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Objective Measurement of Heat Transport through Clothing

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Abstract—Heat transport analysis of any solid or porous material is an important issue for textile, mechanical, chemical, production, aeronautical and metallurgical engineers. The maintenance of thermal balance is probably the most important physical comfort attribute of clothing and has occupied the attention of many textile research workers. Transmission of heat through a fabric occurs both by conduction through the fibre and the entrapped air and by radiation. Practical methods of test for thermal conductivity measure the total heat transmitted by both mechanism. An objective measure is one carried out with the aid of instruments that do not depend on the opinion of a human being. In this paper, the various instruments which are utilized for objective measurement of the heat transport properties of clothing; are discussed.

Keywords— Alambeta, Guarded hot plate, Heat transmission, Togmeter

I. INTRODUCTION

The heat transmission behavior of a fabric critically important for human survival and plays a very important role in maintaining thermo-physiological comfort [1]. Clothing is an important issue for general consumer, active athletes and for those who practice jogging, skiing, golf or other sports just for fitness in their time [2]. Many researches and industries are engaged to develop the functional active fabrics that are most suitable for the comfort point of view.

A number of desirable attributes of functional sports and leisurewear were identified [3] in which heat regulation is important property in one of them. Thermo-physiological wear comfort [4,5] means that the core body temperature of approximately 37°C is maintained. Depending upon the level of physical activity and temperature of the climate, the body temperature increases or decreases which must requires dissipation or conservation respectively to balance the heat of the body. The clothing insulation helps to maintain the heat transmission from body to environment or vice-versa.

For measuring the heat transmission behavior of the fabrics basically two methods are utilized: subjective and objective evaluation methods. An objective measure is one carried out with the aid of instruments that do not depend on the opinion of a human being. A subjective measure, conversely, is one in which the opinion of the person directly involved in carrying out the measurement is the only factor of interest. In subjective assessment no instrument requires to measure what the subject is thinking. There procedure is inaccurate and not easy to carry out any mathematical analysis. An objective measure is simpler to perform accurately and is likely to give results of greater precision than a subjective one. Thus, if an objective measurement is to be carried out, it is customary to setup an experiment with the appropriate apparatus, run the experiment and record the value sought. The mean value is then calculated and used to express the experimental result desired [6].

II. MECHANISM OF HEAT TRANSPORT THROUGH CLOTHING

The mechanisms that allow the body to lose heat to the environment in order to maintain its thermal balance: i. conduction, ii. convection, iii. radiation, and iv. evaporation. The mechanism of dry heat transfer may involve conduction through the solid material of the fibres and intervening air, radiation (both direct and fibre to fibre), and convection of the air within the structure. The heat flow through a fabric is due to combination of conduction and radiation, the convection within a fabric being negligible at low wind speeds i.e. less than 8 km/h. The conduction loss is determined by the thickness of the fabric and its thermal conductivity [5, 7-11]. The heat transfer by conduction depends on the material's heat conductivity, i. e. their capacity from a warmer medium to a cooler one. Thermal conductivity λ (W/mºC) expreses the heat flow (Q), W, passing in 1 h through area (A) of 1 m^2 of the fabric thickness (h) at a temperature difference (T_1-T_2) of 1º C, as given in the following equation:

$$\lambda = \frac{Q.h}{A.t.(T_1 - T_2)}$$

The thermal conductivity of a fabric is itself a combination of the conductivity of air k_A and that of the fibre k_F.

$$Fabric\ Conductivity(k) = (1 - f)\lambda_A + f\lambda_F$$

Where, f - fraction by volume of the fabric taken up by the fibre.

The conductivity of the air is 0.025 W/mK and that of fibre is 0.1 W/mK, therefore in fabrics of fibre content below 10% the conductivity is effectively that of air.

Thermal resistance, (resistance to heat flow) is inversely proportional to thermal conductivity and is defined by the following equation [7]:

$$Thermal\ Resistance\ (R) = \frac{h}{\lambda}$$

Where, h = thickness of the material
λ = thermal conductivity

Since λ is roughly constant for different fabrics, thermal resistance is approximately proportional to fabric thickness. It is therefore the thickness of the garment that determines its thermal resistance and gives the wearer protection against cold.

