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Temperature and Moisture Distribution in Contact Drying of Thick Beds

M. RATNA PRABHU
Ahmedabad Textile Industry's Research Association, Ahmedabad 380 015

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Experimental findings relating to temperature and moisture distribution during contact drying of a thick bed of wet textile material are presented. Two striking phenomena have emerged from the study : (i) drop in temperature occurring at a certain stage of drying, and (ii) uniform distribution of moisture in the entire bed even when different sections are exposed to different conditions. Details of experimental procedure and analytical data explaining these phenomena are presented. Further work is recommended for obtaining a proper understanding of the contact drying process.

DRYING is a commonplace and seemingly simple process, but when studied in detail, it reveals itself as a complex and often a baffling process. Of the various forms of drying, convective drying is perhaps the one most widely used and has been studied extensively[1-10]. In textile mills, contact drying is also used extensively, as it is economical in terms of drying costs, capital costs, steam/power consumption, space requirements, etc. But basic studies on contact drying are scarce and extremely limited literature references are available[11-13]. Many of these reports deal with contact drying through mathematically complicated approaches, and are largely theoretical in nature. This paper presents certain interesting experimental results obtained while studying the basic characteristics of contact drying[14] using a simple experimental set-up in which a thick bed of wet material, placed on a hot plate, was subjected to contact drying.

Experimental Procedure

Drying bed — The drying bed was built by placing a number of layers of woollen felt of size 150 × 50 mm, one on top of the other. Usually 4 layers were used and these formed a thick bed, which was placed upon the hot plate. A compacting frame was placed on top of the bed to apply a constant compacting load upon the bed. This frame, weighing about 100 g, was so designed as to offer minimum obstruction to evaporation.

Hot plate — The hot plate was fabricated by having a flat 100W heater, called a heating mat, sandwiched between two flat aluminium plates. The drying area was arbitrarily chosen to be 150 × 50 mm. Holes were bored on the side of the plate for inserting thermocouple junctions.

Thermal insulation — The set-up had to be properly insulated and at the same time it had to be convenient for placing and removing the felt layers and thermocouples. So, the entire set-up was built up with loose insulating boards and blocks which were assembled around the hot plate for each experiment. They consisted of 12 mm thick compacted lime-silica boards next to the drying bed, surrounded by 175 mm thick expanded polystyrene on all sides. The entire set-up, shown in Fig. 1, was placed on asbestos boards.

Temperature measurement — Fine gauge copper-constantan thermocouples were used along with a sensitive spot galvanometer to measure temperature at 6 points in the bed. By connecting a 6-pole selector switch (Fig. 2), a common cold junction and a common galvanometer could be used for all the measuring points. The switch was shifted from one pole to another after every 30 sec, so that at each point the temperature was measured at intervals of 3 min. To minimize errors due to spurious thermo-emf generated by different sections of the circuit, all connections on the copper side of the circuit were made with copper wires and on the constantan side with constantan wires. Further, whenever the circuit was reconnected, the circuit was calibrated afresh.

Moisture measurements — Moisture regain was determined by the oven drying method. For finding out the weight of the felt samples special "self-seal" polythene bags were used. The "self-seal" bags could be sealed quickly and conveniently and provided a satisfactory seal.

Results

Temperature changes during contact drying — Data on the temperature changes that take place at the interfaces of four layers of wet woollen felt, laid one on top of the other, are presented in Fig. 3. The temperatures of the hot plate and the evaporating surface are also indicated in Fig. 3. The most striking feature of these curves is the temperature drop which occurs almost simultaneously at all layers after drying has progressed for a certain duration. Such a temperature drop occurring while heat is being continuously supplied to the system was unexpected and seldom occurs in thermal processes. However, this feature was invariably reproduced in each of the numerous repeat experiments which were conducted with different number of layers and different rates of heating.

