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DRYING OF PAPER – AN OVERVIEW, THE STATE OF PAPER DRYING KNOWLEDGE

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ABSTRACT

The paper concerns various present and projected future drying technologies employed to dry paper and paperboard products. The topics discussed include moisture distribution and mobility within the web and how this can effect important paper properties. It is suggested that dryer sections have a much higher potential than their present role of simply drying and transporting the web from press to reel and that their future active role will be made possible by sophisticated new drying models specifically developed to predict and control web defects such as curl, mottle and others. Also covered are economics of drying alternatives for various paper and board grades and an overall assessment of future drying technologies including impingement drying, Condebelt drying, impulse drying, direct steam drying, IR and induction and microwave drying. The paper concludes with a look at further needs in fundamental and applied research in drying.

1 INTRODUCTION

The Paper Industry has traditionally looked for improvements in productivity as the most effective means of achieving low specific cost, high quality products and highest returns on capital. An essential prerequisite to this has been higher and higher papermachine speeds, since to increase output by increasing machine width is no longer possible. Today, new technologies have been developed to meet speed demands in excess of 2000 m/min. This has been made possible by major advances in web-support technology, shoe pressing technology, drying technology and the ability of new surface treatment equipment to deliver superior sheet runnability at high efficiency.

The conventional dryer section has remained a dilemma for machine builders and papermakers – how to increase its speed and decrease its length. The latest designs involving totally closed single tier runs with increasingly sophisticated runnability components have adequately addressed web threading, web handling and runnability issues, but have made the dryer section even longer and more expensive. Another dilemma is that despite their potential to significantly contribute to the development of properties of the dried product, present dryers sections remain simply dryers and transporters of web. Aided by emerging new process simulation techniques and control systems, future dryer sections will become much more active in determining and controlling important paper properties on line.

Impingement drying, Condebelt drying and impulse drying technologies discussed below are all intensive drying processes requiring different forms of energy. They can be employed most effectively within a properly designed energy grid which normally employs different forms of energy which varies with mill location and infrastructure. Various economical alternatives of such grids have been analyzed and reported on elsewhere.

2 TYPES OF DRYING TECHNOLOGIES EMPLOYED TO DATE

The following are the drying methods commonly used in paper and board machine applications [8]:

- Multi-cylinder drying
  – Printing papers and base papers
  – Boards
- Yankee cylinder drying
  – Soft tissues (wet and dry crepe)
  – Boards
- Through air drying (TAD)
  – Soft tissues
- Airborne drying or nozzle drying (air jets blown through nozzles support the web travel)
  – Drying of coated and surface-sized paper
  – Drying of market pulp
- Infrared drying (IR, electric and gas)
  – Drying in surface sizing and coating
  – Web heating
  – Moisture profile control

• Condebelt – In production scale	– Primarily boards (liner and fluting)
Impingement and high intensity drying (hoods located in the paper machine dryer section and placed against the web supported by a drying cylinder, yankee cylinder, roll or fabric)	– Increased drying rate compared to conventional cylinder drying
• Induction drying	– Moisture profile control
• Microwave drying	– Moisture profile control
• Impulse drying	– Pilot stage
• Drying with superheated steam	– Laboratory stage
• Other gas heated dryers, e.g.	– ABB's dryer [9]

The dominant position of cylinder drying on paper and board machines is due to the following factors:

- Cylinder drying is a cost-effective method with regard to use of energy. The unit has a hood with an efficient heat recovery system operating at high dew point. The heat source is low-pressure steam. Such steam is often surplus and therefore the most inexpensive form of energy produced in a paper mill or in a thermo mechanical pulp mill (TMP-mill).
- Cylinder drying imparts a degree of smoothness to the web as well as restriction in cross machine shrinkage, particularly in single-felted designs with no open draws.
- Runnability of a single-felted dryer group is good. Top-felted configuration can be self-cleaning during a web break, and tail threading is simple.

Cylinder drying also has weaknesses compared to other paper and board drying methods:

- Large space requirement.
- Slow response to controls.
- Lack of effective control of the cross-machine drying profile.
- Deterioration in specific evaporation with speed as the result of reduced dwell time and heat transfer at paper dryer interface.

3 EFFECT OF DRYING ON PAPER PROPERTIES

The role of future dryers will depend on the target function, i.e. a clearly defined target function will clearly define the optimal dryer principles to be used. The main objective of this section is to show the fundamental aspects to bear in mind during drying and rewetting of the paper web. Figure 1 shows the history behind the forming of a structured paper web, where drying is the process step often producing the final and desired end product.

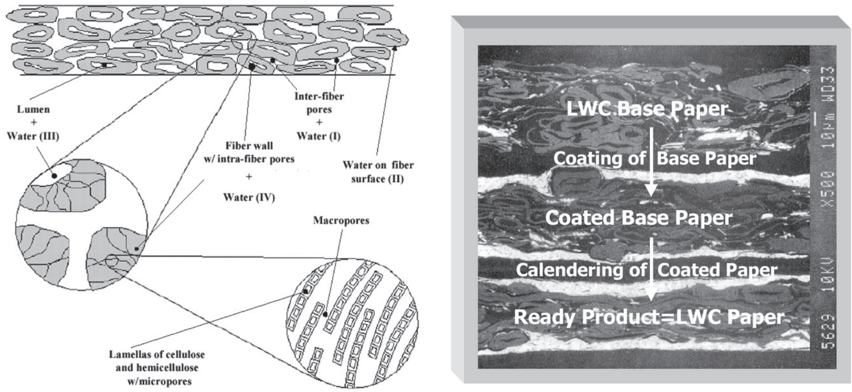

Figure 1 On the left is a schematic picture of the structure of paper sheet and fibers including the possible positions of water in a network of wetted fibers [6]. To the right is a scanning electron micrograph of a cross section of the history of the structure changes of a calendered LWC paper (Light Weight Coated), = 1530 kg/m^3 and w_b = 62 g/m^2, (photos obtained from [26]).

From Figure 1 we may conclude that the quality requirements of paper obviously vary with the grade. In the dryer section, the basic requirement is the same for all paper grades: a uniform cross-machine moisture profile of the web after the dryer section. A uniform profile along the entire dryer section would be even more desirable. For other paper properties, the profiles should be as uniform as possible. These cross-direction profiles include shrinkage, curl, and machine direction web tension all of which to some extent effect paper machine runnability. The following are some of the quality parameters imparted to the web by the drying section:

- Optical properties (strongly influenced by choice of drying method).
- Mechanical properties (strength (TEA), curl control e.g., with impingement drying).
- Storage properties (influenced by choice of drying method e.g., Condebelt drying).
- CD and MD shrinkage (affects e.g., printability).
- Smoothness (e.g., Cylinder drying, Condebelt drying and Impingement drying).

