

Theoretical Study of Shell-and-Tube Heat Exchanger Effectiveness on Batch Drying of Sawdust Utilizing Waste Heat from Organic Rankine Cycle

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ABSTRACT

Steam power plant has flue gas that are generally discharged into environment. The exhaust gases from internal combustion contain thermal energy that can be utilized for drying processes, which can enhance the energy efficiency of the Organic Rankine Cycle (ORC) system. This research focuses on the use of waste heat for drying applications through heat exchangers. The objective of this work is to study the performance of shell-and-tube type heat exchanger in utilizing waste heat from an ORC system for drying applications. Experimental data was obtained by varying the air velocity of the dryer to validate the numerical simulations. The results showed that increasing air velocity in the heat exchanger caused a decrease in heat exchanger outlet temperature, water vapor mass, and heat exchanger effectiveness. The decrease in these parameters reduces heat transfer required for drying, so water mass rate of material decreases and drying time gets longer. Validation of simulation and experiment data for outlet heat exchanger temperature was determined by MAPE value of less than 20% which means good prediction model.

1. INTRODUCTION

Steam power plants produce flue gas, which is the main source of waste heat. Waste heat is the energy associated with the flow of waste air, exhaust gases, and liquids leaving industrial facilities into the environment. This flue gas has potential for further utilization through the use of a regenerative system (Permana & Mahardika, 2019). Regenerating waste heat can be carried out through various waste heat recovery technologies, which aim to provide a valuable energy source and reduce overall energy consumption (Oyadepo & Fakeye, 2020). In a steam power plant system, not all combustion energy is converted into electrical energy (Suntoro *et al.*, 2018). The combustion energy that is not utilized as electricity is in the form of thermal energy. Around 30-40% of the thermal energy lost from a combustion process, depending on the engine load and is generally released to the environment (Jadhao *et al.*, 2013; Nadaf *et al.*, 2014; Dubey *et al.*, 2015). Research by Yulianto *et al.* (2022) shows that flue gas from coconut shell boilers can reach a maximum temperature of 500 °C.

One interesting use of waste heat is for drying. This alternative has attracted researchers and several studies using waste heat have been reported. Agustina *et al.* (2020), used a condenser waste heat in a vacuum freeze dryer for yam. Research by Zainuddin *et al.* (2016), utilized exhaust gas of a diesel engine through a shell helical coil multi tube type heat exchanger. Ansar *et al.* (2022) reported the utilization of condenser exhaust gas in vacuum freeze drying. Nasruddin *et al.* (2011) utilized waste heat from a condenser for drying aloe vera.

Utilization of waste heat for drying using a heat exchanger is need to be considered. Heat exchanger is equipment used to transfer heat from one to another fluid due to temperature differences (Cengel, 2002; Incropera *et al.* 2006). A

heat exchanger functions to transfer heat from a medium that has a high temperature (hot) to a medium that has a lower temperature (cold) in a system. In other words, this device is used to cool or heat fluids or gases by transferring heat between the two media (Mendivelso *et al.* 2022). The use of a heat exchanger in the dryer is beneficial in term that the dried material is not contaminated from the combustion of fuel during the drying process (Farak, 1991). Research by Susana & Alit (2020) showed that application of a heat exchanger avoid the dried material from contamination due to burning of husks. Based on the direction of fluid flow, heat exchangers are generally divided into three types, namely parallel flow, counter flow, and cross flow (Azwinur & Zulkifli, 2019). Tubular exchangers are widely used, and are manufactured in a variety of sizes, flow settings, and types. The advantage of this heat exchanger is that it can accommodate various operating pressures and temperatures as well as being easy to manufacture with relatively low cost. The design commonly used is a shell-and-tube type heat exchanger (Septian *et al.*, 2021).

In this research, a numerical simulation was carried out to utilize waste heat from an Organic Rankine Cycle (ORC) system using a shell-and-tube type heat exchanger by varying the drying air speed. Simulation data is used to design a heat exchanger so that waste heat can be used for efficient drying. The research results are useful for determining the thermal potential of waste heat from ORC generator for drying the biomass fuel used.

2. MATERIALS AND METHODS

2.1. Tools and materials

Numerical simulation was used as the main approach to predict the effectiveness of heat exchangers due to drying air velocity. The parameters used in the numerical simulation model such as air speed variations and efficiency were implemented through Excel software. The CAD software was used to create a heat exchanger design that will be applied to the sawdust drying equipment. Data acquisition and thermocouples were used for measuring the experimental temperature. The materials used in this research were sawdust of gamal and sengon wood.

