human being can be direct or indirect. The direct effects of cold include the frostbite. The indirect effects are the slippery grounds in the passage and working area. This results the slipping and tripping in winter which increase the hazards of cold environment [4].

For long time exposure in cold, tissues reduce the tactile sensation of the skin and dexterity of the fingers. Therefore, hands lacking the power to perform physically demanding tasks and difficult to handle which results in the mistakes. Thick clothing also interferes the movements. The brain storming work, the ability of decision making, responding rate and mental power reduce in cold environment. This would result in the discomfort state and ability to concentrate (attentiveness) diminishes [4].

Human body feels the systematic response in the cold temperature. In early stages, human body suffer from vasoconstriction that conserve the core temperature by driving the oxygenated blood to vital organs. Further exposure, results heat lost in the periphery via radiation, which in turn decrease the core temperature. This would cause muscle contractions, shivering, increased heart rates (tachycardia), and rapid breathing (tachypnea). Further inhalation of cold air may result in the bronchoconstriction [5, 7, 8].

As the body temperature falls below 35°C, the cardiac and cerebrovascular functions are impaired such as cardiac arrhythmias, ventricular, fibrillation, cardiac arrest, reduced cerebral blood flow and oxygen consumption. Cardiovascular system stop working in extreme cold conditions. The deficiency of oxygen in the brain eventually results in the loss of consciousness, amnestic episodes, ischemic stokes. If the core body temperature falls to 25-30°C then respiration rate becomes shallow and erratic [5, 9-11]

Elderly people are more vulnerable to cold weather because they cannot thermo-regulate themselves. It has been reported that mortality rate is higher among age group above 65 living in cold climates [12]. Similarly, women living in cold climate have higher cold related deaths than their male counterparts [13]. Younger population (below 65) are more susceptible to cardiovascular related deaths in the cold weather. Cold weather vulnerability vary across geographic locations, cities, regions and countries

[14]. Cardiovascular related deaths are more common in smaller and rural communities as compare to urban settlements[5, 15].

1.4 Metrological Perspective of Wind Chill Factor

Metrological departments around the globe take into account wind chill factor. They often report is as ‘feels like temperature’. For example,

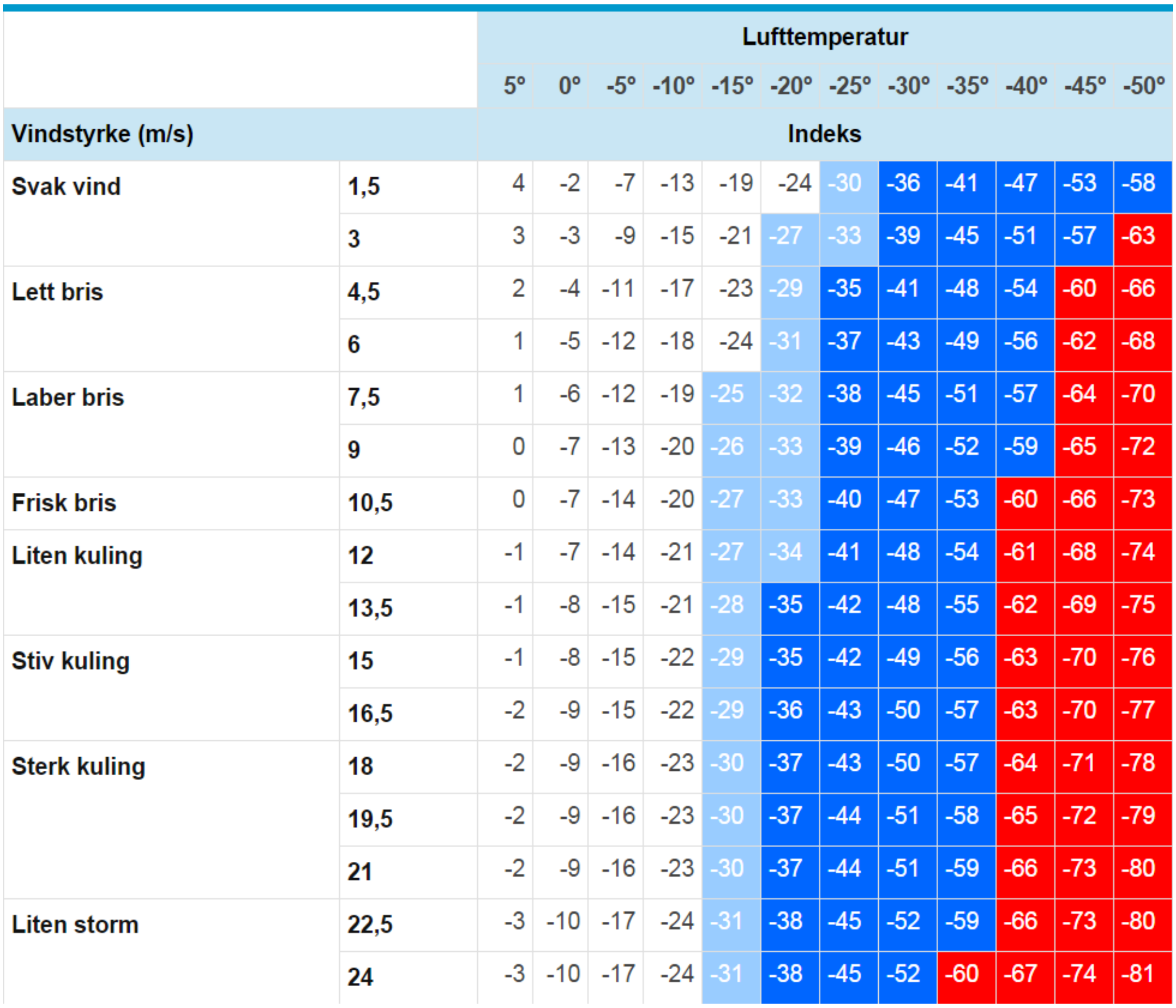
In a news article titled Who, What, Why: What is wind chill factor? published by BBC on 11th March 2013 mentions that the forecast temperature for the City of London at 0900 GMT is 0°C but it would feel like -6°C [16].

Similarly, an article titled ‘Dangerously Cold Wind Chills’ Await published by The Buffalo News on 13th February 2013 mentions that even though the temperature is -5°C but due to the winds, it would feel like -25°C in western New York [17].

Another news report titled Wind chills expected to be -20°C this afternoon, -35°C overnight published by Daily Herald on 7th January 2015 mentions that Wind chill values are expected to make temperatures feel 30°C to 35°C below zero [18].

NRK news report titled Freezing in most of the country (In Norwegian: ‘Iskaldt i det meste av landet’) on 3rd February 2012 mentions that temperature in Berlevåg is -15.8°C however, due to wind speed of 25 m/s, it feels like -40°C [19].

Norwegian weather forecasting website yr.no explains such that a thermometer is not enough to specify the degree of cooling when there are windy conditions [20]. Under such conditions, the effective temperature is calculated which may be lower than the thermometer indicates. One way is to convert the actual temperature and wind conditions into an effective temperature or feel like temperature according to the wind chill factor models (Figure 1.2).



		Lufttemperatur											
		5°	0°	-5°	-10°	-15°	-20°	-25°	-30°	-35°	-40°	-45°	-50°
Vindstyrke (m/s)		**Indeks**											
Svak vind	**1,5**	4	-2	-7	-13	-19	-24	-30	-36	-41	-47	-53	-58
	3	3	-3	-9	-15	-21	-27	-33	-39	-45	-51	-57	-63
Lett bris	**4,5**	2	-4	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66
	6	1	-5	-12	-18	-24	-31	-37	-43	-49	-56	-62	-68
Laber bris	**7,5**	1	-6	-12	-19	-25	-32	-38	-45	-51	-57	-64	-70
	9	0	-7	-13	-20	-26	-33	-39	-46	-52	-59	-65	-72
Frisk bris	**10,5**	0	-7	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73
Liten kuling	**12**	-1	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74
	13,5	-1	-8	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75
Stiv kuling	**15**	-1	-8	-15	-22	-29	-35	-42	-49	-56	-63	-70	-76
	16,5	-2	-9	-15	-22	-29	-36	-43	-50	-57	-63	-70	-77
Sterk kuling	**18**	-2	-9	-16	-23	-30	-37	-43	-50	-57	-64	-71	-78
	19,5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79
	21	-2	-9	-16	-23	-30	-37	-44	-51	-59	-66	-73	-80
Liten storm	**22,5**	-3	-10	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80
	24	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81

Figure 1.2: Effective / Feel like Temperature with respect to Actual Temperature (In Norwegian: Lufttemperatur) and Wind Velocity (In Norwegian: Vindstyrke). All given temperature values are in degree centigrade [20].

It is important to note in all of the above discussed examples that the real-time temperature is higher than the stated ‘feels like temperature’. The reason is associated with the fact that the heat transfer is enhanced due to the windy conditions.

1.5 Protective Clothing – Thermal Insulation in Cold Environment

Cold environment is characterized as an environment with the effective temperatures below –5 °C [21]. It is considered to be a health hazard; therefore, protective measures are necessary. Among them, clothing and garments are the most important. The clothing and garments used in cold climates must have required insulation to keep the necessary body heat [22]. In order to do so, thermal insulation is commonly associated with the garments and clothing. It accounts for the effect of layers, fit, drape, coverage and shape. Thermal insulation varies with fabrics/clothing and is tested with new ensembles and garments. Substandard garments may reduce the thermal insulation due to laundering, wear and tear than good quality products [21]. Thermal insulation value decreases with the moisture in the garments. This moisture may be introduced internally via sweating or externally through rain/shower, etc. There are following standards, which are used in cold climatic conditions. These standards specify requirements and test methods for the performance of clothing in cold climates.

- EN 340, Protective clothing — General requirements.
- EN 20811, Textiles — Determination of resistance to water penetration — Hydrostatic pressure test.
- EN 31092, Textiles —Determination of physiological properties — Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test) (ISO 11092:1993.)
- EN 511, Protective gloves against cold
- ENV-342 (2008) Protective clothing – Ensembles and garments for protection against cold.
- ISO 9237, Textiles — Determination of permeability of fabrics to air (ISO 9237:1995).
- ISO 15831, Clothing — Physiological effects — Measurement of thermal insulation by means of a thermal manikin (ISO 15831:2004).
- ISO 4674-1, Rubber- or plastics-coated fabrics — Determination of tear resistance — Part 1: Constant rate of tear methods (ISO 4674-1:2003).
- ISO 11079:2007 Ergonomics of the thermal environment-Determination and interpretation of cold stress when using required clothing insulation (IREQ).

1.6 Structure of the Report

This project is on building the understanding of the wind chill factor from the perspective of physics, prove the theory of heat loss in windy condition, calculate the required thermal insulation for different clothing and find out the thermal comfort for individuals. Following points are being focused on,

- Literature review of the wind chill factor models. Identifying the key parameters and associated risks. It also discusses clothing thermal insulation as protective measure.

- Review the phenomenon of heat transfer such as conduction convection and radiation.

- Laying down the methodology with the specification and limitation of equipment and experimental setup.

- Preliminary experiment to demonstrate that Infrared imaging can be used to observe the wind chill effect.

- Experiments include the capturing of thermal image of different clothing using IR camera and calculate the Relative Required Clothing Insulation (IREQ*).

- Conclusion sums up the discussion in the report.

- Future work highlights possibility of extending this work by using state of the art equipment such as Infrared (IR) imaging camera.

Chapter 2. Literature Review

2.1 Review of Wind Chill Factor Models

This section discusses the literature regarding the Wind Chill Factor Models, risk associated and protective measures.

2.1.1 Siple and Passel's Wind Chill Experiment

One of earliest wind chill index model was developed by Paul Siple and Charles Passel in year 1945 [23, 24]. Their experiment was based on water filled plastic container exposed to cold wind of Antarctica. They recorded the time taken for water to freeze over a range of temperatures and wind speeds. They used that data to calculate the heat transfer coefficient as shown in Equation (2.1).

$$h_{wc} = 10.45 + 10V^{\frac{1}{2}} - V \tag{2.1}$$

Where h_{wc} is the heat transfer coefficient in (kCal/m^{2}h°C) and V is wind velocity in m/s.

Using the Equation (2.1), they calculated the wind chill index as shown in Equation (2.2).

$$WCI = h_{wc}(33 - T_{air}) \tag{2.2}$$

Where WCI is an arbitrary wind chill index in (kCal/m^{2}h), T_{air} is the temperature of the surroundings and it is assumed that the skin temperature is 33°C.

WCI was later calibrated against cold sensation such as Cold, Very Cold, Bitterly Cold and Exposed Flesh Freezes.

Their model was too crude and went through serious criticism in scientific literature [25]. As mentioned in [26], Siple admitted by giving following response

"Looking back, we perhaps made a rather too naive approach, and we may have made assumptions which were a little careless. However, from practical standpoint, I think we evolved a schema that has been of some use."

2.1.2 Osczevski Wind Chill Model

Osczevski model consider various parts of human body and modes of heat transfer [26, 27]. In his studies, heat transfer coefficients were computed for head and face separately as shown in Equations (2.3) and (2.4).

$$h_{head} = 11.5\, V^{0.68} \qquad (2.3)$$

Where $h_{head}$the head is heat transfer coefficient in (W/m^{2}K) and V is wind velocity in m/s.

$$h_{face} = 14.4\ V^{0.61} \qquad (2.4)$$

Where $h_{face}$the facial heat is transfer coefficient in (W/m^{2}K) and V is wind velocity in m/s.

Osczevski model takes into account the radiative and convective factor of the heat loss as shown in Equations (2.5) and (2.6).

$$h_r = 4\varepsilon\sigma\bar{T}^3 \qquad (2.5)$$

Where h_r is the radiative heat transfer coefficient in (W/m^{2}K), ε is the emissivity, σ is the Stefan-Boltzmann constant and $\bar{T}$ is the mean air temperature.

$$h_c = 8.7\ V^{0.6} \qquad (2.6)$$

Where h_c is the convective heat transfer coefficient in (W/m^{2}K) and V is wind velocity in m/s.

Osczevski [26] gave Wind Chill Index model for facial cooling. His model is based on heat flow per unit area as shown in Equation (2.7).

$$Q = \frac{37 - T_{cheek}}{R_{cheek}} \tag{2.7}$$

Where Q is the heat flow per unit area (W/m^2), T_{cheek} is the cheek skin temperature (°C), R_{cheek} is the thermal resistant of skin in (m^{2}K/W) and it is assumed that the core body temperature is 37°C.

Using the calculated value of Q, Osczevski Wind Chill Index for facial cooling can be calculated using Equation (2.8).

$$WCI = 4.2Q - f(T_{air}) \tag{2.8}$$

Where WCI is the Wind Chill Index (kCal/m^{2}h) and $f(\,T_{air})$ is a function based on the temperature of the surroundings.

Osczevski [26] associated the discomfort descriptor with various values of Wind Chill Index as shown in Table 2.1. In addition, this work also gives a plot of Wind Chill Index with wind speed for various facial temperatures (given in Figure 2.1).

Table 2.1 Discomfort Descriptor with Wind Chill Index Value [26].

Discomfort Descriptor	**Wind Chill Index ($kCal/m^2h$)**
Cold	800
Very Cold	1000
Bitterly Cold	1200
Exposed Flesh Freezes	1400

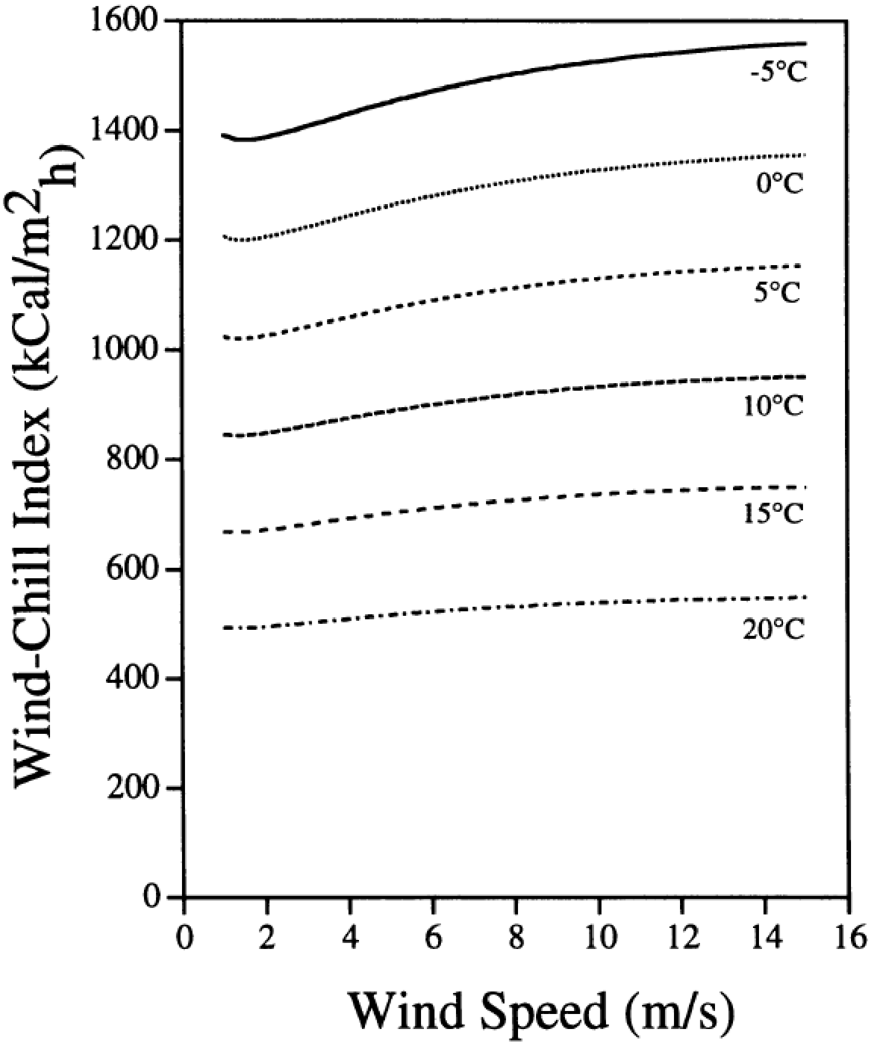


Figure 2.1: Wind Chill Index ($kCal/m^2$) with Wind Speed (m/s) for various facial temperatures ranging from -5°C to 20°C [26].

