Papermaking

PAPERMACHINE – DRYING

Introduction

Drying in papermaking serves two functions. First, it removes the remaining water in the web that cannot be removed by vacuum or pressing. Second, it causes fibres to bond together by hydrogen bonding.

Types of Water in Web:

The water remaining in a web after pressing is of several types.

Free Water

This water is held in pores, interstices between fibres, and in lumens of fibres. The water is held in place by capillary forces. Water between 35-70% consistency is generally free water.

Imbibed Water

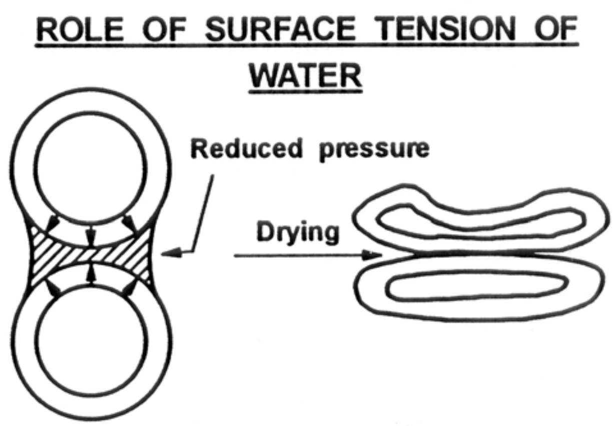
This is water held within the swollen cell walls of fibres. It is the water which makes up the “fibre saturation” point of pulp (water to completely saturate fibre wall without filling lumen). It is more difficult to remove than free water. Water removed between 70-90% consistency is generally imbibed water.

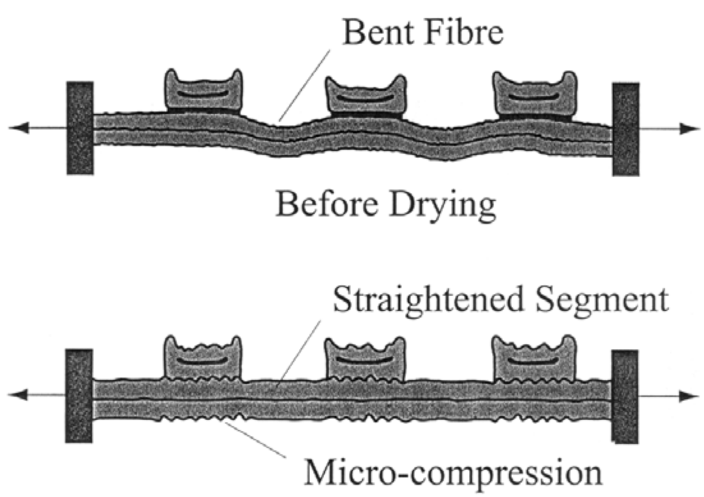
Chemically Bound Water

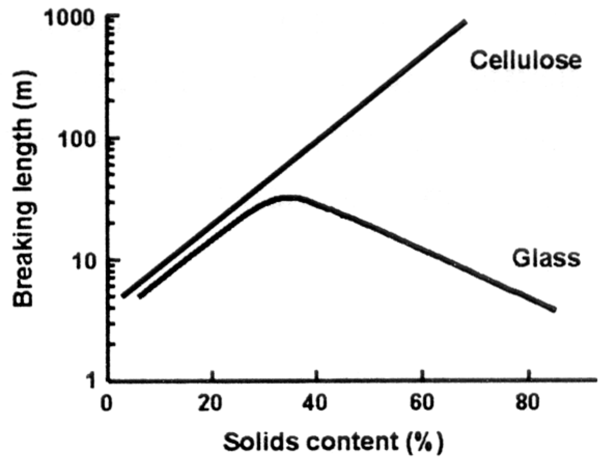
This water is chemically bound to cellulose. It has zero vapour pressure and is not removed in the papermaking process.

