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Analysis of Grain Drying Using the Pressure the Flow of Air Heat Forced Convection Method

Peter Sahupala, Reinyelda D. Latuheru*

Department of Mechanical Engineering, Musamus University, Merauke-South Papua 99610, Indonesia

Corresponding Author Email: latuheru@unmus.ac.id

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ABSTRACT

Farmers in Merauke traditionally dry rice using an old method, which involves spreading the grains in an open field under the hot sun. This drying process can take up to 14 days and sometimes requires additional labor for assistance. The research focuses on designing a rice grain dryer that utilizes the pressure of hot air or gas generated from the combustion process in a furnace. The objectives include developing an effective grain drying system, employing the Pressure Flow Heat Forced Convection method as the air heating mechanism for the drying chamber, determining the moisture content reduction percentage using both free and forced convection over the drying period, and calculating the efficiency of the forced convection drying system. The analysis revealed that heat transfer within the hot air/fluid section of the pipe occurred at a temperature of 375 K, with a convective heat transfer coefficient outside the pipe of 10.2251 W/m²·°C. This resulted in a straight heat transfer rate of 84.87461 W/m²·°C. At a motor rotation speed of 1725 rpm, the moisture content in 12,000 kg of rice grain was reduced by 11%, calculated as follows: initial moisture content of 25% minus the target of 14%.

1. INTRODUCTION

Rice production by Merauke farmers in the 2021 planting season is targeted to reach 141,764 tons of rice. The target of 141,764 tons of rice is the result of production during the Rendeng and double Anam or Gadu planting seasons managed independently by Merauke farmers. One of the key factors affecting rice quality is the significant impact of weather conditions on the rice drying process. Traditional drying methods, such as drying rice on the road or in open yards, are often ineffective in unfavorable weather. Although rice production in Merauke is currently abundant, improving its quality remains a critical challenge. To address this, in addition to the six rice drying units available in Merauke, although their current performance is less than optimal, efforts are being made to explore alternative drying methods that prioritize maintaining rice quality. Improving harvesting and post-harvest technology is a promising strategy to reduce yield losses and encourage production growth [1].

Historically, local farmers in Merauke have relied on traditional sun drying methods in open fields. Under ideal weather conditions, this process can be completed in less than 14 days. However, when field or yard space is insufficient, farmers often rely on external drying services to complete the process [2].

Dryer design that can help farmers dry agricultural products, especially rice. The drying device studied operates using a method that utilizes hot air pressure or gas produced from the combustion process in the furnace. Air from outside is drawn in by the blower, passes through the fire pipe in the furnace, and is then forced into the drying chamber. By optimizing this device, it is expected to achieve uniform dryness (water content) throughout the material. In addition, the use of this drying system aims to maximize the use of heat energy from the combustion furnace [3]. The goal to be achieved in this study is to increase the efficiency of the rice drying process using the Pressure The Flow of Air Heat Forced Convection (PFAHFC) technology method [4].

Drying of paddy is a crucial stage in the agricultural production chain, because it directly affects the quality of the harvest and its storage life. The traditional drying method, which is still commonly used by farmers in Wonorejo Village, Kurik District, Merauke, relies on direct sunlight exposure, with the paddy spread on a drying floor or tarpaulin. Although this method is cheap and does not require special equipment, there are several major obstacles faced, namely dependence on weather conditions - in the rainy season or when the weather is cloudy, the drying process takes longer, causing an increase in the water content of the paddy, which can trigger mold growth and reduce the quality of the harvest, uneven heat distribution - uneven exposure to sunlight causes an imbalance in the water content of the paddy, increasing the risk of damage during storage, Significant post-harvest losses - Drying in the open increases the risk of contamination by dust, dirt, and insect and animal attacks, which can cause a decrease in the quality and selling price of the paddy, limited drying capacity - on a larger production scale, traditional methods are unable to accommodate high harvest volumes effectively [5].

To overcome these obstacles, Pressure The Flow of Air Heat Forced Convection (PFAHFC) technology is applied, namely a forced convection-based drying system that utilizes pressurized hot air flow to optimize the drying process. This technology works by heating the air and flowing it convectively through the drying chamber, resulting in faster, more efficient, and uniform drying.

Several previous studies have developed various mechanical drying methods to improve the efficiency and quality of grain between drying with natural hot air - Some systems use hot air from biomass combustion or solar energy to increase the temperature of the drying environment [6], however, this method still faces obstacles in temperature control and heat distribution efficiency. Fluidization-based drying technology - This system relies on the principle of lifting grain by air flow to accelerate the drying process [7], although efficient in reducing water content, this system requires high energy and is not economical for small-scale farmers. Fan and heater-based forced convection system - This technology has been applied in various studies, showing that the use of fans to maximize heat transfer can increase drying efficiency by up to 60% compared to traditional methods [8], however, further studies are still needed regarding the optimization of air speed, temperature, and heat distribution. Using natural heat sources such as sunlight or biomass combustion to increase the temperature of the drying environment, shows that this method can speed up drying time by up to 30% compared to direct drying under the sun [9] the disadvantage is that the heat distribution is not uniform and less efficient on a large scale. Forced Convection Drying This technology uses a fan to maximize heat transfer, so that hot air can move faster and evenly throughout the grain [10] the disadvantage Requires additional energy sources, such as electricity or fuel, so there are operational costs to consider.

The main innovation of this research is the use of forced convection with controlled air pressure, so that the drying process can be more efficient and even. Based on initial research, this technology is able to reduce water content by 12% -14% in a faster time than other methods, increase energy efficiency by utilizing a more optimal hot air circulation system, reduce post-harvest loss rates from 15% to below 3%. From the various methods that have been studied, it can be concluded that forced convection with controlled air pressure (PFAHFC) is the most efficient approach [5].

