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# MEASUREMENT OF THERMAL CONDUCTIVITY OF FABRICS

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خلاصه البحث الحالى هو دراسة لامكانية التنبؤ بمعامل التوصيل الحرارى للاقمشة المستخدمة فى القمصان. وقد أمكن التوصل الى معادله رياضية للتنبؤ بخاصية الدفىء فى الاقمشة وذلك بواسطة استخدام موديل هندسى لربط معامل التوصيل الحرارى للقماش مع نسبة تغطية الخيوط المكونه له. من ناحية اخرى فان القياسات العمليةلمعامل التوصيل الحرارى للقماش قد أمكن الحصول عليها بواسطة استحداث جهاز بسيط اسطوانى الشكل حيث يمثل الى حد كبير ذراع الانسان. وهذا الجهاز قد تم انشاؤه بواسطة الباحث. النتائج المحسوبه بواسطة المعادله النظريه التى قد تم التوصل اليها وجد أنها قريبة الى حد كبير من النتائج العملية المقاسة على الجهاز السابق الذكر. هكذا من الدراسة السابقة امكن التنبؤ بسلوك الدفىء (معامل التوصيل الحرارى) فى اقمشة القمصان وذلك بمعرفة نسبة تغطية الخيوط فى القماش والمادة الخام للخيوط أو معامل التوصيل الحرارى للخيوط.

ABSTRACT- The present investigation deals with the study of thermal conductivity of fabrics used for shirts. A mathematical approach on a geometrical model is attempted to relate the fabric thermal conductivity to its cover ratio. Experimental results were obtained by using a new simplified apparatus in the form of a cylinderical shape of heat source closely represents a human arm. The derived relation was found to be farily close to those observed experimentally.

## 1. INTRODUCTION

The number and size of the air spaces per unit area in a fabric greatly affect its thermal properties. Although-in general-fibres themselves are not good heat insulators the air spaces trapped by the fibres and yarns are very efficient heat insulators provided that, air is not in motion. As the thermal property of a fabric is its ability to resist or permit heat transmition through its thickness, it must be related to porosity and air permeability [1].

Previons work [2-6] on the subject of heat transmition through fabrics has concerned with the type of fibres, yarn parameters, fabric construction, fabric weight, density and thickness and very little work has been done on the effect of the yarn thermal conductivity, fabric prosity or cover ratio for predicting fabric thermal conductivity.

The object of this paper is to fill this gap and to design a new simplified apparatus to investigate the important factors influencing the fabric warmth property in terms of its thermal conductivity.

## 2. EXPERIMENTAL WORK

### 2.1. Fabrics

Measurements of warmth property were made on seven different shirt fabrics, represent the range which is commercially available in Egypt in winter 1985. The characteristics of these fabrics are given in Table 1.