Fibre Bonding

As free and imbibed water are removed from the web, strong surface tension forces develop between fibres, causing them to come into intimate contact as shown in Figure 1a. This leads to molecular (hydrogen) bonding. These forces also cause fibre straightening and microcompressions at bonding sites, as shown in Figure 1b. This starts at a consistency of about 20%, as shown by the comparison to glass fibres in Figure 2. This hydrogen bonding provides all the strength needed for most papers, i.e. adhesives are not added.







The Drying Process

Drying Stages

Drying is achieved by raising the web temperature in the web to a level at which the vapour pressure of water in the paper exceeds the partial pressure of water vapour in the ambient. This pressure difference is the driving force for the evaporation of water from the web.

The drying process consists of a) heat transfer to the web and b) mass transfer of vapour from the web. Drying of paper has three stages, as shown in Figure 3.

The first stage is a warm up stage.

The second stage is a “constant-rate stage”. Here the drying rate is constant because sufficient water remains in the web that heat and mass transfer within the web are not rate controlling steps.

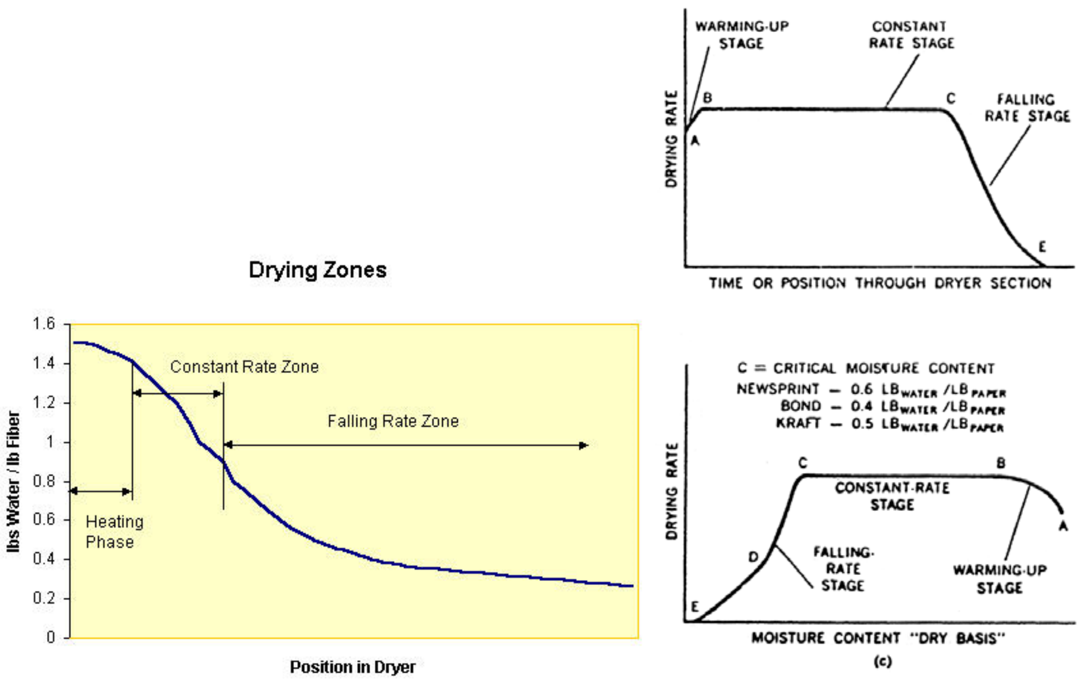


Figure Drying rate through dryer

The third stage is the "falling-rate stage". Here there is not sufficient water to completely fill the web. Water near the paper surface in contact with the hot roll evaporates, causing complex mass transfer of vapour and liquid diffusion within the web. Water near the hot surface evaporates and diffuses outward. Some liquid flows in towards the hot surface. The final point of evaporation (determined form dye tests) takes place from both surfaces.