Unlike conventional drying technologies that have been developed previously, the innovation in this research involves optimizing hot air flow with a controlled pressure system to ensure uniform heat distribution throughout the grain, increasing energy efficiency through the use of a more stable heat source, thereby reducing operational costs, integration of temperature and humidity monitoring systems, which allows more accurate control of the drying process, real-world application trials to measure the effectiveness of this technology compared to traditional methods. The application of Pressure The Flow of Air Heat Forced Convection (PFAHFC) technology can increase the efficiency of grain drying, reduce water content by 12% -14% in a shorter time, and produce higher quality grain with lower post-harvest loss rates compared to traditional methods. The objectives of the study were to analyze the effect of air velocity and heating temperature on drying efficiency in the PFAHFC system, compare the rate of grain moisture reduction between traditional methods and PFAHFC technology, measure the impact of implementing this technology on grain quality and the potential for increasing farmer income.

Pressure The Flow of Air Heat Forced Convection (PFAHFC) technology works based on the principle of forced convection heat transfer, where pressurized hot air is flowed through a pile of grain to reduce water content efficiently, in addition there are also supporting theories including the Law of thermodynamics plays a role in regulating temperature and air flow to ensure energy efficiency and stability of the drying process, Fluid aerodynamics theory is used to design air flow to be even and increase drying effectiveness. In its application, this post-harvest grain drying technology replaces traditional methods that depend on the weather, increases drying time efficiency by up to 70% compared to the sun drying method, reduces water content by up to 12%-14%, according to market quality standards, can be adapted for other commodities, such as corn and coffee beans, by adjusting temperature and air flow parameters.

In addition, there are challenges in the application of this technology, namely the need for electrical power for fans can be an obstacle for areas with limited access to electricity but can still be overcome by using solar cells, the initial installation cost is relatively higher than traditional methods, although more economical in the long term, maintenance and operations require training for farmers to be able to use and maintain the equipment properly and further testing is needed to adjust the optimal parameters in various environmental conditions and different types of rice [11].

The application of PFAHFC technology offers a modern solution to increase the efficiency of rice drying, but its implementation requires support in terms of energy access, initial investment costs, and technical training for users.

2. THEORETICAL BASIS

This research plan adopts the concept of forced convection to regulate the flow of heated air. The heat generated by combustion in the furnace is transferred to the air pipe inside the furnace. Using a blower, air is forcibly drawn through the heating pipe, where it is heated, and then directed to the heating chamber. The heating process involves conduction, convection, and radiation mechanisms as the air flows through the pipe. As the air heats up, its temperature increases, causing a decrease in density and an increase in velocity. The blower then pushes the hot air (or gas) into the heating chamber, where it is used to heat or dry the rice grains placed on the chamber. The rice grains are placed on an iron net located above the heating grid. The moisture in the rice grains is absorbed by the hot air or gas until it reaches a point where the density of the gas increases, causing a phase change. The blower installed at the top of the drying chamber discharges the moisture-laden gas into the atmosphere, while fresh hot air or gas is continuously forced into the heating chamber by the blower, maintaining circulation inside the drying chamber. This decrease in air density will cause air to flow from the drying chamber to the chimney.

Conduction is the process of heat transfer from a region of higher temperature to a region of lower temperature, occurring in one medium (solid, liquid, or gas) or across different media in direct contact [12]. In the conduction process, energy transfer occurs through direct interaction between molecules without significant movement of the molecules themselves. According to the kinetic theory, the temperature of a substance is directly related to the average kinetic energy of its molecules. Conduction is the only mechanism by which heat can be transferred in an opaque solid [13]. According to the second law of thermodynamics, heat naturally moves from a region of higher temperature to a region of lower temperature. Consequently, heat flow is considered positive when the temperature gradient is negative [14].

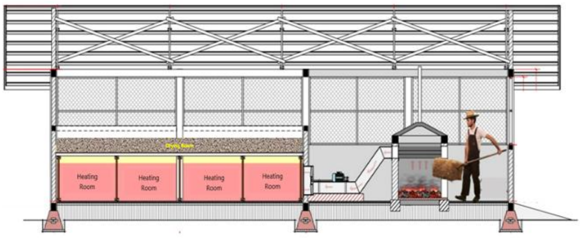

Figure 1. Installation of grain dryer using convection method

Convection is an energy transfer process that combines heat transfer, energy retention, and fluid agitation. It plays an important role as a mechanism for transferring energy across the surface of a solid material and the surrounding liquid or gas [15].

Energy transfer by convection from a surface with a higher temperature than the surrounding fluid involves several stages. Initially, heat is transferred by conduction from the surface to adjacent fluid particles. This energy transfer increases the temperature and energy of these fluid particles [16].

Convection heat transfer is categorized into two types: free convection and forced convection [17]. Free convection occurs when the fluid movement results only from the density difference caused by the temperature gradient. The greater the density difference, the faster the air flow, accelerating the drying process, as in Figure 1. On the other hand, forced convection occurs when the fluid movement is driven by an external device, such as a pump or fan [18]. The energy balance in the system can be calculated by considering several factors: heat from the flue gas entering the heating chamber (Q_{gbi}), heat absorbed in the grain drying chamber (Q_{abs}), heat escaping through the fan to the surrounding air (Q_{gbo}), heat lost through the walls of the heating chamber (Q_d), and total additional heat losses (Q_{losses}) [19].