2.1.3 New Wind Chill Equivalent Temperature Chart

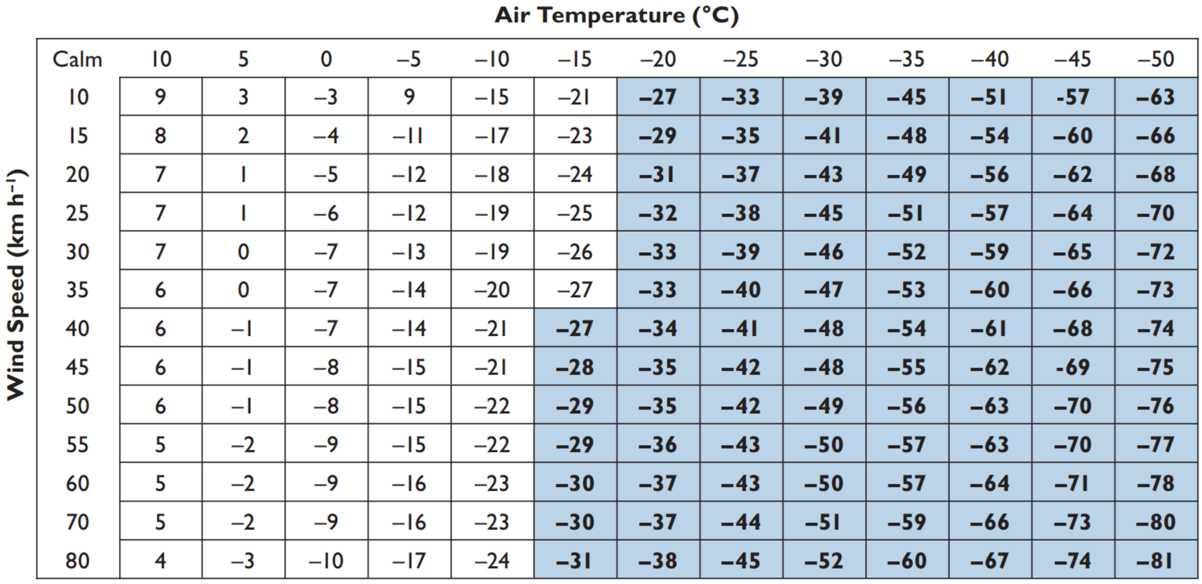
Osczevski and Bluestein published new wind chill equivalent chart in 2005 [28]. This model is widely accepted and being used by various metrological departments around the globe [20].

This model computes the Wind Chill Temperature also known as Effective or feel like temperature from wind speed and surrounding temperature as shown in Equation (2.9).

$$WCT = 13.2 + 0.6215\, T_{air} - 11.37\, V_s^{0.16} + 0.3965\, T_{air}\, V_s^{0.16} \qquad (2.9)$$

Where WCT is Wind Chill Temperature in (°C), T_{air} is temperature of the surrounding air in (°C) and V_s is the wind speed in (km/h).

The results can be plotted in a chart as given in Figure 1.2.



Air Temperature (°C)

Wind Speed (km h^{-1})

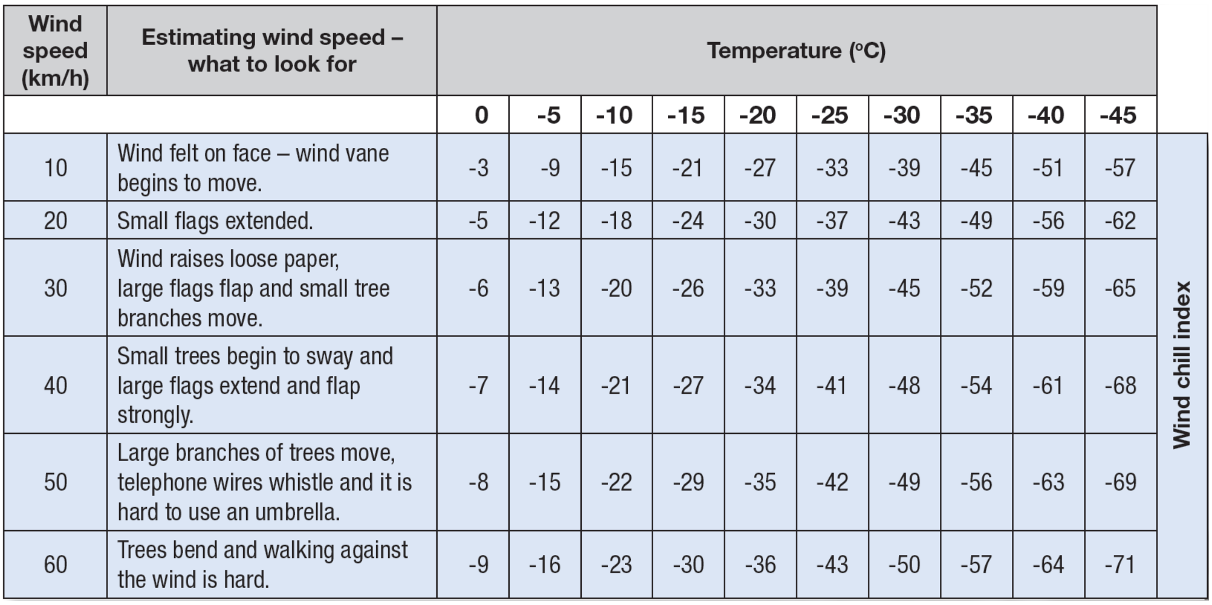
Calm	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45	–50
10	9	3	–3	9	–15	–21	**–27**	**–33**	**–39**	**–45**	**–51**	**-57**	**–63**
15	8	2	–4	–11	–17	–23	**–29**	**–35**	**–41**	**–48**	**–54**	**–60**	**–66**
20	7	1	–5	–12	–18	–24	**–31**	**–37**	**–43**	**–49**	**–56**	**–62**	**–68**
25	7	1	–6	–12	–19	–25	**–32**	**–38**	**–45**	**–51**	**–57**	**–64**	**–70**
30	7	0	–7	–13	–19	–26	**–33**	**–39**	**–46**	**–52**	**–59**	**–65**	**–72**
35	6	0	–7	–14	–20	–27	**–33**	**–40**	**–47**	**–53**	**–60**	**–66**	**–73**
40	6	–1	–7	–14	–21	**–27**	**–34**	**–41**	**–48**	**–54**	**–61**	**–68**	**–74**
45	6	–1	–8	–15	–21	**–28**	**–35**	**–42**	**–48**	**–55**	**–62**	**-69**	**–75**
50	6	–1	–8	–15	–22	**–29**	**–35**	**–42**	**–49**	**–56**	**–63**	**–70**	**–76**
55	5	–2	–9	–15	–22	**–29**	**–36**	**–43**	**–50**	**–57**	**–63**	**–70**	**–77**
60	5	–2	–9	–16	–23	**–30**	**–37**	**–43**	**–50**	**–57**	**–64**	**–71**	**–78**
70	5	–2	–9	–16	–23	**–30**	**–37**	**–44**	**–51**	**–59**	**–66**	**–73**	**–80**
80	4	–3	–10	–17	–24	**–31**	**–38**	**–45**	**–52**	**–60**	**–67**	**–74**	**–81**

Figure 2.2: Wind Chill Temperature (°C) with Air Temperature (°C) and Wind Speed (km/h). Shaded region shows when frostbite may occur.

2.2 Risk Associated with Wind Chill Factor

Wind chill factor can be hazardous in Arctic and cold region. It increases the rate at which our body loses the heat. A report published by Department of National Defence Canada in 2010 [29] summarises the risk posed due to the wind chill. Figure 2.3 shows the categorization of wind chill index [29].

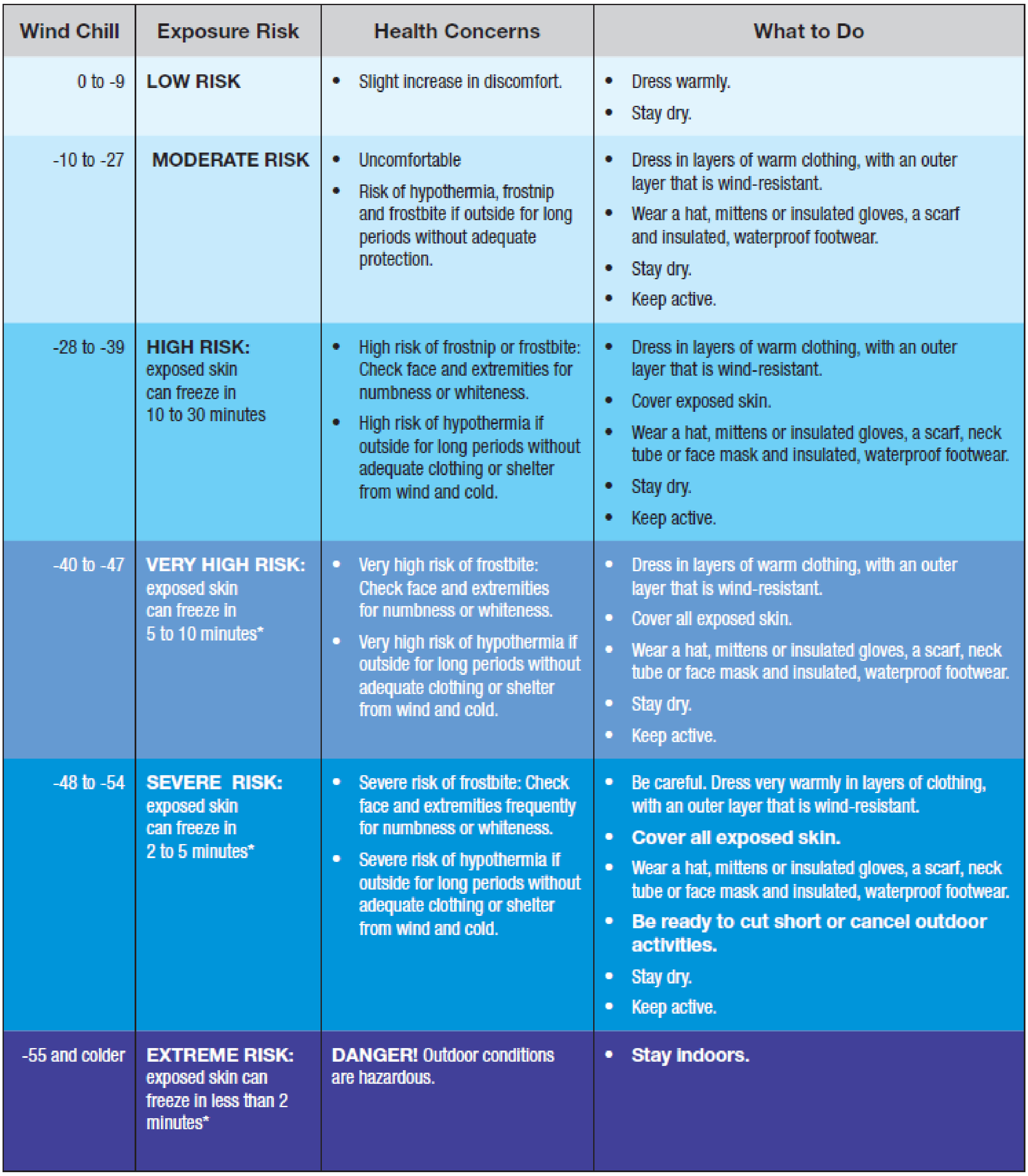
The health risks in cold regions depend on several factors: temperature, wind, activity, duration, protective clothing, personal fitness and acclimatisation. The risk factor are associated with general as well as local cooling.



Wind speed (km/h)	Estimating wind speed – what to look for	Temperature (°C)										
		0	**-5**	**-10**	**-15**	**-20**	**-25**	**-30**	**-35**	**-40**	**-45**	
10	Wind felt on face – wind vane begins to move.	-3	-9	-15	-21	-27	-33	-39	-45	-51	-57	**Wind chill index**
20	Small flags extended.	-5	-12	-18	-24	-30	-37	-43	-49	-56	-62	
30	Wind raises loose paper, large flags flap and small tree branches move.	-6	-13	-20	-26	-33	-39	-45	-52	-59	-65	
40	Small trees begin to sway and large flags extend and flap strongly.	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	
50	Large branches of trees move, telephone wires whistle and it is hard to use an umbrella.	-8	-15	-22	-29	-35	-42	-49	-56	-63	-69	
60	Trees bend and walking against the wind is hard.	-9	-16	-23	-30	-36	-43	-50	-57	-64	-71	

Figure 2.3: Categorization of Wind Chill Index [29]

In addition, the exposure risk, health concerns and recommended actions under various wind chill conditions are given in Figure 2.4 [29].



Wind Chill	Exposure Risk	Health Concerns	What to Do
0 to -9	**LOW RISK**	• Slight increase in discomfort.	• Dress warmly. • Stay dry.
-10 to -27	**MODERATE RISK**	• Uncomfortable • Risk of hypothermia, frostnip and frostbite if outside for long periods without adequate protection.	• Dress in layers of warm clothing, with an outer layer that is wind-resistant. • Wear a hat, mittens or insulated gloves, a scarf and insulated, waterproof footwear. • Stay dry. • Keep active.
-28 to -39	**HIGH RISK:** exposed skin can freeze in 10 to 30 minutes	• High risk of frostnip or frostbite: Check face and extremities for numbness or whiteness. • High risk of hypothermia if outside for long periods without adequate clothing or shelter from wind and cold.	• Dress in layers of warm clothing, with an outer layer that is wind-resistant. • Cover exposed skin. • Wear a hat, mittens or insulated gloves, a scarf, neck tube or face mask and insulated, waterproof footwear. • Stay dry. • Keep active.
-40 to -47	**VERY HIGH RISK:** exposed skin can freeze in 5 to 10 minutes*	• Very high risk of frostbite: Check face and extremities for numbness or whiteness. • Very high risk of hypothermia if outside for long periods without adequate clothing or shelter from wind and cold.	• Dress in layers of warm clothing, with an outer layer that is wind-resistant. • Cover all exposed skin. • Wear a hat, mittens or insulated gloves, a scarf, neck tube or face mask and insulated, waterproof footwear. • Stay dry. • Keep active.
-48 to -54	**SEVERE RISK:** exposed skin can freeze in 2 to 5 minutes*	• Severe risk of frostbite: Check face and extremities frequently for numbness or whiteness. • Severe risk of hypothermia if outside for long periods without adequate clothing or shelter from wind and cold.	• Be careful. Dress very warmly in layers of clothing, with an outer layer that is wind-resistant. • **Cover all exposed skin.** • Wear a hat, mittens or insulated gloves, a scarf, neck tube or face mask and insulated, waterproof footwear. • **Be ready to cut short or cancel outdoor activities.** • Stay dry. • Keep active.
-55 and colder	**EXTREME RISK:** exposed skin can freeze in less than 2 minutes*	**DANGER!** Outdoor conditions are hazardous.	• **Stay indoors.**

Figure 2.4: Exposure Risk, Health Concerns and What to Do under various Wind Chill conditions [29].

2.3 Protective Clothing

Wind chill factor results the heat loss from human body in cold climate that can be a health hazard. Therefore, protective measures are taken through clothing that control and regulate the heat loss. Clothing and garments used in cold climates should be highly insulated to maintain the thermal balance of the body [22].

Thermal insulation is the general term commonly used for garments and reference clothing that provide adequate protection against the cold and prevent the heat loss from human body. It accounts for the effect of layers, fit, drape, coverage and shape. Thermal insulation varies with fabrics/clothing and is tested with new ensembles and garments. Substandard garments may reduce the thermal insulation significantly due to laundering and wear than good quality products [21].

Thermal insulation value decreases with moisture in garments. This moisture comes from sweating in continuous cold exposure.

There are two well accepted standards to define the clothing thermal insulation/thermal comfort; British Standard – EN 342 and ISO 11079:2007 (E) [21, 22] (Appendix - A). Terms defined in each standards are discussed below.

2.3.1 British Standard-EN 342 [21]

(a) Cold Environment

Cold environment characterized by the combination of humidity and wind at air temperature below – 5 °C.

(b) Garment

It is the individual component of a clothing ensemble, the wearing of which provides protection to the part of the body that it covers.

(c) Ensemble

Ensemble is the clothing consisting of a two-piece suit or one-piece suit (coverall) or a number of garments covering the body, but do not cover head, hands and feet.

(d) Outer shell material

The protective clothing containing the outermost material is termed as outer shell material.

(e) Liner

Liner is the type of cloth with a watertight property.

(f) Thermal lining

Thermal lining is the non-watertight layer providing thermal insulation.

(g) Thermal liner

It is the layer with a watertight property that provide additional thermal insulation.

(h) Lining

Lining is the innermost material without watertight property.

(i) Thermal resistance (insulation)

It is the temperature difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. Heat can be transferred through conduction, convection and radiation. This quantity is specific to textile materials. A list of thermal resistance values are given in Table 2.2.

Table 2.2: Thermal resistance of various protective clothing.

Garment	Thermal Resistance $\frac{m^2.K}{W} \pm 10\%$
Undershirt with long sleeves	0,060
Long underpants	0,060
Socks (up to the knee)	0,053
Boots	0,189
Thermo-jacket	0,100
Thermo-pants	0,100
Knitted gloves	0,082
Balaclava	0,060

(j) Water vapours resistance

It is the pressure difference between the two faces of a material divided by the resultant evaporative heat flux per unit area in the direction of the gradient. The evaporative heat flux may happen through diffusion and convection. This is a quantity is specific to textile material.

