ALTERNATIVE METHOD OF DETERMINATION OF EVAPORATIVE RESISTANCE OF SOCKS MEASURED ON DRY THERMAL FOOT MODEL

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Abstract: This paper introduces an alternative method to test the evaporative resistance (Ret) of clothing using a dry thermal foot model. In a regular regime, when testing Ret of clothing, a sweating thermal foot model would be used; however, the expensive cost, high maintenance and malfunction of sweating holes cause many problems. A different method of Ret measure is recommended. Experiments were according to the ISO 11092 standard[1-2] when the environmental climate is in a steady-state to measure the Ret of samples. In the experiment, a wet (but not dripping wet) 100% cotton sock was put onto the thermal foot model as the base of the "sweating layer." Tailor-made socks from testing materials were put on the thermal foot model until steady-state, then measurement started. The tailor-made sock[3] was introduced to create a closely fitted sock to wear on top of the sweating layer for the experiment. In the Result section, the dry measurements - thermal resistance (Rct) - were also taken for comparison and discussion to the wet measurements - evaporative resistance (Ret).

Keywords: *Thermal resistance; Evaporative resistance; Alternative method; Thermal foot model; Tailor-made*

1. Introduction

In the clothing industry, thermal manikins, thermal foot models, and thermal hand models[4-6] are commonly used electrical devices for testing clothing properties. These electrical devices can give the thermal resistance (Rct) values of the tested garment or clothing. However, when testing for the evaporative resistance (Ret) of clothing, a "sweating" thermal model is needed. The sweating version of the thermal model contains sweating holes embedded on the surface of the device from where water droplets are being secreted to stimulate the process of sweating. The sweating thermal models usually cost a lot more than the dry thermal models; maintenance difficulties and sweating holes are easily clogged that not many research institutes nor universities own them. In order to solve this problem, a different method of Ret measure on the dry thermal model is needed to develop.
In this paper, a different approach of measuring Ret of sock on a dry thermal foot model is applied by using a sock of 100% cotton that fits closely to the thermal foot model, and the sock was wetted before putting on the foot model to create the layer of sweat. Then, wait until the climatic chamber conditions were steady-state before the Ret measurement started. Details of the process are explained in the following sections.

2. Material and Experiment

$$Ret_{Tot} = Ret_O + Ret_A + Ret_M \quad (1)$$

When the climatic chamber conditions are in a steady-state, the total evaporative resistance (Ret_{Tot}) is equal to the summary of the boundary layer of the sweating thermal foot model (Ret_O), the air gap (Ret_A) and the evaporative resistance of the material (Ret_M) as shown in Eq. (1). Indirect contact of material to the sweating thermal foot model, the air gap layer will be minimized that the total evaporative resistance will be equal to the sweating thermal foot model (Ret_O) plus the evaporative resistance of the material (Ret_M) only as in Eq. (2).

$$Ret_{Tot} = Ret_O + Ret_M \quad (2)$$

When calculating the Ret_M of the material in direct contact on the foot model, the total evaporative resistance minus the boundary sweating layer of the thermal foot model; is equal to Eq. (3), and all units of Ret are in [m^2/Pa/W].

$$Ret_M = Ret_{Tot} - Ret_O \quad (3)$$

For the thermal resistance (Rct), the total thermal resistance (Rct_{Tot}) is equal to the summary of the naked thermal foot model (Rct_O), the air gap (Rct_A) and the thermal resistance of the material (Rct_M) as shown in Eq. (4). The unit of Rct is [m²/°C/W].

$$Rct_{Tot} = Rct_O + Rct_A + Rct_M \tag{4}$$

When in direct contact of material to the thermal foot model, the air gap layer will be minimized that the total thermal resistance will be equal to the thermal foot model (Rct_O) and the thermal resistance of the material (Rct_M) only as in Eq. (5),

$$Rct_{Tot} = Rct_O + Rct_M \tag{5}$$

Also, under the direct contact condition, calculating the Rct_M of the material is the total thermal resistance minus the boundary layer of the thermal foot model; that is equal to Eq. (6),

$$Rct_M = Rct_{Tot} - Rct_O \tag{6}$$

2.1 Thermal Foot Device and Software

From the above equation 1 to 3, the Ret_o sweating layer is needed to be established. The thermal foot model was used, and a sock of 100% cotton was wetted and put on it, as shown in Figures 1 and 2. When the thermal foot software showed that the climatic chamber conditions were in a steady-state, the measurement started.