Some examples of typical methods to control quality properties in the dryer section include:

- Dryer geometry and the degree of web restraint during drying.
- CD moisture control by steam showers.
- Vacuum boxes to control CD-tension and web porosity.

In order to control quality properties during drying we need to accurately define moisture mobility and hence moisture distribution within the web. Moisture profiles and moisture transport in paper are of great importance in a number of practical applications, for example in printing and coating of paper webs. In the drying process there is a clear coupling between moisture gradients, shrinkage and a number of other paper quality parameters. In several paper grades, the moisture distribution is closely related to paper shrinkage, which affects the final paper strength (less shrinkage more strength and vice-versa) and the tendency to curl, i.e. how paper changes its shape during exposure to temperature and moisture. Application of excessive steam pressure in the dryer increases the web temperature and thus vapor pressure inside the web too rapidly. For high basis weight sheets, such as cardboard, the increased pressure may cause delamination of the web and completely destroy the product. Recent development in the field of non-intrusive methods [26, 15] for determination of moisture profile/paper structure during drying include the magnetic resonance imaging (MRI) and Confocal Laser Scanning Microscopy (CLSM) techniques. The MRI measurements in Figure 2 were performed on paperboard sheets having a similar dryness as paper entering the drying section of a

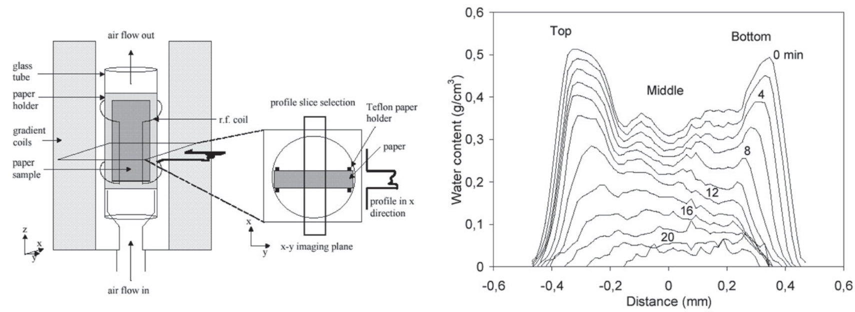

Figure 2 To the left is a schematic representation of the experimental set-up including the paper probes in the MRI-measurements, and measurement units surrounding the holder. The thickness of the dried cardboard shown in the Figure was in the range (0.8...3) mm [11]. To the right are moisture profiles for a three layer cardboard. The detection limit of the instrument is 0.003 g/cm^3.

paperboard machine. The latter is in the area of the Fiber Saturation Point (FSP).

The first thing to notice in Figure 2 is the shape of the profiles. There are two very distinct peaks, the top and bottom layer, and a more or less constant water content level between the two peaks, the middle layer. There seems to be an initial concentration gradient of water at the two surfaces, suggesting that water is located inside the cellulose fibers and not in capillaries between the fibers in the macro pores of the cardboard. Thus, a higher layer density gives a higher amount of water. The top and bottom layers both have a higher density than the middle layer and therefore a higher water content level. The two peaks decrease faster than the plateau in the middle of the cardboard and this will eventually lead to the development of the classical bell shaped moisture profile.

The decreasing moisture profiles in Figure 2, suggests that drying is faster in the bottom layer than the top layer. One important question is whether the free moisture is located in the fibers or in the macro pores between the fibers. The fibers in the outer layers, bleached or unbleached Kraft pulp, are more porous than the fibers in the middle layer, consisting of CTMP, due to the removed lignin, and therefore the two outer layers have a higher moisture ratio. As stated above, unbleached Kraft pulp is more porous than bleached and thus each fiber in the bottom layer can contain more moisture [11]. The MRI-technique is a promising technique for detailed analyses of the relationship between paper quality and drying. It is not yet commercially available and the resolution in time and space still needs improvement. However, the MRI-technique has already shown that simple models cannot describe the complexity of actual moisture mobility during drying.

Berg et al. [4] have developed another promising technique to measure very fast liquid movement in coating processes, a technique shown in Figure 3. In this process the experimental data is obtained by coating a base paper on a laboratory coater and by scraping off some of the coating color after a certain amount of time. The weight and moisture content of the scraped off coating color is measured enabling the amount of liquid that has been absorbed by the base paper from the coating color to be determined. The mechanical analogy of a laboratory coater and pilot coater, and the analogy of the measurements indicate that measured water drainage on the laboratory coater may be used to analyze a pilot machine and even a full-scale machine, i.e., the dominating physical phenomena closely match those of the laboratory apparatus.

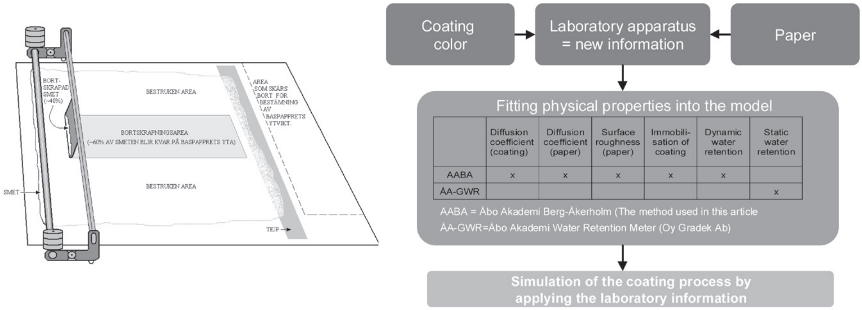

Figure 3 On the left is a schematic of the measurement of moisture movement into the paper web. On the right is a schematic description of how the laboratory method (AABA) may be used to simulate water movement in a real paper coating process.

4 DRYING MODELS

Drying and its effect on web properties has gained importance in modern paper and paperboard machines due to the dramatic increase in speed and to the fact that new paper machines increasingly include numerous steps of application of wet coating which increases the number of required drying cycles. Initial drying simulation models considered drying only and were used exclusively for determining the required drying capacity for a given production rate. Next came models which included various quality aspects which a given drying concept imparted to the web such as shrinkage, curl, mottle, smoothness two-sidedness, porosity and others. The continued increase in production speeds and integration of conventional drying with high intensity drying saw the emergence of integrated models which further considered the optimum use of drying energy within the total mill environment. Future modeling will expand this still further to include new developments within the drying section such as integration of drying with other unit processes. This is illustrated in Figure 4.

