The Dual Mechanism in Machine Drying of Paper

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Since early days of Paper making upto this date, various methods have been tried for drying paper. A broad classification of those methods may be made as follows :

(i) Air drying — natural and forced

(ii) drying on steam heated cylinders

(iii) drying by electric or high frequency electronic heating

(iv) drying by application of Radiant heat

(v) Fluidised-Bed drying

Of these, Air drying method though not suitable for high or even moderately high speed machines, a limited application of it are still to be found in several mills mostly engaged in the manufacture of very high grade papers. The last three i.e. Electric, Radiant heat and Fluidised bed drying are comparatively recent methods which are still under experimental stage and the economical advantages of these methods are yet to be proved. The second method viz., drying by steam heated cylinders is by far and large the most popular and conventional means of drying on which we shall presently concentrate. The scope of this paper is limited to a discussion on the two principal mechanisms involved in drying of paper on a Conventional Fourdrinier Machine.

Assuming 0.5% B. D. consistency of stock flowing on the wire from Machine flow box, we have to handle 199 tons of water for each ton of paper to be made. The sheet leaving suction couch roll normally contains moisture in the region of 85% so that, nearly 193.50 tons of water is removed by the wire part. It then enters the press parts and while leaving the last press contains approximately 65% of moisture effecting a further quality of 3.70 tons of water removal by application of mechanical force. Although it is always economical to remove water mechanically than to remove water by evaporation (the cost being approximately 10 times more in the latter case) - there is a limit beyond which water cannot be removed by mechanical means. On attaining this limit water could be further removed by evaporation only. Hence the need for dryers. Out of this remaining 1.80 tons of water nearly 1.75 tons (assuming 7% moisture in final paper) are to be evaporated in the dryer section. The highest efficiency of dryer section then lies in the minimum quantity of heat (or, steam at any particular pressure) that can effectively evaporate this 1.75 tons of water from the paper sheet. But before making any attempt to achieve this goal a reasonable understanding of the principal mechanisms involved in machine drying of paper is necessary.

The two most important mechanisms involved are :—

1. Mechanism of drying or water evaporation
2. Mechanism of heat transfer

DRYING MECHANISM :

Paper being porous by nature, drying of it is analogous to the drying of porous material. All such materials when dried under steady conditions exhibit an initial phase known as the *Constant Rate Period,* in which the rate of drying is constant. This rate does not continue till

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such material is completely dried, but as some definite moisture content known as *Critical Moisture Content* is reached the rate of drying begins to decrease. The period extending from the critical moisture content to complete drying is a gradual decreasing phase of drying which is known as *Falling Rate Period.* No solid can however be completely dried unless the surrounding atmosphere is absolutely dry. It will retain a cretain amount of moisture however prolonged the drying period be continued. This *"Equilibrium or Hygroscopic moisture content"* depends on the nature and structure of the substance and on the humidity of the ambient air.

While being dried, a porous solid like paper is regarded as consisting of a complex system of pores and capillaries which extend from the surface into the interior of the solid in a randomly distributed fashion. The distribution being such, some capillaries have their smallest openings on the surface while others have their largest openings. Since capillary rise is inversely proportional to the diameter of the capillary, it follows that more water will tend to flow on that part of the solid surface where concentration of smaller opening capillaries are more. Also a solid with a close-packed structure will have capillary forces larger when compared to those of a loose, fibrous material.

Before drying commences, the surface of Paper sheet is thoroughly wet with water which is contained in numerous pores and surface voids. As drying proceeds, this surface water is the first one to evaporte and so long this process continues the drying rate remains constant. During this period the efficiency of drying process or the rate of drying does not entirely depend on the evaporative capacity of the dryers only but is largely controlled by the capacity of surrounding (or Forced) air to remove the water vapour thus released from the paper sheet. In other words it is the vapour pressure difference between the surface of wet sheet and the surrounding atmosphere, which plays an important role in determining the rate of drying. As long as enough of water is available on the sheet surface for evaporation by the driers and the quality and quantity of air (i.e. temperature, Humidity and velocity at which air is impinging on the sheet) used for removing the water vapour remains constant, this phase of constant drying rate will be continued.