2.2. Design Concept

The heat exchanger design was portrayed schematically in Figure 1. The heat exchanger was designed to utilize waste heat from an ORC system in the form of flue gas. Flue gas with a high temperature enters through the flue gas inlet and flows through the tube section causing a convection process to occur on the inner copper pipe wall. The conduction process occurs from the inside of the copper pipe wall to the outside. Next, a convection process occurs between the outer wall of the copper pipe and the air entering through the heat exchanger inlet which causes heat transfer from the flue gas to the drying air.

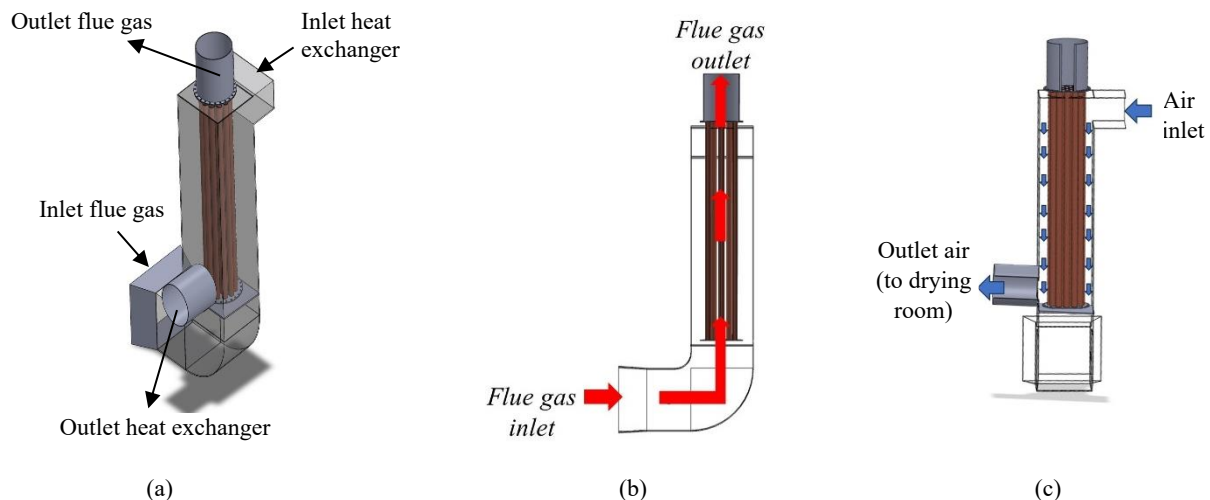


Figure 1. Heat exchanger design: (a) isometric view, (b) flue gas flow, (c) air flow

2.3. Input Parameters

The input parameters for heat exchanger calculations were carried out by analyzing the batch dryer system. The heat exchanger was applied for sawdust drying machines which utilize waste heat of an ORC system. The technical analysis was based on the characteristics of the materials used in the construction of heat exchangers available on the market. Flue gas temperature was an important parameter for fluid properties in the heat exchanger. The flue gas properties was approached using air. Flue gas temperature values were based on research by [Yulianto *et al.* \(2017\)](#). Design criteria for the heat exchanger was presented in Table 1.

Table 1. Design criteria

No	Parameter	Quantity	Unit
1	Flue gas temperature entering the boiler	250	°C
2	Flue gas temperature leaving the boiler	100	°C
3	Heat exchanger inlet air temperature	30	°C
4	Heat exchanger exit air temperature	60	°C
5	Pipe inner diameter	0.01194	m
6	Outside diameter of pipe	0.0127	m
7	Thick copper pipe	0.00076	m
8	Copper conductivity	385	W/m°C
9	Initial Water Content of Material	20	%bb
10	Final Water Content of Material	10	%bb
11	Drying Tub Volume	0.42	m ³
12	Airspeed variations	1.2	m/s
		3.8	
		10.8	
13	Efficiency	100	%
		80	
		60	
		40	

This research also varied the efficiency of the equipment where the heat engine efficiency is assumed as less than 100%. According to [Ni \(2023\)](#), basically the thermal system cannot convert all the heat absorbed from the heat source into work. The efficiency of a heat engine is expressed as the ratio between the work produced by the engine and the heat absorbed from the heat source. Some heat always lost during the process, for example in the form of heat that cannot be converted into work or heat coming out of the engine.

