Fundamentals of Paper Drying – Theory and Application from Industrial Perspective

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1. Introduction

No manufactured product plays a more significant role in every area of human activity than paper and paper products. Its importance in everyday life is obvious from its use in recording, storage and dissemination of information. Virtually all writing and printing is done on paper. It is the most widely used wrapping and packaging material, and is important for structural applications. The uses and applications for pulp and paper products are virtually limitless. Apart from the products and services that it provides, the paper and pulp industry is one of the major manufacturing industries in the world providing employment for vast number of people and contribute to national economy.

The paper making process is essentially a very large dewatering operation where a diluted solution of pulp suspension with less than 0.5% fibre solid is used. The major sections of a paper machine consist of: forming section, press section and dryer section. In the forming section, the fibres present in the diluted pulp and water slurry form paper web through drainage by gravity and applied suction below the forming fabric. In the press section additional water in removed by mechanical pressure applied through the nips of a series of presses or rotating rolls and the wet web is consolidated in this section. Most of the remaining water is evaporated and inter-fibre binding developed as the paper contacts a series of steam heated cylinder in the dryer section. Water removal from the wet web to the final moisture level between 6% and 7% is a critical step of papermaking. Majority of the functional properties of paper are developed in this section.

In spite of its key role in papermaking, large equipment size, and large capital and operating costs, drying is arguably the least understood papermaking operation. Books on papermaking technology generally devote fewer pages to drying than other papermaking operations such as forming, pressing or calendaring. A similar situation is found in papermaking courses, in which drying occupies a shorter time than the proportion of space it takes in a paper machine. Furthermore, a large portion of that time is devoted to the description of the equipment by its suppliers rather than to its operation by the papermakers.

The dryer section of a paper machine removes between 1.1 and 1.3 kg of water per kg of paper compared to 200 kg and 2.6 kg in the forming and press sections respectively. It is significantly more expensive to remove this water than for any other section of the machine (Reese, 1988). The relative costs of dewatering are: forming section 10%; press section 12% and dryer section 78%. The dryer section is by far the largest consumer of thermal energy of a paper machine. Other important facts about the dryer section and paper drying are the dryer section constitutes approximately 60% of the total length of a paper machine, except for a tissue machine; and almost 40% of total capital cost of the machine.

The lack of knowledge about drying also persists in the mills. Detailed information and knowledge on the theory and operation of the other sections of the paper machine are quite often at the fingertip of the machine operators and technical staffs, while the dryer section is often at the bottom of the mills' priority list. There are several reasons for this lack of knowledge and interest in this important papermaking operation. Perhaps the first among them is the wrong perception that drying has little effect on product quality. The other reason is the complexity of the paper drying process that involves heat transfer, evaporation and water removal processes where steam pressure, cylinder surface temperature, dryer pocket conditions, hood balance and condensate removal play key roles in determining drying capacity and final product quality. The operator and papermakers often treat the dryer section as a black box.

Rising energy costs are forcing papermakers to pay more attention to energy efficiency, and specially steam usage. In many mills due attention is given to the steam and condensate system. However, the importance of hood balance and pocket air ventilation is quite often ignored. This could result in excessive energy consumption in the dryer section and/or reduction in drying efficiency with consequential loss in productivity. Deterioration of product quality could also be due to neglect in optimization of pocket ventilation system (Ghosh and Oxley, 2007).

1.1 Manufacture of paper

The art of papermaking had its origin in China as early as 100 AD. The first mechanized papermaking process was carried out by Foudrinier brothers in UK in 1804. Since that time many improvements over the original paper machine have been made, but the basic construction remains basically the same. In virtually all papermaking of today, cellulose fibres are used as the raw material. The prime source of cellulose is trees, especially pine, spruce, birch and eucalyptus. Modern papermaking uses both virgin and recycled fibres, depending on the requirements of the final products.

Pulp production from virgin fibres is generally divided into two main categories: chemical and mechanical pulping. In chemical pulping process wood chips are cooked in a digester with chemicals under pressure and at elevated temperatures. The relatively undamaged fibres are recovered via various unit operations. The yield is around 50%. Mechanical pulps have a much higher yield, more than 95%, but the fibres are treated more violently and are significantly shorter than chemically treated fibres. The most common method of mechanical pulping employs large rotating discs with sharp edges. The wood chips are pressed against the discs so that the chips are torn apart. Recycled fibres could be mixtures of both chemical and mechanical pulps at various proportions with varying level of contaminations as the papers used are post-consumer. The recycled papers are reslushed with water followed by separation of contaminants before being used in the papermaking process.

Regardless of the nature of the pulp, whether it is chemical, mechanical or recycled, is either softwood or hardwood, the basics of papermaking are similar. Many chemical additives are used to promote certain properties of the final products, such as optical properties, dry and wet strength or resistance to water absorption. The pulp and additives are mixed in water slurry having a dry substance content of less than 1%. There are three basic steps in the paper manufacturing process (i) forming (ii) pressing and (iii) drying. In the forming stage, the slurry is distributed evenly across a moving perforated screen, the wire. The dewatering in this part of the paper machine, known as the wire or forming section, occurs mainly under gravitational forces. A continuous web, with a dry solids content between 15% and 25%, is formed at the end of the wire section. The web enters the press section next. Mechanical compression in the press section removes water to solid level between 33% and 55%, depending on the paper grade and press section design. The third part of the paper machine is called the drying or dryer section. The paper web passes over rotating, heated cast iron cylinders and the most of the remaining water is removed by evaporation. When the paper leaves the dryer section its solid content has increased to about 90-95%. Thermal energy is alone used for the dewatering in the dryer section and application of heat transfer is fully operational in this stage of papermaking. A schematic drawing of a paper machine is shown in Figure 1.

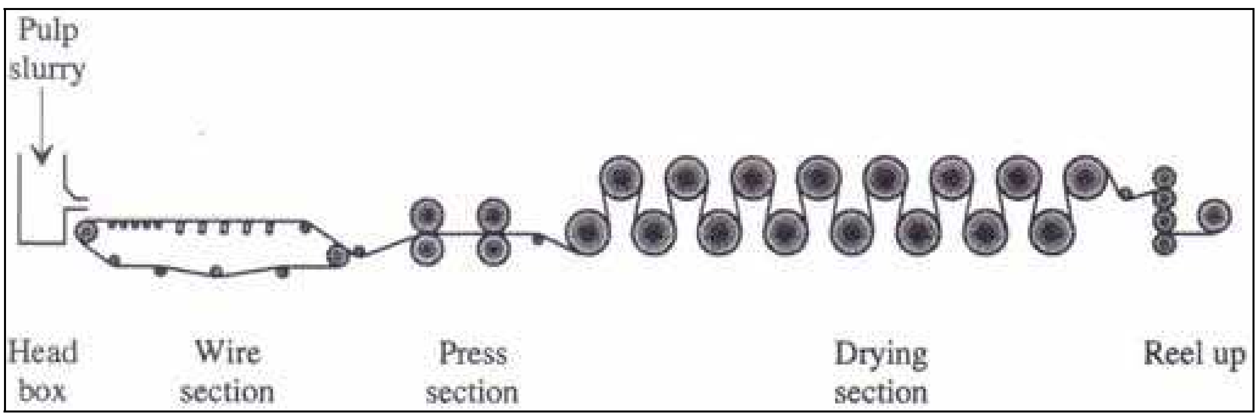

Fig. 1.1 Schematic layout of a paper machine with multi-cylinder dryer section

2. Fundamentals of paper drying

Contact drying with steam heated cylinders is the predominant method of drying in paper and paperboard machines. Besides conductive heat transfer between hot cylinder surface and the wet web, the role of air that is either the drying medium or surrounds the drying atmosphere is very significant. Paper drying is associated with both heat and mass transfer. The heat energy released when steam condenses is transmitted through the dryer shell to the wet paper and this constitutes the heat transfer aspect of drying. The air receives the water vapour evaporated from the paper. The removal of this vapour from the sheet into the air stream constitutes the mass transfer aspect of paper drying. As a result, the operation of a dryer section must be optimized in terms of both heat transfer and water removal. The factors which most influence paper drying operation are (i) steam pressure and temperature; (ii) temperature and humidity of air; (iii) energy content of steam and (iv) heat and mass transfer coefficients.

2.1 Properties of air

Atmospheric air is almost never dry and contains a certain amount of water vapour, which depend on the temperature of the air and the amount of water vapour available. Warm air can absorb more water vapour than the same volume of cold air. Thus the condition of air in the dryer section is important. The relationship between the temperature of the air and the amount of water it contains is described by the psychorometric chart, which plots humidity versus temperature. Well established equations can also be used to calculate thermodynamic properties of air.

2.1.1 Partial vapour pressure

Partial vapour pressure of free water can be calculated using Antoine's equation (Perry, 1997):

$$\ln(p) = A - \frac{B}{T + C} \tag{1}$$

where

p partial pressure, kPa

T temperature, Abs

A, B, C constants; A= 8.007131; B = 1730.630; C= 233.426

At the beginning of drying, partial vapour pressure at the paper surface is the same as for a free water surface at corresponding temperature and this condition prevails as long as transport can bring new water to the surface replacing the water that evaporated. In the end phase of drying, partial vapour pressure on the web surface is lower than for free water surface at the corresponding temperature. This is because diffusion from the interior from the web controls vapour transport to the web surface and the hygroscopic nature of pulp fibres.

2.1.2 Relative humidity

Relative humidity is the ratio between the amount of water contained in the air and the total amount it can contain at the same temperature and is expressed as percentage. When relative humidity reaches 100%, the air is said to be saturated and water vapour condenses in the air and falls out as small droplets. Relative humidity can be calculated from the following equation:

$$RH = p^{*}100 \ / P_s \tag{2}$$

where

RH % relative humidity

p partial vapour pressure, kPa

P_s saturated vapour pressure of water at temperature T.

Evaporation can still take place at 100% RH if the vapour pressure of the water in the drying surface exceeds that of water at the same temperature, i.e. the drying surface is hotter than the surrounding saturated air. However, the water evaporated from the drying surface will form a mist since the ambient air is incapable of absorbing any more water vapour.

2.1.3 Absolute humidity

Absolute humidity refers to the moisture content of the air and the typical units are kg H_2O/kg dry air. Psychometric chart could be used to obtain humidity value provided wet and dry bulb temperatures are known. Alternatively, it can be calculated from the partial vapour pressure of water in the air from the following equation:

$$H = M_w p / \left[M_a * (P - p) \right] \tag{3}$$

where
- H absolute humidity, H_2O/kg dry air
- p partial vapour pressure, kPa
- P barometric pressure, kPa
- M_w Molecular weight of water: 18.02
- M_a Molecular weight of air: 28.97

If relative humidity and temperature values are known, the absolute humidity can also be calculated using the following equation:

$$H = 0.00620689 * RH * p / (1 - .01 * RH * p) \tag{4}$$

where
- H Absolute humidity, H_2O/kg dry air
- p partial vapour pressure, kPa and can be calculated using equation (1)
- RH relative humidity, %

2.1.4 Sorption isotherm

Due to hygroscopic nature of paper, partial vapour pressure at the web surface or anywhere inside the web is a function of local temperature and moisture content. A correlation between relative humidity and the equilibrium moisture content at a constant temperature is a sorption isotherm. Equilibrium moisture content at a certain relative humidity gives slightly different values depending on whether the equilibrium is approached through wetting of initial dry materials (adsorption) or through drying (desorption). This phenomenon is called hysteresis.

The sorption isotherm of paper depends on the type of fibres that have been used to manufacture the paper. Various correlations for sorption isotherms are available in the literature (Karlsson et al.,, 1993; Lampinen and Toivonen, 1984). The following one is best suitable for mechanical pulp (Heikkila, 1993):

$$\rho = 1 - e^{-\{(C_1 Z^{C_2}) + (C_3 T Z^{C_4})\}} \tag{5}$$

where
- $C_1 = 47.58$; $C_2 = 1.877$; $C_3 = 0.10085/\ ^{o}C$; $C_4 = 1.0585$
- ρ Relative Humidity of air inside chamber/room/store ;
- ρ*100 Relative Humidity, %
- Z Equilibrium Moisture Ratio; Z*100 = Moisture Uptake, %
- T Temperature, °C

Graphical representation of equation (5) is shown in Figure 2.1.

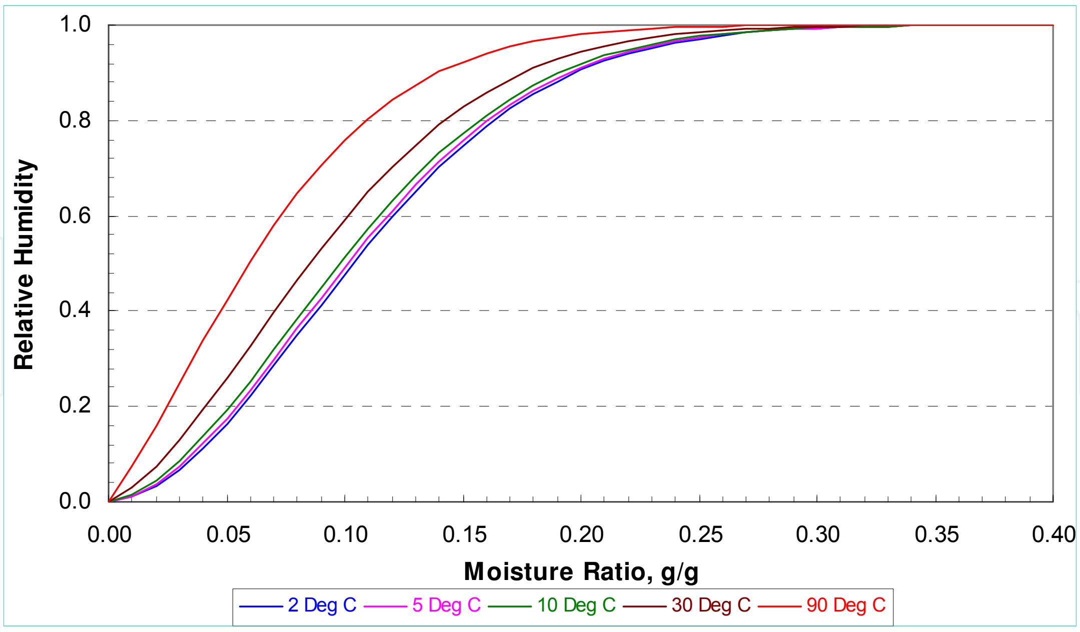

Fig. 2.1 Figure 16 Moisture Uptakes vs. Relative Humidity at Various Temperatures

2.1.5 Heat transfer

In paper drying the predominant mode of heat transfer is by conduction for manufacturing majority of paper grades. Convective heat transfer also play significant role in dryer pocket ventilation system. For tissue grades where hot air impingement on the web is applied, heat transfer by convection is most important. Radiation heat transfer is usually ignored in conventional paper drying since its contribution to the overall heat transfer is much less than that due to conduction and convection.

The basic form for one dimensional steady state heat *conduction* is shown in equation (6), while that of *convective* heat transfer is shown in equation (7). :

$$Q = kA\Delta T / \Delta X \tag{6}$$

$$Q = hA\Delta T \tag{7}$$

where

- Q heat transfer rate, J/s (W)
- k thermal conductivity, W/m.K
- A heat transfer surface area, m^2
- T Temperature, K
- X diameter or thickness, m
- H heat transfer coefficient, $W/m^2\,^oC$

The rate of conduction heat transfer is directly proportional to the thermal conductivity k of the material and to the temperature gradient, $\Delta T/\Delta X$. Heat transfer coefficients depend on both the physical properties of the fluid and the flow conditions. In paper drying, forced convective heat transfer occurs at the interface between steam and condensate in the cylinder, and between paper and air outside the cylinder. The type of flow is turbulent. The evaluation of heat transfer is difficult. Convective heat transfer is regarded as the flow of a fluid and dimensional analysis is used to characterize heat transfer coefficient, h. The parameters involved in convection may be grouped into three dimensionless numbers; the Nusselt number, the Reynolds number and the Prandlt number. These are defined as:

$$\text{Nusselt number} = \text{Nu} = \text{hD}/\text{k} \quad (8)$$

$$\text{Reynolds number} = \text{Re} = \text{DV}\rho/\mu \quad (9)$$

$$\text{Prandlt number} = \text{Pr} = \text{C}_\text{p}\mu/\text{k} \quad (10)$$

where

- h thermal conductance
- D characteristic dimension, e.g. diameter
- k thermal conductivity of fluid
- V fluid velocity; μ fluid viscosity
- C_p specific heat of fluid; ρ density

2.1.5.1 Heat transfer resistance

Heat is transferred from high temperature areas to the low temperature areas. The rate of heat transferred from the hot steam inside the cylinder to the cooler paper on the outside depends on the overall temperature gradient and on the different resistances to heat transfer:

$$Q = UA\left(T_s - T_p\right) \quad (11)$$

Where

- Q rate of heat flow from inside dryer to paper
- U overall heat transfer coefficient
- T_s steam temperature
- T_p paper temperature

Figure 2.2 shows the different heat and mass transfer resistances involved when the paper web is in contact with the cylinder. Modeling of paper drying process is a matter of describing correctly the transport mechanisms involved. The most crucial and certainly most difficult issue is to obtain correct transport coefficients.

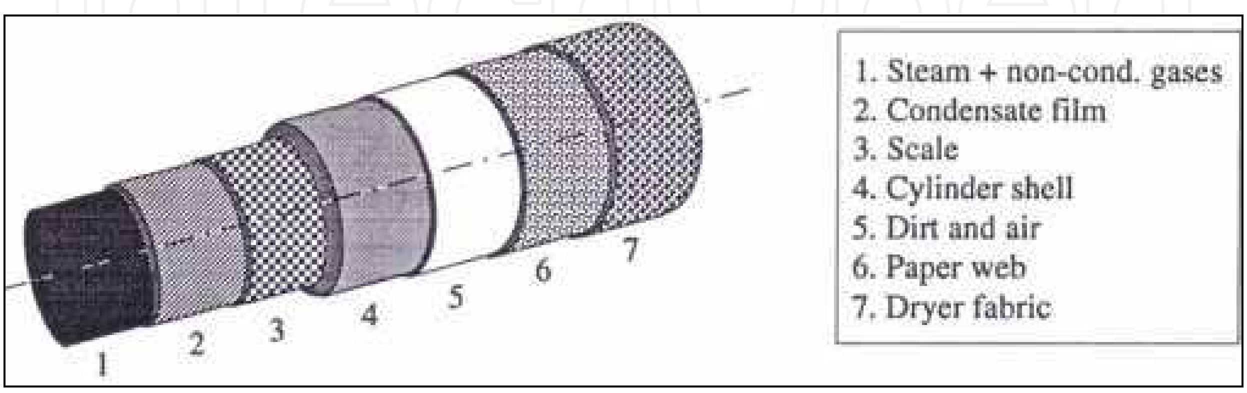

Fig. 2.2 Cut-way drawing of a dryer cylinder illustrating heat and mass transfer resistance.

The resistance due to scaling inside the cylinder could be lumped together as resistance due to dryer shell. The various resistances to heat flows are shown in Table 2.1.

