

Study of the required thermal insulation (IREQ) of clothing using infrared imaging

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ABSTRACT

The sense of cold develops due to the increase in heat loss from a human body. Excessive cold can be a health hazard, since excessive heat loss from the body may result in hypothermia/frostbite. Decreased body temperature due to heat loss also affects the physical, manual and perceptive performance of individuals. Therefore, protective measures are taken through clothing that controls and regulates heat loss. Clothing is a protective means for thermal insulation. Clothing and garments used in cold climates should have sufficient insulation to maintain the thermal balance of the body. The required clothing insulation (IREQ) is calculated on the basis of the hypothesis concerning the heat flow by conduction, convection, radiation and evaporation. This term is well defined in standards such as BS-EN 342 and ISO 11079:2007 (E). This paper presents an experimental study of the use of state-of-the-art Infrared (IR) thermography to estimate IREQ values. However, real IREQ values are difficult to estimate, considering that parameters, such as individual metabolism, are unknown and subject to change. Therefore, relative IREQ (IREQ*) values are computed and compared. Experiments were also conducted to measure the relative IREQ of winter jackets, summer jackets, and sweaters. The infrared images were obtained using a FLIR® T1030sc camera and analyzed using FLIR® Researcher Max software. The experiments were performed under conditions of -20°C to -35°C in the cold room at UiT- The Arctic University of Norway.

1. INTRODUCTION

A cold environment is characterized as one in which effective temperatures are below -5°C [1]. The real-time temperature is higher than the stated 'feels like temperature'. This is associated with the fact that heat transfer from the human body is enhanced due to windy conditions [1-6].

Working conditions are more severe in a cold environment than in a warmer environment. The decreased body temperature due to heat loss affects individuals' physical, manual and perceptive performance. The physiological function's efficiency diminishes in the cold [7]. People face many other problems, such as depression, dissatisfaction, insomnia, decrease in decision-making ability and response rate, and lack of motivation because of the cold and darkness during winter. It is important to provide special safety precautions, prevention means and risk management to minimize health hazards in cold weather [8-12].

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Wind velocity induces the wind chill factor, hence increasing heat loss from the human body [2, 13-15]. This may result in a challenge for the human body to maintain its core temperature (37°C or 98.6°F), which may cause hypothermia, frostbite, pneumonia or influenza and cardiovascular diseases. Infectious diseases, such as influenza, are more common during the winter because of higher levels of air pollution. Physiological function and performance of individuals are slower in the cold due to cooling of the body (heat loss) [11, 13, 16-19].

The wind chill factor, resulting in heat loss from the human body in cold climates, can be a health hazard. Therefore, protective measures are taken through clothing that controls and regulates heat loss. Clothing and garments used in cold climates should be highly insulated to maintain the body's thermal balance [11, 20, 21].

Thermal insulation is the general term, commonly used for garments that provide adequate protection against the cold and prevent heat loss from the 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 more significantly, due to laundering and wear, than is the case with high quality products [1, 22]. There are two well-accepted standards to define clothing thermal insulation/thermal comfort: British Standard – EN 342 and ISO 11079:2007 (E) [1, 20].

Infrared imaging is becoming popular for the study of surface temperatures. It has been used in various scientific studies [2, 23-25].

The primary objective of the paper is to estimate the required clothing insulation (IREQ) for different clothing and to find out the thermal comfort of individuals, by means of infrared imaging.

2. LITERATURE REVIEW

2.1. Required Clothing Insulation (IREQ)

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

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

IREQ is calculated by the analysis of a human body's heat exchange with the environment. The mathematical expression of IREQ is the general heat balance equation, as shown in Equation (1).

$$M - W = E_{res} + C_{res} + E + K + R + C + S \quad (1)$$

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

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

Heat loss from the human body through clothing takes place by four modes of heat transfer: conduction, convection, radiation and evaporated sweat. Heat exchange depends on the thermal insulation of the clothing ensemble and the 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 (2).

$$\frac{T_{sk}-T_c}{I_{cl,r}} = R + C = M - W - E_{res} - C_{res} - E - S \quad (2)$$

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 is also expressed in Clo , where $1 Clo = 0.155 m^2 K W^{-1}$.