Table 1

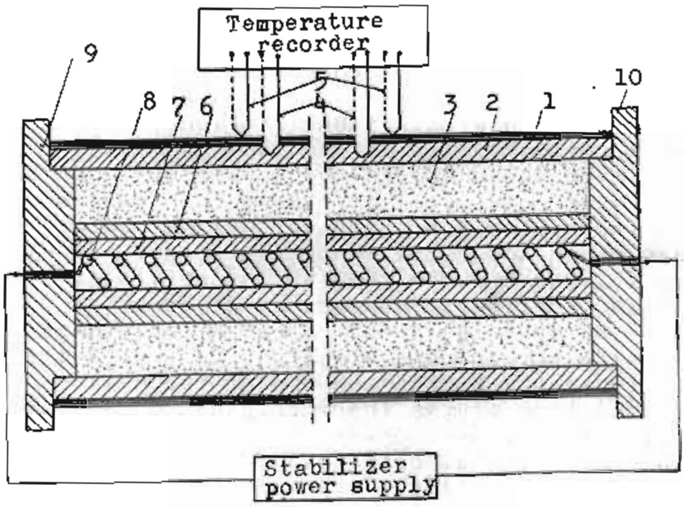
. Fabric Characteristics

| Fabric Sample | Type of Material | | Linear Density (tex) | | Threads/10 cm, n | | Fabric Weight $(g/m^2)$ | Fabric Thickness (mm) | Fabric Density $(g/cm^3)$ |
|---|---|---|---|---|---|---|---|---|---|
| | Warp | Weft | Warp | Weft | Warp | Weft | | | |
| 1 | 100 %C* | 100 %C | 23 | 25 | 450 | 200 | 160 | 0.328 | 0.4878 |
| 2 | 42%P*/58%C | 47%P/53%C | 32 | 29 | 230 | 210 | 151 | 0.298 | 0.5067 |
| 3 | 100 %C | 100 %C | 15x2 | 29 | 250 | 230 | 143 | 0.258 | 0.5543 |
| 4 | 68%P/32%C | 52%P/48%C | 19 | 23 | 280 | 280 | 126 | 0.236 | 0.5339 |
| 5 | 31%P/69%C | 90%P/10%C | 15 | 10 | 350 | 350 | 119 | 0.204 | 0.5833 |
| 6 | 56%P/44%C | 56%P/44%C | 15 | 24 | 320 | 270 | 112 | 0.172 | 0.6510 |
| 7 | 68%P/32%C | 63%P/37%C | 14 | 14 | 370 | 230 | 94 | 0.130 | 0.7230 |

* C = Cotton Fibres. * P = Polyester fibers.

### 2.2. Apparatus Used For Testing Fabric Thermal Conductivity:

The apparatus used was established by the author as illustrated in Figures 1,2 and 3 which consists of a copper cylinder (2) (4.45 cm in diameter and 100 cm in length) provided with an inner heat source made of a nikel chrome wire heater (8) of 325 ohm resistance. The temperature of cylinder surface was determined by means of temperature recorder connected to two copper constantan thermocouples (4) attached to the cylinder surface at its middle. The inner heat source was insulated by beeds of china (7) and laid into an aluminium tube(6), where the gap in between the two tubes was filled with dry sand (3) in order to distribute regularly the heat along the perimeter of the cylinder. The cylinder sides were firmly closed by two Teflon disks (9, 10) to decrease heat loss through the cylinder sides. The insulated heater was connected to an electrical stabilized power supply (Fig.2) which can control properly the cylinder surface temperature in a range of 32°C to 33 °C by means of changing the circuit input voltage (autotransformer). The apparatus was supported horizontally, to eliminate the effect of cylinder length on the heat distribution along the cylinder.



1. Fabric specimen
2. Copper cylinder
3. Dry sand
4&5. Two pairs of thermocouple
6. Aluminium tube
7. Beeds of china
8. Wire heater
9&10. Two Teflon disks.

Fig. 1
Schematic diagram showing constructional details of the apparatus.

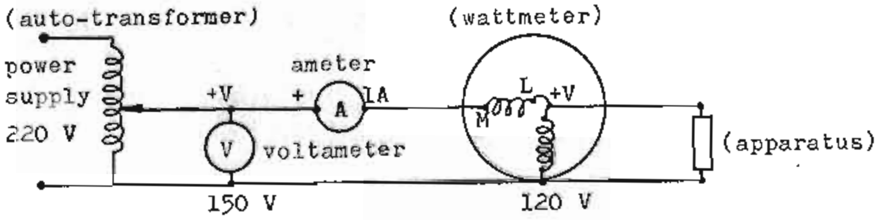


Fig. 2
Circuit diagram of the apparatus.

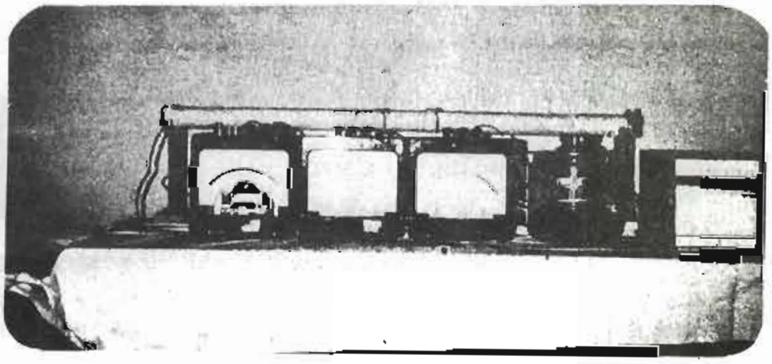


Fig. 3
Over-all view of the apparatus.

