

Modeling of industrial through air dryers: effect of humidity ratio and air temperature on energy consumption

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ABSTRACT

Through Air Drying (TAD) commonly used in tissue paper manufacture is an energy intensive process. Therefore, there is a large industrial interest in optimizing energy use while having a high drying capacity. For instance, typical industrial TAD systems have associated annual expenses in thermal energy in the drying section of around 2 million USD. This study aims to understand the effect of the process variables in the supply on the gas and electrical energy consumption, as well as their effect on the drying capacity. A theoretical model was developed to predict the fans' speed and the burner duty based on the type of product and operating parameters. The model showed good agreement to the industrial plant behavior and allowed insight of the drying system. The effect of two important process variables, namely the inlet air's temperature and humidity ratio were related to the energy consumption. It was found that the use of large amounts of make-up air, which corresponds to low humidity ratios and high temperatures largely increased the overall energy consumption. The model results were validated in industrial trials and implemented in an industrial TAD system. This study, and the associated industrial implementation resulting from it, has led to savings of around of 250.000 USD associated with the TAD energy consumption in a single tissue making facility.

1. INTRODUCTION

Tissue paper has become one of the most used consumer products worldwide, due to its properties such as softness, bulk, absorption capacity and absorption rate. Bulk is the compactness of paper, and it can be calculated by dividing the thickness of the sheet by its basis weight; Absorption capacity is the ability to hold a liquid in both a specific area and a weight of paper, and absorption rate is the required time to absorb a specific quantity of a liquid in a specific weight of paper. Among the main types of tissue paper are bath tissues, napkins, hand towels, kitchen towels and facial tissues. Each of them has their own requirements, which depend on their usage.

Paper tissue demand has steadily grown every year since 1940s in United State and in Europe after of 1960s when paper tissue was produced at industrial scale. In 2017 the global tissue production exceeded 35 million tons, which represent a market of 60 billion US dollars, an increase of 35% from 2007. The main tissue paper producing companies in the world are Georgia-Pacific, Procter and Gamble, Kimberly Clark and SCA.

There are different techniques to produce tissue paper, with the most used being LDC, TAD and ATMOS. The main difference among them is the drying section basically. LDC has been the most used worldwide, with around 80% of the paper machines in the US and 92% in Europe. However, in the recent years TAD and ATMOS have gained relevance, due to the increase in the price of the fibers, which represent around of 50% of total production cost of tissue paper, because these processes allow to produce better quality products, more absorbent, softer using less fibers for the same paper tissue area [1].

TAD has an energy consumption of around 28GJ/Mt, whereas LDC requires 11GJ/Mt. The energy required for TAD drying represents around 15% [1] of the total production costs in tissue paper manufacture. Therefore, there is a large interest in finding ways to reduce the

costs and increase the energy efficiency of the drying process to increase the competitiveness of TAD versus conventional drying

A reduction of energy consumption in TAD systems requires an understanding of the fluid flows, and the heat and mass transfer. Most previous studies have characterized TAD systems at lab scales, which requires less intense drying conditions and lower drying rates than the industrial systems. Commercial machines run at temperatures in the range of 200 to 400°C, and air flows from 50 to 200 m^3/s [Pendiente Referencia]. This causes a high rate of drying that it is hard to model accurately using the kinetic parameters of the process. The influence of air flow, recirculating air moisture and air temperature in TAD at industrial scale have not to have been extensively studied. Hence, the aim of this study is to perform different trials in a TAD industrial machine to understand the effect of the air flow, the recirculating air moisture and air temperature in TAD on the drying rate.

2. TISSUE PAPER

The paper production process is composed by three fundamental stages: stock preparation, manufacturing and converting. (i) In the stock preparation raw materials are blended and processed to get the optimal conditions for feeding the tissue machine. The term stock is used in the paper industry to describe the suspension composed of fibers, chemicals and water. (ii) Manufacturing is the process of formation of big parent rolls through a tissue machine, where almost all the water used in the stock preparation is removed by dewatering and drying. (iii) Converting is the process of transforming parent rolls into rolls or folds according to the final requirements. Different raw materials, paper machines and converting lines are used depending on the requirements of paper quality and type. The stock preparation, manufacturing and converting processes are composed by different stages, which are described briefly in the following sections. Given that the focus of this work is the drying process in tissue paper manufacture, readers interested in detailed descriptions of the equipment used in paper manufacture are referred to specialized literature [2].

2.1 Fiber preparation and stock approach

The virgin and recycled fibers are the raw materials of paper manufacture. The conventional fibers are obtained from cellulose, and two kind of virgin fibers, or virgin pulps, exist: (i) softwood or long fibers, which come from pine trees and are used to give tensile strength to the paper, the length of these fibers ranges from 2,0 to 2,7 mm; (ii) hardwood or short fibers, which come from eucalyptus trees and are typically used to give softness to the paper, the length of short fibers ranges from 0,8 to 1,1 mm. However, recently, eucalyptus species, hardwood, have been found capable of replacing the pine long fibers, softwood, and getting high tensile strength and softness, with lower production costs. [3]. One of the largest producers of hardwood in the world is the company Suzano Pulp and Paper from Brazil.

The biggest suppliers of virgin pulps are Canada, USA, Sweden, Finland, Germany, Russia, Brazil, Austria and Chile. [4] However, due to demand increase of fibers around the world, nowadays other non-wood fibers such as: straws, sugar cane bagasse, bamboo, kenaf, hemp, jute, sisal, abaca, cotton linters, and reeds are being used or paper manufacture [5]

The virgin pulps enter the paper mill in bales of 100 cm by 120 cm. This pulp must be put in a suspension to separate the individual fibers and to ease their pumping through the process. Hence, the pulp is feed to a pulper where it is mixed with water until a consistency of 5% is obtained. As is shown in the equation (1), consistency is defined as the percentage of dry solids in a mixture of solids and water.

$$\% \text{ Consistency} = \frac{\text{Weight dry solids of sample}}{\text{Total weight of sample}} \times 100 \quad (1)$$

The recycled fibers also enter the mill in bales, however unlike virgin pulps, recycled fiber bales have different forms and weights. Recycled fiber bales correspond mainly of sorted office waste, newspaper waste and old corrugated carton. Therefore, it is necessary to pretreat these fibers before their use for paper production. These recycled fibers enter the process mixed with dyes, plastic, sand, stickies (tacky substances) and other undesirable substances for papermaking. The pretreatment process begins in the pulper, there the recycled fibers are mixed with water to reach a consistency of 15%. The fiber proceeds to the cleaning stages, where coarse and fine screening remove sand, staples, plastic, and stickies mixed with the recycled pulp. The screens are metallic plates with holes or slots and the fibers are forced to pass through them aided by a rotor. The screens separate the substances with a particle size larger than the apertures, removing them from the process. The cleaned fibers are pumped to the deinking stage where the inks and a part of the ashes present in the fibers are removed. This process requires a consistency of 1%. The fibers are then taken to the washing stage to eliminate fine particles and ashes. Finally, at the dispersing stage the smallest particles are dispersed, and the suspension is concentrated to 30% consistency, before proceeding to the bleaching stage. At the bleaching stage, hydrogen peroxide, caustic soda and chelants are used to achieve the required whiteness for the paper. At this stage the fiber is called deinked pulp, and it is stored in a large tank, called high density tower. The high-density tower stores the deinked pulp until it is required in the paper manufacture process.

The virgin fibers (hardwood and softwood) and deinked pulp are mixed in what is called the stock approach stage. The main goal of this stage is to prepare the blend of fibers before feeding them to the tissue machine. Chemical additives, such as defoamer; wet strength agents; dry strength agents; biocides; and optical bleaching agents are added at this stage according to the requirements of the product. Refiners are used to fibrillate, that is to make more flexible fibers and increase bonds among fibers, allowing to increase the tensile strength in the paper sheet. This fibrillation process has a large effect in the fiber properties, which affects the drying stage. Fibrillation causes a decrease of drainability, that is, it is more difficult

to remove water from the fiber. Hence, a larger energy consumption in the drying stage will be necessary. The drainability is known in the paper industry as freeness test or drainage rate, it is designed to give a measure of the rate at which a dilute suspension of pulp (3 g of pulp in 1 L of water) may be drained. The freeness, or drainage rate [6], has been shown to be related to the surface conditions and swelling of the fibers.

After refining, chemical dosing and mixing the fibers according to the paper requirements, a blend with a consistency between 3,5% to 4,5% is obtained. This suspension, called stock, is stored in a tank, called machine tank. From the machine tank, the stock continues to the fan pump where it is diluted to a consistency between 0,15% to 0,20% before being feed to the head box. The head box finishes the stock approach stage and begins the forming section of the tissue machine. Therefore, the head box is the joint between the flowing and molding sections of paper making, and its basic task is to provide good preconditioning for forming sheets. Forming section is the first stage of a paper machine, here the web is formed, it means, the fibers are oriented according of the paper characteristics required

Paper production is a water intensive process, due to the requirements of flow solid concentration during the fiber preparation process. Before obtaining the final product, it is necessary to remove most of the water. Therefore, the process is also energy intensive. A combination of different processes are used to remove the free and bound water from the fiber, such as: vacuum, steam, hot air, pressing, infrared light, among others. The consistency of the final product varies from 94% to 98%. Thus, water removal from the stock must be performed efficiently to minimize the use of energy.

In many respects, tissue making is a series of processes where water is first added to fibers before the headbox, and then removed from the fibers after the headbox. In general paper machines are big structures composed by rolls, fabrics, cleaning showers and dryers, where the diluted stock is injected from a head box into the forming section where the sheet is formed, then, the sheet is carried on fabrics to be dewatered and finally it is transferred to the drying section to get a final product with the desired moisture

The Fourdrinier former was used originally to produce all kinds of paper, from tissue paper to packaging paper. Then, because of the increase in paper demand and the mills necessity to become more competitive, paper machines were customized according to the kind of paper, quality requirements, fibers availability, operational costs and multiple customer necessities. Therefore, newer machines were developed, and nowadays it is possible to group all paper machines in 5 kinds: packaging paper machines, graphic paper machines, carton board machines, tissue machines and special paper machines [7] Tissue machines are focused on producing: bath tissues, napkins, kitchen towels, hand towels and facial tissues. Therefore, throughout this work we will focus on tissue machines.

At its peak, the ratio of water to fibers is as high as 1000 kg water/kg fiber (at the headbox). After the headbox, water is removed in three processes: drainage through the forming fabric, dewatering either by press or vacuum, and evaporation in the dryer/hood. Most of the steps to make tissue paper are identical to the steps to make other types of paper. Creping is the

key part of the production process that distinguishes tissue from other paper grades, and the term creping describes the process used to make paper with a wrinkled or ridged surface [2]

2.2 Tissue machine

Besides the different types of paper machines, there are also different classes of tissue machines in the market as shown by Table 1 depending on the drying technology: (i) LDC with Yankee dryer (Light dry creping) or conventional tissue machine, (ii) TAD, (through air drying), or (iii) ATMOS (advanced tissue molding system). However, their basic production principles are similar: web forming, dewatering, drying and reel.

Table 1. Main characteristics of different kinds of tissue machine

Type of tissue machine	Web forming	Dewatering	Drying	Operating speed (m min ⁻¹)
LDC	1. Fourdrinier 2. Crescent 3. Twin Wire	1. Shoe press roll 2. Suction press roll	1. Drying cylinders 2. Yankee 3. Air impingement 4. Combinations	1500- 2200
TAD	Twin wire	Suction vacuum boxes	Through air dryer and Yankee Dryer	800-1400
ATMOS	Crescent with molding fabric	ATMOS module with suction roll and ATMOS press	Yankee and Air impingement hood	1000-1600

As shown in Figure 1, the common sections of a tissue machine are: the forming section, where the stock is dewatered using centrifugal forces and it is introduced between fabric and felt or two fabrics to form the sheet, in the end of section, with a consistency from 15% to 20%; the dewatering section, which uses mechanical pressing or vacuum to extract water and obtain a consistency between 25 to 55%; the drying section, where the largest quantity of water is taken off the sheet to achieve a final moisture between 94 to 98%, mainly using rotary cylinders with steam or hot air; and the reel section, where the sheet is rolled up to produce the parent roll.