From Equations (1) and (2), the required clothing insulation, IREQ, is calculated on the basis of the hypothesis concerning heat flow by conduction, as shown in Equation (3).

$$IREQ = \frac{T_{sk}-T_c}{R+C} \quad (3)$$

The values of R and C depend on metabolism rate and can be determined using Equation (1). It is to be noted that human beings' metabolism rates vary ($50 - 400 W m^{-2}$) [26].

3. METHODOLOGY

The research work is carried out using infrared imaging. Experiments include the capturing of thermal images of different clothing using a FLIR® T1030sc IR camera and calculating the relative required clothing insulation (IREQ*).

In this study, a cold room at the Arctic University of Norway, Tromsø, is used to capture the thermal image of different clothing. This cold room provides a suitable environment for calculating the relative required clothing insulation (IREQ*) for different clothing [2].

The clothing insulation study was carried out using a FLIR T1030sc camera, shown in Figure 1. Table 1 summarizes the features of the Flir® T1030sc IR camera [27]. FLIR ResearchIR Max® [28] image analysis software was used to analyze the data.

FLIR ResearchIR Max® is a thermal analysis software tool for FLIR R&D/science cameras, as shown in Figure 2 [27].

Clothing is a protective means for thermal insulation. The study was carried out on a subject wearing basic clothing of t-shirt, jeans, underwear, socks, and shoes (Figure 4). In addition, the subject was asked to put on either of the winter jackets, summer jackets or sweaters (Table 2, Figure 5). Brands selected for the study were based on availability. In these experiments, the subject was imaged before and after going into the cold room. The subject was also imaged without the additional clothing after coming out of the cold room.

The temperature reading was averaged in the area covered by the additional clothing, as shown in Figure 6, and by the basic clothing, as shown in Figure 7.



Figure 1: Flir® T1030sc camera

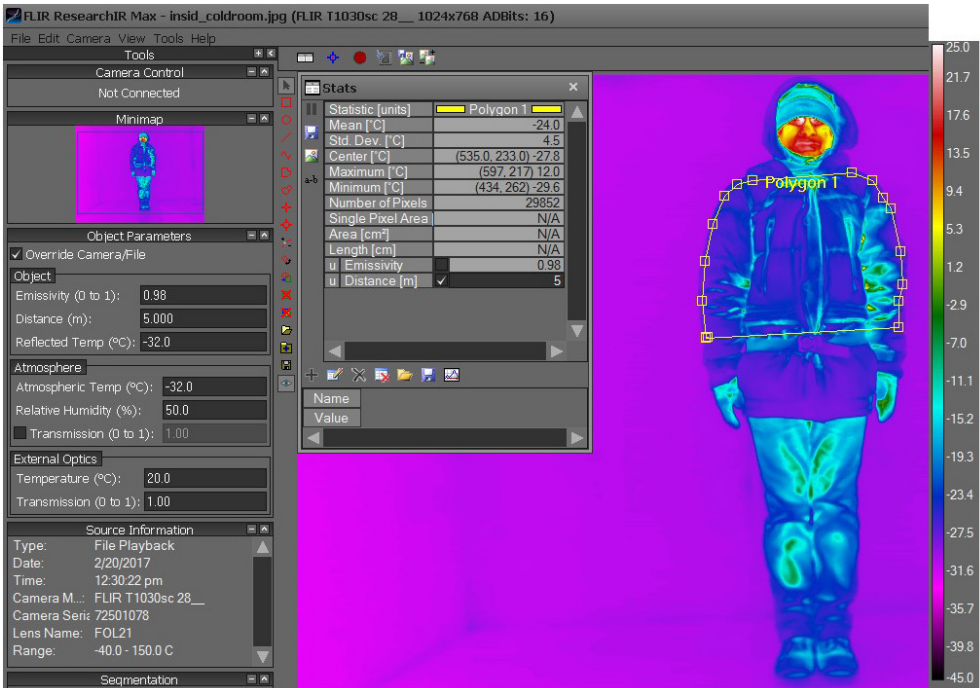


Figure 2: IR image analyzed with FLIR ResearchIR Max® software (image taken in cold room with FLIR® T1030sc camera)

