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Process Engineering Optimization and Validation of Measurement Parameters at The Biomass Drying Test Stand

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ABSTRACT

This research is motivated by the need for the efficiency of the biomass solid fuel drying process in existing dryer installations. This study aims to optimize the insulation on the primary and secondary sides of the spiral heat exchanger and validate the electrical power on the heater register and the heat flow measured by the system. The approach used was the application of a mixture of 25 ml ISO PUR K 760 and 100 ml ISO-PUR K760 Härter (ISO-ELEKTRA Elektrochemische Fabrik GmbH) and the comparison of thermal and electrical power results calculated using temperature difference data between the inlet and outlet of the heater register without readings in a PC regulator. Experiments were conducted with constant parameters, i.e. target temperature 50°C, fan power level 7, and compressor electricity consumption 541 W. This study proves that after sealing the spiral heat exchanger, there is an increase in energy consumption efficiency. In addition, the approach based on temperature difference in calculating heat power can improve the accuracy in observing energy in the biomass drying system.

INTRODUCTION

National strategic projects (PSN) in Merauke in Papua are infrastructure projects in the context of economic development, equitable development, local community welfare, and acceleration of multi-sector development in the region. Biomass Power Plant Potential for Renewable Energy Transition in South Papua Province, Indonesia (Martoyoede Satryo et al., 2024)This research also shows that the potential for bio pellet development in Merauke is very promising and can be realized through the participation and joint commitment of the government, local wood industry, and indigenous peoples. This is in line with pellets' role and the main challenges in their development globally. (Pradhan et al., 2018) In his study, he found that one of the challenges of pellet commercialization at the household scale is the availability of wood chip drying technologies such as heat registers and heat exchangers. Thus, this study not only introduces the technology of the electric dryer (Register Heater) and spiral heat exchanger but also provides additional knowledge in validating the thermal and electrical loads on the Register Heater and optimizing the spiral heat exchanger.

The drying process of solid fuels derived from biomass sources is electrically using heat registers. (Vorotinskienė, 2019) Examined the parameters contributing to sawdust drying in an oven dryer with four moving drying boards. The results of his study indicated that the drying of wood in the top layer is more influenced by radiation from the surface of the heat source. In addition, hot air convection, infrared, and a combination system can be used to optimize the biomass drying process (EL-Mesery, 2019). This study shows that the combination of infrared and convection hot air at 60°C, 0.3 W/cm^2, and 0.5 m/s is the optimum condition for the drying efficiency of biomass with high water concentration. (Mason et al., 2015) examined the UK's transition to a decarbonized electricity sector by 2050, which relies heavily on converting existing coal-based pulverized fuel plants. The combustion behavior of solid biomass fuels must match the original plant design. Detailed measurements of the individual particles of various fuels were conducted to improve boiler plant adaptation and design. Typical power plant biomass fuels, including pine, eucalyptus, and willow, were investigated with ignition delay measurements, volatile matter burning time, and char burning time. Empirical expressions for each combustion stage have been derived and validated.

Spiral heat exchanger optimization opportunities include selecting a spiral cross-section channel capable of meeting optimum velocity, automatically minimizing scraping in the spiral chamber, minimizing pressure drop, reducing materials, and improving heat transfer efficiency. (Nithin, 2024) Comprehensively examined the opportunities, challenges, and circumstances of heat exchanger pipes with the potential for high heat flux. The research focuses on flexible heat pipes that are efficient in heat transfer, recovery, and regenerative configurations. This research underscores the selection of the operating fluid and the selected load, which significantly affect the performance of flexible heat pipes. (Anwajler, 2024) Examined 3D printing to optimize heat transfer in heat exchangers. This research emphasizes lightweight and efficient solutions by using waste in manufacturing to reduce energy consumption and carbon emissions. (Ibrić et al., 2024) Also, the simultaneous optimization of the work network and heat exchange was introduced. After being identified in the model, the heat and cold flows were reduced with a two-strategy approach of initialization and design. The results of this study propose integrating the modified superstructure heat transfer network and the minimum network total price per year.