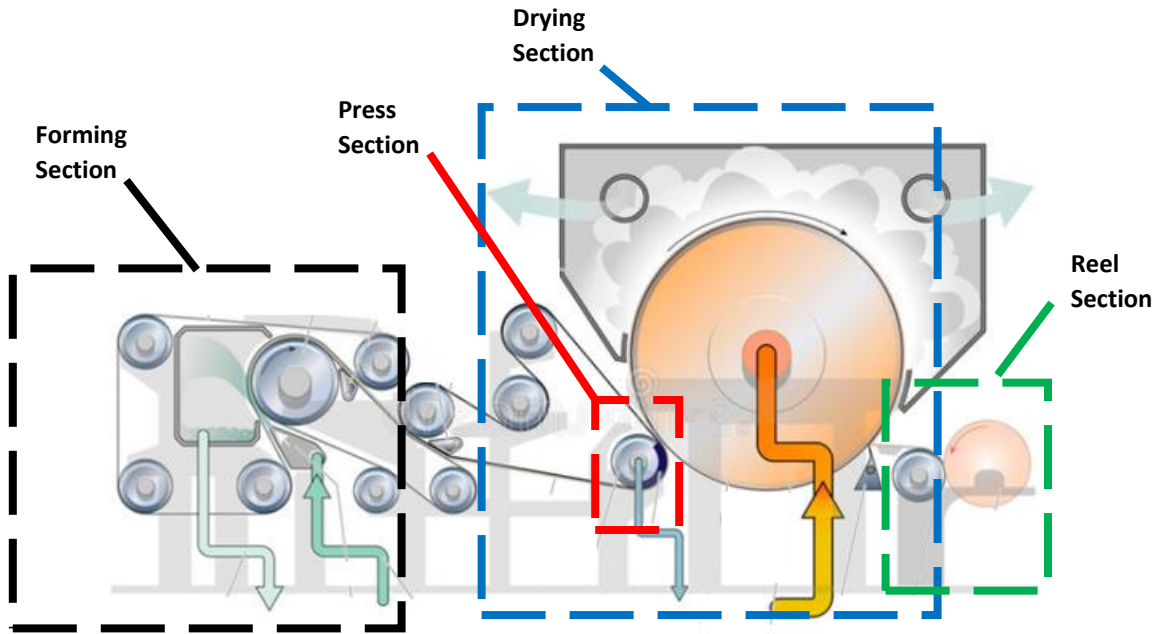


Figure 1. Schematic of a conventional tissue machine, with twin-wire former, press dewatering and Yankee dryer

2.2.1 Forming section:

Forming fabrics are filters designed to retain most of the fiber and at same time take off as much water as possible from the sheet. Also, the fabrics serve as support for the fibers and allow to guide the fibers in the machine direction or cross machine direction. Machine direction (MD) is the direction of the paper that matches the longitudinal direction of the web. Whereas, cross direction (CD) is the direction perpendicular to the machine direction. The forming fabrics are responsible of forming and appearance of the sheet, hence, their design and conditioning during the process is critical. Normally, these fabrics are produced from nylon or polyester, and the style varies depending of mesh, count, topography, air permeability, and yarns and strand configuration. The mesh means number of MD yarns per lineal inch of the fabric, and count is the number of CD yarns per lineal inch of the fabric. In the market it is possible to find fabrics of: (i) single layer, which has one MD strand and one CD strand; (ii) double layer, which has one MD strand and three CD strands; and (iii) triple layer, which has two MD yarns and three CD yarns. The press felt is an endless textile material. It can be built of natural fiber such as wool or animal fur, or of synthetic fiber as acrylic or acrylonitrile. The felt, like the fabrics, is responsible for forming sheet, but it also carries the wet sheet to the press.

The forming section has as function to form the sheet and dewater the dilute stock delivered by the head box with consistency of 0,2% up to a 15% to 25%. There are three types of forming sections: (i) one endless fabric (Fourdrinier design), (ii) two endless fabrics (twin wire design), or (iii) one endless fabric and one felt (crescent former design). Other important accessories in the section are: (i) the rolls, to support and tense the fabrics, which can be of

ceramic, chrome or rubber; (ii) blades, to clean the rolls; (iii) showers to clean and lubricate the fabrics; (iv) foils, to dewater the sheet; and (v) vacuum boxes to transfer sheet and extract water.

The main forming section designs are:

- The oldest design, the Fourdrinier design includes the forming and dewatering sections. It is used in paper machines with low speeds. This design uses generally an open head box (not pressurized), foils and vacuum for dewatering the sheet. In a conventional Fourdrinier former, the dilute stock is introduced into a single endless fabric from the head box. The foils located under the fabric generate a vibration effect over the fabric and the dilute stock is dewatered. More water is extracted through vacuum boxes. In this kind of former the use of high vibration or high vacuum at the beginning can seal the sheet, making more difficult to extract water in the following boxes, and hence lowering consistency at the end of section. Figure 2 shows a typical Fourdrinier former. In this type of paper machine is possible to produce every kind of paper with basis weight ranging from 15 to 150 grams per square meter. The basis weight is one of the most controlled variables in the paper-making process. It indicates how many grams of dried fiber are present per each square meter of sheet or web. The Fourdrinier production rate are very low due to their low dewatering capacities, because consistency at the end of the forming section is around of 20%.

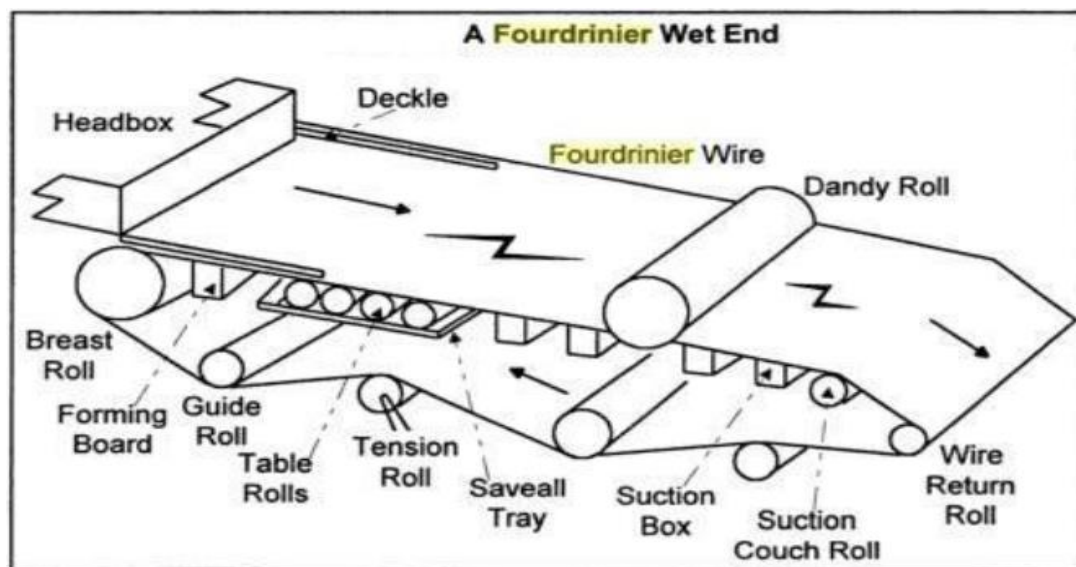


Figure 2. Schematic of a typical Fourdrinier forming section with Head box, forming fabric, rolls, showers and vacuum boxes.

- As shown in Figure 3 a twin-wire former is composed by two fabrics, inner and outer, and an air jet that circulates between two wires wrapping a solid or open forming roll. In contrast to the Fourdrinier former, dewatering occurs without pulsations at a constant pressure. The air jet is rapidly set in position, requiring a headbox that provides excellent fiber dispersion on a small scale. Dewatering may be two sided at the forming roll if it is open, and a relatively easy adjustment of the split of water removal between sides is possible if the forming roll is vacuum equipped. However, some roll formers designed for low drainage resistance stock (for example, towel or light-weight tissue papers) feature one-sided drainage around a solid forming roll only. The inner fabric carries the sheet through vacuum boxes for dewatering, and a steam box is used to decrease the water viscosity.

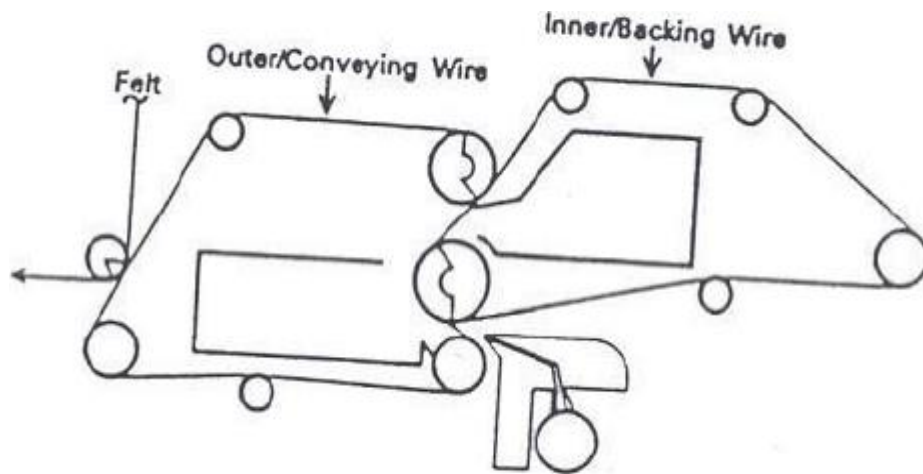


Figure 3. Schematic of a typical twin-wire former with headbox, Inner and outer fabric

- The most current design is the Crescent former, a pressurized head box normally located on machined top injects the dilute stock between a fabric and a felt as shown in Figure 4. The water is extracted through centrifugal forces and in contrast to the twin wire design it does not require a vacuum box, which makes this design more efficient due to lower energy consumption. Furthermore, the friction between fabric and felt with the vacuum boxes is eliminated, increasing its lifetime. Moreover, is easier to clean and perform maintenance in the head box due to its position. At the end of the Crescent former the sheet is transferred through a press to the drying section with a consistency around of 45%

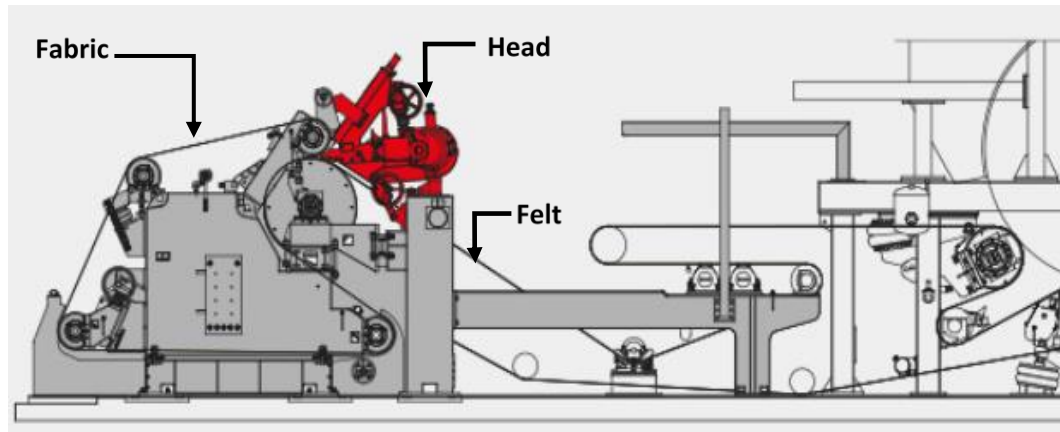


Figure 4. Schematic of a typical crescent former with head box, fabric and felt

2.2.2 Dewatering section

Between the forming and drying sections is the dewatering section, which has a very important role in paper manufacturing. The dewatering section determines how much energy is required in the drying section to remove most of the remaining water. There are two types of dewatering systems: pressing or vacuum, which depend on the kind of dryer used in the process. Typically, pressing is used for Yankee dryers, whereas vacuum is used for TAD dryers.

2.2.2.1 Pressing dewatering

Generally wet pressing must increase the consistency to 40% or higher before the beginning of the dryer section. During wet pressing three important processes occur: (i) dewatering, or the removal of water from the web by compression of the fiber network; (ii) densification, or the consolidation of the web by closing the fiber enough together to form hydrogen bonds; and (iii) web transfer, or bonding of the web to the Yankee dryer.