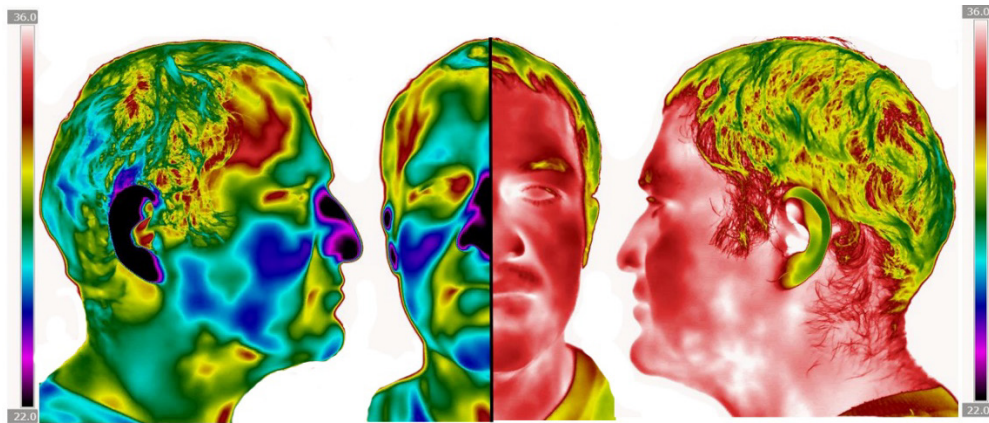


Figure 3: False colored infrared image taken with Flir® T1030sc IR camera



Figure 4: Subject is wearing basic clothing of t-shirt, jeans, underwear, socks, and shoes



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

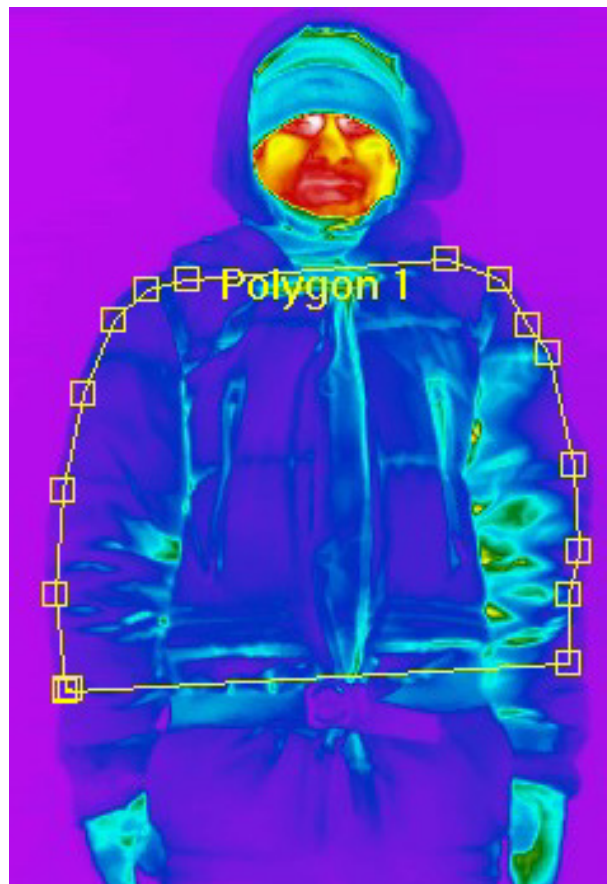


Figure 6: Temperature data was averaged using a polygon for determining the surface temperature with additional clothing T_c

