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Comfort Properties of Textiles

by

K. Slater, M.Sc., Ph.D., F.T.I.

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TEXTILE PROGRESS

COMFORT PROPERTIES OF TEXTILES

By K. Slater, M.Sc., Ph.D., F.T.I.

1. GENERAL ASPECTS OF COMFORT

1.1 The Meaning of Comfort

The term 'comfort' is a nebulous one, which defies definition, but the sensation of comfort is easily recognized by the person experiencing it. Many attempts have been made, without success as yet, to define the state in physical terms. Bekesius[1] has surveyed the literature and quotes such definitions as 'the absence of unpleasantness or discomfort' or 'a neutral state compared to the more active state of pleasure' originally made by authors over twenty years earlier. Fourt and Hollies[2] carried out an even more extensive survey, incorporating all the literature relating to comfort that they could find, and again did not provide an objective definition of comfort. Rodwell *et al.*[3] state that comfort is influenced by the physiological reactions of the wearer, but Yaglou[4] suggests that a satisfactory physical definition will never be achieved because such a definition is not possible.

Despite this pessimism, the subject has aroused much interest in recent years, and several authors have attempted to connect comfort with clothing. There is general agreement that the movement of heat and water vapour through a garment are probably the most important factors in clothing comfort, and Rees[5] describes the temperature regulation of the body in order to define the system in which comfort must be maintained. Greenwood[6] approaches the problem of describing comfort by attempting to provide a common language, understood by textile producers, physiologists, and users, which includes clear definitions of terms used in measurement, units quoted with test results, conditions of use, and measures of comfort performance obtained. Kemp[7] examines the reasons why clothing is bought, in an attempt to summarize the practical attitudes of individuals to garment comfort, and Renbourn[8] carries out a similar examination from a psychological point of view. Dayal[9] summarizes the problems encountered in trying to make clothing attractive and comfortable simultaneously, and Hollies[10] stresses the importance of 'contact comfort' in dealing with a clothing system. Best-Gordon[11] attempts to relate fibre type and fabric construction to comfort, but his discussion is presented only in the most general terms. Fanger[12] discusses the effect of physiological and environmental conditions on comfort in an attempt to define comfort in clinical terms.

There is, however, fairly widespread agreement on two facts in the body of literature on comfort. The first of these, which will be discussed in due course, clearly identifies a satisfactory thermal equilibrium as the most important single comfort criterion for modern man. Secondly, it is obvious that, notwithstanding this predominance, the state of comfort can only be achieved when the most complex interactions between a range of physiological, psychological, and physical factors have taken place in a satisfactory manner. It is possible to examine these subjective and objective factors independently in some detail.

1.2 Physiological and Psychological Aspects of Comfort

In addition to the work already quoted above, other reports dealing with subjective comfort factors have appeared. Kostrz[13] discusses the physiological effects of such climatic variables as temperature, relative humidity, and air movement on a body situated in the particular conditions studied. Welfers[14] surveys the effect of clothing factors, particularly fabric geometry, pore volume, and enclosed-air content, on physiological, as well as physical, parameters. Wichfeld[15] discusses the factors involved in deciding garment

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comfort and reports a subjective ranking trial based on an assessment of individual properties. Shohji and Mizunashi[16] issued a questionnaire to consumers in an attempt to identify motivation in selecting a garment. In analysing their results, they classify answers according to age or sex of the subject, district, season, and garment class in order to identify any specific trends. Bekesius[17] carries out a more comprehensive survey of a similar type, in which consumers are asked to rate the comfort factors of stretch, absorbency, fibre type, thickness, texture, weight, breathability, and fit in order of importance for purchase, satisfaction, and comfort criteria of a range of garments. Her exhaustive analysis of environmental, economic, educational, and other demographic factors reveals no strongly consistent trends in the preferences of the respondents. Denton[18] concentrates on the effect of garment fit on comfort and examines in detail the relationship between body location and fabric movement by extension or slip. Vokac, Køpke, and Keül[19] report experiments in which the thermal comfort of subjects dressed in ski clothing is assessed both subjectively and objectively, their observations demonstrating that the peripheral parts of the body play an important (and previously unrecognized) rôle in maintaining a general feeling of comfort.

Finally, three examples of testing related to practical performance should suffice to represent the type of application for which these matters are important. Bolton and Simpson[20] report an investigation of materials for use in jungle and desert conditions. A range of fabrics is used, and physical factors relating to wear life are tested in conjunction with subjective evaluation in simulated extreme climatic conditions. Gilling[21] discusses the factors to be considered in carrying out physiological testing with human subjects and gives the results of field trials of rain-protective garments of different types. In a different area, Czelny[22] examines the contribution made by textile materials to the comfort of a vehicle driver, with particular reference to seat-covering materials and automobile carpets.

1.3 Physical Aspects of Comfort

It is in this area, of course, that objective testing can most easily be carried out. Rees[23] summarizes the physical factors determining the comfort performance of textiles and concludes that heat transfer between man and his environment, together with the movement of moisture for insensible heat transfer, constitutes the major comfort-maintaining mechanism. Crockford[24] points out that conflicting requirements for comfort may frequently occur and uses as an example the needs of a trawler fisherman with regard to protective clothing at sea. Kerslake[25] discusses the comfort requirements of different areas of the body with particular reference to thermal factors and provides a rough quantitative estimate of the local needs. Van Rensburg *et al.*[26] suggest the use of microclimate conditioning, in the form of a water-cooled vest and pre-frozen jacket, in restoring to a normal level the working ability of men exposed to conditions of heat that are normally enervating. Goldman[27] reports a comprehensive survey of the mechanisms of heat transer. in such conditions and relates his results to the performance of clothing during field trials Similar work in the area is to be reported in a later section.

