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Original article

Thermal Insulation of Protective Clothing Materials in Extreme Cold Conditions

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ABSTRACT

Background: Thermophysiological comfort in a cold environment is mainly ensured by clothing. However, the thermal performance and protective abilities of textile fabrics may be sensitive to extreme environmental conditions. This article evaluated the thermal insulation properties of three technical textile assemblies and determined the influence of environmental parameters (temperature, humidity, and wind speed) on their insulation capacity.
Methods: Thermal insulation capacity and air permeability of the assemblies were determined experimentally. A sweating-guarded hotplate apparatus, commonly called the "skin model," based on International Organization for Standardization (ISO) 11092 standard and simulating the heat transfer from the body surface to the environment through clothing material, was adopted for the thermal resistance measurements.
Results: It was found that the assemblies lost about 85% of their thermal insulation with increasing wind speed from 0 to 16 km/h. Under certain conditions, values approaching 1 clo have been measured. On the other hand, the results showed that temperature variation in the range (−40°C, 30°C), as well as humidity ratio changes (5 g/kg, 20 g/kg), had a limited influence on the thermal insulation of the studied assemblies.
Conclusion: The present study showed that the most important variable impacting the thermal performance and protective abilities of textile fabrics is the wind speed, a parameter not taken into account by ISO 11092.

1. Introduction

Thermal stress can have harmful effects on the function, performance, and health of the human body [1].

In a cold thermal environment, defined in the ISO standard 12894 [2] as an air temperature of 0°C below, the heat loss from the body exceeds the basal metabolic rate, and the internal temperature will drop. Such a condition can only be maintained for short periods before a dangerous state of hypothermia is reached [3].

The role of cold weather clothing is to maintain the user's thermal balance despite variations in environmental conditions and metabolic fluctuations. For cold climates, clothing must limit the rate of heat transfer between the user's body and environment and protect from the wind, without affecting movement [4].

Four environmental parameters influence thermophysiological comfort in cold conditions: dry air temperature, relative humidity (RH), wind, and radiant temperature [5]. These factors directly affect thermal comfort. An understanding of the mechanisms of heat exchange through garments as well as the impacts of environmental parameters on textile assemblies are necessary for the successful design of cold effective clothes.

The measurement of the thermal resistance of insulating textiles is standardized by ISO 11092-2014 [6]. In this standard, a sweating-guarded hot plate apparatus called "the skin model" is maintained at 35°C by electrical resistances located under the plate. A textile assembly is placed on the heated plate, and the tests must be performed under steady state condition at an air temperature of 20°C and RH of 65% under an airspeed of 1 m/s. However, the

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validity of the standard's method outside of the prescribed conditions is not well documented.

Havelka et al have carried out a comparative study of the thermal insulation of some textile insulators and measured their efficacy as a function of temperature variation in the range (−5°C, 20°C) [7]. Their findings did not show a significant effect of temperature variation on the thermal resistance of tested materials. To the best of our knowledge, the influence of temperature on thermal resistance below −5°C has not been investigated.

On the other hand, Ke et al have modeled the influence of wind speed and air permeability on the thermal insulation of certain textile assemblies [8,9]. Their work resulted in the ISO 9920-2007 standard [10]. However, studies have shown that wind also affects the morphology of the assemblies, which considerably reduces their thermal insulation. Glombikova et al investigated the performance of high-loft thermal insulations in terms of their compression properties, recovery behavior, and thermal resistance. Their results showed some correlation between the rate of compression after dynamic loading and the drop in thermal resistance of tested fillings. Nevertheless, this aspect is omitted by the models developed in the aforementioned standard [11].

The main objective of this article was to determine the thermal resistance of three technical textile assemblies, subjected to environmental conditions encountered in extremely cold environments.

The evaluation of thermal insulation properties was performed by a standard guarded hotplate device, commonly referred to as a "skin model." This test bench is recognized as the most accurate technique for determining the thermal resistance of insulating materials [12–14]. The skin model simulates the heat and moisture transfer from the body surface through clothing layers to the environment and thus measures the thermal resistance (insulation value) and water vapor transmission resistance of textiles.

2. Materials and methods

2.1. Materials

Three technical textile assemblies, ACA, DCA, and DPG, were used for this study. Each assembly comprised three layers of a nonwoven insulating material sandwiched between two protective fabrics. Two insulating materials (IM1 and IM2) were considered. ACA and DCA are made of the same insulating material (IM1) but have different assembling configurations. Alternatively, DCA and DPG are made of different insulating materials (IM1 and IM2, respectively) but share the same assembling configuration. Both insulators are made of 100% polyester long filaments and short fibers, respectively. Insulator IM1 uses long continuous polyester fibers that provide shape recovery after compression and stretching. The insulation is made of 100% fibers 11.5 μm in diameter. On the other hand, insulator IM2 comprised 85% staple polyester discontinuous fibers 7.7 μm in diameter and 15% thicker polyester fibers (20 μm in diameter). Heat treatment in the oven ensures the bonding of the microfibers, which strengthens the two-phase matrix. The microfibers also undergo a surface treatment with (poly)dimethylsiloxane, which ensures water resistance and improves the washing durability. These insulators are frequently used in the production of sportswear and sleeping bags.

The average surface weight of each assembly is 400 (g/m^2). For each type of assembly, nine samples were tested to minimize the effect of permanent deformation on thermal insulation results.

All these structural characteristics are provided by our industrial partner.

2.2. Theory

The thermal insulation property of the studied assemblies was measured by the skin model based on a standardized technique ruled by ISO 11092-2014 [6]. This test allows the evaluation of the thermal resistance of a sample subjected to a temperature differential of 15°C.