The transfer of heat from the human body to the environment through convection process is expressed as [12]:

$$C = f_{cl}.h_c.(T_{cl} - T_a)$$

Where, C - heat loss by convection
f_{cl} - clothing area factor (clo)
h_c - coefficient of convection heat transfer(W/m^{2}K)
T_{cl} and T_a - clothing surface temperature and ambient air temperature respectively (ºC)

The heat transfer coefficient (h_c) depends on the air velocity across the body and also upon the position of the person and orientation to the air current. An approximate value of h_c during forced convection can be evaluated from the following empirical equation:

$$h_c = 12.1(V_a)^{0.5}$$

Where, V_a - velocity of air (m/s)

The clothing area factor (f_{cl}) can be evaluated by the following empirical equation:

$$f_{cl} = 1.05 + 0.1\ I_{cl}$$

Where, I_{cl} - thermal insulation of clothing (clo)

The heat flow due to radiation is more complex as it is governed by the temperature difference between the heat emitter and the heat absorber. The infra-red radiation only travels a few millimetres into a fabric as it is either scattered or absorbed by the fibres. These fibres in turn emit radiation which travels a further short distance to the next fibres and so on until it reaches the far surface. Therefore the radiative heat transfer between the body and the external environment is indirect and depends on the absorption and emission properties of the fibres [5].

In order to predict the heat flow due to radiation through a fabric, it is necessary to know the temperature profile. The simplest assumption is a linear change in temperature with distance through the fabric which is true in case of conduction heat flow. At the edges of a fabric the situation is more complex than this, but in the centre of a thick specimen the conductivity due to radiation can be simplified as given in the following relationship [10]:

$$Radiative\ conductivity = (8\,\sigma\,T^3 R)/f\varepsilon$$

Where, σ - Stefan-Boltzmann constant (5.67 X l0^{-8}W/m^{2}K^4),
T- mean temperature between heat source and sink (K),
R - radius of fibres,
f - fractional fibre volume,
ε - thermal emissivity.

This means that the heat loss from radiation is higher at low fibre volumes (less than 5%) but is reduced by the use *of fine fibres and higher fibre volumes.*

III. HEAT TRANSPORT MEASURING APPARATUS

Various methods [5,11] are used for measuring the thermal-insulating values of clothing materials. Generally three different methods have been used in the determination of the thermal insulation of fabrics. The first is *cooling method* in which a hot body is surrounded by a fabric whose outer surface is exposed to the air, and the rate of cooling of the body is determined. Second is *disc method*, where the fabric is held between two metal plates at different temperatures, and the rate of flow of heat is measured and third is *constant temperature method*, where the fabric is wrapped around a hot body and the energy required to maintain the body at a constant temperature is found.

The thermal properties of a fabric will determine not only its warmth in wear but also how warm or cool the fabric feels when first handled. In general, the heat transport properties can be divided into two groups [13]: steady-state thermal properties such as thermal conductivity and resistance which provide the information on the warmth of a fabric; and transient-state thermal properties such as thermal absorptivity which provides the information of warm-cool feeling when fabric handled first.

In practice the measurement of the rate of heat flow in particular direction is difficult as a heater, even when supplied with a known amount of power, dissipates its heat in all directions. Most success full heat transport measuring instruments are: Togmeter [7], Guarded hot plate [8] and Alambeta instrument [9].

3.1. Togmeter

The apparatus as described in BS 4745:1971 [7] is used to determine of thermal resistance of a textile fabrics or of a fibre aggregate to the transmission of heat through in the study state condition. The principle of the apparatus is that for conductors in serious with respect to the direction of heat flow the ratio of the temperature drop across the conductors is equal to the ratio of their thermal resistance. Thus, if the temperature drop across a material of known thermal resistance (the standard resistance) and across a test specimen in series with it are measured, the thermal resistance of the test specimen can be evaluated.

The tog meter [5,7] consists of a thermostatically controlled heating plate which covered with a layer of insulating board of known thermal resistance. The temperature is measured at both faces of the standard. The heater is adjusted so that the temperature of the upper face of the standard is at skin temperature (31-35°C). A small airflow is maintained over the apparatus. There are two methods of test that can be used with the tog meter: two plate method and ii. single plate method.

In *two plate method* (Figure 1), the specimen under test is placed between the heated lower plate and an insulated top plate. The top plate has low mass so that it does not compress the fabric. The temperature is measured at the heater (T_1), between the standard and test fabric (T_2) and between the fabric and the top plate (T_3). In single plate method (Figure 2) the specimen under test is placed on the heated lower plate as above but it is left uncovered, the top plate being used to measure the air temperature (T_3).