(k) Effective thermal insulation

It is measured from skin to outer clothing surface under defined conditions with a stationary manikin. Effective thermal insulation is determined in relation to the naked body surface area.

(l) Resultant effective thermal insulation

If the thermal insulation is measured from skin to outer clothing surface under defined conditions with a moving manikin then it is known as resultant effective thermal insulation. The resultant effective thermal insulation value is determined in relation to the naked body surface area.

(m) Insulation Required (IREQ)

It is the required resultant thermal insulation calculated based on the specific thermal parameter of the environment such as air temperature, mean radiant temperature, air velocity, relative humidity and the body metabolism.

Thermal insulation of a clothing depends on the measured insulation values. The capacity of the clothing ensemble or garments to preserve heat at core body temperature depends on the internal body heat production (metabolism). Therefore protective insulation value of clothing ensemble or garments is find out by comparing its measured insulation value with calculated required insulation value (IREQ).

(n) Resistance to water penetration (WP)

It is the measure of the opposition to the passage of water through the material due to hydrostatic pressure supported by a material. The resistance to water penetration of the outer shell material together with any incorporated watertight layer and is given in Table 2.3.

Table 2.3: Classification of resistance to water penetration (WP).

Water Protection (Pa)	Class
8000 ≤ WP ≤ 13000	1
WP >13000	2

(o) Tear resistance of outer shell material

The tearing force of the outer shell material (with the exception of vests and excluding elasticated and knitted materials) is defined at minimum value of 25 N in both orthogonal directions of the material.

2.3.2 ISO 11079:2007 (E) [22]

(a) Insulation Required IREQ

It is the required thermal insulation for the preservation of the body heat balance at defined levels of physiological strain.

(b) Thermo-neutral zone

The body maintains heat balance exclusively by vasomotor reactions within the temperature interval. This temperature interval is known as Thermo-neutral zone.

(c) Wind chill temperature

The temperature related to the cooling effect on a local skin segments is known as wind chill temperature.

(d) Thermal Comfort

It is defined as the condition of mind which expresses satisfaction with the thermal environment. Thermal environment depends upon many factors such as air temperature, wind velocity, humidity, noise level and light. Thermal comfort influences our work efficiency.

(e) Conditions for Thermal Comfort

One condition of thermal comfort is the thermal neutrality at which one feels neither too warm nor too cold. Thermal neutrality accounts the combination of skin temperature and the body's core temperature. Thermal comfort also deals with fulfilment of the body's energy balance: the heat produced by the metabolism should be equal to the amount of heat lost from the body.

(f) Method for evaluation

The climatic condition under which the body heat exchange such as cold temperature and wind velocity causes the heat loss from human body rapidly, putting them at risk of cold stress. Cold stress is assessed with both general cooling of the body and local cooling of particular parts of the body (e.g. extremities and face).

General cooling deal with analytical method for the evaluation and interpretation of thermal stress. These methods calculate the body heat exchange, the required clothing insulation (IREQ) for maintaining the heat balance and thermal insulation provided by the clothing ensemble. Then this IREQ is subsequently compared with the insulation offered by the clothing. If clothing's insulation is less than required then duration limited exposure is calculated but it depends on the acceptable levels of body cooling.

The general method constitutes the following steps and given in Figure 2.5.

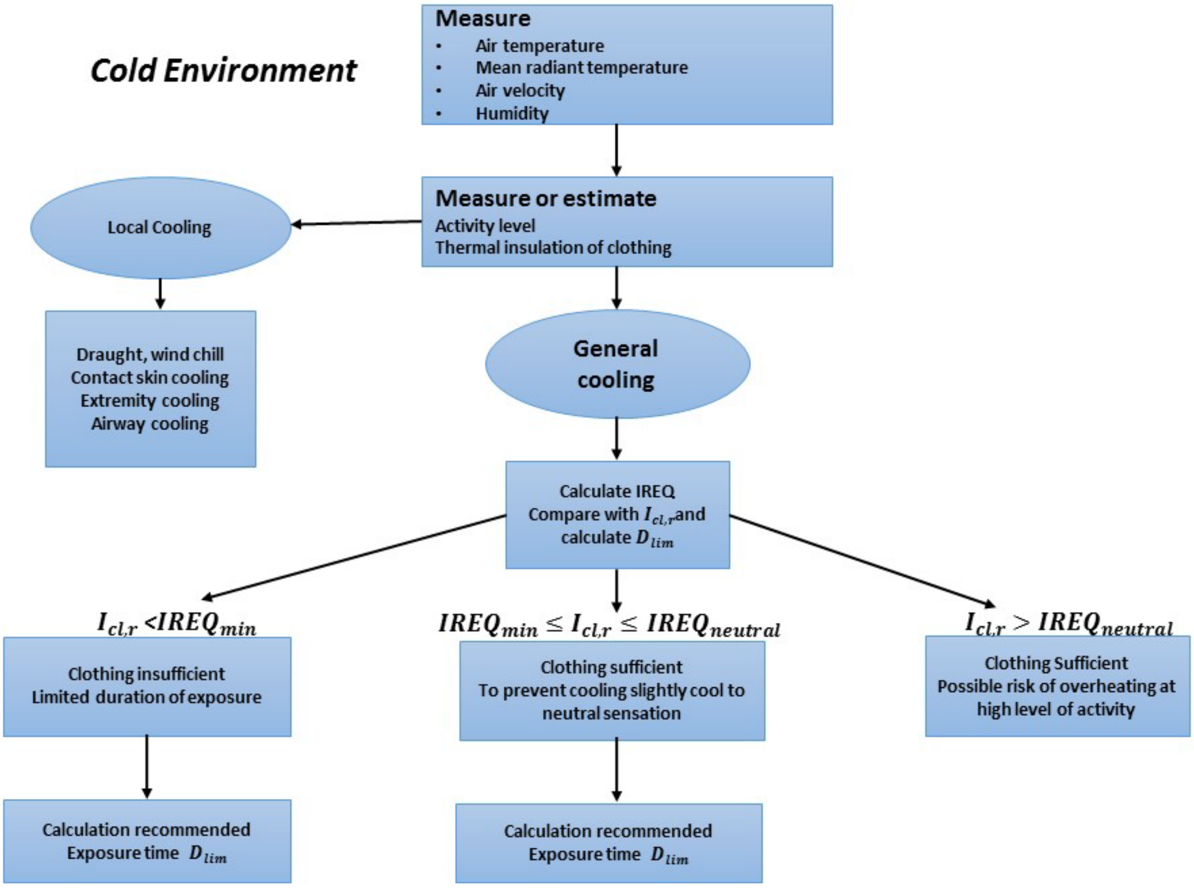


Figure 2.5: Procedure for evaluation of cold environments.

(g) Required Clothing insulation (IREQ)

IREQ represents the resultant clothing insulation required in cold environment to maintain the body in a state of thermal equilibrium at acceptable level of body and skin temperatures.

IREQ measure the cold stress combining the effects of air temperature, mean radiant temperature, relative humidity, air velocity for defined level of metabolic rate. It analysis the effects of the cold environment and the metabolic rate in human body. It also deal with requirement of specific clothing insulation and subsequent selection of clothing to be used under actual conditions. It evaluates the change in heat balance parameters to provide the suitable design and planning of the work time and work regimes under cold conditions.

(h) Calculation of IREQ

IREQ is calculated by the analysis of a human body heat exchange with the environment. The mathematical expression of IREQ is the general heat balance equation as shown in Equation (2.10).

$$M - W = E_{res} + C_{res} + E + K + R + C + S \tag{2.10}$$

Where M is the metabolic rate, W is the effective mechanical power, E_{res} is Respiratory evaporative heat loss, C_{res} is the Respiratory convective heat loss, E is the evaporative heat exchange, K is the conductive heat exchange, R is the radiative heat exchange, C is the convective heat exchange, and S is body heat storage rate.

The left side of the equation indicates the internal heat production of the body, which balanced by the right side which denotes the sum of heat exchanges in the respiratory tract, heat exchanges on the skin and the heat storage accumulation in the body.

Heat loss from human body through clothing take place by four modes of heat transfer such as conduction, convection, radiation and evaporated sweat. Heat exchange depends on the thermal insulation of the clothing ensemble and skin-to-clothing surface temperature gradient. Dry heat flow to the clothing surface is equivalent to the heat transfer between the clothing surface and the environment. Therefore, heat exchange through clothing is determined by the resultant, thermal insulation of clothing. It is given in equation in Equation (2.11).

$$\frac{T_{sk} - T_c}{I_{cl,r}} = R + C = M - W - E_{res} - C_{res} - E - S \qquad (2.11)$$

Where T_{sk} is mean skin temperature, T_c is clothing surface temperature, $I_{cl,r}$ is resultant clothing insulation, and IREQ is required clothing insulation. IREQ is expressed in $m^2\ K\ W^{-1}$. It also expressed in Clo where $1\ Clo = 0.155\ m^2\ K\ W^{-1}$.

From Equations (2.10) and (2.11), the required clothing insulation, IREQ, is calculated on the basis of the hypothesis concerning heat flow by conduction.

$$IREQ = \frac{T_{sk} - T_c}{R + C} \qquad (2.12)$$

The values of R and C depends on metabolism rate and can be determined using Equation (2.10). It is to be noted that metabolism rate for human beings varies (50 - 400 Wm^{-2}) [30].

2.4 Review of the Phenomenon of Heat Transfer

This section discusses the phenomenon of heat transfer. The topic of heat transfer has been discussed in many books of heat and thermodynamics. Majority of the laws describing the phenomenon of heat transfer has been published from 1800s. This chapter focuses on three modes of heat transfer namely conduction, convection and radiation.

2.4.1 First Mode of Heat Transfer: Conduction

Heat transfer through conduction occurs due to atomic and molecular activity. The molecules with high energy collide with neighbouring molecules having lower energy. The atomic activity in conduction involves the lattice vibration and electron migration. Heat transfer through conduction is directly proportional to temperature gradient and can be written as shown in Equation (2.13) and explained in Figure 2.6 [31].

$$q''_x = -k\frac{\partial T}{\partial x} \tag{2.13}$$

Where q''_x is the heat transfer per unit area in (W/m^2), k is coefficient of thermal conduction in (W/(m.K)), T is the temperature in (K) and x is the unit direction in (m). The negative sign donates that the heat energy is transferred in the direction of decreasing temperature.

As shown in Figure 2.6, heat transfer through conduction can be linear or non-linear. Linear behaviour is under steady state conditions when wall temperatures are not changing over time. Non-linear behaviour exists when wall temperature varies with time.

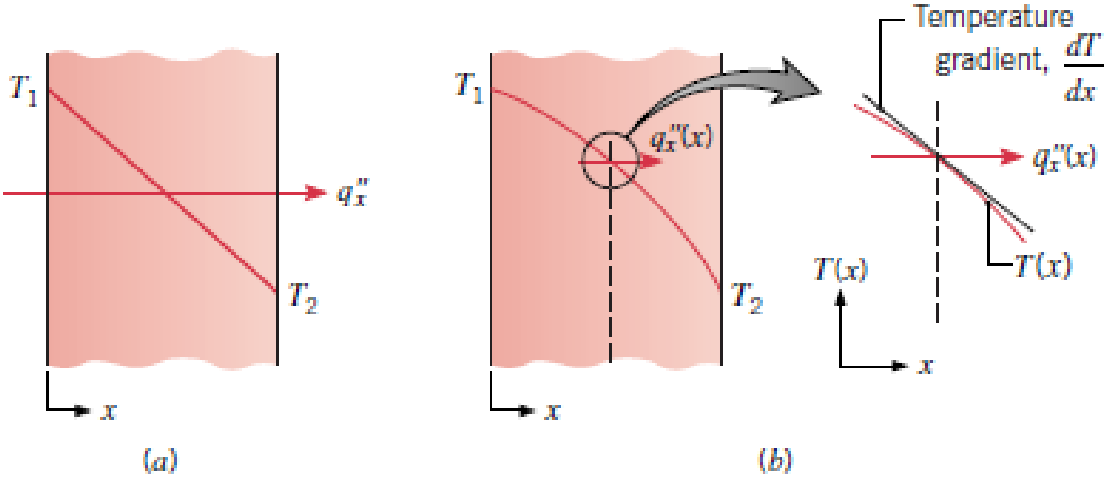


Figure 2.6: Heat transfer through conduction (a) Linear heat transfer (or constant heat flux) (b) Nonlinear heat transfer (or variable heat flux)

Heat transfer through conduction can be in more than one direction. In such case, Equation (2.13) can be expanded to take into account multi-directions. Three dimensional heat equation is shown in Equation (2.14).

$$q''_n = q''_x + q''_y + q''_z = -k\left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}\right) \tag{2.14}$$

Where q''_n is the multi-directional heat transfer per unit area in (W/m^2), k is coefficient of thermal conduction in (W/(m.K)), T is the temperature in (K) and x, y, z are the unit directions in (m). The negative sign donates that the heat energy is transferred in the direction of decreasing temperature.

2.4.2 Second Mode of Heat Transfer: Convection

Convection is the mode of heat transfer within a moving or stationary fluid. Convection may also takes place between a solid surface and the interacting fluid. In this mode, heat energy is transferred either by the bulk or macroscopic motion of the fluid through random motion of molecules. The amount of heat transfer through convection is directly proportional to the temperature difference as shown in Equation (2.15) [31].

$$q'' = h(T_s - T_\infty) \tag{2.15}$$

Where q'' is the heat transfer per unit area in (W/m^2), h is convective heat transfer coefficient in (W/(m^2.K)), T_s is the surface temperature in (K) interacting with the fluid at T_∞ temperature in (K).

Convection heat transfer coefficient depends on boundary layer condition which is influenced by the surface, geometry, nature of the fluid motion, fluid dynamics and transport properties. Convection can be categorized in two main types namely free convection and forced convection.

Free Convection (also known as 'Natural Convection') occurs when the flow is induced by the buoyancy forces. These buoyancy forces are caused by the difference in the density that is due to temperature variation in the fluid.

Forced convection occurs due to the flow caused by the external means such as fan, pump, or atmospheric wind.

It is common in real case scenarios that the two modes of heat transfer such as conduction and convection takes place simultaneously. One of the scenario is shown in Figure 2.7. It is shown that fluid on one side of the wall is warmer than the other. Due to which a constant thermal gradient is established within the solid wall. Heat transfer through the mode of convection is taking place on either sides of the wall and heat transfer through the mode of conduction is taking place within the wall itself. This can be illustrated as shown in Equation (2.16).

$$q'' = h_1(T_{s,1} - T_{\infty,1}) = -k\frac{(T_{s,1} - T_{s,2})}{L} = -h_2(T_{s,2} - T_{\infty,2}) \qquad (2.16)$$

Where q'' is the heat transfer per unit area in (W/m^2), h_1 and h_2 are convective heat transfer coefficients in (W/(m^2.K)) of hot and cold fluids respectively, $T_{s,1}$ and $T_{s,2}$ are the surface temperatures in (K) of the wall interacting with the corresponding fluids, and $T_{\infty,1}$ and $T_{\infty,2}$ are hot and cold fluid temperatures in (K) respectively.

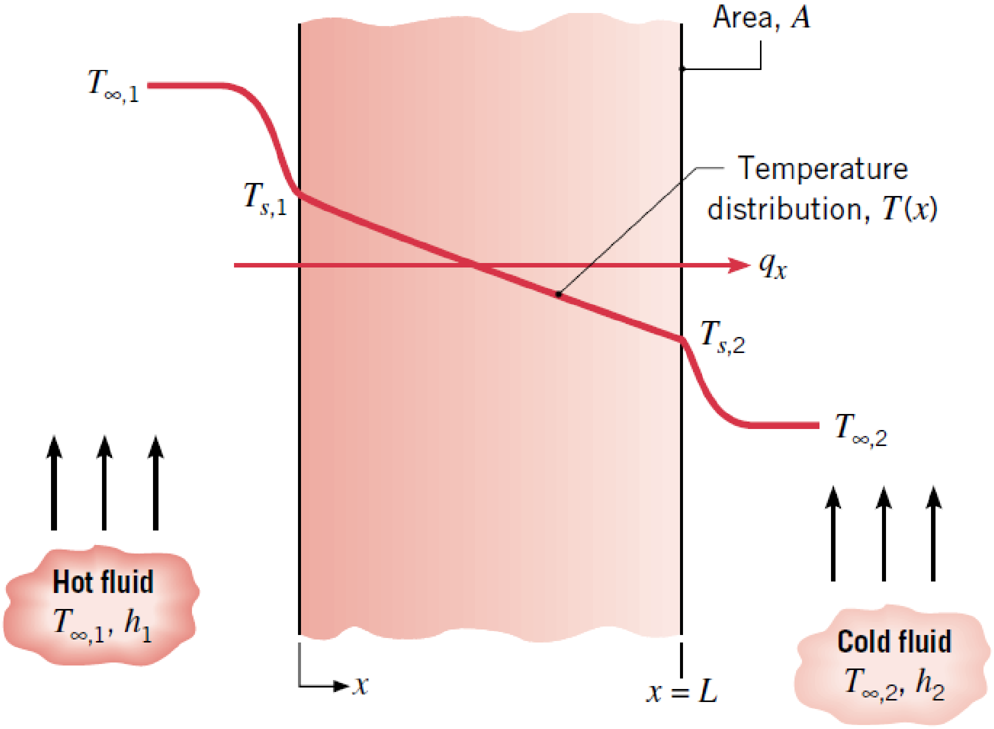


Figure 2.7: Heat transfer through a wall. Wall is warmed by hot fluid on one side and cooled by cold fluid on other. A steady state temperature gradient exists within the solid wall.