1). Total heat from flue gas to the heating chamber

$$Q_{\mathrm{gbt}} = m_g \times \mathrm{C_{pg}} \times \mathrm{T_{gbt}} (\mathrm{kJ}) \tag{1}$$

2). The total heat from the flue gas is absorbed

$$Q_{\mathrm{abs}} = m_a \times \mathrm{C_{pa}} \times (T_s - T_a) + m_a \times \mathrm{h_{fg}} (\mathrm{kJ}) \tag{2}$$

3). The total heat of the flue gas goes to the heat exhaust fan to the environment

$$Q_{\mathrm{gbo}} = m_g \mathrm{x} \mathrm{Cp}_g \mathrm{x} \mathrm{T_{gbo}} (\mathrm{kJ}) \tag{3}$$

4). Other heat losses (losses)

$$Q_{gbt} = Q_{\mathrm{abs}} + Q_{\mathrm{gbo}} + Q_{\mathrm{losses}} \text{ (kJ)} \tag{4}$$

$$\mathrm{Q_{losses}} = \mathrm{Q_{gbt}} + \left(\mathrm{Q_{abs}} + \mathrm{Q_{gbo}}\right) (\mathrm{kJ}) \tag{5}$$

5). Exhaust gas mass flow rate

$$\dot{m}_g = \rho \times U_m \times A_i (\mathrm{kg/s}) \tag{6}$$

6). Reynolds number

$$R_n = \frac{G \times d_i}{\mu} \tag{7}$$

7). Nusselt numbers

$$N_u = \frac{h_o \times d_o}{k} = 5 + 0.016 \times {R_e}^a \times Pr^b \tag{8}$$

8). Overall heat transfer coefficient

$$h_i = \frac{N_u \times k}{d_o} W/_{m^2.\ ^oC} \tag{9}$$

9). Air section (hot fluid) outside the pipe

$$T_f = \frac{(T_{ui} + T_{uo})}{2} {}^\circ\mathrm{C} \tag{10}$$

10). Overall Heat Transfer Coefficient (*U*)

$$U = \frac{1}{\frac{d_o}{d_i h_o} + \frac{d_o}{2 \times k} \times \ln \frac{d_o}{d_i} + \frac{1}{h_i}} \mathrm{W/m^2.^\circ C} \tag{11}$$

11). Logarithmic Mean Temperature Difference (LMTD)

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} {}^\circ\mathrm{C} \tag{12}$$

12). Total heat transfer area

$$A_{tot} = \pi \times d_o \times L \times n (\mathrm{m^2}) \tag{13}$$

13). Total heat transfer in the heat exchanger

$$Q_{tot} = A_{tot} \times U \times LMTD \text{ (kJ/h)} \tag{14}$$

This drying system uses the principle of forced convection (Forced Convection Drying), where hot air is forced to flow through the pile of rice with the help of a fan. Hot air is produced from a biomass (rice husk) combustion furnace and is channeled into the drying chamber through an isolated air duct. The main principles of this design include:

1). Heating the air using a biomass-fueled furnace.

2). Even distribution of hot air with a fan and air duct system.

3). Control of temperature and humidity in the drying chamber.

4). High energy efficiency, with the use of rice husks as the main fuel.

Main components of the dryer installation and design parameters and technical calculations:

a. Furnace

i. Fuel: Rice husk or other biomass

ii. Combustion efficiency: 80%

iii. Fuel calorific value: 3,800 kCal/kg

iv. Burning capacity: 3 kg of husk/ton of grain

The combustion furnace uses rice husk or biomass fuel, temperature 450°C and is equipped with air heating pipes.

Calculation of the heat energy produced:

$$Q_{\mathrm{losses}} = Q_{\mathrm{gbt}} + \left(Q_{\mathrm{abs}} + Q_{\mathrm{gbo}}\right) (\mathrm{kJ})\ Q = m \times CV \tag{15}$$

where,

Q=total heat energy (Kcal)

m=mass of rice husk burned (kg)

CV=calorific value of rice husk (kCal/kg)

So we get:

Q=3 kg×3800 Kcal/kg=11400 Kcal

b. Hot Air Duct

i. Material: Heat-resistant steel plate

ii. Duct length: 4 meters

iii. Duct diameter: 0.3 meters

iv. Air velocity in the duct: 3 m/s

Centrifugal fan (blower) with 2 HP power to produce optimal air pressure, Air velocity 2-5 m/s, depending on the thickness of the grain pile, air distribution is equipped with ducting so that the air flow is evenly distributed throughout the grain layer.

Calculation of air flow rate:

$$Q_{air} = A x v \left(m^3 / s\right) \tag{16}$$

where,

Q_{air} =air flow rate (m³/s)

A =duct cross-sectional area (πr2)

υ=air velocity in the duct (m/s)

$Q_{air} = (\pi \times (0,15)^2 \times 3) = 0.21\, {m^3}/{s}$

c. Centrifugal Fan

i. Fan power (P): 1.5 kW

ii. Air flow velocity: 2-3.5 m/s

iii. Hot air discharge (Q): 0.21-0.3 m³/s

iv. Fan efficiency (η): 85%

Fan power calculation:

$$P = \frac{Q \times \Delta P}{\eta} (\text{Watt}) \tag{17}$$

$$P = \frac{0.25 \times 100}{0.85} = 29.4\, Watt$$

d. Drying Room

i. Capacity (Q): 12 tons of grain

ii. Dimensions of drying room: 6 m×3 m×2.5 m

iii. Initial grain moisture: 22%

iv. Final grain moisture: 12%

v. Inlet air temperature: 55-65℃

vi. Exit air temperature: 40-50℃

$$Q_{drying} = m \times Cp \times \Delta T (\text{Kcal}) \tag{18}$$

where,

Q_{drying}=total energy for drying (Kcal)

m=mass of grain dried (kg)

Cp=specific heat of grain (Kcal/kg℃)

ΔT=change in air temperature (℃)

Then obtained

Q_{drying}=12000×1.5×(65-30)=630000 Kcal

Energy Efficiency Analysis of drying is calculated as follows:

$$\eta = \frac{Q_{drying}}{Q_{input}} \tag{19}$$

$$\eta = \frac{630000}{760000} \times 100\% = 82.9\%$$

Drying efficiency reaches 82.9%, indicating optimal energy utilization. This system only requires 3kg of husk per ton of grain, making it fuel efficient. With optimal temperature and air velocity settings, moisture content can be reduced by up to 10% in 10 hours.