2.4. Calculation Method

2.4.1. Heat Exchanger Design Calculations

The initial stage of this research was designing a heat exchanger using air as the fluid at 1 atm. The important properties of the air include density (ρ), fluid conductivity (k), Prandtl number (Pr), dynamic viscosity (μ), and specific heat (C_p). The fluid characteristics were used to determine the Reynolds number (Re) and Nusselt number (Nu) calculated as the following ([Holman 2010](#)):

$$Re = \frac{(\rho V D)}{\mu} \quad (1)$$

where ρ is flue gas density (kg/m³), V is air speed (m/s), D is inner pipe diameter (m), and μ is dynamic viscosity (kg/m.s). There are two flow regimes: turbulent and laminar. In this research, the Reynolds number is included in the turbulent flow, namely $2300 < Re < 10^6$, and the Nusselt number (Nu) was calculated as follows ([Holman, 2010](#)):

$$Nu = 0.023.Re^{1/3}.Pr^{1/2} \quad (2)$$

The Nu is used to find the value of heat transfer coefficient inside (h_i) and outside (h_o) the pipe. The heat transfer coefficients h_i and h_o were calculated according to ([Holman, 2010](#)) as the following:

$$h_i = Nu \frac{k}{d_i} \quad (3)$$

$$h_o = Nu \frac{k}{d_o} \quad (4)$$

where k is flue gas conductivity (W/mK), d_i and d_o is respectively inner and outer diameter of the tube.

The thermal resistances on the copper pipe wall were calculated per unit of length as follows (Holman, 2010):

$$R_s = \frac{\ln(\frac{r_o}{r_i})}{2\pi k} \quad (5)$$

$$R_i = \frac{1}{h_i \cdot A_i} = \frac{1}{h_i (\pi \cdot d_i)} \quad (6)$$

$$R_o = \frac{1}{h_o \cdot A_o} = \frac{1}{h_o (\pi \cdot d_o)} \quad (7)$$

where R_s is conductive thermal resistance through the pipe wall, R is convective resistance on the pipe, r is pipe radius (m), k is thermal conductivity of copper pipe (W/m.°C), A is cross-sectional area of the pipe (m²). Subscript i and o respectively denoted for inner and outer of the pipe.

The next step is calculating the total heat transfer (Q), the overall heat transfer coefficient outside the pipe (U_o), and the overall ΔT using the LMTD (log mean temperature difference) method to obtain the value of the heat transfer surface area (A). In this study the overall heat transfer coefficient inside the pipe (U_i) was based on flue gas entering through the inside of the tube and can be ignored, so that the thermal resistance on the inside (R_i) is relatively small and its effect on overall heat transfer is negligible. The U_o (in W/m².°C) was calculated as follows (Holman, 2010):

$$U_o = \frac{1}{\frac{R_i A_o}{A_i} + \frac{A_o}{R_s} + R_o} \quad (8)$$

The overall ΔT was calculated using the LMTD method as in Equation (9) (Holman, 2010):

$$\Delta LMTD = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln(\frac{T_{hi} - T_{co}}{T_{ho} - T_{ci}})} \quad (9)$$

where $\Delta LMTD$ is average temperature difference (°C), T_{hi} is inlet flue gas temperature (°C), T_{co} is inlet air temperature (°C), T_{ho} is exit flue gas temperature (°C), T_{ci} is outlet air temperature (°C). The surface area of the pipe was calculated using Equation (11) (Holman, 2010):

$$Q = U \cdot A \cdot \Delta LMTD \quad (10)$$

$$A = \frac{Q}{U \cdot \Delta LMTD} \quad (11)$$

where U is overall heat transfer coefficient (W/m².°C), and Q is heat rate (W).

The required number (n) of tubes can be calculated for a given tube length (L) as follows (Holman, 2010):

$$n = \frac{A}{\pi \cdot L \cdot d_o} \quad (12)$$

Dryer optimization has two main objectives, namely minimizing energy costs and maximizing drying capacity (Ghiasi *et al.*, 2016). Determination of dryer capacity using Equation (13) following:

$$V = \frac{Kap}{\rho} \quad (13)$$

where V is dryer volume (m³), Kap is material capacity (kg), and ρ is density of wood (kg/m³)

2.4.2. Heat Exchanger Simulation

The simulation approach used is a thermodynamic process approach to the thermal requirements required for the drying process. Calculations for the mass rate of water vapor and drying time are obtained from thermal calculations

produced from the heat exchanger. So, the parameters required are the heat energy required by the dryer, heat conductivity, and fluid flow rate. The required heat exchanger size has been obtained, then the temperature coming out of the heat exchanger is calculated using Equation (14) following:

$$Q = \dot{m} \cdot C_p \cdot \Delta T = (\rho \cdot A \cdot V) \cdot C_p \cdot (T_2 - T_1) \quad (14)$$

$$T_2 = \frac{Q}{(\rho \cdot A \cdot V) \cdot C_p} + (T_1) \quad (15)$$

where Q is drying energy (kJ/s), $\dot{m}$ is dryer inlet air mass flow rate (kg/s), C_p is specific heat (kJ/ kg°C), T_1 is environmental temperature (°C), T_2 is temperature leaving the heat exchanger (°C), and V is air speed (m/s).