Nusselt number (dimensionless quantity) is used to estimate the convective heat transfer coefficient. The relation between Nusselt number and convective heat transfer is shown in Equation (2.17).

$$Nu = h\frac{L}{k} \tag{2.17}$$

Where Nu is the Nusselt number, L is the characteristics length in (m) and k is thermal conductivity in (W/(m.K)).

Nusselt number is a function of the Reynolds number and Prandtl number. It can be estimated locally or can be averaged over a surface as shown in Equations (2.18) and (2.19). These functions depend upon the geometry of the surface, flow conditions, and flow properties.

$$Nu_x = f(x^*, Re_x, Pr) \quad - \quad Local \tag{2.18}$$

Where Nu_x is the local Nusselt number, Re_x is local Reynolds number, Pr is the Prandtl number and x^* is the dimensionless distance at a particular location on the surface in (m).

$$\overline{Nu_x} = f(Re_x, Pr) \quad - \quad Average \tag{2.19}$$

Where $\overline{Nu_x}$ is the average Nusselt number, Re_x is local Reynolds number and Pr is the Prandtl number.

2.4.3 Third Mode of Heat Transfer: Radiation

Radiative mode of heat transfer occurs when the surfaces of finite temperature emit energy in form of electromagnetic waves (photons) in the absence of an intervening medium. The rate at which energy is released in the radiation is shown in Equation (2.20) and illustrated in Figure 2.8.

$$q'' = \varepsilon\sigma T_s^4 \tag{2.20}$$

Where q'' is the heat transfer per unit area in (W/m^2), σ is the Stefan-Boltzmann constant, ε is the thermal emissivity and T_s is the surface temperature.

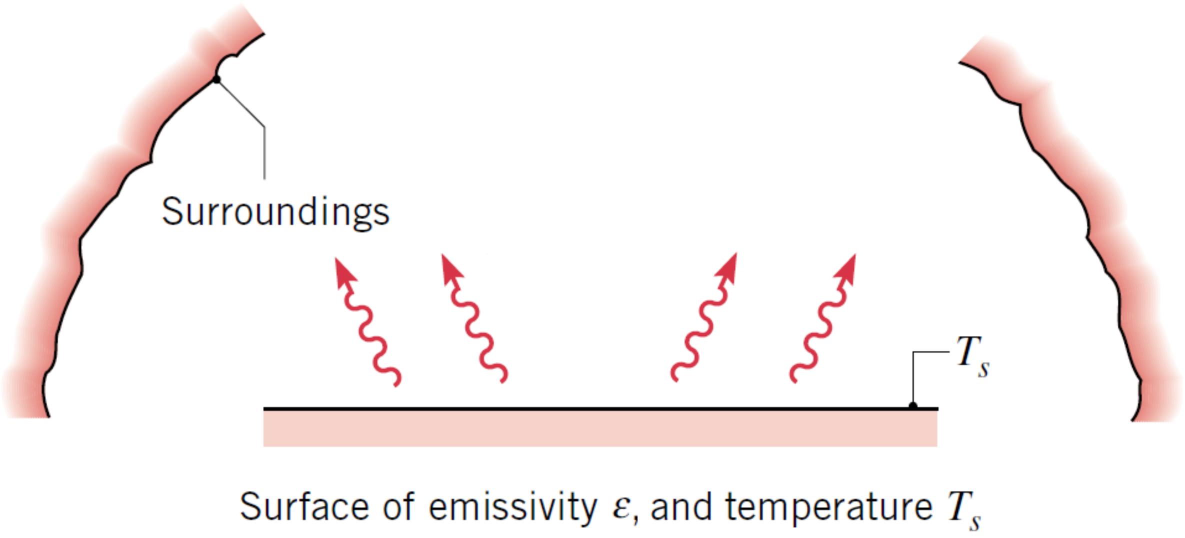


Figure 2.8: A surface emitting thermal radiations [31].

Chapter 3. Methodology

This chapter discusses the experimental methodology used to study the wind chill factor and to calculate the clothing insulation. The study is carried out using infrared imaging. The chapter gives detailed overview of the experimental setup and the devices used to carry out the study.

3.1 Infrared Imaging

Electromagnetic radiation is a form of energy propagated both through free space and a medium in the form of waves. Electromagnetic radiation exhibit the dual nature: it acts as a wave properties and also particulate (photon) properties. The electromagnetic radiation is divided into further sub categories based on wavelengths such as radio waves, microwaves, ultraviolet rays, visible light, X-rays, and gamma rays. These rays (band) combined to make up the electromagnetic spectrum and each band in the spectrum has different wavelength and different amount of energy they transmit [32].

The infrared rays are a form of electromagnetic radiation with wavelength longer than that of the visible light. The wavelength of Infrared (IR) ranges from 1mm (frequency of 300 GHz) to 0.7μm (frequency of 430 THz) and possessed photon energy from 1.24meV to 1.7eV. The position of IR lies next to the red light of the visible electromagnetic spectrum as shown in Figure 3.1 [32, 33].

The amount of heat can be determined using the Stefan-Boltzmann Law [34] based on the different temperature difference as given in Equation (3.1).

$$q'' = \varepsilon\, \sigma\, (T_s^4 - T_\infty^4) \tag{3.1}$$

Where q'' is the heat loss, ε is emissivity in comparison to black body (dimensionless), σ is Stefan-Boltzmann constant (W/(m^2.K^4)), and T_s is the surface temperature (°C) and T_∞ is the room (surrounding) temperature (°C).

At a given temperature the body with higher emissivity will emit more radiations; a body with emissivity value of 1 is perfect emitter and called a blackbody.

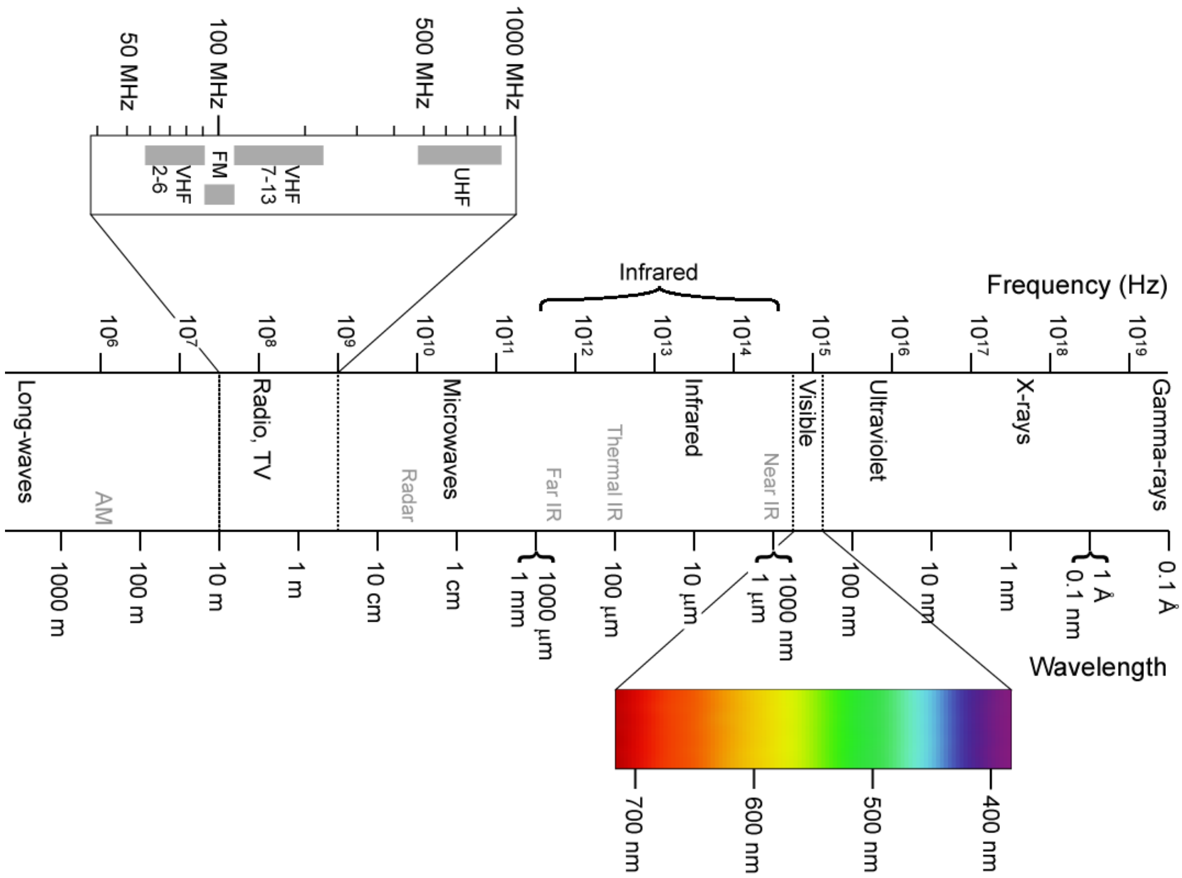


Figure 3.1: Electromagnetic Spectrum [34].

IR spectral band is subdivided on the basis of the range of wavelength as shown in Figure 3.2. Each of which is named as follows:

- Near Infrared (NIR): Wavelength ranges in near infrared from 0.75-1µm.
- Short Infrared (SIR): Wavelength ranges in short infrared from 1-2.5µm.
- Middle Wave (MWIR): Wavelength ranges in middle wave infrared from 3-5µm.
- Long Wave Infrared (LWIR): Wavelength ranges in long wave infrared from 8-14µm.

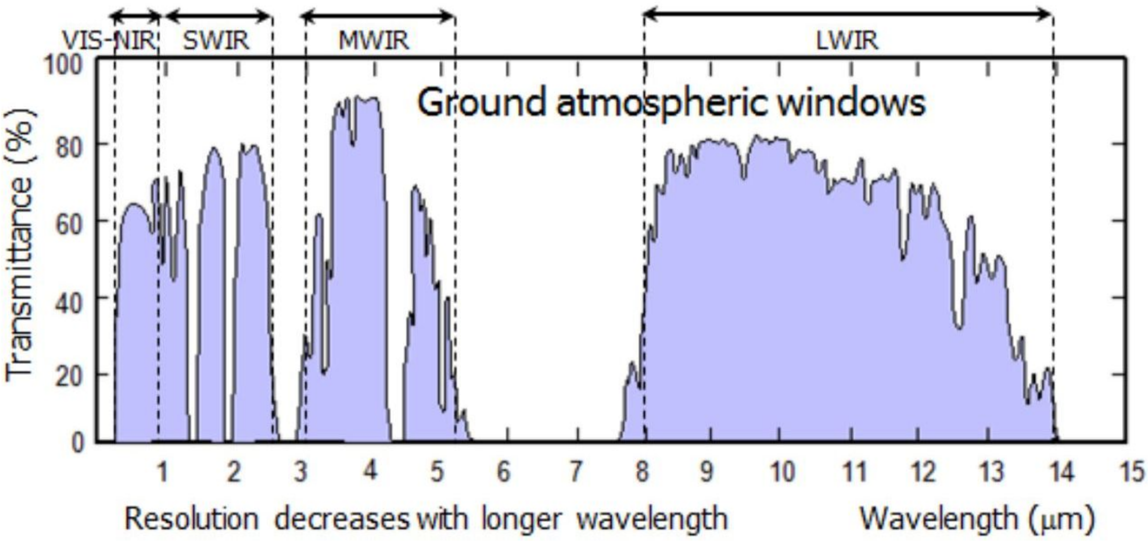


Figure 3.2: Infrared Spectrum [35].

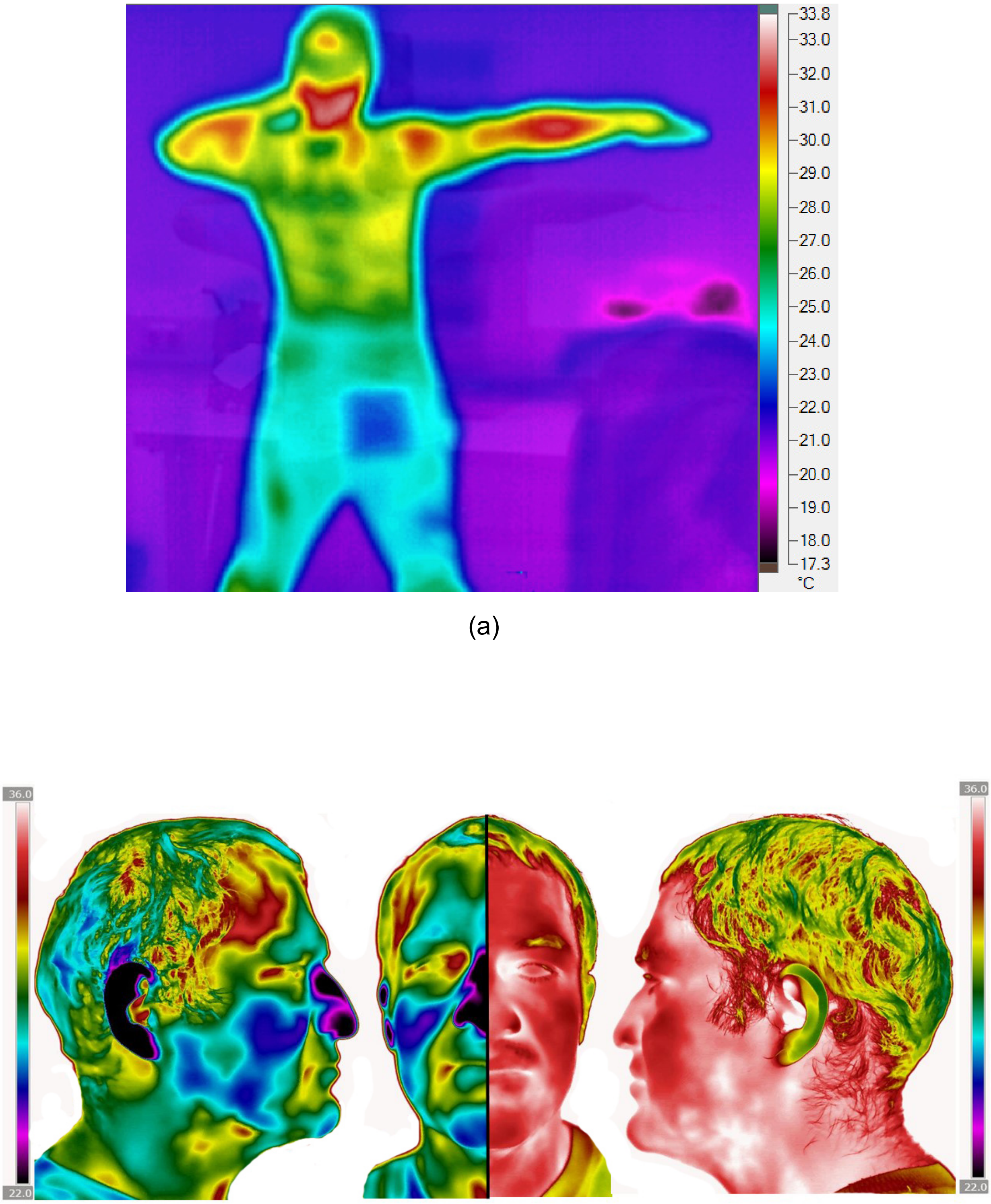
3.1.1 Infrared Camera

Infrared (IR) camera works on thermography imaging technique. It detects the infrared radiation of different wavelengths and calculate the thermal signature. The IR camera provides the temperature profile of the object as shown in Figure 3.3.

IR camera consists of lens, detector, video processing electronics and user interface control. The lens focuses the incident beam on the detector which comprises the arrangement of IR sensitive elements called focal plane array (FPA). The resolution of thermographic image of IR camera is defined by the resolution of FPA.

The basic working principle for an IR camera and its components are shown in Figure 3.4.

In this study, we have used Fluke® Ti55 and Flir® T1030sc cameras.The cameras are shown in Figure 3.5 and Figure 3.6



(a)

(b)

Figure 3.3: False Coloured Infrared Image (a) taken with Fluke® Ti55 IR camera; (b) taken with Flir® T1030sc IR camera.

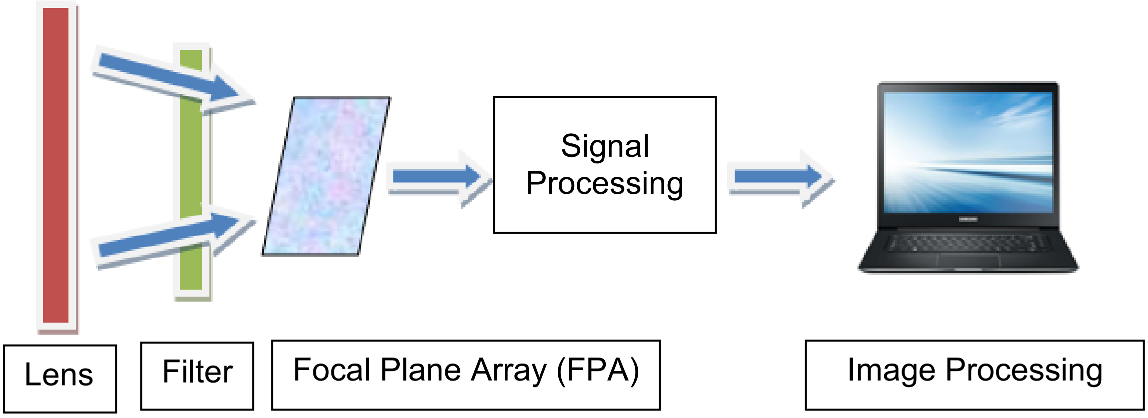


Figure 3.4: Working Principle of an IR Camera

Figure 3.5: Fluke® Ti55 IR Camera

Figure 3.6: Flir® T1030sc Camera

Both Fluke® Ti55 and Flir® T1030sc cameras have following components as discussed below:

- Optical Lens

The main function of optical lens is to transfer IR radiation toward the filter at specific range normally at long wave infrared (LWIR).

- Filter

The filter in IR camera sort out the IR radiations for certain spectral range.