Pressing dewatering is used for Yankee dryers, and as shown in Figure 5 it consists of a single felt and one suction pressure roll. The sheet passes between the pressure roll and the Yankee dryer before being transferred to the dryer. Therefore, the sheet is exposed only to a single compressive step

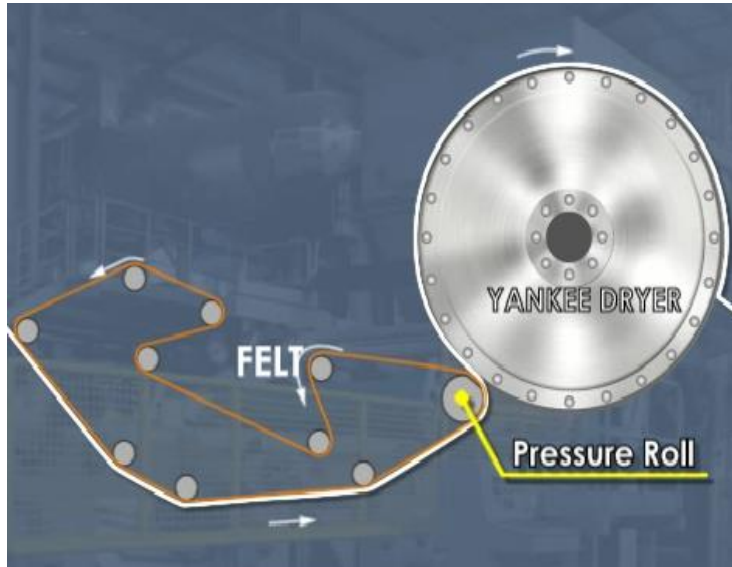


Figure 5. Schematic of a typical pressing dewatering section, with felt, press roll and Yankee dryer.

The two main pieces of equipment used in wet pressing are: the suction pressure roll and the press felt. The suction pressure roll is composed by: head, shell, cover and vacuum box as seen, in Figure 6 the holes drilled through the cover and shell allow the application of suction. Typical press nip of wet pressing tissue machines operate between 200 to 300 psi (1,4 – 2,1 MPa) at dwell times of 1,5 to 2,0 seconds.

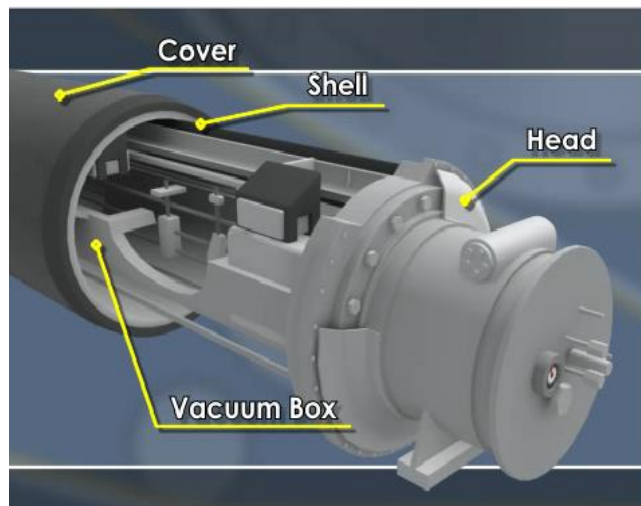


Figure 6. Illustration of a typical pressing dewatering roll and its main components

Wet pressing has wide effect on the operation cost, the performance of the tissue machine and quality of the final product. Some of operational cost and performance aspect affected by

pressing are: energy usage, speed, waste and delay. The quality aspects affected are: softness, bulk (or compactness), absorbent capacity and absorbent rate. PPRC is one of the most important variables in wet pressing, PPRC are the initials of Post Pressure Roll Consistency, which means the inlet consistency at the Yankee dryer. PPRC is controlled by the degree to which the fiber web is compressed, and the amount of hydraulic pressure developed inside the sheet structure. At industrial conditions, PPRC is affected by the peak pressure applied in the pressure roll nip, the basis weight, the machine speed, the fibers, the freeness or the pre-pressure roll consistency.

Three important aspects characterize the pressing dewatering:

- All modern tissue presses are traverse flow presses that allow water to flow from the sheet, through a felt, and into voids in the surface of the pressure roll.
- Wet pressing is a process predominantly controlled by pressure.
- Nip pressure is the controlling variable in tissue pressing, it is modified by adjusting the pressure roll line load and the hardness of the pressure roll cover.

In summary the objectives of press section are: (i) remove the maximum amount of water from the web, (ii) thicken and make even the paper web structure, (iii) smoothen the surface of the paper web, (iv) ensure a sufficiently high wet strength with the press in order to enable web transferring to the dryer section without any breaks, and (v) compress the paper web in order to enable the formation of strong interfiber bonds during the web drying

2.2.2.2 Vacuum dewatering

Vacuum dewatering is used to remove water from the post-forming consistency (5 – 10%) to approximately 30%. The water is removed by suction provided by pumps that cause vacuum beneath the sheet, which in turn induce an air flow through the sheet, mechanically stripping water from the fibers. Using vacuum only is possible to remove water on the surface of the fiber. Therefore, it means, bound water remains inside the fiber. The vacuum system can use dedicated pumps for each box or a common vacuum header. [2]. A general target for post vacuum box consistency is around 25 – 28%. Typically, vacuum dewatering is used in through air drying tissue machines.

As is shown in Figure 7, three or more vacuum boxes are commonly used, with the vacuum level increasing as the sheet goes through the process to avoid sealing of the sheet. The covers can be slotted or drilled holes. The first vacuum box operates at low vacuum levels, normally around 3,4 psi. The intermediate vacuum boxes, which can be more than one, are designed to operate at about 5,9 psi. The last vacuum box operates at the maximum of 9,3 psi. Traditionally, to reduce the energy consumption in vacuum dewatering a steam box is used in the last vacuum boxes to supply steam, near the saturation point, over the sheet. Initially, this makes sheet more wet, however it reduces surface tension and viscosity of the water making vacuum dewatering more effective. The typical steam flow is around 0,54 kg of steam per kg of dry fiber. [2]

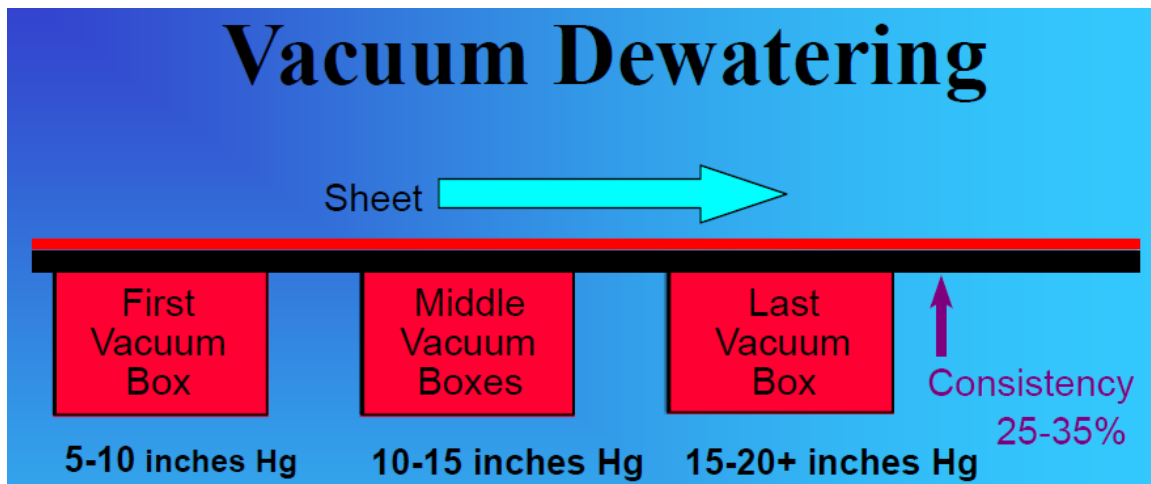


Figure 7. Diagram of a typical configuration of vacuum boxes for the dewatering section.

Liquid ring vacuum pumps, blowers and turbo blowers are used to supply vacuum. As is shown in Figure 8, a vacuum system for a Tissue machine is composed by a number of vacuum pumps, which can be identical, or each pump must be selected for a specific purpose. Sometimes the vacuum pumps are connected to a common header, which is connected to several vacuum boxes. In other cases, one or more vacuum pumps are dedicated to a specific vacuum box.

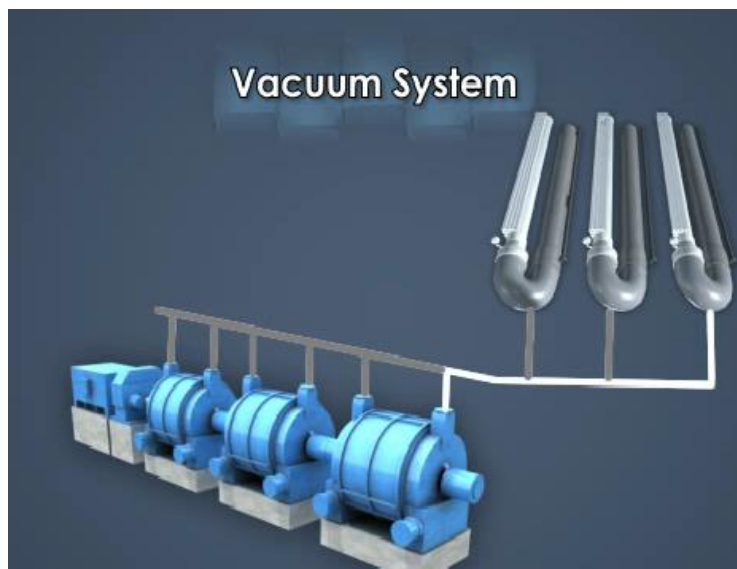


Figure 8. Vacuum pumps system used in a conventional dewatering section.

The main operating cost of the vacuum dewatering system is the electricity required to operate the vacuum pump motors. The power required, and hence the cost of the vacuum dewatering, increases as less water remains in the web. At roughly 25% consistency the cost

becomes high enough that it is less expensive to remove the remaining water by thermally drying the web. [2]

In Summary, vacuum dewatering compared with press dewatering, yields high moistures and has higher energy consumption, which make it a higher energy demand process compared to conventional drying techniques, such as Yankee drying. However, the final product of through air drying is a product with lower density, higher absorbency and better softness, which enable the manufacturer to produce sheets with lower basis weight. Therefore, lower fiber consumption can be obtained for products with the same or better performance than other tissue papers with higher basis weight. [8]

2.2.3 Drying section:

The drying section is where most of the functional properties are developed, the sheet achieves its final moisture, between 3 to 6%, which is the moisture that the product reaches the end users. The main reason to remove the remaining water from dewatering section is to allow the fibers bonds together through the Hydrogen bonds and the sheet can reach required characteristics about formation, strength, and absorption. As is shown in Table 2, although the drying section removes less water than the forming and the dewatering sections, its energy consumption is much higher than both other sections. This is mainly because a large percentage of the moisture in the drying section, corresponds to water bound to the cell walls. It means, a consistency from 70% to 94%, this water is more difficult to take off than free water that is stored in pores, interstices and lumens of fiber that represents a moisture from 35% to 70%

Table 2. Typical consistency and water removed through the tissue machine sections.