In case of drying coated paper, it is important to detect and control moisture mobility in the base paper and in the coating color. This is established by:

- Dryer lay-out for base paper.
- Base paper properties.
- Added base paper chemicals and coating color properties.
- Coating methods and coating colors.
- The coater layout and type of dryers used.

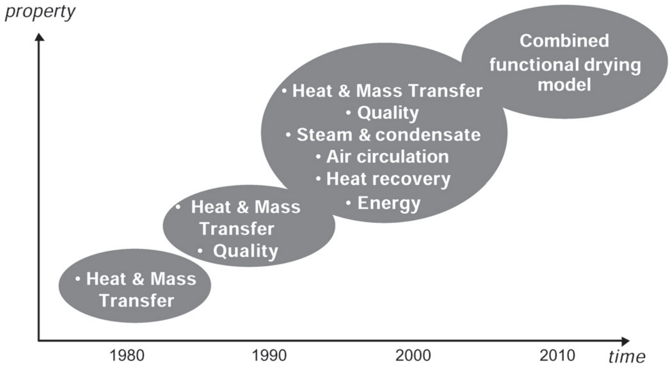

Figure 4 Paper drying model development.

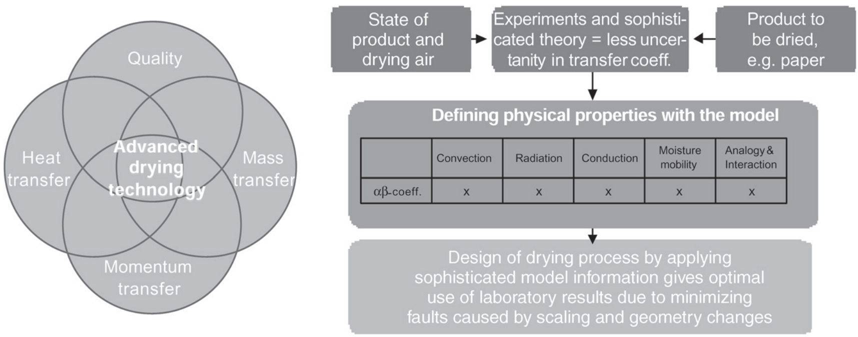

Figure 5 On the right is shown the design of a drying process which applies sophisticated model information to minimize faults caused by scaling and geometry [5]. On the left is the principal structure of the drying model for the local water movement in moist air [2, 3]. A new drying strategy or novel drying equipment needs very careful fitting of less costly laboratory experiments before implementation in practice (see Figure 12).

Figure 5 describes the main aspects to be considered when analyzing a given drying experiment. Transport coefficients must be experimentally and theoretically determined because we often need to:

- Evaluate the state of the drying surface based on air state measurements and surface temperature measurements.
- Evaluate laboratory or industrial drying performances based on temperature measurements.
- Scale-up dryers and heat recovery where the interaction of the inlet and outlet air states and product surface temperatures are relevant.

Mottle in sensitive coatings caused by uneven drying is a major concern and may often represent the main line speed limitation. Sensitive coatings need very careful design of dryers since color differences, which can be thought of as quality variations, are very much a function of variations in local drying rates. Mottle is an irregularly patterned defect seen as an optical density variation (color variation) with the naked eye with size scale of 0.5 to 5 cm, sometimes oriented. Mottle is a function of the following parameters:

- Property variations of base paper (porosity, density, thickness, surface or base structure, etc.).
- Coating method (interaction of coating method, coating color and base paper).
- Drying method (drying lay-out, drying intensity profile in MD).
- Property variations of coating and its surface (porosity, density, thickness of coating, structure of coating, etc.).

Process parameters causing mottle include disturbances in the coating caused by air, rolls etc. The duration of the disturbance, type of coating employed and the state of the coating during the disturbance are key factors which affect mottle. The effect of uneven moisture mobility and drying rate is the cause of the blue color variations. Uneven drying will elevate the risk of secondary problems such as deteriorating printing properties with secondary mottling in printing colors or loss of gloss. Therefore we may state that:

- Drying has to be uniform in cross and machine directions as well as in web thickness in order to obtain a dimensionally stable paper.
- Different and novel drying concepts require novel models and experimental methods to describe in detail what happens during the drying process, making it possible to obtain predictions of the final paper quality in all considered process situations. It is known for example, that the design of the conventional multi-cylinder dryer has to be modified at the edges to

reduce edge shrinkage. This is not the case for novel drying processes where at present such effects must be determined experimentally.

5 ECONOMICS OF DRYING ALTERNATIVES

The paper making process is essentially a sequence of drainage and dehydration processes which ideally should be as economical and efficient as possible and, at the same time contribute to the development of paper properties. When the web dry solids content after the paper machine press section is approximately 50% (1 g dry solids/g H_2O) for example, the dryer section is left to remove less than 1% of water by volume originally deposited onto the paper machine. High dryness after the press section is desirable because water removal by evaporation in the dryer section is much more expensive than mechanical drainage in forming and press sections in terms of both capital and operating costs. High web dryness before the dryer section also improves runnability because web strength increases with dryness. It is limited by press technology and by rapid loss in bulk with increased pressing which is why high bulk grades are lightly pressed.

Most of the paper web strength is established during thermal drying, i.e., in a dryer section with suitable conditions for creating bonds between fibers. Web shrinkage primarily occurs in the dryer section. An important and continuing objective in the paper making process is to reduce the overall energy consumption, particularly in the drying process. This requires development and integration of new drying concepts such as impulse and impingement drying or high intensity drying [27]. It also means developing existing concepts to better advantage [11]. Use of energy in the various processes requires a review of the entire mill and integration level, with proper regard to use of energy and thermal flows in various different forms. For example, drainage on a paper machine requires review from the forming section to the dryer section with consideration of closed water circulation and drying concepts with different energy requirements. Sources of drying energy, their cost structure, and the resulting price of total energy are essential factors for new drying concepts. New technology primarily achieves higher local drying performance to reduce dryer section space and increase speed and efficiency. A further essential is that quality should remain at the same or improved level compared to that achieved with conventional drying technology.