Vokac, Køpke, and Keül[28] carry out an evaluation of clothing comfort in ski clothes and attempt to relate the water balance of their subjects to the thermal resistance, water-vapour resistance, air permeability, and moisture-holding ability of the garments worn. In a later paper, they describe an attempt to separate quantitatively the effects of forced air exchange and thermal or moisture gradients in determining the flow of heat and water between the body and the environment[29]. The same authors[30] subsequently carry out a more extensive investigation of the physiological changes occurring during activity and obtain relations between skin temperature, microclimate within the clothing system, and subjective evaluations of thermal, humidity, and comfort sensations. Hole and Keech[31], in an investigation of the comfort properties of shoe materials, include water-vapour absorption and permeability, elastic moduli, thermal conductivity, shape stability, water-penetration resistance, wind-resistance, and abrasion-resistance in their list of relevant physical

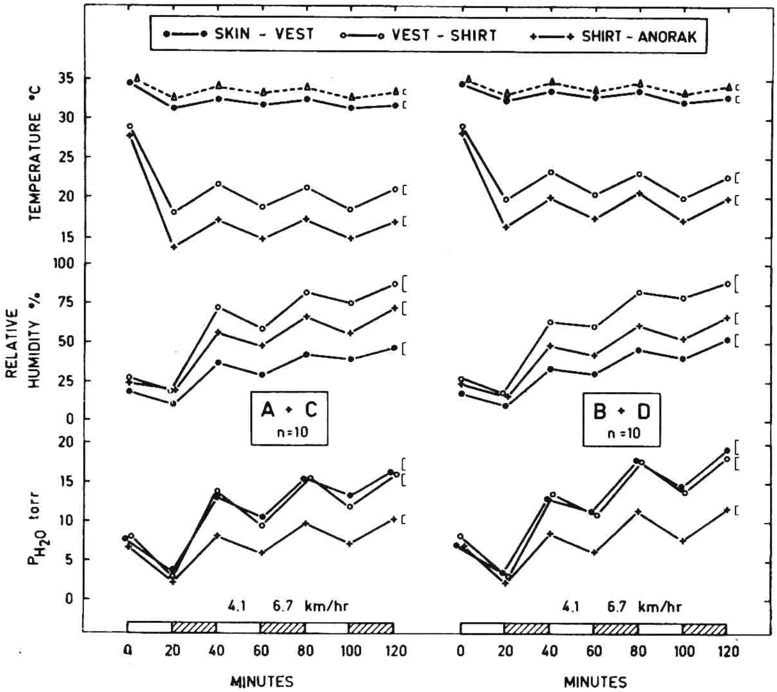

Fig. 1
Temperature, relative humidity, and partial pressure of water vapour in spaces between the skin of the back and vest, between the vest and shirt, and between the shirt and anorak; mean and average standard error of the mean (denoted by [) in experiments A, C (woven dress) and B, D (knitted dress); broken line: skin temperature of the back (from Vokac, Køpke, and Keül[28])

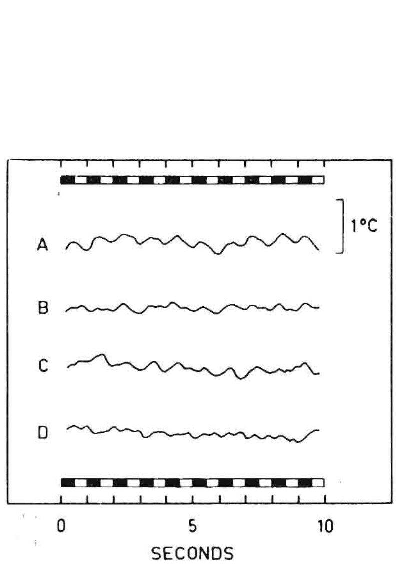

Fig. 2
Continuous recordings of periodic changes of air temperature next to the skin of the back; alternating black and white rectangles indicate the frequency of steps (2/sec) (from Vokac, Køpke, and Keül[29])

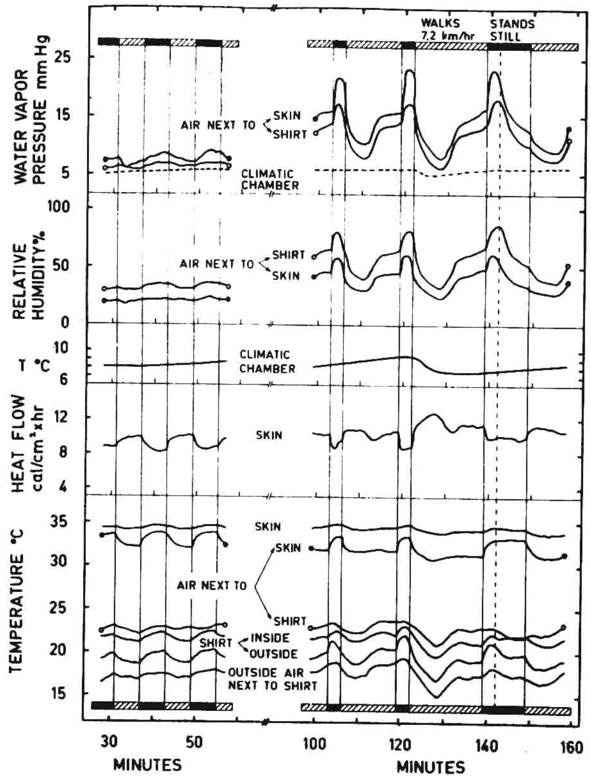

Fig. 3
Variation in selected comfort properties with time (from Vokac, Køpke, and Keül[29])