Several methods, including orbital welding, manual, automatic, and hybrid methods, do heat transfer welding. (Adamiec & Urbańczyk, 2023) Their research on finned tubes used in heat transfer concluded that laser welding is better recommended than MAG welding. Then (Chu & Wang, 2017) in research on welding quality inspection systems for selltube heat exchangers, the image algorithm has high precision, strong resistance, and can accurately detect defects. Besides that, (Mortean et al., 2016) examined the development of diffusion-welded compact heat exchanger technology, whose results showed that the comb-like stack of plate layers joined together with flat plates was the most promising fabrication technology, which was used to make copper prototypes that were tested using water as a hot and cold liquid. And finally, (Saffiudeen et al., 2022) In their comparative study on carbon steel-stainless steel, stainless steel-stainless steel, and alloy steel-alloy steel material combinations, they were first tested in the laboratory as criteria for experimentation. The study proposed using current I, voltage V, and walking speed (mm/sec) to qualify.

Experimentally and numerically, mechanical, thermodynamic, fluid dynamic and chemical aspects can be analysed and assessed. Heat transfer devices can be analyzed and tested by measuring the dimensions of heat transfer pipes, energy equilibrium, overall heat transfer, radiator effectiveness, and fluid temperature differences in incoming and outgoing energy. (Bae et al., 2019) Conducted an evaluation study on the thermal performance of various heat exchangers using the same conditioning and testing. In the study, 4 heat exchangers were built and measured for inlet and outlet temperatures, thermal resistance, and boreholes. The study's results on the Thermal Response Test (TRT) showed that the average borehole thermal resistance is a crucial factor in TRT, where the effectiveness of the pipe material's thermal conductivity is insignificant. The following, (Aghaei, 2023) Examined the fluid flow in nanothermal oil/γ-AlOOH Syltherm 800 in two phases and heat transfer in a shell and tube heat exchanger insulated with corrugated helical tubes. The recommended configuration is with a performance evaluation criterion of 9.32. (Bagherzadeh et al., 2017) numerically investigated convective heat transfer in nanofluids present in a helically twisted pipe. The study was conducted at a constant temperature and flux. With a volume of 0.2% Water/CuO and 0.003% Water/Ag at the boundary conditions, this model better fits the experiment than the homogeneous model.

The objectives of this study were, first, sealing the primary and secondary sides of the spiral heat exchanger and adjusting the volume flow based on the temperature difference ΔT through the heating register. Optimization through sealing of the spiral heat exchanger is very important because the device is constructively welded from the outside. So, sealing is done to minimize the possibility of leakage inside the surface of the spiral heat exchanger. In this heat exchanger optimization, leakage-related issues must be addressed to reduce thermal losses. Thus, the spiral heat exchanger can make the heat loss recovery more efficient. Secondly, volume flow adjustment through the temperature difference by the heater is achieved so that the heater's electric power can be mathematically recognized. In contrast, until now, only the total power was detected and displayed on the regulator screen. Therefore, in this laboratory project, a new calculation concept had to be developed to calculate the corresponding power of the heater register. The power calculation of the register heater itself is only calculated based on the temperature difference because the manufacturer already integrates the thermoelement into the heater.

RESEARCH METHODS

From September to December 2024, experimental research on optimizing the efficiency of the biomass solid fuel dryer was carried out in the laboratory of the Department of Mechanical Engineering, Cenderawasih University.