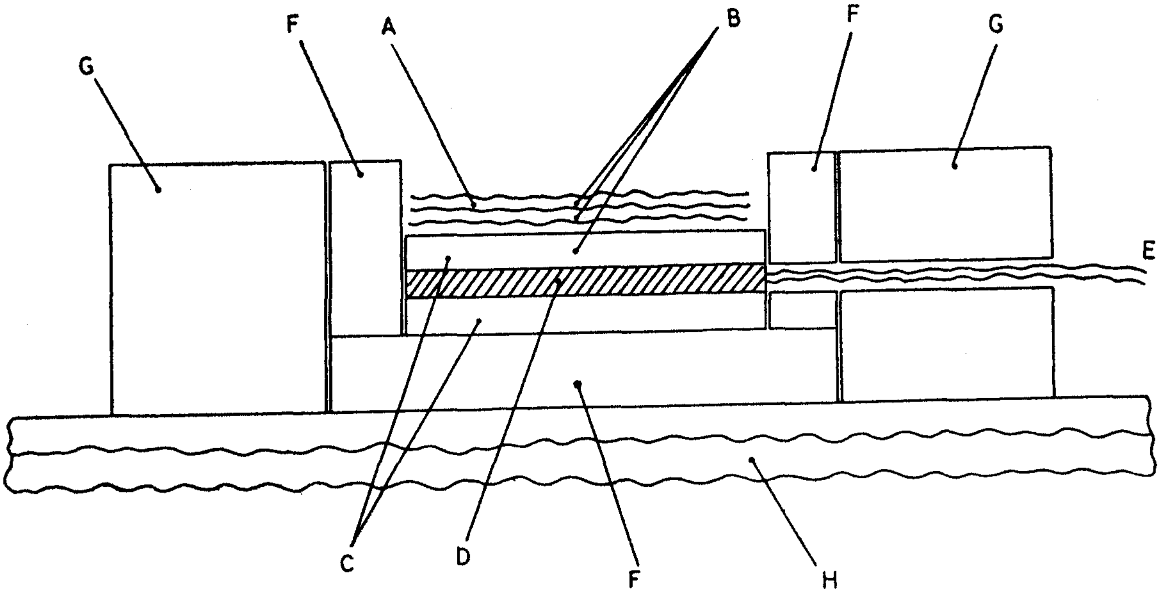

Fig. 1 — Experimental set-up [A, drying material (layers of woollen felt); B, thermocouple junctions; C, aluminium plates; D, flat electrical heating mat; E, electrical supply connections to heater; F, compacted lime-silica boards; G, expanded polystyrene blocks; and H, asbestos boards]

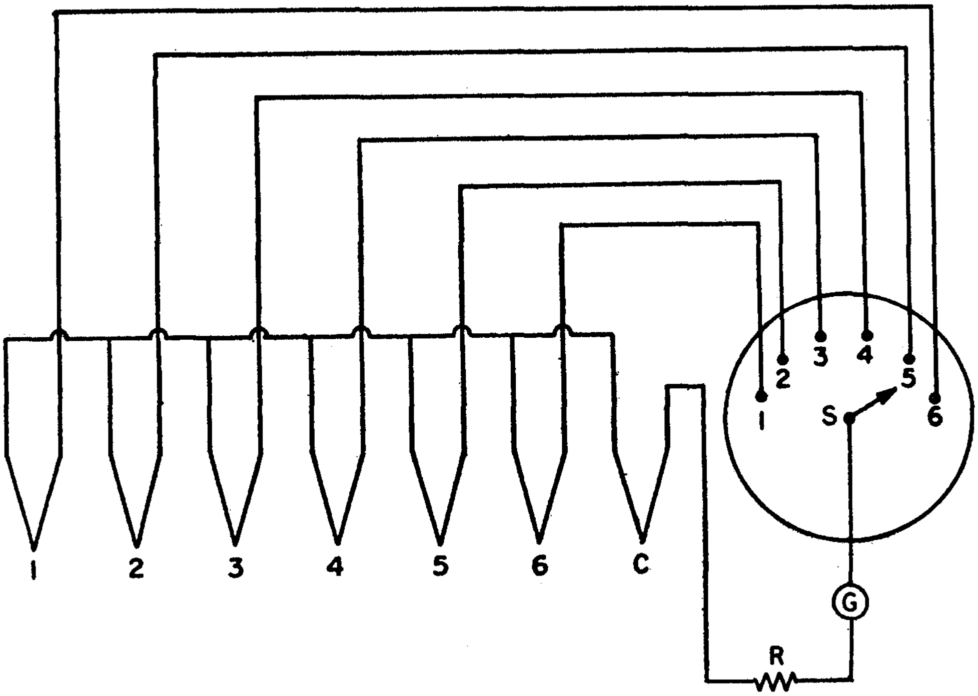

Fig. 2 — Thermocouple connections for a common cold junction and galvanometer [1,2,3,4,5,6, thermocouple junctions; C, common cold junction; S, selector switch; and G, common galvanometer]

Moisture changes during contact drying — The layer by layer moisture changes that take place during the progress of drying are shown in Fig. 4. There are two interesting features of these characteristics. Firstly, during the initial phase, the moisture content decreases at the same rate in all the layers, whether it is the contact layer, the interior layer or the evaporating layer. This means that during this initial period, the moisture content is uniformly distributed over all the layers. The second interesting feature evident from Fig. 5 is that at a certain point, A, the moisture loss rate increases steeply for the contact layers, while in all other layers it decreases. Point A was found to coincide with the point at which temperature begins to drop in the temperature curves. To confirm this, a number of experiments were conducted in which the temperature was noted continuously. As soon as the temperature began to drop, the experiment was stopped and the layers were peeled out for moisture determination. In each of these experiments it was found that the upper layers had more or less the same moisture regain, while that in the contact layer was much lower.