Figure 1: Bare thermal foot model hanging inside a climatic chamber

Figure 2: A 100% wetted cotton sock is put on the thermal foot model as the sweating layer

The software (Figure 3) is directly connected to the thermal foot model. On the visual panel, the left side shows the device's power consumption [W] and surface temperature [°C] through the sensors built-in the thermal foot. The right side of the panel is divided into three parts: the top part shows the current ambient temperature [°C], relative humidity [%] and the wind speed [m/s]; the middle part is recording twenty tested values (each test lasts for one minute) and the current conditions (device surface temperature, power consumption and Rct/Ret) of the thermal foot in line graphs; the lower part is presenting the final mean values of the surface temperature and the power consumption of the thermal foot; Rct/Ret/Clo of the material or the Rct_o/Ret_o/Clo when the device is naked.

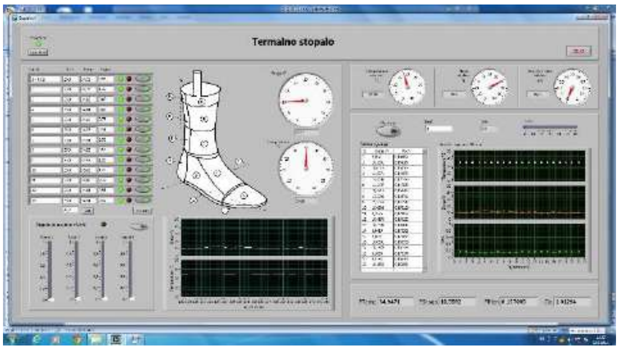


Figure 3: Thermal foot model software shows the power and temperature of the device on the left panel; 20 tested values on the right panel; the bottom right panel shows the mean Rct/Ret result from the above 20 testing values

The thermal foot model[7] is a silver-made, true human foot proportion composed of thirteen heat zones that the temperature of each heat zone can be adjusted individually. The dimension of the device is 26cm height, 26cm length, 10cm width. The thermal foot is suspended in the center of the climatic chamber, and the operating conditions are shown in Table 1.

Table 1: Standard ISO 11092 operating conditions

Test Standard	Type of Test	Thermal Foot Temperature (ºC)	Ambient Temperature (ºC)	Ambient Relative Humidity (%)	Air Velocity (m/s)
ISO 11092 Non-isothermal	Thermal Resistance (Rct)	35±2	20±5	65±5	1±0.5
ISO 11092 Isothermal	Evaporative Resistance (Ret)	35±2	35±5	40±5	1±0.5

2.2 Sample Preparation

Sample materials were plain-woven, including two 100% cotton and two 100% polyester; each was of different thickness and weight. The basic properties of these four materials are shown in Table 2.

Table 2: Basic properties of four materials

	Structure	Thickness (mm)	Square Mass (g/m²)	Fabric Density. warp/weft(threads/10cm)
Cot W	Plain woven	0.3	130	26/24
Cot P	Plain woven	0.39	140	26/24
Pes G	Plain woven	0.39	170	22/16
Pes B	Plain woven	0.26	170	14/12

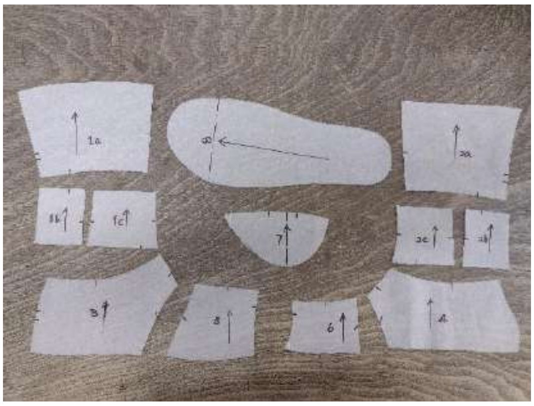
In order to fit materials to the thermal foot model, a sock pattern set is needed. By using molding method[3], the base sock patterns were created. Procedures of sock patternmaking are shown in Figure 4a-g.

