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Wind Chill Effect in Cold Climate

Study of Wind Chill Effect Using Infrared Imaging

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Preface

This report is submitted in the course TEK-3004 (Specialisation Project) 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 2015-16. 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 6300 words, 24 figures and 2 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 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. Preliminary experiments in cold room at The Arctic University of Norway clearly demonstrates higher heat transfer under wind chill conditions.

“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}	[℃]	Temperature of the surroundings
$\bar{T}$	[℃]	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_{∞}	$[K\ ]$	Fluid 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	$[W/m^2K]$	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}	[℃]	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

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)

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 Metrological Perspective of Wind Chill Factor

Metrological department 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^{o}C but it would feel like -6^{o}C [1].

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^{o}C but due to the winds, it would feel like -25^{o}C in western New York [2].

Another news report titled Wind chills expected to be -20^{o}C this afternoon, -35^{o}C overnight published by Daily Herald on 7th January 2015 mentions that Wind chill values are expected to make temperatures feel 30^{o}C to 35^{o}C below zero [3].

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^{o}C however, due to wind speed of 25 m/s, it feels like -40^{o}C [4].

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 [5]. 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 [5].

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.

1.3 Structure of the Report

This project is on building the understanding of the wind chill factor from the perspective of physics. Following points are being focused on,

- Literature review of the wind chill factor models. Identifying the key parameters and associated risks.

- 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.

- 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. A vast amount of literature is available on the effects of Wind Chill. From the middle of the last century, thousands of papers have been published in the scientific and engineering literature on the subject. This chapter only presents some of the key models.

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 [6, 7]. 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).

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

Where h_{wc} is the heat transfer coefficient in (kCal/m^{2}h^{o}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).

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

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^{o}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 [8]. As mentioned in [9], Siple admitted by giving following response

“Looking back, we perhaps made a rather too naïve 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 [9, 10]. In his studies, heat transfer coefficients were computed for head and face separately as shown in Equations (2.3) and (2.4).

$$h_{head} = 11.5\, V^{0.68} \tag{2.3}$$

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

$$h_{face} = 14.4\ V^{0.61} \tag{2.4}$$

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).

$$h_r = 4\varepsilon\sigma\bar{T}^3 \tag{2.5}$$

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.

$$h_c = 8.7\ V^{0.6} \tag{2.6}$$

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

Osczevski [9] 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 (^{o}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^{o}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 [9] 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 X).

Table 2.1 Discomfort Descriptor with Wind Chill Index Value [9].

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

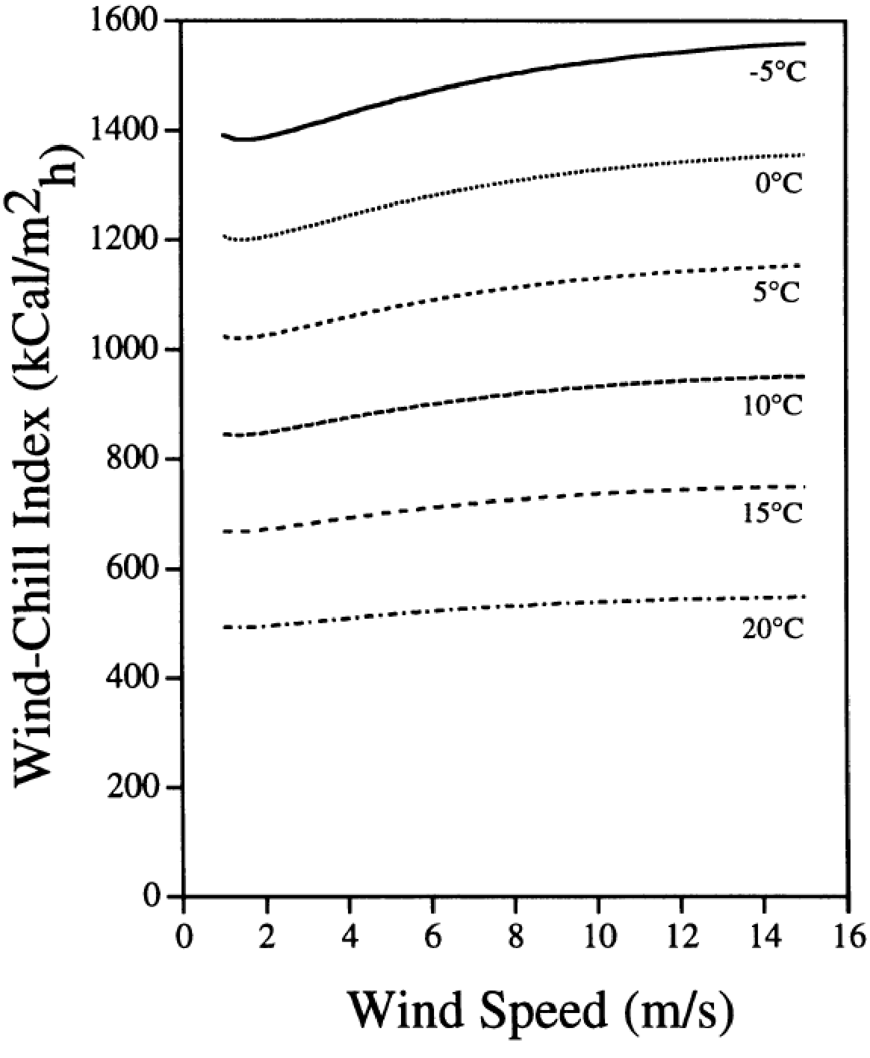


Figure 2.1: Wind Chill Index ($kCal/m^2$) with Wind Speed (m/s) for various facial temperatures ranging from -5°C to 20°C [9].

2.1.3 New Wind Chill Equivalent Temperature Chart

Osczevski and Bluestein published new wind chill equivalent chart in 2005 [11]. This model is widely accepted and being used by various metrological departments around the globe [5].

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.

Wind Speed (km h⁻¹) \ Air Temperature (°C)													
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.

2.1.4 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 [12] summarises the risk posed due to the wind chill. Figure 2.3 shows the categorization of wind chill index [12].

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 [12]

In addition, the exposure risk, health concerns and recommended actions under various wind chill conditions are given in Figure 2.4 [12].

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 [12].

2.2 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.

2.2.1 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 (2.10) and explained in Figure 2.5 [13].

$$q''_x = -k\frac{\partial T}{\partial x} \tag{2.10}$$

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 2.5, 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.