After this free water has evaporated from the surface, the capillaries will continue to supply moisture to the surface of the sheet. As long as this supply of water to the surface is sufficient to cope with the evaporative capacity of dryers and the vapour removal capacity of the surrounding air, the rate of drying will also remain constant. But as the sheet dries, a stage is soon reached when depletion of moisture occurs at the surface, i. e., the internal diffusion through capillaries fail to supply as much moisture as is demanded by the drying conditions. The falling rate of drying occurs at this time. The moisture of a paper sheet at which the drying changes from constant rate to falling rate is known as the critical moisture content. It marks the end of constant rate period and the beginning of falling rate period and denotes that the drying rate is no longer governed by the resistance to removal of water from the surface but by another mechanism where resistance to internal diffusion of moisture towards the surface predominates. In the falling rate period, lying between the critical moisture content and the hygroscopic moisture content, the rate at which the liquid can diffuse to the surface is the dominant and deciding factor in determining the rate of drying. The rate at which moisture can be removed at the surface or the atmospheric conditions play little part in determining the rate of drying. In other words the type and nature of the solid material being dried is of prime importance. The heat input and the heat transfer area remaining the same, the surplus heat must be absorbed by the material, effecting an increase in temperature of the sheet.

If the capillaries and pores are very small then water is drawn to the surface in a relatively rapid manner. But if the structure of the solid is loose and fibrous (as is paper sheet) the capillary tension is small which implies that water coming to the surface by internal diffusion is removed still faster than it can be replenished by the capillaries from the interior, so that passages near the surface are depleted of water. This occurs naturally at some later stage of the falling rate period—vaporisation then takes place beneath the material surface and vapour so formed diffuses through the air-filled passages in the relatively dry surface layer. The size of the capillaries, the external pressure and the drying temperature largely determine whether moisture transfer from the interior to the surface is primarily by liquid or vapour movement or by both. For example, with a porous solid like clay where large capillary forces and high resistance to vapour diffusion exists, vaporisation takes place at the surface down to a very low moisture content. But with a loose fibrous material like paper, the zone of vaporisation retreats from the surface little after passing the critical moisture content as the tendency for water to move to the surface is small. A thick sheet of paper while being dried will exhibit this phenomenon in a marked way as capillary forces are likely to produce a more prominent effect on thicker sheet than the thinner ones.

These being the general mechanism of drying, there is another phase in the process often referred to by some schools of thought as "*Zone of Unsaturated Surface Drying*". Immediately after the constant rate period and at the beginning of falling rate period a stage comes when evaporation occurs at the surface but the concentration of water being uneven on the surface the drying rate is decreased. This decrease in drying rate is ascribed to the surface effects and not the internal diffusion of moisture Although the rate of evaporation per unit area of free liquid remains unchanged but the surface inequalities give rise to uneven drying and the rate of drying per unit total surface area is less. This is referred to as the *Zone of unsaturated surface drying*.

The drying process and the mechanism of it may therefore be divided in the three main groups as follows—

(1) **Evaporation at the surface :—**

Resistance to the internal diffusion of liquid being small in comparision with the resistance to the removal of water at the surface. Water is either available at the surface or is supplied to the surface by internal diffusion as fast as it can be evaporated and keeps pace with the rate at which the surrounding (or, forced) air can remove this vapour. Since, rate of vapour removal is constant for constant atmospheric conditions, the rate of drying is also constant.

(2) **Evaporation at the Surface :—**

Resistance to the internal diffusion being large as compared with the resistance to the removal of water at the surface. Potentially, moisture can be removed from the surface by evaporation at a faster rate than it can be supplied by internal diffusion. Hence the drying rate decreases.

(3) **Evaporation in the interior of the solid :—**

Resistance to the internal diffusion of liquid being still larger in comparison with the total resistance to removal of water vapour. The liquid does not move up into the surface and vaporisation takes place at a plane beneath the material surface. The rate of drying is further reduced.