Efficiency of thermal energy consumption in a paper mill depends primarily on the use of recovered excess process heat. Efficiency of heat recovery with new drying concepts may be difficult to improve over that of the present dryers because the former tend to decrease the use of steam and increase the use of other energy sources. On the other hand this makes it possible to divert excess steam to sludge dewatering and other evaporation processes required to close paper mill effluent flows. The web conditions in the dryer section including temperature, moisture content, and state of stresses have a significant effect on properties of the final product. Due to evaporative dewatering, the fibers shrink and cause stresses in the web. Controlling these stresses in the dryer section can improve the strength properties of the web. Non-uniform cross-machine shrinkage can cause quality and runnability problems. The main purpose and only reason for heat recovery is to replace primary energy in an economically profitable way. When designing a heat recovery system, examination of total use of mill energy is necessary. Obviously a study of this nature depends greatly on individual mill characteristics – paper grade, degree of closure of the mill, and whether a pulp mill is integrated with the paper mill.

Need of actual heating energy may vary considerably during a year. Therefore, the duration curves for outside air temperature and other parameters must also be included since they may play an important role in obtaining a correct and optimal layout for the considered paper mill. Special demands regarding the building, available space for the equipment, and the price of energy being replaced or used for the same purpose require further consideration. This means that energy sources must be evaluated and compared to each other to ensure that the most economical type of heat recovery system is chosen for each case.

Like all other papermaking processes, drying should have maximum closure to minimize the amounts of exhaust air and waste heat. This minimizes the energy consumption of the process and increases the energy content of the hood exhaust air making it even more suitable as a heat recovery source. When a process becomes more closed, the use of waste heat typically decreases while the amount of primary energy remains relatively constant. As a result, much release of "extra" waste heat occurs, the heat energy which is generally difficult to re-use. When considering heat input to a drying process, heat recovery is always an alternative for the heat energy input and hence the basis for planning a drying process. Table 1 shows an example of a comparison of different methods of heat recovery for hood supply air.

Heat pump technology could be used to further enhance use of waste energy in the hood exhaust air. Some applications of heat pumps have been used for heating hood supply air. The economics of these installations depend very much on the price of available electrical energy compared to the prize of available thermal energy. To obtain tangible benefits the heat exchanger networks generated and analyzed in the optimization must be practically applicable in a mill installation. A network consisting of many interconnected

Table 1 Comparison of different methods of heat recovery for hood supply air [8].

Heat source	Hood exhaust air, air/air heat exchangers	Hood exhaust air, circulation water	Mixing with vacuum pump exhaust air	Heating with flash steam	Heat from PGW plant, circulation water
Supply air temperature after heat recovery, (°C)	60–70	40–50	90–100	70–80	60–80
Heating source at disposal when required	++	++	++	++	–
Dependent on production	++	++	++	–	–
Dependent on season	++	++	++	++	–
Need for standby heat source	++	++	++	–	––
Negative effects			Humidity and fibers		
Investment costs	––	–	–	+	–
Operating costs	–	–	+	+	+
Alternative reuse possibilities	++	–	++	+	––

+ = Favourable. – = Unfavourable.

separate units may give good performance but generate considerable costs for auxiliary equipment such as ducts, piping, valves, pumps, etc., and maintenance. Savings made possible by using heat recovery can be expressed in terms of less consumption of primary energy and, if different system solutions are compared, more reliable operation, less space requirement, and simpler construction.

Plant modifications of an existing dryer are expensive due to loss of production from downtime, which must be added to the capital cost of the new equipment. Therefore, it is far easier to implement new and drastic solutions at the design stage of a new dryer. The overall thermal efficiency of the dryer can be expressed as the ratio of the evaporation heat load to the gross heat supplied by the heater. This will typically be in the range 20–40% for a once-through dryer; the higher efficiency being achieved at high inlet air temperature and low bed temperature. A closed-loop recycle system may improve on this, but the removal of excess vapor causes heat losses with severe drop in thermal efficiency. For further information see Table 2 showing energy consumption per kg H_2O.

Table 2 Paper industry dryer distribution based on application [8].

Dryer	Industry share (%)	Distribution (%) / Energy consumption (MJ/kg H_2O)[1] Drying rate (kg H_2O/hm^2)/Paper quality (+,~,–)[2]			
		Tissue	Paper	Board	Coating
Cylinder	85–90	5/2.8–4.0/20/~	95/2.8–4.0/20/ +	95/2.8–4.0/15–35/ +	35/3.0–4.5/5–10/~
Yankee	4–5	84/4.0–5.0/200/ +	0	3/2.8–3.5/30–50/ +	0
Infrared	3–4	0	1/5.0–8.0/ 10–30/~	1/5.0–8.0/10–30/~	15/5.0–8.0/70–120/~
Impingement	2–3	0	4/2.8–3.5/ 50–120/~	0	50/3.0–5.0/40–140/~
Through	1–2	11/3.4–4.5/ 170–550/ +	0	0	0
Condebelt[3]				1 /2.6–3.6/200/ + ,–	
Impulse			0/0.55–1.4/ 500–8000/ + ,–	0/0.55–1.4/ 500–8000/ + ,–	

[1] Pulp dryers excluded. [2] ~ indicates quality might improve or worsen depending on paper grade. [3]Condebelt is a trademark of Metso Paper Oy.

6 FUTURE DRYER SECTIONS

The common theme in future drying applications will be the ability of the drying section to actively control the drying dependent quality properties of paper and to maximize its economic performance. The latter entails size, capital and operating costs and energy consumption. For various reasons, the conventional cylinder drying process does not lend itself to dramatic improvements in quality control of the dried product. Cylinder drying will nevertheless continue to be employed for most commodity grades such as newsprint.

Today a typical dryer cylinder diameter on paper and board machines varies between 1.5 and 2.2 m with 1.8 m being most common. The advantage of larger cylinder size is a smaller number of dryer groups and auxiliary equipment. Larger diameter cylinders are more effective at the beginning of a dryer section due to a longer dwell time heating zone. This advantage is lost in the subsequent drying sections where evaporation from the web occurs primarily in the free draw between the dryer cylinders.

The cylinder drying process has limitations due to the boundary conditions formed at the fabric, web and cylinder interfaces.[12, 13, 14, 16, 17, 18] These conditions are dependent on time, geometry, drying process parameters and paper properties. The following are some of the factors which effect the total heat transfer:

- Wet pressing (controls the initial moisture content and drying properties of the paper web).
- Machine speed (affects time dependent phenomena).
- Heat transfer from steam, i.e., condensate coefficient (condensate behavior in the cylinder,[1] dryer with smooth inner surface, spoiler bars).
- Contact coefficient (paper moisture content, fabric or web tension, speed dependent accumulation of air or steam film between the web and the dryer surface, surface smoothness of paper and dryer, roughness and dirt scaling on the dryer surface, thermal conductivity of paper web, use of press roll (Yankee dryers).
- Material and thickness of cylinder shell (established by structural requirements).

