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Design, simulation, and experimental validation of a 50 kg biomass-fired coffee drying oven

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Abstract

Despite coffee is one of the leading commodities in Bengkulu Province, the traditional drying process of coffee beans for 10-14 days are still a common practice. This research aims to design, fabricate, and evaluate the thermal performance of a 50 kg capacity wood-fueled coffee drying oven. A three-dimensional CFD model was developed using ANSYS Fluent to analyze temperature distribution within the drying chamber and optimize thermal performance prior to fabrication. Experimental testing was conducted to validate the numerical predictions under controlled operating conditions. The proposed technology is distinguished by its use of locally available biomass fuel. The results of the coffee drying oven simulation, under empty conditions, achieved the desired temperature based. The drying time for coffee beans in this research was 9 hours, achieving a moisture content of 10% to 13% (a moisture content of 12.5% is the Indonesian National Standard. Simulation results predicted chamber temperatures ranging from 67°C to 87°C with an inlet temperature of approximately 100°C, indicating adequate thermal conditions for drying. Experimental measurements showed good agreement with the CFD model, reaching near-steady thermal conditions within 25 minutes.

Keywords:
CFD, coffee beans, drying, oven, temperature

1 Introduction

Coffee is one of the leading commodities among the 40 national prime commodities and is included as a main commodity in Bengkulu Province. The Indonesian Coffee Statistics 2018 (BPS) recorded that Bengkulu Province is one of the largest coffee producers nationally, ranking sixth in 2018 with production of 55,385 tons and coffee plantation area of 88,962 hectares, while the largest national producer is South Sumatra Province with production of 184,168 tons and an area of 250,193 hectares. The production figures for Bengkulu Province compared to the previous year, 2017 experienced a decrease of 5.98% [1], [2].

Coffee still undergoes quite a long process to produce ready-to-consume coffee powder. The process starts with hulling, drying, roasting [3], [4], and grinding, which are still done traditionally. The coffee bean drying process is still largely carried out traditionally, namely by drying wet coffee beans under direct sunlight. This traditional drying process has the advantage of having a free energy source and evenly distributed drying quality. However, this method also has disadvantages, namely taking quite a long time, which is 10-14 days, and dependence on the climate, where many coffee-producing areas are in areas with high rainfall.

Drying coffee beans aims to prevent microorganisms and chemical compounds that can damage them. Coffee beans must be dried to have a moisture content of 12% so that they are declared suitable by Indonesian National Standards [5], [6], [7]. The drying process is influenced by air flow velocity, which is recommended between 1.5 and 2 m/s, and drying temperature, which is recommended between 50°C–55°C. The inlet temperature was intentionally set higher than the recommended drying temperature to compensate for heat losses in the heat transfer chamber, ensuring that the effective drying temperature inside the oven chamber remains within the acceptable range for coffee drying.

Experimental studies on coffee dryer machine development have been widely conducted to obtain optimal results. Based on energy sources, several studies have designed drying machines with hybrid modified solar dryers [8], using electric heaters [9], utilizing tray dryers using hot air [10], [11], water heaters [12], [13], gas fuel, and mechanical drying equipment in the form of rotary dryers [14], [15], and solar energy sources. To monitor dryer conditions remotely, drying machines equipped with Android systems have been developed. Android is used to control and monitor temperature in the drying equipment, and buzzers are used for notifications that the drying equipment has been activated and deactivated [16], [17]. Meanwhile, to maintain a more stable temperature inside the oven, insulation walls in the furnace have been developed using brick powder [18]. In addition to experimental studies, the development of dryer machine design concepts through simulation using Computational Fluid Dynamics (CFD) for rotary drum dryer types and LPG heaters [19]. A fixed-chamber oven was selected instead of a rotary drum dryer due to its simpler mechanical design, lower energy and maintenance requirements, and better suitability for small-scale rural coffee processing while still enabling stable thermal control during drying. 3D modeling of rotary drum dryers, including the surrounding air, was made considering a transient simulation. Research results show that the internal air temperature in the drum model increases in relation to increasing time [20]. Previous three-dimensional CFD studies on rotary drum dryers have shown that internal air temperature increases over time due to heat accumulation during rotation. In contrast, this study applies CFD analysis to the design of a 50 kg capacity wood-fueled fixed-chamber coffee drying oven, focusing on temperature distribution without rotational effects.

