Turbulence Analysis of Pulp Drying Process in Cylindrical Dryer Using Mass and Heat Transfer Method

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Abstract: ***The drying process is an essential step in paper making. The process generally consists of two stages: pre-drying and after-drying using drying process technology. This drying process requires a certain amount of energy, namely heat from steam. The analytical method uses a heat and mass transfer model approach. The heat transfer and mass transfer models can determine the amount of water content reduction in the cylinder dryer. Turbulence analysis in the drying process aims to see whether there is a relationship between turbulence with mass transfer rate and heat transfer rate. The analysis results show that wet paper's turbulence is proportional to the mass and heat transfer rates. The highest and lowest heat transfer results in the pre-dryer are 5.28 x 10^{-7} kg mol/m^2 and 4.8 x 10^{-7} kg mol/m^2 s, while in the after-dryer; it is 6.5 x 10^{-8} kg moles /m^2 s and 5.8 x 10^{-8} kg mol/m^2 s. The highest and lowest turbulence values in the Pre-dryer are 9200 and 8131, respectively, while in the After-dryer are 6144 and 5426.***

Keywords: dryer, energy, paper, cylinder, steam**.**

1. Introduction

Drying a solid generally means removing a small amount of water or other liquid material to reduce the residual liquid content to a sufficiently low value. Drying is usually the last step in a series of operations, and the product from the dryer is often ready for final packaging [1]. The process of reducing the content of water or other liquids from a solid is mechanical or by evaporation. Generally, centrifugal drying is less expensive than thermal drying and, therefore, reduces the liquid content as much as possible before introducing the material to the thermal drying process [2-3].

There has been much research on the drying process, both in terms of intelligent equipment equipped with computer and control technology [4], encapsulation technology [5], and drying operating conditions [6-8]. The drying process is a process that involves mass transfer (the presence of a concentration gradient around the interface) and heat transfer (due to a temperature gradient). For example, the reduction of water content in coffee considering the thermal conductivity and effective diffusion coefficient [9], the use of porous media [10], and ultrasonic equipment increase the yield by 20-80% [11]. This study focuses on the effect of turbulence. The drying process consists of two stages, namely, Pre-dryer and After-dryer.

The drying principle needs to pay attention to the temperature pattern in the dryer, heat transfer in dryers, heat load calculations, heat transfer unit, and mass transfer in the dryer. This research will study the effect of heat transfer and mass transfer on the drying process, especially the turbulence factor. This turbulence factor is an analysis that has never existed in previous research.

- Column Height – 271.4 mm (10.69")
- Space/Gap between Columns - 5.0 mm (0.2").

2. Transfer of Mass and Heat in The Drying Process

Drying involves the transfer of mass (vapor) from the material and heat energy to the material simultaneously. The heat transfer process from the environment around the material will evaporate the water on the material's surface. Water can be transferred to the product's surface and then vanished, or internally at a vapor and liquid interface, then carried as a vapor to the surface.

There are six physical mechanisms to explain the movement of water in the material, namely 1) the movement of fluids due to surface forces (capillary flow), 2) diffusion of liquids due to differences in concentration, 3) surface diffusion, 4) diffusion of water vapor in the pores filled with air, 5) flow due to pressure differences, 6) flow due to evaporation and condensation. The drying air is very influential in the drying process, especially temperature, relative humidity, and airflow speed.

2.1 Drying Rate

The drying rate in the drying process of a material has a significant meaning, where the drying rate will describe how the drying speed takes place. Drying rate is the ratio between the weight of water evaporated per unit of dry weight per hour. The water that can disappear from the material to be dried consists of free water and bound water. Free water is on the surface and is the first to evaporate. The evaporation rate of free water is proportional to the difference in vapor pressure at the water's surface to the drying water vapor.

Surface water runs out, and there is a water-water vapor diffusion process from within the material due to the

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difference in vapor pressure inside and outside. The drying rate is proportional to the difference in the material's internal and external vapor pressures. The drying rate is constant, and the difference in vapor pressure is stable too, but with evaporation, the vapor pressure in the material gets lower; therefore, the drying rate decreases.