Estimated Drying Time Based on testing Drying from 30% moisture content to 12%-14% takes 6-8 hours at a temperature of 50°C and an air velocity of 3m/s. Drying is 70% faster than conventional methods, which usually take 2-3 days.

The advantages of the PFAHFC Dryer Design are that it is faster than natural drying, which takes 40 hours, energy efficient, with an efficiency of 82.9%, low operational costs, because it only uses husk as fuel and produces better quality grain, with a more stable moisture content.

The dryer design is designed to dry 12 tons of wet grain with high efficiency using a forced convection system. The following are the main parameters used as listed in Table 1.

Table 1. Dryer design parameters

Parameter	Symbol	Value	Unit	Description
Grain Capacity	M	12	ton	Amount of wet grain dried
Initial Water Content	MCi	22-24	%	Initial moisture content of grain after harvest
Final Water Content	MCf	12-14	%	Standard moisture content for storage
Hot Air Temperature	Th	50-80	℃	Heating air temperature from the furnace
Air Flow Speed	V	2-5	m/s	Air speed blown by the fan
Drying Time	t	6-8	jam	Drying time duration
Thermal Efficiency	η	75-85	%	Efficiency of the heating system
Energy Required	Q	-	kJ	Heat energy required
Fan Capacity	Pf	3-5	HP	Power of the blower/fan used
Furnace Capacity	Pt	150-200	kW	Heat power produced by the furnace

3. METHODOLOGY

This research involves designing a rice grain dryer using the Pressure Flow of Air Heat Forced Convection method. The drying room will be built with dimensions of 8 meters long and 4 meters wide, with a capacity to dry 12 tons of rice grain. This research is experimental and application, with research data analyzed using the principle of heat transfer, including conduction and convection methods [5].

This device is equipped with a blower that functions as a suction and pressure system, drawing hot air or gas from the pipe in the combustion furnace to the heating chamber and then directing it to the drying chamber. The absorption of heat generated from the combustion process in the furnace, it will provide heating to the air passing through it. The result of this heating, the air temperature rises so that its density decreases, smaller than the density of the air in the drying chamber.

This research uses an experimental method, by designing a rice grain drying installation using the forced convection method with air pressure flow for heating [5].

The installation covers an area of 4×8 meters and has a maximum capacity of 12 tons of wet rice grains. The structure consists of two levels: the lower level serves as a heating air chamber, while the upper level is intended to place wet rice grains. These levels are separated by wire mesh to allow hot air or gas from the lower chamber to flow upwards and heat or dry the rice grains above. The chamber is designed as a closed system to maintain the temperature of the hot air before it is released into the atmosphere through a chimney equipped with a blower. The setup also includes a heating furnace, equipped with a thermocouple, and a blower to direct the hot air efficiently to the heating chamber. The goal for the first year is to use the farmer's rice grain drying system while evaluating the performance of the drying installation. This will help identify any components that need to be improved to increase its efficiency and effectiveness [19].

4. RESULTS AND DISCUSSION

This study was conducted during the drying process twice to obtain more precise drying results. Before the drying process, the grain was weighed first with a weight of 12,000 kg.

After that, put it in the oven for the drying process. The moisture content of the grain before the drying process was 25% but after drying it decreased to 14%, this means that there was a decrease in water content of 11%.

This calculation was carried out under stable conditions with a blower rotation of 1725 rpm and the results of the study produced the following data:

a. Room temperature, (t_{Gi}): 30°C
b. Outlet Pipe Temperature, (Tp): 174°C
c. Combustion Chamber Temperature, (Tw): 450°C
d. Evaporator temperature, (Ta): 169°C
e. grain temperature, (tg): 38°C
f. Grain weight before drying: 12000 kg
g. Grain weight after drying (12 hours): 11621 kg
h. Heating pipe outer diameter, (do): 7.62 cm
i. Heating pipe inner diameter, (di): 7.42 cm
j. Blower rotation used (n): 1725 rpm

The results of the heat transfer process calculations can be seen in Table 2.

Weight measurements were taken at 90-minute intervals over a total drying duration of 720 minutes. The mass of the grain in the bottom layer decreased more rapidly because it received the hot gas flow initially, followed by the heat gradually rising to the top layer. To ensure uniform drying throughout the grain pile, stirring was carried out every four hours.

For this calculation, sample data were collected during a four-hour test period, with the blower operating at 1725 rpm. The drying process aimed to reduce the moisture content of the rice grains which initially reached 14%. Samples were taken from four points in each layer of the grain pile inside the drying chamber. It was observed that every 4.0 hours, the weight of the samples decreased by 0.04167 grams per hour. Based on these findings, the most significant weight loss occurred between 540 and 620 minutes, with a weight loss of 0.125 kg. From the initial 12,000 kg of wet grain, the drying process resulted in a final weight of 11,500 kg after 12 hours. For a 3 kg sample, 0.125 kg of water evaporated, leaving 2.875 kg of dry grain. Scaling this to the entire batch, the total amount of water evaporated is calculated as 0.125×(12,000 kg/3 kg)=500 kg. This shows that the heat used in the drying process is utilized effectively, achieving an efficiency of 71% for the rice drying system [5]. The heat transfer in the hot air/fluid area inside the pipe with a temperature of 375 K and the heat transfer coefficient with convection outside the pipe is 10.2251 W/m^2 °C so that the overall heat transfer of 84.87461W/m^2 °C is obtained.