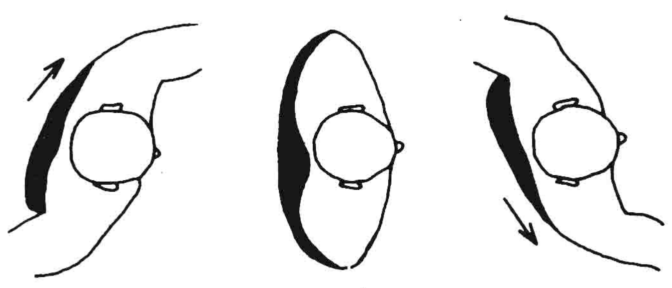

Fig. 4
Suggested scheme of the mechanism of bellows ventilation of the back in walking (from Vokac, Køpke, and Keül[29])

properties. Although shoe uppers are a little outside the normal range of textile materials, it is easy to visualize the pertinence of such properties in the comfort behaviour of other parts of the clothing system. Rangan, Chatterji, and Nadkarni[32] include strength, crease-retention, and cost, in addition to more conventional properties, in an assessment of comfort and conclude that, for service uniforms, a high polyester-fibre proportion (in a blend with cotton) gives optimum performance characteristics. Muminov, Shchenkov, and Khamraeva[33] carry out a statistical analysis of the correlations existing between each of an extensive range of properties that have all been used to assess the suitability of fabrics for wear in hot, dry weather. Their aim is to reduce the number of tests needed to establish a fabric's performance, and they conclude that porosity and total moisture permeability are the two most critical factors.

Comfort aspects of a different kind are considered by other workers. Feather[34] reviews the attempts to assess the walking comfort of floor-coverings, and Herzog[35] studies the contribution of the backing material in this respect. Ainsworth[36] examines the conflicting requirements imposed by chemically protective clothing, which must simultaneously provide a barrier against a wide range of harmful, reactive materials and yet allow the wearer to remain comfortable enough to continue to function. Hackenburg *et al.*[37] investigate the comfort requirements peculiar to swimwear, with emphasis on drying capacity, skin adaptability, fit, the adhesion of sand, and the effect of the garment on air or water-vapour circulation about the body.

It is obvious, then, that comfort involves a complex combination of properties, both subjective and physical. There is general agreement that the movements of heat, moisture, and air through a fabric are the major factors governing comfort, but some of the subjective factors, such as size, fit, and aesthetic behaviour (softness, handle, and drape, for example) are obviously very important in the textile field. In addition, other factors, such as the generation of static electricity and the control of noise, are closely connected with textile use and should not be ignored. It is the purpose of this issue to review recent work carried out in each of these areas, in so far as it pertains to comfort. In order to avoid unnecessary duplication, developments reviewed in other issues of *Textile Progress* will be avoided as far as possible, unless their treatment elsewhere has not emphasized sufficiently any important aspect related to comfort.

2. THERMAL PROPERTIES AND COMFORT

2.1 Thermal Comfort

The fact that the body temperature is the most critical factor in deciding comfort means that we must examine more closely the mechanisms by which textile fabrics assist or hinder the maintenance of a uniform temperature in the body that they enclose. Fahmy[38] has surveyed the literature concerning body-temperature regulation and finds good agreement between authors on the mechanism employed. Heat is gained by the body from the sun (or intermediate sources of energy indirectly deriving their fuel ability from it), by internal metabolism, by physical exercise, or by involuntary contractions of skeletal muscles in shivering. Heat loss, by conduction, convection, or radiation, depends partly on the temperature gradient between skin and environment, and this gradient is modified by varying the skin temperature. Blood flow near, and evaporation from, the body surface control the skin temperature, and one function of clothing is the support of these processes. Excessive heat may be dissipated rapidly by vaporization of body water, the body being used as a source of latent heat for the purpose, and clothing systems that hinder free evaporation to any appreciable extent will thus be uncomfortable. On the other hand, undesirable heat loss can be prevented by increasing the thermal resistance of the barrier between the body and its environment, and a fabric with a low resistance will again result in discomfort for the wearer.

Fanger[39] reviews the existing knowledge regarding the conditions for thermal comfort and attempts to relate physical, physiological, and environmental factors. He illustrates comfort criteria diagrammatically and discusses the effect of such factors as age, sex, adaptation, season, and heat-flow conditions on comfort. In an earlier book, he also attempts to integrate the various disciplines that have traditionally been involved in the study of comfort[40]. Clark[41] concentrates his attention on the physical conditions existing next to the skin surface and uses infra-red thermography to demonstrate temperature variations over the body in the presence and absence of clothing. In the nude body, an envelope of warm air moves by convection upwards around the body surface and facilitates heat exchange, by convection or evaporation, with the surrounding environment. The presence of clothing interferes with the freedom of this process and thus modifies the amount and rate of heat loss in a complex manner.