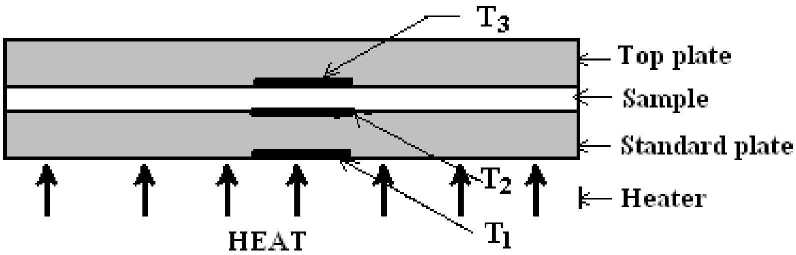

Figure 1: Togmeter: Two plate method

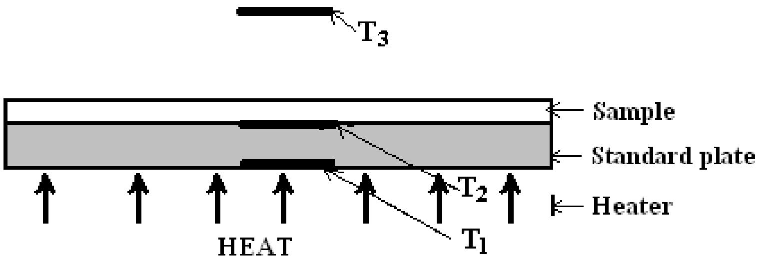

Figure 2: Togmeter: Single plate method

The air above the test specimen has a considerable thermal resistance itself so that the method is in fact measuring the sum of the specimen thermal resistance and the air thermal resistance. A separate experiment is there performed without the specimen (i.e. a bare-plate test) to measure the resistance of the air (R_{air}).

To determine the air resistance, the heater and the fan are switched on and the apparatus is allowed to reach thermal equilibrium with no specimen present. The top plate is placed underneath the apparatus shielded from radiation by a foil-covered plate, in order to measure air temperature. The temperature should remain steady at each thermocouple for 30 min. It may take some time for equilibrium to be reached. Then thermal resistance of air R_{air} can be calculated from the following equation:

$$R_{air} = R_{std} \; X \; \frac{T_2 - T_3}{T_1 - T_2}$$

To determine the sample resistance, the above experiment is repeated with the test sample placed on the bottom plate and apparatus again allowed to reach thermal equilibrium. Thermal resistance of sample is to be calculated from following equation:

$$R_{sample} = R_{std} \; X \; \frac{T_2 - T_3}{T_1 - T_2} - R_{air}$$

3.2. Guarded hot plate method

The top and side view of *guarded hot plate* [5,8] is shown in Figure 3. It is used to measure thermal transmittance, which is the reciprocal of the thermal resistance. The apparatus consist of a heated test plate surrounded by a guard ring and with a bottom plate underneath. All three plates consist of heating elements sandwiched between aluminum sheets. All the plates maintained at the same constant temperature in the range of human skin temperature (33-36°C).

With the test fabric in place the apparatus is allowed to reach equilibrium before any reading is taken. The amount of heat passing through the sample in watts per square meter is measured from the power consumption of the test plate heater. The temperature of the test plate and the air 500 mm above the test plate are measured. The measured thermal transmittance consists of the thermal transmittance of the fabric plus the thermal transmittance of the air layer above the fabric which is not negligible. The test is repeated without any fabric sample present to give to above plate transmittance.

A standard test method for thermal transmittance of textile material described in ASTM D 1518-85 (Re-approved 1990) [8]. The test method covers the determination of the overall thermal transmission coefficients due to the combined action of conduction, convection, and radiation for dry specimens of textile fabrics and other materials having thermal transmittance (U_2) within the range of 0.7 to 14 W/m^2.K and thickness not in excess of 50 mm.

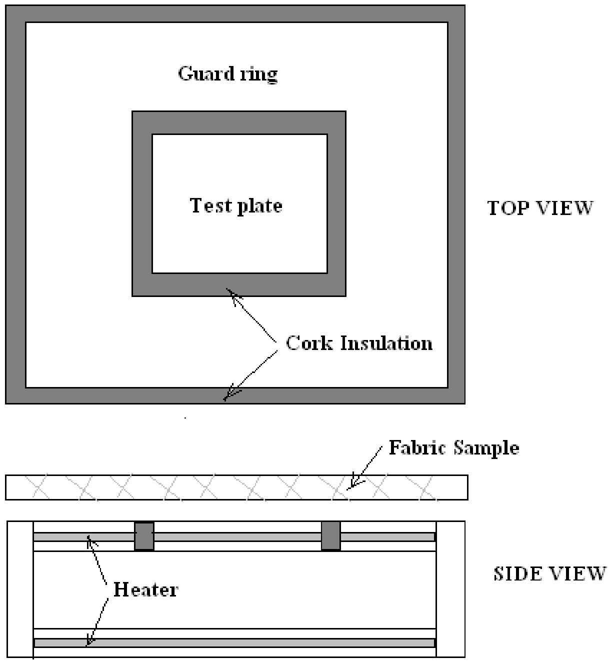

Figure 3: Guarded hotplate

Thermal conductivity and thermal resistance can be calculated with the following procedure:

1. Calculate the combined transmittance of the specimen plus the air, U_1 to within 0.005 W/ m^2.K

$$U_1 = \frac{P}{[A\ x\ (T_p - T_a)]}$$

Where, P = power loss from test plate
A = Area of test plate
T_p and T_a = Test plate temperature and air temp., °C, respectively

2. Calculate bare – plate transmittance, U_{bp}
3. Calculate the intrinsic transmittance of the fabric alone using following equation:

$$\frac{1}{U_2} = \frac{1}{U_1} - \frac{1}{U_{bp}}$$

4. Calculate the intrinsic thermal conductivity of the fabric alone, *k*, using following equation:

$$k = U_2\ x\ \frac{t_i}{1000}$$

Where, t_i = thickness of the specimen, mm, at 0.07 kPa pressure.