- Focal Plane Array (FPA)

FPA consists of an array of light sensing pixels and acts as an imaging sensing module which detects the lights as shown in Figure 3.7 [36, 37].

Figure 3.7: Focal plane Array model.

- Electronic Module

Electronic module consists of signal processing unit which converts the output data from FPA into electronic signal by applying some corrections. The electronic signal is transferred into the display unit (computer) and displayed as a thermal image of the body [36].

Following parameter settings is required prior to use IR camera.

- Field of View (FOV)

FOV represents the angle seen by the camera and measured in degree horizontal and vertical.

- Minimum Focal Distance

The distance at which the object can be viewed at optimum details with given FOV is represented by the minimum focal distance [36, 37].

- IR Resolution

IR Resolution is the number of pixels or observation points on the focal plane arrays. It represents the image quality and read as row x columns [36, 37].

- Emissivity Correction

Emissivity correction is applied when the object emits more/less radiations than expected at given temperature. This correction limits the radiations relative to the surrounding temperature [38].

- Detector Pitch

Detector pitch is the distance between centers of two consecutive pixels of the focal plane array. Smaller distance results the high resolution [36, 37].

- Spectral Range

It represents the range of wavelength of radiation that IR camera will be able to capture. The IR spectrum is further divided into three categories namely Near, Short, Middle, Long depending upon wavelength. IR cameras are equipped with passive long wavelength infrared detectors [36, 37].

- Temperature Range

Temperature range is the maximum and minimum temperature values, which the IR cameras can detect.

- Accuracy

Accuracy handles systematic, consistent and random errors in the temperature values [16].

Table 3.1 summarizes the features of Fluke® Ti55 and Flir® T1030sc IR cameras.

Table 3.1: Features of Fluke® Ti55 and Flir® T1030sc IR cameras.

	Fluke® Ti55	**Flir® T1030sc**
IR Resolution	320 × 240 pixels	1024 × 768 pixels
Emissivity Correction	Variable from 0.1 to 1.0	Variable from 0.1 to 1.0
Detector Pitch	25 μm	17 μm
Spectral Range	8 μm to 14 μm	7.5 μm to 14 μm
Operating Temperature Range	– 20°C to +100°C	-40°C to +70°C
Accuracy	± 2°C or ± 2% of reading	± 1°C or ± 1% of reading

3.1.2 Image Analysis

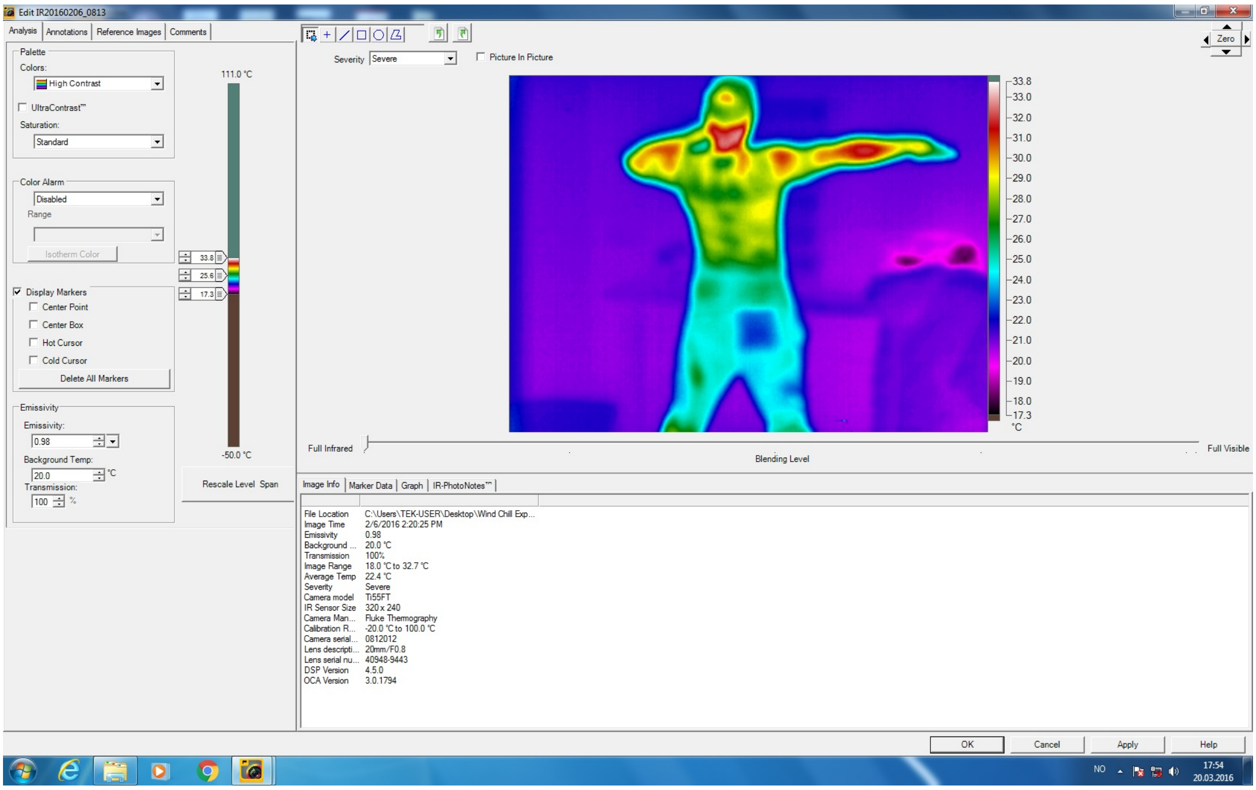
For image analysis we have used two software SmartView® for Fluke® Ti55 IR camera and FLIR ResearchIR Max® for Flir® T1030sc IR camera.

- SmartView®

SmartView® image analysis software is used to analyze the data from the Fluke® Ti55 IR Camera. The software provides a number of features to analyze the images according the needs of the user.

SmartView® software helps to visualize the both digital and IR images in a same profile as shown in Figure 3.8.

There are different analysis settings in SmartView® software to change color saturation, color alarm, display markers, emissivity settings, and background temperature.



Colors: High Contrast
☐ UltraContrast™
Saturation: Standard
Color Alarm: Disabled
Range:
☑ Display Markers
☐ Center Point
☐ Center Box
☐ Hot Cursor
☐ Cold Cursor
Emissivity: 0.98
Background Temp: 20.0 °C
Transmission: 100 %
Severity: Severe
☐ Picture In Picture

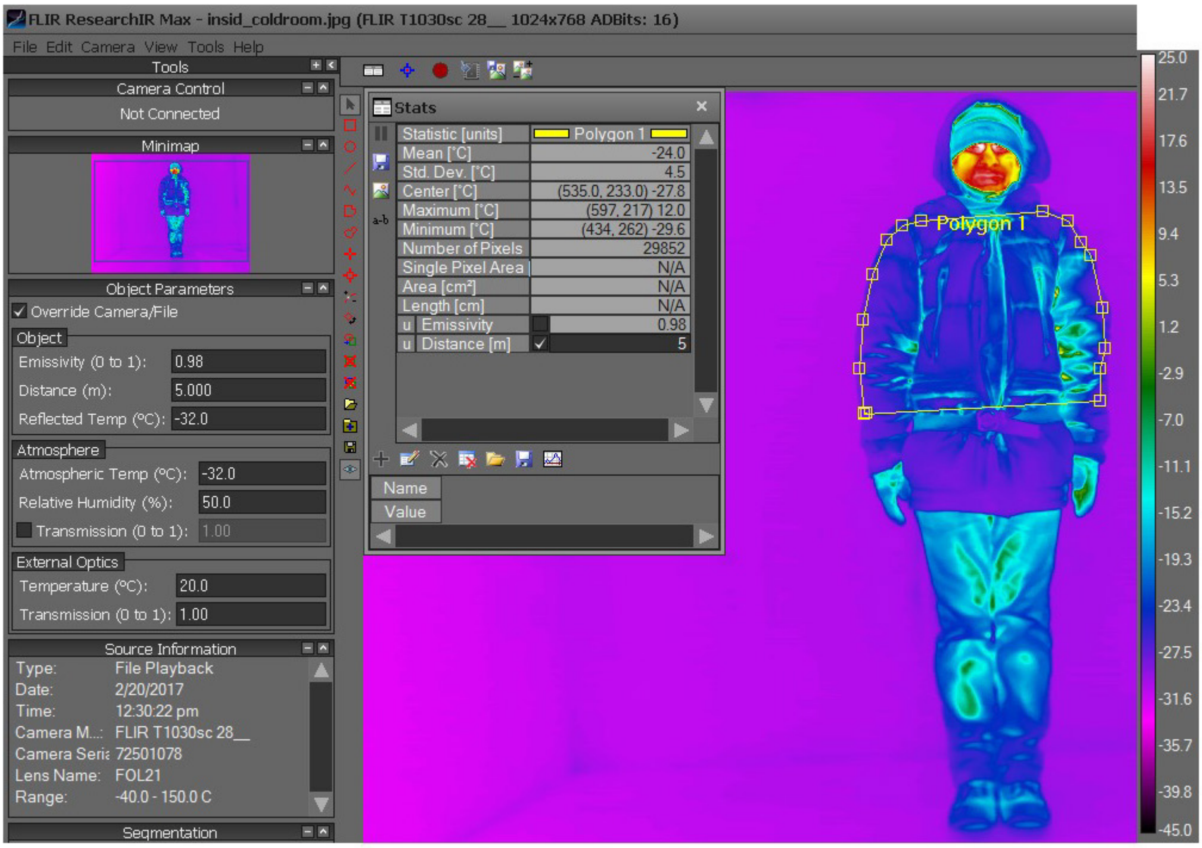
File Location C:\Users\TEK-USER\Desktop\Wind Chill Exp...
Image Time 2/6/2016 2:20:25 PM
Emissivity 0.98
Background ... 20.0 °C
Transmission 100%
Image Range 18.0 °C to 32.7 °C
Average Temp 22.4 °C
Severity Severe
Camera model Ti55FT
IR Sensor Size 320 x 240
Camera Man... Fluke Thermography
Calibration R... -20.0 °C to 100.0 °C
Camera serial... 0812012
Lens descripti... 20mm/F0.8
Lens serial nu... 40948-9443
DSP Version 4.5.0
OCA Version 3.0.1794

Figure 3.8: IR image analyzed with SmartView®) software (Image taken with Fluke® Ti55 IR Camera and analyzed in SmartView®).

- FLIR ResearchIR Max®

FLIR ResearchIR Max® is a thermal analysis software tool for FLIR R&D/science cameras as shown in Figure 3.9. It provides camera control, high speed data recording, image analysis, and data sharing. This software connects directly with the T1030sc and supports multiple acquisition options, including high-speed burst recording and slow-speed data logging. This software is highly customizable, with the ability to set everything from the number of frames acquired to the thermographic and radiometric calibrations.

FLIR ResearchIR Max® offers real-time image analysis with spots, lines, and other measurement tools. This software's charting and plotting capabilities include line profiles, histograms, and temporal plots for all measurement tools.



FLIR ResearchIR Max - insid_coldroom.jpg (FLIR T1030sc 28__ 1024x768 ADBits: 16)

Not Connected

☑ Override Camera/File

Object
Emissivity (0 to 1): 0.98
Distance (m): 5.000
Reflected Temp (°C): -32.0

Atmosphere
Atmospheric Temp (°C): -32.0
Relative Humidity (%): 50.0
☐ Transmission (0 to 1): 1.00

External Optics
Temperature (°C): 20.0
Transmission (0 to 1): 1.00

Type: File Playback
Date: 2/20/2017
Time: 12:30:22 pm
Camera M...: FLIR T1030sc 28__
Camera Seri: 72501078
Lens Name: FOL21
Range: -40.0 - 150.0 C

Statistic [units]	Polygon 1
Mean [°C]	-24.0
Std. Dev. [°C]	4.5
Center [°C]	(535.0, 233.0) -27.8
Maximum [°C]	(597, 217) 12.0
Minimum [°C]	(434, 262) -29.6
Number of Pixels	29852
Single Pixel Area	N/A
Area [cm²]	N/A
Length [cm]	N/A
u Emissivity	☐ 0.98
u Distance [m]	✓ 5

Figure 3.9: IR image analyzed with FLIR ResearchIR Max® software (Image taken in Cold Room with FLIR® T1030sc camera).

3.2 Cold Room

Cold room at The Arctic University of Norway, Tromsø provides a suitable environment for testing wind chill effect. The dimensions of the room are shown in Figure 3.10.The cold room can be set as low as -40°C, however due to technical limitation with its cooling system, it is not advisable to keep this temperature for long period of time. The ideal operating condition for the cold room chamber is between -20°C to -35°C.

The room is mounted with an evaporator with two fans. The fans provides variable wind drift in the room as shown in Figure 3.11. This wind drift velocities are measured using anemometer (TSI® Velocicalc® Air Velocity Meter Model 5725) as shown in Figure 3.12. These are average velocity values.

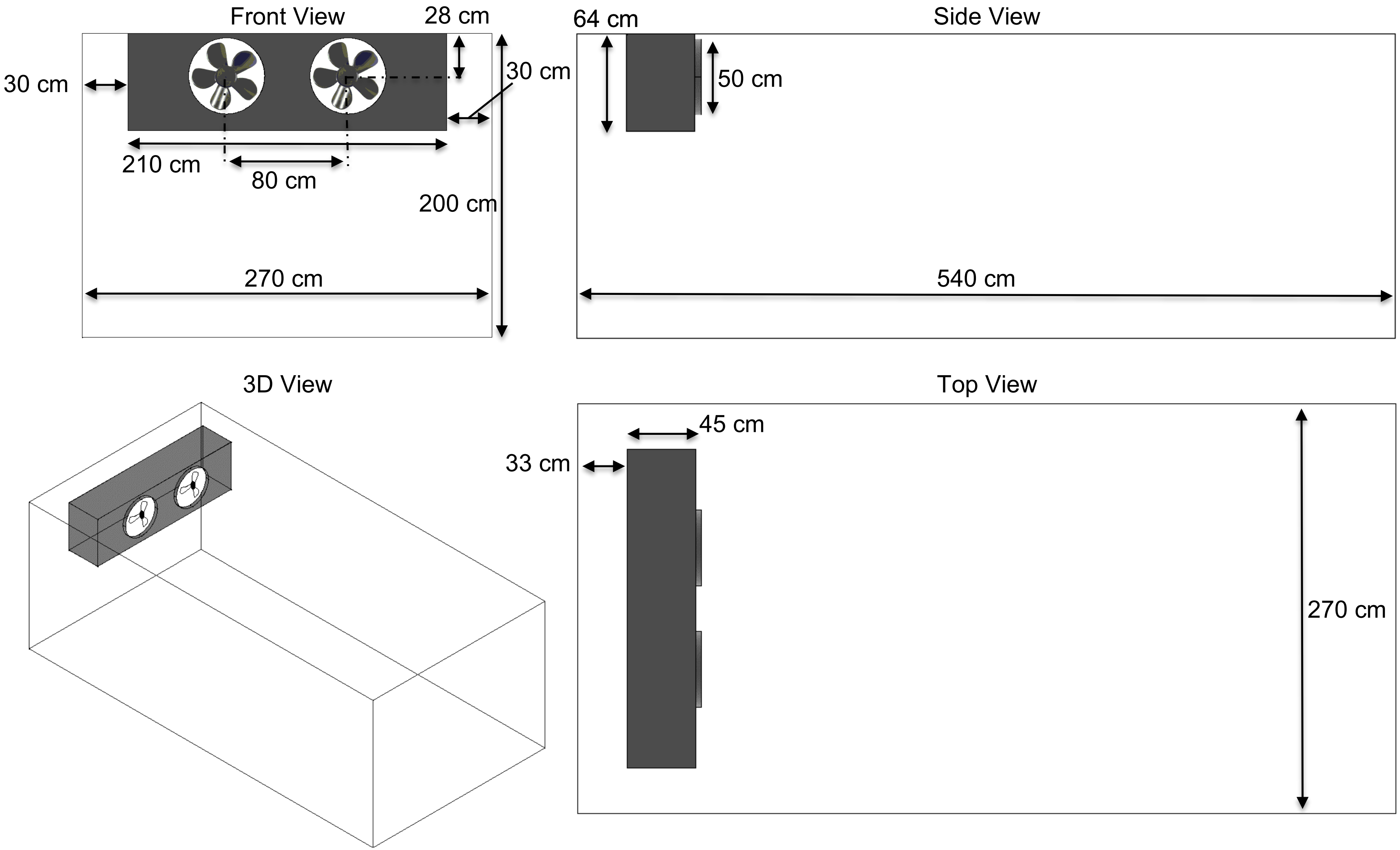


Figure 3.10: Technical Drawings of Cold Room at the Arctic University of Norway, Tromsø.

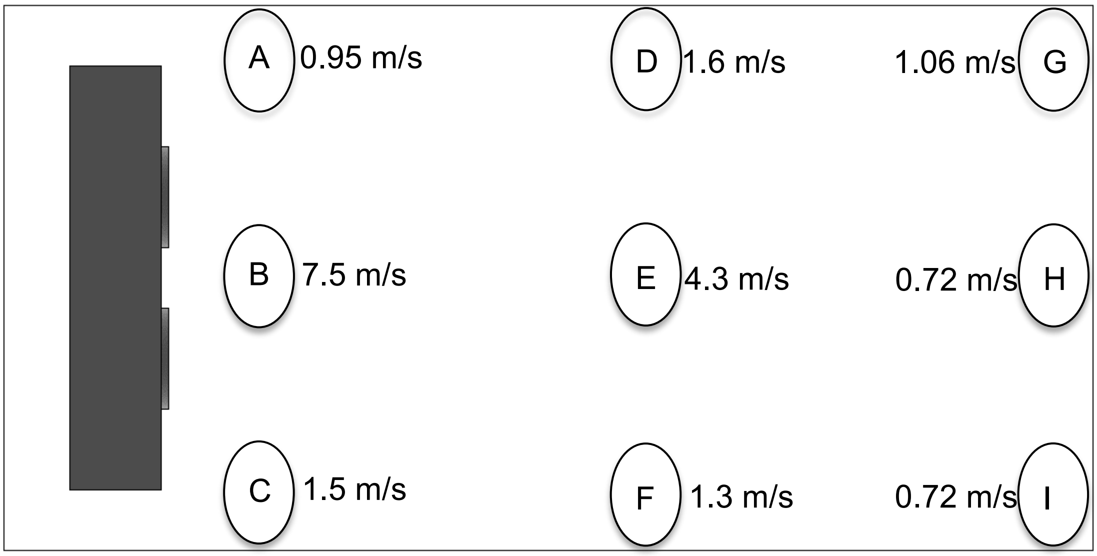


Figure 3.11: Wind Drift Velocities in Cold Room at the Arctic University of Norway, Tromsø.