Figure 4a: The base sock (sweating layer) is on the thermal foot, and elastic bands are used to divide the foot into sections for unmolding and patternmaking

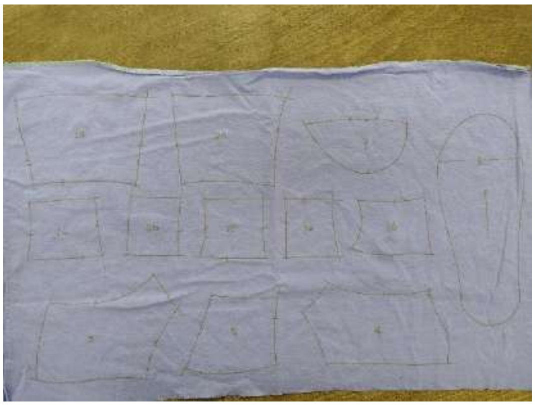
4b: A plastic shrinkwrap is applied to cover the entire foot model

4c: Fabric backing electrical tape is used to reinforce the plastic shrinkwrap, mold the shape of the foot; and transfer the elastic band markings onto it

4d: After unmolding, the form is cut open along the elastic band markings and the contour of the shape; then numbered



4e: From 3D pattern pieces turn into 2D pieces; noticed all the small wedge-like cuts and overlapping are smoothed out in each pattern piece



4f: 2D pattern pieces are traced onto the material, 1cm seam allowance is added onto the surrounding of each pattern piece for sewing

4g: After the cut and sew process, material pattern pieces are turned into a 3D sock that is ready to be tested

An air gap is minimized in the base sock pattern pieces; however, an air gap can be added. The method is to treat the foot model as a cylindrical column, then find out the radius by the circumference formula (4).

$$\text{Circumference} = (2\text{radius})\cdot\boldsymbol{\pi} \tag{4}$$

When desired air gap distance adds to the radius, it becomes the new circumference with a built-in air gap as in Eq. (5).

$$\text{Circumference with air gap} = 2(\text{radius} + \text{air gap})\cdot\boldsymbol{\pi} \tag{5}$$

When Eq. (5) minus Eq. (4) increases the length of the circumference, which can be equally distributed to the pattern pieces. In this experiment, 5mm and 10mm air gap distances were added to the basic sock patterns before the cut and sewed process.

2.3 Experiment

In the experiment, two socks were prepared from each material (a total of four materials); one with 5mm air gap distance, another with 10mm for a total of eight socks. Each sock was tested for Rct and Ret on the thermal foot model. Each Rct/Ret measurement was the mean value of twenty tests and each test lasted for one minute. The final result was the mean taken from three measurements.

3. Results

Each sock's evaporative resistance (Ret) and thermal resistance (Rct) were tested according to each ISO standard. After six measurements, the mean Ret_o and Rct_o are 0.1702 [m^2/Pa/W], 0.1316 [m^2/^{o}C/W]; respectively. The Ret and

Rct results of materials with 5mm and 10mm air gap distance are calculated by Eq. (1) and (4). They are shown in Table 3 as follows:

Table 3: Ret and Rct results from the combinations of 4 materials and 2 air gap sizes

Ret [m²/Pa/W]	Cot W	Cot P	Pes B	Pes G
5mm	0.1397	0.1372	0.1195	0.1421
10mm	0.1421	0.1439	0.1324	0.1447
Rct [m²/ºC/W]	Cot W	Cot P	Pes B	Pes G
5mm	0.0546	0.0572	0.0488	0.0517
10mm	0.0577	0.0626	0.0593	0.06