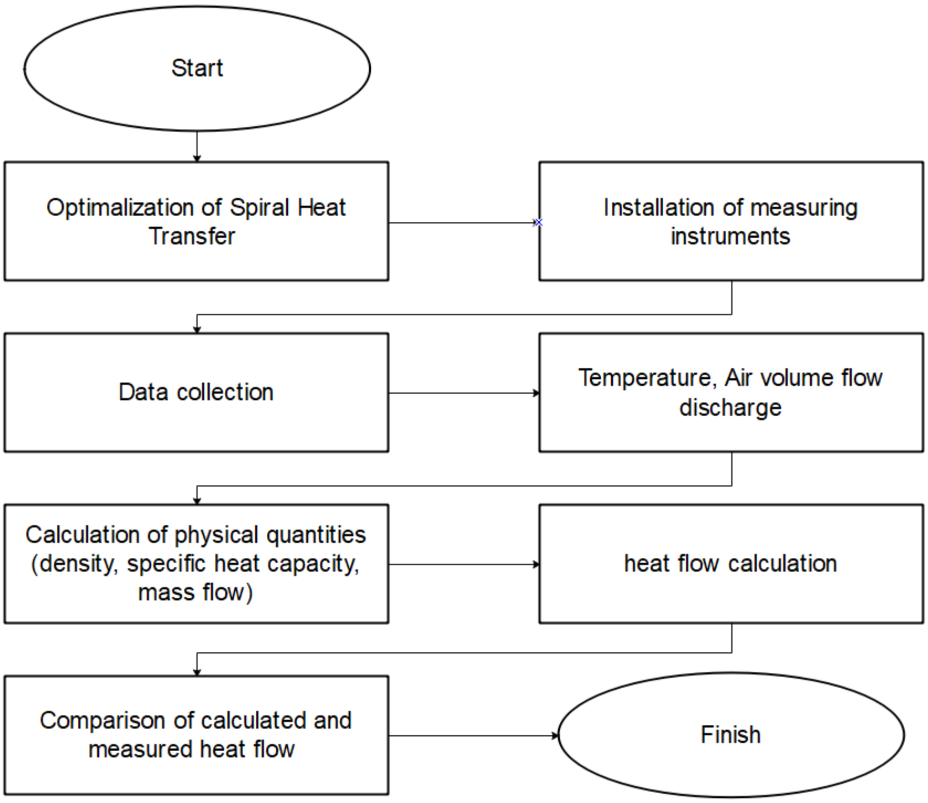

Figure 1. Research flow

In this study, four activities were carried out: optimization of spiral heat transfer equipment, installation of measuring devices, data collection and management, calculation of the heat balance of energy flow in the air, and comparison of calculated and measured heat flow in the system (see Fig. 1).

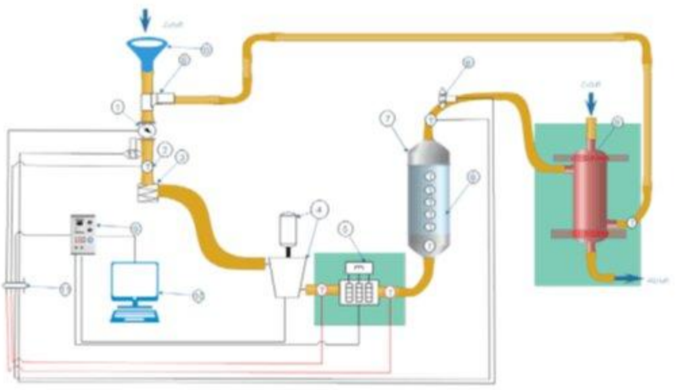

Figure 2. Schematic of Biopellet sawdust heating device + spiral heat exchanger

Figure 3. Spiral heat exchanger

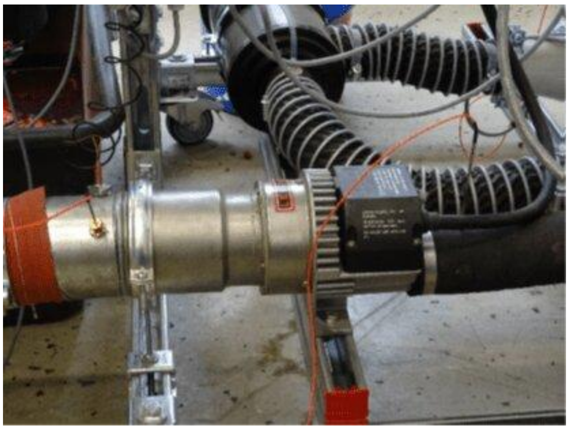

Figure 4. Heat Register

Table 1. Table Components of Biopellet wood dryer installation (see Fig. 1)

No.	Components	No.	Components
0	Air inlet trichter	6	Dryer Tube
1	Air volume flow meter	7	Air outlet trichter
2	Thermoelement	8	Inertia meter +Spiral heat transfer device
3	Air filter	9	Control box
4	Compressor	10	PC
5	Heat register	11	Cable terminal

The electric heat register (see Fig. 4) used in this study is the LE 5000 (H. J. Kretzschmar & Kraft, 2016) which serves to heat the air that will enter the drying tube. Furthemore to heat the air sucked in by the compressor before entering the heat register is a spiral heat transfer (see Fig. 2). The components that make up this installation can be seen in the schematic drawing in Table 1. Meanwhile, to seal possible leaks in the welds of the spiral heat transfer device (see Fig. 3), 25 ml ISO PUR K 760 and 100 ml ISO-PUR K760 Härter (Iso Elektra.de, 2025) were used. The two fluids were mixed and left to mix evenly for three minutes. Then, the mixed fluid was injected through 19 pre-drilled holes on the primary and secondary sides of the heat transfer device.

