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The Thermal Behaviour of Textiles

by

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

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TEXTILE PROGRESS

THE THERMAL BEHAVIOUR OF TEXTILES

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

1. THE DRYING PROCESS

1.1 Theoretical and General

The process of drying is probably the most common process to which textile materials are subjected. Drying, defined as the removal of moisture or other liquid from the textile, may be carried out at the polymer, fibre, yarn, or fabric stage and is frequently utilized more than once at any one of these stages in the production process. In addition to its primary role, the action of drying may bring about, simultaneously or separately, other changes; the production of bonded-fibre fabrics or of heat-set materials are two obvious examples of this supplementary feature. In order to avoid possible duplication of other issues of *Textile Progress*, however, such auxiliary uses of the drying process will not be discussed except where the accompanying liquid removal is concerned. For the same reason, loss of water at room temperature, as in hydro-extraction or other mechanical finishing processes, will not generally be considered, so that, for the purposes of this chapter, the drying process will essentially consist of the removal of a liquid by the use of heat or other electromagnetic radiation. The most frequently used liquid in textile processing is, of course, water and most of the work carried out in the area of drying has been concerned only with this substance; it should be remembered, however, that many of the theoretical or practical results obtained for this medium are also valid for application to other solvents. This fact may become increasingly important if the current interest in non-aqueous solvent processing continues to be shown by textile technologists.

An analysis of the drying behaviour of fibrous materials has been carried out by Lyons and Vollers[1] and the same authors provide an extensive survey of earlier literature in the area. They summarize the mechanism for water removal as conversion of liquid to vapour, with subsequent removal of the latter, and point out that this process requires the addition of thermal energy nominally equal to the latent heat of vaporization of water. By plotting drying rate as a function of moisture content, they show that the smooth, continuous reduction in moisture content during the drying time is, in fact, achieved in three distinct stages. An initial adjustment period, in which the wet fabric is warming as a result of contact with the drying air at a higher temperature, is followed by a stage referred to as the 'constant rate period'. In this period, the drying rate remains constant as the result of an equilibrium between the rates of heat transfer and vaporization, liquid moisture movement within the fabric being sufficient to maintain a saturation condition at the surface.

Nordon[2] has pointed out that there is a change in the sensible heat of a textile material as a secondary temperature front, closely associated with the concentration (or drying) front, moves through the material. He derives an expression for this change in terms of the distance within the material, the temperatures of the air entering and leaving the material, and the properties of specific heat and packing density of the fibre bed. He then extends the calculation to derive an expression for the change in temperature of the air as it passes through a fabric, from which a drying rate may readily be obtained by the use of psychrometric tables.

At the end of the constant rate period, moisture flow to the surface becomes insufficient to maintain saturation there, so the plane of evaporation moves into the cloth. As a result, the drying rate declines as moisture content is reduced until, at the end of this 'falling rate period', moisture content and drying rate are essentially zero. The discontinuity occurring

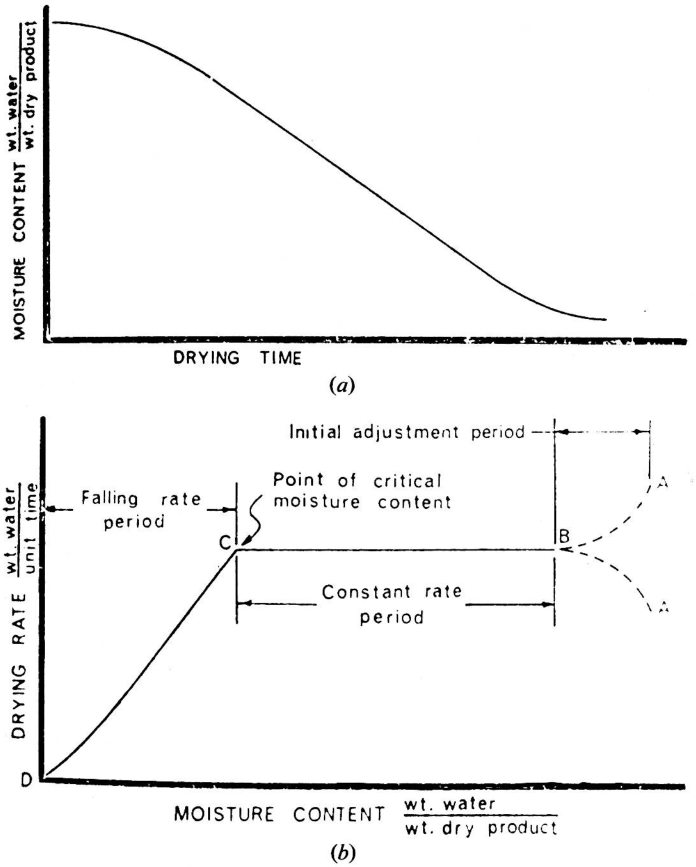

Fig. 1
Typical practical drying-rate curves[1]
(*a*) Variation of moisture content with drying time, (*b*) variation of drying rate with moisture content

between these two periods is named the point of critical moisture content; its precise time of attainment, and its actual value, both depend in a complex manner on the material used and the drying conditions.