Therefore, in this research, a coffee drying device with a capacity of 50 kg using wood fuel was designed. This research contributes by integrating CFD-based thermal analysis with experimental validation for a 50 kg capacity biomass-fueled coffee dryer, providing a practical solution suitable for rural coffee processing. The selection of wood as fuel is based on the fact that in coffee-producing areas, there is a lot of wood and twigs that are not utilized, so they can be used as cheap fuel. The coffee dryer design process was carried out using CFD software. The equipment design process was done manually, then simulations were performed on the designs that had been made using CFD software. The resulting design was then manufactured with the addition of several temperature sensors. Subsequently, the coffee drying process was carried out using this equipment. From the drying results, the drying time for wet coffee beans to reach the Indonesian National Standards was obtained. This study employs a dual-heater system consisting of a biomass combustion chamber and an auxiliary electrical heater. The biomass heater serves as the primary heat source, utilizing wood fuel to generate hot air, while the electrical heater functions as a secondary heat stabilizer during the initial heating stage and temperature fluctuations. This dual-heater configuration is designed to ensure stable inlet air temperature and improve overall drying performance, particularly under variable operating conditions. This research aims to design, simulate, manufacture, and experimentally validate a biomass-fueled coffee drying oven with a capacity of 50 kg, focusing on temperature distribution and drying performance.

2 Methods

This research designs a wet coffee dryer with a capacity of 50 kg in three (3) stages: optimization of dryer dimensions and shape through simulation, manufacturing and assembly of the drying equipment, and testing the performance of the coffee drying equipment. A simulation was conducted using CFD software on several designs to ensure that the temperature distribution meets the requirements for coffee drying. From the simulation of these designs, the design with the best heat distribution was selected. Subsequently, the coffee dryer was manufactured based on that design. After the coffee dryer was made, testing was conducted on the equipment to obtain heat distribution data that would be used for validation against the simulations that had been performed, and to determine the time needed to dry wet coffee beans to reach Indonesian National Standards. With the validated design, scaling of the coffee drying equipment can be performed according to needs. The coffee bean drying machine to be made uses wood fuel as the heat source. Generally, this machine consists of a blower fan, heating furnace, oven, heat transfer chamber, and racks, as shown in Fig. 1. Description in Fig. 1 are, 1. Force draft fan, 2. Furnace, 3. Chimney, 4. Control box, 5. Oven box, 6. Hot air duct, and 7. Coffee bean rack.

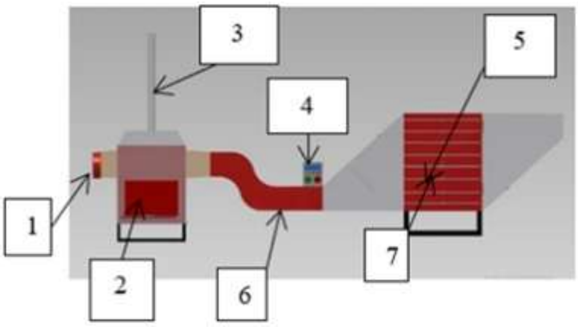


Fig. 1. Schematic of a coffee bean dryer design, geometry of a 50 kg capacity coffee drying machine

This coffee drying oven utilizes hot steam from wood combustion results that are burned to heat pipes and is channeled to the oven and blown with a fan toward the oven. To read the temperature inside the oven, there are four thermocouple sensors, each located between the racks, and one thermocouple sensor is in the transfer chamber as the hot steam pathway to the oven in Fig. 2. The coffee drying oven measures 80cm × 80cm × 100cm, with a capacity of 50kg divided into 8 levels, and each level has a capacity of 6-7 kg. Fig. 3 shows the dimensions of the 50 kg capacity coffee drying system.