Let :

m = total moisture content expressed as the weight of water per unit weight of bone dry solid (i.e. stock)

t = drying time

Then, Rate of drying is given by the expression $R_d = -\dfrac{dm}{dt}$

If now this values of R_d at different stages of drying are plotted against their respective percentage moisture content (calculated on B, D solid basis), discontinuities will appear on the curve at points where changes in drying phases occur. The curve thus obtained (see figure 1) not only serves to locate accurately the critical points by simple inspection but the shape of the curve in the falling rate period, frequently gives information on the drying mechanism which is of great value in analysing the experimental data. A typical of such curves is represented below.

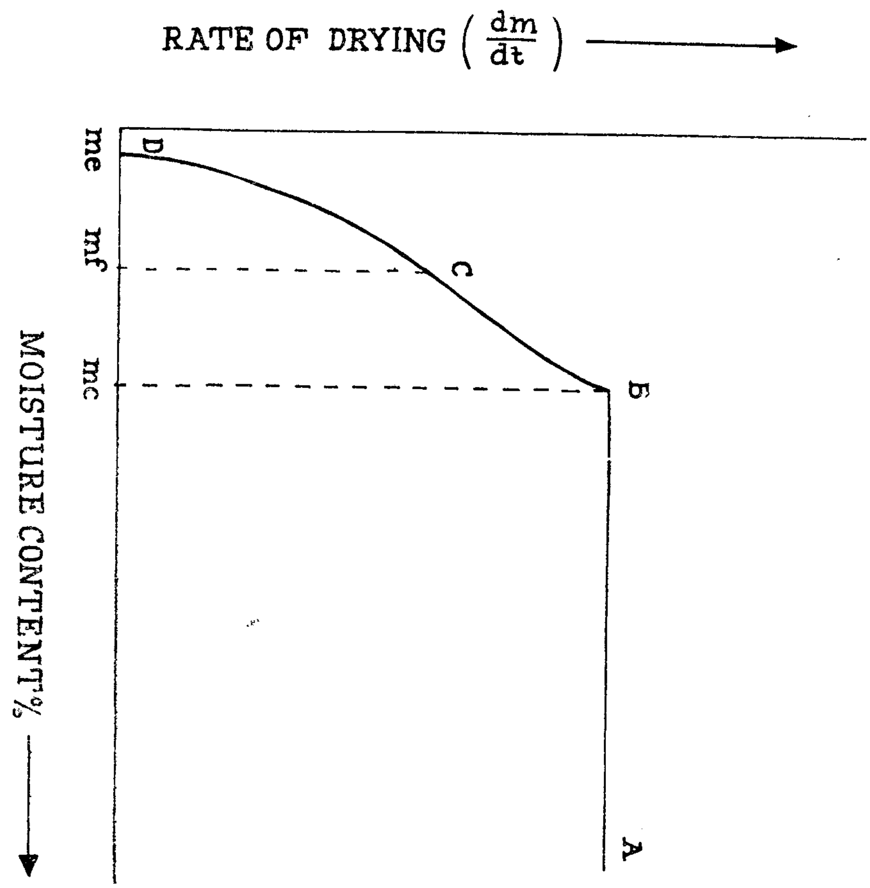

Fig. 1

The critical points on the curve will vary with various grades of paper, initial moisture content of wet sheet and drying conditions but in most cases the general shape will be nearly identical. In figure 1, the phase A,B represents the constant rate period which cases at point B and m_c, the corresponding point on 'X' axis represents the critical moisture content. The zone BC represents the earlier part of falling rate period when evaporation takes place on the surface, but internal diffusion of moisture to the surface cannot cope with the potential drying capability. This phase ends at point C, the corresponding moisture content being m_f. The last zone CD represents that phase where the plane of evaporation recedes into the sheet and vaporisation takes place into the interior of the paper body, m_e

being the equilibrium or hygroscopic moisture content corresponding to the ambient air condition.