In an examination of the drying characteristics of scoured wool, however, Walker[3] finds that the drying-rate curves do not follow the classical format, but show evidence of

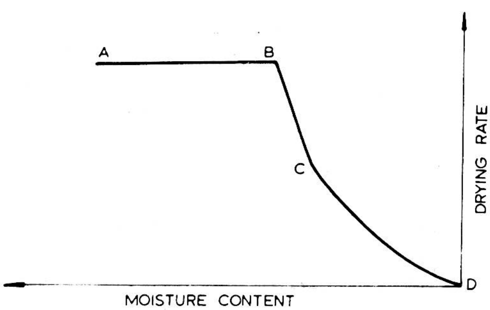

Fig. 2
Classical drying-rate curve of porous materials[3]
(AB—constant-rate period, BD—falling-rate period)

three falling-rate regions with no constant-rate zone. His drying experiments are carried out in tins and he assumes that gravitational movement, in opposition to capillary movement of water to the upper surface, has some effect and that some capillary paths dry out earlier than other, thus diminishing the net flow rate to the surface and causing a slow drift away from saturated surface conditions. The possibility of a similar deviation from classical conditions in the drying of an extremely thick fabric obviously exists, but no work appears to have been carried out on this topic.

Nordon and Bainbridge[4], in a mathematical analysis of the drying process, derive and solve partial differential equations that enable them to predict the changes in vapour content and temperature during the time of drying. Their analysis is limited to the case of evaporation of free liquid only and is thus not generally applicable to textile drying. By selecting examples where absorbed liquid is not present, i.e., water–polyester and butanol–wool, however, they are able to show good agreement between their predicted drying curves and those obtained in practice.

Several authors have attempted to derive mathematical equations to describe the changes taking place within the cloth during drying. An increase in the efficiency or rate of drying is usually sought, together with a reduction in the cost or damage associated with the process. Cannon, Johnson, and Meenaghan[5] derive the generalized partial differential equation for mass, momentum, and energy conservation by making use of a film-theory transport model. They then proceed to show how the evaporative rate of a fabric may be predicted. Hilgeroth[6] carries out an analysis of water removal and derives equations for heat transfer. He takes into account the effects of air-flow direction, atmospheric humidity, and fabric moisture content and shows how each factor affects the drying rate. Tikhomirov and Kan[7,8] derive an equation relating the moisture content of a non-woven material to its composition and to the conditions used in drying. The process of drying polyamide granules is described in terms of temperature, time, and the partial pressure of water vapour by Schmalz *et al*[9]. They then extend their work to establish the applicability of their results to large-scale drying processes. Aboul-Fetouh and Saad[10] suggest a formula for calculating the amount of solute, for example a dyeing or finishing auxiliary, that can diffuse from the surface into the individual fibres at different rates of drying during the falling-rate period. Fast-drying rates are shown to reduce migration of this kind.

Lyons and Vollers[11] continue their analysis with a consideration of the changes taking place within the textile material during drying. They point out that, although the internal processes vary with the type or rate of heating and with the fibre material, there are instances where vaporization takes place within the fabric. This is the case in the falling-rate period for surface heating and during the entire process if a microwave energy source is used. In their report, typical curves of temperature and moisture distribution within a textile material are shown during the warm-up, constant-rate, and falling-rate periods for convection or radiation heating. The general shape of these curves supports the conclusion that, as a dry, outer layer forms during the falling-rate period, the energy flow to the interior is restricted by the thermal resistance of the dry fibre and the internal drying rate is reduced. Thus the wet, internal portions of the material approach a constant temperature between those of a wet bulb and of boiling water.

Similar reasoning is then applied to the drying of fabrics by conduction and microwave methods. In the first case, energy and moisture flow are in the same direction, because of the blocking effect of the contacting heating surface, and the material adjacent to this surface dries first. The general configuration of the curves is similar in this case but, when microwave heating is used, significant differences are observed. With this energy source, heating occurs internally, so that the wet material is heated uniformly throughout its bulk. Thus, vaporization occurs at all parts of the structure and, as the surface is cooled by heat loss to the surrounding air, the inner portions dry more rapidly than the surface. As a result of the heat distribution, temperature and moisture content are fairly uniform throughout the material at any stage in the process, so that the material temperature remains below the boiling point of water until drying is virtually complete. In consequence, energy may be added rapidly without risk of scorching the surface by over-drying in contrast to other heating methods currently used.

Crow, Gillespie, and Slater[12,13] have established relations between the properties of a drying fabric and the air in contact with it. They demonstrate that there is a special relation between the amount of moisture in the air, as measured by dew-point or wet-bulb techniques, and the moisture content of the fabric determined under static-equilibrium conditions. In addition, they show that, during the falling-rate period, the cloth temperature is linearly related to the theoretical wet-bulb temperature, but that the cloth temperaturc during the constant-rate period does not correspond either with the true wet-bulb temperature or with the 'pseudo-wet-bulb' temperature postulated by Nissan[14], probably because of inaccuracies in the temperature-measuring technique.