When the plate is covered with a textile assembly, the thermal power required to maintain it at 35°C is a function of the thermal resistance of the assembly under consideration. Fig. 1 presents a schematic view of the apparatus and the thermal resistances involved. To study the effects of temperature, humidity ratio, and wind speed, the skin model and the sample are placed in an environmental chamber (ESPEC Platinous Series EPX-4H). Two thermocouples that equip the chamber allow to control the temperature and to ensure an isothermal climate with a precision of ±1°C. Fig. 2 presents the bench test inside the environmental chamber and the wind tunnel design to generate the airflow on the textile assembly. The thermal resistance is calculated by measuring the temperature difference between the surface of the measurement area of the heating plate and the temperature of the ambient air "away" from the outer surface of the assemblies. It is this temperature difference that causes heat transfer through the textile assembly.

The equation used to calculate the thermal resistance is as follows[6]:

$$R_{ct} = A \times \left(t_{plate} - t_{air}\right) \Big/ Q \tag{1}$$

where:

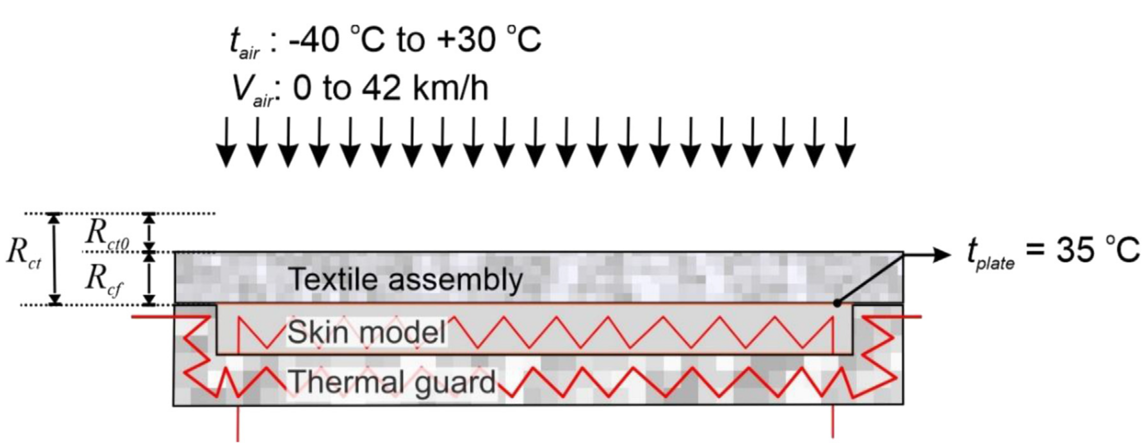

Fig. 1. Schematic view of the apparatus and the thermal resistances.

- R_{ct} is the total thermal resistance, in $m^2 \cdot °C\ W^{-1}$. Thermal insulation results are generally expressed in clo (1 clo = 0.155 $m^2 \cdot °C \cdot W^{-1}$)
- A is the area of the tested sample, in m^2
- t_{plate} is the temperature of the heating plate, in °C
- t_{air} is the temperature of the air in the test chamber, in °C
- Q is the heating power supplied to the measuring unit, in W

The total thermal resistance includes the thermal resistance of the boundary layer above the surface of the test material (R_{ct0}) and the intrinsic thermal resistance of the material itself (R_{cf}) [10]. The thermal contact resistance between the heating plate and the assemblies is considered negligible.

2.3. Environmental conditions

As RH depends on dry temperature, the three independent environmental parameters adopted to evaluate their influence on the thermal insulation of the studied assemblies were ambient temperature (dry temperature), humidity ratio, and wind speed.

To study these three parameters, both skin model and sample were placed in an environmental chamber (ESPEC Platinous Series EPX-4H). Total thermal resistance R_{ct} measurements were performed over a temperature range (−40°C, 30°C) at a 10°C interval.

The R_{ct} of the assemblies was measured at a humidity ratio (ω) between 5 and 20 g/kg at an interval of 5 g/kg. The environmental chamber allowed to control the RH% between 10 and 98%, with an uncertainty of ±3%. A psychrometric diagram, at atmospheric pressure, allowed the conversion between the two quantities, ω and RH%, for each ambient temperature value studied.

The influence of the wind on the R_{ct} was assessed through an axial fan mounted on a pyramidal section with a square opening at the outlet (Fig. 2). This setup generated an airflow perpendicular to the surface of a sample placed on top of the skin model. The fan ensured an average wind speed at the outlet of up to 42 km/h. A variable-frequency drive was used to control the generated wind speed (Fig. 3). The R_{ct} was measured for three wind speed values: 0, 4, and 16 km/h.

Fig. 2. Wind tunnel designed to generate a vertical airflow at a controlled speed simulating wind.

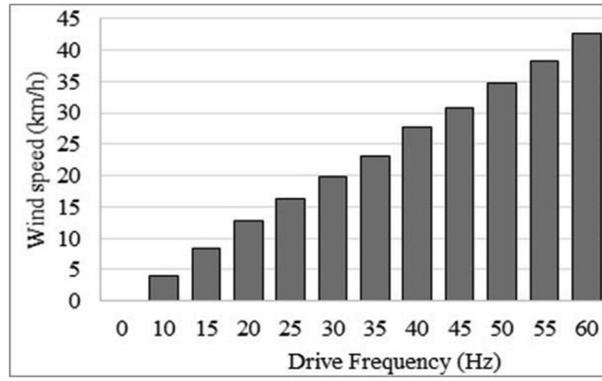

Fig. 3. Average wind speed generated as a function of power frequency.

2.4. Experimental planification and protocol

To better organize the experiments and to obtain maximum information on the effect of parameters on R_{ct}, an experimental design was adopted. The applied plan was a generalized full-factorial design that was adapted to model a three-factor system (temperature, humidity ratio, and wind speed) at mixed levels. The plan was designed and subsequently implemented on Minitab software [15].

At temperatures below 10°C, the limitations related to the test bench made it not possible to precisely control the RH due to the risk of condensation. Therefore, the humidity ratio parameter was only considered for the temperature interval (10°C, 30°C). In the (−40°C, 0°C) interval, only the influences of temperature and wind were studied.