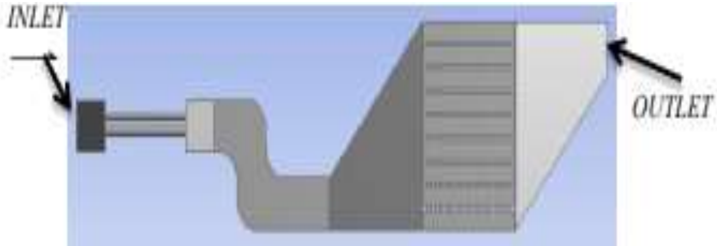


Fig. 2. Boundary conditions of the coffee dryer machine

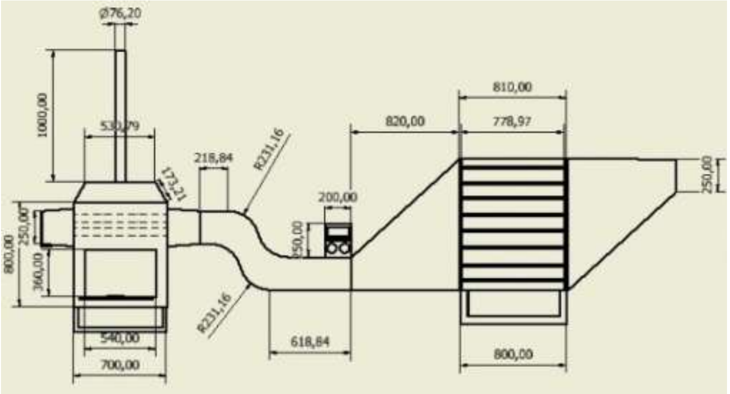


Fig. 3. Design of the coffee dryer

2.1 CFD simulation on drying machine using ANSYS®

The initial stage in designing this coffee drying machine is simulation modeling using ANSYS®, using the CFD method [21]. The ANSYS® modeling design aims to analyze the temperature distribution rate and temperature contour in the coffee drying oven chamber. The chimney was excluded from the CFD geometry because it mainly functions as an exhaust to the ambient environment and does not significantly affect the internal airflow and temperature distribution inside the drying chamber. The model made in 3-dimensional form is presented in Fig. 4.

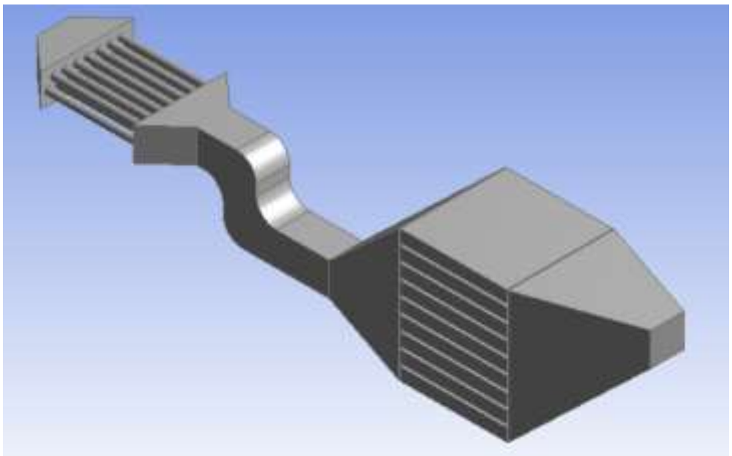


Fig. 4. Three-dimensional model of the coffee dryer

After modeling, the next step is the meshing process, which aims to divide solid model elements into small elements that function as areas for calculation and iteration of a simulation. The meshing results can be seen in Fig. 5.