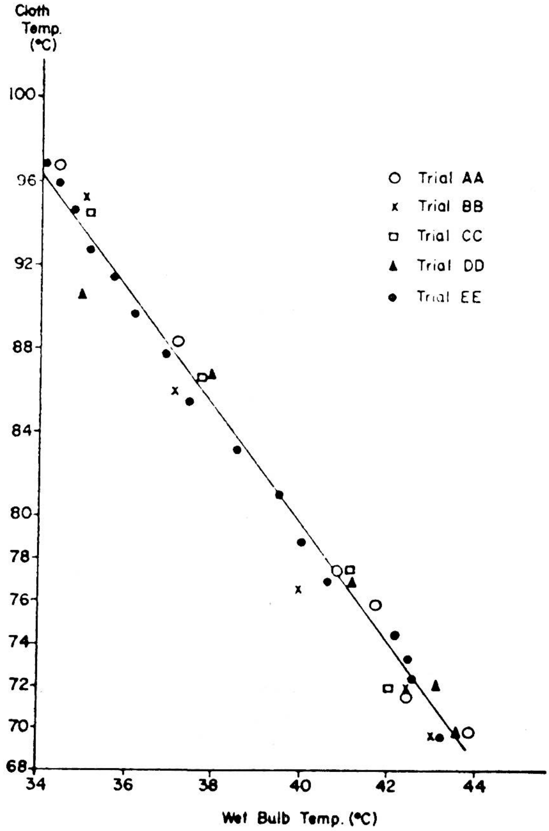

Fig. 3
Relation between cloth temperature and wet-bulb temperature[13]

A factor of major importance in drying is, of course, that of economics and the manufacturer's concern to reduce costs has been heightened in recent years by the realization that the energy resources available to man are not limitless. Gläser and Klemm[15] have carried out a detailed analysis of the cost of drying with stenters. They have calculated the effect of drying temperature, exhaust moisture, water evaporation, and dryer length and determined the optimum exhaust moisture. In addition, they have studied mathematically the relation between these factors. Vernazza[16] has compared the effects of different types of heat sources (steam, steam and electricity, indirect oil-circulation, direct oil, direct gas, indirect oil and indirect gas heating) on cost and concludes that direct gas heating with natural gas is the most economical. Bonkalo[17] has reached the same conclusion and, in addition, suggests that the practice of separating dryers into zones should be extended as an increase in the number of drying zones in a stenter would lead to a reduction in costs. He also recommends pre-drying to allow mill space to be used more efficiently, thus also reducing the overall cost of the drying operation. Franke[18] suggests monitoring the exhaust air from the stenter air re-circulation system so that air exhaust is regulated in order to economize on heat by ensuring that outlet air moisture content is approaching saturation. He does not, however, consider the effect of the resulting loss in drying efficiency (and hence speed) on the total mill operation and a better use of exhaust air is suggested by Jakubowicz[19]. The latter author estimates that 60–80% of the air used in any drying machine goes to waste and takes with it the heat energy used to raise its temperature. As a result of the impurities and moisture that it contains, it is not feasible to use this air directly for air conditioning, but Jakubowicz points out that heat exchangers would make it possible to use the energy for air-conditioning and water-heating purposes.

The rate of drying is also important, not only from the obvious point of view of economy in heating, but also for its effect on other mill operations. As already mentioned, drying is the most common process in the plant and any means of increasing the throughput at this stage will reduce the tendency for a bottleneck to be created, impeding other processes before or after the drying machine. Optimum drying conditions, with particular reference to water-removal rate, have been derived mathematically or experimentally[20–26]. However, the conclusions relate only to a very specific process and no attempt has been made to establish a generalized definition of optimum drying rate. Other equations for the calculation of drying rate or time, at conditions that may not necessarily be optimum ones, have been given[27–30]. Fedorenko and Parfenov[31] carry out a theoretical analysis of moisture removal during yarn drying in sizing and use it as a basis for determining optimum conditions in practice. In addition, they describe the adverse effects accompanying attempts to increase the drying rate by increasing the temperature. They also suggest, once again, that drying should be carried out in zones, a procedure which has been investigated practically in a stenter by Valu and Malcomete[32] to determine the effects of temperature, time, and tension on heat-setting efficiency. Niyazov, Erofeeva, and Umarov[33] suggest that the rate of drying can be increased without loss of quality for raw cotton, by alternating hot and cool air in an intensive drying process. Wallianos[34] treats drying as an exchange of heat and material, in which the interchange takes place gently and with as little damage to the textile substrate as possible. He suggests that vacuum techniques and artificial moistening of the drying air can help to achieve separation of the heat-transport media at the textile boundary, thus meeting the demands for a gentle process and maintaining a higher quality in the drying material. Other ways of improving drying efficiency, without necessarily increasing the rate, are given by Peryman and Barker[35], who suggest improved control of the feeding rate in loose wool dryers, and by Gel'perin, Kvasha, and Seregin[36], who investigate the effect of various factors in drying polymers with fluidized-bed techniques. Ouchi and Ikeda[37] show that drying rate depends more on fabric thickness than on fibre content and Lehmann[38] indicates that the changes in moisture content and temperature with time may be used to monitor the progress of finishing treatments. Tyczkowski[39] recommends routine operational measurements to monitor the efficiency of a dryer, and Wolansky[40] provides details of methods of measuring the rate of evaporation and the consumption of steam per unit of evaporated moisture.

The nature of the evaporative process easily may be assumed to cause unevenness in drying, particularly where the textile material is itself not uniform. This problem has been examined by Gavrilova and Khomutskii[41,42] who concern themselves with the uneven drying of layers of bast-fibre materials. Problems of colour variation directly attributable to non-uniform drying have also been discussed by Fleming and Poole[43], and by Gerber[44]. A method for selecting the correct relation between mechanical and thermal drying treatments is suggested by Sczigel, Seidl, and Latorcai[45], who also examine briefly the differing requirements for non-aqueous solvent removal. Migration of bonding material during the drying of non-woven fabrics has been assessed by Jorder[46], who states that the drying method used may be responsible and suggests ways of reducing the undesirable process.