These three stages of drying are illustrated in Figure 3. The consistency (or moisture ratio) at which the constant rate ends and the falling rate begins coincides approximately with the transition from free to imbibed water remaining in the web.

Dryers on Paper Machines

On a paper machine, drying is accomplished by passing the web around a series of steam-heated cylinders. There are about 40 to 70 dryer cylinders on a typical paper machines, and this is by far the largest part of a papermachine.

The dryer cylinders are grouped in sections having 8-10 dryer cylinders. Two such sections are shown in Figure 4. Each section is independently driven, and has a felt or fabric threaded in it to press the paper on to the hot rolls, as shown in Figure 4.

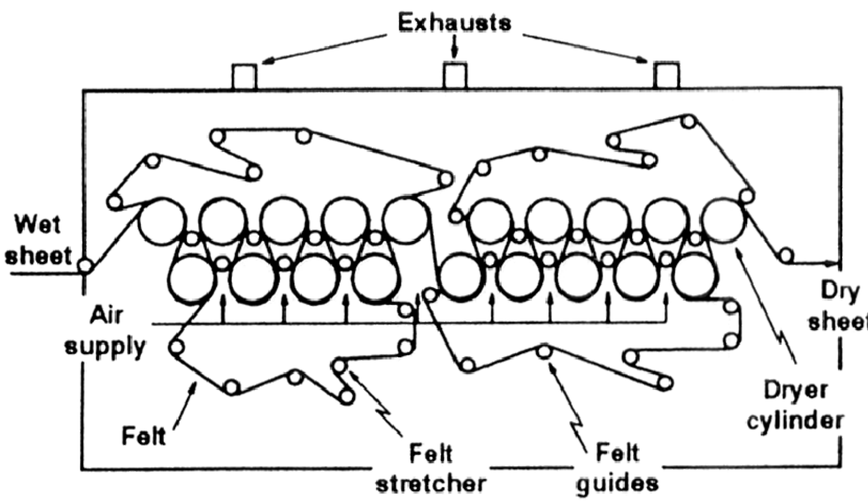
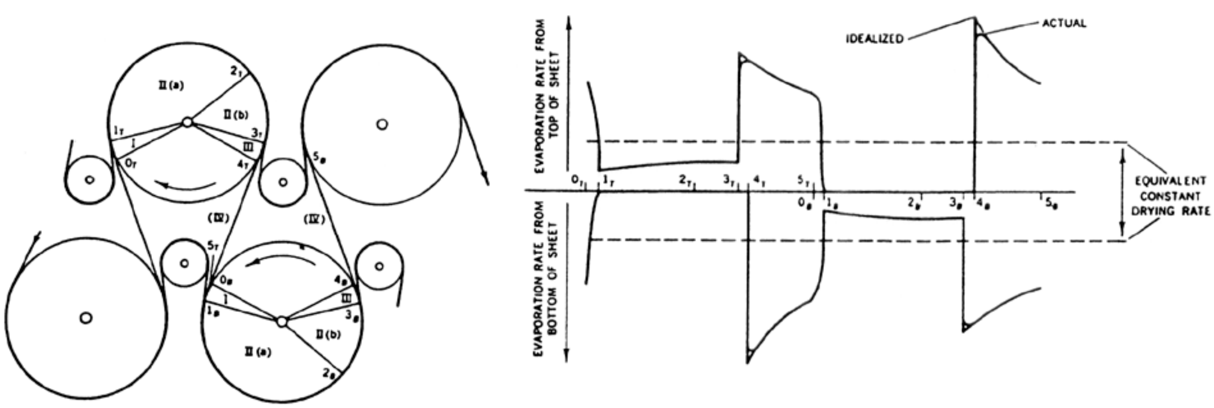


Figure: Conventional Cylinder Dryer

The drying rate around one cylinder is shown below. This shows that most of the mass transfer tales place in the draw between cylinders. Heat transfer takes place while the web is in contact with the roll.