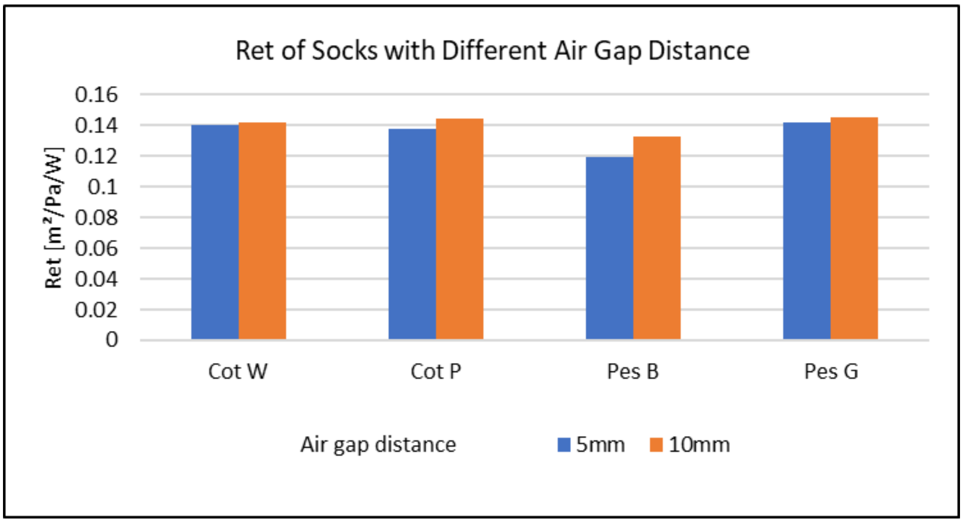


Figure 5: Comparing Ret results of the combinations of 4 materials and 2 air gap sizes

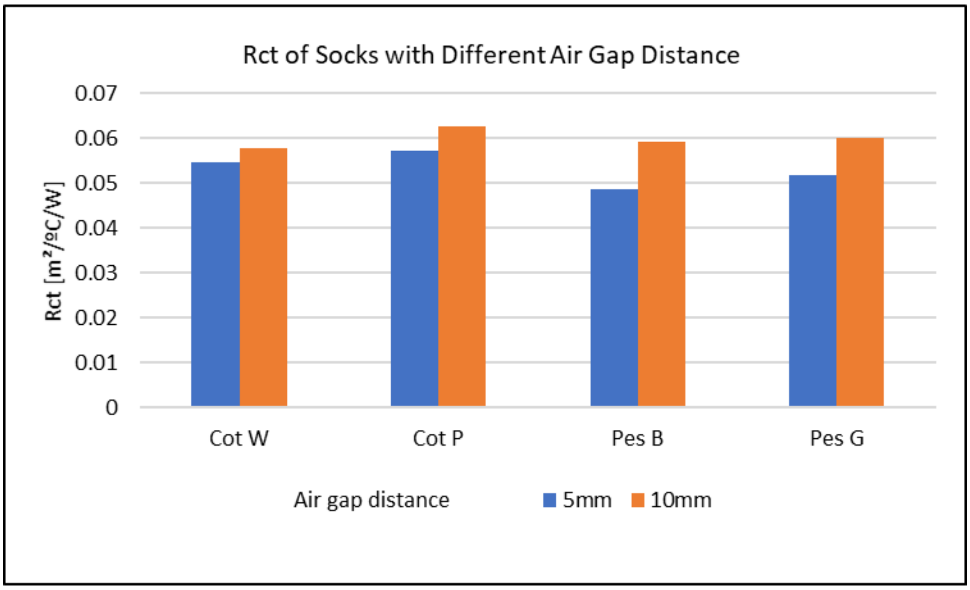


Figure 6: Comparing Rct results of the combinations of 4 materials and 2 air gap sizes

4. Conclusion

This paper used an alternative method to determine the evaporative resistance (Ret) from the dry thermal foot model. Combinations of four materials (made into socks) and two air gap distances (5mm and 10mm) were tested for their Ret values using the alternative method. Same combinations of materials and air gap distances were also tested for their Rct values for comparison. Results show that when air gap distance increases, resistance increases in both Ret and Rct test results (Figure 5-6), though the increase in Ret resultant values is less compared to Rct resultant values. This scenario may be caused by 1). Labour error - the first time experimenting with the alternative method; 2). The wetness of sock control; 3). Isothermal condition - conditions of the climatic chamber are not fully automatic; manual labour is needed. However, the overall results are expected: an increase in air gap distance and an increase in resistance until free convection comes in[8-10]. These logical and expected results have already been experienced and written by many researchers regarding air gaps, heat and mass transfer topics[11-14], which concluded that the alternative method of using a "sweating layer" on a thermal foot model could determine the Ret value of the material. Further development and verification are needed for the Ret alternative method improvement.

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