1.2 Drying Methods

The methods commonly available for drying textile materials involve heat transfer from an external source to the material by some means. The energy transfer, which may occur by conduction, convection, radiation, or a combination of two or all of these mechanisms, is necessary to supply the latent heat of vaporization required in removal of the water (or other solvent).

Conduction heating consists essentially of physical contact between the textile and a hot surface, by which heat is transferred efficiently across the boundary. Heating rates can be very high, but there is a risk of damage to the material surface. Convection heating depends on the tendency of water vapour to pass from a wet surface into unsaturated air, the state of unsaturation being maintained both by heating the air and by causing it to circulate, thus removing the water from the evaporating surface. Energy interchange between the hot air and the fabric is usually poor, so that drying is relatively slow, and the evaporation is further impeded by the presence of a boundary layer of saturated air at the surface of the drying material. Radiation heating involves the transfer of energy by electromagnetic radiation from a source to the fabric across an intervening air gap. The characteristic features of each type are summarized by Lyons and Vollers[47], who also point out that radiation heating is particularly suitable for drying materials with water-saturated surfaces, because water absorbs infra-red radiation very readily and rapid heating is thus encouraged. As long as surface water remains, the material is protected from scorching, but damage can occur very rapidly if a part of the surface dries and this constitutes a serious disadvantage of this method. Landgrof[48] and Gallagher[49] also discuss, independently, the three general mechanisms for transferring heat into textile goods, particularly from the point of view of efficiency. Landgrof points out that dielectric heating is costly to install and to operate and mentions the lack of a satisfactory method of drying heavy fabrics with low air-permeability.

The most obvious example of textile drying by conduction heating occurs when a fabric, or other material, is held in contact with a hot plate or drum and the technique has been in use for an appreciable time. A number of authors have reported adaptations of this basic principle in the recent literature[50–54], usually a method to enable the drying process to be combined with some other process, such as heat treatment, decatizing, or dimensional change. Others have suggested the use of circulating hot air to improve the uniformity or speed of drying[55–58], the possibility of minimizing damage by reduced contact between heat source and textile material[59–61], or the provision of porous channels in the drying surface to improve the free diffusion of water vapour away from the textile[62]. Pai and Hyman[63] have carried out a study of the surface temperature of heating rollers and the effect of this parameter on other process variables. They show that a significant variation in temperature occurs over the roller surface and, although their results are directed specifically to heat treatments, there is no reason to assume that the surface temperature of rollers used in drying would be any more uniform. The risk of uneven drying, or even of local damage by over-drying, is obvious. Hyncica and Kozlov[64], ignoring these local variations, suggest the use of contact drying for a rapid determination of moisture content, while Khranilov[65] compares experimental results with his predictions for the drying time of a fabric after removal from contact with a surface at a specified temperature for a given length of time.

Convection heating, in the form most familiar to textile manufacturers, uses the hot-air stenter. Gallagher[66] lists the basic design requirements for stenters and comments on such factors as nozzle design, drying temperature, and types of heating method available. Vidal[67] categorizes these in three groups: those with air flowing in the stenter direction, those with jet blowers impinging on the surface from both sides, and those with air passing through the material from one side to the other. His work refers particularly to drying plants for non-wovens, but his classification is a useful one for all stenters. Minor variations in the principle of surface flow have recently been claimed in the patent literature[68–70], particularly in the area of solvent drying[71,72]. The technique of directing air-jets on to both surfaces of a fabric is also frequently used[73–76], the main reason being that this method of water removal apparently achieves more uniform drying than any other. Heilemann[77], who has used impinging air to dry rubberized fabrics, has studied the effect of varying temperature and flow rate on the rate of drying and quotes an optimum velocity of 6–8 m/s for the air flow. Equipment in which the drying air is forced through the material has been reported recently, but appears destined predominantly for thick or heavy layers of textiles. Carpets are the obvious instance of this type of structure and patents for two such applications have been issued[78,79]. The same technique has been suggested, however, for delicate or voluminous fabrics on a supporting mesh[80] and has also been adapted in a commercial instrument for measuring loss of mass during drying[81]. One piece of drying apparatus alternates a blast of air through the fabric with simultaneous air streams from each side, in order to produce agitation of the material rather than an unvarying configuration, as the material moves through the drying zone[82].

Air circulation over or through a textile material is also present in festoon and sieve-drum dryers. Recent reports pertaining to the former type include work by Gavrilova[83], who derives equations for the aerodynamic resistance of flax straw in drying machines, together with minor variants on the basic festoon dryer[84–87]. Minor modifications to the well-known sieve-drum apparatus, with or without the addition of vacuum-extraction to increase the drying rate, are also suggested[88–93]. Reeker[94] surveys the methods of circulating air round or through a yarn package and gives a theoretical treatment of the process of drying with air or steam. In theory, superheated steam is capable of absorbing considerable amounts of water and is thus a useful drying agent. Attempts to overcome the practical difficulties of maintaining steam temperature (and hence degree of superheating) have so far thwarted the development of a practical dryer using the principle, though Moyer[95] has recently claimed a device which successfully achieves the aim. A commercial dryer using superheated steam as the heat source is expected to give more uniform drying, and to prevent scorching, because the continuous presence of water molecules in the drying medium will enable equilibrium with fabric moisture to be attained.