Heat Transfer

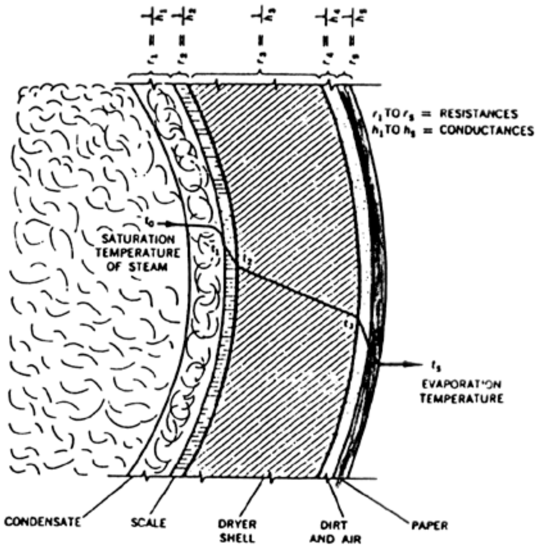
The first requirement of a dryer is to transfer heat efficiently from the condensing steam to the paper. The resistances to overcome are depicted. The resulting heat transfer is determined by the combined effect of these resistances, which is given by the resistance law, Some typical values for the coefficients are also given in Figure 7.

Condensate

This is the first resistance encountered in heat transfer. It is governed by the condensate thickness and its velocity is relative to the cylinder. These give three regimes of condensate behaviour shown in Figure 8: ponding, cascading, and rimming.

The ponding and cascading regimes generally occur with slower board machines. As can be determined from equation (1) in Figure 8, speeds over about 300 m/min give "rimming".

In the rimming regime, condensate is held on the dryer surface by centrifugal forces. Nevertheless, there is a relative velocity between the condensate and cylinder, as given by equation (2) in Figure 8. This is called "sloshing". This is important in attaining convective heat transfer through the condensate, thereby increasing the heat transfer coefficient by a factor of 5 or more over pure conduction. Indeed, sometimes "breaker bars" are installed in drying cylinders to cause the condensate to adopt turbulent flow, and thereby increase heat transfer.



Heat Transfer

$$Q = h_T A \Delta T$$

$$\Delta T = T_{steam} - T_{paper}$$

$$\frac{1}{h_T} = \sum_{i}^{N} \frac{1}{h_i}$$

Typical Values of h_i ($W/m^2 \cdot K$)

	Wet End	Dry End
Condensate	1700	2270
Shell	1700	1700
Contact	1420	1130
Web	5680	2270

Figure: Heat transfer through condensate, cylinder and paper

Rimming Speed, V_R

(1) $$\frac{V_R}{(\bar{\delta} g)^{1/2}} = 9.1 \left(\frac{R}{\bar{\delta}}\right)^{0.2} \left(\frac{\upsilon}{\bar{\delta}^{3/2} \cdot g^{1/2}}\right)^{-0.026}$$

Condensate Thickness, δ

(2) $$\frac{\delta}{\bar{\delta}} = \frac{V_0}{V} = \left(1 - \frac{2gR}{V_0^2} \sin \varphi\right)^{-1/2}$$

V **condensate velocity**
V_0 **cylinder velocity**
δ **local condensate thickness**
δ **average condensate thickness**

Figure: Condensate Behaviour

Heat Transfer in the Web

In Figure 7 it may be noted that the heat transfer coefficient for the “web” at the dry end of a paper machine is only half that at the wet end. Thus, the “falling rate” stage is due in part to diminished heat transfer. This occurs because water evaporation away from the hot surface creates a layer of dry paper in contact with the roll. Dry paper is a poor conductor of heat; indeed, it is a good insulator. This in effect insulates the moist part of the web from the hot dryer surface.

Mass Transfer

Once liquid water has been vapourized, it is necessary to transport the vapour through the web and out of the paper machine.