A constant drying rate occurs at the beginning of the drying process, followed by a decrease in drying; the critical moisture content (Mc) limits the drying rate in both periods. The drying rate reduction period has two subperiods: namely: 1) decreasing drying rate I, which occurs when the water on the surface of the product has run out, and the surface begins to dry, and 2) drying rate II, starting from when the surface is dehydrated. Materials to pass through all four periods. This drying process varies depending on the initial moisture content of the material and the drying conditions.

2.2 Cylinder Dryer

Cylindrical drying is a type of dryer consisting of one or more cylinders. The material is metal that rotates on its axis horizontally by internal heating by water vapor or another liquid medium. Using steam as the primary source of heat energy and a rotating cylindrical surface as the heat transfer area is the most common drying method for pulp into paper products. Almost all paper machines in the paper industry use conventional hot steam cylinders or multi-cylinder drying configurations. In addition to providing good energy efficiency, cylinder drying enables good pulper transfer and improves pulper drying smoothness.

2.3 Mass Transfer

The drying process is a mass transfer of water vapor from the air to the environment. The mass transfer equation is the heating air velocity at which water affects the physical condition of the material. The contact area between the substance and air is the more significant the mean mass transfer coefficient; the greater the contact surface area, the greater the water vapor. The displacement or change in mass can be measured using a formula. Mass transfer operations will take advantage of the motion of a component in the mixture. Mass transfer in the drying process, water diffuses through the solid to the surface of the concrete and evaporates; the vapor diffuses into the gas. The calculation of the mass transfer rate uses the following equation [12]:

$$J = k_c (C_i - C) \quad (1)$$

Where C_i (kg mol/m^3) and C (kg mol/m^3) are the initial mass fraction and final mass fraction, J (kg mol/m^2 s) is the mass transfer rate per unit surface area, and k_c (cm/s) is an individual mass-transfer coefficient. Calculation of k_c using the following equation:

$$k_c = 0,023 \frac{D_v}{D} N_{\mathrm{Re}}^{0,8} N_{Sc}^{1/3} \quad (2)$$

D (m) is cylinder diameter, and D_v (m^2/s) is diffusivity. N_{Re} and N_{Sc} (dimensionless) are Reynolds numbers and Schmidt numbers. Reynolds number (Re) is a comparison between the inertia force and the frictional force of the fluid, which is the magnitude is:

$$N_{\mathrm{Re}} = \frac{\rho \times d \times v}{\mu} \quad (3)$$

Where, G (kg/m^2 s) is mass velocity, μ (kg/m s) is viscosity. The Schmidt number is the ratio of the kinematic viscosity to the mass diffusivity. This figure characterizes the fluid flow in the simultaneous momentum and convection mass diffusion processes. Calculation of N_{Sc} using the following equation:

$$N_{Sc} = \frac{\mu}{\rho \times D_v} \quad (4)$$

2.4 Heat Transfer

The heat transfer occurs because the temperature is more through the material's surface by convection or by walls heat by conduction. Process drying transfer in the form of water vapor in the material is in equilibrium with the water vapor pressure in the surrounding air. At the start of drying, the material receives heat, increasing the vapor pressure of water, especially in line with the increase in the temperature. There are two forms of heat transfer from the paper to the surrounding air: heat due to evaporation (evaporation) and heat due to convection. Heat transfer by mechanism convection depends on the heat transfer coefficient. In other words, the heat transfer coefficient is the proportionality coefficient between the heat transfer rate and the temperature difference, which is the primary driver of heat transfer. The science of thermodynamics, mechanics, and chemical engineering extensively uses the heat transfer coefficient value. Heat occurs due to convection due to the temperature difference between the air and the wet paper surface. The heat due to evaporation is latent heat that arises from a partial pressure difference between water vapor in the air and water pressure on damp paper. In the general case, the calculation of the total heat transfer rate is as follows:

$$q_T = h \times A_{eff} \times \overline{\Delta T_L} \quad (5)$$

Where h (W/m^2 ^{o} C) is the individual heat transfer coefficient, A_{eff} (m^2) is the effective area, 85% of the total area, and $\overline{\Delta T_L}$ (^{o} C) is the logarithmic mean temperature difference.
Calculation of h using the following equation:

$$h = 1,17 \frac{k}{D} N_{\mathrm{Re}}^{0,585} N_{\mathrm{Pr}}^{1/3} \quad (6)$$

The value of k ((W/m ^{o} C) is the thermal conductivity**.**

The Prandtl number is the ratio between the kinematic viscosity of the fluid and the thermal diffusion. The fluid's