Other noteworthy convective drying techniques suggested recently include the use of high air-pressure[96], saturation of the material with a combustible liquid that is subsequently ignited[97,98], and heat-shock pre-drying with subsequent low-temperature drying to eliminate scorching[99,100]. Pre-drying followed by vacuum drying[101], or by normal stenter drying[102–104], has also been suggested to avoid the problem of scorched material. Nossar, Chaikin, and Datyner[105,106], have investigated the flow of air through beds of drying fibres, in an attempt to develop high-intensity drying methods. They show that flow is non-laminar and that the pressure drop resulting from flow is almost proportional to the square of the air velocity. In addition, they develop equations predicting the external pressure drop needed to maintain air flow at a given rate through an assembly of wet fibres, in terms of fibre, bed, and air properties. Their experimental results indicate good agreement in the early stages of drying, but their equations are not yet applicable to the more critical stage of the drying process when the residual moisture content is low.

Radiation heating, in which an electromagnetic energy source is used to provide the latent heat of vaporization, is a fairly recent development. Three major types of dryers, using infra-red, dielectric, and microwave techniques respectively for supplying energy, are currently in the process of development. Ilg, Krentz, and Bechter[107] examine the energy distribution in textile materials absorbing infra-red radiation and conclude that, although there is a risk of fibre damage, heater design and the use of reflectors could assist in achieving uniformity of surface heating. Jakubowicz[108] carries out experimental drying with an infra-red source and makes a brief comparison with results from traditional convective drying techniques. Bottger[109] and Heidemann and Stillig[110] discuss the possibility of using infra-red radiation in practical drying. Bottger suggests that this type of source would be more suitable as a pre-dryer to prevent substance migration or overdrying. Pijanowski[111] discusses the advantages and disadvantages of infra-red drying and suggests ways of controlling the temperature of radiation heaters. A few practical dryers using infra-red energy sources are reported in the literature[112–116], but the textile industry as a whole has not yet made great use of this potentially valuable technique.

The same general statement is true to an even greater extent in the case of dielectric, or high-frequency, and microwave drying. Roscher[117] uses high-frequency electrical energy to fix a coating on a substrate in a dryer and Hanff, with Licentia Patent-Verwaltungs G.m.b.H., uses the same principle for drying purposes only[118,119]. Lytzen[120] uses a high frequency pulse to produce compressions in a circulating stream of hot air moving along the surface of yarns or webs; by this means, a shock effect is achieved and the air is directed more forcefully against the material. A device reported by two sources[121,122] uses specially designed yarn spools so that high-frequency drying of filaments can take place on the surface and, by making a winding core serve as an electrode, within the layers of spooled yarn as winding takes place. An additional advantage of this type of drying, as reported by several authors, is the fact that tensile behaviour is enhanced after the irradiation has taken place[123–125].

Microwave heating is an even more recent innovation in textile processing. Menschner G.m.b.H. have reported a microwave device for drying sheet materials[126] and later improvements for textile purposes by the incorporation of a heated air stream in the wave guide of the apparatus[127]. Dawson[128] discusses microwave heating equipment briefly and states that the use of such a technique is attractive because it gives rapid rates of fixation. He points out, however, that the cost of the microwave method constitutes a serious drawback in comparison with traditional steam heating. Hazel[129] discusses the principle of microwave heating and its application to drying, but does not undertake an economic analysis. Small, Hatcher, and Lyons[130] suggest that, for latex carpet backings, drying time may be reduced significantly with no loss of quality if attention is paid to the power setting of the microwave heater. Evans[131] uses microwave energy to complete the drying and curing of a latex foam that has first been subjected to hot-air or infra-red drying to reduce the moisture content. By this compromise, drying costs are reduced while the advantages of the technique are maintained to an appreciable extent. Microwave dryers, like infra-red or high-frequency ones, are obviously destined to be of wide and valuable use to the textile manufacturer, though it is unlikely that they will replace completely the more traditional heating techniques for some considerable time, if ever.

1.3 Temperature Measurement

No matter what method is used for drying the textile material, one vital consideration must be foremost throughout the water removal process. The fabric must not be allowed to suffer thermal degradation owing to overheating. To allow such damage to occur not only wastes the time and cost of the drying process itself, but also sacrifices the entire outlay invested in the production of the fabric from its starting materials, since the thermal change is an irreversible one. Even mild overheating may make heat-sensitive fibres unusable owing to objectionable colour changes, and more severe degradation can reduce tensile strength so drastically that virtually any fabric becomes weakened sufficiently to be rendered useless.

When thermal energy, from any source, is present in a wet fabric, an equilibrium is set up between the heat supplied to the fabric from the source and the heat used in providing the latent heat necessary for evaporation of water to take place. As a result, the temperature of the fabric is theoretically prevented from rising above 100°C as long as liquid water is present among the fibres, though in practice uneven heat distribution, or abnormally high rates of energy absorption, can render this generalization false. The phenomenon does, however, suggest that thermal degradation can be avoided if cloth temperature changes are monitored and heating is discontinued before the fabric becomes undesirably hot. One method of achieving this aim, naturally, is to maintain the heat source at a 'safe' level of, say, less than 105°C so that drying without damage can occur. This procedure is commonly used in laboratory situations but is not practicable, for two reasons, in production drying. In the first case, the rate of drying under these circumstances is so slow that the textile material would have to spend an inordinately long period of time in the dryer. This is not feasible in continuous-flow stenters, though the technique is used in stationary drying with festoon or loop equipment. Secondly, many modern finishes require heat, as an integral part of the application process, to bring about polymerization of a compound on the fibres. For economy of time, this 'fixing' is often combined with the drying process and, as temperatures of 150°C or higher may be necessary to bring about the chemical transformation, brief cloth exposure at these high temperatures must be accepted as part of the drying stage. For these reasons, then, it is of some considerable advantage to the finisher to know both the time and temperature of exposure of the material in order to minimize damage.