## 2.3. Test Method

Specimens of 100 Cm length and 15.2 Cm width were cut parallel to either warp or weft directions. Two small holes - 10 Cm apart from each other - were made in the specimen middle along its length, in order to permit passing the cylinder thermocomples wiring (4). One layer of the fabric specimen (1) was firmly wound around the copper cylinder in a way so that the two fabric small holes will be facing the connection positions of the cylinder thermocouples, to avoid any wiring contact with the cylinder surface and hence any false temperature reading. A second pair of thermocouples (5) was stuk to the fabric surface at the same two positions for measuring the fabric surface temperature.
As the copper cylinder is considered to be a hot object with respect to the surrounding air the rising air streams will tend to make a slight temperature difference between the bottom and top of the cylinder. Therefore, the most suitable position of the thermocouples (4,5) will be at the middle of the intersection lines between the cylinder surface and the horizontal plane which contains the cylinder axis. By means of an auto-transformer the input voltage was controlled (32% of 220 Volts) so that the cylinder surface temperature will be in a range of 32 $^oC$ to 33 $^oC$. When temperature steady state was reached the cylinder temperature ($t_1$), and the fabric surface temperature ($t_2$) were recorded and so the temperature gradient $\Delta t = t_1 - t_2$ could be calculated. The power consumed to compensate heat losses from both the cylinder and fabric could be measured by means of an ordinary wattmeter (Fig. 2). Therefore, the fabric thermal conductivity $\lambda_f$ could be calculated [7] by the following Equation:

$$\lambda_f = \frac{Q.Ln(r_o/r_i)}{2\pi\ L\ \Delta t}\ ,\ watt/(m.^oC) \quad ......(1)$$

where, Q- heat flow through cylinderical fabric sample, watt;
L- cylinder length, meter; $\Delta t$- temperature gradient, $^oC$ and
$r_o, r_i$- the outer and inner radius of the sample respectively, mm.

Because of $(r_o/r_i) = 1.0104$ in our case, Equation (1) can be rewritten in the following form [7]:

$$\lambda_f = \frac{Q\ (r_o - r_i)}{2\pi\ rm\ L.\Delta t}\ ,\ watt/(m.^oC).$$

where $rm = \frac{r_o + r_i}{2}$

Five tests were carried out in each case and the average value is obtained.

## 3. MATHEMATICAL PREDICTION OF FABRIC THERMAL CONDUCTIVITY

The study of heat flow from the human body to the surrounding atmosphere through a fabric or the reverse could be made by considering the model shown in Fig. 4

The total heat flow through a unit fabric structural element ABCD (Fig. 4) will be equal to the sum of heat flow through the yarns and air space.

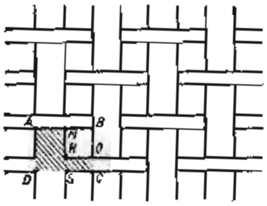


Fig. 4

Geometrical model of cloth cover

Therefore, $Q_f = Q_y + Q_a$, ......(2)

$$\frac{\lambda_f A_f \Delta t_f}{\delta_f} = \frac{\lambda_y A_y \Delta t_y}{\delta_y} + \frac{\lambda_a A_a \Delta t_a}{\delta_a}, \qquad ......(3)$$

Where $Q_f$, $Q_y$, $Q_a$ - heat flow transmitted through fabric, yarn and air space respectively, watt; $\lambda f$, $\lambda y$, $\lambda a$ - thermal conductivity of fabric, yarn and air space, watt/(m.$^o$C); $\Delta t_f$, $\Delta t_y$, $\Delta t_a$ - temperature difference between the two sides of the fabric, yarn and air space respectively, degree centigrade; $\delta_f$, $\delta_y$, $\delta_a$ - thickness of fabric, yarn and air space respectively, metre.

Assuming that fabric thickness = yarn thickness = air space thickness = $\delta$ and temperature difference between the two sides of the fabric, yarn and air space are equal $\Delta t$.

Then, $\lambda_f A_f = \lambda_y A_y + \lambda_a A_a$ ......(4)

$$\lambda_f A_f = \lambda_{warp} \text{ (area AMSD)} + \lambda_{weft} \text{ (area HOCS)} + \lambda_a A_a \qquad ...(5)$$

Assuming also that, thermal conductivity of both warp and weft yarns are equal $\lambda_y$ and that the total area of yarns $A_t = A_{warp} + A_{weft}$ = AMHOCD. Hence, from Equations (4) and (5):

$$\lambda_f A_f = \lambda_y A_t + \lambda_a A_a \qquad ......(6)$$

$$\therefore \lambda_f = \lambda_y \left(\frac{\text{area AMHOCD}}{\text{area ABCD}}\right) + \lambda_a \left(1 - \frac{\text{area AMHOCD}}{\text{area ABCD}}\right) \qquad ......(7)$$

$$\text{But } \frac{\text{area AMHOCD}}{\text{area ABCD}} = \text{Cover ratio (Kc)} \qquad ......(8)$$

and, from Equations (7) and (8):

$$\lambda_f = \lambda_y Kc + \lambda_a (1-Kc), \qquad ......(9)$$

where $\lambda_a$ = 0.02 watt/(m.$^o$C) - thermal conductivity of air.