First, each sample was conditioned at 65% RH and 21°C for at least 4 hours before testing began. Special care was given to the storage of the textile assemblies before testing by keeping them suspended at all times and avoiding stacking them to prevent compression. At the same time, the skin model was started to stabilize the temperature of its heating plate at 35°C (skin temperature). The climate chamber was also started with the desired temperature/humidity combination setting. The assembly was carefully placed on the skin model and then held in place with a flap clamp. The variable-frequency drive was then adjusted to provide the desired airflow. Once all parameters were set and equilibrium state was reached, data acquisition was initiated for a 20-minute test period, with data being acquired every 30 seconds. At the end of the test, the thermal insulation data R_{ct} and R_{cf} were generated as well as the setpoints of all the sensors that monitored the state of the heating plate (temperatures, electrical power, etc.) and the environmental conditions in the chamber. Three replicates were performed for each set of conditions.

3. Results and discussion

3.1. Thermal insulation and effect of environmental parameters

3.1.1. Effect of the assembly's nature and the temperature on the R_{ct}

The average thermal insulation results for the ACA, DCA, and DPG assemblies at temperatures ranging from −40°C to 30°C and zero wind speed are shown in Fig. 4.

The R_{ct} of the DPG assembly was higher than that of the other two assemblies at all temperatures. It ranged from 7.36 ± 0.86 clo at 30°C to 10.95 ± 1.39 clo at −40°C. Although DPG assemblies are thinner than ACA and DCA at equivalent weight, they have better thermal insulation. This is due to the nature of the insulator used.

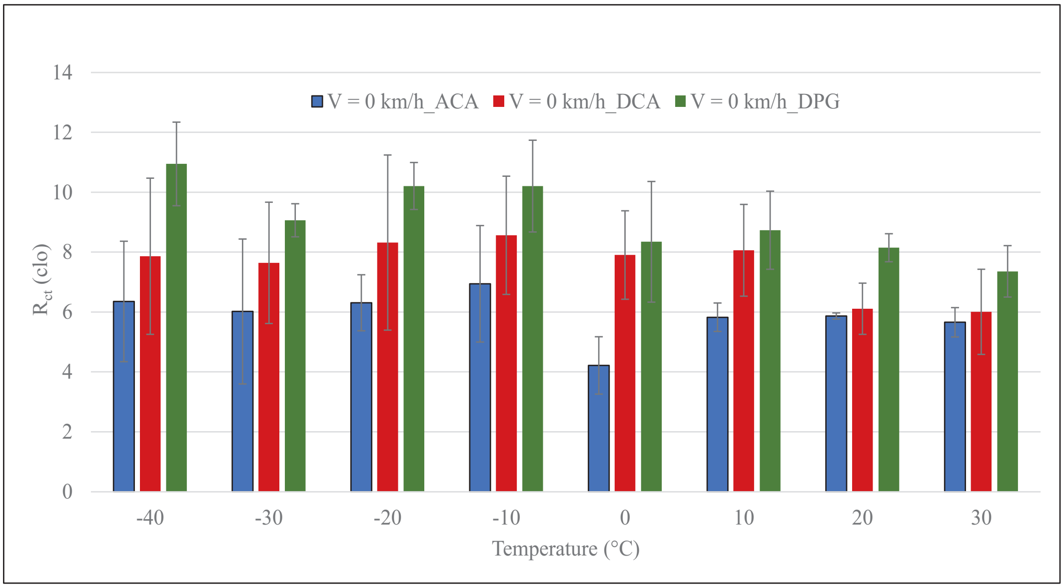

Fig. 4. Effect of temperature on the R_{ct} of the three assemblies at wind speed V = 0 km/h.

Within confidence intervals, the R_{ct} of ACA and DCA present no significant difference, regardless of the temperature. It must be said, however, that some values would require further investigation, such as the R_{ct} of ACA at 0°C, which was between 2 and 3 clo below the R_{ct} obtained at other temperatures. In the case of DPG, the temperature seemed to have a slightly more pronounced effect. The R_{ct} increased from 7.4 clo to 11 clo when the temperature decreased from 30°C to −40°C.

It should be noted that the thermal conductivity of airdrops by about 20% between 30°C and −40°C and its density increases by 25% between 30°C and −40°C. In addition, polyester fibers have been shown to lose some of its insulating values as temperature drops [16]. Despite the variation in the thermophysical properties of air and a possible variation of the fiber's thermal conductivity, the results presented do not allow us to conclude that there is a significant effect of temperature on thermal resistance.

3.1.2. Effect of wind speed on R_{ct}

Several research works have highlighted the effect of airflow on the thermal insulation of textile assemblies [9,17,18]. Previous works have studied the influence of tangential airflow on the surface of the tested samples as mentioned in ISO 11092 standard. In real conditions of the use of cold protective clothing, the wearer may be exposed to winds with variable angles of incidence, which may be perpendicular to the surface of the garment.

Fig. 5 represents the variation of thermal insulation of the ACA assembly as a function of the three wind speeds, 0, 4, and 16 km/h, perpendicular to the garment and in a temperature range between 30°C to −40°C. The results associated with DCA and DPG assemblies are presented in the table of Appendix I.