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Prandtl number (P_r) is crucial because it connects the momentum boundary layer with the thermal layer during heat transfer through the liquid. Calculation of N_{Pr} using the following equation:

$$N_{\mathrm{Pr}} = \frac{C_p \times \mu}{k} \tag{7}$$

Variable Cp (kJ/kg °C) is heat capacity.
The LMTD (log mean temperature difference) is the logarithmic average temperature difference between the hot and cold streams. The LMTD determines the temperature driving force for heat transfer in flow systems, especially heat exchangers. Calculation of using the following equation:

$$\overline{\Delta T_L} = \frac{(T_{ha} - T_{wa}) - (T_{hb} - T_{wb})}{\ln\left[\dfrac{(T_{ha} - T_{wa}}{T_{hb} - T_{wb}}\right]} \tag{8}$$

Where T_{ha} (°C) and T_{hb} (°C) are the temperatures of the heating medium at the inlet and outlet, T_{wa} (°C) and T_{wb} (°C) are wet bulb temperatures at the inlet and outlet.

3. Method

Heat transfer occurs from hot air to the paper's surface, so the water content decreases. Heat transfer can occur due to the significant temperature difference between the two surfaces. The material is dried using an airflow dryer at a reasonable temperature between 45°C to 75°C. If drying at a temperature below 45°C, microbes and fungi still damage the product, so the product's durability and quality are low. However, the drying air temperature above 75°C causes the chemical and physical structure of the product to be damaged due to heat and water mass transfer, causing changes in cell structure. The operating temperature in this study is 45°C to 65°C, as in the following method steps (Radka *et al.*, 2020):

(1) Approach the heat transfer model by varying the input temperature, namely at 50°C for pre-dryer and 65°C for after dryer
(2) The approach of the mass transfer model by varying the mass flow rate is as follows:
   a. wet paper in Pre-dryer, namely: 4.9 kg/s; 5.2 kg/s and 5.5 kg/s
   b. wet paper in After-dryer, namely: 3.2 kg/s; 3.5 kg/s and 3.7 kg/s
(3) The paper size variables are: 215 g/m^2, 235 g/m^2, 285 g/m^2 and 335 g/m^2. We will measure paper temperature during the drying process and take air measurements in a dryer.

Before and after drying the paper, they were doing the size of the water content base. This method could immediately know the results of the measurement of water content. This research will also calculate the heat transfer rate using the equation. The mass transfer calculation in the drying process meets the primary heat transfer mechanism, especially conduction and convection presence of fluid flow, for calculating mass transfer using the rate equation water evaporation.

4. Results and Discussions

Wet paper sheets (paper web) pass through the press section; the sheets still have a reasonably high moisture content and cannot be separated using the continuous pressing method. The drying method is the process of evaporation of water in solids. Drying equipment uses a dryer cylinder. The sheet from the press section uses canvas in the pre-dryer, and the paper sheet is on the canvas paper through the cylinders contained in the pre-dryer. The cylinder uses steam as a heater, so the heat transfer occurs from the steam to the material. Soon a cylinder, there are three main layers, the outermost layer is paper, the middle layer is canvas, and the innermost layer is steam. This condition results in heat transfer by convection and conduction.

4.1 Mass Transfer

The wet paper contains water, experiencing evaporation from 36.64% to 8.26% pre- and 10% to 5.24% for After-dryer. Form with various sizes evaporated differently, as shown in Figure 2 for the Pre-Dryer process and Figure 3 for the After-dryer. Figure 4 shows the dryer's mass transfer per surface area in the Pre-dryer and After-dryer processes. Figures 2 and 3 show the results of the calculation of the rate of evaporation of water, which is fast at first, then tends to slow down.