Less important factors are:

[1] Stationary and rotary siphons have use in board machine dryer cylinders. Spoiler bars are standard equipment on high speed machines.

- Periodic variation of dryer surface temperature (normally below 1°C).
- Heating of dryer section supply air (to avoid condensation in the hood).

Individual drying components contribute differently to overall heat transfer. As an example, the condensate coefficient for a plain shell dryer in one instance was 4,260 W/(m^2°C) and for a ribbed cylinder dryer with optimally designed ribs, 5,730 W/(m^2°C), or 35% higher. Based on certain assumptions, this resulted in only 3.5% increase in heat flow through the cylinder [8, 14]. The place where we may most improve cylinder dryers is by further improving the contact coefficient and moisture mobility.

6.1 Speed potential

The weak web must be supported at the beginning of the dryer section. As machine speeds increase, the importance of the support increases, a consequence which saw the introduction of a single tier run in the 1970s, in which modification the web was constantly in supported contact with the fabric. Initially, the surfaces of passive cylinders in the slalom groups were smooth but as speeds increased, the web could no longer remain attached to the fabric. As the result, machines today have grooved, drilled, or grooved and drilled types of suction rolls. The web remains with the fabric due to vacuum across the draws between the dryers and suction rolls supplied by runnability components with ejection flow or suction. On high-speed paper machines, the entire dryer section is single tier.

As speeds increase, the problems caused by higher air flows become substantially larger. Air handling is therefore an important task for a dryer fabric in a high-speed machine. An accompanying risk is that the contact between fabric and paper may break. The forces acting on the web increase with the square of the machine speed, and the tensile strength of the web decreases with increased moisture content, lower basis weight, and increased use of recycled fibers and mineral fillers. Cross-directional air flows due to an unbalanced ventilation of the dryer pockets cause web edge flutter when air flows around the fabric edge from over-pressurized side to under-pressurized side of the pocket. In double-felted dryer sections at the fabric surfaces, moving air flows cause sheet flutter especially at web edges.

If close to one half of the pre-dryer section dryers (bottom dryers) is unheated, drying performance especially with light paper grades is not significantly decreased. This is due to lower humidity level in the pockets with more time for evaporation from paper not in contact with dryers. The longer evaporation time gives a lower paper temperature and more effective heat transfer from the top heated dryers to paper. A more uniform moisture profile and higher speed potential due to improved runnability is the result.

Increasing paper machine speeds and new demands on the dryer to more effectively contribute to web quality development has brought about new dryer designs incorporating cylinder drying with novel drying methods such as hot air impingement drying, see Figure 5. Future high speed machines will see more of similar combinations together with runnability improvement measures such as drying without fabrics and reduced free draws.

6.2 Impingement drying [25]

The Impingement Drying Concept shown in Figure 6 was developed by Valmet specifically for printing and writing paper grades. The purpose was to speed up existing dryer limited paper machines and to construct new machines with substantially shorter and more cost effective dryer sections.

The concept comprises a combination of conventional cylinder dryers and high intensity drying units. There may be up to three such units in the dryer section, as shown in the Figure, located below the machine floor. Each unit has a large diameter roll and two retractable air impingement hoods. Cylinder drying is employed in the latter part of the drying process since it is easier and more effective drying means to control paper quality. Throughout the entire dryer section the sheet runs outside the dryer fabric, which makes for easy broke removal in case of a web break. One feature which contributes to high efficiency of the process is ropeless tail threading, a procedure and equipment similar to that perfected over many years in previous dryer concepts.

One principal target of the development was to substantially reduce the overall length of the dryer section and the machine room which houses it. This has been accomplished with the new design through a 25% reduction in

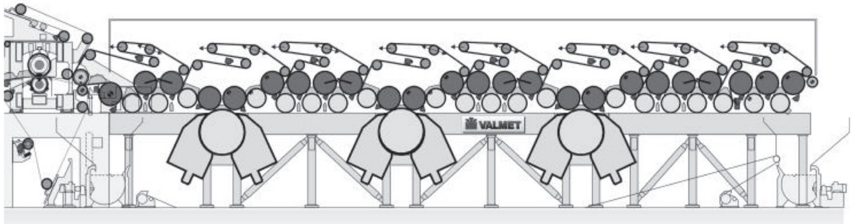

Figure 6 Impingement drying concept.

length, compared to a conventional single tier conventional dryer section, and a corresponding reduction in investment costs. The new concept uses air impingement drying to increase the specific drying capacity. Dry, hot air at temperatures up to 450°C is blown directly onto the web surface at speeds up to 150 m/min. Water vapor evaporated from the web is recirculated with the exhaust air through the hood exhaust chamber. Such high intensity, direct impingement drying makes it possible to reach drying rates many times higher than with cylinder dryers and therefore to substantially reduce the overall length of the dryer section.

The new concept incorporates an integrated impingement hood technology, in which the equipment necessary to circulate and heat the air is located inside, rather than outside the impingement hood. This makes for a much more compact external air system and substantial saving of space outside the dryer. One important feature of the process is its ability to control the web's CD drying rate profile, as required. This is done by dividing the impingement hood into cross machine sections and use different air temperatures and /or impingement air velocities in each section to control the drying profile across the sheet. This is also a potential tool to control paper quality. In impingement drying the drying conditions can be changed much faster than in cylinder drying, which enhances its overall control response and makes for faster, more efficient grade changes.

The system is gas fired as the air temperatures required are much higher (up to 450°C) than is practical with steam. The evaporation rate achievable is 80–160 kg water/m^2/hr, depending on air temperature and location in the drying section. The corresponding range for traditional steam and cast iron cylinders is 20–40 kg water/m^2/hr.

The steam normally used in paper mills does not have a sufficiently high temperature for use in impingement drying, which is why other sources of energy must be used for heating the impingement air. Natural gas is a good choice. The exhaust from a gas burner mixed with proper amounts of circulation and fresh make-up air is used for direct impingement.

The specific energy consumption in MJ/ton of paper, is almost exactly the same as in the corresponding conventional dryer case. The difference is in the share of the different forms of energy. Conventional can dryer uses steam energy only, while the new dryer uses both gas and steam energy. The consumption of electric energy is roughly the same for both. Figure 7 shows the energy use comparison for the two concepts.