The measurement data taken is the inlet temperature T_{in} through signal 3505 and outlet temperature T_{out} through signal 3504 on the heat register. Then, signals 3303 and 3205 were installed to measure the total power Q_{tot} (heat register and compressor) and air volume. From signals 3302 and 3402, electrical voltage and initial air temperature signals are taken. The initial air temperature in the calculation is considered the same as the room temperature $T_R = 20°C$.

Data collection of heat-carrying fluid was carried out three times experimentally, starting with turning on the compressor, which was set at a rotating frequency of 7 with the initial fluid fan power at 541 W. The soil temperature was set at 50°C in the control box for the heat register. After sitting on the computer, data collection was carried out, where data was taken through signal recording by measuring instruments installed in the installation, which were then recorded within a specific time frame. Data collection in experiment I was taken under conditions where the heat transfer device had not been optimized for 6 hours and 43 minutes. While Experiments I and II were both taken after optimizing the spiral heat transfer device in a time frame of 7 hours 12 minutes and 4 hours 39 minutes. In validating the heat transfer data, the spiral heat transfer optimization was carried out, the replacement of the connecting pipe before the thermocouple with signal 3505, and finally, the positioning of the thermocouple to the third barrel (pressed deeper than the top). The measuring parameters selected in this research are based on the research objectives, where the heat flow measured by the system will be validated, which is calculated using the energy balance equation in a single phase, namely gas (air). Thus, temperature, fluid flow, and measurement time were selected.

First, calculate the pressure difference Δp in Pa with signal 3302 using linear equation (1) from the five installed experimental signal data. This signal works in the range of 0.25–4 volts, where no electrical energy flows at a voltage of 0.25 volts.

$$\Delta p = \frac{125 \cdot ("3302" - 0{,}25)}{3{,}75} \tag{1}$$

Then the air flow $\dot{V}_u$ in (l/s) is calculated by the equation Lin-Dab Software gives (2).

$$\dot{V}_u = 125 \cdot \sqrt{\Delta p} \tag{2}$$

Followed by calculating the total power $\dot{Q}_{Total}$ in measured on the 3305 signal in (mA) using the linear equation (3).

$$\dot{Q}_{Total} = 0{,}8125 \cdot "3305" - 3{,}25\sqrt{\Delta p} \tag{3}$$

In the calculation of the thermal energy flow of the Heat Registers $\dot{Q}_{ther,RP}$ using the first thermodynamic law (H. J. Kretzschmar & Kraft, 2016). The thermal energy in the heating register is assumed to be equal to the electrical power of the heat register, as in equation (4). This study does not consider pressure changes that result in temperature changes and produce thermal energy changes in the air. It is assumed that the electric flow in the register is directly converted to heat flow $Q_{ther,RP}$.

$$\dot{Q}_{ther,RP} = P_{elek,RP} = \dot{m}_u \cdot c_{pm,u}\Big|_{T_{in}}^{T_{out}} \cdot (T_{out} - T_{in}) \tag{4}$$

The average specific heat capacity $c_{pm,u}\Big|_{T_{in}}^{T_{out}}$ can be calculated using the following equation (5)..

$$c_{pm,u}\Big|_{T_{in}}^{T_{out}} = \frac{c_{pm,u}\Big|_{T_0}^{T_{out}} - c_{pm,u}\Big|_{T_0}^{T_{in}}}{T_{out} - T_{in}} \tag{5}$$

The determination of the average specific heat capacity $c_{pm,u}\Big|_{T_0}^{T_{out}}$ and $c_{pm,u}\Big|_{T_0}^{T_{in}}$ d can be seen in the thermodynamic table as an ideal gas (Meinert, 2023) r through calculation. The mass flow $\dot{m}_u$ in (kg/s) can be calculated using the following equation (6).

$$\dot{m}_u = \rho_u \cdot \dot{V}_u \tag{6}$$

Where $\dot{m}_u$ air mass flow, $\rho_u = \frac{1}{v} = f(T)$ air density. v is the specific volume of air (H.-J. Kretzschmar & Wagner, 2019).