But, what is the value of critical moisture content and where in the dryer bank it occurs? To answer these questions are not very easy as these depends on the nature and property of the material being dried, the initial moisture content of the material when it enters the dryers section and the drying conditions, all of whom vary to a considerable extent. Depending on these factors the constant rate period may take up an insignificant or a major portion of total drying time. When resistance to diffusion and rate of evaporation is low, the constant rate period is prolonged aad a very low value of critical moisture content results. On the other hand with a high diffusional resistance and high rate of evaporation, the constant rate period will be cut short resulting in a high value of critical moisture content. However, a point of interest is that, resistance to internal diffusion is somewhat reduced by application of heat by conduction or radiation resulting in an increased diffusion to the surface and consequently an extended constant rate period. With ordinary grades of paper and normal drying conditions the critical moisture content is probably attained when nearly 3/10 (between 1/5th and 2/5th) of the total water which came with the sheet at the time of entering the dryer section still remains within the sheet. This gives an approximate value of critical moisture content to be 50% calculated on B. D. solid basis or 33% calculated on total weight of solid and moisture basis. The location of it's occurance is possibly at a point lying between 2/5th and 3/5th of the way along the dryers under such normal conditions, although, as mentioned above they cannot be stated in a generalised manner.

MECHANISM OF HEAT TRANSFER :

In conventional drying of paper, heat is transferred from steam in the drying cylinders to the sheet of paper being dried, through various layers interposed between them. The study of heat transfer of any kind is based on the following Fundamental conception—

"When a difference of temperature exists between two points, energy in the form of heat is transferred from the point or region at higher temperature to that at lower temperature in such a way that the heat emitted from warmer region is balanced by the heat absorbed by the cooler region."

The three essential mechanisms by which heat may be transferred are (1) conduction ; (2) convection & (3) radiation. Evaporation and condensation although are customarily regarded as separate processes, strictly, they are only special forms of convection. In actual drying on the paper machine, all three methods of heat transfer occur simultaneously. In studying them however, their effect is combined and considered as conduction.

1. Conduction :

Transfer of heat by conduction from one part of the body to another part arises from the fact that the Kinetic energy of the molecules in a region of the body at higher temperature is greater than that of molecules in a region of lower temperature. This excess energy at the warmer region is transmitted to the cooler region without discontinuity, and is accompanied by a continuous fall of temperature in the former region.

Fourier's law states that—"The rate of Flow of heat through a material is proportional to the cross-sectional area of the material and the temperature gradient between the two surfaces." or, if—

Q = Quantity of heat flowing in time 't'

A = Cross-sectional area perpendicular to the direction of flow

θ = temperature at the warmer surface.

X = thickness of the material in the direction of flow

then, according to Fourier's Law :-

$$\text{Rate of heat flow} = q = \frac{dq}{dt} = -K.A\frac{d\theta}{dx}$$

Where K is a factor known as the "Thermal conductivity of the material and defined as the quantity of heat passing in unit time between the opposite faces of a unit cube of the material when unit temperature difference is maintained between the surfaces. In British unit 'K' is expressed as B. Th. U ; per hour ; per square foot area ; per foot thickness ; per °F.

In the study of conduction of heat as applied to machine drying of paper, the following two aspects are important :—

(a) conduction of heat by radial flow through a thick hollow cylinder, which conforms to the manner in which heat is conducted through the walls of steam heated drying cylinders.

(b) conduction of heat through concentric layers of different materials. — This, of course assumes the condition as if heat transfer is effected from steam to wet sheet of Paper by conduction only through the concentric layers of various materials interposed between them, which is obviously not the case. Further, perfect contact between the concentric layers is also assumed making no allowances for losses of heat at edges, boundaries and interfaces. But the fact remains that, when two surfaces are brought together, the contact is not perfect.

However, by extending the fundamental equation of heat conduction (Fourier's Law), the following mathematical expressions could be established—

(i) Rate of flow of heat per unit length of the drying cylinder,

$$q_1 = \frac{2\pi k(\theta_1 - \theta_2)}{\log_e\left(\frac{R_2}{R_1}\right)}$$

(ii) Rate of flow of heat per unit area of the outer surface of the cylinder

$$q_2 = \frac{k(\theta_1 - \theta_2)}{R_2 \log_e\left(\frac{R_2}{R_1}\right)}$$

Where, K = Mean value of Thermal conductivity of the material of the cylinder over a temperature range of θ_1 and θ_2.