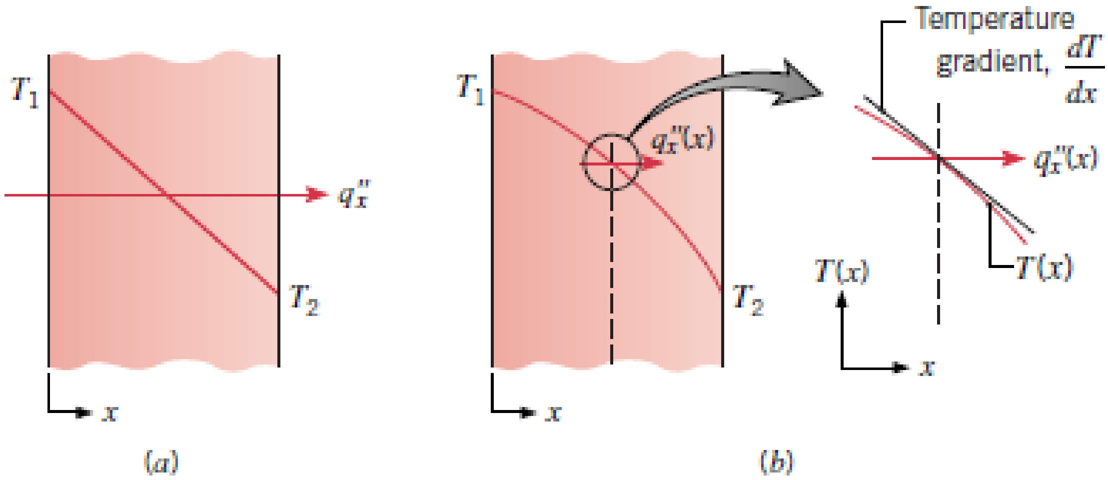


Figure 2.5: Heat transfer through conduction (a) Linear heat transfer (or constant heat flux) (b) Nonlinear heat transfer (or variable heat flux)

Heat transfer through conduction can be in more than one direction. In such case, Equation (2.10) can be expanded to take into account multi-directions. Three dimensional heat equation is shown in Equation (2.11).

$$q''_n = q''_x + q''_y + q''_z = -k\left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}\right) \tag{2.11}$$

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.

2.2.2 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 (2.12) [13].

$$q'' = h(T_s - T_\infty) \tag{2.12}$$

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 2.6. 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 (2.13).

$$q'' = h_1(T_{s,1} - T_{\infty,1}) = -k\frac{(T_{s,1} - T_{s,2})}{L} = -h_2(T_{s,2} - T_{\infty,2}) \tag{2.13}$$

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.

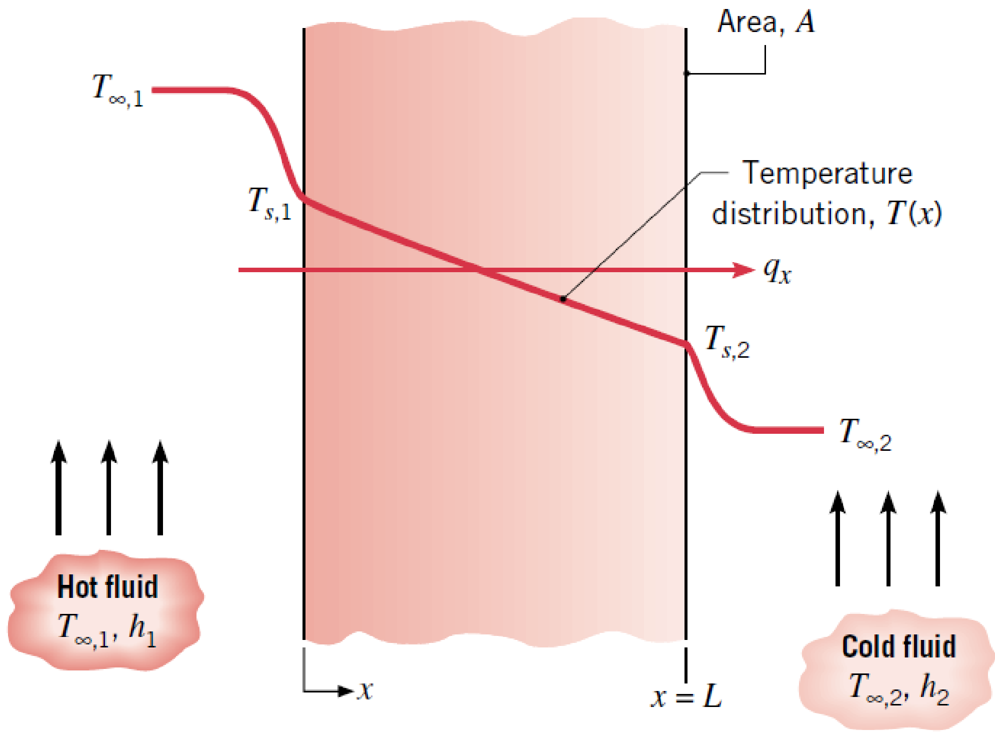


Figure 2.6: Heat transfer through a wall. Wall is warmed by hot fluid on one side and cooled by cold fluid on other. A steady state temperature gradient exists within the solid wall.

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 (2.14).

$$Nu = h\frac{L}{k} \quad (2.14)$$

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 (2.15) and (2.16). These functions depend upon the geometry of the surface, flow conditions, and flow properties.

$$Nu_x = f(x^*, Re_x, Pr) \quad - \quad Local \quad (2.15)$$

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).

$$\overline{Nu_x} = f(Re_x, Pr) \quad - \quad Average \quad (2.16)$$

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

2.2.3 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 (2.17) and illustrated in Figure 2.7.

$$q'' = \varepsilon \sigma T_s^4 \tag{2.17}$$

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.

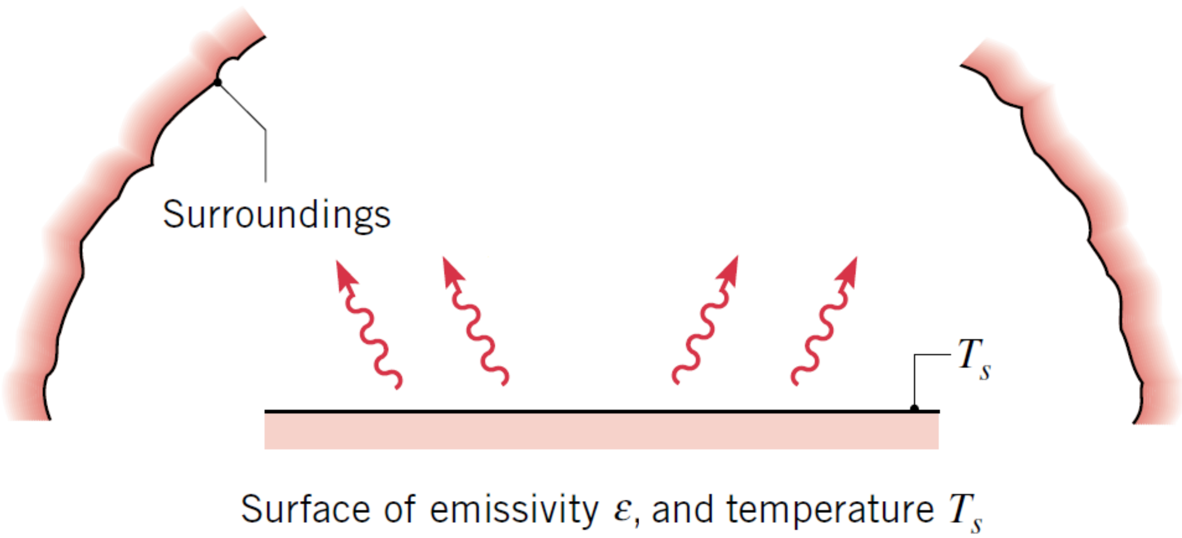


Figure 2.7: A surface emitting thermal radiations [13].