First, for all temperatures, it was noticed that the higher the wind speed, the lower the confidence interval. This is because the wind applies a relatively uniform pressure on the tested assembly,

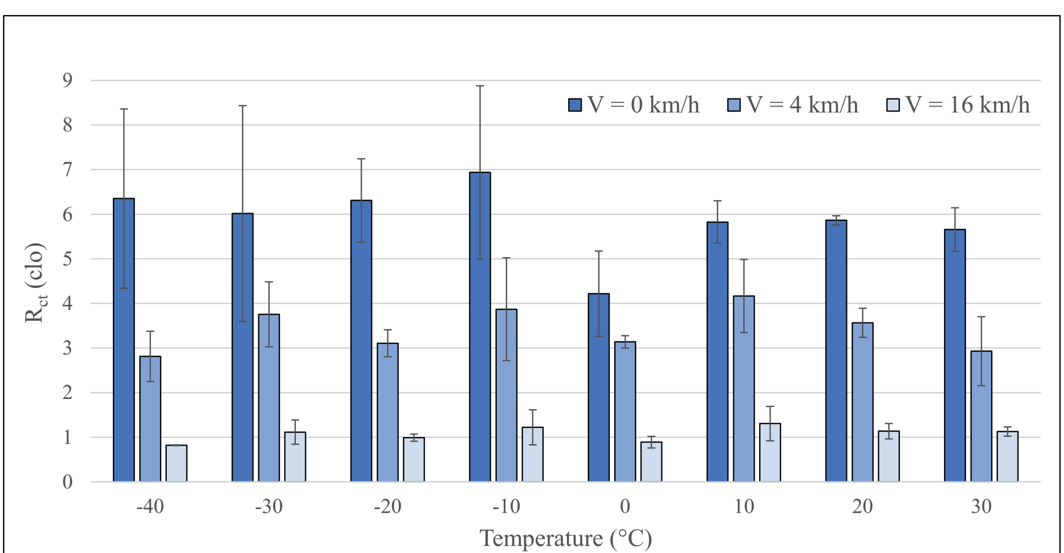

Fig. 5. Effect of temperature on the R_{ct} of the ACA assembly at three wind speeds: V = 0, 4, and 16 km/h.

which is likely to homogenize the thickness in different zones on the surface, leading to a decrease in the deviation of the measurements between the replicas.

Second, the relative independence of R_{ct} in relation to temperature observed in the previous section was more pronounced at higher wind speeds. As an indication, the R_{ct} of ACA at a wind speed of 16 km/h and 30°C (Fig. 5) was 1.13 ± 0.10 clo. At −40°C, the R_{ct} decreased slightly to 0.82 ± 0.01 clo. Similar findings apply to the DCA and DPG assemblies (Appendix I).

3.1.3. *Effect of humidity on R_{ct}*

The effect of the humidity ratio on the thermal insulation of ACA, DCA, and DPG assemblies was also investigated in this study. Fig. 6 represents the main effects plot of temperature, humidity, and wind speed parameters on the R_{ct} of the ACA assembly as generated by the experimental design. The plots associated with the DCA and DPG assemblies are presented in Appendix II. Taking confidence intervals into account, the results show a slight increase in R_{ct} with increasing the humidity ratio from 5 to 20 g/kg. At temperatures below 30°C, the variations in thermal conductivity of the air as a function of humidity ratio were not significant and do not explain the obtained results. Change in the thermal properties of the polyester fibers as a function of ω could be involved but is not reported in the literature, and nothing can be concluded with data collected from the skin model.

3.2. *Discussion on the effect of wind*

From the results presented in the previous section, it can be concluded that wind speed is the most influential parameter on the thermal insulation of the textile assemblies studied. Several factors can be the reason for this, namely, the pumping effect, the air permeability of the assemblies, and the presence of seams in the fabrics.

3.2.1. *Effect of compression and air permeability*

The effect of compression of the assemblies on the R_{ct} was preceded by several tests carried out on an incompressible rigid extruded polystyrene panel. The objective was to compare the experimentally measured thermal resistance with the value provided by the manufacturer and to verify if this resistance was independent of the wind speed because it was an incompressible material.

The characteristics of the insulating panel and the R_{ct} at 0 and 23 km/h are given in Appendix III. It should be noted that at 23 km/h, there was a 7.5% difference between the measured thermal resistance and the one specified by the manufacturer. Without the wind, the measured thermal resistance of the panel increased by 0.08 clo. This slight increase is explained by the change in the mode of heat transfer (forced convection vs. natural convection) at the surface of the polystyrene panel. Appendix III also compares the thermal resistance of the panel to that of the ACA assembly. At zero wind speed, the thickness and thermal resistance of the ACA and the panel were comparable, but at 23 km/h, a significant difference was observed between the two. It should be noted that this verification test did not fully isolate the effect of compressibility on the thermal insulation of the tested samples because in addition to being incompressible, the insulation board was also air impermeable. Other solutions can be suggested to identify the influence of compression on R_{ct}. The structure of the textile assembly can be reinforced by a rigid framework that prevents its compression under the effect of wind and whose presence does not affect the thermal resistance of the assembly. Another solution is to establish a correlation between the thermal resistance and the thickness of the sample as a function of the wind.