Time measurement is simple, but temperature measurement is hampered by experimental difficulties, as can be appreciated by an examination of the comparatively rare literature on the subject. Immersion of a normal thermometer bulb in the wet fabric is obviously impossible, but any attempt to embed deeply a detector in a moving textile is negated by the damage that results to the material in consequence. Light contact is unreliable because heat flow from the ambient air to the detecting element can cause erroneous readings to be made and vibration of the textile can have the same effect by making the contact a discontinuous one. Some authors, nevertheless, have attempted contact temperature measurements. Beckstein[132] surveys the methods of monitoring that have so far been used, and shows that there are objections to virtually all of them.

Latorcai, Megyeri, and Sczigel[133] have used a contact device to traverse a cloth in an attempt to measure temperature distribution on stenter frames, but give no specific details of the construction of the sensing unit, nor of any steps taken to ensure accurate readings. Hoischen[134] discusses the use of heat-sensitive papers and electrical thermometers in setting presses, where the risk of inaccurate temperature recording is reduced because the measuring element is not exposed to the air. Nevertheless, any reading obtained will still be erroneous because of the presence of the high-temperature pressing-bed and a correction factor, dependent on the thermal gradient within the press, must be devised before accurate cloth temperatures can be derived by the technique. Becker[135] describes the use of five thermo-elements, attached to a test fabric, in measuring stenter temperatures, but again does not discuss the problem of measurement inaccuracy. Kvapil[136] suggests a procedure for using thermo-elements to measure the temperature of a continuously-moving fabric but, once more, ignores the risk of erroneous results.

Crow, Gillespie, and Slater[137] use a thermistor to measure cloth surface temperature during static drying in a laboratory oven, by embedding the minute tip of the detecting device in the weave of the cloth. Even with these precautions, however, they are unable to derive an accurate drying curve, on a graph of temperature *vs* time, that is repeatable for successive trials carried out on the same fabric specimen. They assume that the discrepancies arise as a direct result of incomplete encasement of the thermistor tip, and suggest that this problem precludes the use of contact temperature measurement for fabrics. Medley questions this assumption[138] and claims that a probe reported earlier[139] is capable of exact temperature measurement when in contact with a cloth. He stipulates that, for accurate measurement, the cloth must be in motion relative to the probe, there must be good thermal contact between probe and cloth, and there must be good thermal insulation between the probe and the air in the dryer. In their reply, the former authors point out that, for free evaporation of moisture from wet fabrics these conditions are impossible to achieve in practice[140] and that Medley's earlier paper[139] gives no indication of how the apparently insurmountable practical difficulties are overcome. Until this disagreement is resolved, however, it may be more constructive to seek other methods of temperature measurement.

Contactless temperature measurement has attracted the attention of several workers in recent years. Kuz'min[141] adopts a potentiometric technique to record surface and internal temperatures of bonded non-woven fabrics during drying. He uses convection and radiation methods, together with a combination of the two, to derive his readings, but gives no clear indication of how he correlates these readings with other techniques designed to establish true surface or internal temperatures. Temperature measurement by radiation methods are discussed by Kyncl both alone[142] and in conjunction with Sveceny[143]. The two authors discuss the principles and equipment involved in several different measurement techniques and mention restricting factors that limit the choice of detector and the temperature range measureable. They point out the need for the development of improved infra-red radiation detectors in order to enable advances in contactless temperature measurement to be made.

Infra-red radiation is also used for temperature measurement by other authors. Druzhinin[144] presents a theoretical method of yarn temperature measurement in which the infra-red radiation is sensed by a detector after passing through an optical focussing system. He calculates that, for temperatures encountered in drying or finishing of high-bulk yarns, the necessary sensitivity for satisfactory detection is easily attainable. In a subsequent paper by the same author with Kudryatsev and Usenko[145], a more detailed discussion of the principles of infra-red–spectroscopic measurement of thermal emission is presented, and the range of processing temperatures (60–300°C) is shown to correspond to wavelengths of 2–30μ, in the electromagnetic spectrum. Mester and Glockmann[146] establish a relationship between the temperature of running thread and the emitted radiation sensed in an infra-red pyrometer. They then suggest the use of two pyrometers, monitoring background and yarn radiation respectively, to derive a value of yarn temperature. They point out that materials transparent to infra-red radiation, or with a low emission, may not be examined satisfactorily by the method, but suggest that synthetic polymer filaments, with absorption bands in the wavelength region 6·8–8 μm, are suitable targets for available spectral pyrometers. Some discussion of a commercial instrument is also presented. Röben[147] suggests an experimental arrangement for measuring the temperature of cotton fabrics partially permeable to infra-red wavelengths, using radiation techniques. He discusses the effects of the presence of dyestuffs on the fabric and steam in the atmosphere on the measurement accuracy. In addition, he presents an equation that may be used to determine the effect of these parameters on the reading obtained, so enabling a correction factor to be applied if the technique is to be used in obtaining accurate fabric temperature measurements.