Source of resistance	Heat flow, q_i (driving force/resistance)
Steam film	$q_1 = \frac{(T_1 - T_2)}{1/(A_1 h_s)}$
Condensate layer	$q_2 = \frac{(T_2 - T_3)}{Lc/(A_2 k_c)}$
Dryer shell	$q_3 = \frac{(T_3 - T_4)}{L_s/(A_3 k_s)}$
Contact resistance	$q_4 = \frac{(T_4 - T_5)}{1/(A_4 k_k)}$
Paper	$q_5 = \frac{(T_5 - T_6)}{L_p/(A_5 k_p)}$
Air film	$q_6 = \frac{(T_6 - T_7)}{1/(A_6 k_a)}$

Table 2.1 Sources of heat transfer resistance and heat flow

Where

A Area
h thermal conductive conductance
k thermal conductivity
L length

Since under the steady state conditions heat transferred through each layer is the same, all q's are equal. The heat flow is equal to the total driving force divided by the total resistance, therefore:

$$q = \frac{\sum \Delta T_i}{\sum R_i} \quad (12)$$

$$q = UA\Delta T \quad (13)$$

where

$$U = \frac{1}{1/h_s A_1 + L_c/k_c A_2 + ... + 1/h_a A} \quad (14)$$

It is evident from equation (11) that the amount of heat transferred may be increased by increasing U (reduce condensate layer inside cylinder, eliminate non-condensibles, increase felt tension, increase contact area of felt, increase contact felt permeability, ensure dryer surface is clean, optimal shell thickness) ; increasing A (add more dryer cylinders, increase contact area with larger diameter dryer or single tier arrangement with larger sheet wrap); increasing T_s (raise steam temperature) and decreasing T_p (lower sheet temperature by good pocket ventilation).

2.1.6 Mass transfer

In paper drying, mass transfer occurs after a sufficient amount of heat energy has been transmitted to the web, resulting in the transfer of mass of water from the paper to the air in the dryer section. The driving force for mass transfer is a concentration (or partial pressure) difference between two points. Mass transfer of water can occur by three different modes: molecular diffusion, convective or eddy diffusion and bulk movement or ventilation.
The mass transfer occurring in paper drying can be described as molecular diffusion. Water is transferred from the moist paper surface through a boundary layer of air. Convective mass transfer involves this molecular diffusion through a laminar sub layer, a combination of molecular diffusion and turbulent mixing through a buffer layer, and turbulent mixing with the main body of air in a turbulent boundary layer. The process of convective mass transfer is shown in Figure 2.3.

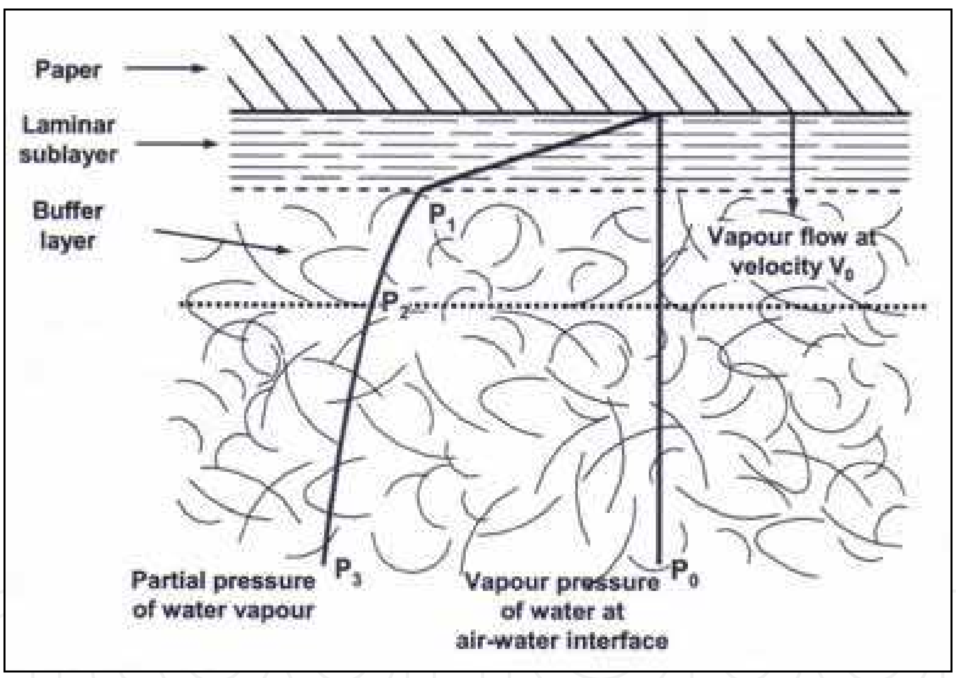

Fig. 2.3 Mass Transfer at web-air interface

The rate of molecular diffusion is described by Fick's law:

$$M_A = -D_v \frac{dC_A}{dx} \tag{15}$$

Where

- M_A mass transfer of A per unit area, kg/hr.m^2
- D_v molecular diffusivity (area/time)
- C_A concentration of A
- x distance

For water vapour diffusing from the paper into the surroundings, this concentration gradient is expressed as a partial pressure difference:

$$M_A = k_g\left(P_o - P_l\right) \tag{16}$$

Where

- k_g mass transfer coefficient
- P_o partial pressure of water at sheet surface
- P_l partial pressure of water in surrounding air

Similar to heat transfer, dimensional analysis and experimental evaluation can be used to determine the transfer coefficient. Although k_g can be determined experimentally, for practical uses convective mass transfer can be expressed in the general form:

$$M = KA\left(P_p - P_a\right) \tag{17}$$

Where

- M rate of evaporation
- K overall mass transfer coefficient
- A evaporation area
- P_p vapour pressure of water in the paper
- P_a vapour pressure of water in surrounding air

The overall mass transfer coefficient K is a function of diffusivity within the web and convective air flow in the dryer pocket. Often, the air near the centre of the dryer pocket is more humid than the air at the pocket edges, which gives to non-uniform evaporation rates. Pocket ventilation with warm dry air is used to correct this situation. From the general mass transfer equation it can be seen that the evaporation rate can be maximized by increasing K (reduce the boundary layer of air using pocket ventilation), increasing A (increase the evaporation area), increasing P_p (the vapour pressure of water in the sheet can be increased by sheet temperature) and decreasing P_a (the vapour pressure in the air can be decreased by lowering the humidity through pocket ventilation and/or dryer design).

3. Paper drying principles and web structure

As the paper web leaves the press section of a paper machine, considerably more than half of its weight is water. This water must be removed in the dryer section of the paper machine to the level between 6% and 8% of final water content, before the paper can be suitably used. The removal of water by use of steam heated cylinder, in spite of high capital investment and running cost, is an efficient process. Recent attempts to develop new drying methods other than cylinder drying have targeted to achieve higher drying efficiency, with improved functional properties of finished products. However, such methods are yet to be accepted in commercial paper manufacturing. It appears likely that new paper machines will incorporate multi-cylinder drying for many years to come.

3.1 Drying phases

During the drying process, wet paper passes through three distinct phases before exiting as a dry sheet. Figure 3.1 shows the different phases: warm-up (period AB), constant rate evaporation (period BC) and falling-rate evaporation (period CE). This idealized scheme occurs if drying conditions are similar over the entire drying process. In commercial dryers, the constant rate phase does not often exist.

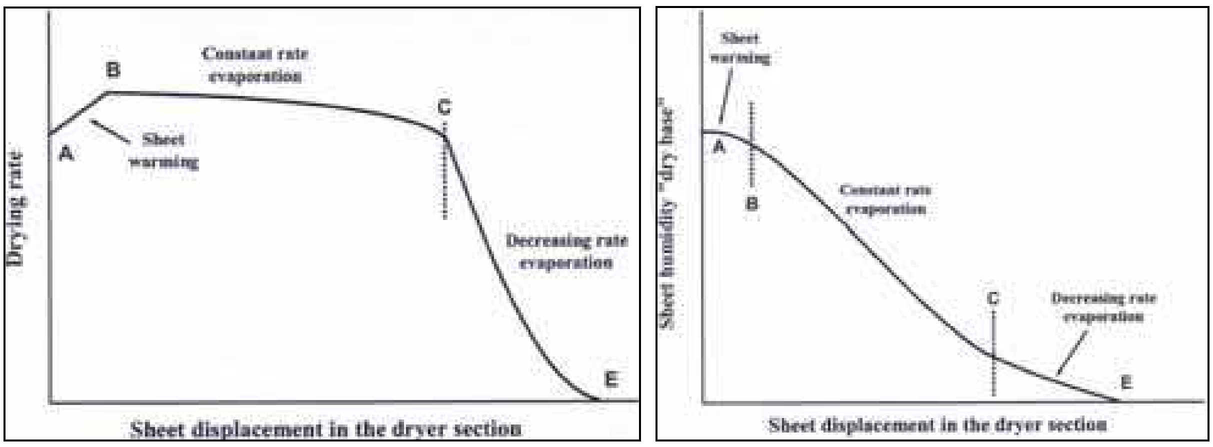

Fig. 3.1 Different drying phases (Karlsson 1995).

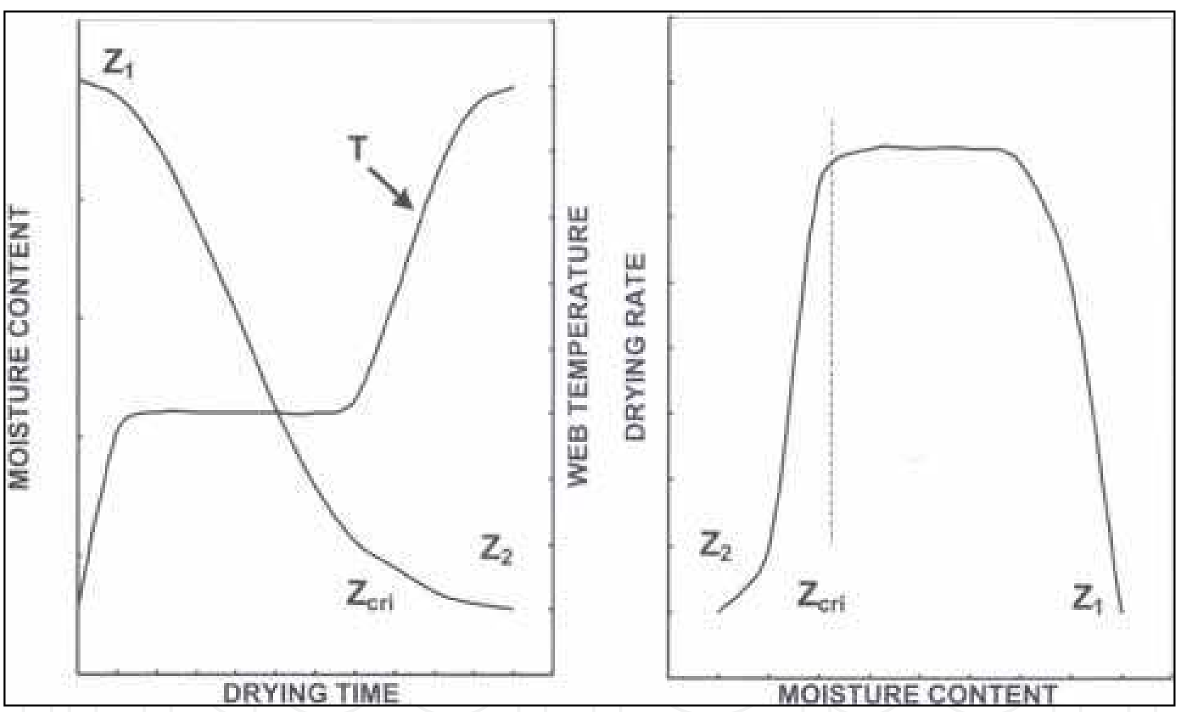

Fig. 3.2 Different drying phases and critical moisture (Karlsson 1995).

Near the end of period AB, an equilibrium between heat transfer to the sheet and evaporation from the sheet surface is reached. This is the beginning of the constant rate period of evaporation, which continues as long as there is free water at the sheet surface. As drying progresses, the waterfront recedes into the sheet, the amount of free water diminishes and capillary forces begin to become important, resulting in changes in sheet and fibre structure. The diffusion of water vapour in the sheet, the decreasing thermal conductivity of the sheet, stronger water-to-fibre bonds, and higher contact resistance between the sheet and the drying cylinder all lead to a reduction in the drying rate once the sheet reached certain moisture content. As a result of decreasing drying rate, the energy used for evaporation also decreases. Web temperature begins to rise when the system tries to find a thermal balance. The inversion point between the constant and falling rate phases is the critical moisture content (shown by Z_{cri} in Figure 3.2).

3.2 Change in web structure during drying

The heat and mass transfer phenomena inside the paper web during drying is considerably influenced by the structure of the network formed by the fibres, liquid water and gas filled pores. Parameters such as volume fractions of different compounds, continuity and tortuosity of the flow paths, and pore size distribution can describe the structure. Web structure after the press section is the initial point where moisture content and web density are significant parameters. Web structure develops in the dryer section when water gradually departs and the volume originally filled with water becomes partly substituted with gas and partly compensated through shrinkage of the web. Paper shrinks during drying in the direction of thickness and in the plane. On the paper machine, the paper web has strains in the machine direction. The web can partially shrink in the cross direction. Shrinkage is typically 30%-40% and 1%-10% in plane.

The path through which the evaporated water escapes during drying is tortuous. The tortuosity changes as the paper dries until reaching the final moisture content and thickness. The pores opening at the paper surface are not necessarily perpendicular to the surface. Vapour finds its way from the paper surface along the path with least resistance.

3.3 Flow of free and bound water

Water present in a moist paper consists of free and bound water. The free water is between the fibres and in large pores (macro pores), while the bound water is in the micro pores at the amorphous region in the cell wall and in accessible hydrophilic groups (Weise, 1997). The thermodynamic and physical properties of free and bound waters in moist web are different, the melting properties of free water being same as that of bulk water. Drying decreases the level of fibre swelling by closing the pores in a fibre cell wall irreversibly. An essential factor describing the state of fibre is the fibre saturation point (FSP). This expresses the amount of water within the fibre cell wall FSP differs to different pulps and is typically 0.7-1.8.

Capillary flow characterizes the flow of liquid water in a paper web, as long as it forms a continuous phase. Such flow for free water can be expressed by Darcy's equation:

$$\frac{m_{ev}}{A} = \rho_w \frac{K}{\mu} \frac{dp_c}{dy} \tag{18}$$

Where

m_{ev} mass flow rate of evaporation

A area

ρ_w water density

K permeability

μ water viscosity

dp_c/dy capillary pressure gradient

The driving force for this flow is a gradient in capillary pressure or capillary suction that results from the moisture gradients in the web. Moisture gradients form in the web due to evaporation from the open surface of the web due to water vaporization at the interface where the wet web presses against a hot dryer surface and the formed water vapour diffuses towards inner parts of the web.

When moisture content of the web decreases, the water phase gradually looses its continuity and splits into separate areas between which liquid flow is not possible anymore. Capillary flow of free water ends totally when moisture content falls below the fibre saturation point and all moisture is in the form of bound water. Bound water present in the micropores is adsorbed on the inner and outer surface of fibre wall as mono or multi-molecular layers. The first layer of water molecules closest to the surface is very strongly bound and has only limited mobility. The molecular movement along these layers is surface diffusion or diffusion of bound water. The driving force for this mass transfer mechanism is a gradient in concentration of bound water. Similar to capillary flow of free water, the movement of bound water can be expressed by similar equation:

$$\frac{m_{bw}}{A} = D_{bw} \rho_d \frac{dz_{bw}}{dy} \tag{19}$$

Where

m_{bw} mass flow rate of bound water

A area; ρ_d = dry material density

D_{bw} diffusivity of bound water

The diffusivity constant, $D_{bw,}$ decreases sharply with decreasing moisture content and increases with increasing temperature.

4. Multicylinder drying and dryer configuration

Use of steam as the main source of heat energy and the surface of rotating cylinder as the heat transfer area is the most common method of drying wet web to the finished products. Almost all paper machines around the globe manufacturing paper and paperboard use conventional steam heated cylinders or multi-cylinder drying configuration. Besides it providing good energy efficiency, cylinder drying enables supported web transfer, facilitates the web transport forward, and improves web smoothness. Cylinder drying also provides a means to prevent some web shrinkage in cross and machine directions.

Most drying cylinders of paper machines are made of cast iron due to higher thermal conductivity compared to stainless steel (47 vs. 16 W/m^{o}C). The dryer ends or heads are also made of cast iron. The heads are bolted to the dryer shell at the ends of the dryer. Figure 4.1 shows a sectional view of dryer cylinder that includes all of its components such as steam supply and condensate exhaust devices. The most common dryers are 1.5 m and 1.8 m diameter. Shell thickness can vary, but 20-40 mm is common with a pressure rating as high as 1000 kPa.

4.1 Configuration of multicylinder dryers

Generally all multi-cylinder dryers are configured either two-tier or single tier. Two-tier configuration is the most common. Such system is continuing since the beginning of paper drying using steam heated cylinder more than 100 years ago. Use of single tier configuration has been commercially introduced in late 1970. In all paper machines that have single tier dryer cylinders also have two-tier cylinder, normally in the later part of the dryer section to avoid single sided appearance of the finished products.

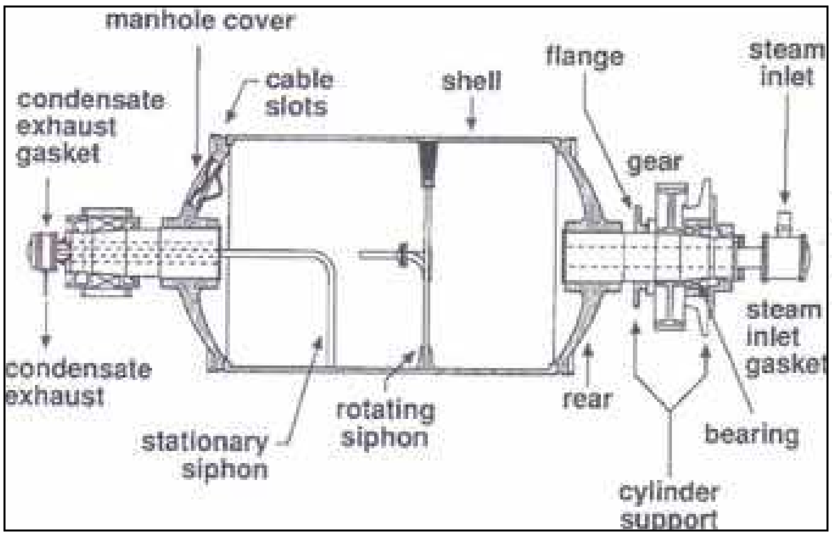

Fig. 4.1 Sectional view of a dryer cylinder

A multi-cylinder dryer section consists of cylinder groups each having its own felting and drive system. Most paper machines have 5-7 independently driven cylinder groups. Each group comprises of several dryer cylinders and has variable speed control to maintain sheet tension between the groups and adjust to any machine direction sheet shrinkage that can occur. The two-tier configuration has two rows of steam heated cylinders and could be single or double felted. The double felted configuration is the so-called conventional system where all the cylinders participate in evaporation. The major disadvantage of such system is that the web moves from one cylinder to the next unsupported. In many modern paper machines, the two-tier system is single felted over an individual dryer group where the web passes through the dryer section with alternating sheet surfaces coming into contact with the successive heated cylinders surfaces.