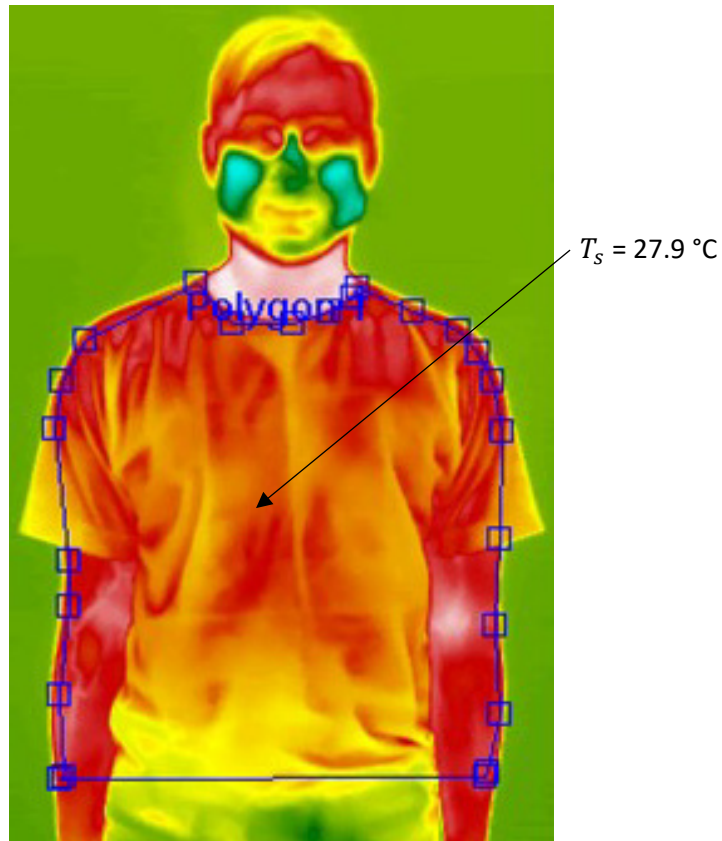


Figure 7: Temperature data was averaged using a polygon for determining the surface temperature with basic clothing T_s

Table 1: Features of Flir® T1030sc IR cameras [27]

| | |
|------------------------------------|---|
| IR Resolution | 1024 × 768 pixels |
| Emissivity Correction | Variable from 0.1 to 1.0 |
| Detector Pitch | 17 μm |
| Spectral Range | 7.5 μm to 14 μm |
| Operating Temperature Range | -40°C to +70°C |
| Accuracy | $\pm 1^\circ\text{C}$ or $\pm 1\%$ of reading |

Table 2: Winter jacket samples; summer jacket samples; sweater samples

| Winter jacket samples | Brand | Summer jacket 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® |

The obtained values were used to calculate the $IREQ^*$ values, as shown in Equation (4).

$$IREQ^* = \frac{T_s - T_c}{R + C} \quad (K \ m^2 W^{-1}) \quad (4)$$

where T_s is the mean surface temperature with basic clothing in $^{\circ}C$ and T_c is the mean surface temperature with additional clothing in $^{\circ}C$. 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 the surface temperature of the basic clothing rather than on skin temperature.

4. RESULTS AND DISCUSSION

This paper 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 for different clothing were obtained using FLIR® T1030sc camera and analyzed using dedicated software.