Section	Water removed (kg of Water/kg dry fiber)	Incoming Consistency (%)	Outcoming Consistency (%)
Forming	320	0,30%	10,00%
Dewatering	7,7	10%	45%
Drying	1,2	45%	95%

The drying section has two main functions, first, it takes off the remaining water of the dewatering section and allows the fibers to bond together by hydrogen bonds. Generally drying removes between 1,1 to 1,4 kg of water by kg of fiber, and compared with 200 kg in the forming section and 2,5 kg in dewatering section, the amount of water removed is lower but the relative cost is much higher. The total cost of energy consumption to achieve a final moisture sheet around of 3 to 5% is divided in 10% forming section, 12% dewatering section and 78% is drying section. This higher cost is because a large section of the remaining water present in this section corresponds to bound water. Free water is stored in pores, interstices and in lumens of fiber, this is the water removed between 35 to 70% consistency. On the other hand, bound water is the water held the cell wall, this water makes up the fiber saturation point, it is more difficult to extract than free water and general represent the removed water between 70 to 94% consistency [9]

Basically, drying consist of increasing the sheet temperature up to a point where vapor pressure of water in the sheet is higher than partial pressure of water vapor in the surroundings. This pressure differential is the driving force to achieve the water evaporation from the sheet. The drying process is composed by two unit operations, heat transfer to the sheet and mass transfer of water from the sheet. The drying has three stages as shown in Figure 9, the first stage is warm-up, and where the sheet warms up until the evaporation temperature is achieved, at the end of this stage the heat transfer to the sheet and evaporation rate from sheet surface reach an equilibrium. In the second stage the evaporation rate keeps constant until all free water in the sheet surface is evaporated, at the end of this period the capillary forces increase their relevance and changes in both the sheet and fiber begin. In the third stage the drying rate begins to decrease once the sheet achieves a certain moisture content and removal of bound water begins. [9]

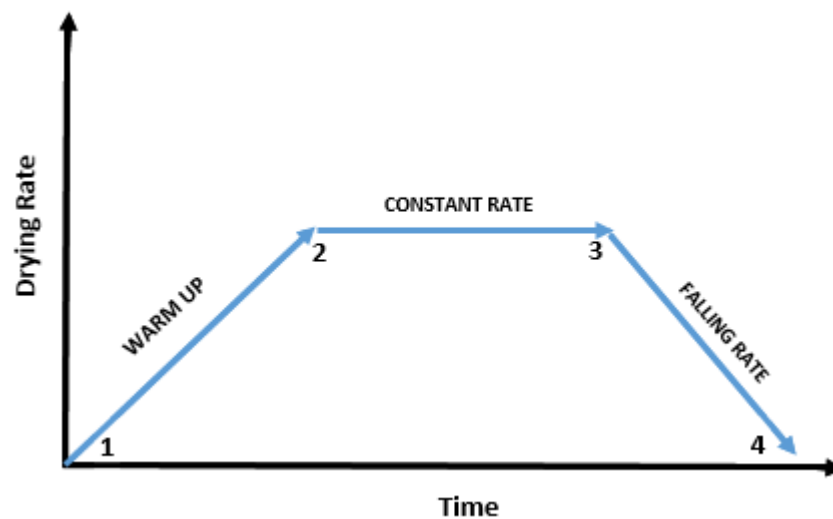


Figure 9. Typical drying curve to illustrate how drying rate change in time

The drying section still represents a large challenge in paper mills, in terms of complete understanding of the underlying and controlling phenomena. While the deinking, refining, forming and dewatering process are commonly known for operators and technicians, the drying section is considered as a black box and is wrongly believed that drying has no effect on the final quality of the product [9]. Traditionally, heat transfer by conduction is the most used technique for drying the sheet, in that case the wet sheet is transported on a hot surface. Convective heat transfer is applied with hot air drying, which could be through air drying or hot air impingement drying. Radiation heat transfer is not common, and it is used with infrared lamps to pre-heat the sheet before the dryer.

The need to develop more efficient processes has led paper industries to develop different kinds of dryers. Among them are: (i) multicylinder dryers, which use steam inside of cylinders as the main source for energy transfer; (ii) Yankee dryers, which have two main sources of drying energy, the first is pressurized steam inside of a cylinder and the second is air impingement over the sheet surface; (iii) through air dryers, which use large fans to blow hot

air through the sheet. The selection of the different type of dryer depends on the kind of paper being produced.

2.2.3.1 Cylindrical dryers

They consist of many cylinders, ranging from 20, in the smallest units, up to 70 in the largest. These cylinders can be of cast iron or steel. They are hollow and can have a diameter from 0,91 to 1,83 m. The wet sheet is transported over a dryer fabric, which wraps the cylinders. The mechanism of heat transfers is conduction since the cylinders have internally pressurized steam and the heat is transferred to the sheet through the metallic wall. The steam is supplied to the cylinder through rotating joint. A typical system is shown in the Figure 10. [10] In the paper industry the most common steam supply is the use of boilers.

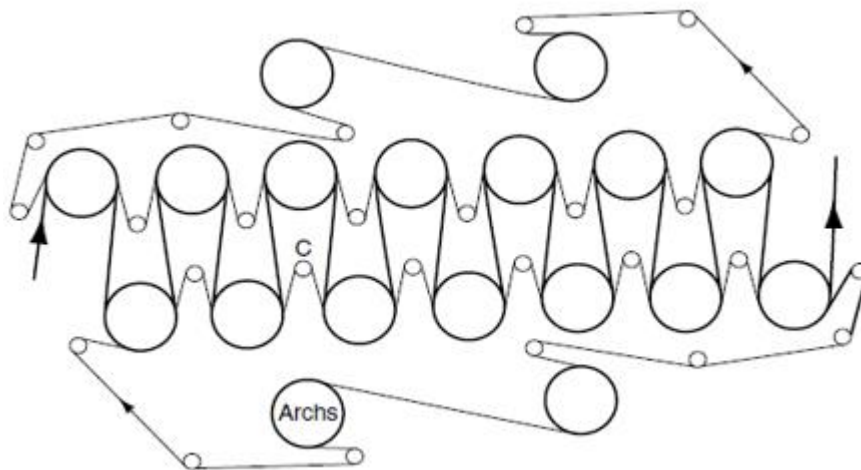


Figure 10. Schematic of a typical multicylinder dryer.

The heat and mass transfer occur simultaneously, and the evaporated water is transferred to surroundings, in older machines, or it can be collected in extraction hoods, in the more modern machines. The cylinders are grouped in two or more stages, each stage has a common steam supply header and operates at one steam pressure. The first stage works with steam at low pressure, used to warm up sheet, and in the next stages the steam pressure becomes higher, since, the wet sheet must be heated to a temperature in which it is possible to evaporate the remaining water.

Before 1940, cylindrical dryers worked at steam pressures 30 to 45 psi, which was a limitation for the drying capacity and the machine speed. After 1944, paper machines increased steam

pressure above 80 psi and nowadays, in the newest machines, steam pressure can be around 150 psi. [10]

To optimize the steam and energy consumption, mills have designed systems where the condensed water of the downstream cylinders is recovered and feed to separators. That is, the water is re-vaporized and recirculated to the first stages, and the condensate of the low steam pressure stages is returned to the boiler in a closed loop cascade system.

2.2.3.2 Yankee dryers

Yankee dryers are a combination of cylinders and impingement dryers [11]. The wet sheet with 40 to 45% consistency is transferred from the press roll to the Yankee dryer as is shown in the Figure 11. The Yankee is large cylinder, the diameters most common for Yankees are between 4 to 6 meters [12]. The operational principle is similar than a cylindrical dryer but with higher steam pressures, that is, above of 175 psi. There is no fabric wrapping over the Yankee, the wet sheet is transferred directly from the felt to the Yankee cylinder and the sheet is carried over the Yankee surface.

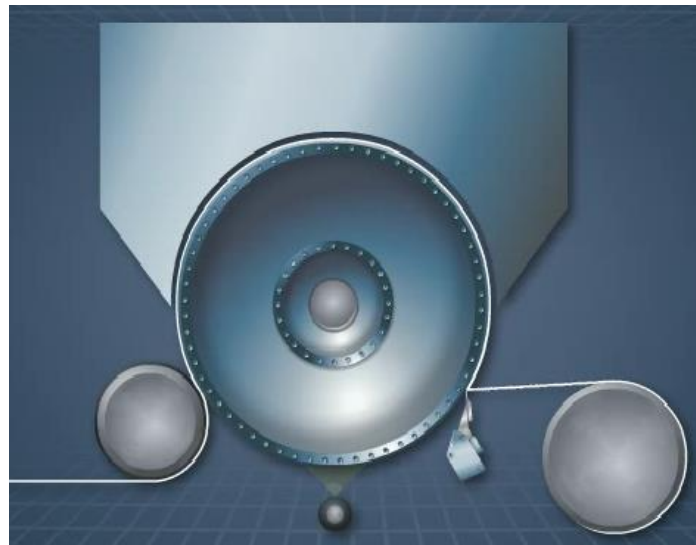


Figure 11. Schematic of Yankee dryer system

The Yankee dryer is a pressurized vessel heated internally by steam, as in cylindrical dryers, the steam is supplied to the interior of the Yankee cylinder. The steam released from the heat of condensation to the shell of the cylinder is transferred by conduction through the metallic wall to the sheet (Figure 12). The steam and condensate system provides a controlled supply of steam to the inside of the dryer, with controlled removal of condensate from the dryer. The

condensate is recirculated to re-vaporizers and remaining condensate is returned to the boiler.

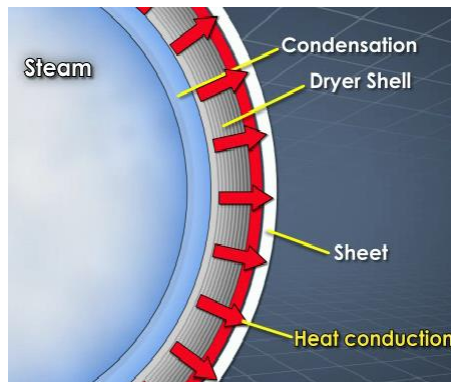


Figure 12. Diagram of the heat transfer by conduction in Yankee dryer

The energy supplied to the sheet boils the water, causing it to migrate outside the surface of the sheet in form of vapor. This vapor is then absorbed by hood air.

The hood supplies high velocity hot air and removes moisture air from the gap between the wet sheet and metallic plate of the hood. The air system has fans and ductwork that supply hood air, control the airflows and air balance, with recirculation of the air to keep an energy efficient operation. The heated supply air is the result of mixing the products of combustion with process air. The combustion system burns fuel, generally, natural gas [CBT Tissue 101 Kimberly Clark] and supplies the hot product of combustion to the process air system in a manner that creates uniform air temperature in the hood. The combustion system includes the burner and gas train.

Although the main function of Yankee dryer is to evaporate the water from the wet sheet it is also used for dewatering pressing and providing the surface for creping of the sheet. Creping is used to give the tissue paper a wrinkled surface and it is considered as the final stage in the drying operation. Creped is giving a crinkly texture to the paper in MD. In paper industry is common to talk about creping ratio, which is the ratio between Yankee dryer speed and the reel roll speed. Creeping as showed in Figure 13 a), is performed by pressing a doctor blade against the dryer surface and scraping off the sheet, the sheet is folded and wrinkled, forming a creped structure as in Figure 13 b).