Hackenberg[42] suggests that the ambient air temperature is the dominant influence in determining the skin temperature and that, at low temperatures, clothing is essential for the regulatory process because the body does not have the ability to continue compensating for heat loss under these conditions. He also points out that, in addition to preventing undue heat loss, winter clothing must also allow the escape of surplus heat or moisture when this is necessary. Harris[43] gives a way of estimating the heat stress experienced by workers under light, moderate, or heavy conditions of work and recommends suitable exposure limits for each case. Thermal comfort is discussed by an author who also relates the performance of various types of clothing to the ambient climate and the work carried out when it is being worn[44]. The ways in which the microclimate within clothing can vary, and the resultant effect on comfort, are discussed by other authors[45–48], estimates of the changes in thermal or moisture conditions being attempted in some way in each case.

Attempts to use clothing-construction factors to modify the microclimate are made by some workers. Forced heat exchange, by using air- or water-cooled suits[49], flexible tubing in the linings[50, 51], solid-carbon-dioxide heat sinks[52], or pre-frozen jackets[53], is credited with varying degrees of success. Van Rensburg *et al.*[53] claim that a water-cooled vest provides such a large degree of protection that its use is equivalent to removal of the entire heat stress, whereas Miura *et al.*[52] report only marginal changes in thermal stress with a dry-ice heat sink covering 800–900 cm^2 of the back and chest. They suggest that the failure of their attempt to demonstrate stress reduction may be caused by the design of their heat sink. A somewhat different approach, with a more limited effectiveness, is suggested by Hansen[54], who used a fabric containing hollow inflatable elements filled with a gas and a solvent material. In cold conditions, the solvent solidifies and expels the gas, and the hollow elements inflate, which thus increases the thermal insulation of the fabric. In theory, this mechanism is a useful one from the point of view of thermal comfort, but loss of gas pressure by diffusion processes will presumably nullify the effectiveness of the change over a period of time. A metallizing process is also reported[55], with the claim that the coating imparts extremely high insulation properties to the fabric. Uses of the technique in clothing and camping applications are suggested, but the scientific evidence on which the claims are based does not yet seem to have been published.

A point that does not appear to have received sufficient attention is, however, brought to light by McIntyre and Griffiths[56]. They expose several subjects to cool temperatures, with increasing amounts of heat insulation in the form of added clothing, and ask for ratings of warmth and comfort. Although warmth increases with added insulation, discomfort remains constant, because the coldness of the subjects' feet is unaffected by the type of clothing (typically sweaters) used in increasing body warmth.

2.2 Heat Transfer

The resistance that a fabric offers to the movement of heat through it is obviously of critical importance to its thermal comfort. Dul'nev and Muratova[57] discuss heat-transfer processes in fibrous materials and derive formulae from which effective thermal conductivity can be calculated from thermal, geometrical, and volumetric parameters of the components. Yankelevich[58–61] provides a series of papers on the subject, dealing with the heat-transfer process and the effect of air layers and of wind; he then gives details of a method of calculating the thermal-insulating properties of garments during wear. He regards the total thermal resistance to transfer of heat from the body to the surrounding air as the sum of three parameters, these being the thermal resistance to transfer of heat from the surface of the material, the thermal resistance of the clothing material, and the thermal resistance of the air interlayer. He gives an expression for the sum of the first two of these factors, which takes into account the movement of air through the material, and a second one for the rate of 'filtration' of air through the clothing assembly for a given wind speed. He goes on to provide a mathematical treatment of the process of air movement through clothing and examines the thermal resistance of the air layers with and without the filtration effect. His theoretical results agree well with experimental data obtained by earlier workers. At a later stage, he finds that the filtration process occurs as a result of the difference in dynamic pressures on the clothing surface and that the effect is significantly greater with an air layer below the material than when clothing is tight-fitting. In calculating heat-insulating properties during wear, he takes account of such factors as air permeability and wind speed, as well as the thermal resistance of the garments.

Mitu and Potoran[62] use formulae derived by earlier workers for calculating the thermal resistance of clothing to determine a series of values of this property that represent acceptable comfort limits for the human body when engaged in lying, sitting, walking, running, and other such activities. In a later paper, Mitu[63] examines the method of calculating clothing thermal-insulation properties and uses thermodynamic principles to relate the internal energy of the system, the heat exchange with the environment, and the mechanical work performed by the system.

Methods of measuring heat transfer are devised by several authors in the recent literature. Prokop[64] uses hot and cold discs separated by his test samples, but Shinkai *et al.*[65] note an anomalous negative value in a similar test as a result of a difference between the emission coefficients of the apparatus and the textile material and cast some doubt on the validity of the technique. Jokl and Stverak[66] determine the heat-resistance of clothing by means of a water calorimeter formed in the shape of the human body, so that the effect of changes in garment style can be assessed. Sukharev and Haase[67] describe two instruments, one measuring several thermal properties, such as resistance or conductivity, thermal activity, and resistance to temperature change, and the other measuring total thermal resistance under convection conditions with a layer of air present beneath the fabric sample. Deli and Durante[68] use a leather-covered cylinder as heat source, cover it with a test sample, and then measure the energy necessary to maintain a constant temperature difference between the cylinder and the ambient temperature of the controlled environment in which the equipment is placed. Zamotaev[69] describes a semi-automatic device in which a recording is made of the temperature difference between two elements when stable conditions are reached, this state being indicated automatically. Buzanov and Sukharev[70] give details of the construction of a bicalorimeter that acts in conjunction with a device for recording moisture content, which thus enables measurements to be made under conditions more closely resembling practical ones. Karlina, Voinov, and Tret'yakova[71] carry this principle a stage further by using temperature sensors at various points on the clothing system of an actual person to provide data on heat flow. Taylor[72], in an article dealing with the properties of blankets, includes an explanation of the methods of measuring their heat insulation.