The logarithmic mean temperature difference (LMTD) in the evaporator is 62.3725°C with a total heat transfer area of 5.2256 m^2. With a motor rotation of 1725 rpm, the total heat transfer achieved in the heat exchanger represents the maximum usable heat of 2.4191588 kW, with the effectiveness of the heat exchanger measured at 63.425%. The use of the Pressure Flow of Air Heat Forced Convection method not only helps the efficiency of rice drying, but also opens up opportunities for farmers in Merauke to diversify their crops. With fast, flexible, and energy-efficient drying, farmers can process various types of crops, increase production capacity, and create a more diverse, sustainable, and profitable agricultural system.

Table 2. Recapitulation of calculation results

No.	Calculation Parameters	The Calculation Results	Unit
	Gas Flow Within Pipes		
1.	Exhaust Gas Bulk Temperature	375	°C
2.	Mass Flow Rate of Exhaust Gas	0.14935	Kg/s
3.	Gas Mass Velocity	36,75	Kg/s.m^2
4.	Reynolds number	117132.6149	-
5.	Nusselt numbers	208.6273	-
6.	Overall Displacement Coefficient	84.87461	W/m^2. °C
	Hot Fluid Area Surrounding the Pipe		
7.	Hot fluid temperature	582.5	°C
8.	Reynolds number	1909.084746	-
9.	Nusslt numbers	17.3146	-
10.	Convection heat transfer coefficient	10.2251	W/m^2. °C
11.	Overall Heat Transfer Coefficient	7.42192	W/m^2. °C
12.	Average Logarithmic Temperature Difference	62.3752	°C
13	Overall heat transfer surface area	5.2256	m^2
14.	Total heat transfer in the heat axchanger	2.4191588	kW
15.	Heat exchanger effectiveness	0.552809	%

Table 3. Initial experimental data

Test	Hot Air Temperature (°C)	Air Velocity (m/s)	Initial Moisture Content (%)	Final Moisture Content (%)	Drying Time (Hours)	Thermal Efficiency (%)
1	55	2.5	24	14	8	72
2	60	3.0	24	14	7	74
3	65	3.5	24	14	6.5	76
4	70	4.0	24	14	6	78

Table 4. Comparison with traditional drying

Drying Method	Average Temperature (°C)	Air Velocity (m/s)	Drying Time (Hours)	Efficiency (%)
Conventional (Solar)	35-40	0.5	24-48	30-40
PFAHFC (New Technology)	55-70	2.5-4.0	6-8	72-78

The following is the initial experimental data obtained from testing the rice drying system using Pressure The Flow of Air Heat Forced Convection (PFAHFC) technology.

Based on the initial data in Table 3, sample data was then taken for traditional drying as a comparison material as shown in Table 4.

The following is a trend of changes in water content over time with variations in hot air temperature based on Table 3.

This graph shows that the higher the hot air temperature (°C), the shorter the time required for the drying process, at a temperature of 55°C, the drying time is around 8 hours, while at a temperature of 70°C, the drying time drops to 6 hours, This indicates that increasing the temperature accelerates the evaporation of moisture in the grain, making the drying process more efficient.

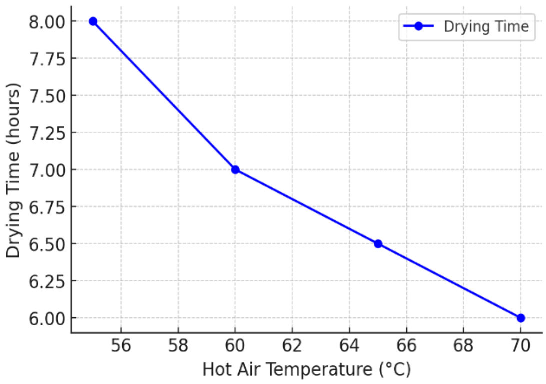

Figure 2. Relationship between hot air temperature and drying time

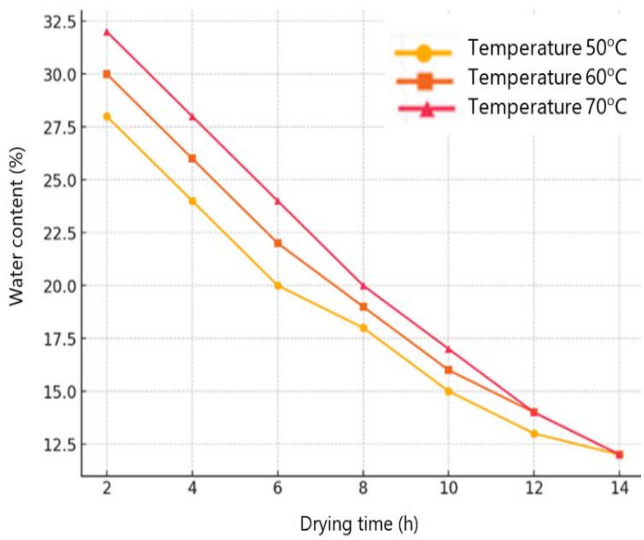

Figure 3. Relationship between water content and and drying time

Figure 2 and Figure 3 above show the effect of hot air temperature on the drying time of the grain. Additional data shows that the higher the temperature of the hot air used, the faster the water content in the grain decreases to reach the standard of 12%.