Chapter 3. Methodology

This chapter discusses the experimental methodology used to study the wind chill factor. The study is carried out using infrared red 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 [14].

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 1 [14, 15].

The amount of heat can be determined using the Stefan-Boltzmann Law [16] 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 body 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.

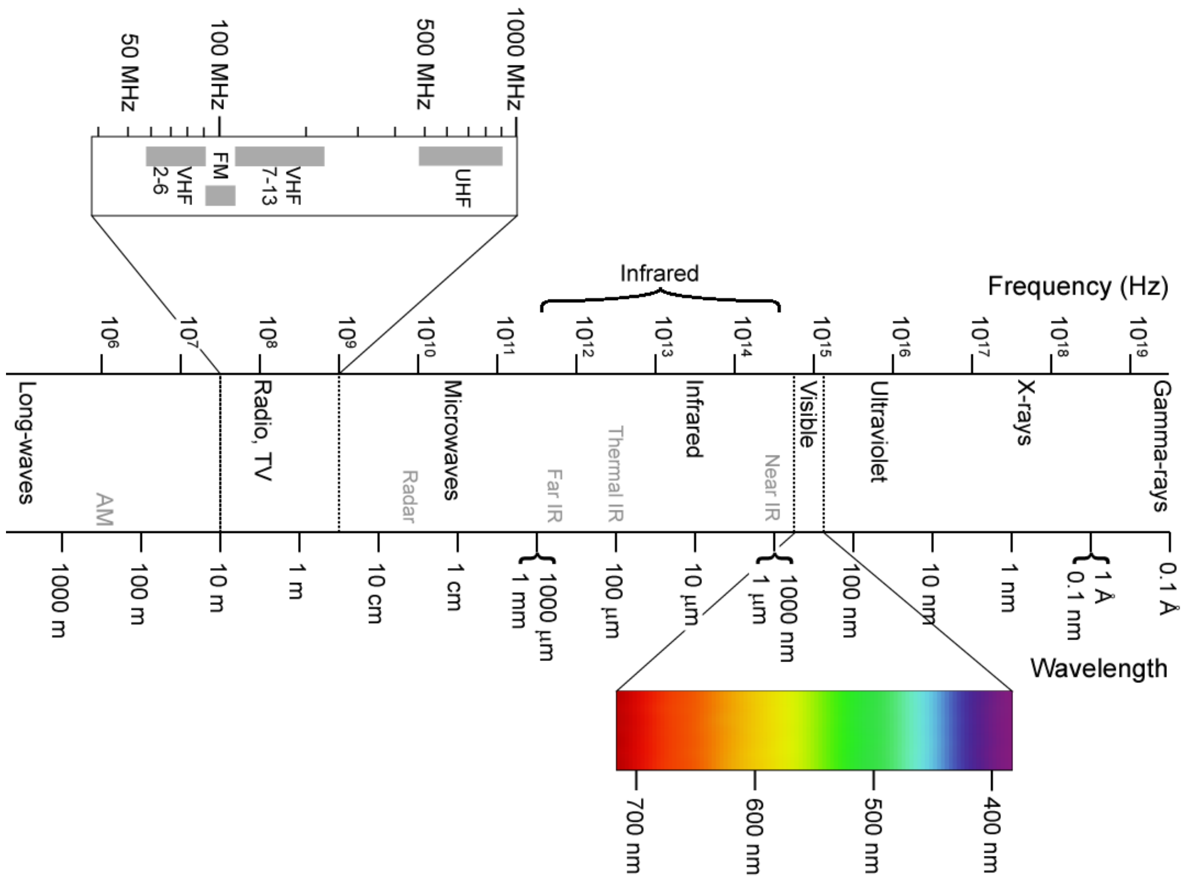


Figure 3.1: Electromagnetic Spectrum [15].

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.

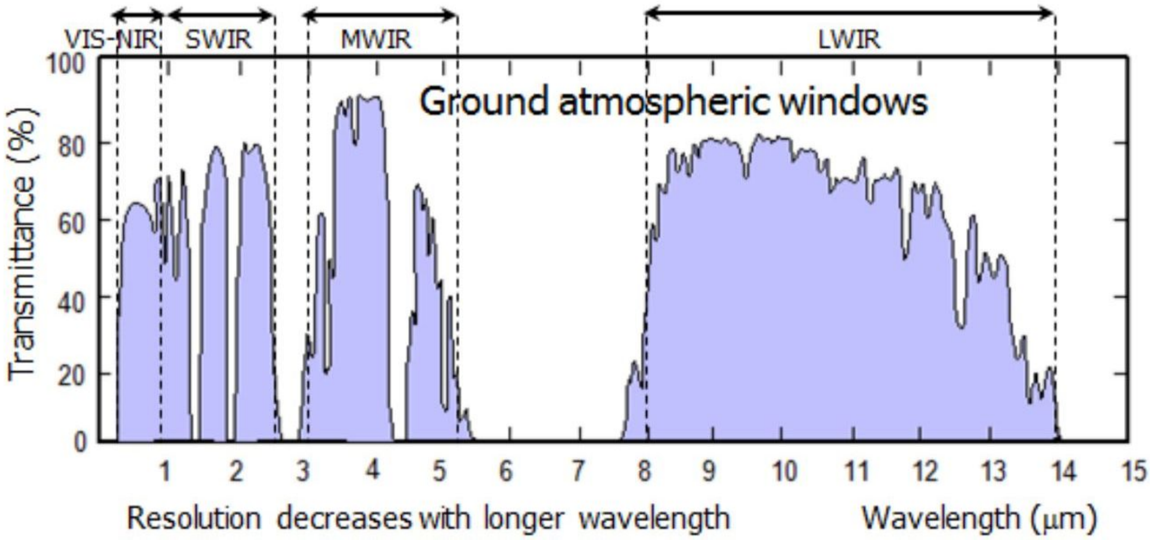


Figure 3.2: Infrared Spectrum [17].

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 IR Camera.The camera is shown in Figure 3.5.