The effectiveness of a heat exchanger is an indicator of heat exchanger efficiency which is influenced by the temperature that occurs during the heat exchange process. Equation (18) following:

$$c = \frac{C_{min}}{C_{max}} = \frac{(m C_p)_{min}}{(m C_p)_{max}} \quad (16)$$

$$c = 1 - e^{-NTU} \quad (17)$$

$$NTU = \frac{A}{C_{min}} \quad (18)$$

where NTU is number of heat transfer units which is a benchmark for heat transfer in a heat exchanger.

The mass rate $\dot{m}$ (kg/s) of evaporated water was calculated based on $Q_{space} = Q_{material}$ as the following:

$$\dot{m} \cdot C_p \cdot \Delta T = m \cdot L \quad (19)$$

where Q is energy entering the dryer (kJ/s), C_p is specific heat (kJ/ kg°C), and L is latent enthalpy (kJ/kg).

2.5. Simulation and Experimental Validation

Mean Absolute Percentage Error (MAPE) is the average value of the absolute difference between the predicted value and the actual value. Validation was carried out on the heat exchanger outlet temperature in the treatment of three variations of air speed in the experiment, namely 1.6 m/s, 2.4 m/s, and 4.6 m/s. Mean Absolute Percentage Error (MAPE) is an evaluation of forecasting results to see the level of accuracy of forecasted and actual values (Nabillah & Ranggadara, 2020). With n is number of data, the MAPE was calculated as the following.

$$MAPE = \frac{\text{experiment-simulation}}{\text{experiment}} \times \frac{100}{n} \quad (20)$$

The lower the MAPE value, the better the ability of the forecasting model used. MAPE also has a range of values that can be used as a benchmark to assess how good a forecasting model is (Maricar, 2019). The meaning of MAPE values to the forecasting strength is: <10% (excellent), 10-20% (good), 20-50% (feasible), and >50% (bad).

2.6. Experimental Set-up

Structural heat exchangers are designed by determining the size and materials used. The application of a heat exchanger in a drying machine can be seen in Figure 2. The chimney in the ORC system is used as a heat exchanger according to the calculations that have been carried out. The parts of the heat exchanger can be seen in Figure 4. Experimental data collection on the heat exchanger outlet temperature using a type k thermocouple was recorded using DAQ (data acquisition) and read by a laptop using Labview. Experimental data collection was carried out for one hour. The calculation flow diagram in this research can be seen in Figure 3.

3. RESULTS AND DISCUSSION

3.1. Simulation and Experimental Validation

The validated data is the temperature coming out of the heat exchanger because it is measured directly and accurately in experiments. The average experimental data for the heat exchanger outlet temperature with air speed variations of