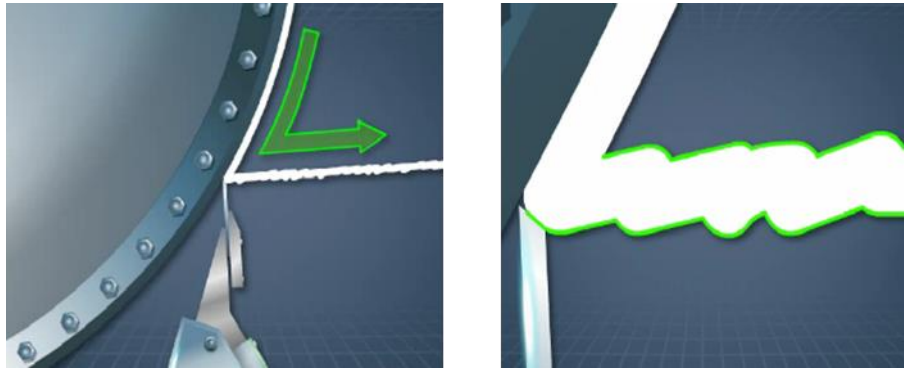


Figure 13. (a) Creeping doctor blade (b) Creeping illustration

2.2.3.3 TAD Dryer

In Figure 14 is shown a typical TAD system, which has a main, or supply fan that blows air through a direct-fired heat that burns natural gas. The heated air flow goes through the sheet and the permeable web. The shell of the TAD cylinder has a honeycomb structure that allows the wet air flow into the cylinder. A portion of the wet air is exhausted by an exhaust fan, and fresh air is taken to keep the balance of system and avoid air saturation, the fresh air and the remain hot air are blended and feed to burner [2]

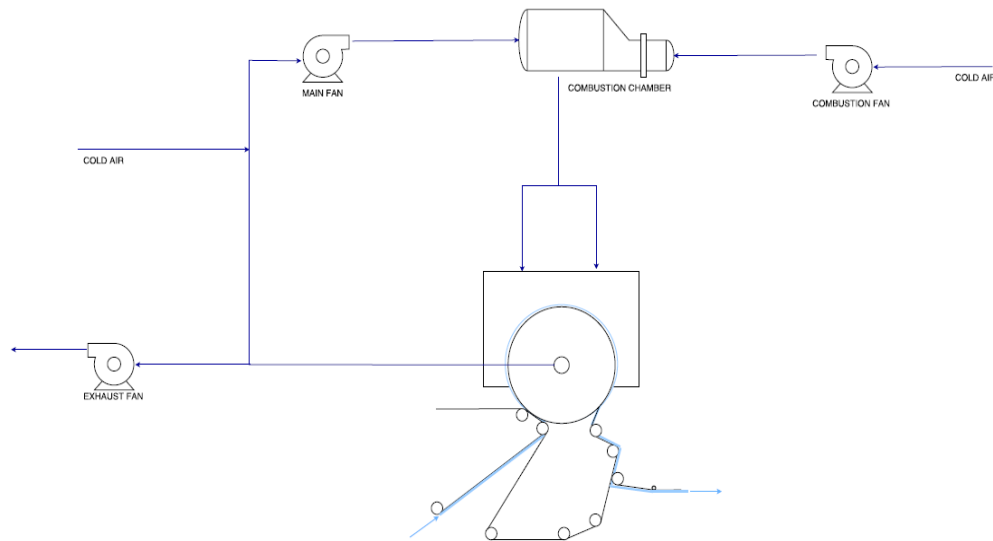


Figure 14. Typical configuration of a through air dryer system

As it was mentioned above, the dewatering for through air drying is with vacuum, hence the consistency before TAD is around 25% (3 kg H₂O/ kg Dry solids), it is rather low compared to traditional dryness reached with pressing which are in the range 40 - 55% (0,82 - 1,5 kg H₂O/ kg Dry solids) before the Yankee. Therefore, the amount water evaporated per unit mass of fiber is

much higher in TAD than in Yankee dryer, it means a higher energy demand in TAD compared with conventional drying techniques. In table 3 is shown typical energy consumptions for both Yankee as TAD dryer. Although TAD has a 60% more energy demand, TAD technology allows products with lower density and higher absorbency, which it makes possible to replace two ply products with one ply, reducing the fiber use. Since, the fibers represent nearly 50% of the total costs of production, it is very important to take in mind all aspect around of paper manufacturing and not only energy requirements.

Table. 3. Comparison between the conventional Yankee and the through drying process [27]

	Natural gas kJ/kg dry solids	Electricity kJ/kg dry solids	Water removed kg H ₂ O / kg dry solids	Spec. thermal energy kJ / kgH ₂ O	Spec. Electr Energy kJ / kgH ₂ O	Spec. Total Energy kJ / kgH ₂ O
Conventional Tissue Machine	7500	3500	1,45	5170	2410	7580
Through air drying process	2000	8000	2,82	7090	2840	9930

In TAD dryers the heat transfer to evaporate remain water occurs by convection, and the mass transfer takes place as evaporated water is transferred to hot air passing through of wet sheet. Through air drying of tissue paper is the only paper drying process does not use steam heated cylinders.

Despite the increase in use of through air drying in the last years, there are not accurate models reported in the literature to predict both the heat transfer and mass transfer in this process. However, it has been reported that it is necessary a minimum pressure drop and below this pressure drop air flow through the sheet does not occur. Also, some of the studies conclude that the air exiting after to pass through the sheet is at the saturation temperature, this is only valid for very thick sheet or for low air flow rates [11]

3. REDUCING ENERGY CONSUMPTION IN A THROUGH AIR DRYER

According to cost distribution in the production of paper industry, the energy cost represents around of 15% of the total cost, taking as reference the global production at the end of 2017 that it was 35 millions of tons and supposing an average production cost per tonne of USD 1000, the paper companies payed near to USD 5.000 million due to energy consumption. TAD technology allows to obtain products softer, with higher caliper, better opacity and less fiber use, however, its energy consumption is 3 times than conventional tissue machine consumption. When it is reviewed with more detail the energy consumption in the paper company it is found 70% of the total consumption is concentrated in the drying section, when it is reviewed with more detail the energy consumption in the paper company it is found around 70% of the total consumption is concentrated in the drying section so that makes mill process engineers make a lot attention in the optimization in the equipment performance of this section and on variables affecting the

drying of sheet. The energy intensity of the through air–drying process makes it very important to be able to optimize the system and run it as efficiently as possible. In order to effectively optimize a TAD system, the mass and energy balance during the drying circuit must be fully understood.

3.1 State of the art

TAD is a relatively new drying process for paper [8], which is not yet as well studied and documented as multi cylinder drying and Yankee drying. Most studies reported in the literature have focused on determining the drying parameter and drying rate curve to make a mathematical model to predict and simulate the real drying conditions. Which, in principle could be used to optimize the energy consumption in the process.

A 1987 study by Polat [13] showed that laboratory scale drying is composed by three stages. In the first stage the drying rate increases from zero to the maximum rate, during this period ~50% of the water is removed. In the second stage, the rate stays at its maximum value, but the moisture remains in 50% as it shown in Figure 9. In the third stage, the rate goes down from its maximum value to zero and the remaining water is removed completely. Based on the Forcheimer equation [41] where the pressure drop through the sheet is due to both viscous and inertial losses, Polat found the coefficients of the equation and built drying rate curves for modeling the behavior of hand sheets drying. Although, the model fitted well, these tests were made at low drying rates of $0,2 \text{ kg/m}^2\text{s}$ and low temperatures of 40°C comparing with industrial conditions where air flows are around of $4 \text{ kg/m}^2\text{s}$ and temperatures near 200°C . Polat and coworkers [14] demonstrated at lab scale that the drying rate increased with both the air flow and temperature increase, and the drying rate decreased when the basis weight increased. Polat concluded that at industrial scale there is not a constant drying rate region, and approximately 50% of the TAD dryers operate in the increasing rate region where the drying is limited due to the superficial area of the sheet pores. Hence, Polat et al. [11] suggest using a combination of impingement drying and through air drying.

Chen and co-workers [15] continued Polat study and proposed a new mathematical model for the drying stages using higher air flow rates and temperatures. They confirmed, that at higher temperatures (90°C) and higher air flow rates ($1,45 \text{ Kg/m}^2\text{s}$) than those used by Polat theory [14] the constant drying rate section does not exist. That is, at high drying rates there are only two rate sections. Chen [15] proposed a model to predict the time and the drying rate as functions of the sheet moisture. This model fitted well their lab tests data. Chen and co-workers [5] observed that the temperature had the largest effect in the drying rate, an increase of 25% in the temperature, increased 30% the drying rate, and 35% the air flow. Whereas a basis weight increase of 25%, increased the drying rate by 15%.

Hashemi and co-workers [16] studied on lab-tests the effect of bleaching, refining, pressing and forming on the drying rate. They used air temperatures from 20 °C to 89°C and air flow rates from 0,0246 Kg/m^2s to 0,40 Kg/m^2s . They found that while bleaching does not have an effect on the TAD drying rate, refining and pressing have low impact, and forming has the largest impact. They [17] [18] found that the drying rate is independent of the refining intensity, which only affects the pressure drop because it modifies the sheet permeability making it more difficult for the air to pass through the sheet. Refining does not affect significantly the drying time. Bleaching has similar effects to refining. Pressing has an important effect on pressure drop but it does not affect the drying rate. On the other hand, forming has the highest effect on the drying rate, with small influence on the pressure drop

Ramaswamy and Takagaki [19] proposed a model to simulate the through air drying under industrial conditions, with air flow rate between 0,5 to 5 m/s, using 128 experiments. They concluded that both the sheet as the fabric that carries the sheet are kept at the same temperature, which is lower than inlet air temperature, the adiabatic saturation temperature. They also found [8] that the air temperature is the variable with highest effect on the drying rate, in a range of inlet air temperature from 238 to 288 °C. A 10% increase in inlet temperature gives a 15% increase in drying rate, then, the pressure drop is the second variable with higher effect, for every 10% increase of pressure drop gives a 5% increase in drying rate and last, the air moisture, since, with a 10% change in inlet air humidity gives only 1% change in drying rate . Also, Ramaswamy and coworkers [20] stated that in TAD it is possible to achieve higher drying rates than in conventional drying due to the larger the interfacial area, which results in a softer and more absorbent product. They concluded that on industrial scale it is very difficult to measure with accuracy the transient parameters of through air drying due to high drying rates thus it is difficult to establish accurate white or grey-box models.

Weineisen and co-workers [21] [22] developed a model to predict TAD behavior. They used basis weight 20, 30 and 40 g/m^2 , air temperatures of 100, 150 and 200°C and pressure drops of 1 and 5 kPa. They found different conclusions than those found Ramaswamy [23]. They concluded that the variable with the largest effect on drying rate was the air flow, in contrast to the results obtained by Ramaswamy and co-workers [23]. They developed a model to simulate TAD behavior using a non-linear correlation between pressure drop and air flow, which accounts for the differences between theoretical values obtained by the model and the values measured in the lab trials. They improved this mathematical model [24] using as reference an industrial system with two TADs. They found that the parameter with the highest incidence in the drying cost is the moisture of the fabric that carries the sheet on the TAD

Tysen and co-workers [25] evaluated at lab scale the effect of basis weight, forming and different kind of pulps on through air drying. They tested basis weights of 15, 25, 35 and 45 g/m^2 and hardwood fibers of eucalyptus and acacia, and softwood fiber of spruce and pine. They found that

the air flow rate decreased with increase of basis weight, while the pressure drop and the drying time increased. In contrast to Hashemi and co-workers [16], Tysen et al. concluded that sheet forming has the lowest effect on the drying rate as the pressure drop. They also found that the highest drying rate and lowest pressure drop are obtained using long fibers from pine comparing to short fiber from eucalyptus.

Although there are different studies in the literature studying TAD parameters, the influence of air flow, recirculating air moisture and air temperature in TAD at industrial scale has not been extensively studied. Most previous studies have been performed at lab scale conditions, with lower air flows and temperatures than those used industrially. The large energy consumption of TAD makes it necessary to study with more detail the variables that have the largest effect on drying rate at industrial scale, in order to improve the energy consumption and increase the competitiveness of TAD compared to conventional drying.

3.2 Industrial scale

Due to practical reasons, most of the experimental studies in TAD have been performed at constant flow rate through the paper. However, at industrial scale, TAD occurs at constant pressure drop across the fiber web, resulting in a constantly increasing air flow rate and permeability.

In a TAD with suction drum, the hot circulating air is sucked uniformly through the paper sheet first and then into the drum. The paper sheet is held on the suction drum, by the difference in pressure on both sides of the sheet. The drum rotates at a fixed speed, which defines the productivity of the process. The wet web is transferred from transfer section to the drying fabric by vacuum. The drying fabric wraps the dryer and carries the web through the dryer while hot air passes through the sheet, like the forming and transfer fabrics, the drying fabric is in a closed loop. Figure 15 shows with blue line the typical journey and consistency of the sheet through the sections and fabrics of a conventional TAD machine.