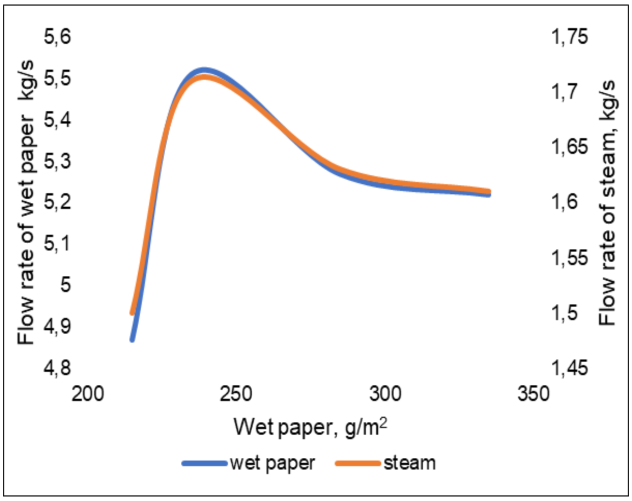

Figure 2: The relationship between wet paper and mass flow rate in Pre-dryer

This condition can happen because, in the beginning, drying occurs in contact between air heat from the dryer with a paper surface, causing evaporation of the water content on the paper surface. Furthermore, the rate of water evaporation slows down and tends to be constant.

The paper sizes are 215 g/m^2, 235 g/m^2, 285 g/m^2 and 335 g/m^2, each having a water flow rate of 1.8 kg/s, 2 kg/s, and 1,9 kg/s. Fig. 2 shows that steam to evaporate the water in the wet paper is highest on paper at 235 g/m^2 and the lowest on paper at 215 g/m^2. The water content in 235 g/m^2 paper is the highest, two kg/s, and the lowest is 215 g/m^2 paper, 1.8 kg/s. The higher the water content in the paper requires more steam.

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The calculation results show that the water material's displacement or evaporating mass will reduce moisture content during drying. In other words, the group of water undergoes diffusion from the inside to the material's surface continuously until the process is completely drying.

The paper sizes are 215 g/m^2, 235 g/m^2, 285 g/m^2 and 335 g/m^2 each having a water flow rate of 0.17 kg/s, 0.19 kg/s, 0.18 kg/s and 0.18 kg/s. Figure 2 shows that steam evaporates the water in the wet paper is highest on paper at 235 g/m^2 and the lowest on paper at 215 g/m^2. The water content in paper at 235 g/m^2 is the highest, 0.19 kg/s, and the lowest is paper at 215 g/m^2, which is 0.17 kg/s.

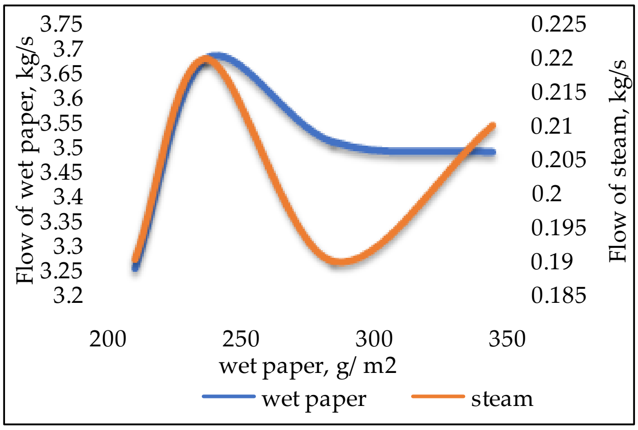

Figure 3: The relationship between wet paper and mass flow rate in After-dryer

Figure 4 shows that if diffusion is the determining factor, the drying rate is directly proportional to the free moisture content and inversely proportional to the thickness square. The figure shows that mapping time against free moisture content will get a straight line and determine the gradient's mass transfer (diffusivity). The highest mass transfer rate for Pre- dryer is 5.28 x 10^{-7} kg mol/m^{2}s, which occurs because the mass transfer coefficient value is the highest [13]. The value of the mass transfer coefficient has something to do with the variable wet paper mass flow rate, where the higher the mass flow rate value will affect the high turbulence, which in turn affects the Sherwood number. The Sherwood number is directly proportional to the mass transfer coefficient [14] and the turbulence.