The concept of energy equilibrium in the heat register consists of energy entering the system, namely heat energy from the compressor $\dot{Q}_{L1}$ and electrical energy received by the heat register P_{elek} and energy leaving the system is heat energy released by the heat register $\dot{Q}_{L2}$.

The total amount of electrical energy converted to mechanical energy for the compressor, heat energy for the heat register, and the control box can be calculated by equation (3), which can be formulated through the following equation (7).

$$\dot{Q}_{tot} = P_{elek,RP} + P_{elek,KB} + P_{Kom} \tag{6}$$

The control box and compressor's electrical power has a maximum operational power of 9 W and 541 W, respectively, but this does not significantly affect data analysis.

RESULTS AND DISCUSSION

The data collection that has been carried out is then analyzed on the measured, calculated heat flow, and the entry temperature in the heat register. The comparison of the amount of heat flow and temperature characteristics on the signal 3505, which tends to rise, indicates a significant improvement in the spiral heat transfer seen in the three experiments below.

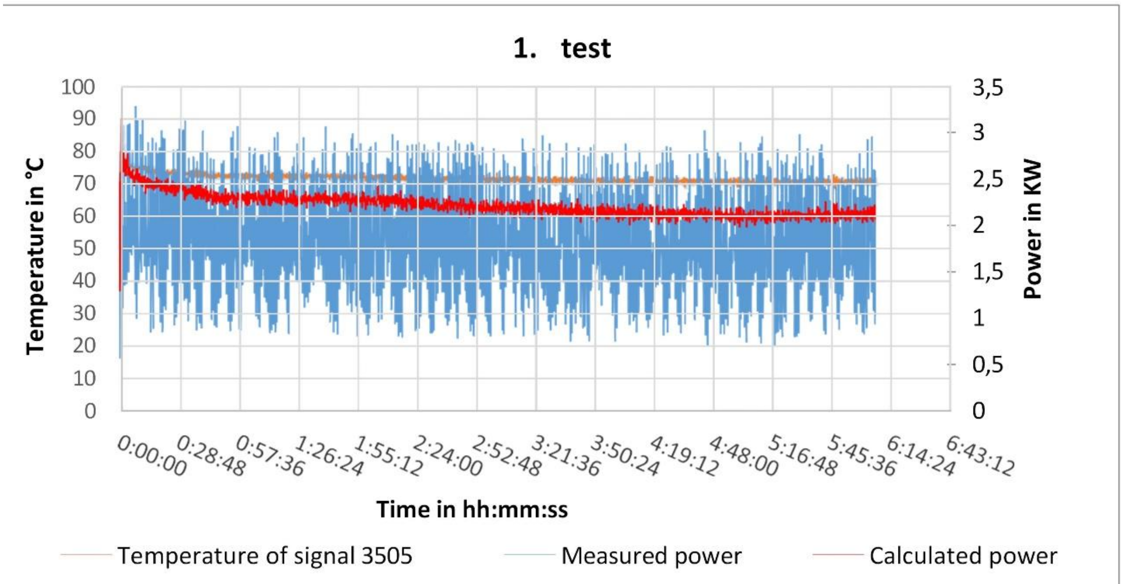

Figure 5. Experiment I in measuring the initial temperature (signal 3505), Power measured and calculated

Data collection for the first test (see Fig. 5) was performed by setting the fan speed on scale 7 with a target temperature of 50 °C. The essential parameters measured in this experiment were the total power, the inlet and outlet temperatures of the heater, and the volume flow of air sucked in by the compressor. The first test data collection time was 6 hours, 8 minutes, and 30 seconds, during which it can be seen that the measured and calculated power graphs are almost parallel, meaning that the calculation with thermodynamic law I is pretty correct. his approach was also taken by (Vogt et al., 2022), who measured forced convection in an air heating installation and found that calculations using the thermodynamic law provided good accuracy in estimating energy use.

This first experiment, when viewed from the aspect of the energy efficiency of electric heaters, aligns with the research (Markov et al., 2019), which studied the efficiency of electric heaters in industrial ventilation systems when compared from the perspective of temperature and power entering the system. The result is a decrease in efficiency caused by the high target temperature. This phenomenon parallels the power supplied by the heater to the heat-carrying fluid in this experiment, which tends to be stable and continuous after some time. Based on the research by (Ali et al., 2024), the study emphasizes that heat loss in a system occurs through radiation and conduction; therefore, this experiment needs further investigation to consider the possibility of heat leakage that can be detected from the system.