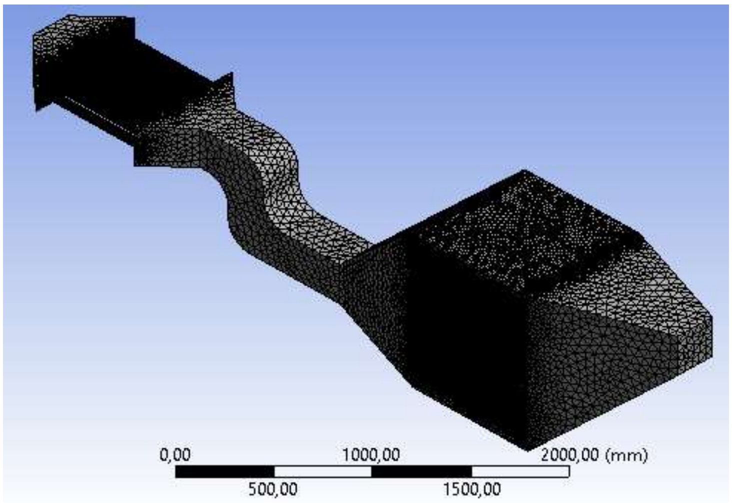


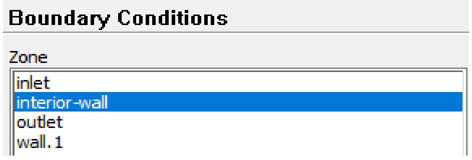
Fig. 5. Meshing result

Fig. 5 shows the meshing result of the coffee drying oven model. A tetrahedral mesh was applied to accommodate the complex geometry of the furnace, ducts, and drying chamber. Mesh refinement was concentrated near the inlet, outlet, and heat transfer surfaces to ensure accurate prediction of airflow and temperature gradients. Mesh independence was ensured by comparing temperature results at key points until variations were insignificant.

2.2 Determination of boundary conditions and materials

In this research, the boundary conditions in this simulation consist of a velocity inlet, a pressure outlet, and interior wall boundaries [23]. The inlet represents hot air flowing from the combustion chamber into the oven, while the outlet allows exhaust air to exit the system. Interior-wall boundaries were applied to represent solid surfaces that separate fluid regions without external heat loss assumptions. These boundary conditions are essential to realistically model heat transfer and airflow behavior inside the oven and to ensure numerical stability and physical accuracy of the CFD simulation. The thermocouple measurement points are indicated in Fig. 2 at three rack levels (A, B, and C), corresponding to the upper, middle, and lower drying trays, which were used for validation of simulation results.

In determining boundary conditions, Fluent tends to automatically name boundary conditions, such as interior and wall. The boundary condition dialog box can be seen in Fig. 6. The interior-wall boundary condition was selected to represent internal surfaces within a single continuous fluid domain, where heat transfer occurs primarily through convection rather than solid conduction. This approach is suitable for modeling the airflow and temperature distribution inside the coffee drying oven, as the structural walls were not explicitly defined as separate solid domains. Using an interior-wall boundary prevents artificial separation of the flow domain and avoids double-counting thermal resistance. Alternative boundary conditions, such as standard walls or porous media, were not applied because the study focused on airflow-driven heat transfer, and the physical properties of solid materials were not included in the CFD model.


Boundary Conditions

Zone

inlet
interior-wall
outlet
wall.1

Fig. 6. Boundary condition dialog box

2.3 Research stage

At this stage, material properties for solid and fluid domains were defined before running the CFD simulation, including thermal conductivity, density, and specific heat capacity, as summarized in Table 1.

Table 1. Material Properties [20]

Material	Density (kg/m^3)	Specific heat (J/kg-K)	Thermal conductivity (W/m-K)	Viscosity (kg/m-s)
Fluid (air)	1225	1006.43	0.0242	1.79E-02
Solid (steel)	8030	502.48	12.27	-

2.4 Simulation data collection

Data collection was performed at several points: at the inlet and outlet, there is 1 point each. For the oven section, there are 3 data collection points in the middle of the racks, namely point A on rack 1, point B on rack 5, and point C on rack 9. Fig. 7 shows the data collection points in the experimental test of the coffee bean drying equipment.

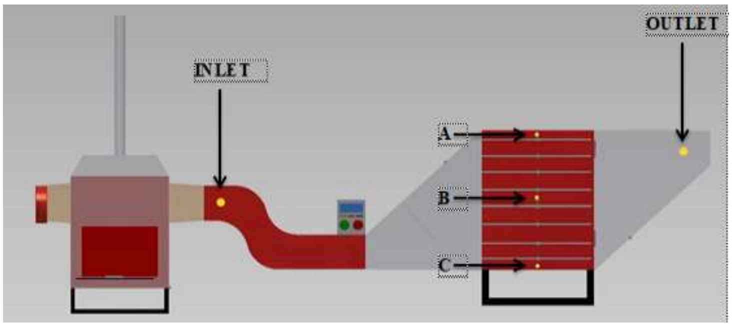


Fig. 7. Data collection points in the experimental test of the coffee bean dryer

2.5 Manufacturing and testing of coffee drying equipment

The next stage is manufacturing and testing the performance of the coffee drying machine. The machine was manufactured based on simulation results of the model [24]. The design results were used as the basis for making the coffee drying equipment using steel plate material. The oven geometry design to be studied in this research uses carbon steel material with dimensions of 80cm x 80cm x 100cm and heat transfer chamber dimensions of 25cm x 25cm.