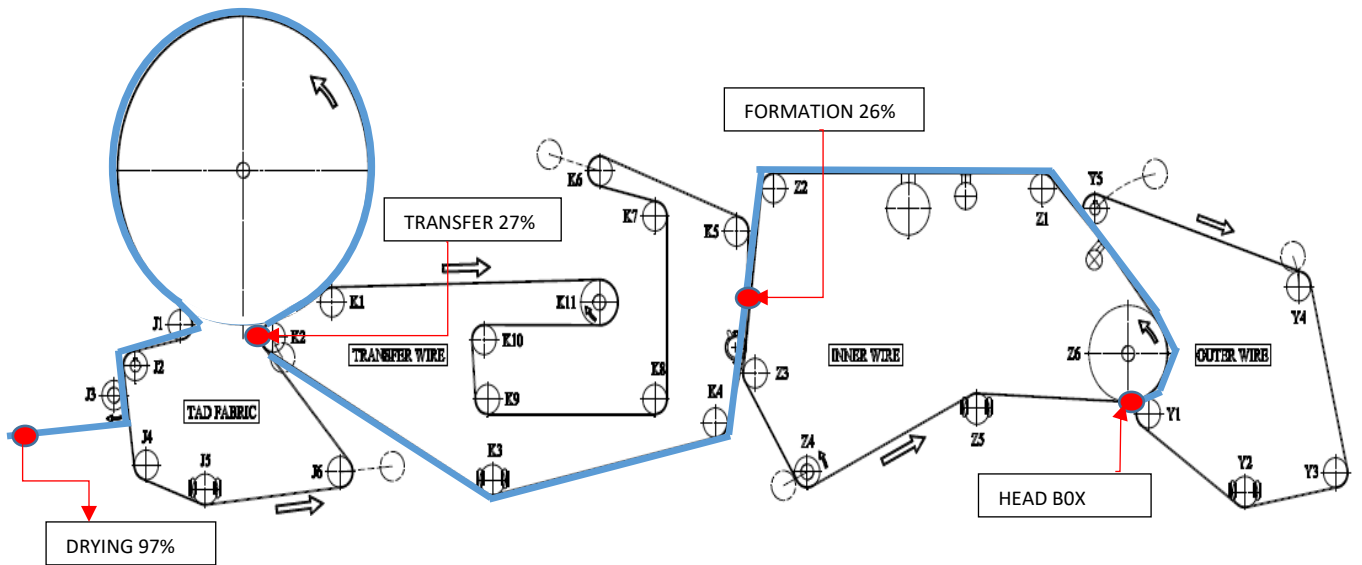


Figure 15. Typical journey and consistency of the web through of a TAD paper machine

A simplified view of the air dryer system is shown in a process flow diagram in Figure 16 with its main components.

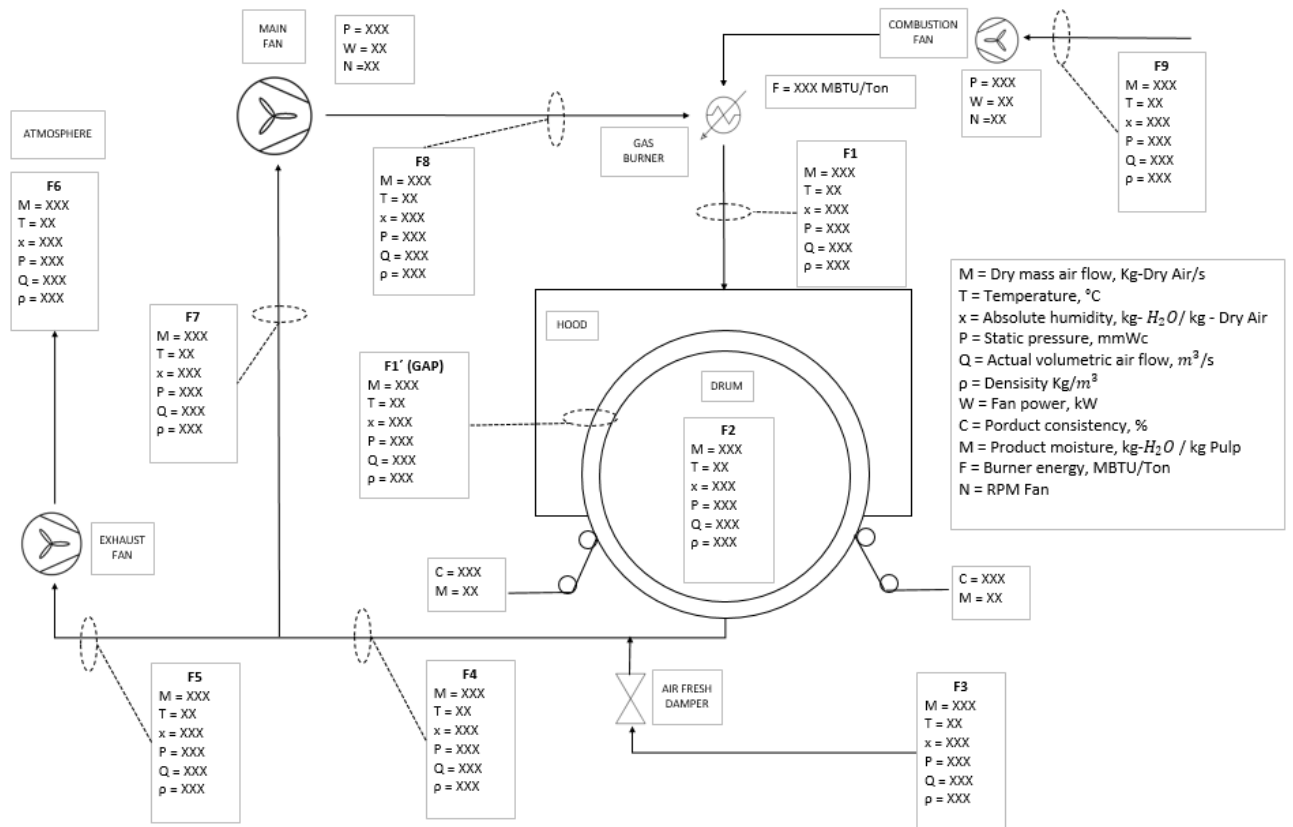


Figure 16. Process flow diagram of a typical through air dryer system

3.2.1 Main Fan

The purpose of this fan is to supply pressurized air to the Burner via drawing air both out from TAD drum as well as in through the fresh air damper. The fan speed is determined from set point that will achieve a certain Drum pressure

3.2.2 Drum pressure

The drum pressure controller controls the overall mass flow by accelerating the main fan speed (Increasing flow) or decelerating the fan speed (Decreasing flow)

3.2.3 Exhaust Fan

The purpose of this fan is to exhaust moisture laden air to the atmosphere, and therefore maintain the target humidity within the system. The exhaust fan also keeps the air system in balance

3.2.4 Fresh air damper

The purpose of this damper is to control the amount of exhaust air and absolute moisture content of the exhaust air

3.2.5 Hood gap pressure

The gap pressure controller controls the overall system mass flow balance by accelerating the fan speed (Reducing the gap pressure) or decelerating the fan speed (Increasing gap pressure)

3.2.6 Burner

The purpose is to control the supply air temperature to a given set point. The burner and the gas train has properly ratios the supply of natural gal and combustion air, and then burns the mixture, which directly heats the air coming out from the main fan.

3.3 TAD modeling

Although it is possible to model the system phenomenologically; using mass balances, thermodynamics and kinetics; the high drying rate at commercial conditions is the main difficulty for accurately reproduce the characteristics of TAD systems. Moreover, commercial dryers run at temperatures in the range of 100 – 400 °C, where the fast drying process hinders measurements of the transient parameters of the process. However, these models can give a qualitative understanding of the process in order to understand the complex interaction among the different variables in the system. A basic model for the process can be established by considering mass and energy balance, initially it will be presented a mass balance around the drum to represent the drying process. F will represent all incoming and outcoming of air, liquid water, vapor and sheet.

$$F_{dry\ sheet\ in} = F_{dry\ sheet\ out} \quad (2)$$

$$F_{liquid\ water\ in} = F_{liquid\ water\ out} + F_{evaporated\ water} \quad (3)$$

$$F_{dry\ air\ in} = F_{dry\ air\ out} \quad (4)$$

$$F_{water\ vapor\ in} + F_{evaporated\ water} = F_{vapor\ water\ out} \quad (5)$$

The moisture content of the sheet both at the inlet and outlet of the dryer is given by:

$$W_{in} = \frac{F_{liquid\ water\ in}}{F_{liquid\ water\ in} + F_{dry\ sheet\ in}} \quad (6)$$

$$W_{out} = \frac{F_{liquid\ water\ out}}{F_{liquid\ water\ out} + F_{dry\ sheet\ out}} \quad (7)$$

The humidity ratio of the air by definition is the amount of water vapor present in a certain volume of air at a specific temperature, for this study, it will be expressed as kilograms of water vapor divided by kilograms of dry air, for any of the air streams, absolute humidity is given by:

$$x = \frac{F_{water\ vapor}}{F_{dry\ air}} \quad (8)$$

And

$$F_{wet\ air} = F_{water\ vapor} + F_{dry\ air} \quad (9)$$

By replacing the Ec. (9) in Ec (8)

$$F_{dry\ air} = \frac{F_{wet\ air}}{1+x} \quad (10)$$

From mass balance of the sheet

$$F_{wet\ sheet} = F_{dry\ sheet} + F_{liquid\ water} \quad (11)$$

And taking in mind the Ec (6) and (7)

$$F_{dry\ sheet} = F_{wet\ sheet} (1 - w_i) \quad (12)$$

$$F_{liquid\ water\ in} = F_{wet\ sheet} w_i \quad (13)$$

Now, as the objective of this work is to present a model to try to predict operational parameters of a TAD system, such as fans' speed, drum pressure, burner duty, total thermal consumption, and total electrical consumption, it is important to consider the energy balance in the TAD system besides the mass balances in the different TAD components. H will represent the enthalpy of all streams of the drying section

$$\begin{aligned} H_{Dry\ air,in} + H_{water\ vapor,in} + H_{Dry\ sheet\ in} + H_{liquied\ water\ in} \\ = H_{Dry\ air,out} + H_{water\ vapor,out} + H_{Dry\ sheet\ out} + H_{liquid\ water\ out} + Q_{heat\ losses} \end{aligned} \quad (14)$$

It is difficult to calculate the heat losses to the surroundings and they could be neglected since the system is designed for an adiabatic operation. Equation 14 can be organized in terms of enthalpy differences as follows.

$$\Delta H_{Dry\ air} + \Delta H_{water\ vapor} + \Delta H_{evaporation} + \Delta H_{Liquid\ water} + \Delta H_{Dry\ sheet} = 0 \quad (15)$$

Where these differences in enthalpies can be calculated as:

$$\Delta H_{Dry\ air} = M_{Dry\ air\ in} C_{p_{Dry\ air}} (T_{air\ in} - T_{air\ out}) \quad (16)$$

$$\Delta H_{water\ vapor} = V_{Water\ vapor\ out} C_{p_{Water\ vapor}} (T_{air\ in} - T_{air\ out}) \quad (17)$$

$$\Delta H_{Evaporation} = V_{Evaporated\ water} (\Delta h) \quad (18)$$

$$\Delta H_{Evaporation} = V_{Evaporated\ water} (h_g - h_l) \quad (19)$$

$$\Delta H_{Liquid\ water} = L_{Liquid\ water\ out} C_{p_{Liquid\ water}} (T_{Sheet\ in} - T_{Sheet\ out}) \quad (20)$$

$$\Delta H_{Dry\ sheet} = S_{Dry\ sheet} C_{p_{Sheet}} (T_{Sheet\ in} - T_{Sheet\ out}) \quad (21)$$

Assuming that the flow through the exhaust fan is balanced by the burner flow and the intake of fresh air, and also that the leakage and infiltration around the TAD is minimal, then the mass flow of air (Qp)

around the system can be considered constant. Where Q is the volumetric flow rate, ρ is the density and s refer to sheet, f to fabric, drum refers to the incoming flow to drum after to pass through sheet and fabric, and mf to Main fan.

$$Q_s \rho_s = Q_f \rho_f = Q_{drum} \rho_{drum} = Q_{ducts} \rho_{ducts} = Q_{mf} \rho_{mf} \quad (22)$$

The Forcheimer Equation [26] across the sheet allow the estimation of the pressure drop across the sheet (ΔP_{sheet}), as function of K_1 and K_2 are the viscous and the inertial permeabilities, A_s is the area of the sheet in the flow, T is the thickness of the sheet, Q_s is the air flow rate through the sheet, and ρ and μ are the density and viscosity evaluated at the average temperature across the sheet.

$$\Delta P_{sheet} = \frac{T\mu}{K_1 A_s} Q_s + \frac{T\rho}{K_2 A_s^2} Q_s^2 \quad (23)$$

The permeability values K_1 and K_2 have been measured in [26]. K_1 is the classic Darcy permeability for a porous material for relatively low flow velocities ($1,61 \cdot 10^{-11} m^2$), and K_2 is an inertial correction ($4,44 \cdot 10^{-5} m$) that accounts for the air acceleration needed at higher velocities.