It is obvious that heat transfer through a fabric is a complex phenomenon affected by many factors, and several of these have been examined by research workers in recent years. The three major factors in normal fabrics appear to be thickness, enclosed still air, and external air movement, and all three are discussed by Yankelevich[73]. He points out that these three properties distinguish air-permeable assemblies from hermetic ones, and his results indicate that, with increasing air permeability, a reduction in thermal resistance takes place once a threshold value, which he terms the limit of a hermetic state, has been reached. He states that this reduction is more intense for a thick assembly than for a thin one and that the intensity of the reduction increases as the wind speed increases. At higher levels of air permeability, after the beginning of what Yankelevich terms the *lattice region*, thermal resistance begins to depend only on air permeability for a given wind speed,

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whereas, for air permeabilities below this critical value, an increase in thickness brings about an increase in thermal resistance. In a later paper, the same author[74] attempts to isolate the effect of an included air layer within clothing assemblies by maintaining a constant, unidirectional wind force throughout the measurement. He shows that heat transfer associated with air filtration is considerably greater when no air layer is present, a result in agreement with empirical ideas of the insulating effects of dead air space. He also shows that the difference in thermal resistance does not depend on the dimensions of the insulated body, a fact that is not predictable intuitively.

Other authors, however, put forth conclusions that appear to be somewhat at variance with his results. Tilajka[75] finds that the heat insulation of a dry garment is determined mainly by its thickness and that the effect of material and structure are negligible in this

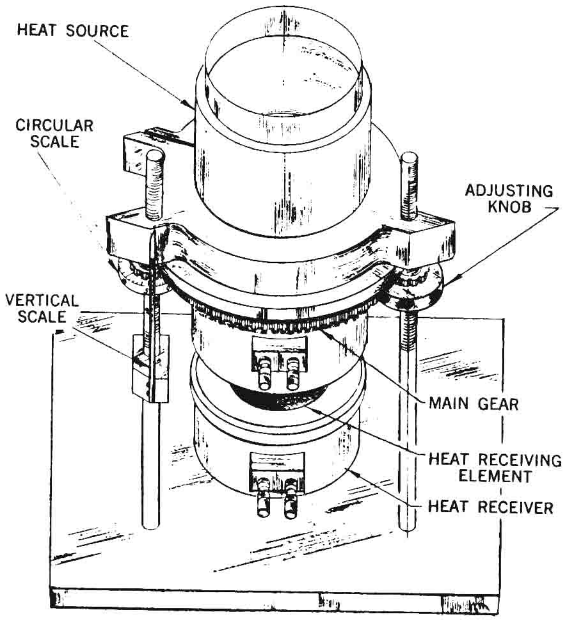

Fig. 5
Apparatus for thermal-resistance measurement used by Weiner and Shah[77]

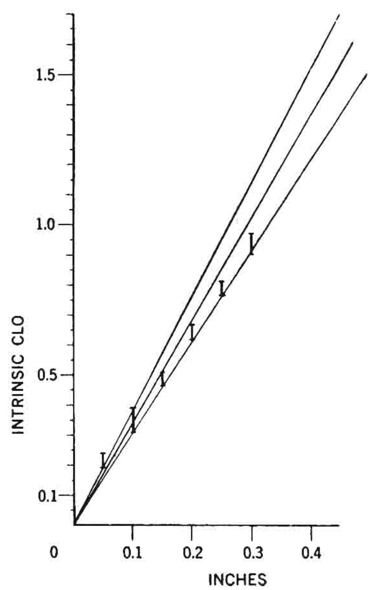

Fig. 6
Relation between intrinsic clo value and thickness (from Weiner and Shah[77])

respect. Voinov and Karlina[76] suggest that, in clothing assemblies that include air layers, the thermal resistance of the air layer varies in a complex manner with the clothing thickness; they use their results to postulate that better use of the insulating ability of air layers could be made by suitable clothing-structure design. Weiner and Shah[77], however, attempt to isolate the factors of thickness and weight and find that, for a fixed weight, thermal insulation increases with thickness (i.e., with increased enclosed air), whereas the property decreases with increased weight (i.e., with decrease in enclosed air) if the thickness is maintained constant. Korlinski, both alone[78] and with co-workers[79], shows that thickness has a decisive effect on thermal-insulation properties under free-convection conditions resembling those pertaining in a clothing assembly and demonstrates a linear relationship between warmth retention and fabric thickness under these conditions. Other publications in this area are reviewed in an article dealing with heat patterns and the aerodynamics of body warmth and cleanliness, with mention of clothing design for extremes of temperature[80].