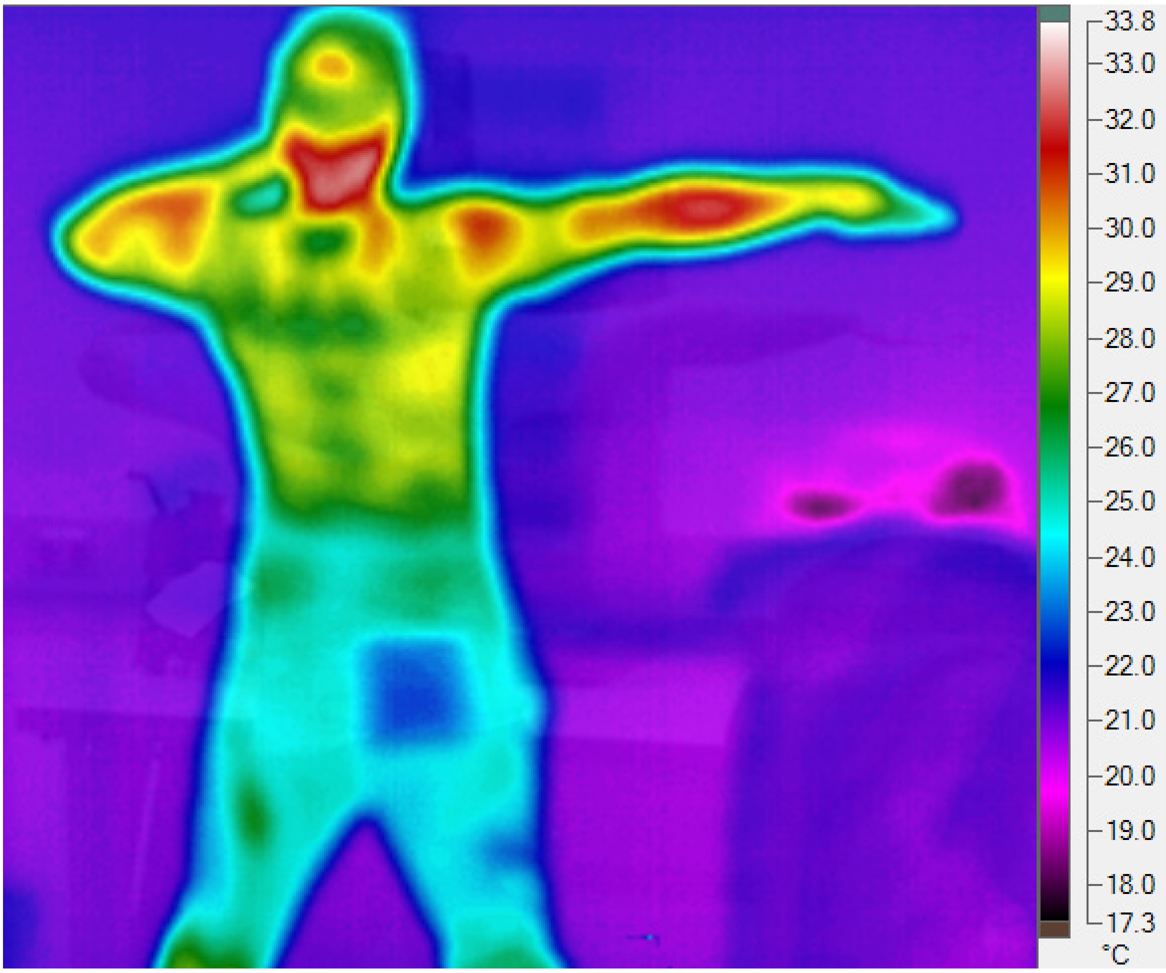


Figure 3.3: False Coloured Infrared Image (Taken with Fluke® Ti55 IR Camera).

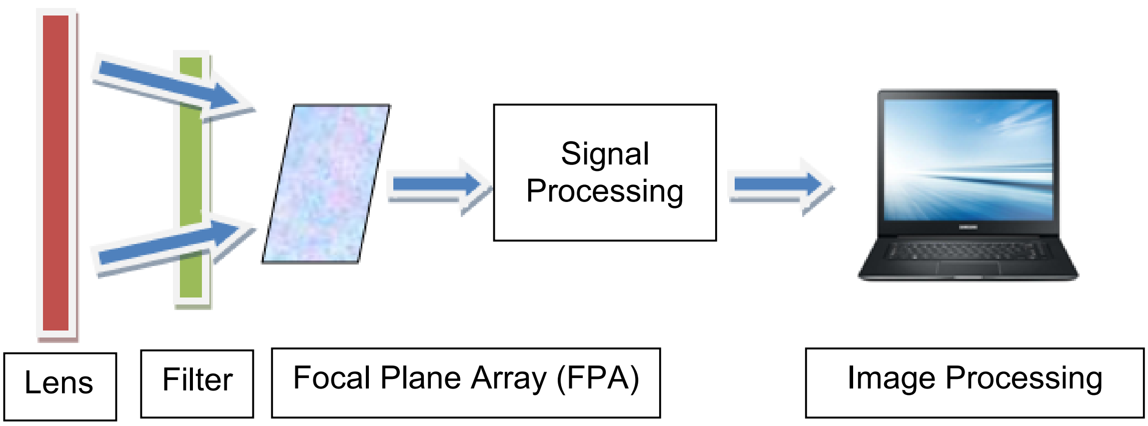


Figure 3.4: Working Principle of an IR Camera

Figure 3.5: Fluke® Ti55 IR Camera

Fluke® Ti55 IR camera has 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) from 8-14μm.

- 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 3.6. FPA control the resolution of the thermal image such as 240 x 320 pixels with pitch distance of 25 μm [18].

Figure 3.6: 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 [18].

Following parameter settings is required prior to use Fluke® Ti55 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 [18].

- 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 [18].

- 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 [19].

- Detector Pitch

Detector pitch is the distance between centers of two consecutive pixels of the focal plane array. Smaller distance results the high resolution [18].

- 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 camera Fluke® Ti55 is equipped with passive long wavelength infrared detectors [18].

- Temperature Range

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

- Accuracy

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

Table 3.1 summarizes the features of Fluke® Ti55 IR camera.

Table 3.1: Features of Fluke® Ti55 IR Camera

Field of View (FOV)	20 mm lens 23°(horizontal) x 17°(vertical) 10.5 mm lens 42°(horizontal)x 32°(vertical) 54 mm lens 9°(horizontal) x 6°(vertical)
Minimum Focal Distance	Not provided
IR Resolution	320 × 240 pixels
Emissivity Correction	Variable from 0.1 to 1.0
Detector Pitch	25 μm
Spectral Range	8 μm to 14 μm
Operating Temperature Range	– 20°C to +100°C
Accuracy	± 2°C or ± 2% of reading

3.1.2 Image Analysis

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 3.7.