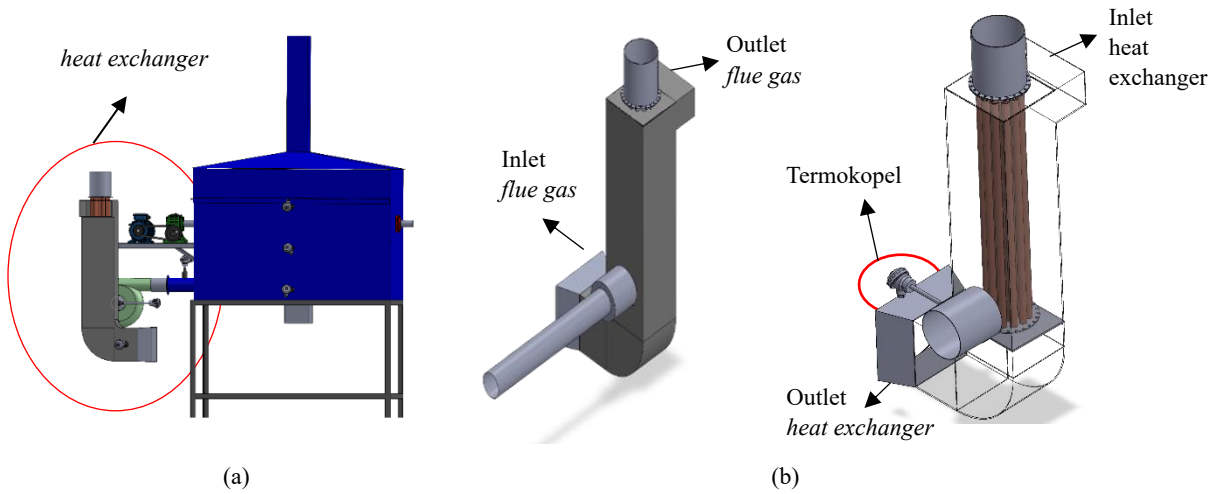


Figure 2. Figure 2. (a) Application of heat exchanger in sawdust dryer, and (b) Heat exchanger design

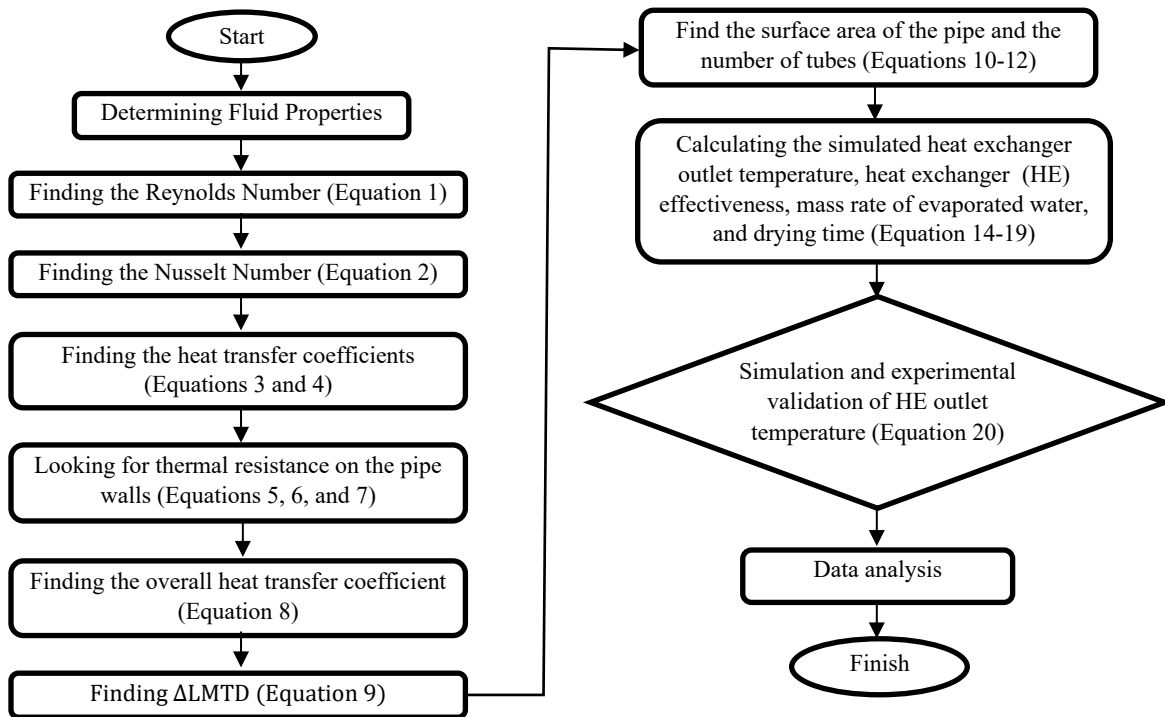


Figure 3. Calculation flow diagram

1.6 m/s, 2.4 m/s, and 4.6 m/s is respectively 131.94°C, 92.38°C, and 70.64°C. Simulation and experimental validation on three air speed variations can be seen in Figure 4. The MAPE values for the three air speed variations are 10.74, 10.12 and 12.72. The MAPE result is less than 20% showing that the forecasting model is good. Several factors cause differences between simulation data and experimental data. One of them is an environment that cannot be fully controlled. Heat losses in real systems, such as through conduction are not fully represented in simulation models which can lead to differences between simulation results and experimental data. Based on the validation results with a MAPE of 12.72%, the numerical model in this research can be used for theoretical studies on the effect of air speed on heat exchanger effectiveness.