R_1 & R_2 = Internal and External radii of the cylinder.

θ_1 & θ_2 = temperatures of the internal and external faces of the cylinder, θ_1 being the higher.

(iii) The rate of heat flow through 'n' concentric layers of various materials interposed between steam and wet sheet of paper :

$$q = \frac{2\pi(\theta_1 - \theta_n + _1)}{\frac{1}{k_1}\log_e\left(\frac{R_2}{R_1}\right) + \frac{1}{k_2}\log_e\left(\frac{R^3}{R_2}\right) + \dots\dots\dots + \frac{1}{k_n}\log_e\left(\frac{R_n + _1}{R_n}\right)}$$

Where :—

K_1 ; K_2 ; K_3 ... K_n = thermal conductivities of successive layers interposed, K_1 being adjacent to steam.

R_2 ; R_3 ; $R_4 \dots R_n + _1$ = outer radii of successive layers respectively

θ_2, θ_3, $\theta_4 \dots \theta_n + _1$ = temperatures at outer surfaces of successive layers respectively.

θ_1 & R_1 = temperature at inner surface and inner radius respectively of the first layer adjacent to steam.

2. Convection :

Transfer of heat by convection is effected by the movement of fluid particles themselves. Since, convection involves the flow of fluids, consideration of the various characteristics of fluid flow such as stream line and turbulent flow are of utmost importance. Reynold's dimensionless number gives a clue to this.

When a fluid flows over any surface, a fluid film is found in contact with the surface irrespective of the character of fluid flow. In streamline flow, a thin film of fluid immediately adjacent to the solid surface becomes stationary but as the distance from the surface increases the velocity is gradually picked up by the fluid until it reaches certain distance when the streamline motion sets in. In case of turbulent flow, apart from this stationary film immediately adjacent to the solid surface, there exists a second or buffer layer forming a transition zone between the first zone and the main turbulent body of the fluid. This transition zone is composed of eddy currents moving at a lower velocity than the main fluid. In the study of heat transfer, this stagnant Film adhering to the surface is regarded as a barrier to the flow of heat but its effectiveness is decreased by increasing the velocity since, this will set up turbulence in the flow thereby reducing the thickness of the stagnant film. Also, the eddies produced by turbulence will continually bring fresh particles of fluid near the surface, effecting a better diffusion of heat through the thin stagnant film.

Transfer of heat between a fluid and a solid surface by convection is often referred to as "surface conductance due to convection" For it is a process of conductance of heat through a stagnant film adhering to the surface. This surface conductance (h_c) when expressed in terms of heat units ; per unit time ; per unit area ; per unit difference of temperature between the fluid and solid surface is known as *"Film co-efficient of surface conductance."*

Derivation of mathematical expressions from a rigid analysis of the analogy between heat transfer and fluid flow are very complicated. But taking into account all the variables which may influence the conductivity and thickness of the stagnant film and employing the technique of dimensional analysis, a simpler expression with reasonable accuracy has been obtained as follows :

$$\left(\frac{h_c d}{K}\right)=\left(\frac{dvp}{n}\right)^x \cdot \left(\frac{c_p . n}{K}\right)^y$$

Where—

h_c = Film co-efficient of surface conductance.
d = diameter of fluid stream.
k = thermal conductivity of film adhering to the surface.
v = Velocity of fluid stream.
p = absolute density of the fluid.
n = co-efficient of viscosity of the fluid.
c_p = specific heat at constant pressure of the fluid.

After detailed investigations undertaken to determine the value of x and y in the above equation, the best agreement between experiment and theory for heating of fluids in turbulent flow in horizonal tubes is given by :

$$h_c = \text{Constant.}\left(\frac{K}{d}\right) \cdot \left(\frac{dvp}{n}\right)^{0 \cdot 8} \cdot \left(\frac{{}^c p \cdot {}^n}{K}\right)^{0 \cdot 4}$$

If h_c is expressed in B. Th. U/hr/Sq. Ft/°F, the constant has a value of 0.0225.