Figure 3.12: TSI® Velocicalc® Air Velocity Meter Model 5725

3.3 Protective Clothing

Clothing is a protective means for thermal insulation. In this study, clothing insulation study was carried out using FLIR T1030sc camera. The study was carried out on a subject wearing basic clothing of t-shirt, jeans, underwear, socks, and shoes (Figure 3.13). In addition, the subject was asked to put on either of the winter jackets, summer jackets or sweaters (Table 3.2, Figure 3.14). There were sets of five samples for each additional clothing Table 2.1 (Appendix - B). Brands selected for the study were based on availability. In these experiments, the subject was imaged before going into cold room and after the cold room. The subject was also imaged without the additional clothing after coming out of the cold room.

Table 3.2: Winter Jackets Samples; Summer Jacket Samples; Sweater Samples

Winter Jackets Samples	Brand	Summer Jackets Samples	Brand	Sweater Samples	Brand
WJ-1	Levi’s®	SJ-1	RR®	SW-1	Twentyfour®
WJ-2	Stormberg®	SJ-2	Springfield®	SW-2	Lerros®
WJ-3	Kraft®	SJ-3	Greenwood®	SW-3	NATO (military issued)
WJ-4	Jean Paul®	SJ-4	Chill Factor®	SW-4	i Solid®
WJ-5	Fjell Raven®	SJ-5	Helly Tech®	SW-5	Kaatiko®

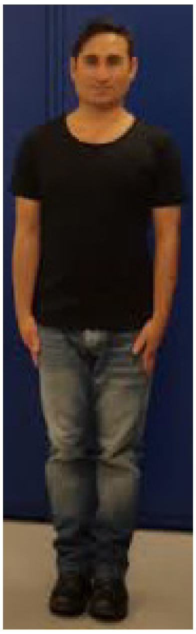


Figure 3.13: Subject is wearing basic clothing of t-shirt, jeans, underwear, socks, and shoes

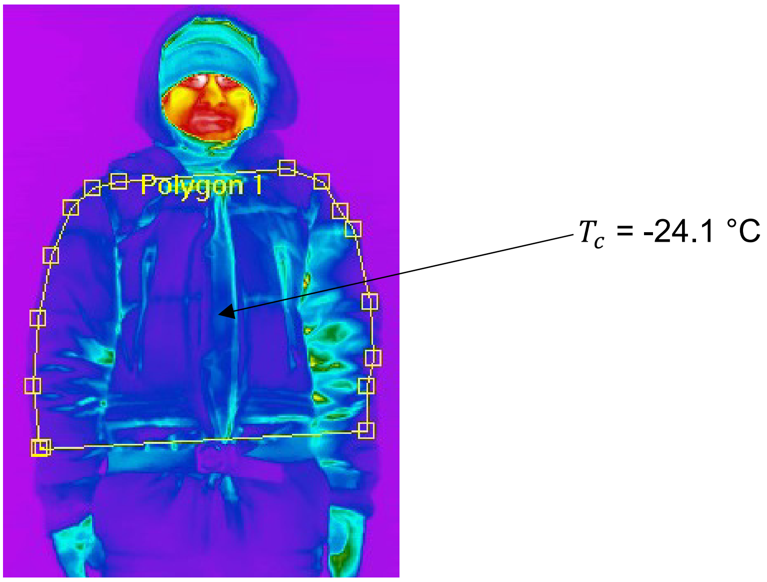
(a) Fjell Raven® Winter Jacket (Sample WJ-5)

(b) Chill Factor® Summer Jacket (Sample SJ-4)

(c) Lerros® Sweater (Sample SW-2)

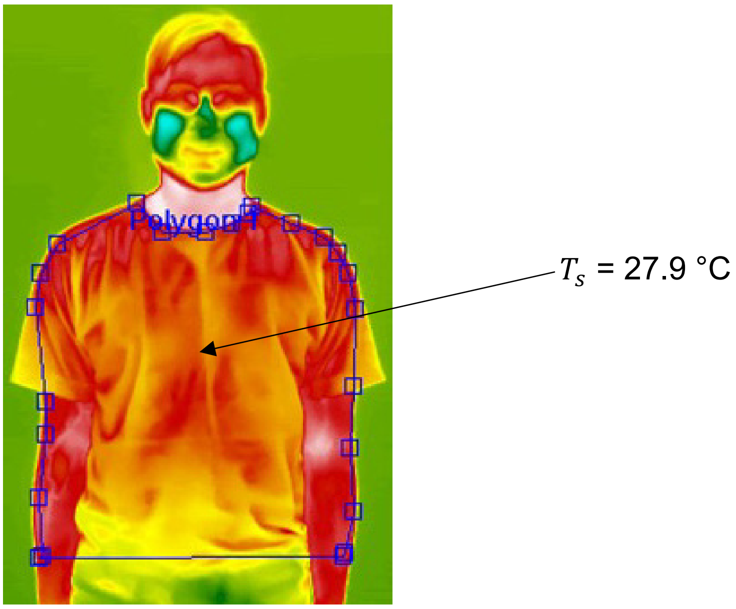
Figure 3.14: (a) Fjell Raven® Winter jacket (sample WJ-5), (b) Chill Factor® summer jacket (sample SJ-4) and (c) Lerros® sweater (sample SW-2)

The temperature reading was averaged in the area covered by the additional clothing as shown in Figure 3.15 and basic clothing as shown in Figure 3.16.



T_c = -24.1 °C

Figure 3.15: Temperature data was averaged using polygon for determining the surface temperature with additional clothing T_c.



T_s = 27.9 °C

Figure 3.16: Temperature data was averaged using polygon for determining the surface temperature with basic clothing T_s.

Obtained values were used to calculate the IREQ* values as shown in Equation (3.2).

$$IREQ *= \frac{T_s - T_c}{R + C} \; (K\, m^2 W^{-1}) \tag{3.2}$$

Where T_s is the mean surface temperature with basic clothing in °C and T_c is the mean surface temperature with additional clothing °C. In this study, the combined value of heat through radiation and convection $R + C$ is assumed to be 55 Wm^{-2}.

In this study, $IREQ *$ is based on surface temperature of the basic clothing instead of skin temperature.

Chapter 4. Results and Discussion

This chapter discusses the results obtained to study the wind chill effect. The study was carried out in the cold room at UiT The Arctic University of Norway, Tromsø. The infrared images were obtained using Fluke® Ti55 IR and FLIR® T1030sc cameras and analysed using dedicated software.

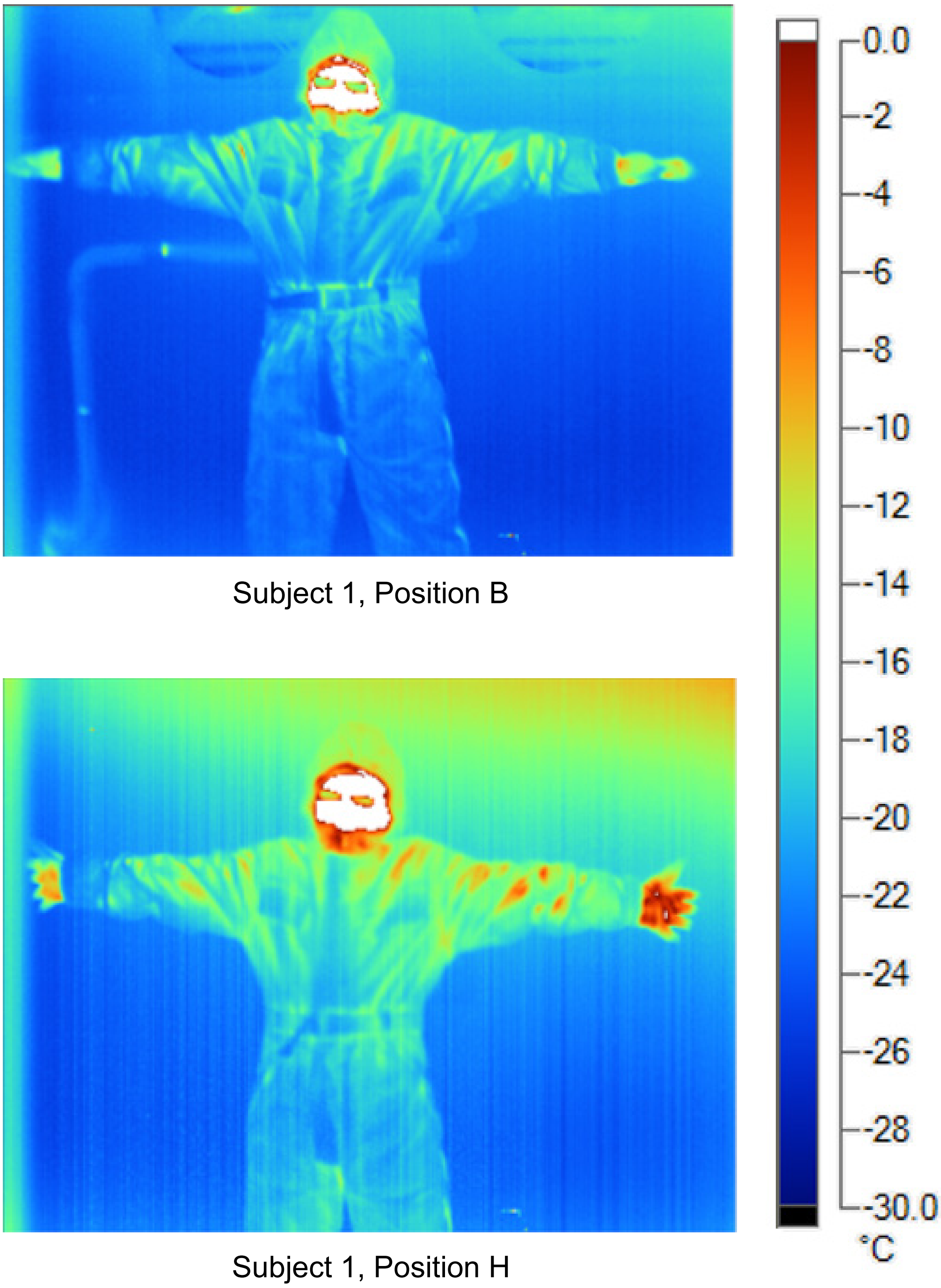
4.1 Wind Chill Study using IR Imagery

In order to see the effect of wind chill, IR images of the subjects were taken in a cold room. The subjects were wearing protective clothing (Figure 4.1) to be safe from any harm during the experiments. The subjects were asked to stay at the position for around 5 minutes before the images were taken.

Figure 4.1: Subject wearing protective clothing. Image taken in Cold Room at the Arctic University of Norway, Tromsø.

Due to the limited Field of View (FOV) of Fluke Ti55 IR Camera (refer to Table 3.1) the subjects can only be placed at two positions in the cold room. These positions were B and H (refer to Figure 3.11).

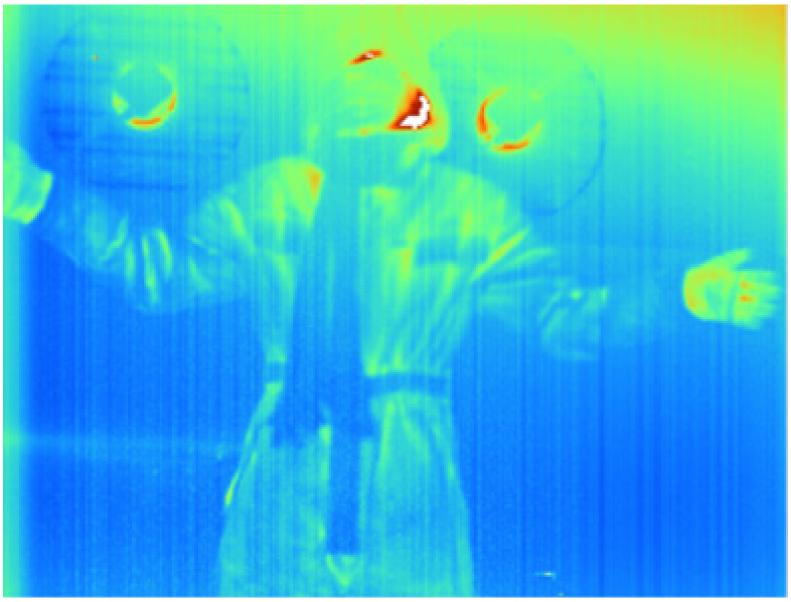
The obtained IR images were analysed in SmartView® software. The results are shown in Figure 4.2 and Figure 4.3.



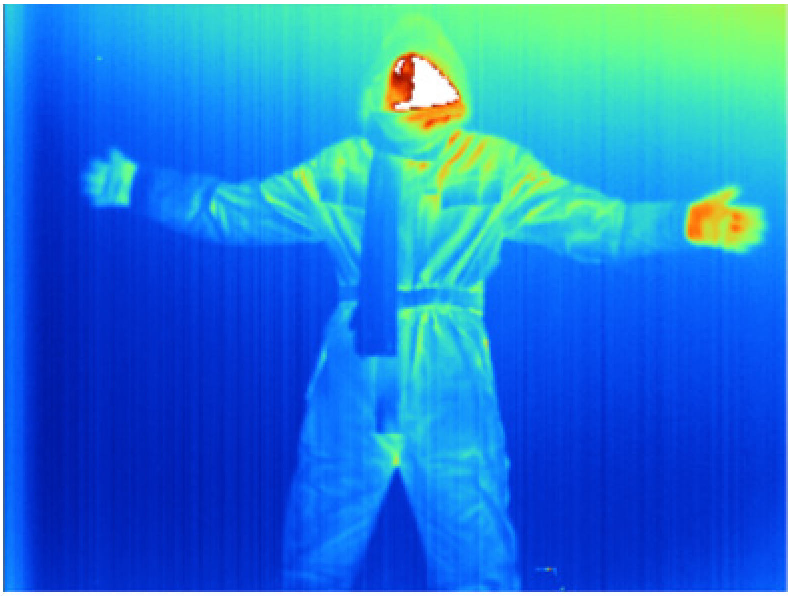
Subject 1, Position B

Subject 1, Position H

Figure 4.2: IR Images of subject 1 at positions B and H respectively.



Subject 2, Position B



Subject 2, Position H

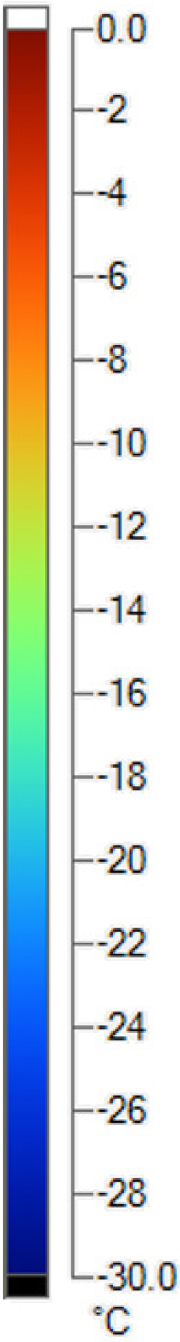


Figure 4.3: IR Images of subject 2 at positions B and H respectively.

It is clear from the images that temperatures were higher at position H in comparison to position B. This is due to the fact that wind velocity was 7.5 m/s at position B and 0.72 m/s at position H.

The same result is illustrated by drawing a line from hand to hand of the subject 1. The temperature profile clearly indicates the temperature differences.