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

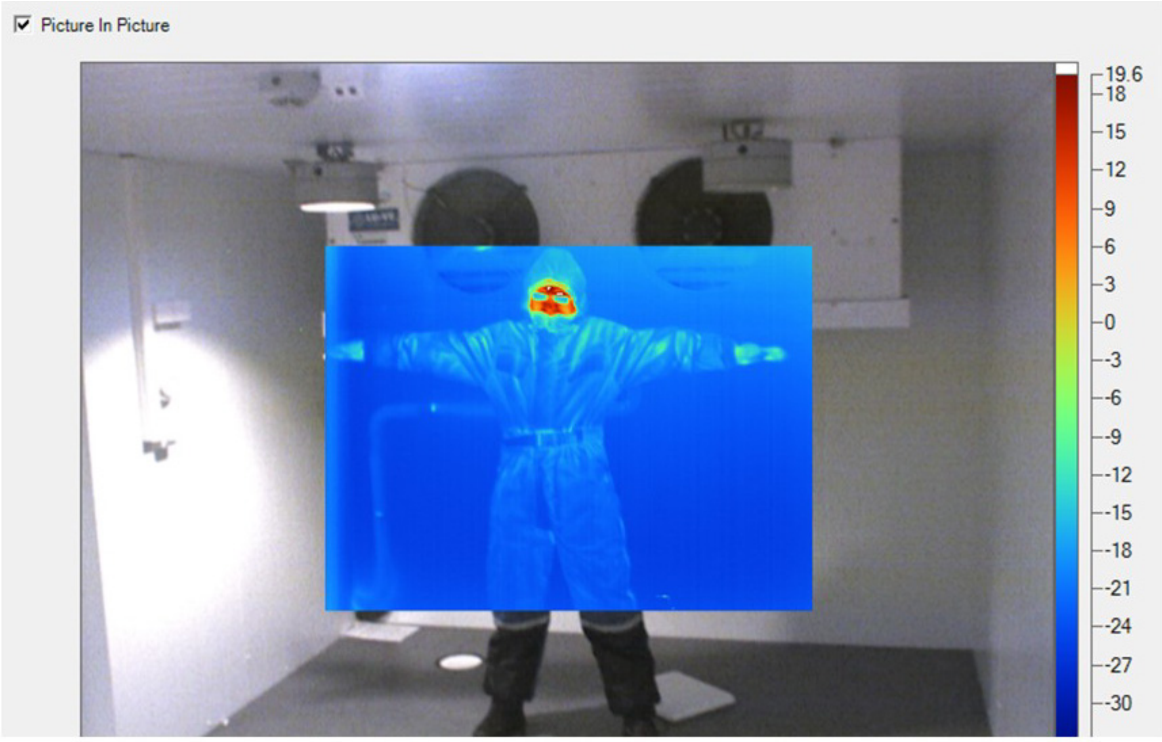


Figure 3.7: IR image overlapped over digital image (Image taken in Cold Room with Fluke® Ti55 IR Camera and analyzed in SmartView®).

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 3.8.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 -25°C.

The room is mounted with an evaporator with two fans. The fans provides variable wind drift in the room as shown in Figure 3.9. This wind drift velocities are measured using anemometer (TSI® Velocicalc® Air Velocity Meter Model 5725) as shown in Figure 3.10. These are average velocity values.

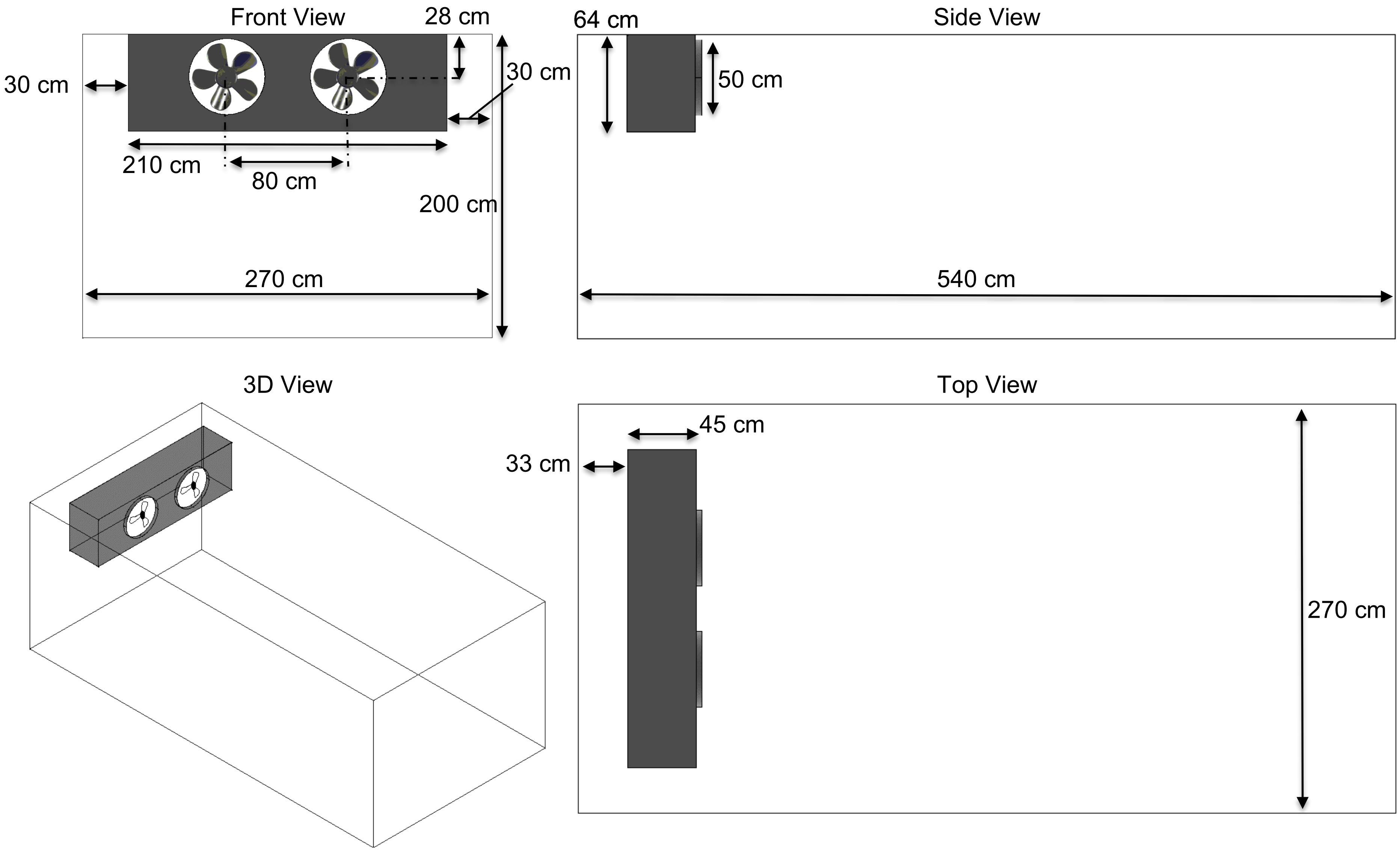


Figure 3.8: Technical Drawings of Cold Room at the Arctic University of Norway, Tromsø.