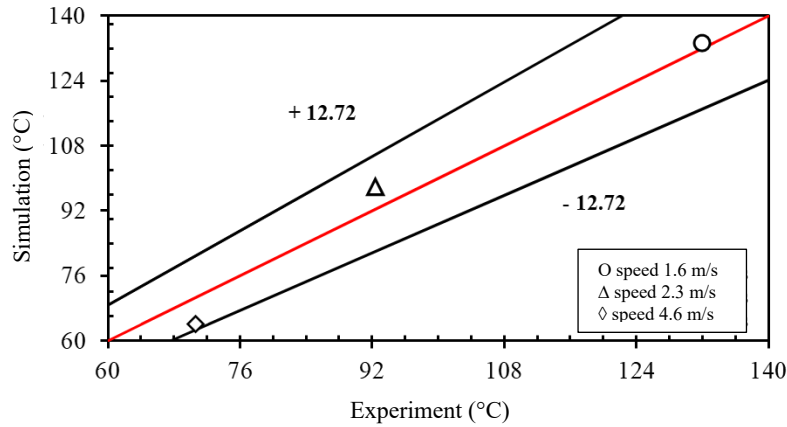


Figure 4. Simulation and experimental validation

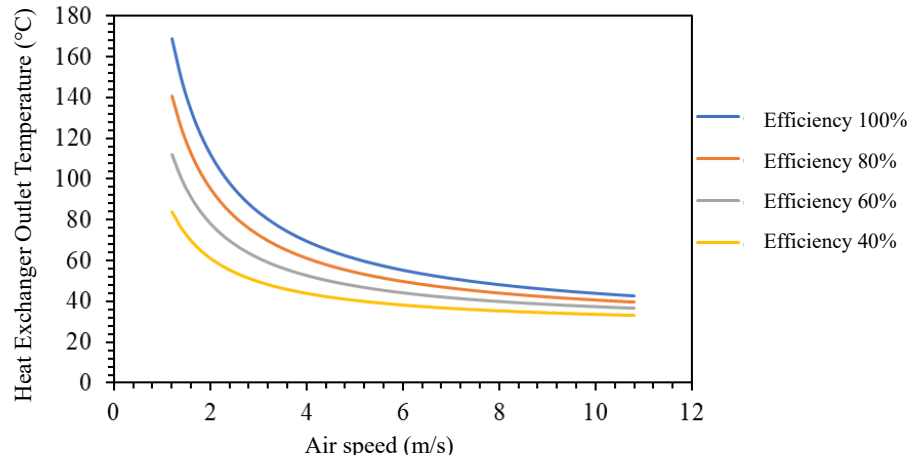


Figure 5. Relationship between heat exchanger outlet temperature and air speed

3.2. Effect of Air Speed on Heat Exchanger Outlet Temperature

The highest temperature coming out of the heat exchanger was produced at an air speed of 1.2 m/s of 169°C and the lowest was produced at an air speed of 10.8 m/s of 42.8°C at 100% efficiency. As air speed increases, the temperature decreases as in Figure 5. When air speed continues to increase, there is a phenomenon called forced convection boundary layer separation. At higher air velocities, the hot boundary layer around the surface can separate or become more unstable, leading to lower thermal resistance.

Even though there is an increase in the mass flow rate at the heat exchanger surface, the increasing mass flow rate limits the contact time between the air and the surface, causing the exit air temperature to be lower. In [Hassan *et al*'s research \(2023\)](#) increasing the air speed in the heat exchanger causes a decrease in ΔT because when the air speed is high there is not enough time for the fluid for the heat exchange process, so the exit air temperature decreases. This is confirmed by [Wirawan's \(2016\)](#) research. The increasing air flow rate in the heating box causes the air speed to increase which affects the interaction between the air and the heating surface in the heat exchanger. This increase in air speed causes the amount of air to absorb heat to be greater, but in a short time of contact it is only able to absorb a smaller amount of heat in each interaction. The resulting temperature greatly influences the heat transfer rate and effectiveness of the heat exchanger.

3.3. Effect of Air Speed on Heat Exchanger Effectiveness

The effect of air speed on the effectiveness of a heat exchanger is closely related to the exit temperature and the mass flow rate of the cold fluid. Increasing the air speed in the heat exchanger can result in a decrease in the temperature of the exiting air. This phenomenon can be explained by several factors, including the influence of air mass speed. When the temperature of the incoming hot fluid has a high value, the temperature difference between the hot fluid and the cooling fluid also tends to be greater. This temperature difference plays a key role in the heat exchange process, where the greater the temperature difference, the greater the potential for heat transfer between the two fluids.

The temperature of the fluid entering the heat exchanger is a relevant factor in increasing the effectiveness of the heat exchanger (Robiyanyusra *et al.*, 2021). This is reinforced by Soegijarto & Arsana (2021), where varying fluid temperatures of 60°C, 70°C, and 80°C in shell-and-tube type heat exchangers, and the lowest effectiveness was obtained at a temperature of 60°C, namely 40% and the highest effectiveness at a temperature of 80°C, namely 50%.