After the equipment was completed, the dryer was operated to obtain a picture of the actual distribution. At the beginning of operation, after the wood fuel was ignited in the furnace, the blower fan was operated at an air velocity of approximately 1.5–2.0 m/s for 30 minutes until the dryer reached its working temperature. Subsequently, coffee beans were placed in the oven and dried for 9 hours, with temperature data recorded at 30-minute intervals until the moisture content decreased below 12% in accordance with Indonesian National Standards. This drying duration is comparable to previous studies on hot-air and biomass-fueled coffee dryers, which reported drying times ranging from 8 to 12 hours under controlled thermal conditions [25], [26]. The design scheme and the manufactured equipment are shown in Fig. 8. Description in Fig. 8 are, 1. Forced draft fan, 2. Furnace, 3. Chimney, 4. Oven box, and 5. Hot air duct.

Fig. 8. Coffee bean drying machine

2.6 Experimental testing of coffee bean drying equipment

After manufacturing, the coffee bean drying equipment was completed, and experimental testing was conducted on the equipment. Equipment testing aims to validate simulation results and to determine the time needed to dry coffee fruit to 12% moisture content.

2.6.1 Tools and materials for data collection

The equipment used in this experimental test includes the coffee bean drying equipment and supporting equipment, including:

1. The equipment used in this experimental study consisted of a coffee bean drying system and supporting instruments. The main equipment was a custom-designed drying oven, developed specifically for this research, which functions as the primary chamber for heat and mass transfer during the drying process.

2. An Arduino MEGA microcontroller was employed as the central control unit to regulate temperature, monitor sensor readings, and record experimental data in real time.

3. Five thermocouples were installed at different measurement points inside the drying chamber to monitor temperature distribution and ensure uniform heat exposure of coffee beans. Temperature data were displayed using a Liquid Crystal Display (LCD) for real-time observation.

4. Jumper cables were used to connect sensors, the microcontroller, and output devices. An air blower fan supplied and circulated hot air throughout the drying chamber to enhance convective heat transfer.

5. A grain moisture meter was used to measure the moisture content of coffee beans at specific drying intervals, while a digital coffee bean scale was utilized to measure mass reduction during the drying process.

The initial moisture content of wet coffee beans used in this experiment ranged from 45% to 55% (wet basis), which is typical for freshly harvested coffee cherries after pulping. Ambient relative humidity before drying was measured at approximately 70–80%. Meanwhile, the materials used in this research are wet coffee beans as research objects and wood fuel as fuel for the furnace. In this experimental test, the oven section will be the place for the coffee bean drying process. This process requires heat transfer by convection from pipes heated in the furnace and channelled to the oven using a blower fan.

2.6.2 Coffee drying machine data collection

The experimental test conducted was divided into 2 testing stages. First stage: experimental testing with an empty oven. This test aims to validate the simulation results that have been performed. Testing was conducted by heating the oven in empty conditions or without coffee beans inside. Testing was conducted from when the fuel was ignited until the inlet temperature reached its working point of 100°C. Data collection was performed every 1 minute. Subsequently, the second stage: experimental testing with an oven containing coffee fruit. This test aims to determine the time needed to dry coffee fruit. After the inlet temperature reached 100°C, coffee beans were placed on the available racks inside the oven, and the drying process was conducted. This process was carried out until coffee beans in one of the racks had a moisture content below 12%. In this second stage, temperature data collection was performed every 30 minutes, while moisture content data in coffee beans was collected every 1 hour.

3 Results and discussion

The CFD simulation results were validated through experimental measurements obtained from the fabricated drying oven. Temperature data collected using thermocouples at multiple locations inside the drying chamber were compared with the simulation results to evaluate the accuracy of the numerical model.