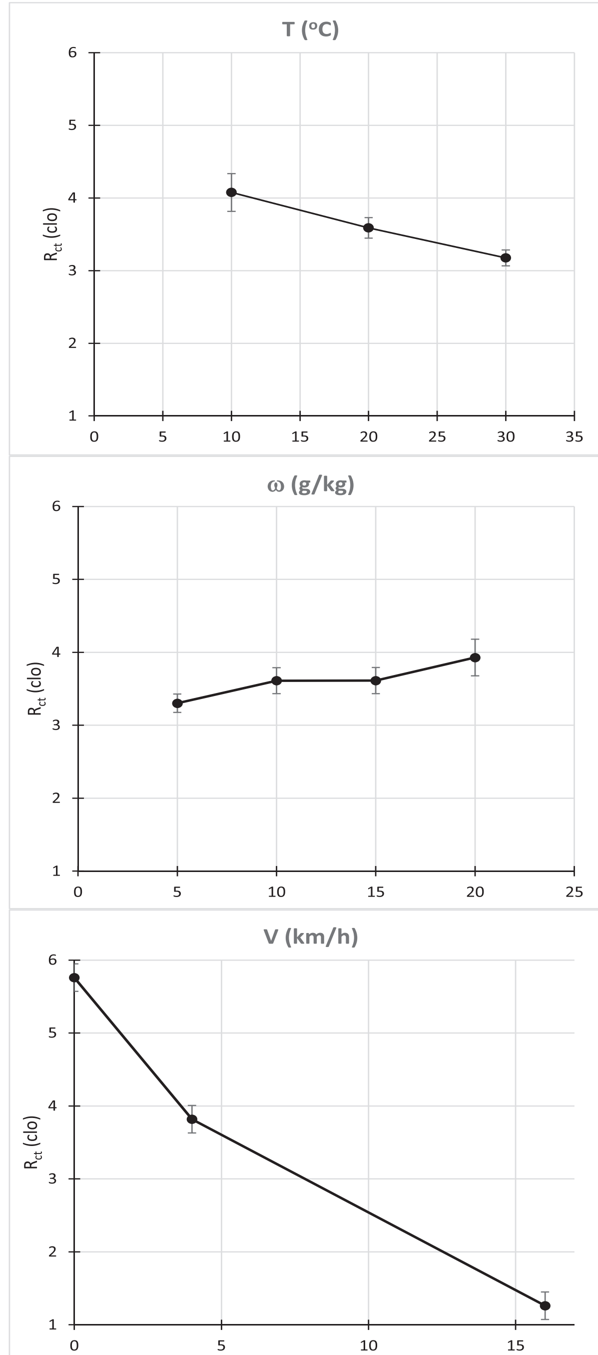

Fig. 6. Diagram of main effects of temperature (T), humidity ratio (ω), and wind speed (V) on the R_{ct} of the ACA assembly.

To determine the effect of air permeability on R_{ct}, an impermeable film on the outer side of the protective fabric was applied to achieve zero permeability. Measurements of the thermal insulation of the three assemblies were then made at ambient temperature and humidity conditions and a wind speed of 16 km/h. The film was chosen so that its thermal resistance was negligible (the R_{ct} of the film was measured at 0.2 clo). The results were compared with measurements made without the impermeable film (Fig. 7). For the ACA, the R_{ct} at a wind speed of 16 km/h was 1.13 ± 0.17 clo. With the addition of the impermeable film, the R_{ct} increased significantly to 5.44 ± 1.01 clo. A similar increase was observed with DCA and DPG.

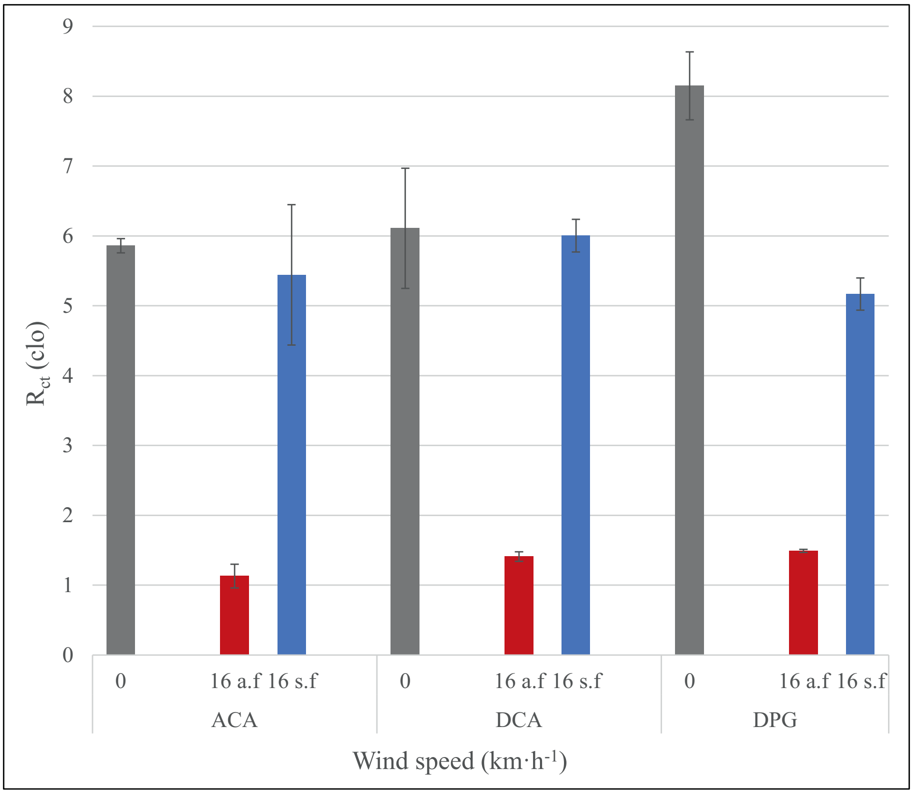

Fig. 7. Effect of the presence of an impermeable film on the R_{ct} of the three assemblies at wind speeds of 0 and 16 km/h. w.f., with film; wt.f., without film.

Measurements with the film have shown that the air permeability of the assemblies plays a significant role in the loss of thermal insulation. Air penetration through the fabric and the insulators leaves room for air to circulate, which increases convective heat exchange and reduces thermal resistance [19].

Additional measurements were made to determine the air permeability characteristic of the assemblies as well as that of their constituent parts in accordance with the American Society for Testing and Materials (ASTM) D737 standard [20]. The permeability of the ACA, DCA, and DPG assemblies was 7.17 ± 0.3, 8.27 ± 0.51, and 8.05 ± 0.45 $cm^3/s/cm$, respectively. According to ISO 9920 standard [10], these values rank the studied assemblies at the level of medium-permeable textiles, which justifies the loss of R_{ct} in the presence of wind. More details on these measurements are given in Appendix IV.