Constant Rate Stage

In the constant rate stage, vapour leaves the surface by diffusion as shown in Figure 9. This is described by equation (1) in Figure 10. Here, the driving force for diffusion is the difference between the vapour pressure of the water at the paper surface and the partial pressure of vapour in the surrounding air. The resistance is given by a mass transfer coefficient, which is determined from correlations such as the one for Sherwood Number shown in Figure 11. For the constant rate stage, the vapour pressure of water on the web surface is approximately the vapour pressure of water alone, and therefore this can be obtained form the steam tables.

In the falling-rate stage, the vapour pressure of water diminishes because water is evaporated from within the web. Here the forces holding water in place differ from those on a free water surface. Studies have yielded expressions for this vapour pressure, but a common way of modelling mass transfer in this stage is by inserting an empirical factor in the constant-rate equation, as shown in equation (2) in Figure 10. This added term accounts for the fact that mass transfer diminishes with decreasing moisture in the web, reaching zero when the moisture content reaches the equilibrium value.

Ventilation

Once the moisture has diffused from the web, it is necessary to remove it from “pockets’ formed between the web and fabrics. This is accomplished by various methods of pocket ventilation. One of these is a natural pumping action caused by the boundary layer flows of the fabrics, illustrated in Figure 12.

Because of the large amount of moisture-laden air generated by a dryer, the entire dryer section of a paper machine is enclosed in a hood. Large fans draw the moisture-laden air away to economizers. These are direct-contact heat exchangers to warm process water. The vapour is then expelled through stacks, as shown in Figure 13.

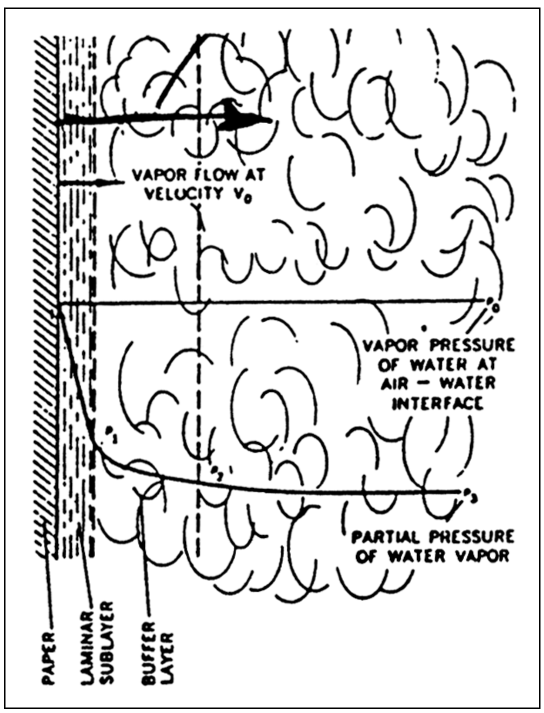


Figure 9

Constant Rate Stage $$\frac{dm}{dt} = \frac{2h_D}{WRT_R}\left(p_S - p_o\right)$$

Falling Rate Stage $$\frac{dm}{dt} = \frac{2h_D}{WRT_R}\left(\frac{m - m_e}{m_c}\right)^{\frac{2}{3}}\left(p_S - p_o\right)$$

m	ratio of water/fibre
m_e	equilibrium moisture ratio (5-10%)
m_c	critical moisture content
p_S	vapour pressure of water in paper web
p_o	partial pressure of vapour in air
h_D	mass transfer coefficient
W	basis weight
R	gas constant for water vapour
T_R	temperature of air around dryer
2	assumes mass transfer from 2 sides

Figure 10

$$\underbrace{\frac{h_d x}{D_v}}_{\text{Sherwood Number}} = 0.324\underbrace{\left(\frac{Ux}{\upsilon}\right)^{1/2}}_{\text{Reynolds Number}}\underbrace{\left(\frac{\upsilon}{D_v}\right)^{1/2}}_{\text{Schmidt Number}}$$

Figure 11

Note: Dv is molecular diffusivity, ν is kinematic viscosity, h_d is diffusion rate and x is paper thickness.