5. Calculate the intrinsic thermal resistance of the fabric alone, *R*, using following equation:

$$R = \frac{1}{U_2}$$

3.3. Alambeta Instrument

In practice the measurement of the rate of heat flow in particular direction is difficult as a heater, even when supplied with a known amount of power, dissipates its heat in all directions. *Togmeter* [7] and *guarded hot plate* [8] which are most commonly used for evaluation steady-state thermal insulation characteristics (mainly thermal resistance and thermal conductivity) have several disadvantages such as the length of time required for testing, the size of the samples and cumbersome sample insertion in the apparatus. In present days, the transient state characteristics of fabrics have become important. *Alambeta instrument* (Figure 4) developed at the technical university of Liberec, Czech Republic is able to determine these characteristics [9].

Alambeta measuring device is the fast measuring of transient and steady state thermo-physical properties (thermal insulation and thermal contact properties). The instrument measures the sample thickness also. The instrument consists of two measuring heads between which the test specimen is placed (Figure 4). Both measuring heads are equipped with thermocouples and so-called heat flow sensors. The lower measuring heads is adjusted to the ambient temperature by suitable cooling means; the upper, heated measuring head is adjusted to a controlled constant differential temperature. The heat flow sensors act up at the contact faces of both measuring heads. When upper measuring head is lowered on the measuring specimen the heat flow at the upper surface and the underside of the test specimen can be measured. The fundamental measuring principal implies the measuring and processing of the heat flows in dependence of time. The instrument measures six parameters: thermal conductivity, thermal diffusion *a*, thermal absorption *b*, thermal resistance *r*, the ratio of maximal to stationary heat flow density (q_{max}/q_s), and stationary heat flow density q_s at the contact point. The instrument also determine the fabric thickness [9].

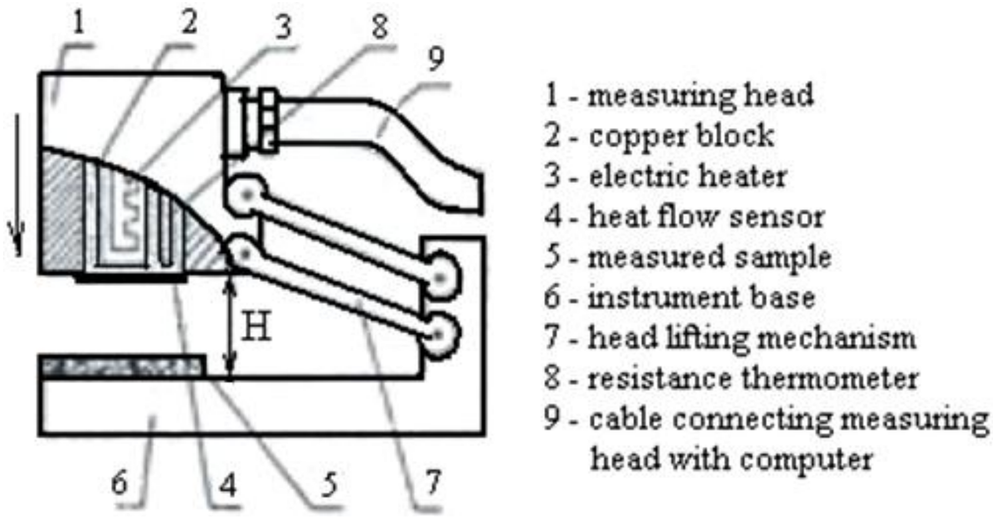

Figure 4: Functional scheme of the computer controlled *Alambeta* [9] instrument.

IV. CONCLUSION

The knowledge of heat transport and its measurement must require to all engineering fields. In the textile engineering, clothing is an important issue for general consumer, active athletes and for other sports just for fitness in their time. The fabrics which are used for above purposes must have good heat transmission properties. The objective measurement is requires for accurate results in evaluation of heat transmission properties. In various instruments, the *Alambeta instrument* found best for measuring the heat transport properties of fabrics as it the measures fast both transient and steady state thermo-physical properties (thermal insulation and thermal contact properties etc.).

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