The seams in the assemblies may have added openings that facilitated air penetration and thus an increase in the permeability of the assembly. The results of the air permeability of the outer

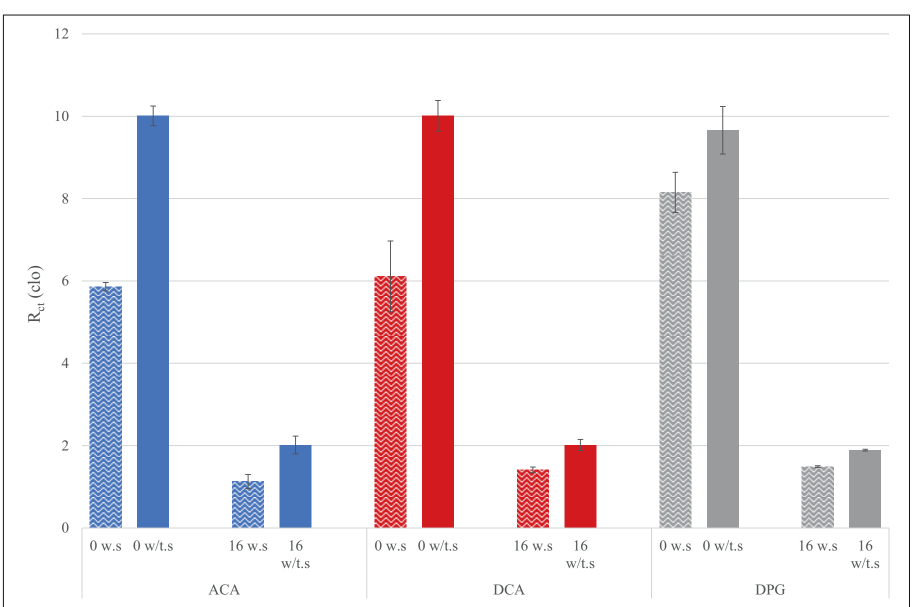

Fig. 8. Influence of sewing on the R_{ct} of the three assemblies at zero wind speed and at a wind speed of 16 km/h. w.s., with sewing; wt.s., without sewing.

protective fabric of the sewn and unsewn assemblies did not show a significant increase in permeability due to the presence of these seams (Appendix IV).

3.2.2. Sewing effect

Although the presence of seams did not affect the air permeability of the assemblies, their influence can be significant on the thermal resistance. Indeed, the presence of the seams causes a localized compression at the spots where the thread passes. This compression reduces the thickness of the structure and increases the effective thermal conductivity of the insulating part because the volume fraction occupied by air is smaller.

Fig. 8 shows the R_{ct} of the three assemblies, with and without seams, at two wind speeds, 0 and 16 km/h. Without wind, eliminating the seams increased the R_{ct} from 5.86 ± 0.10 to 10.13 ± 0.24 clo for the ACA and from 6.11 ± 0.86 to the same value of 10.13 ± 0.37 clo for the DCA (the ACA and DCA without seams boiled down to the same assembly based on insulator A). The R_{ct} of the DPG increased less significantly in the absence of seams, from 8.15 ± 0.49 to 9.67 ± 0.58 clo. A similar increase was observed in the presence of a 16 km/h wind. This is because even in the absence of seams, the influences of compression and air permeability are still present.

It should be noted that the thinning around the seams causes the creation of air cavities underneath the assemblies, thus reducing the contact surface with the skin model's heating plate, which may increase the error bar on R_{ct} measurements.

4. Conclusion

The present study consisted of developing an experimental protocol for measuring the thermal insulation of three textile assemblies while simulating actual conditions of use in extremely cold environments. The effects of temperature, humidity ratio, and wind speed on their thermal insulation were explored.

Measurements showed that the wind, oriented vertically to the assembly, significantly affected the thermal insulation. Regardless of the nature of the insulation and the type of assembly, the R_{ct} of the three textiles studied dropped to less than 15% of its initial value only by the presence of an average wind of 16 km/h. Moreover, the experimental design allowed us to conclude that the effect of the wind is independent of the variation of the ambient temperature or the humidity.

The results also showed that R_{ct} increased slightly with increasing the humidity ratio in the environment. The measurement range was limited to a 5–20 g/kg interval due to technical constraints related to equipment capabilities. Further study over a wider range could confirm the observed trend.

On the other hand, R_{ct} measurements over a temperature range of −40°C to 30°C showed that temperature does not have a significant influence on the thermal insulation performance of the investigated assemblies.

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Conflicts of interest

The authors declare that they have no conflict of interest.