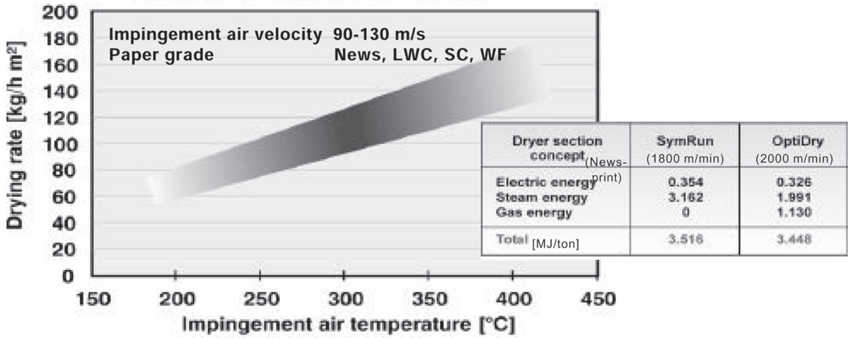

Figure 7 Drying test results.

6.3 Condebelt drying [25]

During the 1970s and 1980s, energy-saving potential was the driving force in developing new dewatering techniques for the pulp and paper industry. One result was Dr. Jukka Lehtinen's invention of the Condebelt drying process. Compared to conventional cylinder drying, the drying rate is substantially higher as is the potential for energy recovery. The major advantages of this process are the improved board properties which, in the process allow for a more economical use of raw materials. The web is fully restrained during drying which radically improves its CD strength properties.

The Condebelt drying process (Figure 8) causes moisture in 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

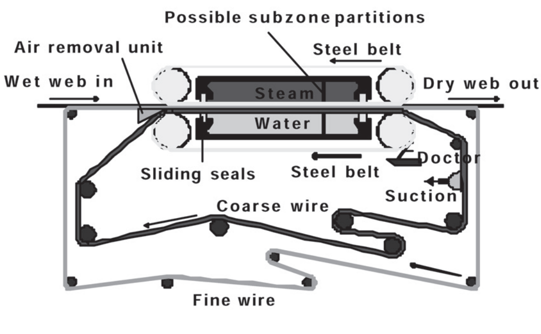

Figure 8 Condebelt drying process.

the web causes evaporation. On the other side of the web is a metal wire mesh and beyond that, an externally cooled metal belt both moving along with the web. The evaporated steam condenses on the cooled metal surface. The wire serves as a water reservoir. Usually, an additional fine-mesh wire is placed against the web to reduce wire marking. The metal belts are made of steel with typical thickness of about 1 mm. There are seals between the steam-fed, hot-side pressure chamber and the heated steel belt and between the cooling water chamber and the cooled metal belt. Edge units seal the web and the wires between the metal belts.

Four primary process variables control the drying process [23]:

- *Z*-pressure supplied by steam and acting on the web during drying.
- The web drying dwell time.
- Average temperature of the web.
- Initial moisture content of the web.

The drying rate, see Figure 9, in the Condebelt drying process is substantially higher than with conventional cylinder drying per web contact surface area at same steam pressure. The drying rate depends on basis weight, local moisture content, and to some degree, on the type of furnish used. The general trend is that lower basis weight and higher moisture content contribute to a higher drying rate.

The process parameters are 110–170°C heated surface temperature, 0.5–7 bars pressure and long dwell time. Such conditions cause the hemicellulose and lignin in the fibers to soften and flow with the following consequences – a

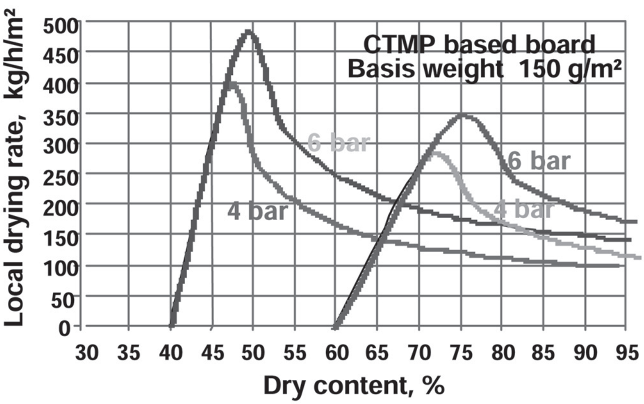

Figure 9 Drying rate at different ingoing moisture and pressures.

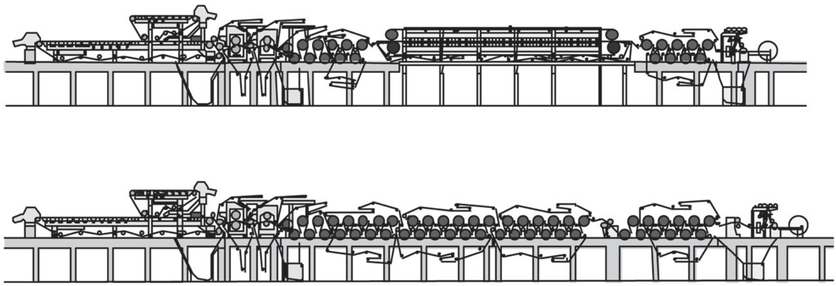

Figure 10 Board machine with Condebelt (above) and cylinder dryers (below).

denser stronger web, a smoother surface in contact with the hot surface approaching that of a supercalendered surface, and a protective film giving the web a higher resistance to changes in humidity. The other process phenomenon is fully restrained drying with virtually zero web shrinkage. The process has so far been confined to drying of board grades with two commercial installations, one in Finland at StoraEnso Pankakoski mill and the other in South Korea at Dongil Paper Ansan mill.

The Condebelt dried products are unique and offer boxmakers several advantages:

- Significantly higher box compression strength (or 20–30% lighter boxes).
- Smooth and appealing surface.
- Good printability and print quality.
- Good runnability in corrugating and converting machines.
- Improved dimensional stability and resistance to humidity.

Whether or not the higher liner strength translates into increased box strength was investigated by making corrugated board and regular slotted containers with three different liners: a cylinder dried and a Condebelt dried testliner from StoraEnso Pankakoski mill, and a well known high quality kraft liner produced in Scandinavia. Cylinder dried NSSC with two different basis weights was used as the corrugating medium. Altogether six different board combinations were tested.

The overall assessment of board makers and their customers were positive. The following is a condensed summary of the converting results:

- Good runnability, no breaks, no serious problems with wrapping or gluing.
- Much better ECT values than with Testliner grade.

- Mullen burst similar to test liner.
- Print quality is good; sharper print image with less printing ink.

6.4 Impulse drying [22,19,20,21]

The commercialization of impingement and Condebelt drying processes represents the first step towards a shorter, more energy and cost effective dryer section and one which will not only dry the product more effectively, but also contribute to the development of its properties. Of all the presently known paper and board drying technologies, the one which holds the highest potential but is yet to find commercial acceptance, is impulse drying.