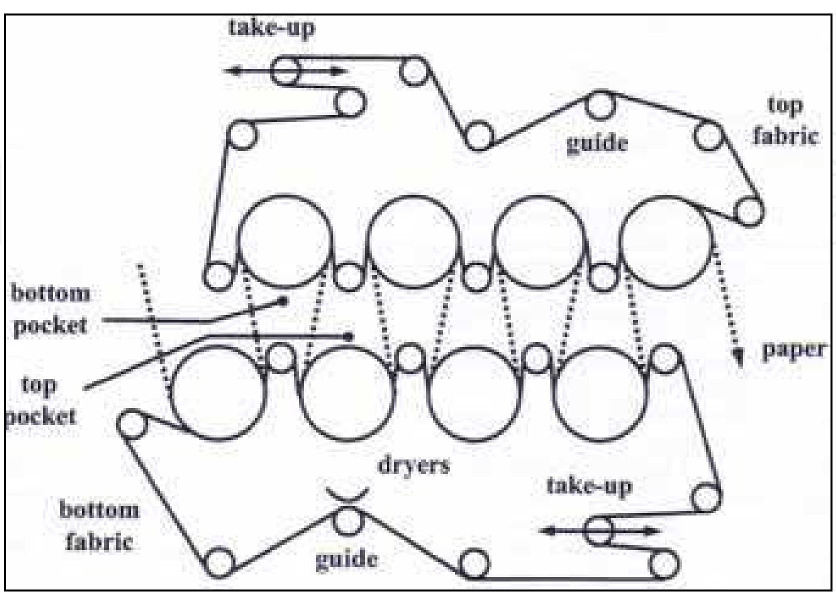

Fig. 4.2 Conventional Two tier dryer configuration

Runnability becomes an important issue with two-tier configuration with increased machine speed due to web and edge breaks. To overcome this problem, single tier configuration was introduced, although later part of the dryer section always has two-tier configuration. Figures 4.2 and 4.3 show the 'conventional' double-felted two-tier and single-tier configuration of multi-cylinder dryers respectively.

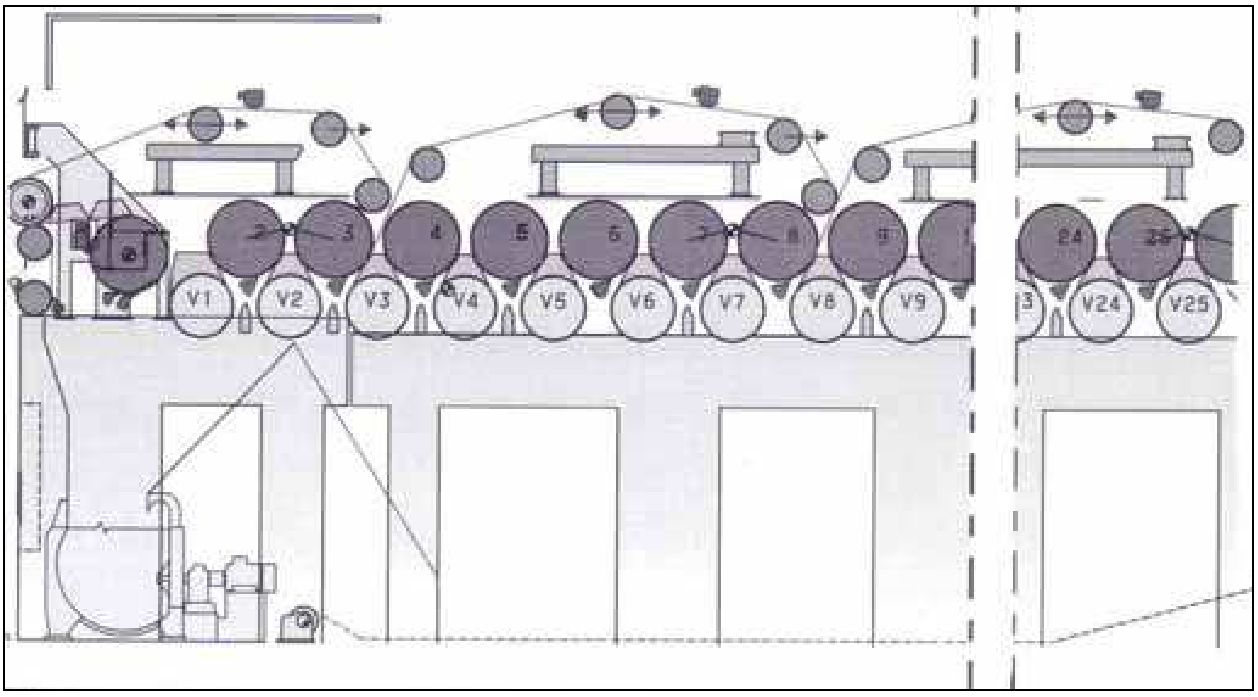

Fig. 4.3 Single dryer configuration

4.2 Drying cycle

The multi-cylinder drying process consists of repeated cycles in the direction of web travel. Each cycle has different phases depending on the dryer configuration (Nissan and Hansen, 1960, 1961). Figure 4.4 shows the four phases of drying cycle for two-tier and double felted configuration. Every phase has individual heat and mass transfer mechanism, a specific evaporation rate and a web temperature

The four phases can be detailed as follows:

- The sheet is in contact with the outer surface of cylinder, while its other side is exposed to air and evaporation is low in this phase.
- The sheet remains in contact with the cylinder surface and is covered on its outer surface by the felt that applies pressure on the web. Heat transferred is increased but mass transfer is limited because of the fabric covering the sheet surface. Sheet temperature increase during this long phase and most of the heat transfer occurs.
- The fabric comes away from the sheet, which remains in contact with the cylinder. Evaporation occurs from the newly exposed surface of the sheet not in contact with the cylinder.
- The sheet is no longer in contact with the cylinder and is moving toward the next cylinder. Evaporation occurs from both sides of the sheet, resulting in a decrease in sheet temperature. It is during this phase that the evaporation rate is highest.

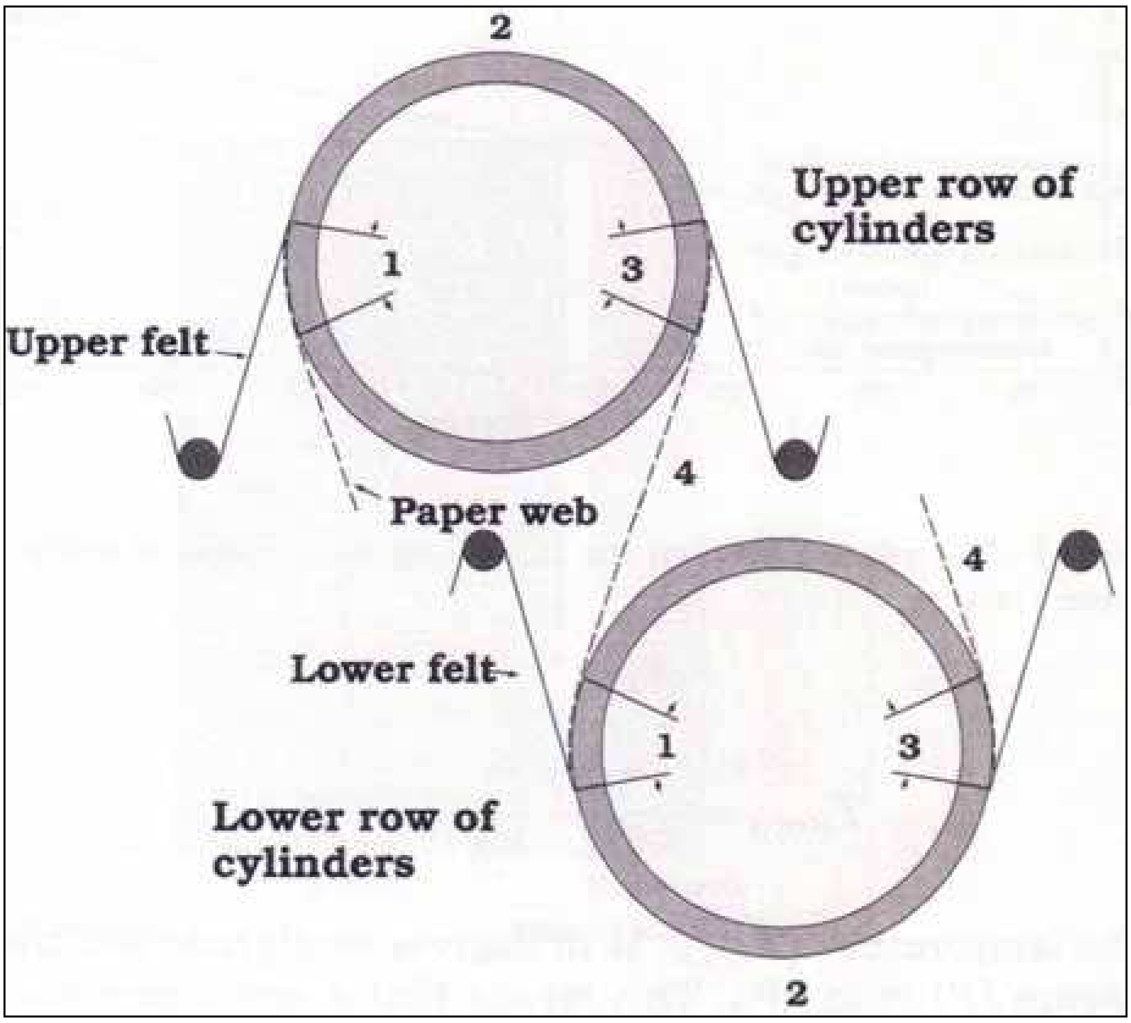

Fig. 4.4 Four phases of drying with conventional double tier configuration.

5. Steam and condensate system

In modern paper machines there are several points in the steam and condensate system. These include dryers, steam box, pocket ventilation equipment, roll handling, wire pit and process water heating and machine room ventilation. In terms of paper drying, the main steam and condensate consumption points are the dryer section and pocket ventilation as heat energy required to dry paper are sourced from dryer cylinders and hot ventilation air. The basic requirements and objectives of the steam and condensate system are to:

- allow maximum unrestricted drying of the paper with a gradual increase in cylinder surface temperature from the wet end to the dry end;
- provide drying control for machine operator; remove air and non-condensibles;
- provide maximum condensate removal at all paper machine speeds;
- economic utilization of steam;
- provide uniform reel moisture and provision of sheet breaks differential and control.

Figure 5.1 shows the basic steam and condensate system of a commercial paper machine. There are a number of variations in steam and condensate system depending upon the machine design. In fact every paper machine has its own unique steam and condensate system. The design of steam and condensate system is influenced by available steam pressure, machine speed, grammage or basis weight range, sheet dryness after the press section and quality requirements of the finished products. The steam and condensate systems for different paper grades are either cascade systems, thermo-compressor systems or combinations of the two.

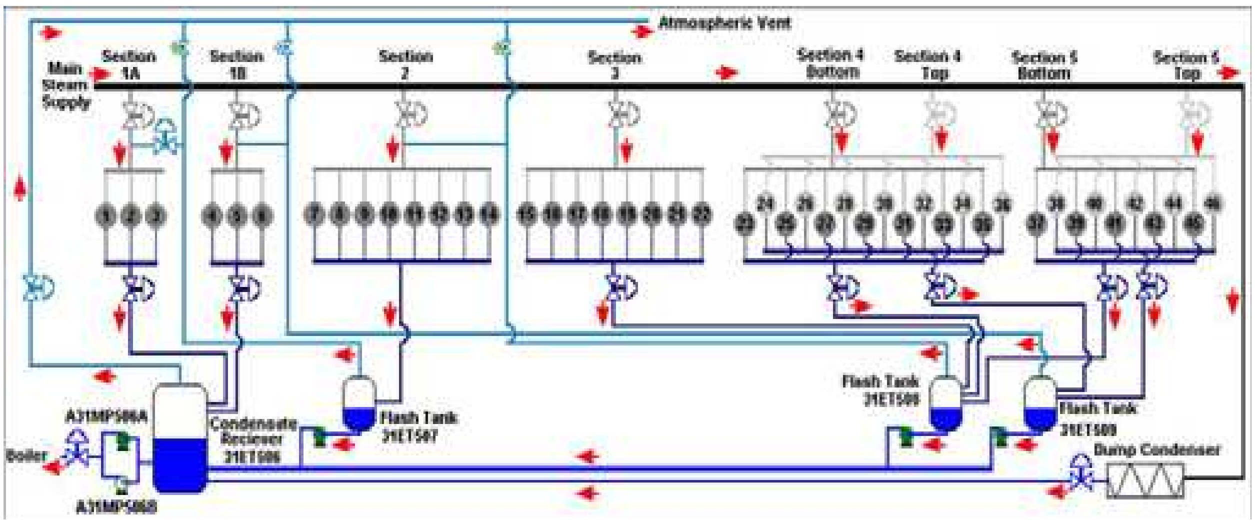

Fig. 5.1 Basic steam and condensate system of a commercial paper machine.

5.1 Condensate behaviour

In multicylinder paper drying system where steam is used as the source of heat energy, the heat inside the cylinder is released by condensation of steam. The condensate inside the cylinder needs to be evacuated for effective heat transfer from inside the dryer cylinder to the dryer surface and subsequently to the paper. Steam is generally introduced into the cylinder on the drive side of the paper machine, while condensate is evacuated from the front side using either rotary or stationary siphons as shown in Figure 4.1 in Section 4.

As indicated earlier, condensate film that are present inside dryer cylinder play significant role in overall heat transfer to the dryer surface. As the dryer begins to rotate and as speed increases, the condensate will go through three stages, puddling, cascading and rimming as shown in Figure 5.2. At *very low speed*, condensate collects at the bottom of dryer as a puddle, and only a thin film or no film at all on the shell wall. Under this condition, the steam entering the dryer can easily condense directly on the wall of the dryer providing excellent heat transfer. As speed increases, the condensate is carried up the cylinder wall and forms a relatively thin uniform film. The velocity of the condensate film is lower than that of the dryer shell and on-set of 'rimming' appear. This produces a slippage, which tends to assist heat transfer. As the speed increases above 300 m/min, the slippage also decreases and eventually complete rimming occurs. Complete rimming is desirable in terms of uniform heat transfer.

To improve heat transfer for dryers operating at higher than the rimming speed, more than 300 m/min, turbulence of the condensate later is generated by installation of turbulator or spoiler bars inside the dryer shell. Depending upon the diameter of the dryer, between 18 and 30 bars per dryer are used. Turbulence generated due to dryer bars is shown in Figure 5.3.

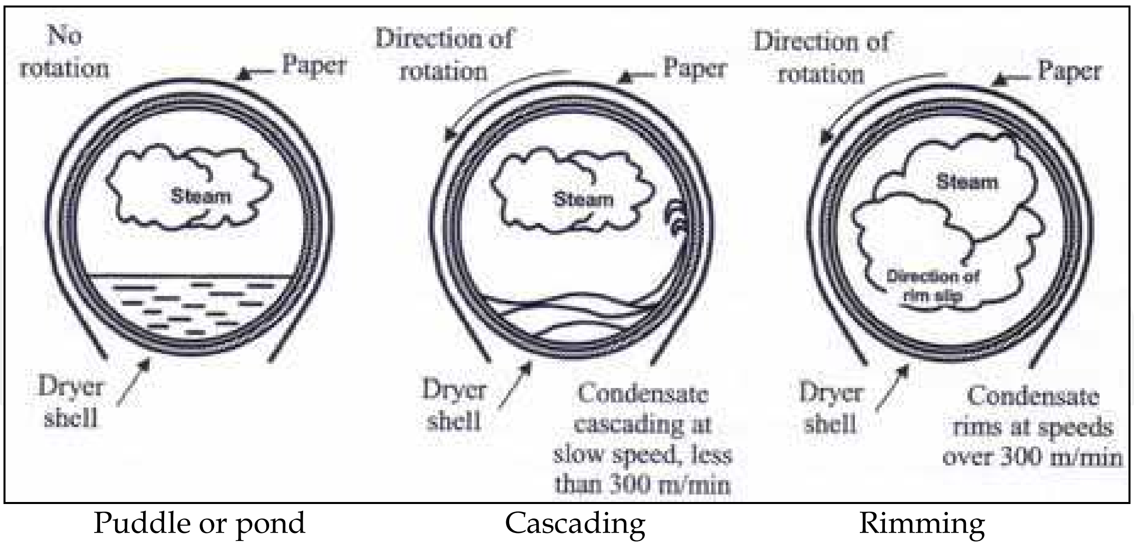

Fig. 5.2 Different forms condensate behaviour inside dryer cylinder

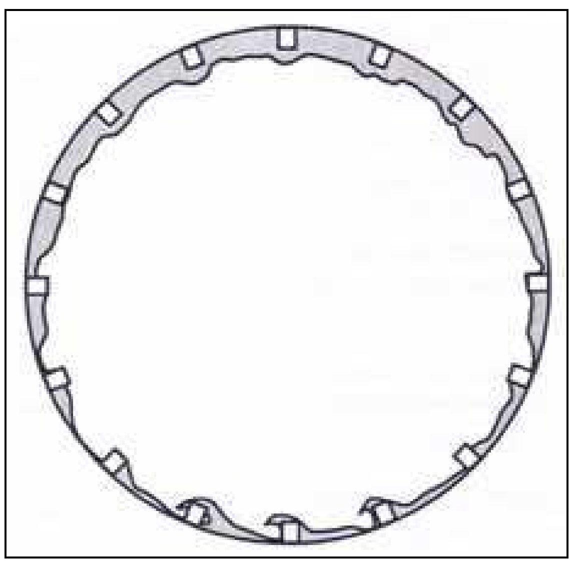

Fig. 5.3 Turbulent action produced by dryer bars

5.2 Condensate evacuation and blow-through steam

Siphon and steam joint are the heart of condensate removal from the dryer shell. To obtain the maximum heat from steam, ideally all the steam must be condensed. In practice, this never happens inside the dryer shell. Depending upon the dryer speed a percentage of steam of total steam entering the dryer shell is never condensed and leaves the dryer mixed with condensate as two-phase flow and the uncondensed steam in the condensate is called 'blow-through steam'. A differential pressure across the dryer or a group of dryer is necessary to obtain continuous evacuation of condensate through a siphon which is located inside the dryer shell.

The siphons could be of stationary or rotary type. The quantity of blow-through steam of the total steam supplied to the dryer is about 10%-20% for stationary siphons and 25%-30% for rotary siphons. Stationary siphons use the condensate kinetic energy in condensate removal. For rotary siphons, the centrifugal force of the condensate must be overcome, meaning requirement of higher differential pressure and higher amount of blow-through steam. Stationary siphons are more efficient and are not very speed dependent with respect to differential pressure.