The fan speed in the grain drying system plays an important role in regulating the distribution of heat and humidity in the drying room. The higher the fan speed, the faster the hot air circulates, which can speed up the drying process. However, improper settings can cause energy inefficiency and decrease the quality of the grain [20].

The trial was conducted with three variations of fan speed:

a. Low (V1=2 m/s)

b. Medium (V2=4 m/s)

c. High (V3=6 m/s)

At each fan speed, the air temperature in the drying room and air humidity were measured every 30 minutes during the drying process. The target final moisture content of the grain is 12-14%.

Analysis and Interpretation based on Table 5 as follows:

1). Effect on temperature

a. The higher the fan speed, the higher the average temperature in the drying room.

b. At high speed (V3=6 m/s), the average temperature reaches 55°C, which accelerates the process of water evaporation from the grain.

2). Effect on humidity

a. The final humidity decreases faster with increasing fan speed.

b. At low speed (V1), air humidity remains high because the circulation of hot air is less than optimal.

3). Drying time efficiency

a. Higher fan speeds significantly reduce drying time.

b. The fastest drying occurs at V3 (6 m/s) with a time of 4.5 hours, compared to 8 hours at V1.

Higher fan speeds increase drying efficiency by accelerating the flow of hot air and reducing moisture more quickly. However, temperatures that are too high (>55°C) have the potential to damage the quality of the grain, so optimizing the fan speed setting needs to be done to achieve a balance between efficiency and quality. A fan speed of 4-5 m/s is recommended to maintain a balance between drying efficiency and grain quality. Further testing can be done by adding parameters such as energy consumption and post-drying grain quality. In the drying efficiency analysis, we will consider the energy input-output ratio to assess the extent to which the energy input into the system is used effectively in drying the grain. This ratio can be calculated using the thermal efficiency of the system, which measures how much energy is used to dry the grain compared to the energy required to increase the air temperature [21].

Table 5. Fan speed test results

Fan Speed (m/s)	Average Temperature (°C)	Final Humidity (%)	Drying Time (Hours)
V1=2 m/s	45°C	20%	8
V2=4 m/s	50°C	15%	6
V3=6 m/s	55°C	10%	4.5

The efficiency of drying paddy is greatly influenced by the ratio of energy used to the water content that can be removed in a certain time. This analysis aims to calculate the energy efficiency of a forced convection-based drying system by considering the energy input-output ratio and other metrics such as thermal efficiency, fuel consumption, and drying time [22]. The main parameters used in this calculation are:

a. Input Energy (Q_{in})

$$Q_{in} = m_{fuel} \times CV \tag{20}$$

where,
m_{fuel} =mass of fuel (kg)
CV =fuel calorific value (MJ/kg)
b. Energy Absorbed by Air (Q_{air})

$$Q_{air} = m_{air} \times Cpair \times \Delta T \tag{21}$$

where,
m_{air} =mass of heated air (kg)
Cp_{air} =specific heat of air (1.005 kJ/kg·K)
ΔT =change in air temperature (K)
c. Energy Used for Evaporation of Water from grain (Q_{evap})

$$Q_{evap} = m_{evap} \times h_{evap} \text{ (kJ)} \tag{22}$$

where,
m_{evap} = mass of water evaporated (kg)
h_{evap} = latent heat of vaporization of water (2260 kJ/kg)

a. Input Energy (Q_{in})
Q_{in}=25×14.5=362.5MJ/hour
b. Energy Absorbed by Air (Q_{air})
Q_{air}=150×1.005×(55−30)
Q_{air}=150×1.005×25=3.77 MJ/hour
c. Mass of Evaporated Water
m_{evap} =m_{grain}×(initial water content−final water content)
m_{evap}=12,000×(0.22−0.12)=1,200kgm
d. Energy Used for Evaporation (Q_{evap})
Q_{evap}=1,200×2260=2,712,000 kJ=2712 MJ
f. Thermal Efficiency of Dryer

$$\eta = \frac{Q_{evap}}{Q_{in} \times time}$$
$$\eta = \frac{2712}{362{,}5 \times 6} \times 100\%$$
$$\eta = 79.1\%$$

The experimental data carried out are shown in Table 6 below.

Table 6. Experimental data and calculations

Parameters	Value
Dryer Capacity	12 tons of grain
Initial Moisture Content	22%
Final Moisture Content	12%
Drying Time	6 jam
Mass of fuel (rice husk)	25 kg/jam
Calorific Value of Rice Husk (CV)	14.5 MJ/kg
Mass of hot air used	150 kg/jam
Initial air temperature	30℃
Air temperature after heating	55℃

Thermal efficiency of 79.1% indicates that most of the energy is used to evaporate water from the grain, while a small portion is lost in the form of residual heat and conduction to the environment.

Table 7. Comparison parameters of dryers

Parameters	Natural Drying (Traditional)	Forced Drying (Forced Convection)
Drying Time	2-3 days (depending on weather)	6-8 hours per batch
Final Moisture (%)	14-16% (less stable)	12-14% (according to standard)
Weather Dependence	Very high	Not dependent on weather
Average Loss (%)	10-15% (damage, contamination)	<3% (more protected)
Energy Efficiency (%)	No additional energy required	~80% (efficient use of heat energy)
Drying Capacity	4-5 tons/day	12 tons/day
Grain Quality	Uneven color, high risk of mold	Uniform color, free from mold
Operating Cost	Low (free, labor only)	Medium (rice husk fuel, fan electricity)

Efficiency can be improved by optimizing the flow of hot air to be more even, improving insulation in the system to reduce heat loss and adjusting the fan speed to suit drying needs [23].