In the study (Huh & Brandemuehl, 2008), the efficiency of electric heaters can be influenced by airflow velocity, the thermal resistance of the heating materials, and the method of heat distribution. In this first experiment, the airspeed was set at the compressor, which also became a factor that affected the heat transfer rate in the heating register. Therefore, optimizing the air flow rate can also potentially improve heating efficiency. This study is also in line with the research conducted by (Vega-Galvez et al., 2024) which compared heating based on natural convection and forced convection in an industrial drying process, concluding that heating with forced convection is more uniform and energy use is more optimal.

From the measurement accuracy in this experiment, the thermocouple sensor is used to measure the air temperature before and after passing through the heating register. Thermocouple sensors do not require sensor calibration during data collection because they are considered to have sufficiently accurate reliability. In addition, it has a slight deviation over a wide temperature range. In addition, thermocouple sensors are more stable within the laboratory working range (Kim et al., 2022).

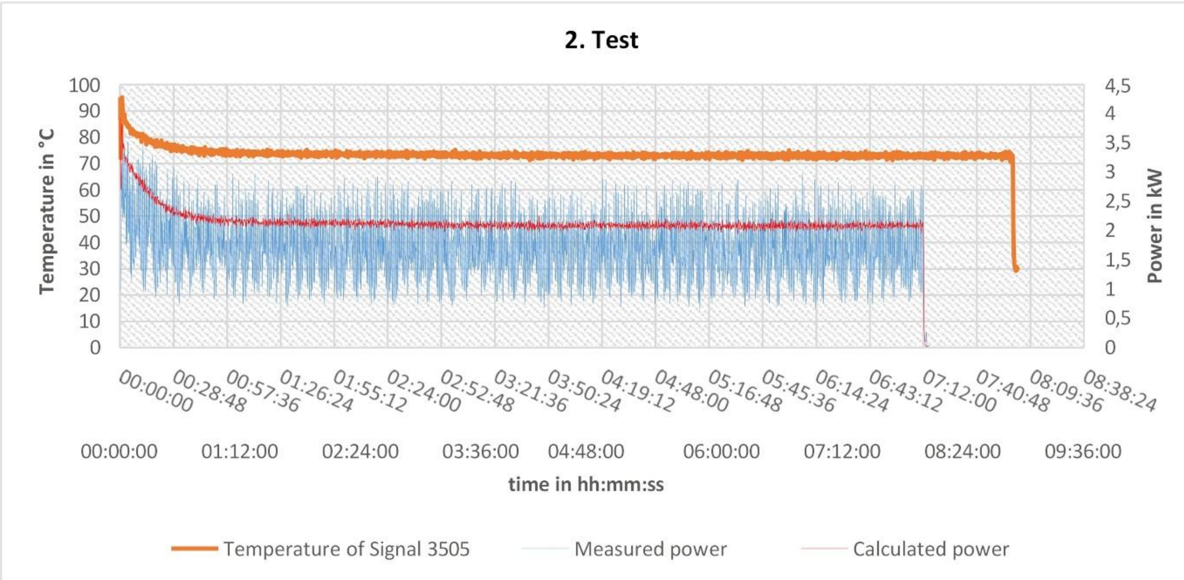

Figure 6. Experiment II in the measurement of initial temperature (signal 3505), Power measured and calculated

The second experiment (see Fig. 6) was conducted with the same parameters as the first. The duration of the experiment was 8 hours and 10 minutes. Besides the temperature, the average power in this experiment is 1.66 kW, which tends to decrease at the beginning and stabilize at the end. This phenomenon is certainly influenced by uneven heat distribution and unaccounted energy loss in the heating register. The graph shows that the calculated power exceeds the measured power, indicating unaccounted heat loss. In this experiment, although the operating parameters were the same as in the first experiment, the different power trends indicate that there are other factors, such as scintillation, environmental factors, or changing heater conditions. Power stability started initially compared to the initial experiment, indicating that heat distribution could be further optimized in the following experiment. The temperature before entering the heat register in this experiment was 74 °C, which is better than the first experiment, where it was done before sealing the primary and secondary sides.