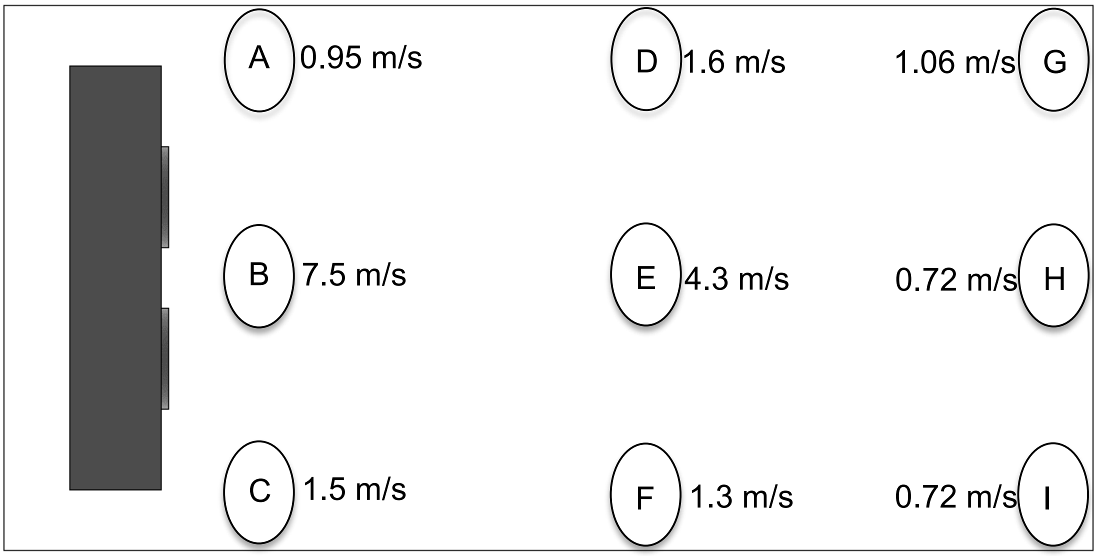


Figure 3.9: Wind Drift Velocities in Cold Room at the Arctic University of Norway, Tromsø.

Figure 3.10: TSI® Velocicalc® Air Velocity Meter Model 5725

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 the Arctic University of Norway, Tromsø. The infrared images were obtained using Fluke® Ti55 IR Camera and analysed using SmartView® software.

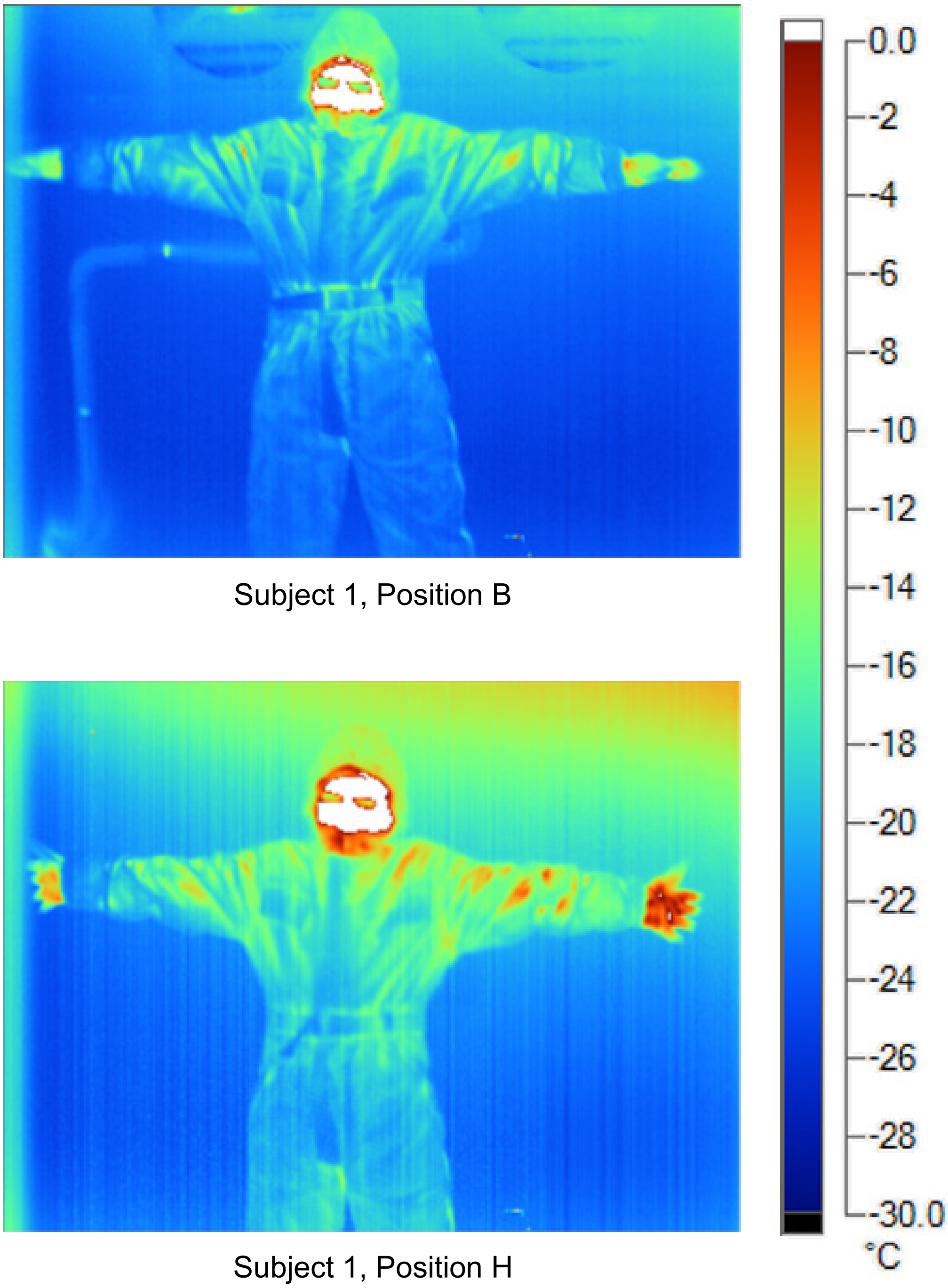
4.1 Wind Chill Study using IR Imagery

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 clothings (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 3.9).