The fabric thermal conductivity-cover ratio relation of shirt fabrics is thus given by Equation(9). Fig. 5 shows this relation at different values of $\lambda_y$. Actual values of the yarn thermal conductivity ($\lambda_y$) could be calculated [8] from the following Equation:

$$\lambda_y = \lambda_D \left[ C \frac{2(1-C)}{C} - \nu (1-C)^2 \right], \qquad .....(10)$$

where $\lambda_D$ = 0.049 watt/(m.$^oC$)-average thermal conductivity of the different textile fibres in the dry state [9];

$C = \cos(\varnothing/3) - 0.143$; $\varnothing = \arc\cos(1-m_2)$; $m_2 = (1-m_1)$;

where $m_2$ - ratio of air to yarn volume; $m_1 = \gamma_1/\gamma$;

where $\gamma_1$ - yarns density, g/Cm$^3$; $\gamma$ -fibres density, g/Cm$^3$.

and $\nu = \lambda_3/\lambda_D = 0.62/0.049 = 12.65$,

where $\lambda_3$ = 0.62 watt/(m.$^oC$)-thermal conductivity of water.

The actual yarn thermal conductivity ($\lambda_y$) could be calculated according to Equation (10) by finding out the average fibre density ($\gamma$) and the yarn density ($\gamma_1$) using the blend ratio and the ratio of warp and weft yarns weight to the fabric weight.

## 4. ILLUSTRATION

The first term of Equation (9) ($\lambda_y$ Kc) for different values of $\lambda_y$ in addition to the second term $\lambda_a$ (1-Kc) are both illustrated in Fig. 5 versus cover ratio (Kc), the two terms could refere to the effect of yarn conductivity (broken lines) and air space conductivity (dotted lines) respectively. The sum of the two terms gives the total fabric thermal conductivity $\lambda_f$ (full straight lines). The slope of these full lines depends on the yarn thermal conductivity $\lambda_y$. Fig. 5 shows that, any increase in the value of cover ratio results in a steady increase in fabric thermal conductivity because as surface porosity (1-Kc) decreases, entrapped air spaces are being replaced by more equipped yarns until Kc = 1 where $\lambda_f = \lambda_y$. Minimum fabric thermal conductivity could be observed at Kc = 0. This graph could be practically useful in predicting the thermal conductivity of shirt fabrics of different fibre composition and cover ratio values.

## 5. COMPARISON BETWEEN PREDICTED AND EXPERIMENTAL RESULTS

From both $\lambda_y$ and Kc, fabric thermal conductivity ($\lambda_f$) could be calculated using Equation (9). The results are listed in Table II. Fig. 6 shows both measured and calculated values for the seven different fabrics given in Table I. It can be seen that the nature of the variation of fabric thermal conductivity with cover ratio simulates closely that calculated in Fig. 5 for ($\lambda_y$ = 0.04 watt/(m.$^oC$).

The theoretical relation obtained in the work discussed in this paper can be therefore considered to agree fairly close with the obtained experimental results, however the exact nature of the relation may vary depending on the yarn thermal conductivity.

Table II
Fabric Thermal Conductivity of Shirt Fabrics
( calculated and measured )

| Fabric Sample | Type of Material |  | $\gamma$ | $\gamma_1$ | $\lambda_y$ | Kc* | $\lambda_f$ ( watt/m.°c ) | $\lambda_f$ ( watt/m.°c ) |
|---|---|---|---|---|---|---|---|---|
|  | Warp | Weft | ( g/ cm³) | ( g/ cm³) | ( watt/m.°c ) |  | calculated | measured |
| 1 | 100 % C | 100 % C | 1.54 | 0.9 | 0.03998 | 0.8829 | 0.0376 | 0.03811 |
| 2 | 42%P/58% | 47%P/53%C | 1.4711 | 0.9129 | 0.04060 | 0.7032 | 0.0345 | 0.03614 |
| 3 | 100 % C | 100 % C | 1.54 | 0.9 | 0.03998 | 0.7411 | 0.0348 | 0.03430 |
| 4 | 68%P/32%C | 52%P/48%C | 1.4489 | 0.9171 | 0.04080 | 0.7279 | 0.0351 | 0.03304 |
| 5 | 31%P/69%C | 90%P/10%C | 1.4383 | 0.9187 | 0.04090 | 0.7097 | 0.0348 | 0.03431 |
| 6 | 56%P/44%C | 56%P/44%C | 1.4532 | 0.9163 | 0.04076 | 0.7274 | 0.0351 | 0.03527 |
| 7 | 68%P/32%C | 63%P/37%C | 1.4379 | 0.9193 | 0.04091 | 0.6708 | 0.0340 | 0.03463 |

* Cover ratio calculated as 0.01 d1n1 + 0.01 d2n2 - 0.0001 d1n1d2n2, where n1 = ends/10 cm, $n_2$ = picks/10 cm, $d_1$ = diameter of warp threads, mm, and $d_2$ = diameter of weft threads, mm.