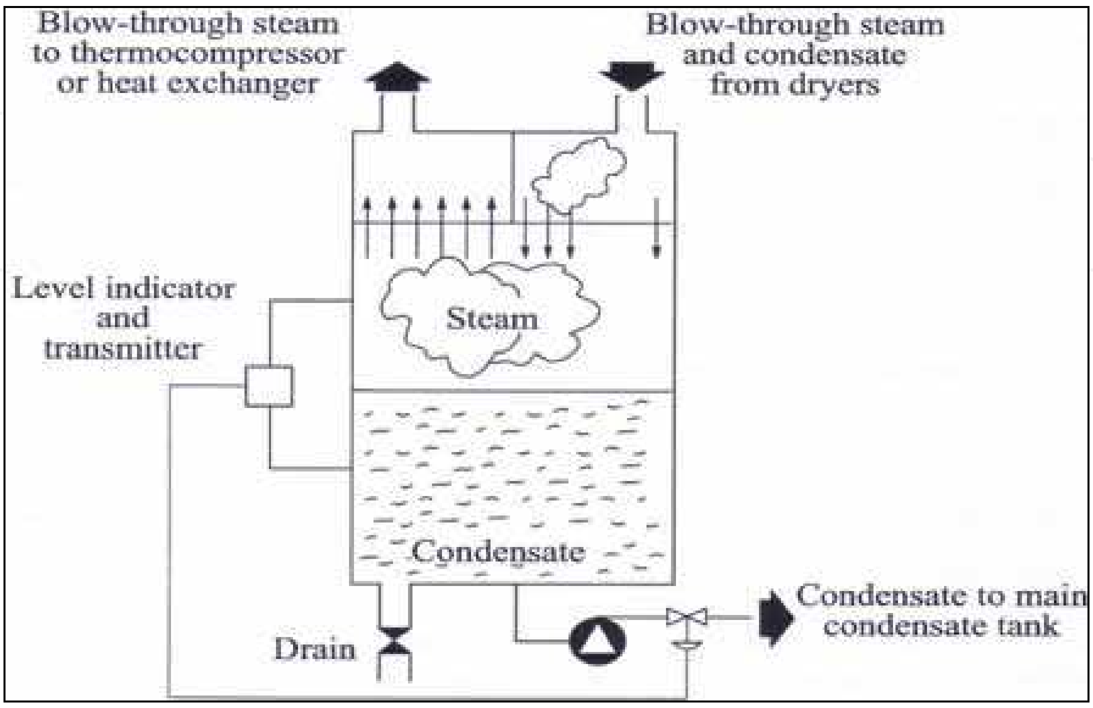

Fig. 5.4 Condensate separator tank

Condensate along with blow-through steam evacuated from the dryer or a dryer group is collected in tank called 'separator'. Here the two-phase steam and condensate mix is 'flashed' to generate low pressure steam in the upper part of the separator as shown in Figure 5.4. The condensate is generally returned to the boiler house. The flash steam contains good valuable heat and should not be wasted by ventilation to the atmosphere. The heat content in terms of latent heat of flash steam is exactly the same as line steam. The flashed steam can be piped to the steam supply header of the normally lower steam pressure preceding group. Quite often a thermo compressor system is used to inject low pressure steam into dryer by using high pressure motive steam.

In many modern paper machines, a flow control system is used to control the steam and condensate system using a orifice plate in the blow-through line. This provides a better control compared to differential pressure control, particularly during web break conditions.

5.3 Troubleshooting of steam and condensate system

Three common problems associated with steam and condensate system are *low efficiency*; *operating problems* and *capacity problems*. These are discussed below.

5.3.1 Low efficiency problems

The *low efficiency* could be due to too much blow-through steam and could result in usage of higher steam per unit mass of water evaporated, siphon failures, steam pressure build-up in separator and higher differential pressure across the dryers. Reduction in differential pressure can help but installation of other accessories such as new siphons (if wrong size) or thermo-compressor is better option in longer term.

5.3.2 Operational problems

Flooded dryer, uneven drying, paper jam and dusting at wet end dryer section are the most common *operational problems* encountered. Symptoms of 'flooded' dryer are cold dryer and oscillating drive motor load. Condensate-filled dryers stay warmer longer even after shutdown. Use of low differential pressure and likely damage of siphon are possible causes for 'flooded' dryer. Similar to corrective action for low efficiency, increase in differential pressure and inspection of condensate evacuation system can improve the situation. Frequent paper jam and excessive dusting in the early dryers could be due to higher surface temperature and 'sticking' of wet web on the dryer surface. This is particularly relevant if recycled pulp furnish is used. In such situation reduction in steam pressure in earlier section, shutting down steam supply to selected cylinders could alleviate the problems. Cylinder surface temperature should be progressively increased to avoid this situation.

5.3.3 Capacity problems

Capacity problems associated with steam and condensate system are machine speed being dryer limited and existence of excessive dryer capacity, the later being less common. Dryer limitation of machine output is reflected at the allowed maximum steam pressure and any attempt to increase machine speed resulting higher reel moisture. Short term actions such as increase in press loading, if possible, increase in stock freeness to maximum allowed by product quality, adjustment of siphon clearance can improve the situation. Redesign of steam and condensate system is the long term solution. In opposite situation where excessive drying capacity exists, reel moisture could not be increased without flooding dryers. Reduced press loading, increase in stock freeness and shutting off selected dryers could be short term solution.

It is important to note that to carry out evaluation of the steam and condensate system, necessary information/data must be available. These include machine speed, basis weight, reel trim, dryer diameter, dryer face width, moisture entering and leaving dryer section, moisture in and out of size press (if present), available steam pressure, type and size of steam joint and siphons.

Measuring sheet and dryer surface temperatures is a good and practical method of evaluating efficiency of heat transfer as well as the performance of the steam and condensate system in general. Dryer surface temperature can also identify if poor moisture profiles are caused by non-uniform heat transfer through the dryer condensate layer of by non-uniform sheet-to-dryer contact. A difference of 10-25^{o}C between steam temperature at the operating pressure and the measured cylinder surface temperature is typical for proper operation. A difference larger than this usually means condensate build-up in the dryer.

Figure 5.5 shows the comparison of measured cylinder surface temperatures with that of steam temperatures at the operating steam pressures for two commercial paper machines producing 80 g/m^2 printing and writing fine paper and heavier linerboard grade packaging paper. Cylinder surface temperatures of the fine paper machine are within the recommended range, except for four cylinders that had low surface temperature due to steam supply to those cylinders being shut off for operational reason. This is an example of normal operation and good heat transfer. For the linerboard machine, the measured surface temperatures of all the cylinders are lower than the recommended range. For several cylinders, the surface temperatures are very low, suggesting inefficient heat transfer and likely 'flooding' of large number of dryer cylinders. Another possibility is inaccurate readings of pressure gauges/transducers of the data of which is used to calculate steam temperature.

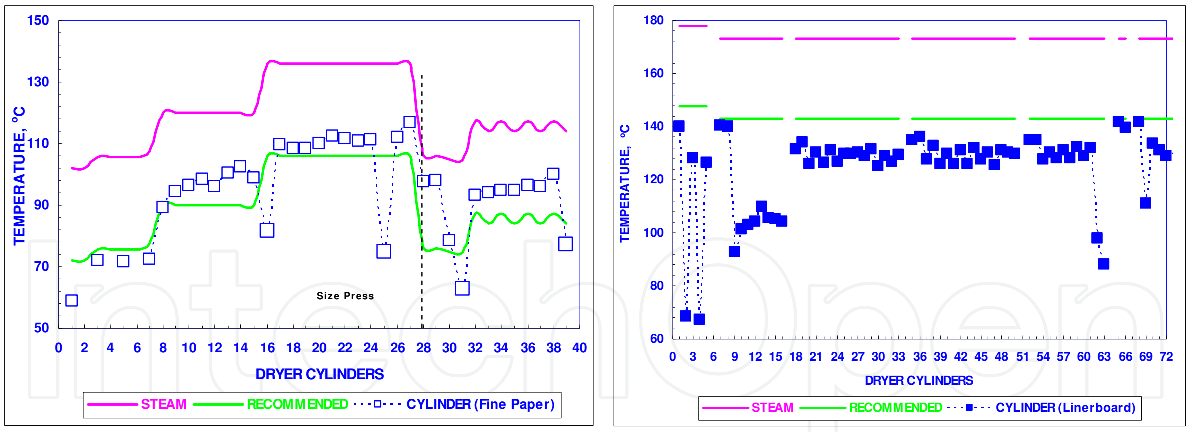

Fig. 5.5 Cylinder surface temperatures of a Fine Paper and Linerboard machines

Comparing machine direction sheet temperature development against dryer surface temperatures can highlight differences within steam groups (for siphon problems).

6. Dryer section ventilation and heat recovery system

As indicated earlier, drying of paper is an interaction between fibres, water and air. In this respect air handling or dyer section ventilation is one of the most important system components of water removal from the dryer section of a paper machine (Virtanen, et. al., 2005). Ever increasing demand for faster paper machine and superior product quality require more efficient air handling and ventilation system. Dryer section ventilation is often linked with heat recovery from the dryer pocket exhaust where heat recovered from the primary stage is used to heat the ventilation air.

6.1 Pocket ventilation

Dryer pocket is defined as the space in the dryer section between two adjacent cylinders, in case of single-tier system, or between three cylinders, in case of conventional two-tier system. Individual pocket is separated by dryer fabric and paper web. In this area majority of evaporation occur from the web. For the efficient drying of paper, it is extremely important to remove the water vapour from around the web to increase the driving force for evaporation. Increasing the cylinder surface temperature does not necessarily improve the water removal rate during paper drying process, as water evaporated from the web must be removed from the pockets by sufficiently hot and dry air. If the movement of air in the pockets is too low or close to stagnation, higher temperature in the pockets does not help in improving drying rate. There should be sufficient airflow in the pockets for efficient drying.
Quite often the importance of dryer pocket ventilation is neglected. This is particularly true for older machines. Due consideration of pocket ventilation and air handling are not given by mills when a major upgrade in dryer section is undertaken. In today's high speed machine, the ventilation systems should be an integral part of the papermaking process and not separately designed from the rest of the dryer section. The hood and the dryer section ventilation system must be able to perform many basic functions (Karlsson, 1995):

- capture and remove water evaporated in the dryer section
- create a controlled and favorable environment for the drying process
- improve energy utilization and energy economy in the drying process

- improve the runnability of the machine not only by means of runnability systems but also through the proper distribution and control of airflows throughout the entire dryer section
- maintain good working conditions in the machine room in terms of heat, humidity and noise
- protect the building and machinery from deterioration because of the humidity
- reduce emissions and mist to the outside of the mill.

The importance of pocket ventilation is illustrated in Figure 6.1. For paper machine equipped with pocket ventilator, will have lower and uniform absolute humidity profile across the width of the dryer pocket. However, for paper machines that do not have pockets ventilator can have very high and non uniform humidity. High pocket humidity can have negative effect on drying energy consumption and non-uniform humidity will create problem reel moisture profile.

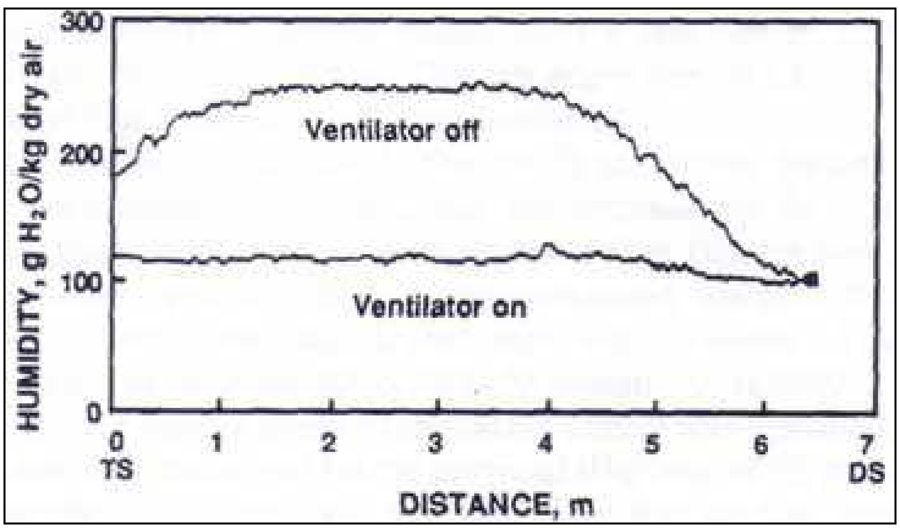

Fig. 6.1 Effect of Pocket Ventilation

An accurate measurement of relevant data (air temperatures or dry bulb temperatures, relative humidity or wet bulb temperatures and air movements in each pocket) that quantify pocket conditions is crucial for performance analysis and subsequent improvement. These data were measured each time the dryer section of a paper machine was audited as part of a systematic approach. In several cases, it is necessary to measure pocket conditions across the full machine width and in such situations, a data logger could be used. A hot-wire anemometer velocity probe is generally used for measurement of air movement in the pockets. Either a humidity probe or dry and wet bulb temperature measurement probe can be used for the measurement of humidity. Depending upon the probe used, thermodynamic equations can be used to calculate absolute humidity (AH), dew point temperatures or relative humidity. Once the pocket air condition data are gathered, detailed analysis of pocket ventilation system can be carried out (Hill, 1993; Afzal, 2000).

Figure 6.2 shows the example of a paper machine producing kraft paper with *poor* pocket conditions. The majority of the pockets in the third or main section and two pockets in the second or intermediate section had absolute humidity values significantly higher than the maximum recommended value of 0.2 g water/g dry air. Cross machine profiles of pocket conditions of this machine was measured. The peak absolute humidity values of each pocket are also shown in this figure. As expected, peak AH value were significantly higher than the pocket average values.

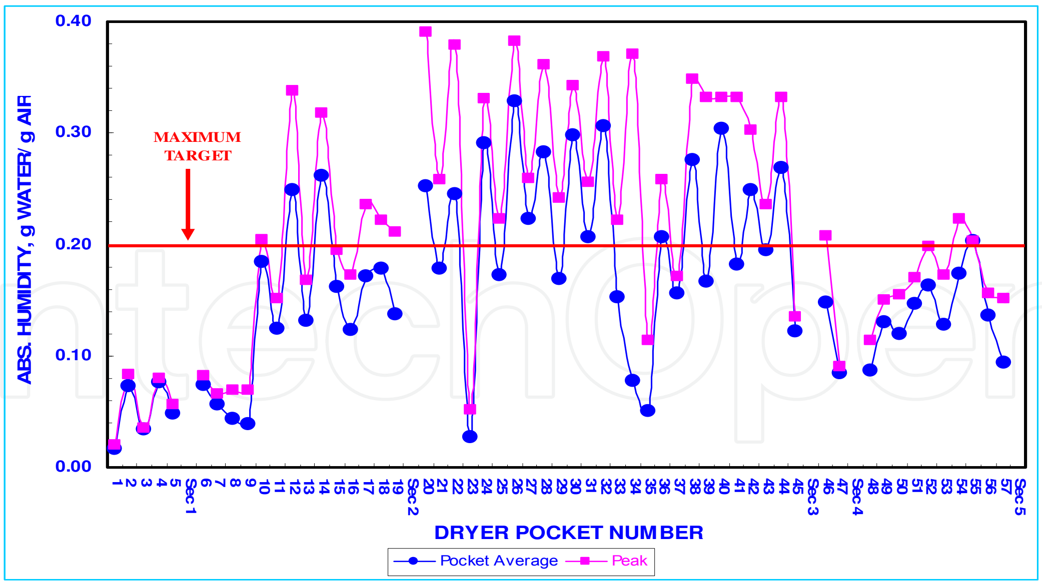

Fig. 6.2 Example of *Poor* pocket conditions (Machine A : Linerboard)

Examples of a paper machine producing newsprint with *good* pocket conditions are shown in Figure 6.3. Except two pockets (#16 and #17), the AH values of all the other pockets were less than 0.20 g water/g dry air. For both these machines, cylinder surface temperatures were within acceptable range at the operating steam pressures. These examples suggest that the steam/ condensate system and the pocket ventilation of the dryer sections are equally important in improving dry-end efficiency of a paper machine. In many newer and also some older machines with upgraded hood and PV system, both 'supply' and 'exhaust' air fans are equipped with variable speed drives. This would enable fine tuning of the air system. Moreover, the supply air is such machines are distributed into individual pockets through headers and damper arrangements. Systematic and extensive audit of the air system in the dryer section can establish precise requirement of the amounts of air in each pocket that could be subsequently adjusted by different damper settings.

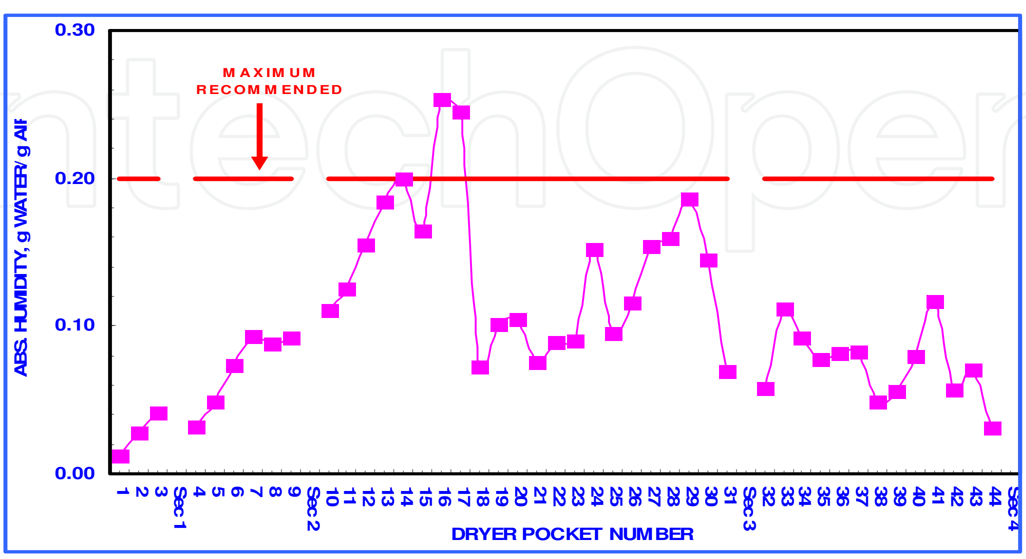

Fig. 6.3 Example of *good* pocket conditions (Machine B : Newsprint)

Besides saving in drying energy and improving reel profiles by optimal pocket ventilation, reducing absolute humidity inside the pockets can lead to increase in drying rate with consequential increase in machine output. The effect of absolute humidity on drying rate is shown in Figure 6.4. The highest benefit could be realized for light-weight grade of paper such as newsprint.

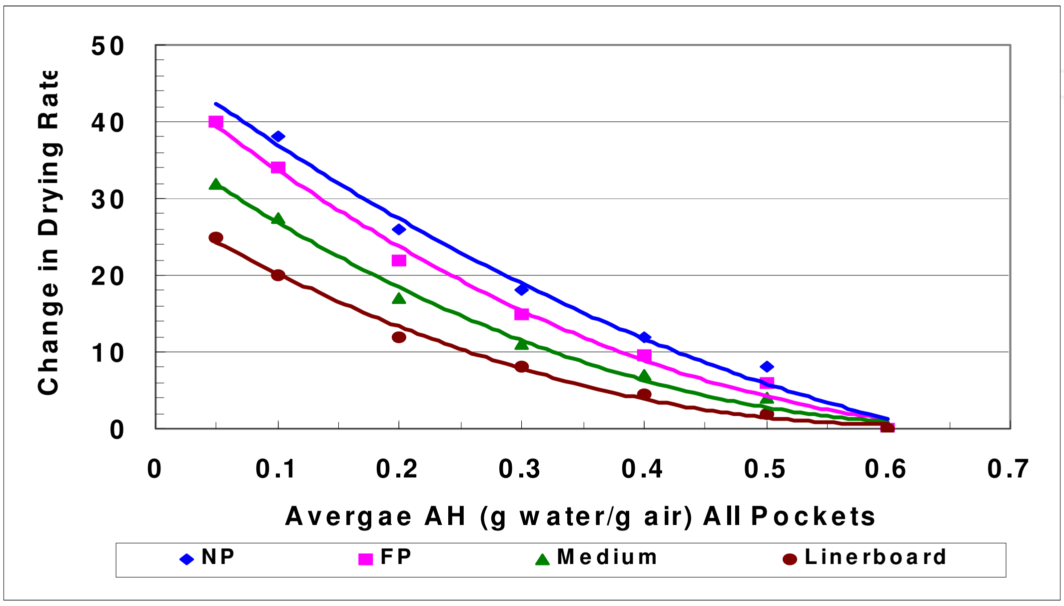

Fig. 6.4 Effect of pocket absolute humidity of drying rate (Perrault, 1989).