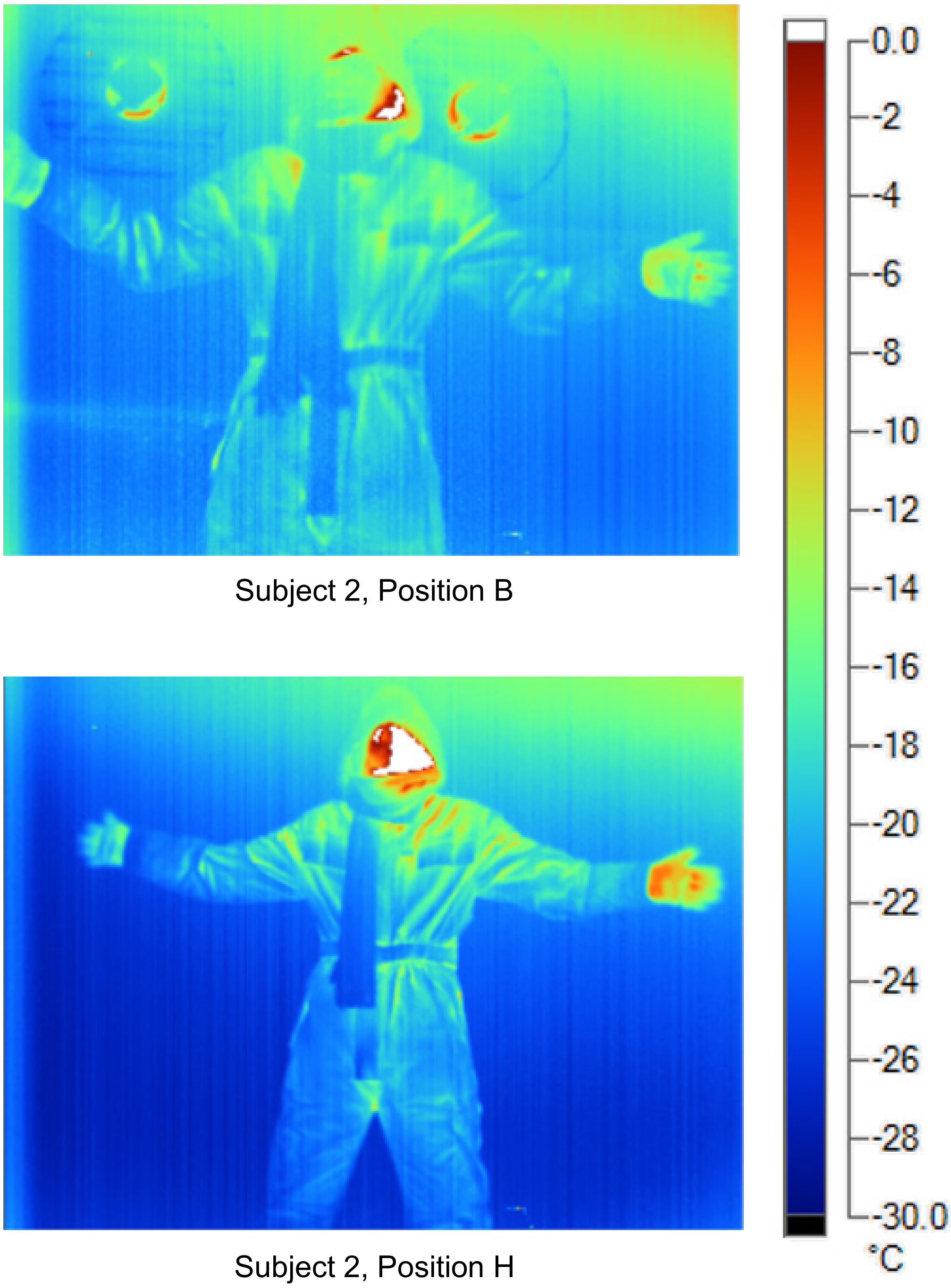
The obtained IR images were analysed in SmartView® software. The results are shown in Figure 4.2 and Figure 4.3.



Subject 1, Position B

Subject 1, Position H

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



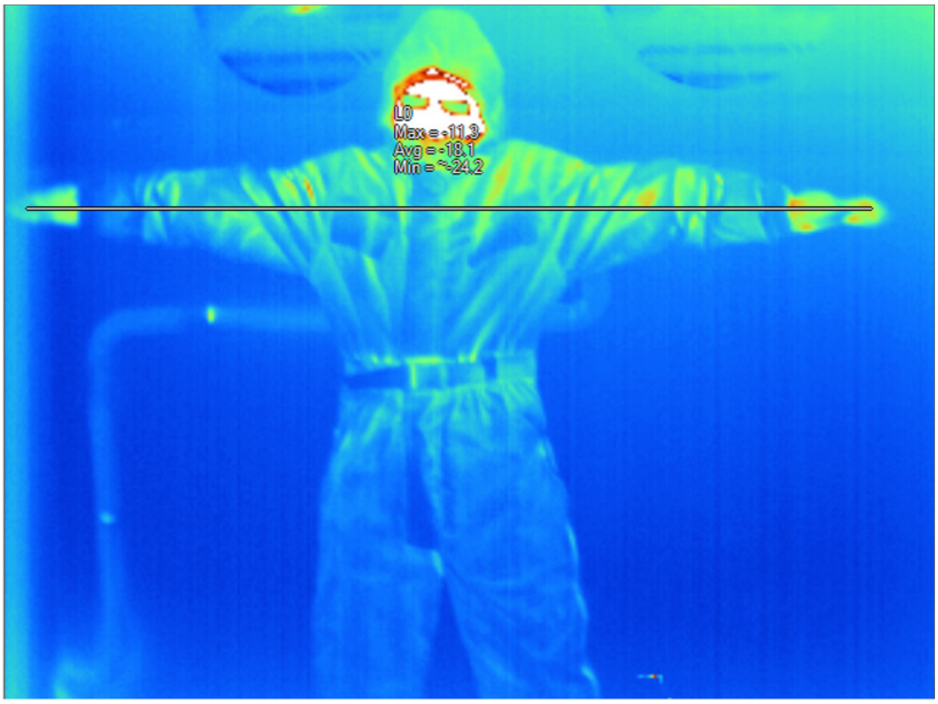
Subject 2, Position B

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.