On the other hand, many authors argue that entrapped air is the most significant factor in determining thermal insulation. Karlina, with various co-workers[81–83], distinguishes microlayers (those between contacting surfaces of the materials) and macrolayers (between non-contacting surfaces) of air enclosed within an assembly and then shows that an increase in either of these can increase thermal insulation. He subsequently uses his results to modify the design of an insulated jacket, a cotton-wadding interlining being replaced with an elastomeric layer without loss of thermal insulation. Fonseca[84], however, explains this lack of change in a somewhat different way. He claims that the thermal characteristics of a clothing assembly are governed decisively by the properties of the outer layer and that any interior layers merely occupy a part of the still-air layer; their presence therefore merely serves to prevent a decrease in size of the still-air layer by collapse of the outer garments onto the body. Bershev, Smirnov, and Sezin[85] use electrostatic-deposition techniques to show that increased pile length (and hence still-air-space thickness) cause an increase in thermal insulation, whereas increased pile density (which brings about a reduction in the volume of enclosed still air but an increase in the number of air pockets) is less effective. Buzanov and Sukharev[86] find that, in wear trials, the thermal conductivity is affected by the dynamic state of the air interlayer, which depends in turn on the activity being performed. Kawabati and Akagi[87] find a close correlation between the feeling of warmth on first touching a fabric and the maximum absorption rate of heat flow as measured physically.

It appears, then, that both thickness and entrapped air play a part in determining thermal insulation. The third factor, that of external air movement, has only recently been subjected to rigorous investigation. Køpke and Knudsen[88] use the Shirley Togmeter to investigate the variation in heat-insulating ability resulting from wind action. They show that, under certain circumstances, the fabric designer may be faced with a dilemma if he attempts to maintain thermal insulation and to prevent access of wind, since the former requirement involves the provision of air pores, whereas these are undesirable for the latter one. Fonseca[89] approaches the problem from a more quantitative aspect and determines the insulation around a sectional manikin in the presence and absence of clothing. He finds that, above an air-flow rate of 2 m/sec, each individual section contributes a constant proportion of the total heat transfer from nude manikin to environment and that the addition of clothing provides a greater relative contribution to the total insulation at higher air flows. He finds reasonably good agreement between his measurements and those obtained earlier by other authors. Jaksic[90] proposes an equation for calculating the thermal resistance of clothing at different wind velocities and finds agreement within $\pm 6\%$ between observed and calculated values of this parameter.

Of the other factors that can affect the thermal resistance of a fabric, moisture is probably the most noticeable, and some work in this area is reported recently. Zamotaev and Skaternikova[91] show that the insulating ability of cellulose triacetate is less affected by moisture than that of wool-blend or cotton fabrics, presumably on account of its lower regain. Smirnov and Zagorodnya[92] investigate the behaviour of several samples of wool, wool–rayon, and polyamide-fibre fabrics over a range of moisture contents. In the dry state, the heat conductivity is approximately the same for all three, but in the region of bound water the heat conductivity of the wool fabrics is much higher than that of the nylon ones. At high water content, the heat conductivity of all the samples again becomes nearly uniform. Suzuki, Sato, and Ohira[93] use a dynamic method and measure the thermal diffusivity of wet fabrics by following periodic temperature changes. They find that, for a wet fabric, this parameter is constant and is independent of fabric water content and quote values of $1–2 \times 10^{-4}$ cal/cm^{-1} sec^{-1} deg^{-1}C (0.42–0.84 mW/cm K) for dry fabrics and a change of $2–10 \times 10^{-4}$ cal/cm^{-1} sec^{-1} deg^{-1}C (0.84–4.19 mW/cm K) as the water content increases. Thibodeaux and Baril[94] bring about a reduction in insulating ability by plating the fibres of a fabric with a continuous metallic coating and briefly discuss uses of the technique.

Finally, work of vital importance in the field of comfort is reported in a few papers, this being the attempt to measure heat transmission through a fabric when accompanied by the movement of moisture, an obvious situation in practical cases. Cohen and Baker[95] design apparatus for this purpose but find a significant lack of agreement between their results and those of earlier workers using conventional techniques to measure the two properties separately. As a result, they do not appear to have pursued this line of research. Larsen *et al.*[96] report in detail on a project in which theoretical and experimental studies of the movement of heat, water vapour, and liquid water through clothing systems are carried out. Mecheels and Schmieder[97] use a skin-model apparatus to investigate the thermal conductivity of dry samples, and the conductivity of heat and moisture, with a wide range of fabrics. They conclude that thickness is the controlling factor in both situations and that thickness effects mask any differences that may be caused by yarn properties. Mecheels and Umbach[98] extend the work to provide a method of measuring thermal insulation, moisture transport, and comfort properties with changes in ambient temperature, air movement, and activity of the wearer. They propose formulae to assist in selecting the appropriate clothing for any given combination of activity and atmospheric conditions in order to dispense with the need for wear trials. Fischer and Fischer[99] develop a new piece of equipment for measuring heat and moisture transmission that simulates skin-surface microclimate conditions by means of a water-filled porous-clay cylinder. The theory of measurement and the initial results are presented, together with some discussion of the merits of the method in comparison with others. In view of the complicated mechanisms by which body heat is lost, there is obviously great scope for further work in this particular area of comfort.

2.3 Thermal Protection

One of the major functions of clothing is to protect the wearer against extremes of environmental temperature, and this aspect, from the standpoint of excessive ambient heat as well as cold, has been explored in several recent papers. Many of the heat-resistant fibres have been reviewed in an earlier publication in this series[100], but some reports are interesting enough from the point of view of comfort to be worth a note in this issue. Stroot[101] discusses fundamental aspects of the development of fibres for clothing to afford protection against either heat or cold (among other hazards), with special reference to fibre selection, blend ratios, and weave structure. In a similar treatment, with particular applicability to military and leisure pursuits, a comparison of the air and water permeabilities of two typical fabrics is given[102].