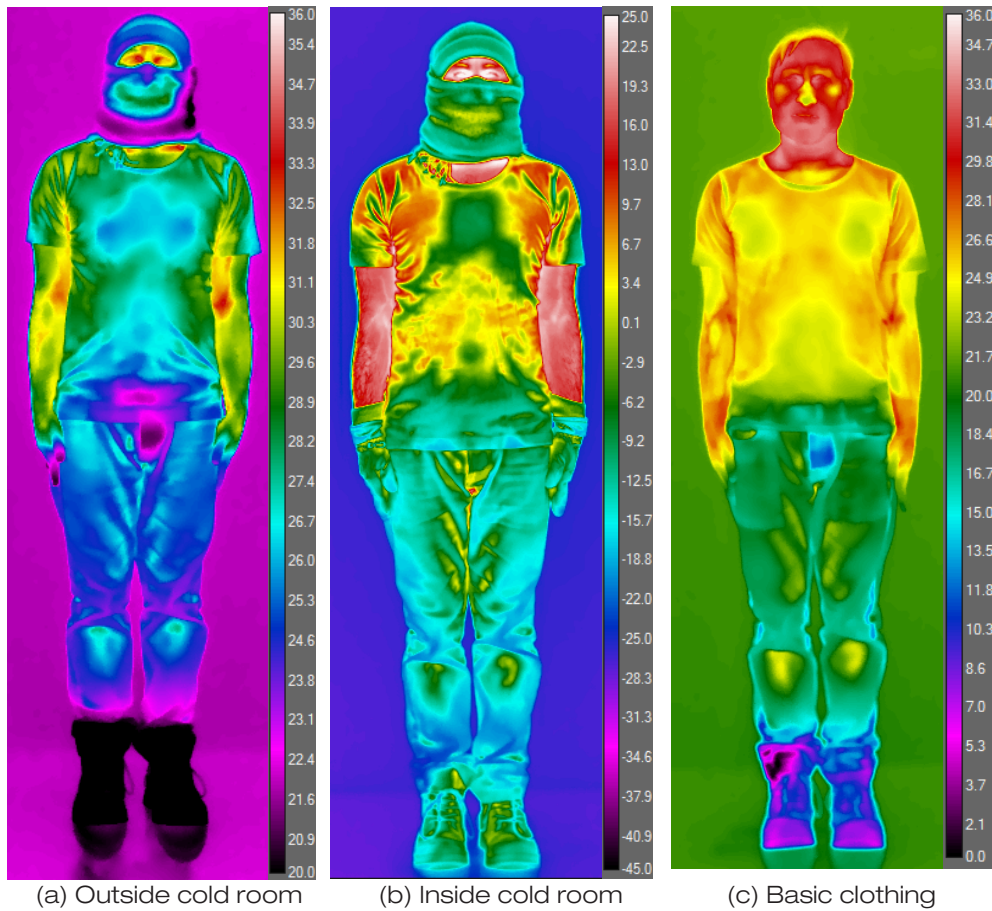


Figure 8: Infrared images of the subject wearing basic clothing of t-shirt, jeans, underwear, socks, and shoes. IR images (a) and (c) were taken immediately after the subject came out of the cold room. Temperatures shown are in $^{\circ}C$.

The IREQ study was carried out using a FLIR® T1030sc camera. The infrared images with basic clothing and with each type of additional clothing are given in Figure 8, Figure 9, Figure 10 and Figure 11, respectively. The results are summarized in Table 3, Table 4, Table 5, and a comparison is provided in Table 6.