The pressure drop through the fabric is a function of the superficial air velocity (v_{sup}) and can be calculated using an empirical correlation [24] for TAD fabrics.

$$\Delta P_{fabric} = 17,3 v_{sup}^{1,869} \quad (24)$$

Whereas the pressure drop through ducts is function of the effective area of the air duct (A_{duct}), the air density and the air volumetric flow. [26]

$$\Delta P_{Ducts} = \frac{\rho}{2A_{ducts}^2} Q_d^2 \quad (25)$$

Therefore, the total pressure drop across the system, which has to be provided by the main fan, can be calculated as the sum of the pressure drop through the sheet, the fabric, the drum and the air duct.

$$\Delta P_{main fan} = \Delta P_{sheet} + \Delta P_{Fabric} + \Delta P_{drum} + \Delta P_{Duct} \quad (26)$$

The starting point for the calculation is the air flow. In order to determine it, it is necessary to define the evaporation rate from the production data and other parameters as absolute humidity of the recirculating air and supply air temperature. Using the machine speed, basis weight, sheet width, incoming sheet moisture to TAD and outcoming sheet moisture, it is possible to calculate the evaporation rate

$$Production\ rate = Machine_{speed} \times Sheet_{width} \times Basis\ weight \quad (27)$$

For example, if the machine speed is 710 meter per minute, the basis weight of 28 grams per square meter and the sheet width is 2,68 meters, the production rate is 53278 g per minute

The product moisture kgH_2O/kg fiber incoming to TAD, it can be calculated

$$y_{in} = \frac{\%Sheet\ Humidity_{in}}{1 - \%Sheet\ Humidity_{in}} \quad (28)$$

By replacing equation 27 in equation 12 and multiplying equation 12 by equation 25 it is obtained the incoming water.

$$F_{liquid\ water\ in} = (Machine_{speed} \times Sheet_{width} \times Basis\ weight) \times y_{in} \quad (29)$$

Of similar way the product moisture kgH_2O/kg fiber outcoming from TAD,

$$y_{out} = \frac{\%Sheet\ Humidity_{out}}{1 - \%Sheet\ Humidity_{out}} \quad (30)$$

$$F_{liquid\ water\ out} = (Machine_{speed} \times Sheet_{width} \times Basis\ weight) \times y_{out} \quad (31)$$

Hence, evaporated water,

$$F_{evaporated\ water} = F_{liquid\ water\ in} - F_{liquid\ water\ out} \quad (32)$$

With $F_{evaporated\ water}$, production rate, $F_{liquid\ water\ out}$, incoming sheet temperature and supposing an outcoming sheet temperature T_{out} as a starting point but then corrected, it is possible to calculate the required energy rate "E" in TAD through equations 3,3 – 18, 19 and 20

$$E_{TAD\ required} = \Delta H_{evaporation} + \Delta H_{Liquid\ water} + \Delta H_{Dry\ sheet} \quad (33)$$

The transferred energy rate by recirculating air in TAD is given by,

$$E_{TAD\ transferred} = hA_{Drying}(T_{in} - T_{out}) \quad (34)$$

Where, h is the global heat transfer coefficient, A_{Drying} is the heat transfer area in TAD, T_{in} supply temperature in hood, T_{out} air temperature after pass through sheet and fabric

Assuming heat losses to surrounding are neglected and the all energy transferred by recirculating air is equal to required energy rate

$$E_{TAD\ required} = hA_{Trans}(T_{in} - T_{out}) \quad (35)$$

The dimensionless heat transfer coefficient (Nusselt Number) for a bed of fibers has been measured and modeled empirically for evaporative coolers [26]:

$$Nu = 0,1 \left(\frac{1}{L \cdot \rho_f \cdot A_v} \right)^{0,12} Re^{0,8} Pr^{1/3} \quad (36)$$

Where ρ_f is the fiber density (typically 1,5 g/cm³), L is the sheet thickness, A_v is the specific surface area of the fibers (measured as 0,32 m²/g for HW and 0,23 m²/g for SW in [27]), Pr is the Prandtl number, Re is the Reynolds number and Nu is the Nusselt number [26]:

$$Pr = \frac{c_p \mu}{k} [=] \frac{\text{viscous diffusion}}{\text{thermal diffusion}} \quad (37)$$

$$Re = \frac{Vd}{\mu} [=] \frac{\text{viscous diffusion}}{\text{thermal diffusion}} \quad (38)$$

$$Nu = \frac{h_0 d}{k} [=] \frac{\text{convection}}{\text{conduction}} \quad (39)$$

Where c_p is the specific heat of the air, μ is the viscosity of the air, k is the thermal conductivity of the air, V is the velocity of the air, d is the effective diameter of the fibers, and h_0 is the heat transfer coefficient at the surface of the fibers. The effective fiber diameter can be related to the fiber density and the fiber surface area by [26]:

$$d = \frac{4}{A_v \rho_f} \quad (40)$$

The heat transfer for the full sheet thickness is obtained by multiplying h_0 by the total surface area of the fibers A_v and basis weight of the sheet BW:

$$h = A_v h_0 BW \quad (41)$$

Moreover, Reynolds number can be expressed in terms of volumetric air flow,

$$Re = \frac{F_{wet\ air} d}{A_{Drying} \mu} \quad (42)$$

Replacing equation 41 in equation 35 and reorganizing equation 38, h can be expressed in term of volumetric air flow

$$h = \left[0,1 \left(\frac{1}{L \rho_f A_v} \right)^{0,12} \left(\frac{F_{wet\ air} d}{A_{Drying} \mu} \right)^{0,8} Pr^{1/3} \right] \times \frac{k A_v BW}{d} \quad (43)$$

Replacing equation 42 in equation 34,

$$E_{TAD\ required} = \left[0,1 \left(\frac{1}{L\rho_f A_v} \right)^{0,12} \left(\frac{F_{wet\ air\ d}}{A_{Drying}\ \mu} \right)^{0,8} Pr^{1/3} \right] \times \frac{kA_v BW}{d} A_{Drying} (T_{in} - T_{out}) \quad (44)$$

Rearranging equation 43,

$$F_{wet\ air} = \left[\frac{Energy\ rate \times 1000}{\left(\frac{0,1 \left(\frac{1}{L\rho_f A_v} \right)^{0,12} Pr^{1/3} k BW A_v}{d} \right) \times A_{Drying} \times (T_{in} - T_{out})} \right]^{1,25} \times \left[\frac{A_{Drying} \mu_{wet\ air}}{\rho_{wet\ air} d} \right] \quad (45)$$

With $F_{wet\ air}$ determined it is possible to calculate the drum pressure drop through an air mass balance around the sheet, using the streams names from figure 16,

$$F_{wet\ air-F1} \rho_{wet\ air-F1} + F_{evaporated\ water} = F_{wet\ air-F2} \rho_{wet\ air-F2} \quad (46)$$

According to Bernoulli's principle,

$$F_{wet\ air-F2} = \sqrt{\frac{P_{static-F2} - P_{static-F1}}{\frac{\rho_{wet\ air-F2}}{\rho_{atmospheric}}}} \quad (47)$$

At industrial scale a best practice to avoid leakage and inflow of fresh air to the Drum is to work with $P_{static-F1}$ equal to zero

And using the ideal gas law for wet air,

$$\rho_{wet\ air-F2} = \frac{(1+x_{F2})(P_{atm} + P_{static-F2})}{4,62(x_{F2} + 0,622)(T_{drum\ out} + 273,15) \times 100} \quad (48)$$

Now, it is possible to calculate the total pressure drop through the system, it means $\Delta P_{main\ fan}$, then, by using the main fan curve delivered by the manufacturer and applying affinity laws, the speed of the fans can be determined. This principle can be applied also to the exhaust and combustion fans. Finally, with all air flows, densities, and temperatures the demanded energy rate in the burner can be computed.

3.4 Operating parameters effect on drying.

The confidentiality of the industrial process studied in this thesis limits the amount and type of proprietary data that can be included in this manuscript. The present report has only an academic purpose and the data shown not necessarily corresponds to the industrial process studied.

The effect of modifying the inlet humidity (x_{F1}) and the supply air temperature (T_{F1}) on the total energy consumption are studied systematically using the model presented in the previous section. For this

analysis some of the process and product variables were kept fixed in a sample scenario, shown in Table 4.

Table 4. Fixed parameters in the production scenario used for the case study

TM speed	710 m/min
Basis weight	28 g/m ²
Drum width	2,68 m
Drum wrapping angle	270°
Production rate	3197 kg/h
Incoming sheet moisture	73%
Outcoming sheet moisture	2%
Incoming sheet temperature	35 °C

3.4.1 Effect of the inlet humidity ratio

In this case the supply temperature was fixed at 210°C. Figure 17 shows the effect of absolute humidity of the supply air on a typical 28 gsm sheet with a 100% Hardwood (0.32 m²/g surface area and 9.52 μm fiber diameter). The pressure drop, calculated using Darcy's Law and Riese Permeability as described in [27], and the supply air, decrease when the humidity ratio increases. Thus, higher humidity ratios require less power of the fans and less gas consumption in the burner to deliver the same tissue machine velocity.

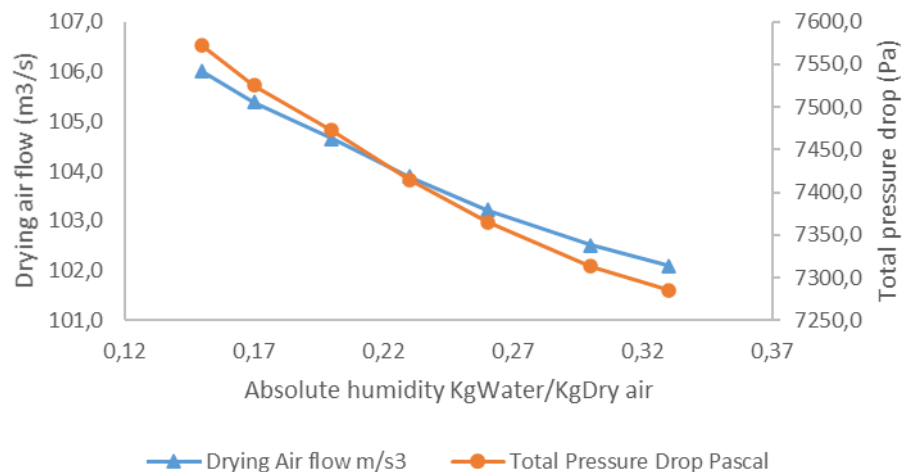


Figure 17. Drying air flow and pressure drop as functions of the supply air humidity ratio for the case study.

Taking as reference an industrial price of electricity of 0,093 USD/kWh and a thermal price of natural gas of 4,7 USD/MMBTU, it is possible to study the economic impact of the changes in the humidity ratio. Figure 18 shows the effect of absolute humidity on the thermal energy and electricity costs. Both electricity and thermal costs decrease with increasing the humidity ratio. The electricity consumption corresponds to the power required by the main fan to operate, and the thermal energy consumption corresponds to the natural gas combustion required to increase the air temperature for drying. This effect is more marked on the electricity costs, for instance increasing the humidity ratio from 0,15 to 0,33 kg-water/kg-dry air reduces the thermal cost in 8% (from 27,5 to 25,5 USD/ton), whereas the electrical reduction is around of 11%.

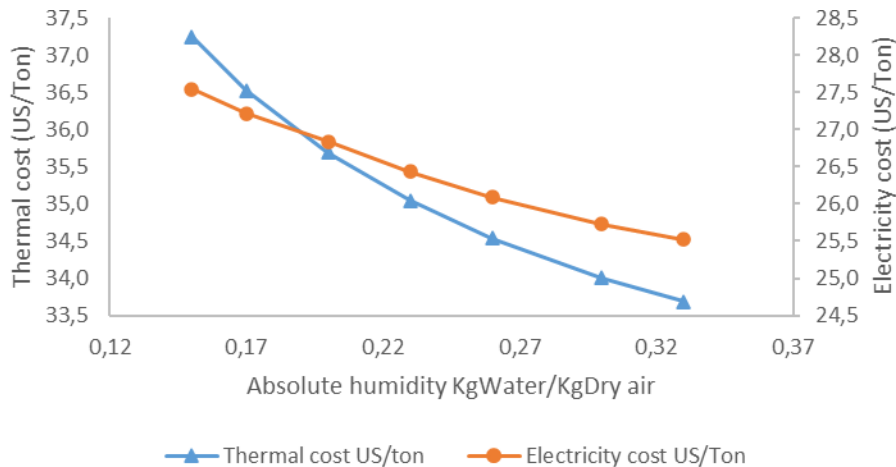


Figure 18. Thermal energy and electricity costs as functions of the supply air humidity ratio for the case study.