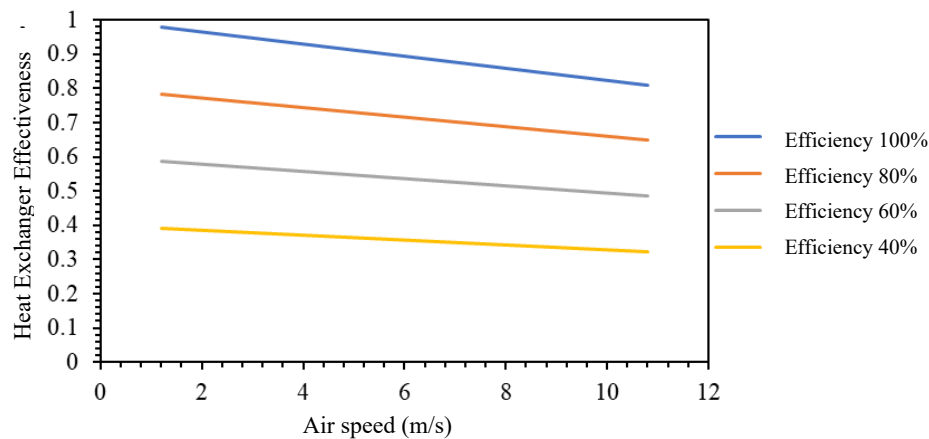


Figure 6. Effect of air speed on heat exchanger effectiveness

The increase in air speed is also related to the speed of the air mass. The higher the air speed, the more the air mass increases. The higher mass rate of the cold fluid compared to the mass rate of the hot fluid causes a decrease in the effectiveness of the heat exchanger because the higher mass rate of cold air flows more quickly through the heat exchanger, reducing the contact time with the hot flue gas. Increasing the cold fluid mass flow rate above the hot fluid mass flow rate will reduce performance (Raghulnath *et al.*, 2021). It can be seen in Figure 6, the highest heat exchanger effectiveness is at the lowest air speed, namely 1.2 m/s with an effectiveness of 0.9. Meanwhile, the lowest effectiveness lies at the lowest air speed, namely 10.98 with an effectiveness of 0.8 at 100% efficiency. A decrease in heat transfer efficiency indicates that heat is lost to the environment so that the actual heat energy is smaller than the quantity of heat possessed by the hot fluid. Apart from that, the reduction in efficiency in the heat exchanger is also influenced by the pressure drop, heat transfer coefficient, fluid mass flow rate, and the level of dirt in the heat exchanger (Prabaswara *et al.*, 2021). Pressure drop is one of the most important factors that influences the work efficiency of a heat exchanger (Shabab & Wahyuningsi, 2023).

3.4. Effect of Air Speed on the Mass of Evaporated Water

The heat potential in the drying process must be in accordance with the target moisture content of the material to be dried. Heat will enter the drying chamber to evaporate the water mass in the material. It is important to pay attention to the heat distribution during drying, there is an inverse relationship between air speed and the mass of water vapor in the material which can be seen in Figure 7. The decrease in the mass of water vapor in the material with increasing air velocity in drying can be explained by a number of factors, including the efficiency of the heat exchanger and the temperature changes that occur in the process.