6.2 Dryer hood

Dryer hood is the enclosed space above the dryer section of a paper machine spanning the length from the last press to the reel. In the early days, paper machine did not have any hood. This used to cause the working condition unbearable for the machine crew. There was continuous dripping of condensed water vapour everywhere with the machine building deteriorating. Later on, dryer sections were covered with open canopy hoods, which made a significant difference. However, these open hoods were not optimal in terms of energy efficiency, nor could the airflows and draft around and within the dryer section be controlled any way. The evolution finally led to closed hoods, with advantages that are well known. From the outside it may appear that the technology is quite simple and that all hoods are alike. However, an efficient hood concept requires a profound knowledge of the paper drying process and the phenomena taking place in the dryer section.

A well designed closed hood is much more than an enclosure over the dryer section. Together with the process ventilation system, and heat recovery, it provides the papermaker with all the tools necessary to ensure full control over drying performance and energy consumption in the dryer section.

6.2.1 Hood balance

The airflows required to ventilate the hood effectively are highly dependent on the construction of the hood and its operation. Enough air must be introduced to the hood to prevent condensation and keep pocket humidities low enough to maintain high drying rates. Exhaust airflows must prevent vapour from spilling into the machine room. It is necessary to carry out a hood balance in order to identify potentials for improving drying

efficiency. Moreover, evaporation rates differ depending on paper grade and production volume. A hood balance should be carried out for the production volume requiring the highest evaporation rates in the dryers.
Depending upon the type of hood present in an existing paper machine dryer section, the optimal amounts of total 'supply' and exhaust air required per unit mass of water evaporated will vary. The required hood balance (defined as the ratio of total 'supply' to total exhaust air) is largely influenced by the hood type i.e., whether the hood is an open, conventional closed or high-humidity closed hood. The hood balance for a modern paper machine with a closed hood should be close to 0.8, while that for an older machine with open hood should be between 0.3 and 0.4. If the hood balance is too high then this results in spillage from the hood into the machine room. A low balance results in sweating, runnability problems and poor profile in the cross direction (CD). Conditions around the machine may become uncomfortable and troubleshooting, broke cleaning and operations may become difficult. In many machines, an actual hood balance is rarely carried out. The importance of air balance is often ignored potentially losing opportunity to improve drying efficiency (Sundqvist, 1996; Ghosh, 2005).

6.2.2 Supply and exhaust airflows

The optimal amounts of total 'supply' and exhaust air required per unit mass of water evaporated will vary depending upon the type of hood present in an existing paper machine dryer section. Fully Closed high humidity hood of modern paper machines can operate at absolute humidity level of up to 0.18 g water/g dry air. Maintaining hood at higher humid condition can have significant benefits: requirement of lower supply and exhaust airflows and higher potential of heat recovery from the dryer exhaust as shown in Figure 6.5 (Sundqvist, 1995). Lower supply air will require less steam consumption motor power.

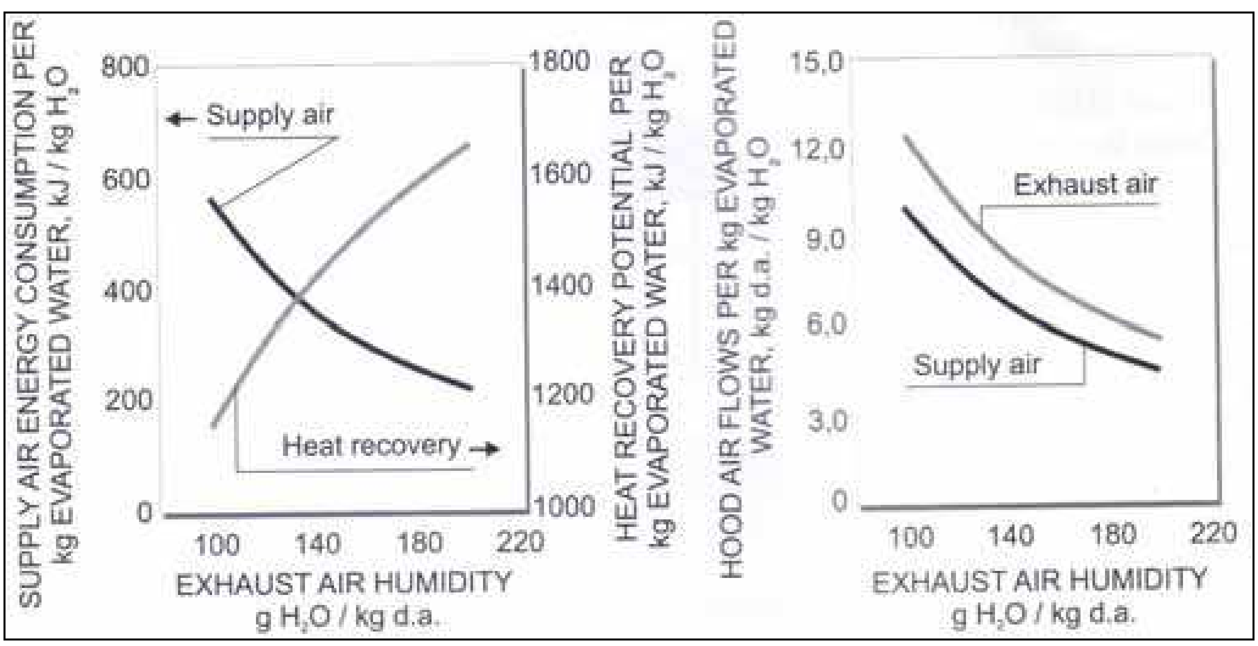

Fig. 6.5 Influence of exhaust air humidity on energy consumption and airflows of the hood

Table 6.1 shows the typical parameters recommended for different type of hood. Pocket ventilation air required for high humidity hood is significantly lower, 6-7 kg/kg water evaporated compared to open hood system that require 20-30 kg/kg water evaporated. For high humidity hood, the basement of the paper machine is also fully enclosed (Panchapakesan, 1991).

Air Stream	Conditions	Hood Type		
		OPEN	MEDIUM	HIGH
Supply	Humidity Range, g water/g dry air	0.01-0.012	0.01	0.012
	Temperature after heat recovery, °C	30-40	55-6590-100	60-65
	Temperature into Hood, °C	40-60	90-100	90-100
	Mass Flow, % of Exhaust	30-50	50-70	70-80
Exhaust	Humidity Range, g H_2O/g dry air	0.04 - 0.07	0.12 - 0.14	0.16-0.18
	Temperature, °C	50-60	80-90	80-90
	Dew Point Temperature, °C	37-46	53-57	61-63
	Mass Flow, kg air/kg evaporated	20-30	9-12	6-7

Table 6.1 Typical parameters for different hood types

6.2.3 Supply air distribution and pocket humidity

It is important to note that proper ventilation of dryer pockets not only required sufficient amount of ventilation but also proper distribution of such air is critical in achieving the optimal benefits of a fully closed hood. Air movement/flow inside the pocket is critical in maintaining dryer pockets reasonably dry and prevents from sweating. Pockets with higher air flow also exhibit lower humidity. This is evident from the measured humidity and air flow inside pockets of a newsprint machine as shown in Figure 6.6.

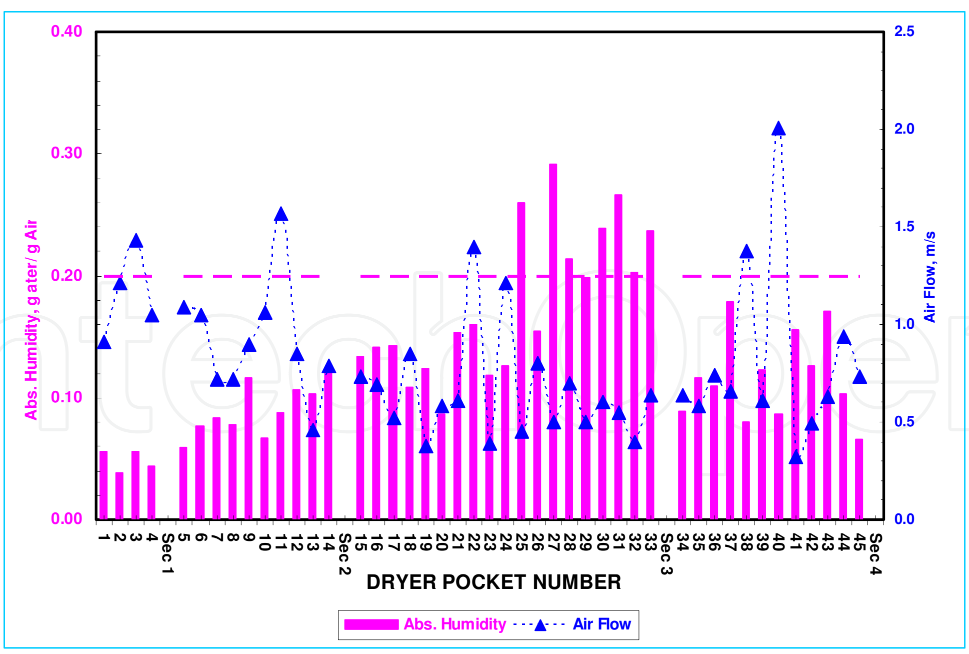

Fig. 6.6 Superimposition of air flow and humidity inside dryer pockets

Many modern machines with high humidity hoods are equipped with variable speed motors for both supply and exhaust air. Installation of temperature, humidity and pressure sensor/transducer on the exhaust can provide operators tool to control the conditions of exhaust air in maintaining high humid conditions within the dryer pockets to conserve drying energy and improved machine runnability.

6.3 Dryer fabric and ventilation

Air handling is an important task for a dryer fabric in a high speed machine. The aerodynamic features of the fabric structures, openness of the fabric, geometry of the dryer pockets and machine determine the air pumping and dragging effect of the fabric. Dryer fabric permeability plays an important role in pocket ventilation and runnability. The dryer fabric is required to perform many functions in the dryer section. It must be mechanically stable as it acts as a drive belt. It must avoid breakdown due to its operating environment and its surface properties must not adversely affect the paper. It must also provide a uniform pressure distribution to maximize heat transfer. The fabric also has a very important function in controlling air movement both in and outside the dryer pocket. The main characteristics which affect these air flows are dryer fabric permeability, aerodynamic properties and the dryer fabrics ability to control air at ingoing nips.

6.3.1 Fabric permeability

The permeability of the dryer fabric is a function of the weave pattern, the yarn sizes and shapes and the density of the yarns in both the machine and cross direction. Conventional practice with the selection of dryer fabric permeability is that the permeability increases following the dryer curve of the machine. That is during the pre heating stage, where the sheet is most wet and requiring maximum support, a dense smooth fabric is required. Consequently this fabric is generally the lowest in permeability.

As the sheet then heats and water evaporation intensifies, the removal of water vapour and steam increases in volume and therefore in order for this to escape, a higher permeable fabric is required. Therefore the air permeability of the fabric has a major impact upon the flow of evaporated water from the heated sheet into the pocket. Any blockages of these paths will result in this flow reducing and possibly being blocked. This will subsequently reduce the overall drying efficiency of this section. As this sheet has not then reached its optimal dryness the next section will be required to remove the remaining moisture. If this section already has inadequate drying efficiency then the problems becomes compounded. The paper maker may have no alternative but to reduce the speed of the machine.

There are limitations on the range of permeability available per drying section. For example in the later sections care must be taken not to have too high permeability as otherwise the sheet may become unstable. For a typical paper machine permeability ranges are 75 to 110 ft^3/min in pre heating, single tier and uno runs, 110 to 250 ft^3/min for conventional top and bottom and single tier drying sections and finally 250 to 700 ft^3/min for final drying sections.

Another of the impacts of dryer fabric permeability is the effect upon systems such as vacuum rolls and blow boxes. These elements are designed to assist with both air and sheet management. Again incorrect selection of fabric permeability may result in the inefficient function of these elements. This may subsequently force the paper maker to make machine adjustments such as increased draws or even reduced overall machine speed.

6.3.2 Aerodynamic properties

The second most important characteristic of a dryer fabric which can adversely affect dryer pocket ventilation is its aerodynamic properties (Joseph, 1988). There are two key issues in relationship to the aerodynamic properties. The first issue is the fabrics affect upon the boundary air layer, the layer of air immediately above the surface of the fabric. In a fabric with a high co-efficient of drag, the fabric will cause the air layer to be disturbed and ultimately cause that layer to flow with the surface. The outcome of this behaviour therefore is that as the paper and fabric converge onto a roll or cylinder, the air between these moving elements becomes trapped and compressed. This compressed air, if unable to be evacuated, results in the formation of areas of trapped air which consequently can force the sheet to leave the surface of the fabric or in the case of open draws, for the sheet to 'flutter' uncontrollably.

As machine speeds have increased sheet control issues have been exacerbated. Consequently machine builders have developed ways to mechanically minimize problems related to the movement of air in pockets. The most common of these elements are anti blow boxes and vacuum rolls on single tier sections as shown in Figure 6.7. The function of vacuum cylinders and anti-blow boxes is to minimize the build up of compressed air. As previously mentioned the permeability of the fabric can affect the efficiency of these elements, especially if the fabric becomes contaminated. The blocking of the voids in the fabric will result in no vacuum being applied through the fabric to the paper sheet (Luc, 2004).

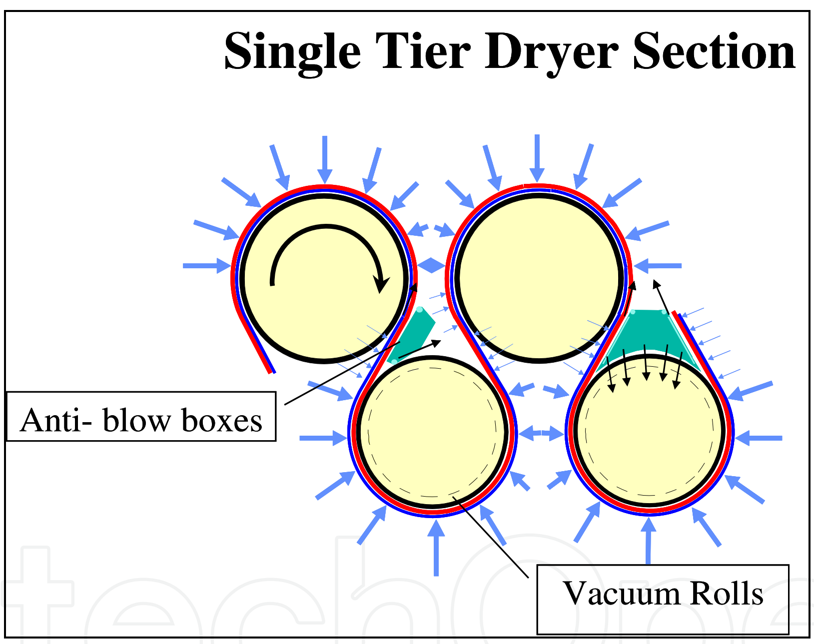

Fig. 6.7 Anti-blow box & vacuum rolls in a single-tier dryer

The way to reduce the flow of boundary air with the dryer fabric is to reduce the co-efficient of drag (COD). As with any aerodynamic surface the principle approach to reducing COD is to minimize variations in the physical surface. With a dryer fabric this means that the fabric is designed to have as planar a surface as possible. This is typically achieved through the use of specific weave patterns and flat yarn materials.

6.4 Heat recovery

Significant amounts of heat energy supplied to the dryer section through the steam in the cylinder and hot supply air ends up in the dryer exhaust stream. In closed hood system, the temperature of exhaust air could be as high as 85 ^{o}C. For economic reason, some of this heat

is recovered and re-used in the drying process. This is particularly true for countries in the northern hemisphere when outside temperature in winter period could be very low. Increasing cost of energy also make it attractive to recover heat from the exhaust stream.
Figure 6.8 shows the schematic of a first stage heat recovery. In this schematic, fresh air is heated by use of heat exchanger, where heat from dryer exhaust air is recovered. Water and heat balance is shown here. Basically four types of heat exchangers are used in dryer section heat recovery systems. Usually, a heat recovery system will use more than one type of exchanger to perform the desired tasks.
In *air/air type of heat exchanger*, hot and humid exhaust air heats an air flow such as dyer section supply air, or machine room ventilation air. The heat transfer occur s through a heat surface, and no contact occurs between the two flows. In *air/water heat exchanger*, hot and humid exhaust air heats a water flow that can be fresh water, white water or a glycol and water mixture used as circulation water in the machine room ventilation air heating system. Also, in this case, heat transfer occurs through a heated surface. In *scrubber*, exhaust air and the water to be heated by direct contact with each other. The scrubber consists of a series of nozzles whose number depends on the amount of water to be heated. The fourth type of heat exchanger is simple *air coils*. Air coil units are used for transferring heat from a water flow to an air flow. A typical application is heating of machine room ventilation air with a circulating water and glycol mixture.

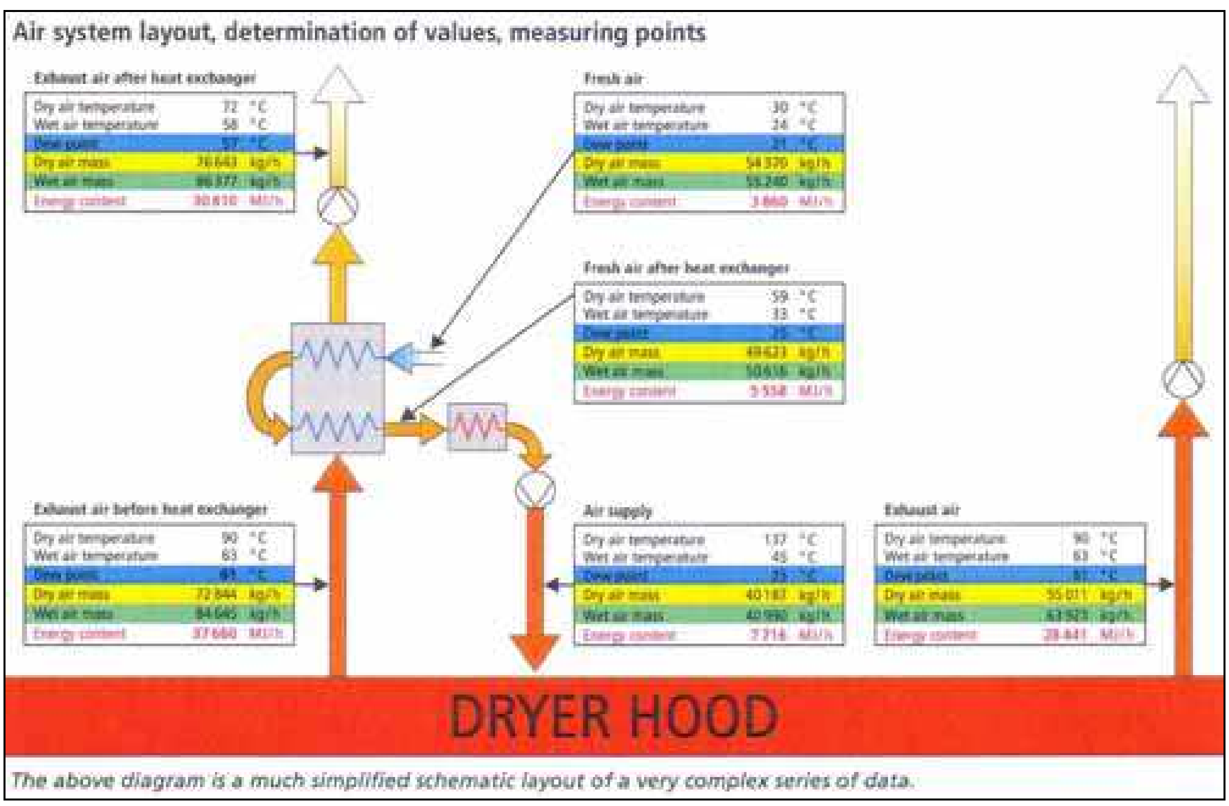

Fig. 6.8 Heat recovery systems from dryer hood exhaust

For a modern linerboard machine producing 450,000 ton per year, the amount of heat energy associated with the exhaust air is shown in Table 6.2. The temperature of the exhaust air in four exhaust outlets vary between 74 and 85 °C and this temperature is quite high and suitable for efficient heat recovery.