The rate of heat flow through any such stagnant film is then given by :

$$q = h_c . \ A. \ \triangle\theta \ ; \ \text{B. Th. u/hr.}$$

where,

A = Area of heat transfer.
$\theta\triangle$ = Temperature difference between two sides of the stagnant film.

(3) Radiation :

In this method, heat is transmitted across the space from a body at higher temperature to another body at lower temperature without heating the medium in the space. In the elementary molecular theory, all mater is assumed to be made up of molecules which are in a state of vibration depending on the temperature. These vibrations will set up radiant heat motions from a hot body in a manner similar to wave motions of light energy (heat waves being longer than light waves). Any colder body having a suitable period of vibration, on encountering this heat wave, will have its vibrations increased thus absorbing heat and rising in temperature. Any heat energy not absorbed by the receiving body will be reflected from or transmitted through the material of the body. At low temperature, heat transfer is chiefly due to conduction and if the system is fluid, it is supplimented by convection. Radiation becomes a noticeable factor at moderately high temperature and increases rapidly with increasing temperature level. At very high temperatures radiation becomes the dominant process.

Different substances vary in their radiating and absorbing properties, the absorptivity of perfect black body being taken as unity. Stephan's law which connects the rate of emission and temperature states that ; the rate of emission of radiant heat from any surface is proportional to the fourth power of the Absolute temperature of the said surface. The total radiant heat energy emitted per unit time, per unit area by a black body is given by the expression :

$Q = \sigma . T^4$ (Absolute). The value of σ , known as Stephan-Boltzmann constant is equal to 5.71×10^{-5} ergs/sq.cm/sec/(°C)^4 or, 17.25×10^{-10} B.Th.u/Sq. Ft./hour/ (°F)^4, when converted into British Units.

A heated cylinder surface of area A_s, emissivity Σ, and temperature T_1 (Abs.) when exposed to a colder surroundings at temperature T_2 (Abs.), the rate of heat transfer by radiation is given by the expression :

$$q = \sigma . \Sigma . A_s (T_1^4 - T_2^4) \quad \text{B.Th.u/hr.}$$

The value of emissivity Σ for a polished iron surface at about 250° is approximately 0.28.

OVERALL HEAT TRANSFER :

In machine drying of paper heat is transferred from steam to the wet sheet of paper by all the three processes described above i.e. conduction, convection and Radiation. Several expressions have been developed for computing the heat transfer effected by each of these processes involved but, in practice it is frequently impossible to isolate the individual contribution made by each of them to the nett heat transfer—the main difficulty being measurement of temperature at the surface boundaries involved. If however, a concept regarding each of the interposed layer forming a resistance to the flow of heat can adopted then a possible expression involving only the inner and outer surface temperatures may be arrived at. This will eliminate the consideration of intermediate surface as far as temperature is concerned.

When two fluids are separated by a solid surface the flow of heat under steady conditions from one fluid to another is given by—

$$Q = H.A. \triangle \theta \quad \text{B. Th.u/hr.}$$

Where : A = Heat transfer area, normal to the direction of flow.

$\triangle\theta$ = temperature difference between the two fluids.

H = overall co-efficient of heat transfer or, Heat transferred/unit time/unit area/unit temperature difference.

Obviously, 'H' can vary over a wide range according to the nature and velocity of the fluids and the material interposed between the fluids. To find out a general expression for the value of 'H' let us assume the overall resistance to heat flow of the interposed materials (comprising all the layers taken together) to be 'R'. Then 'R' is the reciprocal of overall heat transfer co-efficient i.e. 'H', or in otherwords

$$R = \frac{1}{H} \text{ ; and } H = \frac{1}{R}$$

Now, this 'R' is made up of all individual resistances offered by each layer interposed between steam in drying cylinders and fluid film on the outer surface of paper sheet. The resistances likely to be encountered in machine drying of paper are as follows :

(I) R_1=Resistance due to fluid film in contact with the deposit on the inside surface of the cylinder. This can be expressed as $\frac{1}{h_c}$, where h_c = Film co-efficient of Surface conductance.

(II) R_2=Resistance due to deposits or contamination on the inside wall of cylinder --this can only be determined by measuring the overall co-efficients when the surface is clean and when contaminated. This is expressed as $\frac{1}{h_d}$.