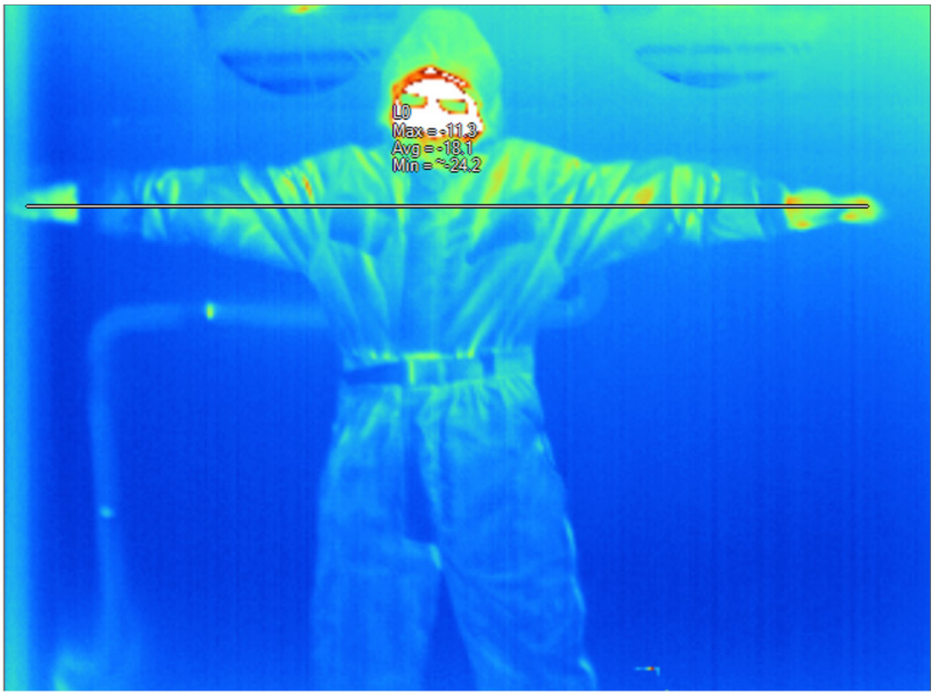
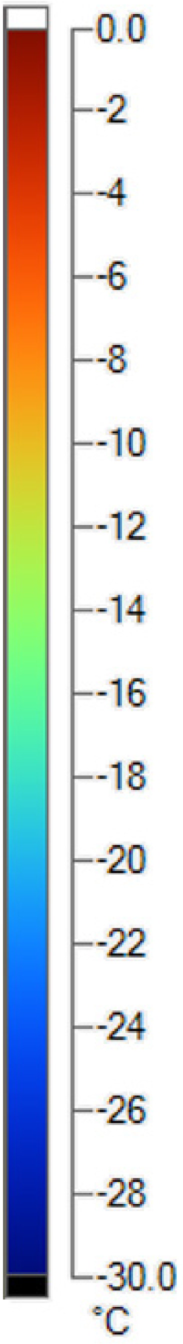
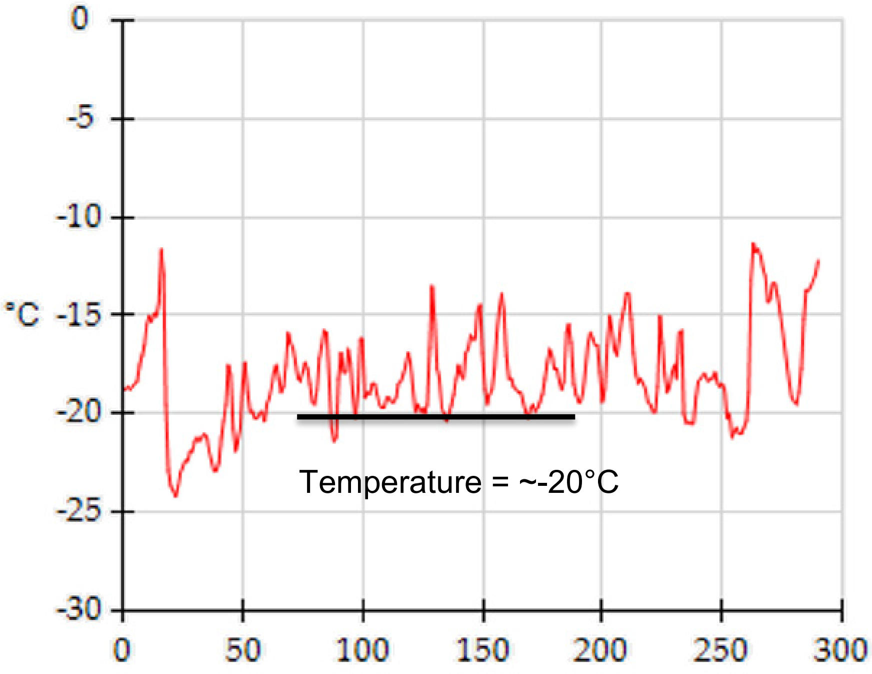


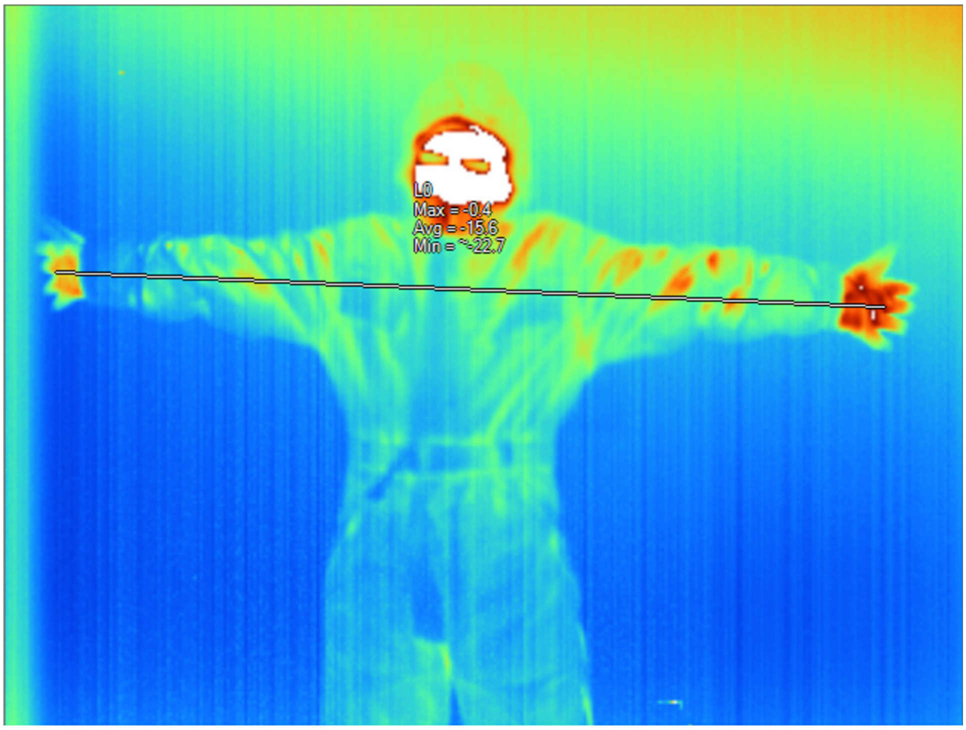
Illustration of hand to hand line at position B





Temperature profile (horizontal axis shows no. of points on the line)

Figure 4.4: Hand to hand line and temperature profile at position B



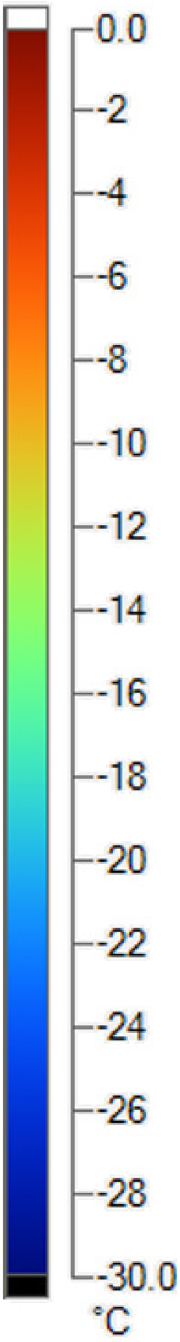
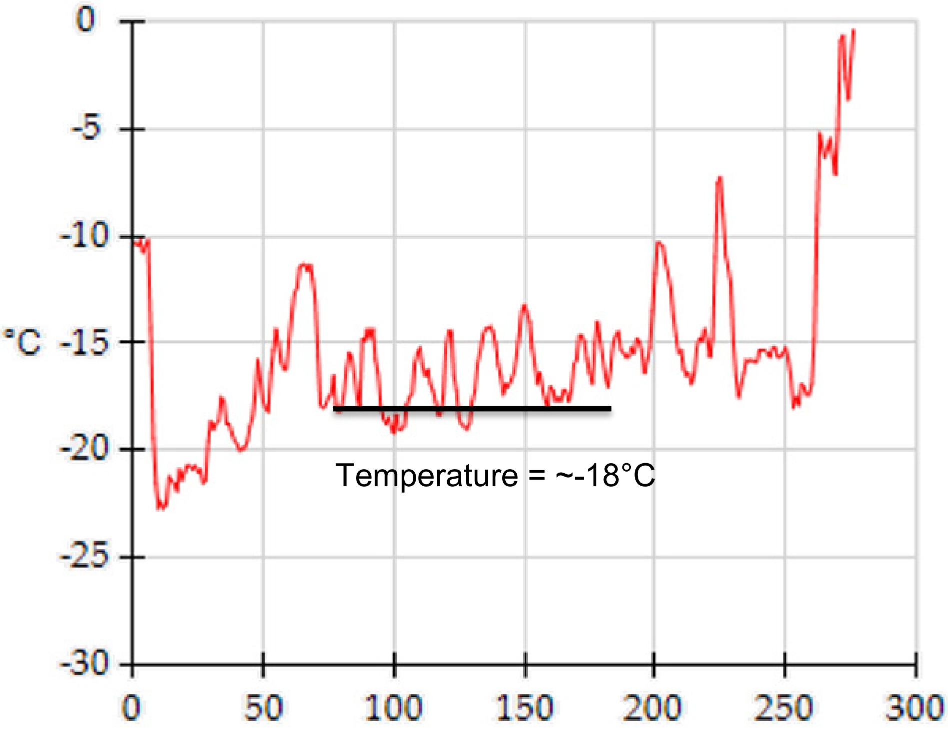


Illustration of hand to hand line at position H



Temperature profile (horizontal axis shows no. of points on the line)

Figure 4.5: Hand to hand line and temperature profile at position H

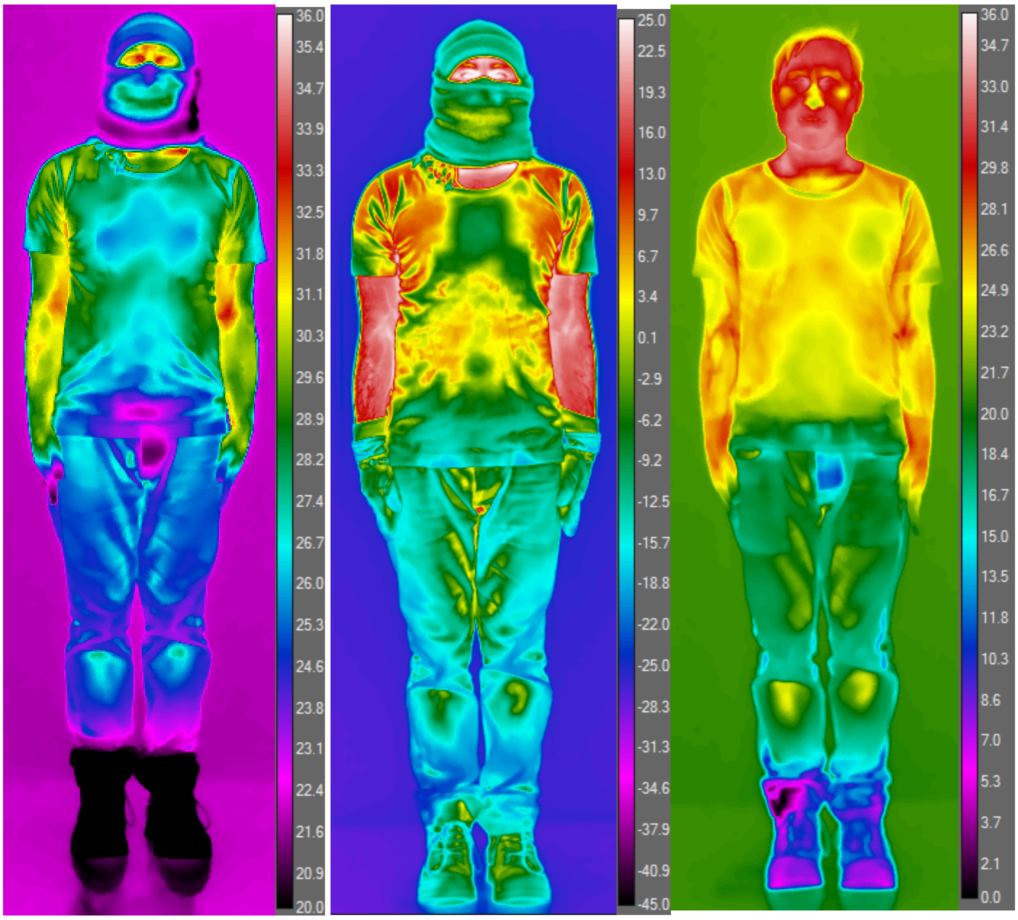
It is shown from Figure 4.4 that minimum temperature is around -20°C. This value increases to -18°C in Figure 4.5. This clearly demonstrates the fact that there is more heat loss at position B in comparison to position H (Table 4.1). During these experiments, the air temperature of the cold room was about -22°C.

Table 4.1: Positions, wind speeds and temperatures

Positions	Wind Speeds (from Figure 3.11)	Temperatures (hand to hand line)
B	7.5 m/s	-20°C (From Figure 4.4)
H	0.72 m/s	-18°C (From Figure 4.5)

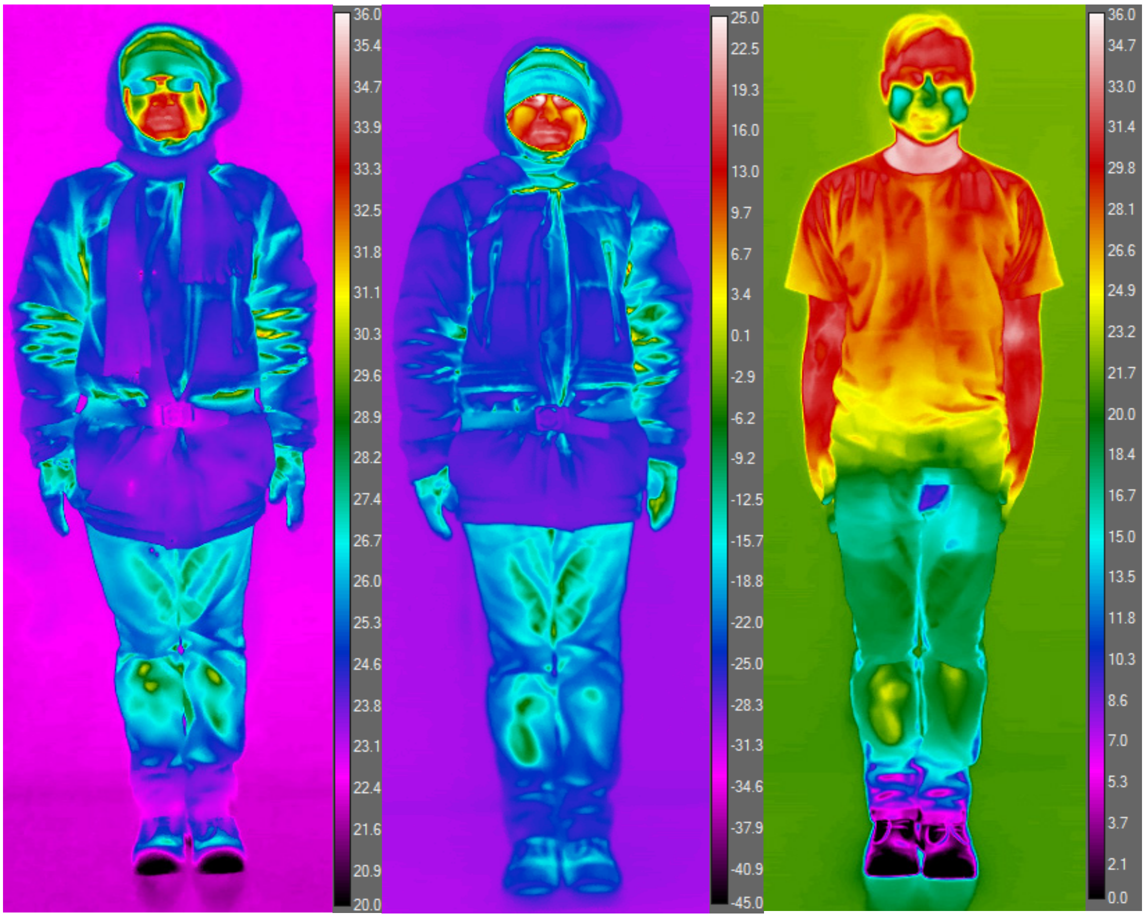
4.2 IREQ Study using IR Imagery

IREQ study was carried out using FLIR® T1030sc camera. The infrared images with basic clothing and with each type of additional clothing are given in Figure 4.6, Figure 4.7, Figure 4.8 and Figure 4.9 respectively. The results are summarised in Table 4.2, Table 4.3, Table 4.4 and comparison is given in Table 4.5.



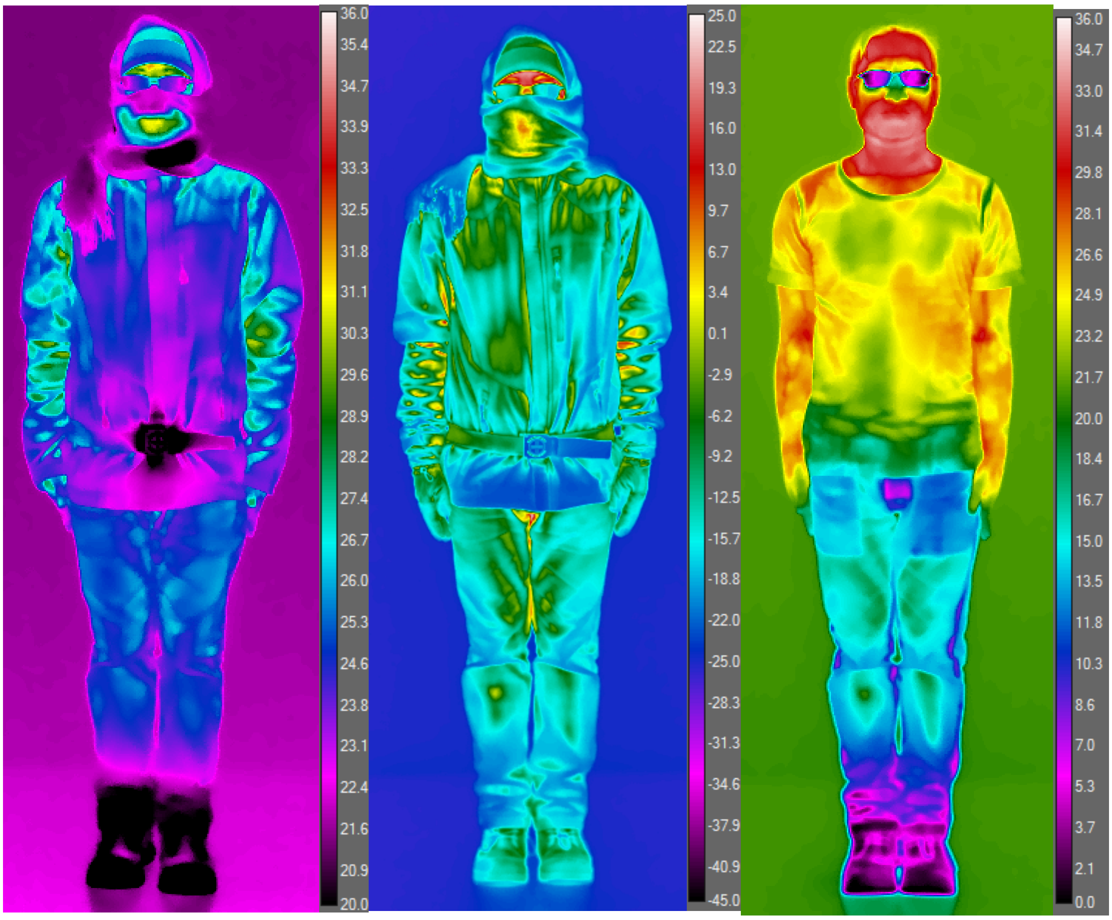
(a) Outside Cold Room (b) Inside Cold Room (c) Basic clothing

Figure 4.6: Infrared images of the subject wearing basic clothing of t-shirt, jeans, underwear, socks, and shoes. Shown temperatures are in °C.