	Exhaust A	Exhaust B	Exhaust C	Exhaust D
Temperature, ^oC	74	77	81	85
Relative Humidity, %	34.1	29.0	26.0	24.0
Duct Area, m^2	0.636	2.466	2.466	2.466
Average Velocity, m/s	22.80	25.80	31.80	31
Dew Point Temperature, ^oC	50.3	49.7	50.7	52.0
Absolute Humidity, g w/g air	0.087	0.084	0.088	0.095
Heat Content, kJ/kg	308.2	304.8	320.5	341.6
Air Mass Flow, ton/hr	46.61	203.4	246.4	235.6
Water Mass Flow, ton/hr	4.04	17.08	21.81	22.42
Volumetric Flow, m^3/hr	4528	19234	24980	26191
Heat Flow, MJhr	**14365**	**61994**	**78986**	**80486**
	Total Heat OUT, MJhr		**235831.0**	

Table 6.2 Actual amounts of Heat energy in dryer exhaust for a Linerboard Machine

7. Use of computer model or simulation in optimizing drying efficiency

A number of models of paper drying have been developed by academics and paper machine manufacturers [Karlson et al., 1995; Bond et al., 1996; Iida, 1985]. However, such models are not always easily available to paper manufacturers. A dryer simulation program developed earlier by the author (Ghosh, 1988) has been used to simulate the moisture and temperature profiles of the web in the middle of free run after each cylinder, as the paper web traveled towards the reel, using the operating conditions of the machine, the pocket and the surface conditions of the dryer cylinders measured during the audit. Measurement of web moisture after each dryer cylinder is very difficult, if not impossible, without breaking the web. Generally only moisture data that are available are after the last press (or at the entrance of the first dryer can) and at the end of the paper machine. In some machines, moisture scanners are located before the size press. Moisture values could be obtained from simulation based on dryer model. Like any other computer model, the usefulness of such tool largely depends upon reliable and practical input data. Such model used real world data obtained from field measurements during systematic audits of the dryer section. The simulated web moisture data were subsequently used to calculate the drying rate and driving force for evaporation of each cylinder. The model has also been used to explore various 'what-if' scenario that could lead to highlight the potential for improvement or energy saving and are often requested by the mill. Model or simulation by itself does not optimize/improve efficiency. It could be used as a tool to supplement system analysis and when used in conjunction with audit and system analysis could be very useful.
The rate of change of moisture and heat content of paper can be expressed by the following equations:

$$\frac{dM}{dt} = -\frac{dV}{db} - \frac{dL}{db} \tag{20}$$

$$\frac{dH}{dt} = \frac{dH_f}{dt} + \frac{d(MH_L)}{dt} \tag{21}$$

$$Q = -F_Q(\frac{dT}{db}) \tag{22}$$

$$V = -F_V(\frac{dC_V}{db}) \tag{23}$$

$$L = -F_L(\frac{dM}{db}) \tag{24}$$

Where

$\frac{dM}{dt}$ =Rate of change of moisture content in paper

$\frac{dH}{dt}$ =Rate of change of heat content of paper

V = vapour flux

L = liquid flux

Q = heat transfer coefficient

C_V= water vapour concentration

H_V, H_L, H_f = heat content of vapour, liquid and dry fibre

F_Q, F_V, F_L = heat, vapour and liquid transfer coefficient = f(M)

M = gm water/gm fibre

b = basis weight, g/m^2

T = sheet temperature

The equation (20) and (21) can be solved by finite difference method. Web length in Machine Direction (MD) is divided into finite lengths (difference). Heat and mass transfer fluxes is calculated using web conditions at a certain location. This gives web condition at the neighboring location determined by the differential equations. This step is repeated from the beginning to the end of the dryer section

In any model and simulation, the output of such model is always dependent on accurate and practical input of process data. When used in conjunction with audit and system analysis, dryer simulation model could be very useful. The model can be used to explore various 'what-if' scenarios such as changes in:

- machine speed, basis weight
- moisture, temperature of web to 1st dryer
- steam pressure in any/whole section
- dryer cylinder surface temperature
- pocket conditions
- size press operation
- reel/size press (if size press is present and operational) moisture

Model only gives temperature and moisture of the sheet at one location in the machine direction. Profile in cross direction is difficult to predict. Prediction of web moisture is useful, as it is difficult to measure on a running web, the speed of which can be as high as 2000 m/min, depending upon the machine design and paper grades made. Drying rate for each cylinder can also be calculated from the simulated moisture and the drying rates thus calculated can be very useful in identifying heat transfer problem with specific cylinder.

Figure 7.1 shows the web moisture and drying rate after each dryer cylinder using the simulation model that used 'real world' audit data for a newsprint machine. Similar results for vapour pressure of each pocket and driving force to evaporate/remove water are shown in Figure 7.2. The measured absolute humidity values of each pocket are also shown. It is evident from these figures that level of absolute humidity of dryer pockets significantly influences water evaporation. For pockets with very high humidity, evaporation is very poor and reverse is the true for less humid pockets.

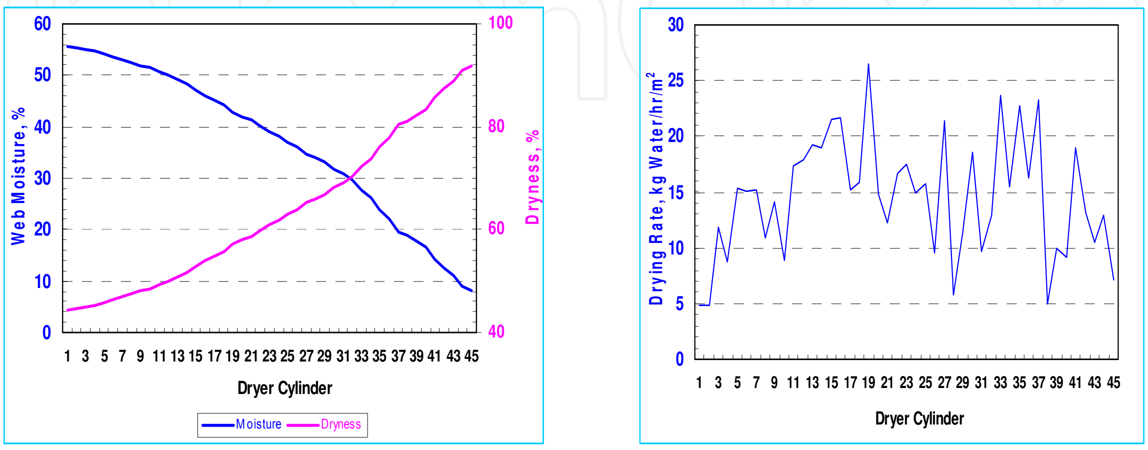

Fig. 7.1 Simulated web moisture and drying rate after each dryer cylinder

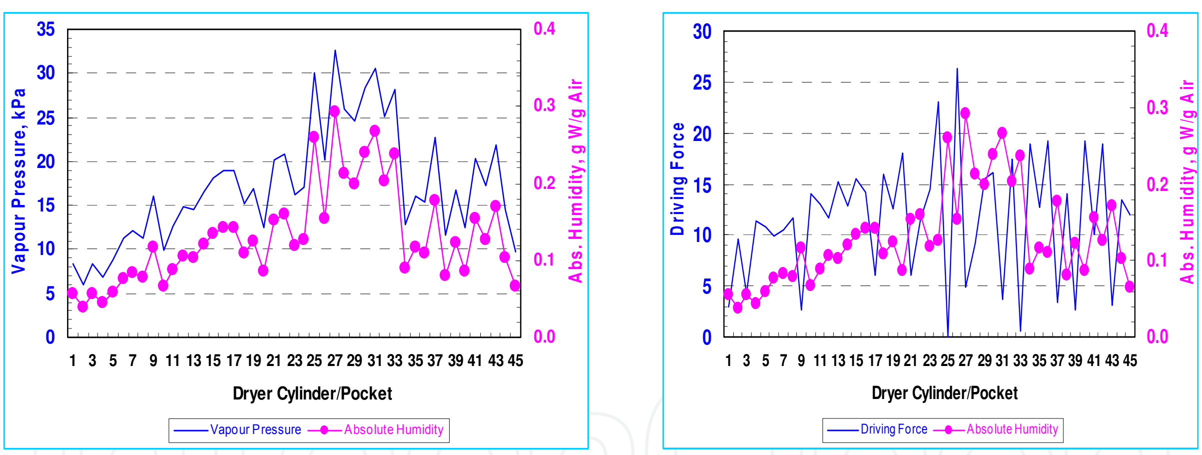

Fig. 7.2 Pocket Vapour pressure/driving force and absolute humidity

8. Performance of dryer section

One of the main objectives of any dryer audit/survey of a paper machine is to establish the thermal performance (efficiency) of the machine at the existing operating conditions and identify any scope of improvements.

8.1 Current performance or benchmarking

Before any improvement or optimization of the dry-end efficiency can be accomplished, the current performance of the dryer section of a paper machine must be established first. The most critical step in performance analysis is to obtain a proper set of field test measurements and observations. All equipment information and sizes must be checked in the field and compared with the flow schematics of the system. Field testing is generally carried out to:

- establish machine operating conditions, speeds and sheet moisture.
- establish drying curves.
- measure energy consumption.
- determine the operating problems and procedures through detailed discussions with the operators.
- obtain physical data for the system analysis.
- assess the physical condition of the equipment.
- establish key performance indicators.
- compare the performance indicators of the machine with similar top performing machines making the same grades.

Systematic measurement of the steam and condensate system, the pocket ventilation system and the hood balance around the dryer section is a pre-requisite in optimizing dryer performance (Hill, 1997; Perrault, 1989). Once such measurements are carried out, proper analysis of such data will quantify the present conditions/performance of the dryer section of a paper machine, compare dry end efficiency of the machine with others in the industry making similar grade, identify the scopes for improvement in drying efficiency and subsequent energy saving. Field data can also be used for simulation model in quantifying potential tangible benefits.

8.2 Field measurements for performance evaluation

Once this has been established further follow on work are required. The systematic approach that can be used comprised the following steps:

- Measurement of cylinder surface temperatures, pocket temperatures, pocket humidity values, air movements in each pocket, web temperature after each dryer cylinder across the full width of the machine/pocket;
- Measurement of condensate flow from each separator and check the steam pressures of each section including the blow-through steam;
- Measurement of air conditions (flow, temperature, humidity) of supply and exhaust air;
- Analysis of data, including overall water and energy balance over the entire dryer section and over individual heat recovery system;
- Exploration of various ‘what-if’ scenario through simulation model using measured data to quantify potential tangible benefits that could be achieved if the problems identified are fixed;
- Repeat audit/surveys following corrective actions based on preceding audits.

8.3 Performance indices

Performance of the dryer section of a paper machine can be described by various means. However, the commonly used dryer performance indicators are :

- TAPPI (Technical Association Pulp and Paper Industry) drying rate (kg water removed/hr/m^2 of surface area);
- steam efficiency (kg steam used/kg of water evaporated);
- production efficiency (kg steam used/kg of paper produced) and
- energy efficiency (mega joule of energy required per ton of water removed).

The steam efficiency is the more rational performance indicator as it reflects the actual amount of water evaporated irrespective of the performance of the press section of a paper machine i.e., whether the dryness entering the dryer section is good or poor. However, from financial view point the total amount of energy used per ton of paper produced is the most important.

8.3.1 Drying rate

Depending upon the use of size press in the paper machine, the Tappi drying rate could be categorized into three rates: *overall, pre-dryer and after-dryer*. If size press is absent or off, only one drying rate (overall) is obtained. If a moisture spray is present to control the CD moisture profile in the reeler, the amounts of extra water spray used should also be included in the calculation of dry end efficiency of the machine.

TAPPI surveyed a large number of paper machines in North America producing similar grade of products and published the drying rate for specific grades such as newsprint, liner board, medium, fine paper etc as function of average dryer steam pressure. From the survey data, TAPPI also recommended mean, upper and lower limits of drying rates for each grade. Figure 8.1 shows the location of actually measured overall drying rates of several machines producing linerboard products.

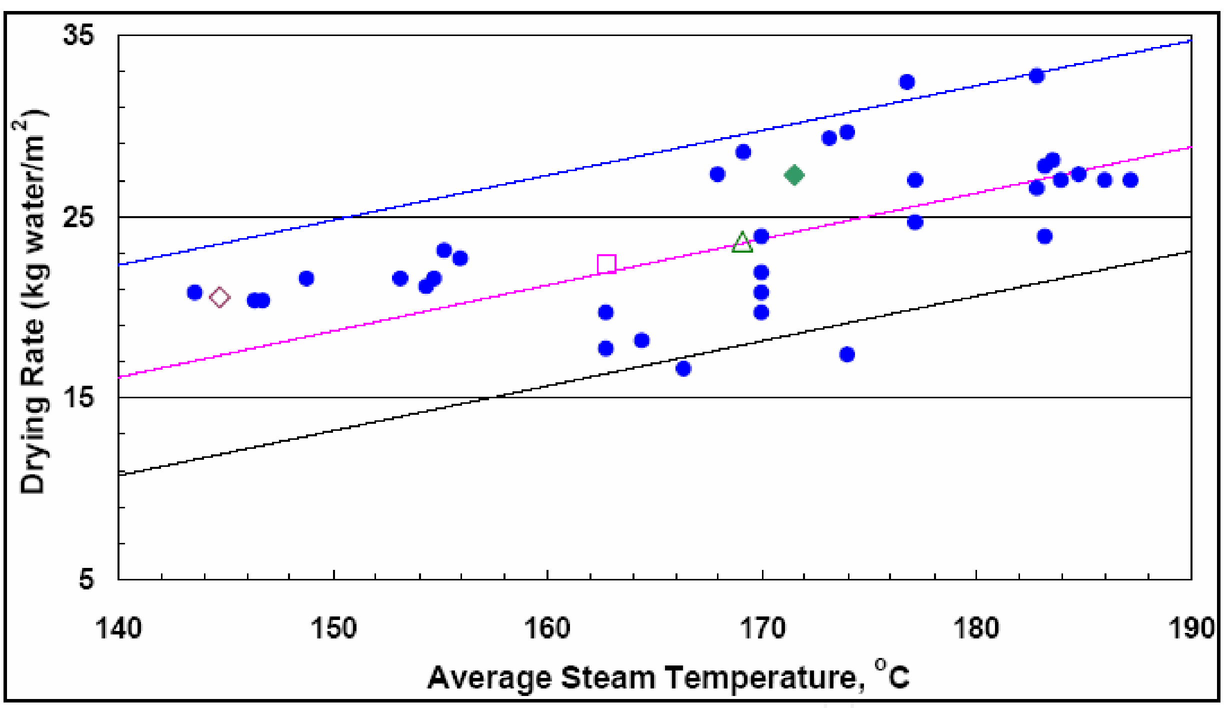

Fig. 8.1 Tappi Drying Rate for Machine A producing Linerboard products

The overall drying rate for Machine A based on the data was 27.3 kg H_2O/hr/m^2 at 171.5°C average steam temperature. This value is higher than the mean value of the TAPPI surveyed machines, and is higher than the corresponding values obtained during previous audits, suggesting improvement in drying rate. It is important to note that the calculation of drying rate is significantly influenced on the web moisture entering the dryer section and also the final web moisture at the reeler. Quite often, web moisture entering the dryer section is not measured and use of mill supplied historical moisture value can affect the overall drying rate.

8.3.2 Steam efficiency

Another indicator of the drying efficiency of the dryer section of the paper machine is the amount of steam used to evaporate unit mass of water. Water removal by drying paper is more expensive than water removal by pressing. Research indicates that somewhere between 1.1 kg and 1.7 kg of water is evaporated in the dryer section per kg of solids, depending on the inlet and outlet sheet moisture. Each kg of water evaporated requires in the area of 1.3 to 1.6 kg of steam.

For the linerboard machine investigated, the steam efficiency of this machine resulted 1.35 ton of steam per ton of water evaporated. In Figure 8.2, the steam efficiency of this machine is compared with large number of machine produced same grade of product surveyed. The steam efficiency of this machine significantly improved from 1.8 kg steam/kg water evaporated in 1996 to the current level of 1.4 kg steam/kg water evaporated in 2007. The improvement was the result of incremental improvement program undertaken by the mill.

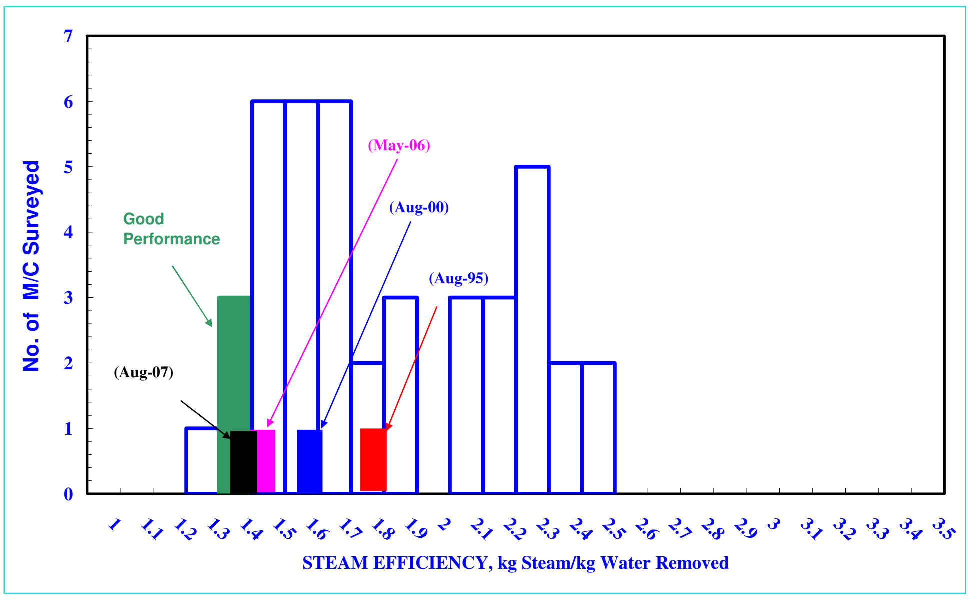

Fig. 8.2 Steam Efficiency improvement of a linerboard machine

8.3.3 Production efficiency

The most important indicator of the performance efficiency of the dryer section of a paper machine from economic point of view is the production rate efficiency or the steam usage per unit mass of paper manufactured. This efficiency strongly influences the manufacturing cost of paper and paperboard. Drying energy cost (typically $10/tonne of steam) is somewhere between $20 to $45 per tonne of paper/ paperboard produced. In Figure 8.3, the production efficiency of Machine A is compared with large number of machine produced same grade of product surveyed. The median value was about 2.2 kg steam/kg of paper produced compared to 2.34 t/ton of paper for this machine.