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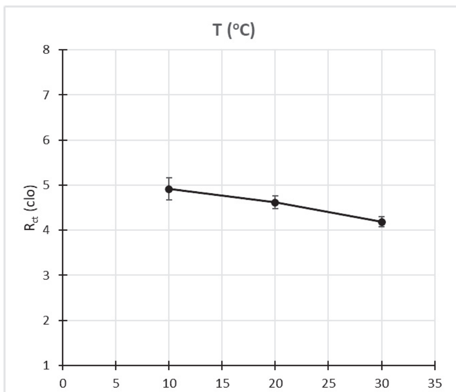
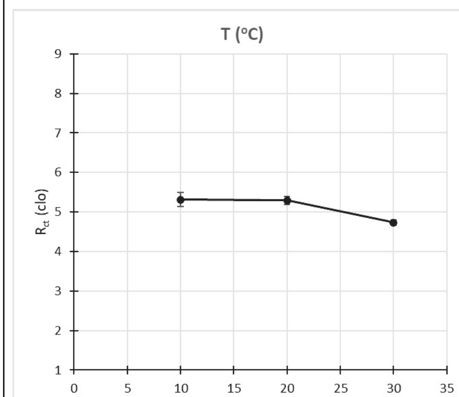
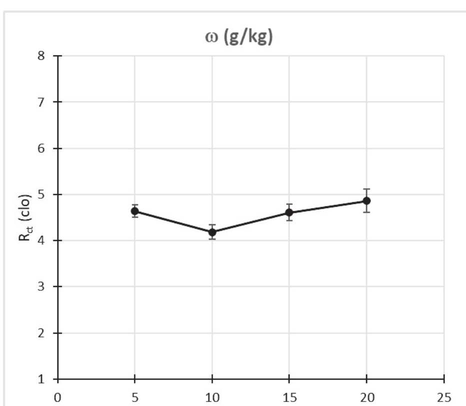
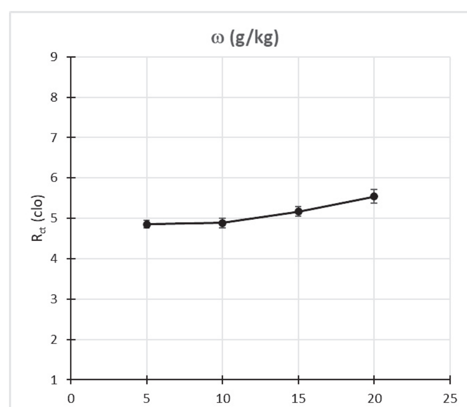
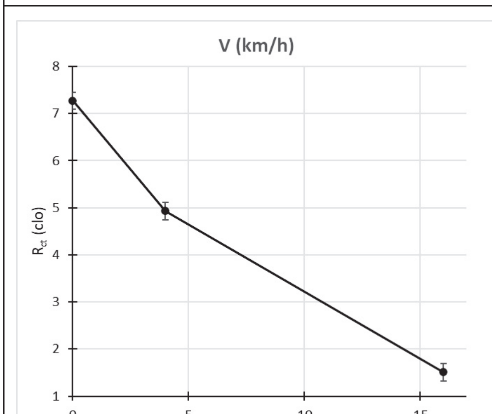
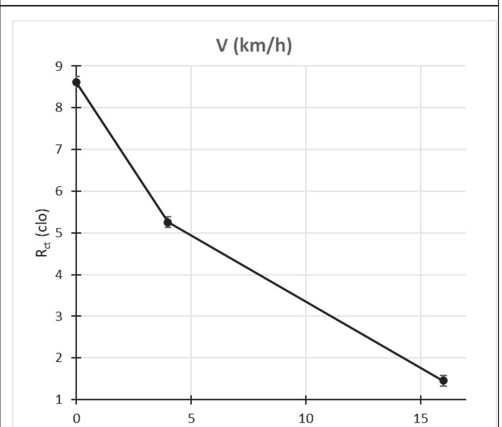
APPENDIX I. Total thermal insulation, R_{ct} (in clo), of DCA and DPG assemblies at three wind speeds and in the temperature range (−40°C, 30°C).

	Wind speed (km/h)	Temperature (°C)							
		−40	−30	−20	−10	0	10	20	30
DCA	0	7.86 ± 2.31	7.64 ± 1.76	8.32 ± 2.59	8.56 ± 1.76	7.91 ± 1.31	8.06 ± 1.35	6.11 ± 0.76	6.01 ± 1.23
	4	4.55 ± 0.20	4.65 ± 0.37	4.59 ± 0.27	4.65 ± 0.35	4.75 ± 0.37	4.90 ± 0.49	4.57 ± 0.40	4.27 ± 0.32
	16	1.12 ± 0.10	1.14 ± 0.04	1.24 ± 0.05	1.41 ± 0.14	1.52 ± 0.08	1.52 ± 0.23	1.41 ± 0.06	1.53 ± 0.02
DPG	0	10.95 ± 1.24	9.06 ± 0.49	10.21 ± 0.68	10.20 ± 1.36	8.35 ± 1.78	8.73 ± 1.16	8.15 ± 0.43	7.36 ± 0.76
	4	4.39 ± 0.94	4.68 ± 0.75	5.43 ± 0.97	4.73 ± 0.28	4.54 ± 0.50	5.04 ± 0.38	5.18 ± 0.25	5.08 ± 0.52
	16	1.13 ± 0.01	1.18 ± 0.02	1.27 ± 0.05	1.31 ± 0.07	1.36 ± 0.04	1.40 ± 0.07	1.49 ± 0.02	1.43 ± 0.10

Appendix II. Plots of main effects associated with the DCA and DPG assemblies

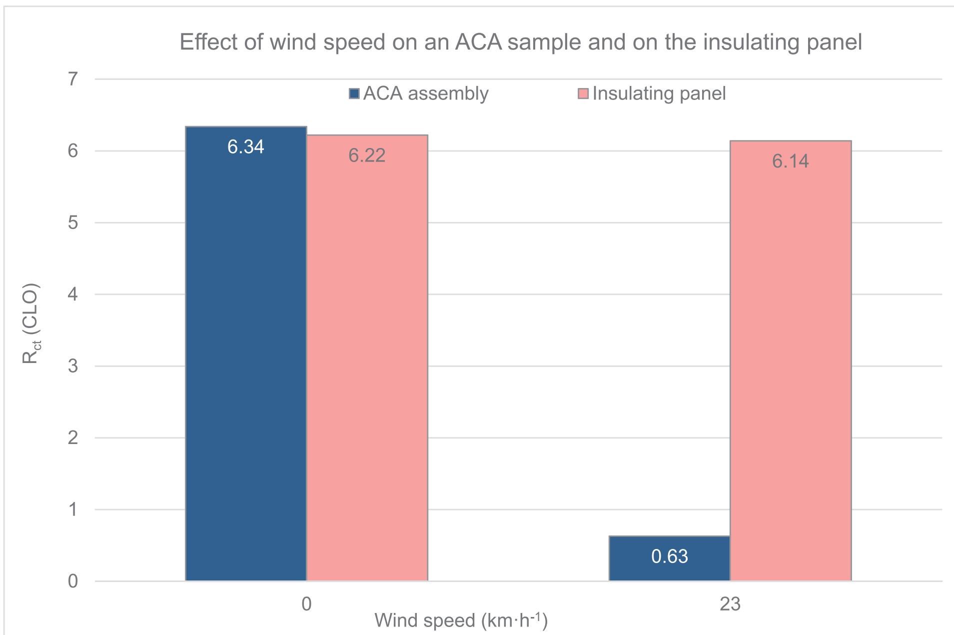
DCA – Graph of main effects for Rct Ajusted average	DPG – Graph of main effects for Rct Ajusted average
	