To begin the discussion, two operating scenarios are presented using the process condition of table No. 4, with a supply air temperature of 210 °C for both conditions. Using the developed model the Figure No.21 shows a complete mass and energy balance of an industrial through air drying system, the intention is to illustrate the main differences about flow, pressure, fan speed and burner duty for two absolute humidity of drying air conditions. In the condition 1 the absolute humidity is 0,21 Kg-Water/Kg-Dry air and for condition 2 is 0,3 Kg-Water/Kg-Dry air.

Some of the main differences to note about Condition 2 in comparison to Condition 1 are:

- Lower mass flow and volumetric flow both the supply and exhaust streams
- The fan differential pressure is 6% less.
- The exhaust temperature is higher.
- The exhaust mass flow to atmosphere mass flow is 45% lower
- The burner duty decreased 4.5% while fan power decreases by 2,8%.
- The total thermal energy (fan & burner) reduces by 4.5%.

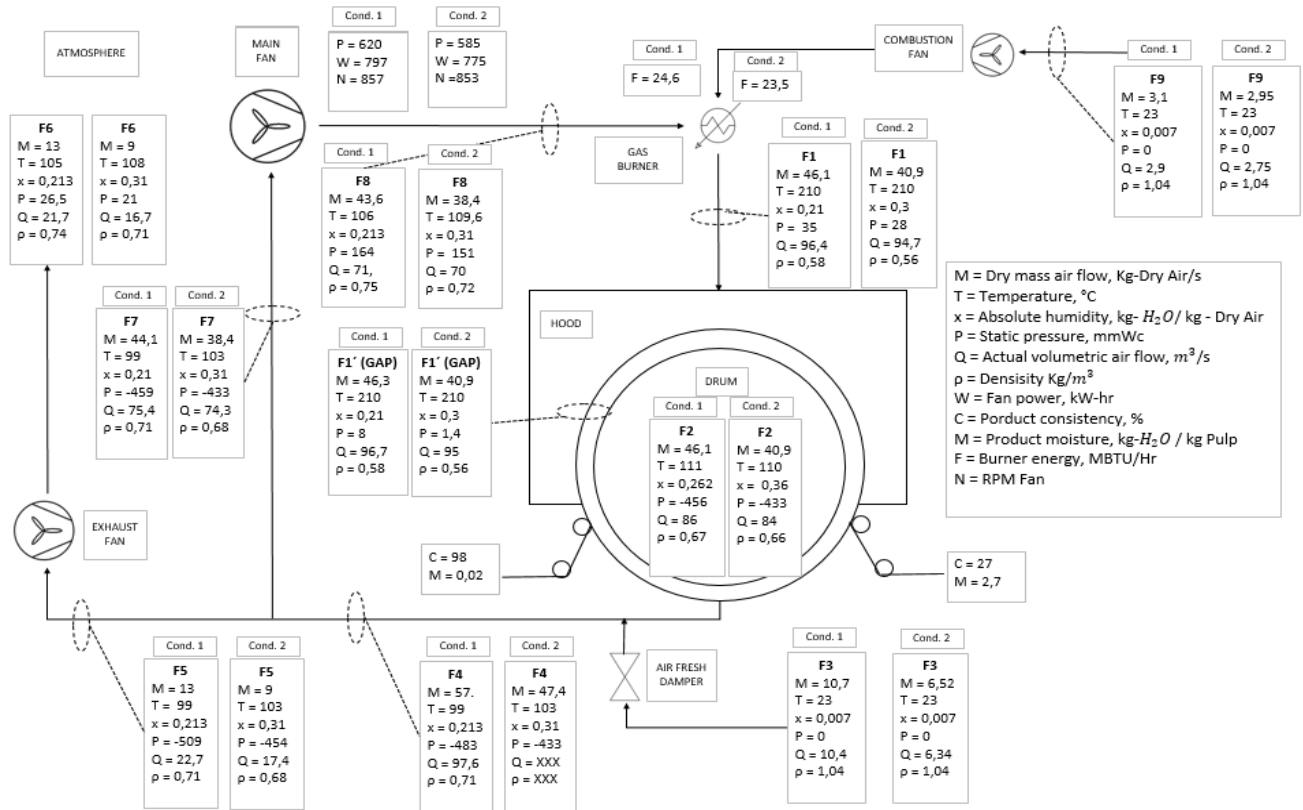


Figure 21. Process schematic showing two different humidity ratios (denoted as cond. 1 and cond. 2 in the figure) for the case study.

3.4.2 Effect of the supply air temperature

In this scenario the humidity ratio is fixed at 0.26. Figure 19 shows the effect of the supply air temperature on a typical 28 gsm sheet with a 100% Hardwood (0.32 m²/g surface area and 9.52 μm fiber diameter [27]). Similar to the previous analysis, the pressure drop and the required supply air decrease with increases in the supply air temperature. Thus, higher supply air temperature will require less power of the fans and less gas consumption in the burner to deliver the same tissue machine velocity.

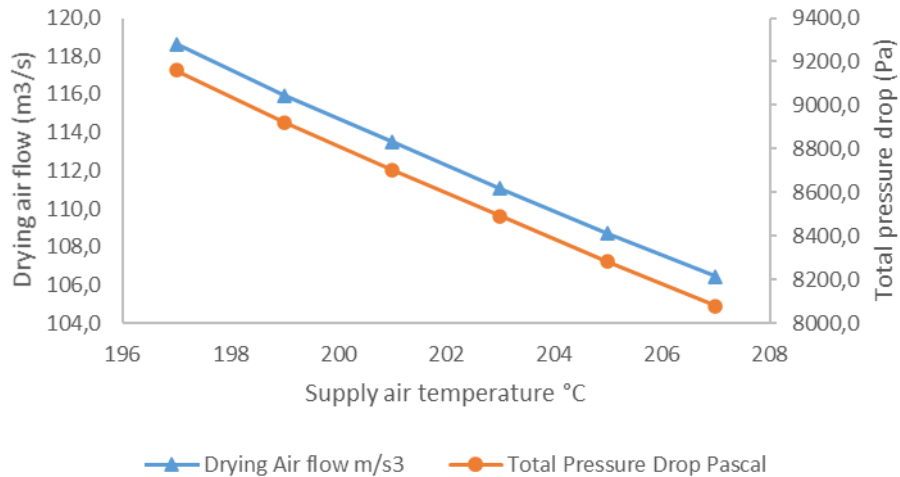


Figure 19. Drying air flow and pressure drop as functions of the supply air temperature for the case study.

Using the same price references as in Figure 18, the energy costs as function of the supply air temperature are shown in figure 20. In this case the electricity and thermal energy cost are monotonically decreasing functions of the supply air temperature. Again, this effect is more marked in the thermal energy. For instance, increasing the temperature from 197 to 209 °C, decreases the electricity cost in 32% (37,3 to 28,3 USD/ton), whereas the thermal reduction is around 3%.

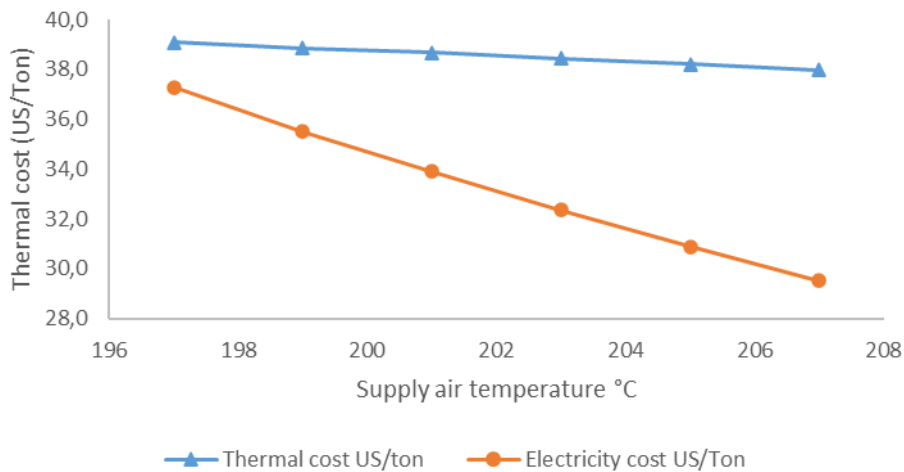


Figure 20. Thermal energy and electricity costs as functions of the supply air temperature for the case study.

3.5 Model validation

Comparing the results to the industrial process the developed model was validated to verify its reliability and accuracy. It is worthwhile to mention that it is difficult to predict accurately each of the process drying condition due to varying atmospheric conditions, heat losses to surroundings or lack of direct measurements of the process variables considered in the models. For instance, there is no online moisture transmitter at the inlet of the TAD and this variable is measured manually by the

operator only one time per shift. Moreover, some parameters such as the fiber matrix density, fiber diameter, among others, were fitted to the industrial data in order to improve the model.

The model presents high accuracy in the main fan speed predictions (with mean average errors of 3%) and a qualitative prediction of the burner duty (mean average error of 10%), as summarized in Table 5. This information helps to understand how the main variables of the system, such as supply air temperature, humidity ratio of the drying air and incoming sheet moisture affect the performance and associated costs of drying.

The results of this study the company have generated important savings in electricity and gas consumption in the industrial facility, around USD 250.000 since 2018 to date. Further, the developed model has been used as training material for operators, supervisors and engineers, and it has allowed to optimize the drying process and increase the rate production. For instance, before the implementation of this thesis, an specific reference had a speed limitation of 650 m/min due to the drying capacity at humidity ratios of 0,24 kg- water / kg-dry air, once the absolute humidity was increased to 0,32 it was possible to increase the speed in 10% (up to 710 m/min). Overall, this represents an increase in the production due to the increased drying capacity.

Table 5. Comparison of the industrial drying data to the values predicted by the developed model

TM speed	Basis weigth	Supply air temperature	Absolute humidity of supply air	Main Fan Speed (Real)	Main Fan speed (Predicted)	Main Fan speed Error vs real	Burner Duty (Real)	Burner Duty (Predicted)	Burner Duty Error vs real
meter/min	g/m ²	°C	Kg-Agua/Kg Dry Air	rpm	rpm	%	MMBTU/Hr	MMBTU/Hr	%
710	28	207	0,213	701	682,5	2,7%	24,1	23,12	4,2%
800	28	209,7	0,286	929	894	3,9%	24,0	26,9	10,8%
870	20	209,7	0,319	836	850	1,6%	26,3	22,5	16,9%
710	27	209,8	0,269	855	841	1,7%	22,0	22,32	1,5%
710	27	209,3	0,282	809	850	4,8%	20,9	22,4	6,8%
930	20	205,5	0,286	895	846	5,8%	24,5	20,7	18,2%

4. Conclusions

The main objective of this study was to develop a simple process model of a through air drying system that allowed to understand the effect of various process variables on the fluid flow and convective heat and mass transfer characteristics of 19 and 28 gsm wet porous sheets at commercially realistic conditions and understand how these variables affected energy consumption and energy cost. This model was developed and implemented. The model accurately predicted process data at commercial conditions, with a mean average error of 3% for the main fan speed and 10% for the burner duty.

The model was used to understand the effect of two important process variables, namely the inlet air's temperature and humidity ratio, on the drying of wet porous sheets. It was found that, counterintuitively, the energy required for the process decreased monotonically with these two variables. This is attributed to water vapor having almost double the specific heat capacity of air and a higher heat transfer coefficient, thus, purging humid air from the system results in energy losses in the form of enthalpy. Moreover, higher temperatures in the supply air result in more efficient drying, and thus a lower flow of air is required to achieve the same drying, which decreases the electricity consumption of the fans.

Moreover, the developed model and the conclusions of this study have contributed to savings of around 250.000 USD since 2018 in thermal and electrical costs and increases of up to 10% of the productivity due to increases in the drying capacity of the process.

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