8.3.4 Overall dry-end efficiency

The most important criterion for efficient drying of paper is achieving target or desired moisture level/profile of web at the reeler using lowest energy consumption and at maximum design speed of the paper machine. Ideal condition at which the drying rate can be increased at decreasing steam usage per unit mass of water evaporation is desirable for achieving the optimal overall dry end efficiency.

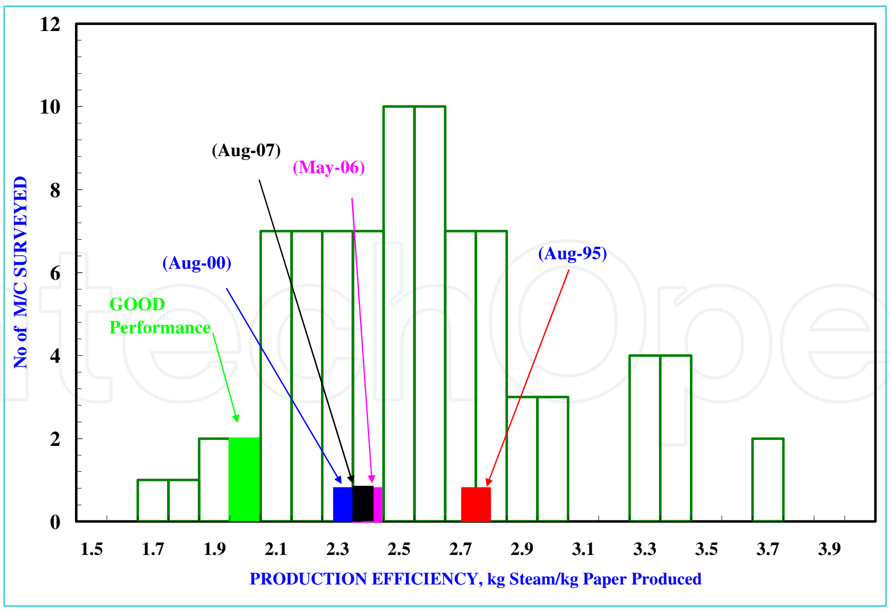

Fig. 8.3 Production Efficiency improvement of a linerboard machine

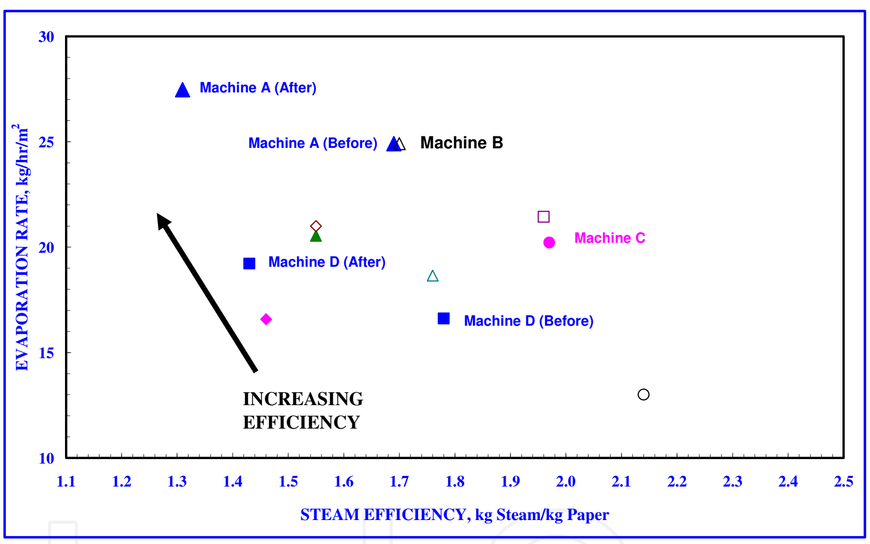

Fig. 8.4 Overall dry-end efficiency for paper machine making corrugating medium

Figure 8.4 shows the comparative overall dry end efficiency of several paper machines producing corrugating medium grade papers. For both Machines A and D, the drying rate increased at reduced steam usage reflecting significant improvement in overall dry end efficiency. The improvement for Machine A was the result of the upgrade of the steam and condensate system along with increasing the number of dryer cylinders. The improvement for Machine B was due to elimination of a moisture streak that was originating in the forming section.

As indicated earlier, the paper drying process is a complex heat and mass transfer process and number of variables and sub-process influence the final outcome of the drying efficiency or performance. The accepted level of various index values influencing the overall dry-end performance of paper machines making three common paper grades are shown in Table 8.1.

Index	Unit	Fine Paper	Linerboard	Medium
Press Dryness	%	40.0	42.0	42.0
Steam-to-surface Temp. difference	^oC	22-28	22-28	22-28
CD Temperature	^oC	2.8	2.8	2.8
Tappi Drying Rate	kg/hr/m^2 @kPa	32 @450	28 @965	24 @965
Condensing Load	kg/hr/m2	17	36	32
Average Pocket AH	g water / g air	0.20	0.20	0.20
Peak Pocket AH	g water / g air	0.25	0.30	0.30
Hood Balance	%	70	70	70
PV Temperature	^oC	82	93	93
Steam Efficiency	Kg / kg H_2O	1.0	1.30	1.30

Table 8.1 Dryer section Performance Levels

The total amount of energy consumed in the dryer section of a paper machine can be broken down into sheet heating, evaporation, air heating, non-condensable bleed and venting. Energy required for evaporating water from the sheet is essentially constant and can not be easily changed. Air heating requirements are a function of pocket ventilation air volume and temperature. The biggest potential energy waste is venting steam to the atmosphere or to a heat exchanger. Steam and condensate systems should be designed in such a way that no venting occurs during normal operation.

8.3.5 Case studies

Results of two case studies are shown in this section. In both cases, the importance of pocket ventilation air system and hood balance is illustrated with realization of tangible benefits.

Case I: Decrease in Machine Speed - Improper Damper Setting of Exhaust Duct.

The paper machine in this mill experienced close to a 20 m/min decrease in machine speed although the press dryness and other machine operating variables did not change. A request was made to establish the cause and subsequently recommend a solution to the mill to rectify the problem. A systematic investigation was undertaken, primarily focused on the dryer section. A comprehensive audit of the dryer section and hood balance of this machine was undertaken previously and this helped for direct comparison with the results obtained from this investigation.

Direct comparison of absolute humidity (AH) values of air in the dryer pockets of the paper machine for the two audit periods is shown in Figure 8.5. Up to dryer pocket 23, the pocket humidity values from the two audits were very similar. However after the 23rd pocket, the absolute humidity values measured from the present survey were much higher than those of the previous audit. The steam pressure values in the dryer sections were not significantly different between the two audit results. The cause of this high absolute humidity values in the second half of the dryer pockets could not be initially identified until a hood balance was undertaken.

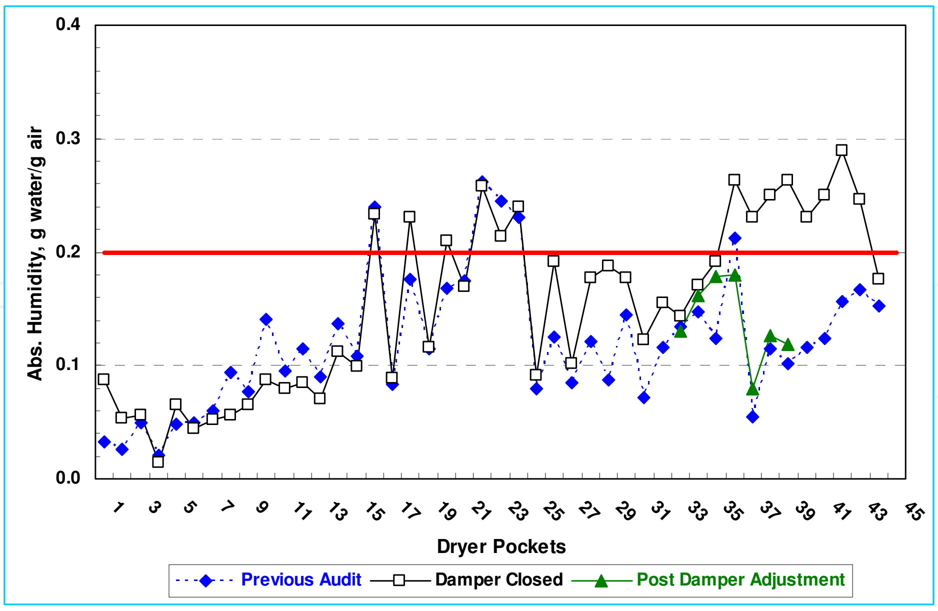

Fig. 8.5 Effect of Damper setting on Pocket Humidity

The hood balance results are shown in Table 8.2**.** It is evident from this table that the amounts of air extracted out through the exhaust Duct #3 based on the current audit was significantly lower than that of the previous audit (28.5 t/hr vs. 76.1 t/hr).

	Audit	Duct 1	Duct 2	Duct 3
Air flow, t/hr	This	76.1	56.3	28.5
	Previous	73.2	64.0	76.1
Water flow, t/hr	This	4.77	4.61	1.15
	Previous	5.34	6.01	6.4
Total Airflow (t/hr)	This	160.9		
	Previous	213.3		
Total Water flow (t/hr)	This	10.5		
	Previous	17.8		
Hood Balance (%)	This	74.5		
	Previous	65.0		

Table 8.2 Exhaust Air and Water Flows

The water flow (with humid air) through this exhaust duct was also significantly lower than the corresponding value calculated from the measured flows during the previous audit. There were no significant difference in flows from the two survey results of both air and water through exhaust Ducts #1 and #2. The total air and water flows through the dryer exhaust system had the consequential effect of reduced flow through exhaust Duct #3. The amounts of ‘introduced’ or pocket ventilation air supplied were similar during the two audits. The apparent higher hood balance was the result of reduced total exhaust air flow.
All these data suggested airflow restriction on the suction side of the exhaust fan in Duct #3. Physical observation of the damper setting of this duct revealed that was the case. After fully opening the damper, the machine speed was increased by 15 m/min within fifteen minutes. This was equivalent to 2% increase in output or 3000 t/yr extra production. To see

the effect of fully opening the damper on the absolute humidity values of the affected pockets (23 through 43), humidity measurements of limited pockets were carried out. The results are also shown in Figure 8.5. It can be seen from this figure that the absolute humidity values fell to the same level as that of the previous audit. This case study demonstrates that if proper attention is given to the pocket ventilation system in the dryer section of a paper machine, there are potentials to improve drying efficiency or increase in production.

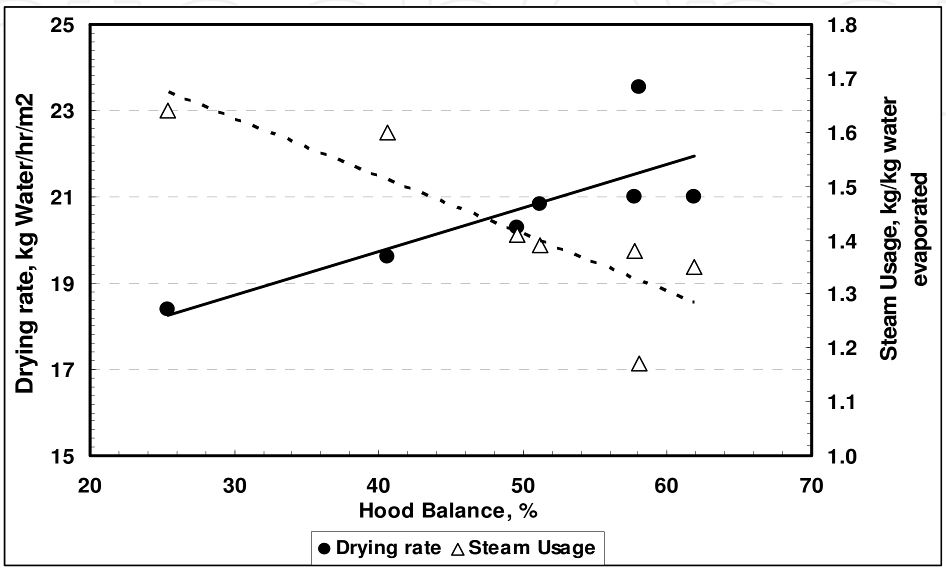

Fig. 8.6 Effect of Hood Balance on drying rate and steam usage

Case II: Hood Balance too low – speed of supply fans not high enough

This is a new machine producing linerboard products. The pocket ventilation (PV) air system of this machine is very good with variable speed drives on all the PV supply and exhaust air streams. Since commissioning the machine, the fan speed of the supply air was set at 65% and the machine was run for almost one year without realizing the full potential of proper hood balance. A comprehensive audit and hood balance of the dryer section was undertaken and it was established that the current setting of the supply fan speed, the hood balance was only 25% and the evaporative drying rate and steam efficiency was 18.2 kg water/hr/m^2 and 1.65 kg steam/kg water evaporated respectively. Multiple hood balance was undertaken over two months' period when the supply fan speeds were increased to various levels in view of obtaining hood balance close to 70%.

Effect of progressive increase in hood balance on improvement on drying rate and reduction on steam usage is shown in Figure 8.6. By increasing the hood balance from 25% to 65% by adjusting the variable speed drives of the supply fans' motors, the drying rate increased from 18.2 kg water/hr/m^2 to 22 kg water/hr/m^2 and the steam usage reduced from 1.65 to 1.25 kg/kg of paper produced. The realized benefits were significant.

9. Alternate non-conventional drying methods

Between 85% and 90% of all commercial paper machines operating globally use steam heated multicylinder system for paper drying. Paper machine equipment manufacturers and researchers working in the field of paper drying are always looking for improved paper drying process that will require less capital investment and can increase drying rate substantially higher compared to conventional paper drying. Some of the alternate drying methods that could be attractive and could be potentially used for commercial application in the future are described below.

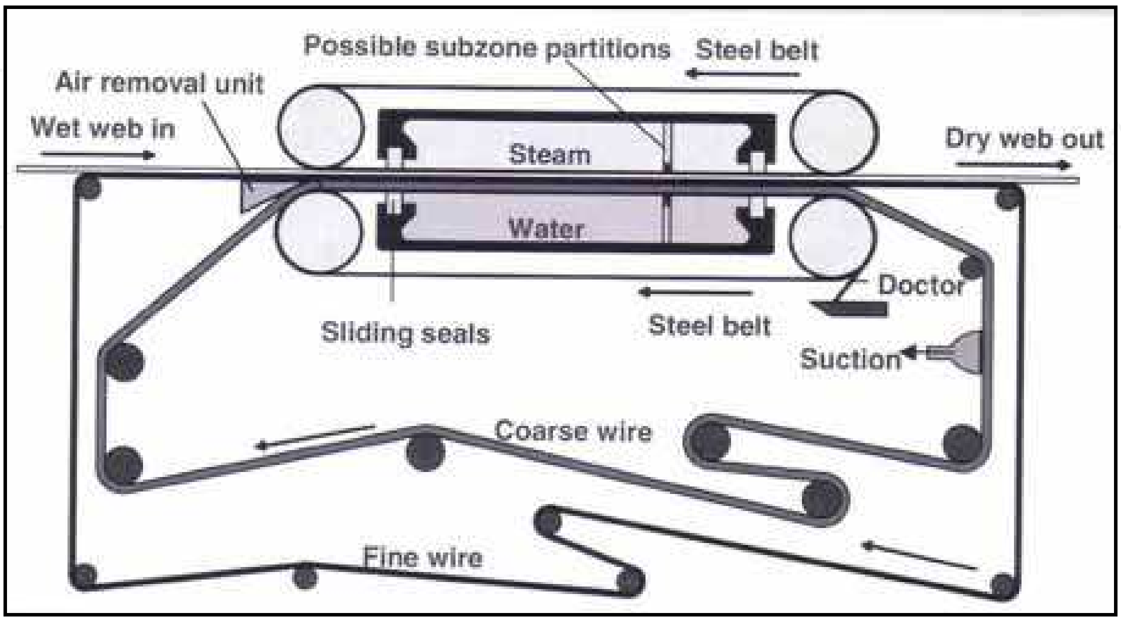

Fig. 9.1 Schematic diagram of Condebelt operating principle

9.1 Condebelt drying

The first alternative to conventional steam heated multicylinder drying was developed in early 1990 and was referred as Condebelt drying (Lehtinen et al, 1995). This process although uses steam, instead of cylinder, steel belt is the heat transfer medium. The Condebelt drying process consists of steel elements causing the moisture of the web to evaporate and the generated steam to condense in a closed unit. The web is dried in contact with an externally heated moving metal belt. Heat transfer to the web causes evaporation. On the other side of the web is a wire and beyond that is an externally cooled metal belt both moving along the web. The metal belts are made of steel with typical thickness of about 1 mm. Figure 9.1 shows the schematic drawing of Condebelt operating principle (Karlsson, 2000).

Compared with conventional cylinder drying, the drying rate is reported substantially higher as the potential for energy recovery along with improved board properties (Lehtinen, 1993). The first commercial installation of Condebelt drying was on a board machine in 1996 followed by a second one in 1999. In spite of the proven benefits of Condebelt drying, this new technology has not been widely accepted.

9.2 Through-air drying

In the through-air drying (TAD) technology hot air is drawn through the web over one or several very open dryers. This process is used for drying tissue paper with improved bulk and more textured web than conventional crepe tissue technology and could not be used for drying non-tissue paper grades. A TAD machine consists of a former, through-air drying section, usually a Yankee section, and dry end with calendar and reel. There is normally not wet pressing in a TAD machine. Figure 9.2 shows TAD tissue machine sections.