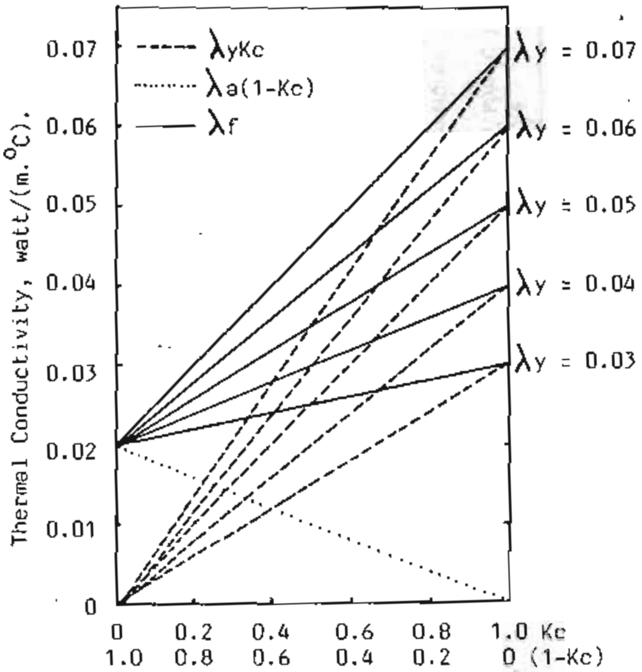


Fig.5

Change of fabric thermal conductivity with cover ratio.

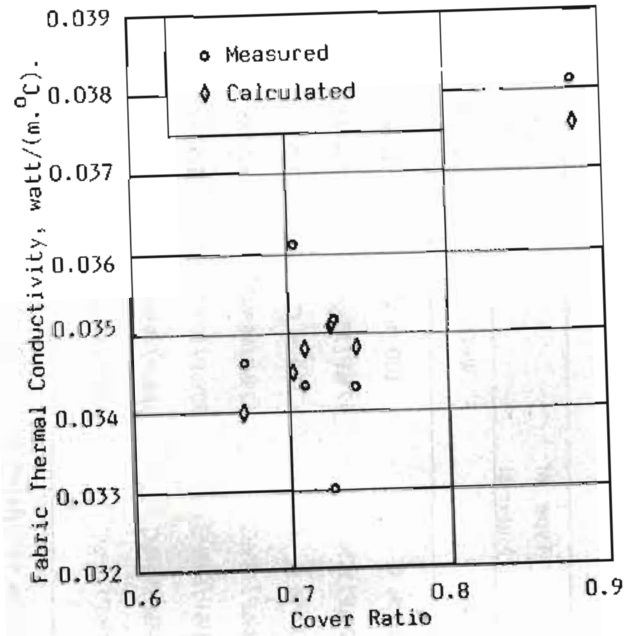


Fig.6

Measured and calculated values of fabric thermal conductivity against fabric cover ratio.

## 6. CONCLUSION

In spite of the important effect of the fabric thermal properties on its end use, there is no agreement-until now-on a certain experimental apparatus or test for measuring thermal conductivity of cylinderical fabric samples.

In this paper a new simple and still efficient apparatus was established by the author on the basis of the constancy of heat flow transmitted from a heating element through a piece of fabric (steady state method). At the same time the thermal conductivity was calculated for a geometrical model of a fabric, by means of knowing the fabric cover ratio and the yarn thermal conductivity, the latter could be predicted [8] by means of knowing fibre and yarn densities.

The comparison between both calculated and measured values was then possible. The good agreement shown by Table II and Fig. 6 supports the validity of the derived Equation (9) at least within the range of material and fabric characteristics used.

From such study a good prediction of fabric thermal conductivity could be calculated by means of knowing its cover ratio and yarn thermal conductivity (Equation 9).

Such study needs to be extended to include wider range of fabric characteristics so that the derived equation could be generalized or modified.

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