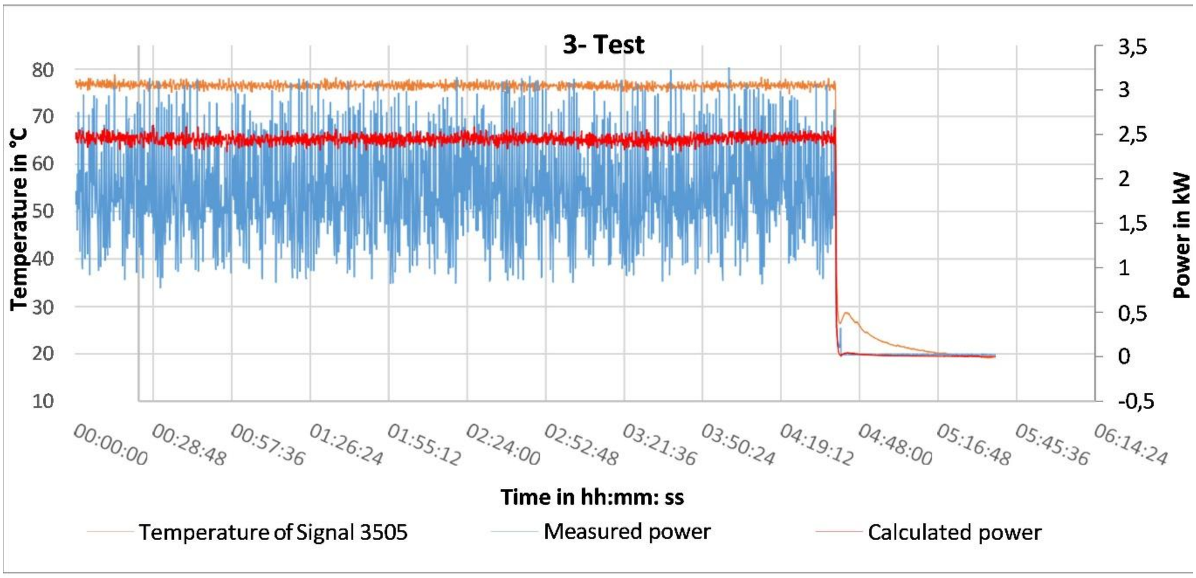

Figure 7. Experiment III in the measurement of initial temperature (signal 3505), Power measured and calculated

The average temperature of the 3505 signal was 76°C, which was better than the second attempt. The third experiment (Fig. 7) was conducted with the same parameters as the first and second experiments. However, the interval was 5 hours and 38 minutes, which was more precise than the two previous experiments. Even so, the average power generated is 1.82 kW, more significant than the second experiment (1.66 kW). The power calculations show that the calculated power is greater than the power consumed, which means there is an imperfection in heat distribution or heat loss within the system. From this experiment, it can also be seen that the airflow after the heater register is laminar, causing the heat distribution to be uneven in order to maximize efficiency. Therefore, optimizing air flow and installing thermal insulation on the hot register are crucial. In addition, the addition of fans or specially designed ducting to increase air turbulence and temperature uniformity becomes important. The average temperature of signal 3505 is 76°C, or better than the second experiment.

CONCLUSION

Based on the research objectives that focus on the optimization and validation of measurement parameters in the Biomass fuel drying system, with aspects of measuring thermal power through temperature differences in the heater register and the primary and secondary sealing sides of the spiral heat exchanger to enhance temperature, two conclusions are drawn. First, with three experiments conducted with the same initial parameters but taken over different periods, the calculated average power output differed, 1.66 kW and 1.82 kW in the second and third experiments. However, the heat distribution after the air passes through the heating register is uneven due to the high temperature differences that tend to cause laminar air flow. Therefore, as an alternative solution, it is recommended to use a DN 100 pipe with an internal fan to create turbulent airflow. Secondly, after sealing using a mixture of ISO-PUR K760 with a ratio of 4:1 injected through holes spaced 7.4 cm apart on the Primary and Secondary sides of the spiral heat exchanger to minimize the potential for leaks on the welding side performed from the outside, there is an increase in heat transfer efficiency, which can be observed through the inlet temperature with a signal of 3505 rising by 3-5 °C. In principle, this research successfully optimized the system's efficiency through better sealing. This provides a good initial input for biomass dryer technology developers to be more efficient and economical. Further implementation is expected to focus more on optimizing air velocity. Improvement of thermal insulation and sensor validation.

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