Discussion

Temperature distribution — Typical temperature distribution characteristics of a thick drying bed are shown in Fig. 6. Initially, the temperature rises at all points, as shown between A and C. This zone may be called the initial temperature rise period or ITRP. At point C, the temperature begins to drop almost simultaneously for all layers within the drying bed. Point C may be called the temperature drop point or TDP and this is followed by the temperature drop zone, CD. After this, there is an isothermal region, DE, which is usually prominent only in the upper layers. This region is called the second constant temperature period or second CTP. The first CTP

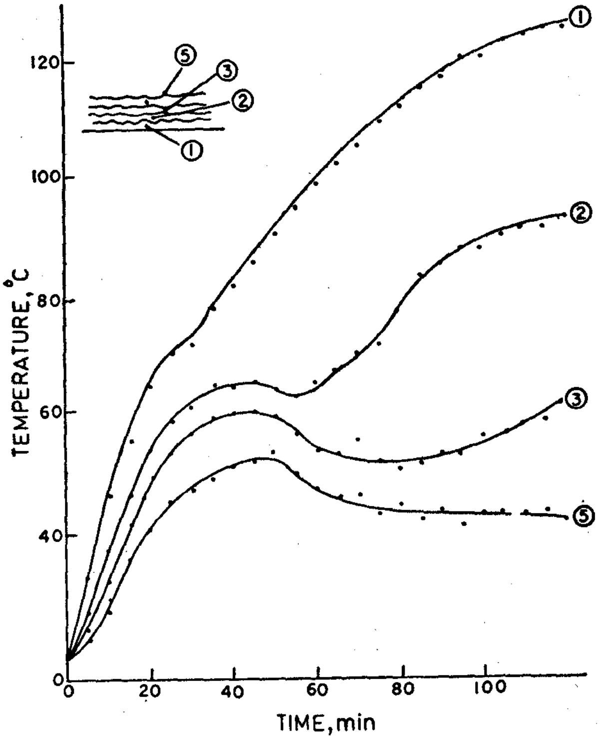

Fig. 3 — Temperature changes during contact drying

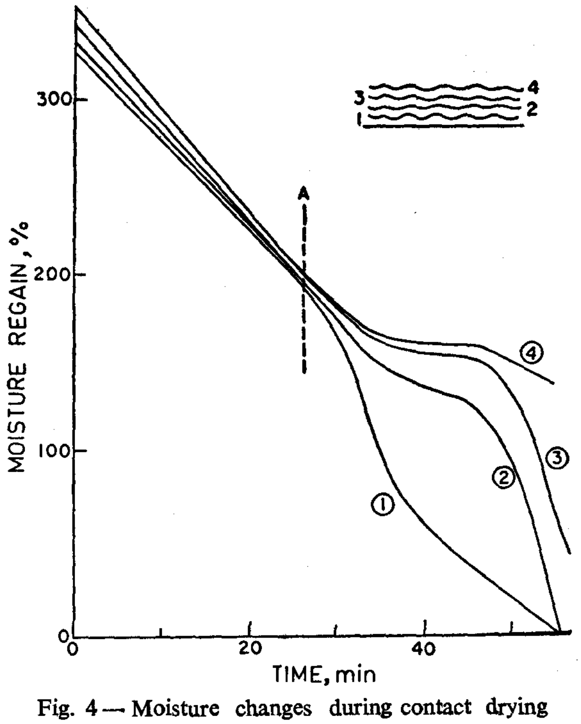

Fig. 4 — Moisture changes during contact drying

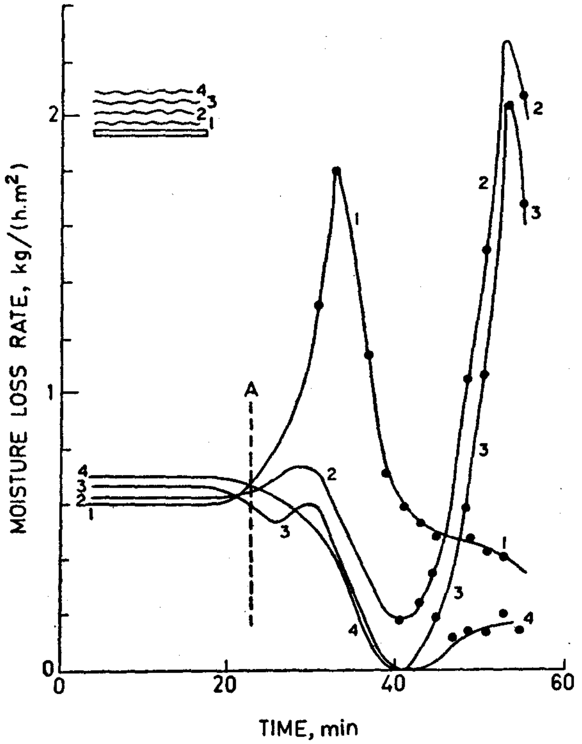

Fig. 5 — Changes in rate of loss of moisture during contact drying

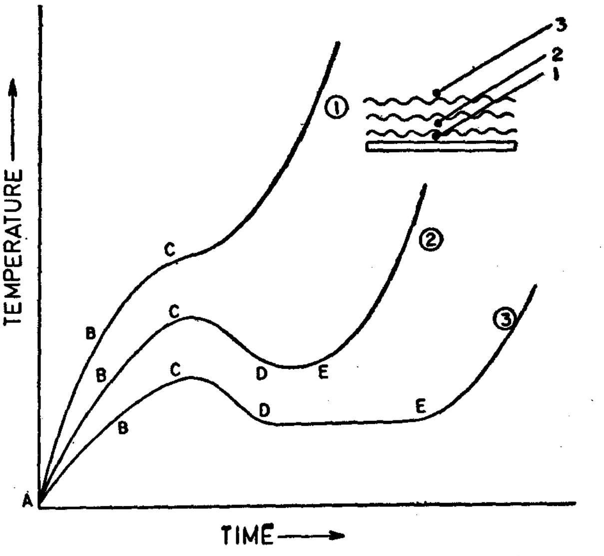

Fig. 6 — Generalized form of temperature characteristics of contact drying

has not been shown in Fig. 6, but such an isothermal phase is useful to incorporate, so that the characteristics will become more generalized and be applicable to other forms of drying also. After the second CTP, the temperature begins to rise at a gradually decreasing rate. This region is called the final temperature rise period or FTRP. This is followed by a third CTP corresponding to dry equilibrium. But the third CTP is of little interest from the practical drying point of view.