(III) R_3=Resistance due to cylinder wall which may be expressed as $\frac{T}{K_m}$ where, T = thickness of cylinder wall and K_m = mean value of thermal conductivity of the material of cylinder over the given range of temperature difference.

(IV) R_4=Resistance due to fluid film between the outer surface of the cylinder and the inner surface of paper sheet, expressed as $\frac{1}{h_f}$. In case of perfect contact between cylinder and paper, R_4 = O.

(V) R_5=Resistance due to paper sheet expressed as $\frac{X}{K_p}$, where X = thickness of paper sheet and K_p = apparent ther-mal-conductivity of paper.

(VI) R_6=Resistance due to fluid film on the outer surface of paper sheet = $\frac{1}{h_o}$

Hence, $R = R_1 + R_2 \quad + R_6$

$$= \frac{1}{h_c} + \frac{1}{h_d} + \frac{T}{K_m} + \frac{1}{h_f} + \frac{X}{K_p} + \frac{1}{h_o}$$

$$\text{Now, } H = \frac{1}{R} = \frac{1}{\frac{1}{h_c} + \frac{1}{h_d} + \frac{T}{K_m} + \frac{1}{h_f} + \frac{X}{K_p} + \frac{1}{h_o}}$$

$$\therefore \ Q = \frac{A. \triangle \theta}{\frac{1}{h_c} + \frac{1}{h_d} + \frac{T}{K_m} + \frac{1}{h_f} + \frac{X}{K_p} + \frac{1}{h_o}} \text{ B.Th.u/hr.}$$

Obviously, the question now left open is how to exploit the principles of above two mechanisms at their best, to extract highest efficiency from our dryer sections. Performance of dryer part is usually expressed in terms of weight of paper dried or, weight of water evaporated per unit area of drying surface per unit time. The expression involving weight of paper dried/unit area of dryer surface/unit time, is not a true guide since, it does not take into account the moisture content of wet sheet while entering the dryers, which may vary considerably. The other expression involving weight of water evaporated/unit area of dryer surface/unit time, gives an idea of the performance level in general, but fails to furnish adequate informations on true efficiency unless the maximum capacity of dryer section is evaluated in the light of above two mechanisms. This becomes more evident when one attempts to compare the drying performances of two or more paper machines. For, even if, the substance and grade of paper remains the same, the mechanisms and characteristics of drying as described above may not be tuned in the same way.

Therefore, if it is desired to establish a true yardstick for evaluating the performance level of our dryers, then the first step is to determine the maximum capacity of these dryers in respect of each individual grade of paper. An interesting experiment could be undertaken in this direction which, besides rendering us the useful knowledge about limitations of our dryer's capability (under optimum operational conditions), is very likely to result in an increase in the machine speed than has been hitherto attained. For convenience, the grade and substance of paper which is manufactured in relatively greater quantity may be taken for experimental purpose.

As for drying rate, it would generally be advantageous to have the continuous rate period extended and falling rate period reduced to the maximum so as to get a minimum value of critical moisture content. By admitting steam inside the successive cylinders in graded manner; maintaining temperatures of dryer surfaces to a steady state paying necessary heed to temperature difference between cylinder surface and paper sheet at each location and controlling temperature, humidity and velocity of surrounding air, this could be achieved with reasonable success. It must however, be pointed out that, beyond a certain limit this shifting of critical moisture content towards a lower value will not pay any dividend. Since, under such circumstances, the rate of drying during continuous rate period will have to be lowered sufficiently so that, in all probability, this rate will not differ to a great extent from the drying rate usually obtained in falling rate period. It is only after a detailed study of the drying mechanisms involved, that this balancing point (i.e. optimum value of critical moisture content for a particular grade of paper) may be determined.

The manner in which the temperature at the surface of successive cylinders should be graded is difficult to predict, but in general, the following temperature curve shall be the natural choice.