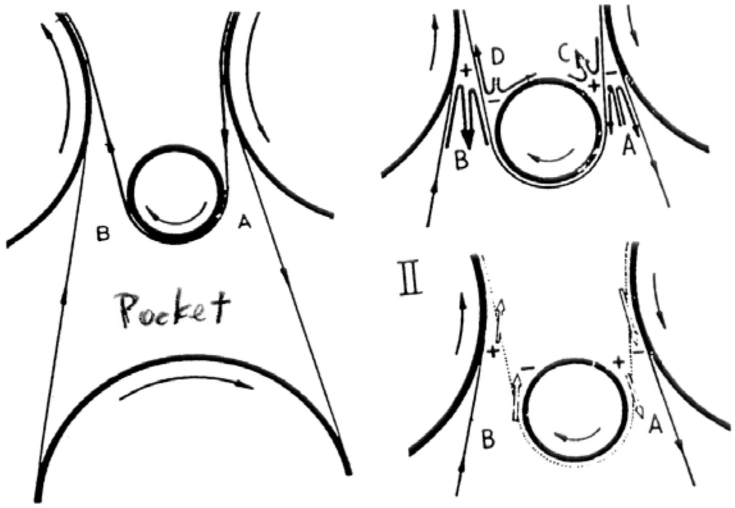


Figure 12

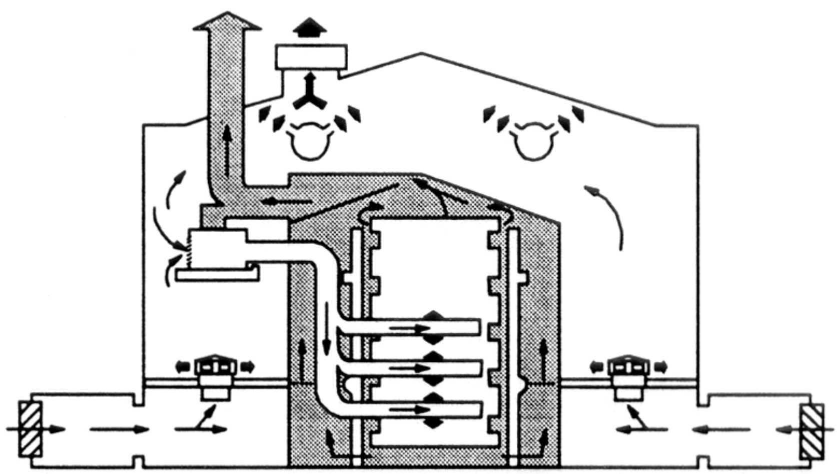


Figure 13

Useful Data

Paper machine dryers have been modelled using computers and rigorous application of heat and mass transfer principles. However, there is often a need for some simple estimates of dryer sections of paper machines. In this case, data compiled from industry averages are frequently used. The TAPPI drying rates shown in Figure 14 are one source. When an approximate value of steam per unit water to be evaporated in needed, the CPPA dryer surveys are useful. For example, a useful average is 1.6 kg steam/kg water evaporated.