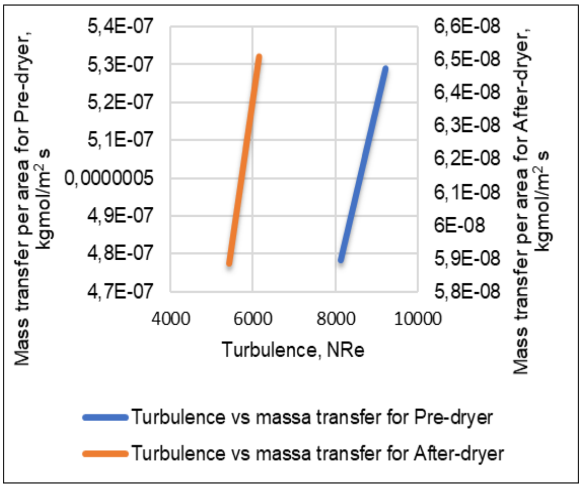

Figure 4: The relationship between turbulence and mass transfer

On the other hand, the lowest mass transfer rate is 4.78 x 10^{-7} kg mol/m^2 s. The mass flow rate is also the lowest and the After-dryer. In the Pre-dryer process, the value of mass transfer rate per surface area is higher than that of the After-dryer because the evaporation of water content decreases from 38.9% to 10%.

4.2 Heat Transfer

Drying wet paper is a thermal process that always involves heat transfer. The graph of the relationship between mass flow rate and turbulence is in Fig. 5, between turbulence and the heat transfer coefficient as in Fig. 6, and between the transfer rate coefficient and the heat transfer rate as in Fig. 7. The mass flow rate value is directly proportional to the turbulence. This value affects the value of the heat transfer coefficient. This coefficient value affects the value of the heat transfer rate, which will ultimately affect the drying process. So the higher the turbulence, the faster the drying process. Figures 5, 6, and 7 show the results of calculating the heat transfer rate in the paper drying process. At the beginning of the drying process, there is a high increase in the heat transfer rate because, at this stage, there is direct contact between the paper and the dryer's hot air.

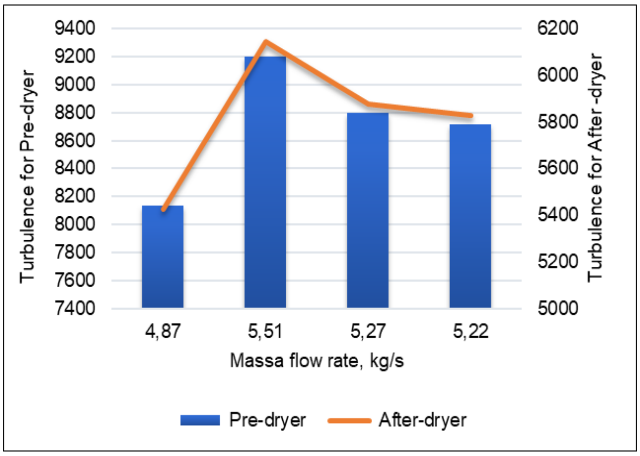

Figure 5: The relationship between mass flow rate and Turbulence

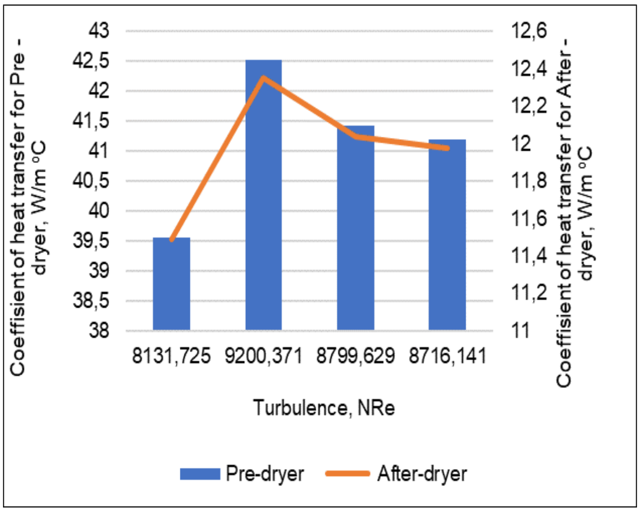

Figure 6: The relationship between turbulence and individual coefficient of heat transfer