	
	

Appendix III. Insulating panel characteristics and R_{ct} comparison results with ACA

PROPERTIES

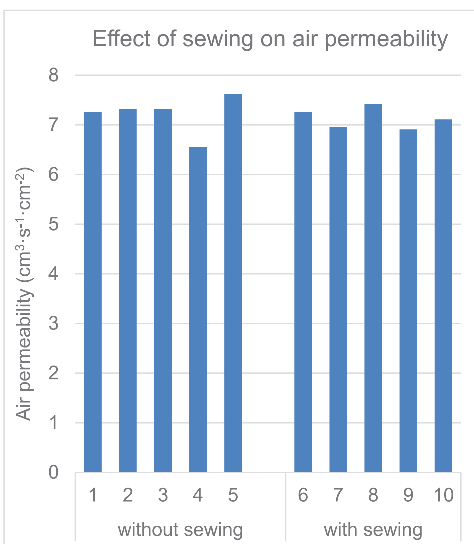
SOPRA-XPS 30 meets the requirements of CAN/ULC S701.1 Type 4 (ASTM C578-14 Type IV).

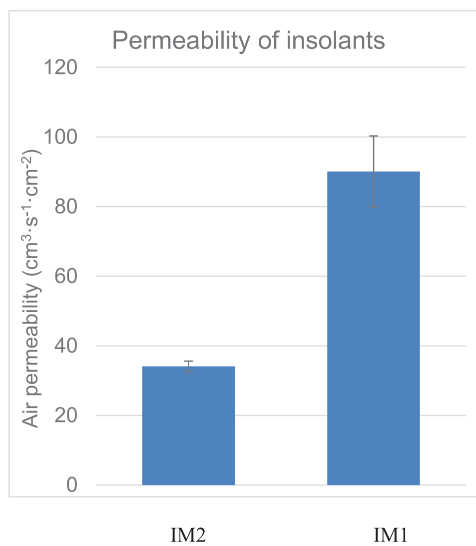
Properties	Standards	SOPRA-XPS 30
Thermal Resistance [(1)] *(RSI-Value [R Value] / 25.4 mm [1 in] @ 24 °C [75 °F])*	ASTM C518	RSI- 0.88 (R – 5.0)
Water Vapour Permeance	ASTM E96 *(Method A)*	52 ng/Pa•s•m² (0.9 perm)



Appendix IV. Assessment of the air permeability of assemblies

Location of the ten measurement spots to determine the average air permeability of assemblies





References

[1] Ray M, King M, Carnahan H. A review of cold exposure and manual performance: implications for safety, training and performance. Saf Sci 2019;115:1–11.
[2] ISO12894. Ergonomics of the thermal environment — medical supervision of individuals exposed to extreme hot or cold environments; 2001. 30 p.
[3] Rathjen NA, Shahbodaghi SD, Brown JA. Hypothermia and cold weather injuries. Am Fam Physician 2019;100(11):680–6.
[4] Watson C, Troynikov O, Lingard H. Design considerations for low-level risk personal protective clothing: a review. Ind Health 2019;57(3):306–25.
[5] Williams JT. Textiles for cold weather apparel. 1st ed. Elsevier Science; 2009. 432 p.
[6] ISO11920. Textiles – physiological effects – measurement of thermal and water vapour resistance under steady-state conditions (sweating guarded hot plate test); 2014. 22 p.
[7] Havelka A, Glombikova V, Kus Z, Chotebor M. The thermal insulation properties of hightech sportswear fillings. Int J Cloth Sci Technol 2015;27(4):549–60.
[8] Ke Y, Havenith G, Li J, Li X. A new experimental study of influence of fabric permeability, clothing sizes, openings and wind on regional ventilation rates. Fibers Polym 2013;14(11). 1906-1.
[9] Ke Y, Havenith G, Zhang X, Li X, Li J. Effects of wind and clothing apertures on local clothing ventilation rates and thermal insulation. Text Res J 2014;84(9):941–52.
[10] ISO09920. Ergonomics of the thermal environment — estimation of thermal insulation and water vapour resistance of a clothing ensemble; 2007. 112 p.
[11] Glombikova V, Komarkova P, Hercikova E, Havelka A. How high-loft textile thermal insulation properties depend on compressibility. Autex Res J 2020;20(3):338–43.
[12] Huang J. Sweating guarded hot plate test method. Polym Test 2006;25(5):709–16.
[13] Salmon D. Thermal conductivity of insulations using guarded hot plates, including recent developments and sources of reference materials. Meas Sci Technol 2001;12(12):R89.
[14] Tleoubaev A, Brzezinski A, editors. Combined guarded-hot-plate and heat flow meter method for absolute thermal conductivity tests excluding thermal contact resistance thermal conductivity 27/thermal expansion 15. 15th thermal expansion conference, thermal conductivity 2003.
[15] Minitab. 2022. Available from: https://www.minitab.com/en-us/.
[16] Drochytka R, Dvorakova M, Hodna J. Performance evaluation and research of alternative thermal insulation based on waste polyester fibers. Procedia Eng 2017;195:236–43.
[17] Bouskill L, Havenith G, Kuklane K, Parsons K, Withey W. Relationship between clothing ventilation and thermal insulation. AIHA J 2002;63(3):262–8.
[18] Holm I, Nilsson H, Anttonen H. Prediction of wind effects on cold protective clothing, NATO. RTO-MP-076; 20016.1–6.
[19] Holmér I, Nilsson H, Havenith G, Parsons K. Clothing convective heat exchange—proposal for improved prediction in standards and models. Ann Occup Hyg 1999;43(5):329–37.
[20] ASTMD737-18. Méthode d'essai standard pour la perméabilité à l'air des tissus textiles. 5 p.