Natural drying (using sunlight) and forced drying (using Pressure The Flow of Air Heat Forced Convection technology), based on the main parameters that affect efficiency and quality of results.

Based on Table 7, a Quantitative Analysis can be made:

1). Drying time
a. Natural drying takes 2-3 days depending on weather conditions.
b. Forced drying only takes 6-8 hours per batch, increasing efficiency by 70-80%.
2). Energy efficiency
a. Forced drying has a thermal efficiency of around 80%, meaning that most of the heat energy is used effectively to dry the grain.
b. Natural drying has no energy control, but does not require fuel input.
3). Crop loss
a. Natural drying causes 10-15% of grain to be damaged, due to rain, dust contamination, or mold.
b. Forced drying only experiences <3% loss, increasing yields and farmer profits.
4. Production capacity
a. Natural drying can dry around 4-5 tons of grain/day.
b. Forced drying can dry up to 12 tons/day, increasing almost 3 times.

Comparatively, it can be concluded that forced drying is superior in terms of time, capacity, and quality of results, natural drying is cheaper because it does not require additional energy, but is very dependent on the weather and has a higher risk of losing results and in terms of economic efficiency, although forced drying has operational costs, increased capacity and higher selling prices of grain make it more profitable in the long term [24].

A more specific quantitative analysis of the comparison of natural drying and forced drying using the Pressure The Flow of Air Heat Forced Convection (PFAHFC) method [25]:

1). Drying time efficiency

Natural drying is highly dependent on weather and sunlight conditions, while forced drying can speed up the drying process with controlled hot air flow.

a. Natural drying: 30-48 hours (depending on the weather).

b. Forced drying: 8-12 hours (controlled).

c. Increased time efficiency: >70%.

2). Grain Moisture Content Before and After Drying

a. Natural drying:

Initial moisture content: 24-26%.

Final moisture content: 14-15% (varies, less uniform).

b. Forced drying:

Initial moisture content: 24-26%.

Final moisture content: 12-14% (more uniform).

3). Post-harvest losses

a. Natural drying: 10-15% yield loss due to mold, fermentation, and contamination.

b. Forced drying: <3% yield loss due to more even and controlled drying.

4). Energy consumption

Natural drying: Does not require fuel or electricity, but requires a large area and is highly dependent on weather.

Table 8. Quantitative comparison

Parameters	Natural Drying	Forced Drying (PFAHFC)
Drying Duration	30-48 hours	8-12 hours
Final Moisture Content	14-15% (less uniform)	12-14% (uniform)
Yield Loss	10-15%	<3%
Energy Consumption	0 (sunlight)	2.5-3.5kg husk/100kg grain

Forced drying: Uses biomass fuel (rice husk) or gas, with a consumption of around 2.5-3.5 kg of husk/100 kg of grain

With the quantitative data in Table 8, we can conclude that forced drying is much more efficient and produces higher quality grain compared to natural drying methods. This study focuses on the development and implementation of forced convection-based grain drying technology (Pressure The Flow of Air Heat Forced Convection - PFAHFC) to improve drying efficiency and effectiveness compared to traditional methods. The scope of this study includes:

1). Energy efficiency analysis

a. Evaluation of biomass fuel consumption (rice husk) in producing hot air.

b. Comparison of energy efficiency between natural and forced drying methods.

2). Drying system performance

a. Measurement of air temperature and humidity during the drying process.

b. Evaluation of drying speed and its impact on grain quality.

3). Drying design optimization

a. Calculation of key parameters such as inlet air temperature, fan speed, and air distribution.

b. Identification of factors affecting drying effectiveness.

4). Field scale application

a. Field trials to assess tool performance under real conditions.

b. Analysis of the impact of technology on farmer productivity.

To understand the effectiveness of the PFAHFC system, this study compares natural drying (without tools) and forced drying (using tools) based on several key parameters.

Look at Table 9, from the table, it can be seen that forced drying is superior to traditional methods because it is faster, more efficient, and produces better quality grain. The application of PFAHFC technology in the real world includes several important aspects:

1). Small and medium farmer production scale

a. Farmers who were previously only able to dry 4 tons per day using traditional methods can now increase their capacity to 12 tons per day.

b. With higher energy efficiency, farmers can save fuel and reduce operational costs.

c. This technology does not depend on the weather, so production is more stable and is not hampered by the rainy season.

2). Sustainability and energy efficiency

a. This system uses rice husks as fuel, which is an abundant agricultural waste.

b. With an efficiency of 82.9%, the heat energy produced is optimally utilized for the drying process.

c. Utilizing renewable energy sources can help reduce dependence on fossil fuels.

3). Economic impact on farmers

a. With shorter drying times, farmers can increase production frequency and accelerate planting cycles.

b. The quality of the rice increases, so that the selling price is higher on the market.

c. Farmers' income increases, because crop losses due to bad weather can be minimized.

4). Implementation on an industrial scale

a. This system can be used in agricultural cooperatives, rice mills, or rice storage warehouses.

b. With faster and more uniform drying, rice stocks can be managed better.

c. Potential for further development with automatic sensors to control temperature and humidity, so that the drying process is more precise.

To improve dryer performance, this study identified and optimized:

a. Design of the combustion furnace and hot air duct.

b. Adjustment of fan capacity and speed to suit drying needs.

c. Use of thermal insulation to reduce heat loss and improve energy efficiency.