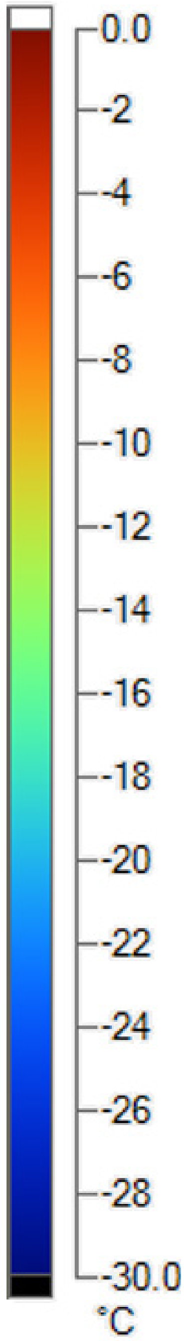
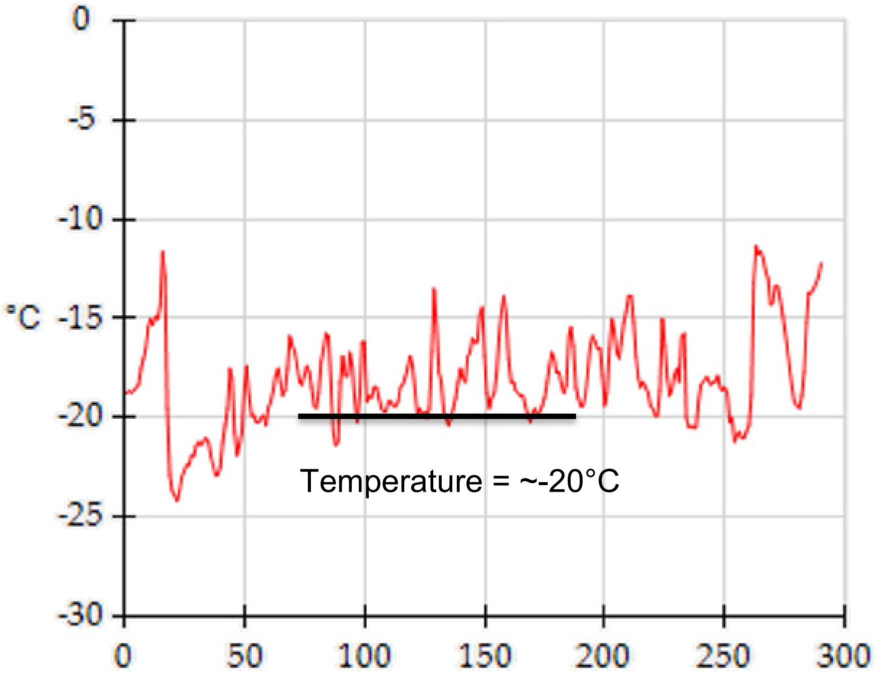
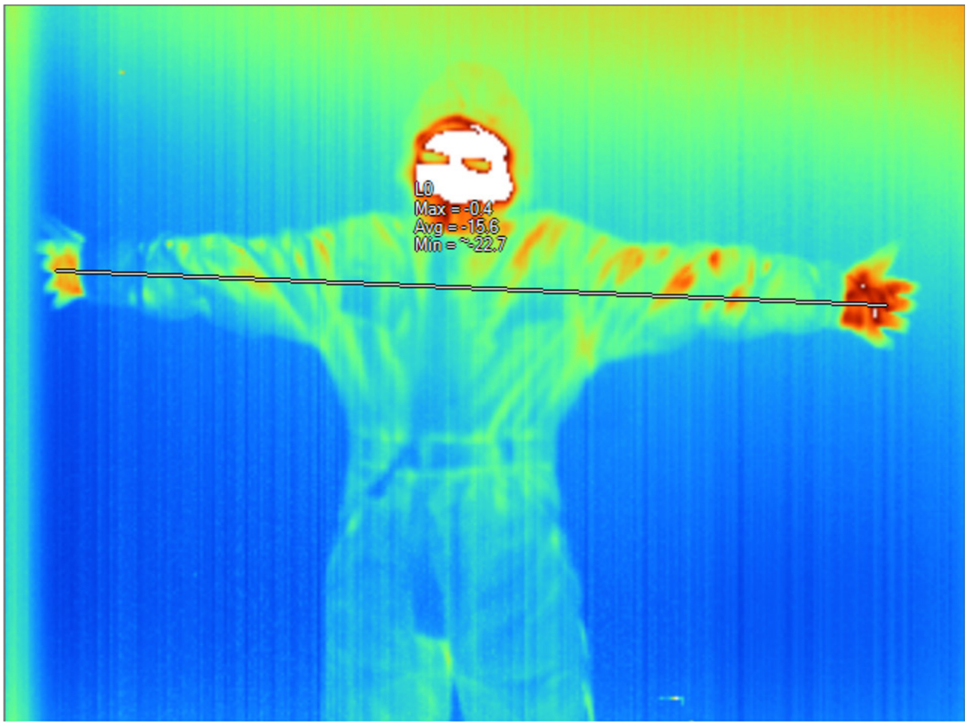


Illustration of hand to hand line at position B



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

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



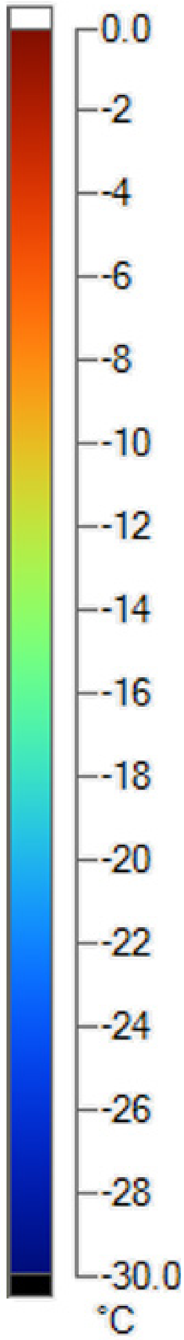
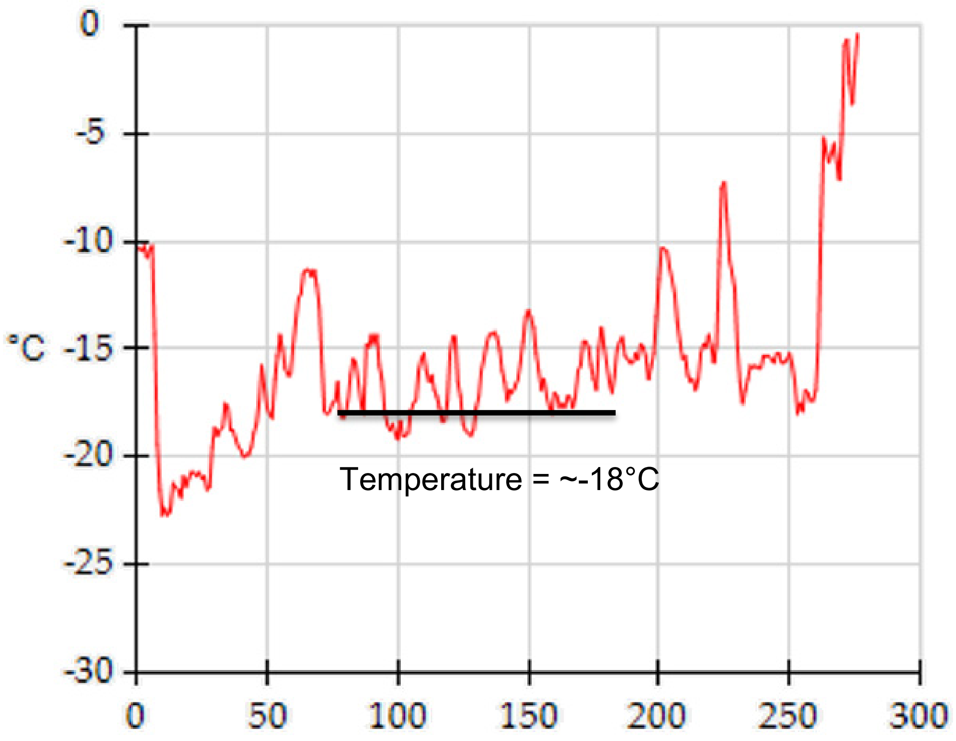


Illustration of hand to hand line at position H



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. During these experiments, the air temperature of the cold room was about -22°C.

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 [6] were the first to specify wind chill index. Their studies were too crude and went through criticism in scientific literature.
- Osczevski Wind Chill Model [9, 10] 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 [11] 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 [12].
- In order 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 [13].
- Experiments at Cold Room at The Arctic University of Norway clearly demonstrates that the heat transfer increases because of higher wind velocities.

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 [17, 20]. 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.

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

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