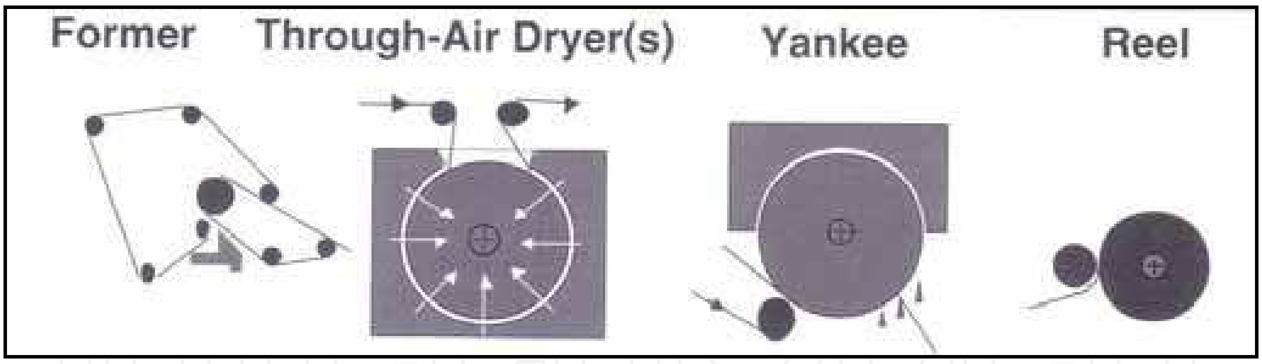

Fig. 9.2 Through-air drying tissue machine sections

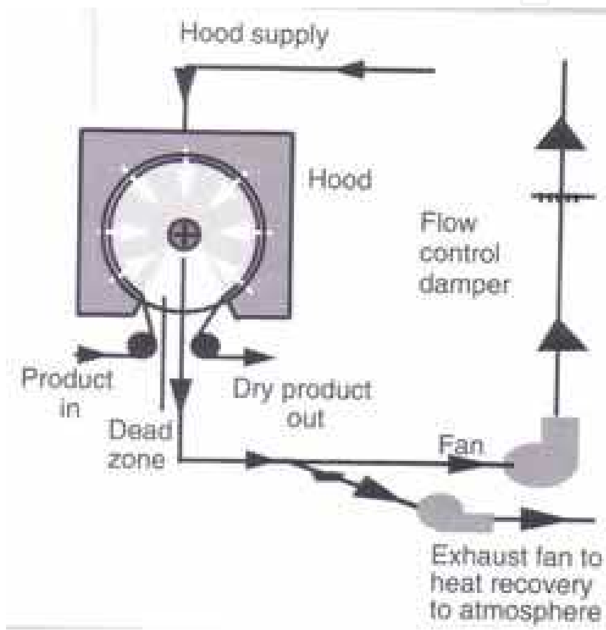

Fig. 9.3 Schematic diagram of through-air drying principle

Through-air drying is a continuous process whereby a mixture of air and water vapour passes through a permeable web causing heat transfer to the web by convection and causes heating and evaporating water from the web. The process air flow schematic shown in Figure 9.3 is representative of a typical through-air drying system.

9.3 Air impingement drying

The idea to use high-temperature, high-velocity air impingement for drying of a paper web was proposed in 1930s (Burgess et al., 1972). The use of air impingement drying is already in use, although to a lesser extent, in some grade of papers such as tissue and sack papers. Impingement technology has common use in Yankee cylinders. In that application, paper attaches to a cylinder, and no dryer fabrics are in use. Air blowing towards paper breaks the stagnant boundary layer and produces a high heat transfer coefficient on the paper surface. Heat transfer primarily occurs through convection. In flotation dryers, sack paper web dries completely without restrain by air impingement drying.

These applications do not use full capacity of air impingement drying since the temperature and nozzle velocity are of modest levels. In air impingement drying, the main process parameters are air temperature, jet velocity, air moisture content and muzzle geometry. Two important parameters concerning evaporation capacity are jet temperature and jet speed. Although the full potential of air impingement drying of paper web is not realized yet, this technology is a very viable alternative to paper drying. It offers many advantages compared with conventional steam drying cylinder, namely, high drying rates, short dryer section, fast drying response, better profiling and curl control.

9.4 Impulse drying

Impulse drying is a water removal process where a moist web passes through a high temperature press nip. The method combines elements of wet pressing and hot surface drying. Typical characteristics of the nip are a roll surface temperature of 150^{o}C-500^{o}C, nip pressure of 0.3-7 MPa, and nip residence time of up to 100 ms. The first detailed published work on impulse drying was made in 1985 (Wahren, 1985). A single unit could replace an extensive part of the current dryer section and last nip of the press section. Besides the high drying capacity, impulse drying provides possibilities to modify paper properties. In spite of promise of huge benefits, the impulse drying technology did not lead to a commercial application. This is largely due to large number of technical problems related to practical operation yet to be resolved.

9.5 Steam drying

The idea to use steam as a drying medium is not new. Some industrial applications for wood and coal drying date from 1930s. Renewed interest for using steam in convective dryers rather than hot air appeared in the late 1970s probably due to energy crisis at that time. In principle, any direct air dryer can operate with steam. To-day, industrial scale steam dryers have use for textile webs, market pulp and lumber. The first patent to apply the concept of steam drying for paper appeared in the early 1950s. A good review of research work on steam drying of paper is available in the literature (Douglas, 1994).

Compare to air drying, steam as a drying medium can offer many advantages. The most interesting is the potential to save energy. If the exhaust steam has use elsewhere in the process, the net energy consumption may be very low. Another advantage is safer operation, i.e., no fire or explosion hazard. The drying rate is higher in steam drying than air drying if the operating temperature is high. Despite intensive theoretical and experimental work on steam drying, no industrial steam drying applications for paper webs exist to-day.

9.6 Micro-Waves drying

The possibilities of using micro-waves for paper drying have been examined extensively. Laboratory equipment for micro-wave drying has been built and many potential advantages have been shown to exist (Warner, 1966). The main advantage of using micro-wave energy for paper drying would seem to be the possibility of obtaining an even and uniform moisture profile at the desired level.

The absorption of micro-wave energy is roughly proportional to the moisture content of the web. This means that areas of higher moisture content will be more strongly heated than areas with lower moisture content which will result in an automatic leveling-out the moisture across the sheet. Use of micro-wave for complete drying of wet paper web is not commercially feasible for number of reasons. However, it could be used at the final stage of paper drying along with conventional cylinder drying process for evening out moisture profile in the reeler. Similar approach using infra-red or impact drying is used in commercial paper machines.

10. Drying and paper quality

The properties of final paper product are strongly influenced by the web conditions in the dryer section including temperature, moisture content and state of stresses. During drying process, due to evaporative dewatering, the fibre shrinks and causes stress on the web. Controlling the stress in the dryer section can improve strength properties in the web. Other major problem is the non-uniformity of shrinkage in the cross direction that can be caused in the dryer section with consequential effect of quality and machine runnability.

By the time the wet web enters the dryer section, the fibre wall has already collapsed due to contraction of fibre network during forming in the forming section. The collapse occurs in the press section and almost all water from the lumen has been removed prior to entering in the dryer section. During drying process, both the bound and free water is progressively diffused out and eventually removed, causing irreversible closure of the macro and micro pores in a fibre cell wall.

Paper shrinks during drying in the direction of thickness and in its plane. On the paper machine, the paper web is strained in the machine direction and allowed to shrink in the cross direction. The edges of the web shrink more than the middle of the web. A shrinkage profile therefore exist in the cross direction. This leads to variation in the properties of the paper in the cross direction. The level of stress during the drying process significantly influences the elastic properties of paper. If the web dries under restraint, it will have a higher modulus of elasticity, higher tensile strength and better dimensional stability than a web allowed to shrink during drying. The differences in paper properties are due to different drying stress and stress concentration levels and changes in crystallinity and fibre orientation (Htun, 1980).

Wire marking on the paper is an important quality issue, particularly for certain papers, such as cigarette paper or special fine paper grades. Three different types of markings are possible: mechanical or imprint marking; evaporation marking and marking due to uneven support. This type of marking is not a marking seen as a plane difference in the paper surface, but as a visual defect especially visible with transillumination. The evaporation marking is usually the result of uneven drying due to permeability differences in the fabric or seam area and web contact.

The drying process in the paper machine dryer section can influence two important quality parameters, paper curl and cockle. Presence of both curl and cockle are undesirable form paper's functionality aspect. The original reason for curl is the difference in fibre orientation through the thickness of a paper. Other factors such as stressing and drying also have significant effects on curl. A sheet with a total uniform structure through its thickness will curl if dried non-uniformly. Non-uniform drying can be the result of a temperature difference between the top and bottom dryer cylinders. Cockle is a localized defect on paper that is the results of shrinkage and deformation of fibres while drying. Drying parameters that can aggravate cockle are sticking of sheet on hot dryer surface, high wet end dryer surface temperature and too rapid drying.

10.1 Drying induced cross direction (CD) profile

Two most critical profiles in the cross direction of paper web that influence its functionality at end-user application are moisture and shrinkage. The dryer section may lead to non-uniform moisture profiles in different ways. The moisture profile of a paper web during drying depends on the web's moisture profile entering the dryer and the uniformity of moisture vaporization during the drying process. The former is due to such factors as basis weight profile, fibre orientation in the web and material distribution profiles established during forming and pressing. This causes an additional effect on edges where the amount of water to be vaporized is less than in the middle of the web. Possible better ventilation at the edge areas can cause a moisture profile of the web where the edges dry faster than the middle. Variations and profiles in surface temperature of dryer cylinders, variations in heat transfer caused by dirt accumulation at heat transfer interface or uneven contacts, profiles in pocket ventilation, felt permeability profiles can cause moisture profile in a web during drying.

In commercial drying of paper, the web's cross direction shrinkage is uneven during the drying process and during the free draw between the last press and the first dryer cylinder where the web undergoes stretching. Improper operation of the dryer section can itself influence the shrinkage profile mostly locally. The CD shrinkage profile is the most important CD profile generated by the dryer section, since it influences several other CD profiles.

Figure 10.1 shows an example of the effect of CD shrinkage profile for sack kraft paper (Ghosh, 2009). In this machine, the CD moisture and shrinkage profiles were very poor, primarily due to absence of adequate pocket ventilation system. For sack paper, the two most important properties are stretch and tensile absorption energy (TEA). Ideally, these profiles be relatively flat so that sack made using papers from different width in the cross direction do not fail on impact. The machine was upgraded with installation of a Clupak system for making semi-extensible sack paper, but without upgrading of the PV system. As a result, the sack paper made had very good stretch and TEA in machine direction, but very poor in cross direction with consequential effect of rupture of sacks in CD on impact. The mill had no choice but to upgrade the PV system to improve both moisture and shrinkage profiles in the cross direction. The CD profiles of TEA and stretch after the PV upgrade are shown in Figure 10.2. Clear improvement in TEA profile is obvious. CD stretch values at the edges are always higher due to unrestrained dryer and more shrinkage at the edges. However, the percentage variation of stretch in the cross direction with respect to the centre of the web decreased from 75% to 40%

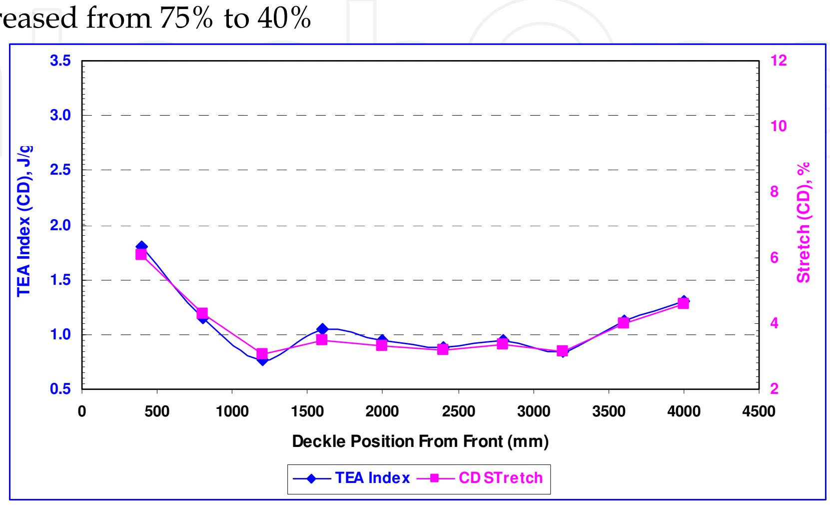

Fig. 10.1 Stretch and TEA profiles of sack paper - before upgrade of pocket ventilation

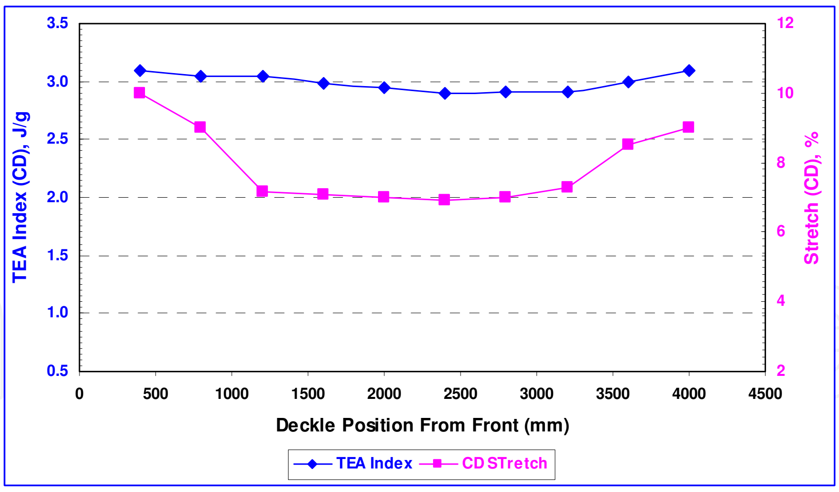

Fig. 10.2 Stretch and TEA profiles of sack paper- pocket ventilation upgrade

10.2 Equipment to improve cross direction moisture profile

Despite uniform heat and mass transfer in the dryer section, variations in cross machine moisture profile can exist because of non uniformity in the wet-end and the press section. For better functionality of the paper, such profiles must be improved. Several means and equipment are available for such improvement.

10.2.1 Water sprays

Water spray is an alternate approach. In this system, instead of adding extra energy to dry moist streaks, fine sprays of water are used at localized areas with 'dry' spots or areas where web moisture is much lower. The energy efficiency of this profiling method is much lower than that of other methods, but has two advantages. With a machine calender, the dampening unit can improve the calendaring effect. The other advantage is the ability to control web curl. A unique aspect of spray dampening, not readily obtained with other moisture control methods, has the potential to relieve stress and consequent correction of cockle and curl at the point of first appearance. These benefits primarily depend on the location of spray bar within the dryer, sprayed water droplet size and uniformity, sprayed water pattern from each nozzle, nozzle flow control resolution, range of water volume and water preparation. An optimal water spray system can also lead to uniform basis water profile resulting improved machine runnability and production of off-quality production.

10.2.2 Steam box

In this system steam shower is use to spread steam on the web primarily on the foudrinier or in the press section. The impinged steam condenses in the web and the resulting web temperature increase reduces the viscosity and surface tension of the water in the web. The sheet therefore dewaters easily at the couch roll and in the press section. The web temperature entering the dryer section is usually higher. Steam showers can be zoned in the cross section. Actual distortion of the moisture profile coming from the press is then possible to correct for anomalies and irregularities that will occur downstream in the dryer section.

10.2.3 Infra-red profiling system

Use of such system is based on modular infra-red generating units are side-by-side across the width of the paper machine near the end of the dryer section. Each module is typically

150 mm wide and represents a separate control zone. An infra red profiler can effectively dry irregular moisture streaks or significantly flatten a moisture profile. Infra-red radiators especially electrical ones have fast response and are used to correct narrow moisture streaks. Infra-red modules could be either gas-fired or electrical.
Various features of the three most common moisture profiling systems are shown in Table 10.1. It is evident from this table that use of water spray is preferred to that of other moisture profiling equipment due to its safe, low maintenance, low energy usage and versatile control options. All most all new modern paper machines now a days is equipped with water spray in addition of steam shower in the press section.

Feature	IR (Electrical)	IR (Gas)	Water spray	Steam shower
Capital Cost	High	High	Moderate	Low
Control Cost	Moderate	Moderate	Moderate	High
Energy Type	Electricity	Gas	Dryer steam	Waste steam
Energy Use	High	High	Low	Net saver
Efficiency, %	17-35	30-50	60-95	50-95
Streak Control	Limited	Limited	Unlimited	Limited
CD Resolution, mm	20-150	150	100-300	75-300
Maintenance	Moderate	Low	Moderate	Low
Safety hazard	Moderate-High	Moderate-High	None	Low

Table 10.1 Options for control of different moisturizing control systems (Cutshall, 1991)

10.2.4 Miscellaneous system

Proper pocket ventilation and installation of turbulator or dryer spoiler bars are two less efficient means of improving moisture profiles. Unlike the three other profiling systems described earlier, use of these approaches can only correct stable profiles. Machines without of adequate pocket ventilation and/or spoiler bars generally produce papers with poor moisture profiles. In most of the modern machines, PV and spoiler bars are integral part of the machine design. Even then, some form of extra moisture profiling units is always present.

11. Conclusion

Paper drying is a complex heat and mass transfer process, where heat is primarily transferred by conduction and to a lesser extent by convection, and mass transfer by evaporation and diffusion of water vapour. Thermal energy in the form of steam is used as the main source of heat to evaporate water from the wet paper entering the dryer section of a paper machine with more than 50% of its weight containing water. Hot air is used as the carrier of water vapour evaporated from the web.
Almost all commercial paper machines operating globally use steam heated multicylinder dryers to dry wet paper to a final moisture content of finished product between 6% and 8%. Although researches on alternate paper drying methods, both in laboratory and pilot scale levels, are being undertaken, commercialization of such methods are yet to be adopted in near future. Through-air drying of tissue paper is the only paper drying process that is primarily of convective heat transfer and does not use steam heated cylinder. Novel technique of Condebelt drying is very promising due to significantly higher drying rate and improved paper quality, but lacks global appeal.
The dryer section of a paper machine removes between 1.1 and 1.3 kg of water per kg of paper compared to 200 kg and 2.6 kg in the forming and press sections respectively. It is

significantly more expensive to remove this water by drying compared to any other mechanical means. In spite of its key role in papermaking, large equipment size, and large capital and operating costs, drying is arguably the least understood papermaking operation. Detailed analysis of the main components involving dryer section by using data from field measurements is vital in identifying root cause(s) of poor dry end efficiency of a paper machine and for potential improvement. Tuning of the steam and condensate, pocket air ventilation systems and hood balance are critical for optimizing dryer section of a paper machine. The importance of pocket air ventilation and hood balance in paper drying is quite often ignored during operation of the dryer section of a paper machine. The case studies presented suggest that significant improvement in paper machine efficiency or product quality can be achieved if due attention is given to the dryer section.

Unlike drying of other materials, paper drying process is different due to unique characteristics of paper sheet that is made of fibre network in which the cellulose fibres are held together through hydrogen bonding. Fibre properties and structure of the paper sheet is strongly influenced by pulping processes and types of fibres used in papermaking, presence of macro and micro pores. Various physical laws control removal and evaporation of free and bound water from wet web. Many of the key functional properties of the finished product are developed during the drying stage of the papermaking process. Controlling of moisture and shrinkage profiles in the cross direction of the width of paper web during paper drying is critical in end-user performance of finished paper products.

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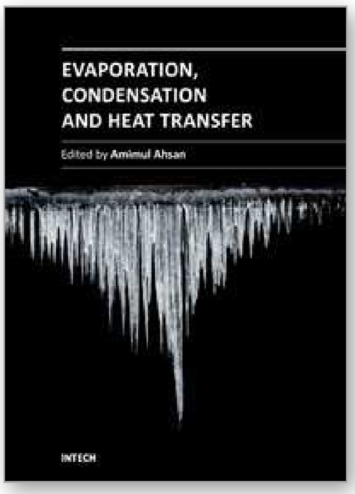

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