Table 9. Comparison of natural and forced drying

Parameters	Natural Drying (Traditional)	Forced Drying (PFAHFC)
Drying Duration	30-40 hours	8-10 hours
Weather Dependence	Very high	Not dependent
Final Moisture	Unstable (12-16%)	Stable (≤12%)
Energy Efficiency	Low	High (82.9%)
Grain Quality	Many breaks, uneven water content	Intact granules, uniform moisture content
Operating Cost	Low, but less than optimal results	Higher, but efficient
Productivity	4 tons/day	12 tons/day

This study not only evaluated the technical aspects but also their impact on production and farmer welfare. Some aspects analyzed include:

a. Increasing drying capacity from 4 tons/day to 12 tons/day.

b. The effect of this technology on the quality and selling price of grain.

c. Savings in operational costs compared to traditional methods.

As a final step, this study tested the application of the PFAHFC system on a field scale to ensure that this technology:

a. Can be easily operated by farmers without the need for high technical skills.

b. Has lower operational costs compared to conventional methods.

c. Is able to increase production efficiency and food security in areas that often experience weather constraints.

Challenges and Solutions in Implementation are as follows:

a. Challenges:

1). The initial investment cost is quite high for small farmers.

2). Technical skills are needed to operate

3). Maintenance of equipment to keep it functioning optimally.

b. Solutions:

a. Assistance from the government to help farmers access this technology.

b. Training and technical assistance for farmers in the use and maintenance of equipment.

Forced convection-based rice drying technology (PFAHFC) has proven to be more efficient and effective than traditional methods. With an efficiency of 82.9%, drying time can be shortened to 8-10 hours, with more uniform results. Implementation of this technology in the field can increase farmer productivity, crop quality, and farmer income. For wider implementation, technical and financial support is needed from the government and the private sector so that this technology can be used massively.

5. CONCLUSIONS

This study comprehensively examines the effectiveness of forced convection-based rice drying technology (Pressure The Flow of Air Heat Forced Convection-PFAHFC) with the aim of increasing drying efficiency, crop quality, and reducing dependence on weather conditions.

Based on the test results, the drying system based on Pressure The Flow of Air Heat Forced Convection (PFAHFC) showed a significant improvement compared to the natural drying method. In terms of time, traditional drying takes about 2 to 3 days, depending on weather conditions, while the forced convection system is able to reduce the drying time to 8 to 12 hours, with more consistent results.

In terms of water content, rice dried using the natural method often has a final water content that varies between 14% and 16%, while with PFAHFC technology, the final water content can be controlled more precisely at 12%, in accordance with industry standards. Drying capacity also increased significantly, from 4 tons per day using the traditional method to 12 tons per day with the forced convection system, indicating efficiency in production scale. In terms of thermal efficiency, traditional methods often have an efficiency below 40%, because much heat is wasted due to uncontrolled air flow and ambient temperature. In contrast, with the PFAHFC system, thermal efficiency increases to 75% to 85%, due to the control of the inlet air temperature which is in the range of 45°C to 60°C, compared to the uncontrolled temperature in the natural method which ranges from 35°C to 40°C.

Fan speed is also an important factor in increasing drying efficiency. In the traditional method, drying relies entirely on natural wind without control, while in the PFAHFC system, the fan speed is controlled in the range of 2 to 4 m/s, ensuring a more even distribution of hot air and increasing drying efficiency. In addition, the humidity of the outgoing air in this system can be controlled in the range of 55% to 65% RH, compared to the traditional method which has no humidity control, allowing for more optimal and consistent drying.

By improving these parameters, PFAHFC technology has been proven to be able to significantly increase drying efficiency, reduce process time, and produce better and more stable quality grain, which ultimately has a positive impact on farmer productivity and welfare.

This drying technology provides various benefits that have a direct impact on farmer productivity and the efficiency of the rice milling industry, including: Drying time is reduced by up to 70% compared to traditional methods, Capacity increases from 4 tons/day to 12 tons/day. Drying is more uniform, reducing broken grains during milling, Dried rice is more resistant to mold and contamination. Utilization of rice husks as fuel reduces fuel costs by up to 30% compared to LPG or electricity-based systems, Forced convection systems optimize heat circulation, reducing energy loss. Does not depend on sunlight, so it can be used at any time, especially during the rainy season, Reduces the risk of rotting due to uneven drying. Although this system shows significant advantages, there are several challenges that need to be overcome so that its application is more widespread and efficient, namely: The initial cost of installing a forced convection drying system is higher than traditional methods, The rice husk combustion system still produces ash residue that needs to be managed, The system still requires manual monitoring of air temperature and humidity. With design optimization, system automation, and farmer education, this technology has great potential to be widely applied, especially in areas that often experience weather constraints in the rice drying process.

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NOMENCLATURE

B	dimensionless heat source length
CP	specific heat, J. kg^{-1}. K^{-1}
g	gravitational acceleration, m.s^{-2}
k	thermal conductivity, W.m^{-1}. K^{-1}
Nu	local Nusselt number along the heat source
Q_{losses}	heat losses
Q_{gbt}	total heat
m_g	gas mass
Q_{gbo}	total heat of the flue gas
Q_{abs}	total heat from the flue gas is absorbed
Q_{gbt}	heat losses
Rn	Reynolds number
U	Overall Heat Transfer Coefficient
A_{tot}	total heat transfer area
Q_{tot}	total heat transfer
Q	total heat energy
m_g	exhaust gas mass
CV	calorific value
P	Power
M	Grain Capacity
MCi	initial water content
V	fan speed

Greek symbols

υ	air velocity, m/s
η	energy efficiency
Θ	dimensionless temperature
μ	dynamic viscosity, $kg.\ m^{-1}.s^{-1}$