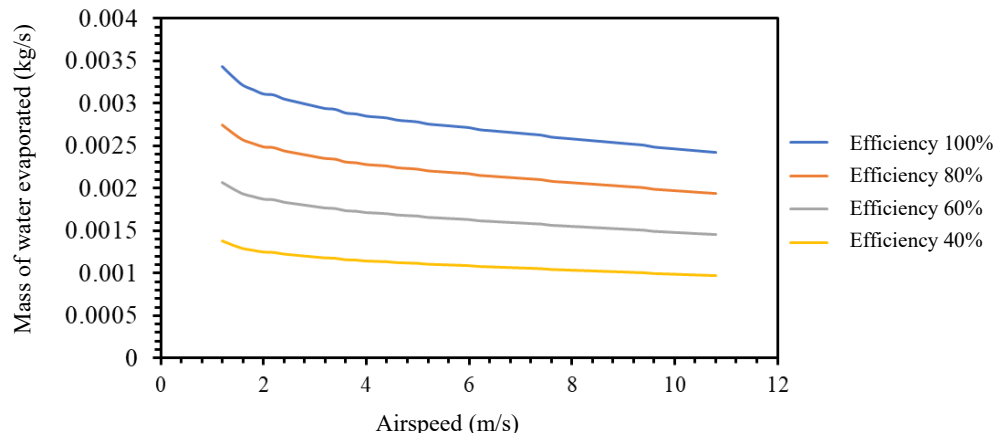


Figure 7. Effect of air speed on the mass of evaporated water

The higher the air speed, the less heat distributed to the dried material. This is confirmed in the research of [Kusuma et al. \(2019\)](#), significant heat losses in the drying process are caused by increased air in the drying room. High air velocity is the main factor, causing heat to be lost quickly into the environment. Disturbed heat distribution, most of the heat energy is not absorbed by the material and is wasted into the atmosphere.

Air speed 1.2 m/s, more efficient heat transfer can produce higher temperature around the material. Higher temperatures can increase the material's ability to release water vapor, so that the amount of water vapor evaporated becomes greater. An air speed of 10.8 m/s means an increase in the rate of heat transfer, lower temperatures can occur due to shorter contact between the air and the material. Lower temperatures can limit the material's ability to release water vapor, so that less water is evaporated and the water content in the material is still high. This statement is strengthened in the research of [Syahrul et al. \(2016\)](#). A drying temperature of 95°C produces a water content of 6.52%, the highest water content of cocoa shell powder is at a drying temperature of 65°C, namely 11.07%. Another study tested temperature variations of 50°C, 60°C, and 70°C, increasing the drying temperature caused an increase in the rate of water evaporation from the material. This higher drying temperature accelerates the reduction of the amount of water vapor in the drying chamber through the evaporation process ([Lestari & Samsuar, 2023](#)). Research by [Isworo & Nuraisyah \(2021\)](#), the water content in bage fish at 50°C is 56.33%, while at 60°C the water content is 28.41%.

3.5. Effect of Speed on Drying Time

The increase in air speed is related to the heat exchanger outlet temperature. An increase in air velocity results in a decrease in outlet temperature which will be transferred to the dryer. Increasing the drying air temperature causes the air to carry more heat, so that more water is evaporated from the surface of the material ([Manfaati et al., 2019](#)). By decreasing the heat exchanger outlet temperature, the heat produced decreases so that the drying time increases. In research by [Syamsuri et al. \(2023\)](#) using three variations of air speed, 3 m/s, 4 m/s and 5 m/s, the highest convection process was at the fluid inlet speed, namely 3 m/s. The heat transfer process when the air is low occurs over a long period of time, so that the temperature of the air entering the dryer will be higher. Hot air at low speed has a long time to transfer heat. The amount of heat transferred becomes higher.

This increase in air speed is also related to the heat transfer rate (kJ/s). This phenomenon can be explained by changes in the air flow characteristics of the heat exchanger, where the higher the air velocity, the thermal resistance in the system can increase, reducing the heat transfer efficiency. A decrease in the heat transfer rate in the heat exchanger causes a shortage of heat energy for drying needs which causes the drying time to be longer as in Table 2. This is because the heat transfer rate plays a key role in the drying process, affecting the system's ability to transfer heat to the material and evaporate the material's moisture content. A decrease in the heat transfer rate results in limited heat energy to evaporate water from the material.

Table 2. Effect of air speed on the drying time

Efficiency (%)	Airspeed (m/s)	Heat transfer rate (kJ/s)	Drying Time 60 kg sawdust (h)
100	1.2	7.04	1.02
	3.8	6.71	1.07
	10.8	5.85	1.23
80	1.2	5.63	1.28
	3.8	5.37	1.34
	10.8	4.6	1.54
60	1.2	4.22	1.7
	3.8	5.37	1.78
	10.8	3.51	2.05
40	1.2	2.81	2.55
	3.8	4.03	2.68
	10.8	2.34	3.077

4. CONCLUSION

Increasing the air speed in the heat exchanger causes a decrease in the air temperature leaving the heat exchanger, the mass of water vapor, and the effectiveness of the heat exchanger. Decreasing temperature and increasing mass flow rate reduce the effectiveness of the heat exchanger. A decrease in the effectiveness of the heat exchanger can reduce the heat transfer required for drying, thereby causing the water mass rate of the material to decrease and the drying time to be longer. The higher efficiency can increase the heat transfer process to the drying chamber so that the mass of material water vapor increases and the drying time becomes shorter. Validation of simulations and experiments on the heat exchanger outlet temperature produces MAPE (Mean Absolute Percentage Error) < 20%, which means the forecasting model is good.

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