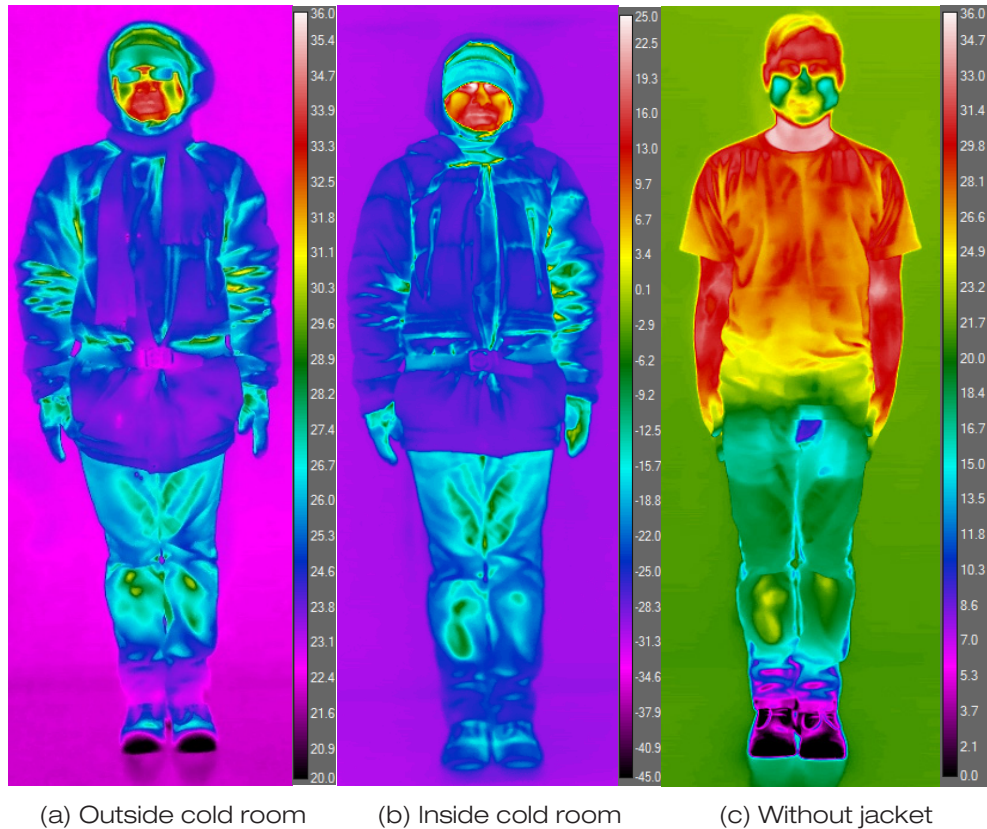
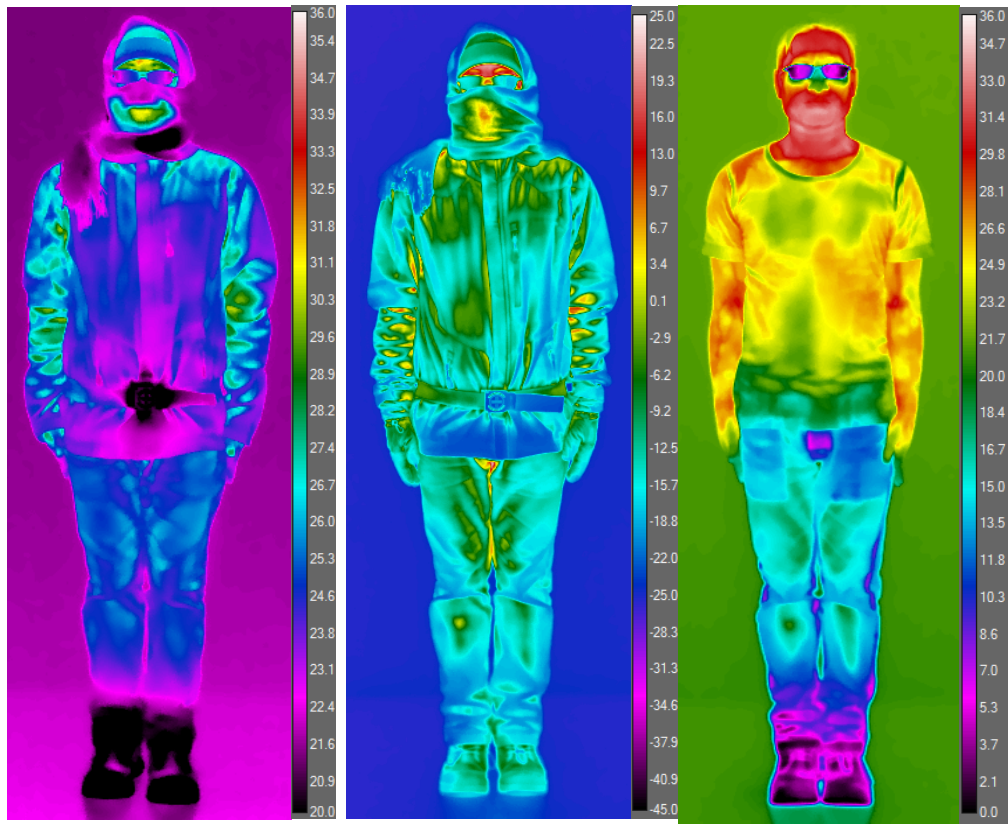


Figure 9: Infrared images of the subject wearing Jean Paul® winter jacket (sample WJ-4). IR images (a) and (c) were taken immediately after the subject came out of the cold room. Temperatures shown are in °C.

Table 3: Surface temperatures 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* ($m^2 K W^{-1}$) $IREQ^* = \frac{T_s - T_c}{55}$ |
|--------------------------|---|--|---|
| 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 |



(a) Outside cold room

(b) Inside cold room

(c) Without jacket

Figure 10: Infrared images of the subject wearing Chill Factor® summer jacket (sample SJ-4). IR images (a) and (c) were taken immediately after the subject came out of the cold room. Temperatures shown are in °C.