Thus, neither of the systems of temperature sensing used at present is entirely satisfactory. Contact methods yield inaccurate results when the fabric is losing evaporative water and cause marks to be impressed on the cloth. Contactless detection by infra-red techniques is hampered by variable sensitivity as the temperature changes and by the presence of unavoidable substances that interfere with accurate calibration in terms of cloth temperature. Until one or the other of these detection methods can be perfected, the problem of drying control remains a difficult one if cloth temperature must be used as the basis for the control system.

1.4 Automatic Control of Textile Drying

In view of the problems associated with the measurement of cloth surface temperature, as just described, it is perhaps not surprising that little practical work on automatic control systems for fabric drying has been reported. Despite the economic importance of devising a successful control mechanism to ensure that fabrics emerge from a stenter at or near their standard moisture regain, no such mechanism appears to exist at present.

Since Chamberlain[148] first formulated the requirements for drying control 30 years ago much work in the area has been carried out, and a survey of the more important articles up to 1972 has been given by Crow[149]. Other recent work indicates that several approaches to the problem have been tried.

Kowalski and Waechter[150] discuss how the measurements of mass per unit area and of moisture can be incorporated into finishing processes, but give no clear indication of how moisture content should be measured. Two patented systems may also be noted, though both are a little defeatist in their approach. Both systems depend on fabric travel at constant velocity through a drying machine with a constant heat input. In the first one[151], residual moisture content (and/or temperature) is sensed at the dryer exit and additional moisture, in liquid or steam form, is added to the fabric before drying, in an amount determined by calibration from the exit reading. No indication is given of how compensation for under-drying is effected, nor do the methods of measuring temperature or moisture content (given in rather vague terms) bear close scrutiny. In the second method[152], the initial moisture content of the fabric is adjusted to a preset value before entry into the dryer, this value presumably being calculated from the 'known' regain moisture content of the fabric in conjunction with the constant heat input supplied to the stenter. The obvious disadvantages of both systems, a need for separate calibration for every combination of mass and fibre content and the effect of a change in external factors such as electrical supply voltage affecting the heating arrangements, make the methods tedious and somewhat unreliable at best.

Other types of control system have been the subject of recent patent specifications. Mather and Platt[153] suggest the use of correlation between fabric temperature and moisture content during the falling-rate period to develop a control system. In their proposal, the difference between the cloth temperature at an intermediate point in the drying machine and at a point near the exit from the machine, indicative of the emergent cloth moisture content, would be used as the sensing element from which control information to govern the speed of cloth transport could be derived. A similar suggestion, proposed jointly by Sira and Wira, is described by Harbert[154]. He uses the temperature of the fabric and the wet-bulb temperature of the air at the stenter exit to define an 'equilibrium relative humidity' measurement as the basic measurement for control. In both methods, however, the cloth temperature is established by the use of probes and, as shown by Crow, Gillespie, and Slater[155], such a measurement is doomed to failure because of imperfect contact of the sensing element and hence inaccurate temperature estimation.

A technique suggested by Roberts[156] and mentioned also by other authors[157,158] uses the electrical resistance of the fabric to give an estimate of the residual moisture content at exit and to derive a control signal again producing corrective changes in fabric transport speed. The occurrence of hunting is reduced by establishing a minimum time interval between successive corrections. The technique, although presumed to be satisfactory in trials, unfortunately has one major defect. In the drying operation, it is very likely that a wet finish may be present on the fabric as a result of the modern tendency to combine treatments wherever possible. In such a case Crow and Slater[159] demonstrate that the presence of common finishes changes the correlation between moisture content and electrical behaviour, such as resistance or capacitance, so drastically that the measurement of such properties is useless for control purposes. The same authors show that cloth temperature during drying is virtually unaffected by the presence of a finish and use this fact elsewhere[160] to suggest a new approach.

In this work they find, by simultaneous monitoring of air temperature, dewpoint temperature, and moisture content of various fabrics during the drying cycle, that a possible control mechanism source emerges. All fabrics appear to reach their standard regain values at the same atmospheric condition, as defined by the air and dewpoint temperatures. Thus, it should be possible to monitor the temperature and the dewpoint of the air in equilibrium with emerging cloth and to establish, from these two readings, the moisture content of the fabric. The values obtained could, of course, then be used to operate a speed control device, as before. The authors point out that stenter modification is needed in order to prevent the large mass of water vapour present at the earlier stages of drying from affecting the reading near the exit. They suggest the use of an enclosure near the exit to isolate the air for sampling but give no indication of the time that fabric must spend in this enclosure in order to allow equilibrium to be attained. This delay will affect not only the speed of cloth travel but, if unduly long, will reduce the sensitivity of the detection to a level that may be unacceptable.

The use of exhaust air in various ways has been suggested by other authors, though apparently not for control purposes of the type just discussed. Franke[161] suggests that its moisture should be monitored to ensure that the full drying capacity of the stenter is used and, in a later article[162], points out the economic advantages of using drying air to its utmost capacity. He does not, however, appear to take account of the fact that hot air becomes less efficient as a drying agent as its moisture content increases. Pabst[163] recommends similar action, for economic reasons and, in suggesting a method for measuring and controlling the moisture content of the exhaust air, quotes sample cost savings that are theoretically possible. Schmidt[164] presents graphs showing the temperature of fabrics and outgoing air in tumbler-dryers as fabric moisture content decreases and suggests use of the exhaust-air temperature to regulate drying time. The principle, of course, relates to batch operation and is not directly applicable to the continuous drying operation taking place in a stenter.