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In the drying process, the higher use, the higher the air heating temperature, the greater the heat energy carried, and the more significant the difference between the heating medium and the paper material. It will encourage more transfer process speed or water evaporation. Time impact drying will be shorter. Following the statement that temperature differences between heating media and the ingredients are getting more significant cause faster heat transfer into the material and the quicker the water vapor moves from materials to the environment. In other words, the higher the air temperature and the greater the temperature difference, the more water moisture evaporates from the material so that the weight of the material increases and the drying rate is getting fast.

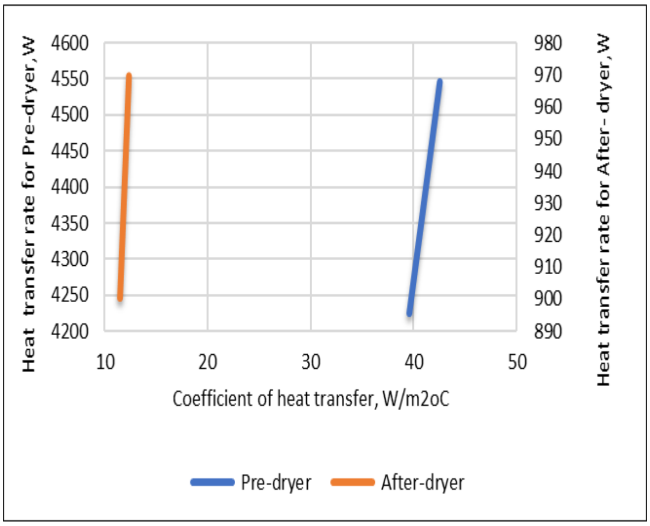

Figure 7: The relationship between the individual coefficient of heat transfer and heat transfer rate

The correlation of heat transfer rate is directly proportional to turbulence. This condition follows Figure 4, which shows that the turbulence depends on the flow rate value. The greater the wet paper flow rate value, the greater the value of the turbulence number (Reynolds number). Figure 5 shows the more significant the turbulence value, the greater the heat transfer coefficient [15], where the heat transfer coefficient is directly proportional to the Nusselt number. The Nusselt number depends on the variable flow rate and the substance's physical properties. Physical properties affect turbulence; the highest turbulence value is 9200 for Pre-dryer and 6140 for After-dryer. The highest value of heat transfer rate in the Pre-dryer for 235 g/m^2 is 4540 W, and the lowest for 215 g/m^2 is 4224 W, while in the After-dryer, the highest is 968 W and the lowest is 900 W. The drying process in saturated conditions cannot but must involve the mass transfer rate. The case in the drying process that does not include the mass transfer rate will occur when the solid is dried using supersaturated steam.

5 Conclusions

The conclusion of this research is as follows:

(1) Mechanism of heat transfer rate and mass during the process of paper drying using drying machine, a displacement event occurs heat is heat transfer by convection which depends on the Reynolds and Prandtl numbers.
(2) Convection heat transfer in the paper drying process occurs from hot air flowing using a blower to wet paper. Displacement of the heat will take place in the material surface slowly until there is even heat distribution. Heat transfer keeps going, and moving some of the heat to various layers of material dried to processing is complete.
(3) At the same time, the mass transfer process heat transfer; The temperature of the paper increases, causing the water vapor pressure of the material to be higher than the water vapor pressure of the air, the process of transferring water vapor from the material to the air, resulting in a decrease in the moisture content of the paper.
(4) The turbulence analysis method correlates with the drying process's mass and heat transfer rates. A high mass transfer rate value is proportional to a high heat transfer rate. Turbulent flows strongly influence the mass transfer and heat transfer rate.

Conflicts of Interest

The authors declare no conflict of interest.

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