Pioneered by STFI researchers in early 1970s culminating in a patent application by Wahren in 1978, impulse drying is a high intensive drying process combining elements of wet pressing and hot surface drying in a roll nip. The process parameters are 150–500°C roll surface temperature, 0.3–7 MPa nip pressure and 10–100 ms nip residence time which produces drying rates 100–1000 times those of conventional dryer cylinders. While the heat and mass transfer mechanisms are still not properly understood after some 25 years of investigation it is generally accepted that the impulse drying nip contains mechanical pressure, creation and expansion of steam which may help to displace free water in the web, conductive heating, convective heating (heat pipe), and flashing in the compressive and expanding modes. These have a potential of dewatering the web up to and even beyond the web's critical moisture level at substantial savings in drying energy – Fig 11.

The presence of a smooth heated surface and rapid heat flow produces two potentially beneficial effects – decrease in fluid viscosity and softening of the cell wall material. The former helps in dewatering the web and the latter to produce enhanced properties of the surface in contact with the hot roll, similar to Condebelt case. The reason for impulse drying continued interest is its potential to achieve high drying rates at significant savings in energy and equipment costs as well as its potential to enhance web quality.

Impulse drying has been extensively studied at various periods by STFI in Sweden, IPST in the US, KCL in Finland, Paprican in Canada and by various machine builders. The latest concerted R&D work started at STFI in 1996 by a consortium of member companies with a task of resolving the outstanding process limitations still inherent in the process. These include energy intensiveness, clothing contamination and the negative aspects of paper properties, notably delamination. Major progress is being achieved in all of these areas and it is expected that continued research will produce a fully acceptable commercial solution in the near future.

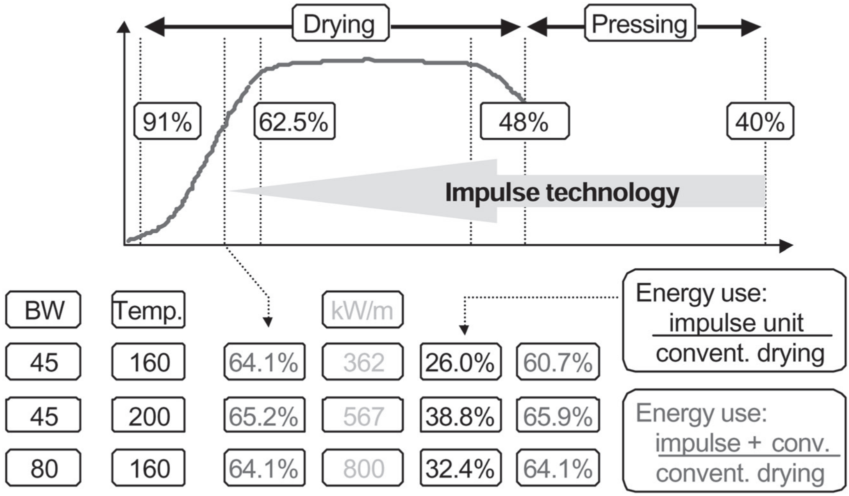

Figure 11 Impulse drying energy balance analysis.

6.5 Direct steam drying

In principle, any direct air dryer could operate with steam. Today, industrial-scale steam dryers are used to dry textile webs, market pulp, and lumber. The first patents to apply the concept of steam drying of paper appeared in the early 1950s. More intensive research work on paper drying started in the early 1980s at McGill University in Canada. A good review of the Canadian work is available in [24]. Despite intensive theoretical and experimental work, no industrial steam drying applications for paper exists today. Compared to drying with air, steam as a drying medium offers many advantages. The most important is the potential to reduce heat energy. If the exhaust steam from the steam dryer could be usefully re-used in some process requiring heat, the net heat energy consumption could be kept very low. Another advantage is safer operation, i.e., no fire or explosion hazard. The drying rate is higher with steam drying than with air drying if the operating temperature is above the so-called "inversion temperature".

Calculation of energy demand uses mass and energy balances. A full comparison between steam and air-drying requires knowledge of the entire energy system including heat reuse, i.e. the layout of the total mill. It can however be said that a partial implementation of steam drying has already found optimal use in steam showers using the "lazy steam" design or impingement design to apply steam to the web. It does not seem very likely that paper dryer of the future will employ direct steam drying extensively, but it is quite likely that direct steam will be used to enhance web profile controllability.

6.6 IR drying

Direct infrared-technique has very fast response to process changes and is therefore partially used as a technique to control web heating and moisture control. It is also a common drying technique for surface sizing and paper coating. Because of the IR-heaters ability for rapid response to high heat flows, this technique could certainly be used as a control tool for high speed dryers.

6.7 Induction and microwave drying

This technique is presently used exclusively for moisture profile control. If any drying process based on primary energy is used as a major drying technique in a newly installed paper dryer, the heat energy added by this dryer will certainly have a major impact on the mill's total heat energy flows. This is true for all new drying concepts not based on the use of low or medium pressure steam.

7 FURTHER R&D NEEDS IN DRYING

The drying concept with ability to more effectively control moisture movement in the web's three principal directions will most likely become the drying concept of tomorrow. The benefits obtained will be reduced equipment cost and size, fast paper grade changes and a more active dryer. The development of the drying section is mainly a question of proper employment of advanced mechanical engineering. Software, control and data technology have already reached a level which makes it possible to significantly advance the drying technology, if only a suitable low cost mechanical solution could be found. The new data technology and sophisticated models of various drying processes is making it possible to evaluate the benefits of novel concepts at a design stage within the total mill concept. The problem which still remains is the accuracy of the models and their physical implementation. To advance the process further and to obtain more meaningful results will require low cost collaborative laboratory data – see Figure 12.

From Figure 12 we may conclude that we are today in a situation where we

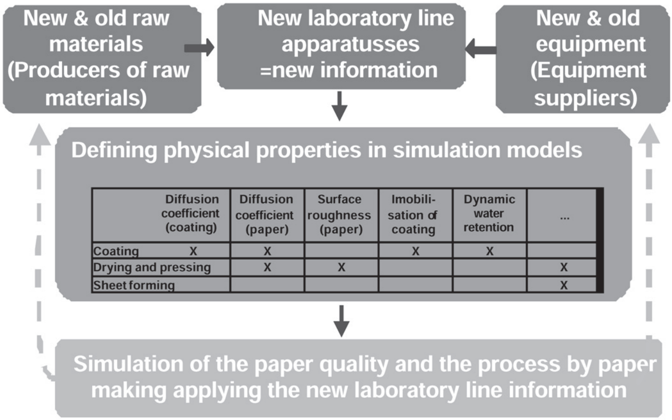

Figure 12 Closing of the data flow from paper sheet laboratory line information to back up the development paper making process and computer aided process engineering (CAPE).

need to put a lot of effort into developing the laboratory environment analogically to add to what has been done within the pilot machine concept. This process is necessary to reduce the development costs and, more importantly the implementation costs of novel products into existing mill concepts.