Table 4: Surface temperatures 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* ($m^2 K W^{-1}$) $IREQ^* = \frac{T_s - T_c}{55}$ |
|--------------------------|---|--|---|
| 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 |

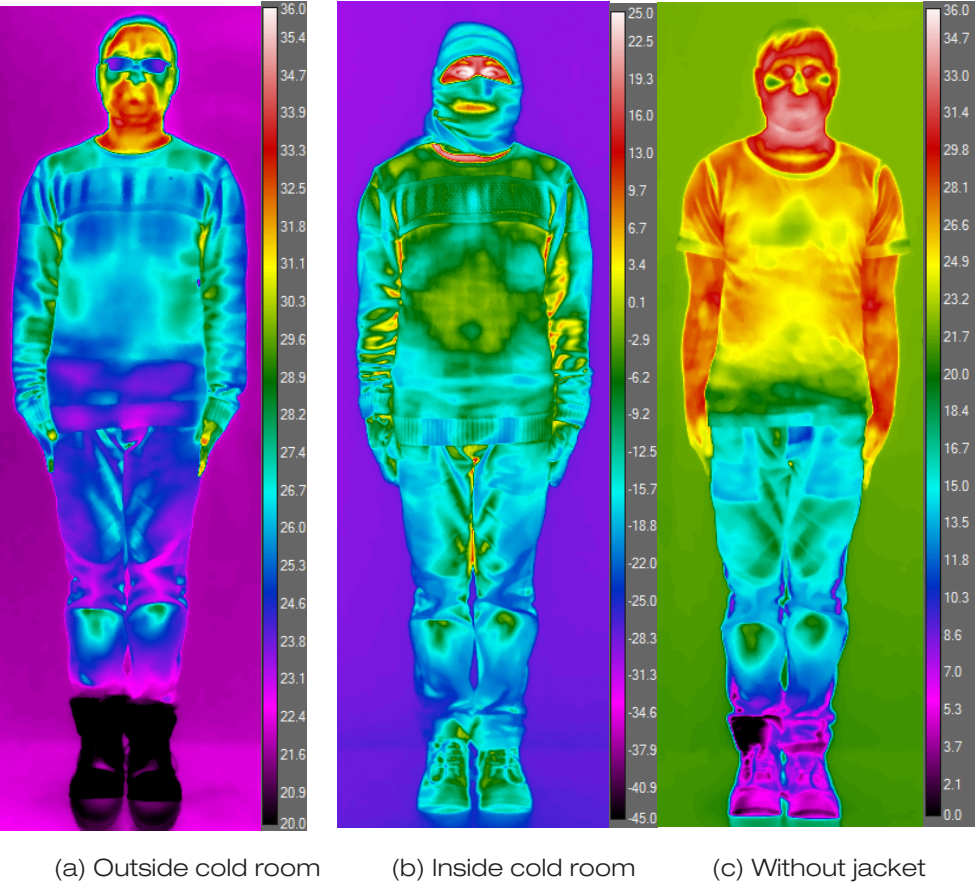


Figure 11: Infrared images of the subject wearing isolid® sweater (sample SW-4). IR images (a) and (c) were taken immediately after the subject came out of the cold room. Temperatures shown are in °C.

Table 5: Surface temperatures 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* ($m^2 K W^{-1}$) $IREQ^* = \frac{T_s - T_c}{55}$ |
|--------------------------|---|--|---|
| 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 6: 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* ($m^2 K W^{-1}$) $IREQ^* = \frac{T_s - T_c}{55}$ |
|--------------------------|---|--|---|
| Winter jacket (average) | 28.0 | -27.54 | 1.01 |
| Summer jacket (average) | 25.7 | -14.4 | 0.731 |
| Sweater (average) | 26.7 | -10.7 | 0.679 |
| Basic clothing | 25.1 | 5.7 | 0.353 |

The results clearly distinguish between different clothing types based on evaluated IREQ* values. Winter jackets have relatively better required insulation (IREQ*), compared to summer jackets and sweaters, which are as expected. Summer jackets have slightly better relative required insulation values (IREQ*) than sweaters; however, the difference is too small to pass a conclusive judgement.

CONCLUSIONS

The following conclusions can be drawn from the study:

- Protective clothing is one of the most effective means against cold. BS-EN 342 and ISO 11079:2007 (E) define the clothing insulation requirements.
- Thermal protection of clothing varies according to mean insulation values (also known as IREQ).
- The given study shows that relative required insulation IREQ* values vary between winter jackets, summer jackets and sweaters.
- Winter jackets have relatively better required insulation (IREQ*) compared to summer jackets and sweaters, which are as expected.
- Summer jackets have slightly better values of relative required insulations (IREQ*) than sweaters; however, the difference is too small to pass a conclusive judgement.
- The study proves that infrared imaging can be used to determine relative required insulation for clothing (IREQ*).

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