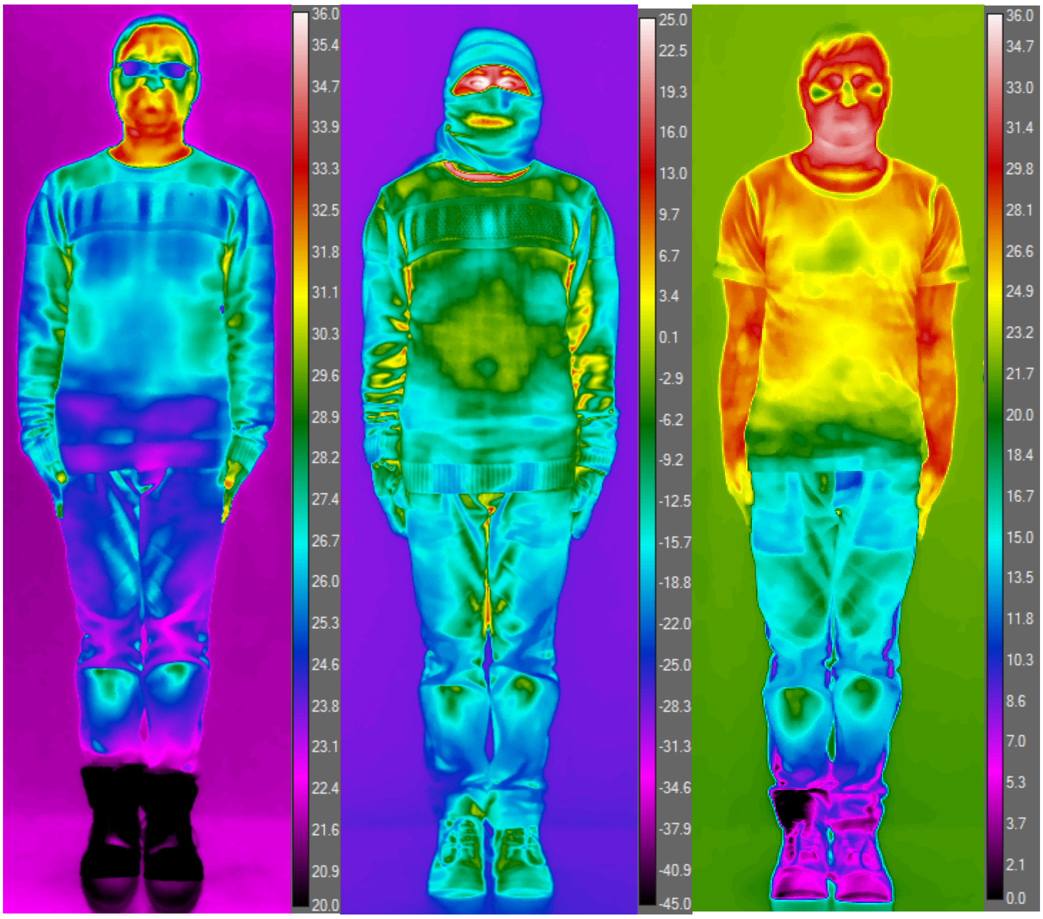
(a) Outside Cold Room (b) Inside Cold Room (c) Without Jacket

Figure 4.7: Infrared images of the subject wearing Jean Paul® winter jacket (Sample WJ-4). Shown temperatures are in °C.



(a) Outside Cold Room (b) Inside Cold Room (c) Without Jacket

Figure 4.8: Infrared images of the subject wearing Chill Factor® Summer Jacket (Sample SJ-4).Shown temperatures are in °C.



(a) Outside Cold Room (b) Inside Cold Room (c) Without Jacket

Figure 4.9: Infrared images of the subject wearing isolid® sweater (Sample SW-4). Shown temperatures are in °C.

Table 4.2: Surface temperature with and without winter jackets and their respective IREQ*.

Additional clothing type	Surface temperature without additional clothing – T_s (K)	Surface temperature with additional clothing – T_c (K)	IREQ* (K m^2 W) $IREQ *= \frac{T_s - T_c}{55}$
Levi's®	28.0	-24.7	0.958
Stormberg®	27.3	-33.6	1.107
Kraft®	29.1	-28.5	1.047
Jean Paul®	27.9	-24.1	0.945
Fjell Raven®	28.0	-26.8	0.996
WJ-Average	**28.0**	**-27.54**	**1.01**

Table 4.3: Surface temperature with and without summer jackets and their respective IREQ*.

Additional clothing type	Surface temperature without additional clothing – T_s (K)	Surface temperature with additional clothing – T_c (K)	IREQ* (K m^2 W) $IREQ *= \frac{T_s - T_c}{55}$
RR®	25.7	-17.1	0.778
Springfield®	26.1	-13.2	0.715
Greenwood®	26.3	-15.7	0.764
Chill Factor®	24.9	-12.0	0.671
Helly Tech®	25.7	-14.2	0.725
SJ - Average	**25.7**	**-14.4**	**0.731**

Table 4.4: Surface temperature with and without sweaters and their respective IREQ*.

Additional clothing type	Surface temperature without additional clothing – T_s (K)	Surface temperature with additional clothing – T_c (K)	IREQ* (K m^2 W) $IREQ *= \frac{T_s - T_c}{55}$
Twentyfour®	26.7	-13.0	0.722
Lerros®	26.5	-8.6	0.638
NATO (Military issued)	27.5	-12.9	0.735
i Solid®	26.0	-8.8	0.633
Kaatiko®	26.6	-10.1	0.667
SW-Average	**26.7**	**-10.7**	**0.679**

Table 4.5: Comparison of basic clothing, winter jackets, summer jackets, and sweaters.

Additional clothing type	Surface temperature without additional clothing – T_s (K)	Surface temperature with additional clothing – T_c (K)	IREQ* (K m^2 W) $IREQ *= \frac{T_s - T_c}{55}$
Winter Jacket (Average)	28.0	-27.54	**1.01**
Sumer Jacket (Average)	25.7	-14.4	**0.731**
Sweater (Average)	26.7	-10.7	**0.679**
Basic clothing	25.1	5.7	**0.353**

Results clearly distinguish between different clothing types based on evaluated IREQ* values.

Chapter 5. Conclusions and Future Work

5.1 Conclusions

Following conclusions can be drawn from this study:

- The wind chill factor is the measure of degree of cooling of a human body when exposed to a wind-temperature environment.

- Wind chill factor depends on air temperature, wind velocity and humidity.

- The convective mode of heat transfer is most dominant in the case of wind chill.

- Effective or feel like temperature depends on the air temperature and the wind condition.

- Siple and Passel's [23] were the first to specify wind chill index. Their studies were too crude and went through criticism in scientific literature.

- Osczevski Wind Chill Model [26, 27] took into account various parts of human body. This model calculates heat transfer coefficients and combine them to specify wind chill index.

- New Wind Chill Equivalent Temperature Chart published by Osczevski and Bluestein [28] specify Wind Chill Temperatures based on Air Temperatures and Wind Velocity. This model is used around the globe in various metrological department.

- Wind chill conditions poses a serious health risk [29].

- To understand the wind chill, it is important to understand the phenomenon of heat transfer. There are three modes of heat transfer namely conduction, convection and radiation [31].

- Infrared experiments at Cold Room at The Arctic University of Norway clearly demonstrates that the heat transfer increases because of higher wind velocities.

- Protective clothing is one of the most effective means against cold. BS-EN 342 and ISO 11079:2007 (E) defines the clothing insulation requirements.

- Thermal protection of clothing varies according to a mean insulation values (also known as IREQ).

- Infrared imaging can be used to determine Relative Require Insulation for Clothing (IREQ*).

- Given study shows that IREQ* values vary between winter jackets, summer jackets and sweaters.

5.2 Future Work

Following future works that can be initiated based on this study,

- A study can be conducted to understand the phenomenon of heat transfer from human body under wind chill conditions. The state of art equipment such as Infrared (IR) cameras can be employed for this purpose [35, 39]. This can be extended to identify the protective measures.

- This study can be extended on a group of volunteers. IR photography of more individuals may reveal some interesting personalised thermal data for various wind chill conditions. For accuracy metabolism rate of the subjects is needed.

- The study may also be extended to understand the heat transfer coefficient of air under various wind chill conditions.

- This study may also be extended to study the thermal efficiency of buildings.

- Further studies can be carried out to determine the relationship between IREQ and IREQ*.

- Studies can be extended to consider the effect of humidity.

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Appendix - A

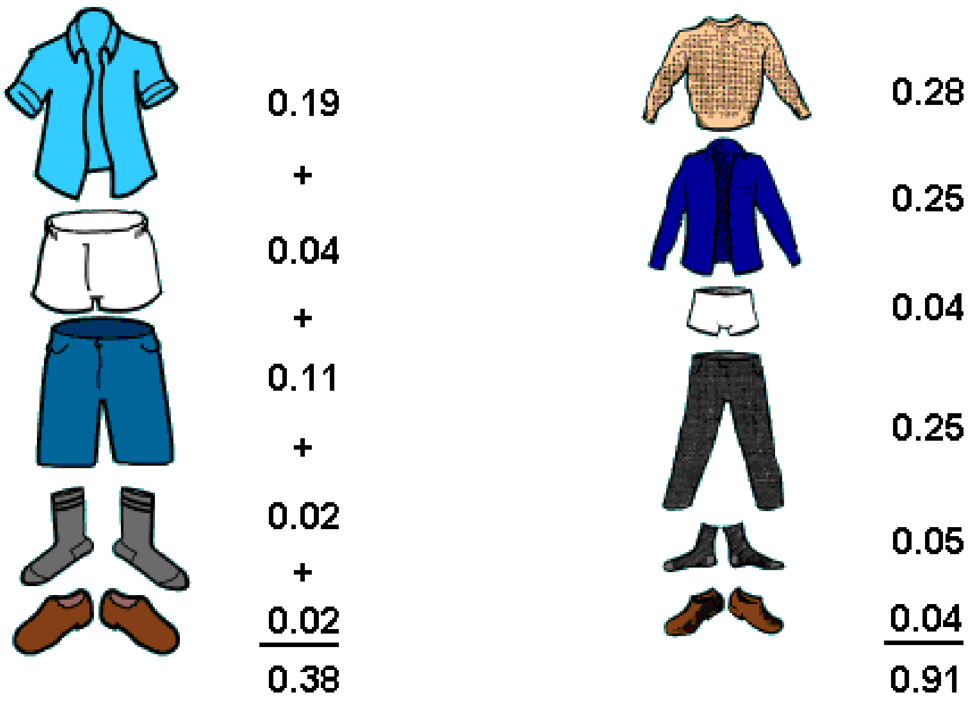
Clo values of various clothing

Garments description		Clo	m^2C°/W
Underwear, pants	Pantyhose	0.02	0.003
	Panties	0.03	0.005
	Briefs	0.04	0.006
	Pants ½ long legs, wool	0.06	0.009
	Pants long legs	0.1	0.016
Underwear, Shirts	Bra	0.01	0.002
	Shirt sleeveless	0.06	0.009
	T-shirt	0.09	0.014
	Shirt with long sleeves	0.12	0.019
	Half-slip,nylon	0.14	0.022
Shirt	Tube top	0.06	0.009
	Short sleeveless	0.09	0.029
	Light weight blouse, long sleeves	0.15	0.023
	Light weight, long sleeves	0.20	0.031
	Normal, long sleeves	0.25	0.039
	Flannel shirt, long sleeves	0.3	0.047
	Long sleeves, turtleneck blouse	0.34	0.053
Trousers	Shorts	0.06	0.009
	Walking shorts	0.11	0.017
	Light-weight trouser	0.20	0.031
	Normal trouser	0.25	0.039
	Flannel trouser	0.28	0.043
	Overalls	0.28	0.043
Coveralls	Daily wear, belted	0.49	0.076
	work	0.50	0.078
Highly-insulating Coveralls	Multi-component, filling	1.03	0.160
	Fiber-pelt	1.13	0.175

Sweaters	Sleeveless vest	0.12	0.019
	Thin sweater	0.2	0.031
	Long sleeves, turtleneck (thin)	0.26	0.040
	Sweater 0.28-0.43 thick sweater	0.35	0.054
	Long sleeves, turtleneck (thick)	0.37	0.057
Jacket	Vest	0.13	0.020
	Light summer jacket	0.25	0.039
	Jacket	0.35	0.054
	Smock	0.3	0.047
Coats and Over jackets and over trousers	Coat	0.6	0.093
	Down jacket	0.25	0.085
	Parka	0.35	0.109
	Overall multi-component	0.3	0.081
Sundries	Socks	0.02	0.003
	Thick, ankle sock	0.05	0.008
	Thick, long socks	0.1	0.016
	Slippers, quilted fleece	0.03	0.005
	Shoes (thin soled)	0.02	0.003
	Shoes (thick soled)	0.04	0.006
	Boots 0.1-0.016 Gloves	0.05	0.008
Skirts, dresses	Light skirt, 15cm. above knee	0.10	0.016
	Light skirt, 15cm. below knee	0.18	0.028
	Heavy skirt, knee-length	0.25	0.039
	Light dress, sleeveless	0.25	0.039
	Winter dress, long sleeves	0.4	0.062
Sleepwear	Long sleeve, long gown	0.3	0.047
	Thin strap, short gown	0.15	0.023
	Hospital gown	0.31	0.048
	Long sleeve, long pyjamas	0.50	0.078
	Body sleep with feet	0.72	0.112
	Undershorts	0.1	0.016

Robes	Long sleeves, wrap, long	0.53	0.082
	Long sleeve, wrap, short	0.41	0.064
Chairs	Wooden or metal	0.00	0.000
	Fabric-covered, cushioned, swivel	0.10	0.016
	Armchair	0.20	0.032

Insulation for the entire clothing: $I_{cl} = \sum I_{clu}$



Basic insulation value (I_{cl}) of selected garment ensembles measured with a thermal manikin (based on ISO 9920)

Clothing Ensemble	$m^2.K.W^{-1}$	Clo
1. Briefs, short-sleeve shirt, fitted trousers, calf length socks, shoes	0.08	0.5
2. Underpants, shirt, fitted trousers, socks, shoes	0.10	0.6
3. Underpants, coverall, socks, shoes	0.11	0.7
4. Underpants, shirt, coverall, socks, shoes	0.13	0.8
5. Underpants, shirt, trousers, smock, socks, shoes	0.14	0.9
6. Briefs, undershirt, underpants, shirt, overalls, calf length socks, shoes	0.16	1.0
7. Underpants, undershirt, shirt, trousers, jacket, vest, socks, shoes	0.17	1.1
8. Underpants, shirt, trousers, jacket, coverall, socks, shoes	0.19	1.3
9. Undershirt, underpants, insulated trousers, insulated jacket, socks, shoes	0.22	1.4
10. Briefs, T–shirt, shirt, fitted trousers, insulated coveralls, calf length socks, shoes	0.23	1.5
11. Underpants, undershirt, shirt, trousers, jacket, over jacket, hat, gloves, socks, shoes	0.25	1.6
12. Underpants, undershirt, shirt, trousers, jacket, over jacket, over trousers, socks, shoes	0.29	1.9
13. Underpants, undershirt, shirt, trousers, jacket, over jacket, over trousers, socks, shoes, hat, gloves	0.31	2.0
14. Undershirt, underpants, insulated trousers, insulated jacket, over trousers, over jacket, socks, shoes	0.34	2.2
15. Undershirt, underpants, insulated trousers, insulated jacket, over trousers, over jacket, socks, shoes, hat, gloves	0.40	2.6
16. Arctic clothing systems	0.46 to 0.70	3 to 4.5
17. Sleeping bags	0.46 to 1.4	3 to 9

Appendix - B

Winter Jackets Samples

Levi's®: WJ-1

Stormberg®: WJ-2

Kraft®: WJ-3

Jean Paul®: WJ-4

Fjell Raven®: WJ-5

Summer Jackets Samples

RR®: SJ-1

Springfield®: SJ-2

Greenwood®: SJ-3

Chill Factor®: SJ-4

Helly Tech®: SJ-5

Sweaters Samples

Twentyfour®: SW-1

Lerros®: SW-2

NATO (military issued): SW-3

i Solid®: SW-4

Kaatiko®: SW-5