Apart from the incorporation of flame-resistant fibres or finishes, the main approach in providing heat protection appears to make use of energy-reflecting surfaces as a part of the garment, in an attempt, for example, to comply with specifications laid down in published standards[103]. Aluminium coatings are used for this purpose by Akvarex[104], and other metals are also mentioned in a patent specification[105]. Keijzer[106] points out that most types of heat-protective clothing are impervious to water, which thus makes them uncomfortable to wear, and suggests aluminizing an open-mesh structure as an optimum compromise solution. Quintiere[107] identifies spectroscopically the effects that colour and type of metallic finish have on the radiative-heat load of cotton and nylon fabrics. Other approaches to the problem have included the use of intumescent or miscellaneous organic coatings[108] and the adhesion of flat heat-resistant flakes to the outer surface of a composite fabric[109]. The opposite intention is explored by Greiter[110], who describes specifications for fabrics permeable to ultra-violet radiation for sun-tan purposes while retaining sufficient opacity to prevent exposure of the indecent kind. For information on protection against cold, several of the references already quoted may be re-examined with advantage, but two hitherto-unmentioned ones are also worthy of note. Fujiwara[111] gives comprehensive details of clothing worn by an Antarctic expedition, an obvious practical example of the implementation of research findings. The use of metallized fibres in a blend, producing a dispersed layer of conducting material that can be electrically heated, is described in a patent specification[112], the advantage of such distribution in avoiding interruption or short-circuit of the heating current in the event of damage being pointed out by the patentees. Görlach[113], discussing the effect of environment on body temperature, points out that comfortable body temperatures may differ widely between active and sedentary occupations. He notes that this fact must be taken into account in the design of protective clothing for miners, chemical workers, foundrymen, firefighters, and other such people.

3. MOISTURE-VAPOUR TRANSMISSION

3.1 Moisture Permeability

The second important property of a fabric, from a comfort standpoint, is the way in which it allows water to pass through it. This process can take place in both the liquid and vapour phases of water, and the difference is an important one. If water evaporates at the skin and passes as a vapour through a fabric (or, to a less extent, if it is transmitted to the surface by movement within fibres), the pores of the fabric remain free. This enables the movement of air through the fabric to continue and allows the heat-insulation value of the air within these pores to be maintained. On the other hand, if skin moisture is transported to the surface in the liquid phase by wicking action and only evaporates on reaching the air layer at the fabric surface, comfort is reduced in two ways. In the first case, the sensation of wetness is perceived by the nerve sensors on the skin, so that the garment feels clammy, and, in addition, the water-filled fabric pores are no longer able to hold dead air pockets so that heat-insulating ability is lost and the garment feels cold. In addition, of course, a garment that permits free access of liquid water can become uncomfortable in wet weather, when the reverse movement of exterior water towards the skin is experienced. The movement of liquid water is to be considered in the next section, but at this point the permeability of a fabric to moisture vapour is of great interest in studying fabric-comfort properties.

Moisture-vapour permeability in fabrics is, as is well known, achieved or lost at either the manufacturing or the finishing stage of the production process, and other reviews in this series have dealt in some detail with progress in these areas. Nevertheless, a few recent publications are specifically directed at the improvement of moisture-vapour permeability for the sake of increased comfort, and it is reasonable to review the techniques employed to ensure completeness in this context. One patented technique for improving permeability[114] uses a coated fabric, and, during a heating process for embossing, the coating is pierced by large numbers of pins to create a network of fine holes through which water vapour (but not liquid) can pass. A second method[115], also patented, involves spraying polymer in filament form onto a substrate, in order to build up micropores within the material. Other techniques reported include ionic deposition[116] and the use of various finishing treatments, which belong more properly in the next section. Two patents aimed at producing increased absorption of moisture in the vapour phase are, however, worthy of note. In the first one, a fabric impregnated with a polymerized ester is heated to a temperature sufficiently high to cause decomposition of the latter, which causes expansion of the polymer units, with the formation of microchannels containing hydrophilic end-groups[117]. In the second method, a similar effect is created by heating a mixture of an elastomer dispersion, a hydrophilic polymer, and a suitable emulsion to a temperature greater than 100°C after fabric impregnation[118]. In virtually all these production methods, the aim is to produce a material suitable for shoe manufacture, though tent and rainwear fabrics are also considered capable of production by some of the authors whose work has been reviewed.