Because of the central role of the dryer in the paper making process as well as within the entire mill infrastructure, there is a need to develop strategic equations describing its technological and economic contribution to today's mills. A novel drying concept, drastically different from conventional cylinder dryers will have a major influence on the structure of the heat recovery system as well as all other processes integrated with that system. There is therefore a danger that with improper combination of research and development we may end up with defective methods for implementing novel drying concepts which will result in excessive costs and in worst cases, poor results.

All cylinder drying processes have limitations due to the boundary conditions formed by the fabric, the web and the cylinder surfaces. The dried paper is an outcome of a number of single process boundaries where the phenomena are strongly dependent on time, geometry, process parameters and paper properties. To develop more effective paper dryers we must undertake and carry out the following work:

A Fundamental research:

- To better characterize drying properties of new raw materials for paper and paperboard.
- Theoretical 2-D and 3-D heat and moisture mobility research [7](fundamental engineering for heat and mass transfer).
- Development of new measurement methods (dynamic water movement, dynamic 2-D and 3-D picture analyses of paper structures, water movement, etc.).
- Theoretical equipment research for high speed machines (fundamental mechanical engineering).

B Fundamental applied research:

- Automation of novel laboratory equipment, the large number of paper quality parameters require automated laboratory devices to make it possible to effectively develop new paper dryers for both old and new paper raw materials.
- Cross-connecting fundamental research findings with existing dryer equipment and applying the knowledge with the aim of advancing controllability of the paper drying process.
- Testing fundamental research and combining the findings with the process equipment developed by the manufacturers.
- Analyze novel techniques. New paper dryer will have a major impact on the mill structure and hence the techniques used to evaluate novel concepts have to be developed (Process Integration and Computer Aided Process Engineering i.e. Total System Thinking).

C Applied research:

- Optimization of conventional and hybrid drying section for high speeds (~2500 m/min).
- Pilot- and full-scale testing of novel dryer concepts; IR-techniques, direct steam drying etc. to further enhance the controllability of the paper dryer by control of heat and moisture mobility.
- Cost analyses based on pilot and full scale.

8 CONCLUSIONS

Dramatic improvement in paper quality control by drying will not be possible with the conventional drying technology employed today. This technology will continue to be employed instead for commodity paper grades since it remains the most viable and economical technology to utilize excess steam produced in many existing and new mills.

A drying concept providing for a more intense and rapid moisture transfer in the web's three principal directions is the most likely candidate for the drying process of the future. The benefits possible with such dryers will be the reduced equipment size and cost, fast paper grade changes and a more active role in the control of paper properties. Sources of drying energy, their cost structure, and the resulting price of total energy use will remain essential factors for new drying concepts. By referring to the theoretical backgrounds and general production aspects of raw material, energy and equipment, it may be deduced that the optimal dryer for drying of a certain paper product must take into consideration the following aspects:

- Paper mill infrastructure, environmental and safety requirements.
- Long term trends in machine technology and energy costs.
- Existing paper mill layout, i.e. existing infrastructure (in case of rebuilds).
- Layout of industrial dryer equipment including heat recovery.
- Paper properties.
- Added chemicals and/or coating color properties.
- Industrial coating methods and coating colors.
- The effect of drying strategy on product quality.

Paper machine speeds have almost quadrupled in the last thirty years to the present over 2000 m/min design levels. The resultant decrease in productivity costs has not, however, been sufficient to effect the high capital expenditures this requires, therefore further economic gains must be achieved through new and more effective technology throughout the entire papermaking process, most notably drying. The dryers drying capacity will vary according to different dry content levels achieved in the press section, final dry content of the web and various properties required for different paper grades. Paper drying models describing heat and mass transfer and temperature distributions are already being employed for active control of quality and paper machine capacity changes.

Paper machine speeds will continue to increase and this will require new technology, especially in drying which today remains the longest and the most costly component of the paper machine. Impingement drying and other novel drying concepts will be increasingly integrated with cylinder drying to improve the drying efficiency and dryer section's ability to more effectively control important paper properties.

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Transcription of Discussion

DRYING OF PAPER – AN OVERVIEW, THE STATE OF PAPER DRYING KNOWLEDGE

Markku Karlsson

Metso Corporation

Kari Ebeling UPM-Kymmene Corporation

Is there the metallurgy and the crane equipment to deal with these optimum diameter driers with a diameter of 3.5 m?

Markku Karlsson

We don't have that equipment at all but I think in the scientific world, we can always consider different types of thought and what is the optimum diameter is of interest. Maybe our customers will require something to take place if there is really an optimum but this is also a question. My understanding is that for dryer section performance the diameter is not so critical. It is more the heat transfer coefficient and other related parameters that change with the speed, because these govern drying efficiency. This is what I show with the simulation.

Murray Douglas McGill University

Your talk alternately stimulates us and discourages us, as you repeatedly point out the enormous potential for changes in drying, both from that fact that it is such a large energy consumer, such a high capital cost, but as soon as someone gets an idea for something new, you remind them that low pressure steam is so cheap and plentiful, that you run into this obstacle. How do you see the balance between these two things? Do you have any hope of achieving major changes because each change is associated with higher cost processing although with higher drying?

Discussion

Markku Karlsson

We can only gradually change it with the new mills. Maybe there is a new type of energy infrastructure which this is dependent on. I am emphasizing that now we have the tools for the first time to simulate different alternatives and make this type of process integration and see how these novel concepts fit the energy structure of the mill. We have the tools now to demonstrate to people better ways than earlier. However, you really need to have a mill-wide approach or total system thinking to be successful with new drying concepts.

Murray Douglas

A quick comment on the final line, on your slide, reminding us about the role of chemistry in drying, I think that is a very appropriate comment and I hope people will listen to it. I tell my own students that they should not think of the dryer as a dryer, they should think of it as a gas-solid reactor. I think that this perspective will lead to future breakthroughs in drying technology.

Markku Karlsson

This idea is to make the dry section active by design so that chemical reactions take place during the drying which favour paper quality, particularly strength properties.