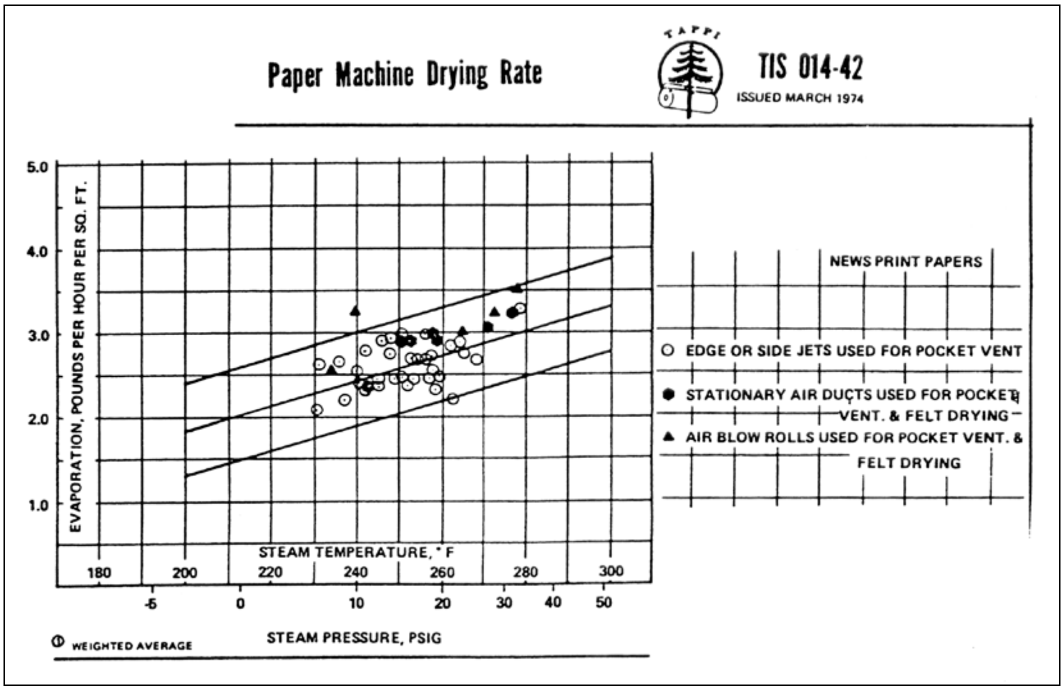


Figure 14

Other Types of Dryers

Other types of dryers than the standard cylinder dryer discussed thus far exist. These are described below briefly:

Single-Tier Dryers

These are newer dryers for high-speed machines to provide high runnability. In essence, the paper web is threaded around one row of dryers with a bottom row of cylinders serving merely as turning rolls. Thus, the web is continuously supported by a fabric; there are no free draws. However, only one side of the paper is heated, and therefore a section with dryers on the bottom row are inserted in the dryer, a shown in Figure 15.

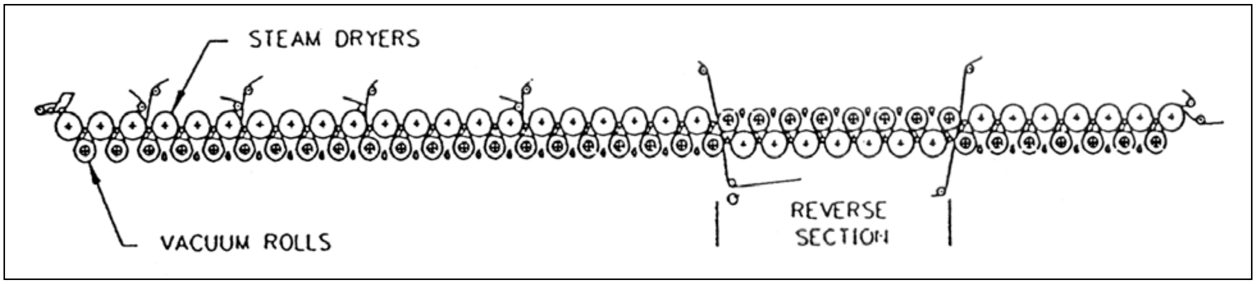


Figure 15

Yankee Dryers

This is essentially one large diameter (8m) steam-heated cylinder with high velocity hoods having jets of hot air blowing on the paper surface. These are used for tissue machines. Being very light weight, tissue can be easily dried, but needs to be continuously supported. Such a dryer is shown in Figure 16.