Temperature drop zone — Temperature drop is the most significant feature of the temperature profile. It is also an unexpected phenomenon, because, when a system is continuously supplied with heat, a drop in temperature does not usually occur. None of the theoretical papers[11-13] has anticipated such an occurrence. However, Wilson[15] has shown such a temperature drop during contact drying in one of his experiments. But his work was concerned mainly with problems of migration and he did not probe deeply into this interesting feature. To understand the underlying mechanism of this unusual phenomenon, various types of analyses were undertaken, such as temperature deficit plots, rate analysis and profile study.

Temperature profile at TDP — The most useful clue came from the plot of the temperature profile at TDP shown in Fig. 7. The thermocouple at the interface of the hot plate and the cloth indicated a temperature between 90° and 100°C, while the temperature of the metallic bulk of the hot plate was about 110°C. If we consider that the actual contact face lies between the region of the thermocouple junction and the bulk of the hot plate, as shown in the inset in Fig. 7, it becomes possible to infer that the temperature at the contact face must be close to 100°C at TDP, i.e. temperature drop occurs when the contact face reaches 100°C, the boiling point of water under atmospheric conditions.

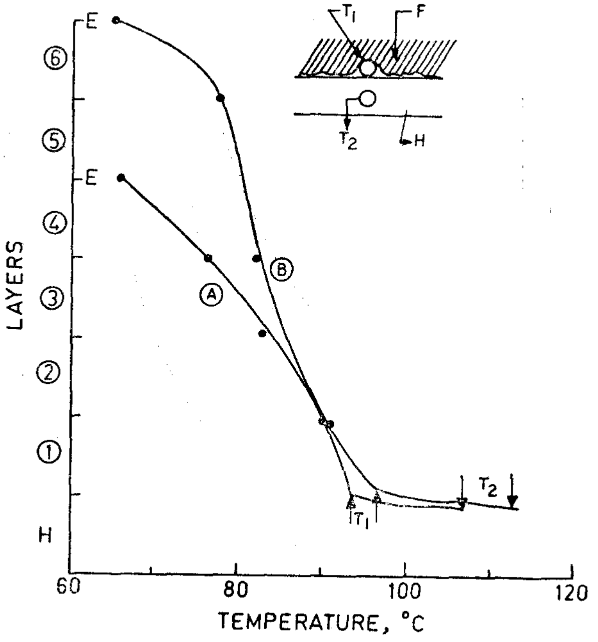

Fig. 7 — Temperature profile at TDP [E, evaporating surface; F, fabric; H, hot plate; and T_1T_2, thermocouples]