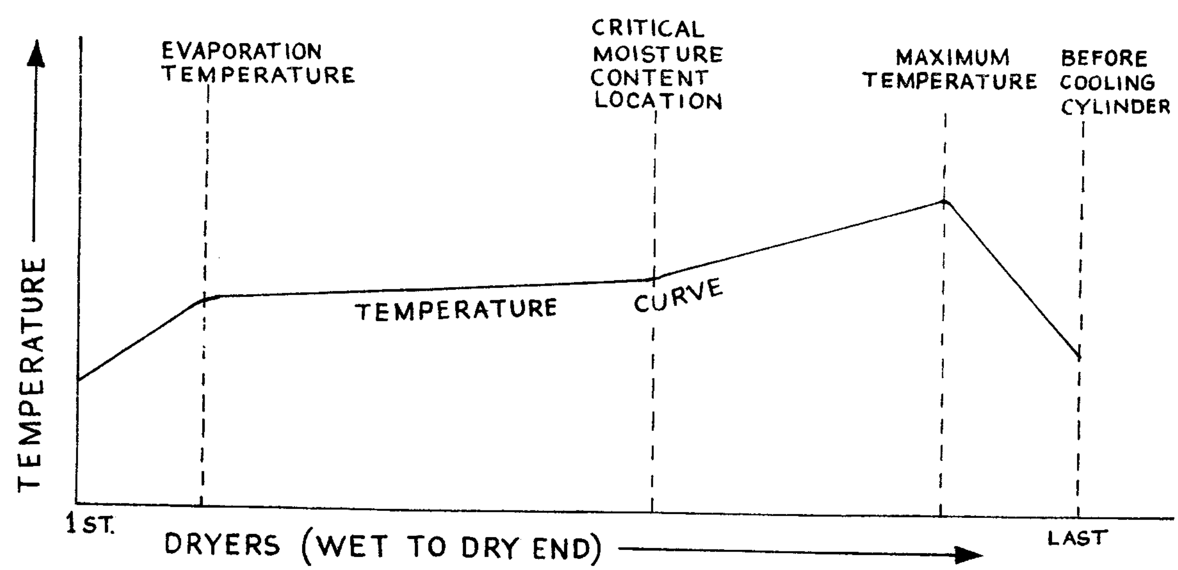

Fig. 2

The first few cylinders will raise the temperature of paper sheet to evaporation temperature. After this, till the end of continuous rate period the sheet temperature will not rise appreciably, Most of the heat transferred will be utilised for evaporation and ideally, the sheet temperature during this period shoud be the same as wet bulb temperature. In practice however, the temperature of the sheet may gradually rise to a little extent as it passes over the successive dryers, due to difficulties in maintaining perfectly steady conditions. The temperature gradient as shown in Fig. 2 during constant rate period is suggested to make allowance for such rise in sheet temperature so that, the difference of temperature between cylinder surface and paper sheet remains the same throughout this phase for effecting steady flow of heat. In the falling rate period the temperature at drying surface must be kept at reasonably higher level, as during this time—

1. High temperature will accelerate the rate of diffusion of moisture from inside the pores and capillaries.
2. Owing to relatively less evaporation in this zone, the temperature of paper sheet will tend to increase and approach the dry bulb temperature, thereby decrasing the temperature difference between dryer surface and paper sheet. This difference in temperature must be kept high in order to facilitate efficient heat transfer.

Another passing point of importance is to keep the inner and outer surface of dryers very clean. The inner surface, to eliminate R_2 as much as possible and the outer surface, to minimise R_4 by ensuring a nearly perfect contact between cylinder surface and paper sheet. This latter aspect is very much improved if the tightness of paper sheet throughout the dryer section and the felt tension are kept considerably high. This of course, will speak on the shrinkage and elasticity of Final paper but here also some sort of balance between the divergent objectives is to be found out. Further, it is possible to analyse the heat transfer efficiency of a dryer in a reasonable measure from the rate of steam flow and rate of condensate flow to and from that dryer. A water—logged cylinder will need more power for drive than is usuall required.

Such an undertaking may prove to be of immense value and guide us in future to handle our dryer sections with perfect confidence. All, that is necessary to embark on such a project include one pyrometer, one hygrometer, and one anemometer.

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