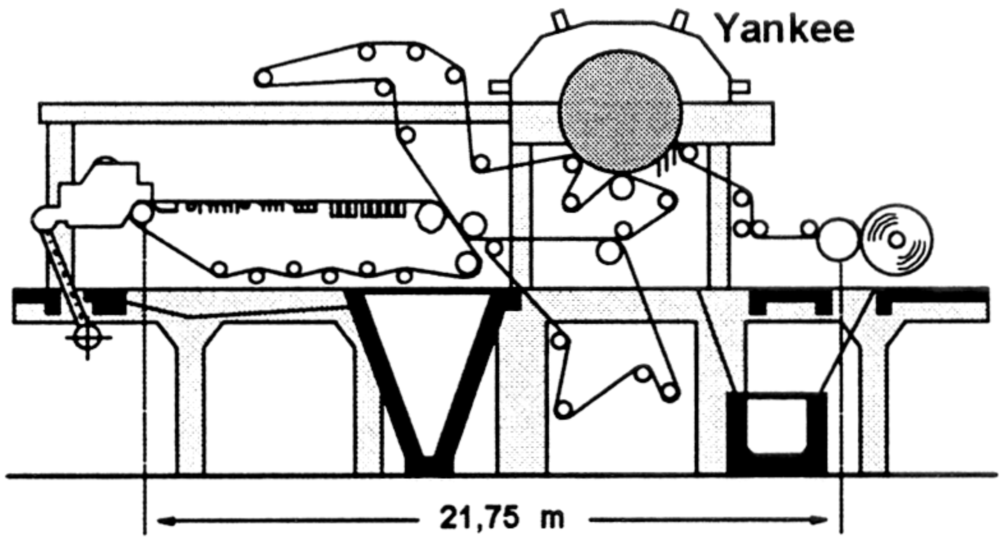


Figure 16

Flakt (Air Flotation) Dryer

This dryer, shown in Figure 17, is commonly used on pulp machines. The web is passes through a number of tiers in which hot air is blown on the web. The gives lower temperature drying than is used for paper. This in turn inhibits darkening, embrittlement, and bonding. These factors are important when the pulp is re-slurried by the papermaker.

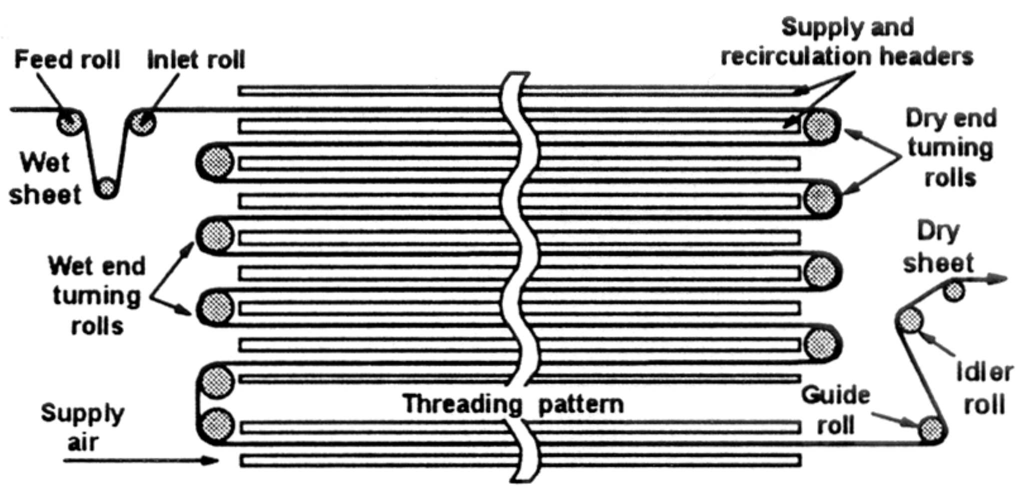


Figure 17