Moisture loss at TDP — As discussed earlier, Figs. 4 and 5 show that the rate of moisture loss remains constant and nearly the same in all the layers till TDP. Thereafter the rate of loss of moisture at the contact layer increases suddenly, while in the other layers it decreases. This gives the second useful clue to the temperature drop occurring during the contact drying process.

Explanation for the temperature drop — The two clues discussed above indicate that the temperature drop is associated with (i) the temperature at the contact surface reaching the boiling point, and (ii) profuse evaporation taking place in the contact region. The latter in turn means two things with respect to heat transfer ; (i) a great deal of heat is dissipated in the contact region itself, and (ii) with the formation of steam at the contact interface, the rate of heat transmission from the hot plate to the interior of the drying bed decreases substantially, because steam forms an insulating layer at the interface. The result of both these factors is that at this stage, the heat received by the upper layers is reduced considerably. At the same time, the evaporation taking place at the top surface does not change immediately, because the conditions of temperature, humidity and moisture in that region have not changed yet. Thus, as far as the top layer is concerned, evaporation continues at the same rate, but the heat received gets reduced considerably, i.e. the heat requirement here is in excess of the heat received. Therefore, to sustain the evaporation, the required heat is drawn from the internal heat content of the material in the neighbourhood and hence, the temperature drops in the upper layers.

The subsequent events can be visualized as follows. The temperature drop causes the evaporative rate to decrease and hence the heat requirement becomes less. Further, at the contact layer, the steam formed builds up pressure and starts percolating into the upper regions where through partial recondensation it transports heat at a gradually increasing rate. But for some time, the heat requirement for evaporation at the top layer continues to be in excess of the heat received from the heater. As long as this is the case, the temperature of the upper layers continues to drop, until the reduced heat requirement due to decreasing evaporation rate at the top layer is balanced by the increasing heat supply from the lower regions. Thereafter, the temperature once again begins to rise.

Moisture distribution during ITRP — The drying bed is composed of several layers, each one of which is exposed to widely different conditions. The contact layer receives all the heat and all the evaporation takes place in the top layer, while the intervening layers transport heat and moisture. Yet, during the first phase, i.e. ITRP, the moisture distribution is uniform throughout the bed, meaning thereby that all the layers share the overall evaporation equally during ITRP. The hypothesis put forward to explain this phenomenon is that during this phase, the interstitial spaces are well-filled with moisture in the liquid phase and spontaneous moisture movements take place within the bed, i.e. any moisture loss in one region, as for example in the evaporating surface, is immediately made up by moisture flowing into it from other parts of the bed. Thus, the moisture gets distributed evenly all over the bed.

This condition continues as long as the capillaries are flooded. But once evaporation occurs at the contact layer and steam starts percolating into the liquid regions in the upper layers, the interconnecting capillary channels get progressively broken up or emptied out and instantaneous exchange or equalization of moisture between different parts of the bed no longer takes place. Hence, after the temperature drop point, the different layers exhibit different patterns of moisture variation, as seen in Figs. 4 and 5.

Summary

Contact drying has not been studied much in detail so far. As such, the experimental studies reported in this paper bring to light some interesting features of the contact drying process. One of these is the occurrence of temperature drop in the drying bed even while heat is being supplied to the system. It was found that just at the onset of temperature drop, the contact surface reaches the boiling point and the contact layer suffers heavy loss of moisture. Based on these findings, the following possible explanation may be put forward. When the contact surface reaches the boiling point, profuse local evaporation take place. This dissipates most of the heat received from the heater, leaving the upper layers starved of heat. Thus, the heat required for evaporation in the top layer has to be layer drawn from the internal heat content of the upper layers, leading to a drop in their temperature.

Another interesting feature of the initial phase of drying is that the moisture distribution is uniform throughout the drying bed in spite of the fact that different layers are under different conditions. This is considered to be due to spontaneous convective movements within the drying bed during this phase when the internal capillaries are flooded with moisture in the liquid phase. This condition is disrupted after the temperature drop point, when the vapours generated at the contact surface break up the flooded state of the capillary channels. Thereafter, the moisture distribution is no longer uniform. These are largely qualitative explanations for the observed phenomena and for a complete understanding of the contact drying process, further studies are required.

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