3.2 Measurement of Moisture-vapour Permeability

The movement of moisture vapour through a fabric is difficult to assess quantitatively because of the presence of air molecules. Water-vapour diffusion must depend on random molecular collisions to bring about movement of the water through a barrier, but the gas molecules of the air are simultaneously moving through the barrier so that any attempt to measure water-vapour movement by a flow-rate technique is doomed to failure. The accepted standard method[119] is tedious and inaccurate; it depends on the weight loss, by diffusion, of water through a 'seal' of the fabric over a 12-hr period and requires so many different correction factors to be applied that its results are open to some considerable doubt. Kokoshinskaya and Yakovleva[120] attempt to reduce the errors of measurement by a series of repeated weighings during the experiment and find that the amount of water absorbed in the fabric itself is of some importance in assessing comfort. Cohen and Baker[121]

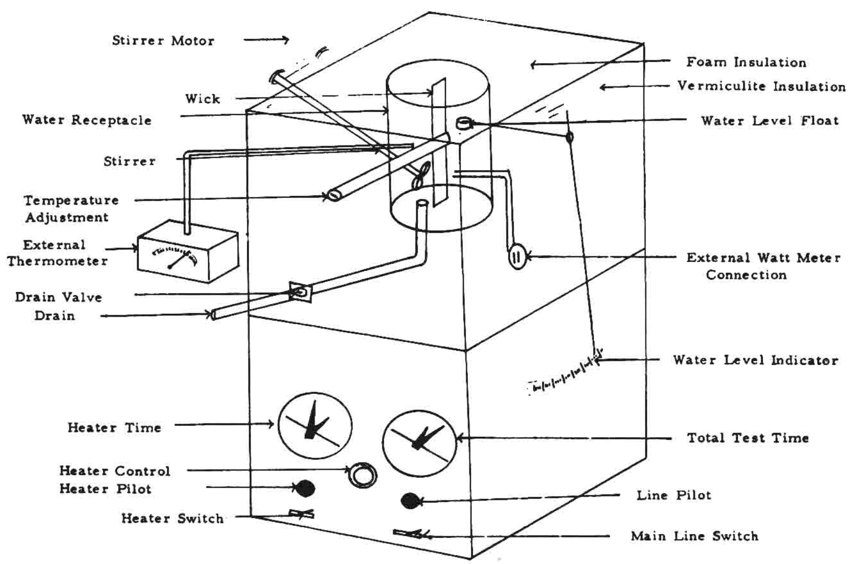

Fig. 7
Schematic diagram of the thermal- and moisture-transmission tester used by Cohen and Baker[121]

use a similar technique in assessing simultaneous heat and moisture movement through a fabric but rely on a volumetric measure, of even lower accuracy, to give an estimate of the amount of water lost. In addition, they do not appear to take into account the different effects that a hydrophilic and a hydrophobic fabric would have on the water passing through them. Weiner[122] attempts a theoretical analysis of the problem and gives a series of equations that are capable of predicting approximately the magnitude of resistance or transmission characteristics of a fabric acting as a barrier to the movement of water vapour. His work, however, does not yet appear to have received any experimental verification. Mecheels and Schmieder[123] use a skin-model plate apparatus developed earlier to measure moisture permeability and find, by weighing, the amount of moisture taken up by dry air moving at a constant rate across the surface of the fabric remote from the water-vapour source.

Chromatographic techniques have been adopted by some workers in an attempt to assign quantitative meaning to the impedance that a fabric offers to the movement of water vapour. Chabert and Chauchard, with different groups of co-workers[124–126], determine sorption isotherms for polyester fibre and nylon chromatographically and then calculate from their results the diffusion coefficient of water vapour in the fibres. The kinetics of water-vapour diffusion are also studied, and the results of this study are shown to agree with those of a gravimetric technique to within 2%.

The final method of measurement that has been reported is the humidity-gradient technique. Suzuki and Ohira[127] discuss the various methods of measuring moisture permeability and point out that a humidity-gradient measurement could be applicable for this purpose. In a later article, they use the technique practically and compare their results with those obtained gravimetrically, excellent agreement being shown between the two techniques[128]. Fahmy and Slater[129] report on apparatus whereby the humidity gradient is established and monitored by means of electrical sensors and the resistance of the fabric to free moisture-vapour movement is derived, very simply, from a graph. A single trial is

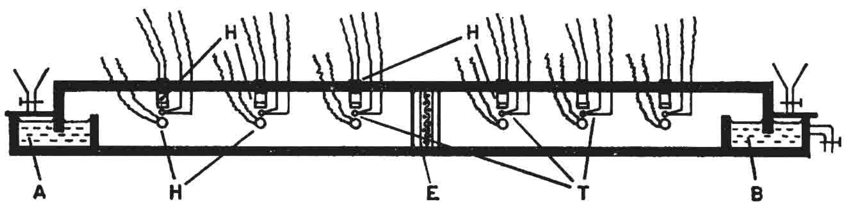

Fig. 8
Schematic diagram of the apparatus used by Fahmy and Slater[129] to measure resistance to water-vapour diffusion

said to take approximately 30 min, but the authors are unable to establish the validity of their results by comparison with the standard technique. Miglyachenko, Orlov, and Onishchenko[130], reporting electromechanical equipment for determining water-vapour transmission of fabrics, give a test time of 2–3 hr, with a relative error of less than 6%, and suggest the use of the technique in selecting treatment conditions for hot wet processes applied to garments.

3.3 Factors Affecting Moisture-vapour Permeability

As has already been discussed, the movement of water vapour through a fabric depends considerably on the microporous nature of the material, and this movement can therefore be modified by any operation that brings about a change in this structure. Gogalla[131] discusses the effect of fabric properties and of finishing treatments on moisture-vapour transport and considers briefly the changes brought about by texturing, different yarn twists, blending, mechanical treatments, and chemical finishing. Greenwood, Rees, and Lord[132] discuss the different mechanisms by which air and water move through a fabric and point out the importance of fibre properties, particularly in close structures, to water-vapour permeability. Clulow[133] contrasts the problems of preventing rain penetration and encouraging moisture-vapour escape and discusses textile structure, together with garment design, in this context.

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