Electrical and electronic engineering techniques have also been used in the search for a satisfactory control system. Higgins and Keey[165] simulate the conditions present in a suction-drum dryer for loose wool. They measure the dynamic characteristics of a typical plant without control, then superimpose on their simulated model the characteristics of standard pneumatic control elements. By using transfer functions, they are able to define the parameters for an electrical-analogue simulation and to show that control of moisture content in the wool is possible, even if the feed-rate fluctuates. It is thus only the problem of measuring moisture content precisely that prevents the development of a satisfactory control system. Beckstein[166] suggests the use of an infra-red radiation pyrometer to control fabric temperature in heat setting, but reverts to the use of electrical conductivity in his reference to control in the drying process. The damping of an oscillatory circuit, by bringing the moist material within the measuring field of the tuning coil of a high-frequency oscillator, has also been suggested[167]. The technique uses the consequent reduction in energy as a measure of the moisture content of the fabric, but is again only applied to a static situaton as it exists in a laundry drying machine. The change in the velocity of sound as a result of change in moisture content has also been proposed[168] as the basis of a control system, but it is somewhat doubtful whether the precision required for stenter control can be achieved by this technique.

Despite the availability of all these procedures, the urgent need for adequate fabric-drying control has not been met. Bennett *et al*[169] discuss each of the available methods in some detail and summarize, in tabular form, the reasons why they are not yet applicable in practice. Infra-red techniques are handicapped by the fact that the presence of dyestuffs can interfere with the measurement, while microwave devices at present suffer from high cost and extensive calibration problems. Resistance and capacitance measurements, in addition to being affected by finishes, are deemed suitable only for measurements outside the stenter at low values of regain, a condition that makes them unsuitable for control purposes. Hygrometric methods are selected by the authors as the most promising ones and a control system based on the use of modified wet-bulb theory is presented. The equilibrium relative humidity (e.r.h.) is calculated as a function of $T_c - T_w$, where T_c is the temperature of the drying cloth and T_w the temperature of a completely wet reference surface exposed to the same environment. This function of the e.r.h. is then used to generate a control signal to adjust the speed of passage of the fabric.

The measurement of cloth temperature, unfortunately, is carried out by means of a lightly-riding contact probe and no experimental results are given to enable the accuracy of this probe to be judged. Crow, Gillespie, and Slater[170] suggest that the use of any probe interferes with the free evaporation of water from the surface and cast doubts upon the ability of the probe to give a true assessment of fabric surface temperature. Bennett *et al*[169] then go on to suggest that radio-frequency (or dielectric) drying may provide a better, and more easily controlled, method of removing moisture and express the hope that progress in this direction may bring about a solution of the current control problems. Until this, or some other, technique is developed to a state of perfection, however, the manufacturer will probably continue to rely on the subjective assessment skills of trained operatives to enable his cloth to be dried to a satisfactory moisture content.

1.5 External Factors

In this section, recent work describing both the effect of external factors on drying conditions and the effect of drying conditions on fabric properties not necessarily associated normally with thermal behaviour will be considered.

It appears that little research of any importance has been carried out in the first of these two areas. Sumetov and Khomutskii[171] investigate the effect of drying conditions on the drying time of flax straw in a convective dryer. They derive relations between the duration of drying and the load, air speed, temperature, relative humidity, and stalk diameter. These relations, derived from experimental measurements, are then used to develop mathematical equations expressing the drying time, but the equations do not appear to have been extensively tested in independent drying trials.

Franke[172] suggests that the efficiency of heat setting in a stenter can be improved by shock cooling to achieve full stability of the heat-set finish. He considers that cooling zones within a stenter are preferable to external ones because hot air from the dryer may be sucked into the cooling fans. He does not mention the possibility of a pressurized external cooling zone, nor does he discuss the effect of moisture, so his conclusions should only be applied to cases where heat setting is carried out after drying to negligibly low moisture contents. It is of interest, however, to note that a final cooling has been recommended[173] as an aid to achieving control measurements to assist cloth to be dried to a pre-determined moisture content.

The effect of drying conditions on fabric properties is included mainly in section 5. A few authors, however, have reported work directly related to the drying process itself, rather than to deliberate thermal treatments, and it is proposed to discuss their results here rather than in the more general section. The need for precise control in heat setting is pointed out by Taylor and Fries[174], and Halboth[175], who relate such phenomena as fibre shrinkage, reduction in pilling, and changes in dyeability to the heat-setting conditions used. Stepanov and Savvin[176] measure the forces arising, during drying, in single filaments and in bundles of synthetic materials. Among other results, they show that these forces are not significantly altered by the adjustment of drying temperatures within the range 50–100°C. Their work is unfortunately not extended to drying temperatures in the higher range at which commercial stenters operate and to which fibres are exposed when overdrying occurs. Research carried out at the International Wool Secretariat[177] investigates the behaviour of wool during overdrying. The changes in colour, physical properties, and chemical structure taking place at elevated temperatures of up to 220°C are described. From the results, the workers proceed to discuss the conditions of tension and relative