This article presents both results from numerical simulation and experimental data. From the CFD simulation analysis, the temperature distribution and temperature contour in the coffee drying oven chamber can be determined. These results will be compared with experimental data that has been collected. From experimental results, the time needed for coffee fruit drying until the moisture content reaches Indonesian National Standards can be determined.

3.1 CFD simulation test results

The results of this CFD simulation test are in the form of temperature contours in the coffee drying oven. The material used in this analysis is carbon steel [27], [28]. The results of this analysis are the temperature distribution and temperature contour. Data collection in this research was conducted by recording values from simulation results under empty oven conditions without coffee beans inside. This was done so that data analysis produces valid data.

The results of this analysis include the temperature values at the inlet, oven chamber, and outlet. The simulation results indicate that the temperature distribution satisfies the drying requirements and shows good agreement with the experimental measurements. This consistency is supported by fundamental heat transfer theory, where convective heat transfer and forced airflow govern the temperature gradient from inlet to outlet, resulting in predictable thermal decay along the flow direction. Consequently, the oven chamber temperatures obtained, ranging from 70°C to 83°C, are consistent with theoretical expectations for forced-convection drying systems. Temperature distribution values in the second design can be seen in Table 2.

Table 2. Temperature distribution in the oven section of the coffee bean drying equipment from simulation results

Rack number	Air temperature at point (°C)				
	Inlet	A	B	C	Outlet
1	100	76	70	70	63
2	100	79	76	73	63
3	100	83	79	73	63
4	100	83	79	73	63
5	100	83	79	73	63
6	100	83	79	73	63
7	100	83	79	73	63
8	100	83	79	73	63
9	100	76	76	70	63

Meanwhile, temperature contours are used to see the temperature distribution occurring in the coffee drying oven at predetermined points. Data at each point has different temperature differences from the center of the chamber. The following are the contours obtained from this analysis.

From simulation results, the temperature in the oven chamber appears uniform. However, different temperatures in the oven chamber already show color differences, as can be seen from the contour, where the oven wall section is already green colored, and the center of the oven has temperatures of 70°C to 83°C, showing temperature differences in areas around the oven walls compared to the center area of the oven chamber. The temperature contour results can be seen in Fig. 9.

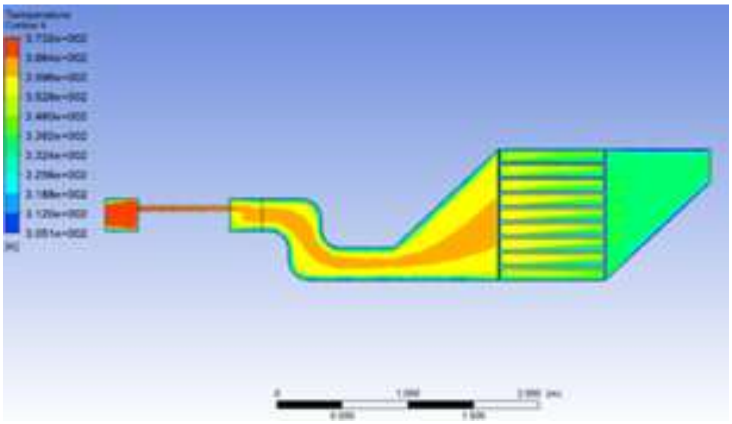


Fig. 9. Temperature contour results in the oven section of the coffee bean dryer from the simulation

3.2 Experimental test results

The results of experimental testing are in the form of temperature distribution occurring during testing. Experimental testing was conducted at predetermined points. The following are the experimental tests conducted:

Data collection was performed at several predetermined points in the oven section and in the form of temperatures at the inlet, oven chamber, and outlet. The target temperature for this test was the simulation result of 70°C to 83°C. This test was conducted only until the temperature reached the target, and the test results to reach the target required 25 minutes. The following temperature distribution values during experimental testing under empty oven conditions can be seen in Table 3.

Table 3. Experimental test results under empty oven conditions

Time (minutes)	Coffee bean moisture at rack number (%)				
	Inlet	A	B	C	Outlet
1	53	46	44	41	40
2	57	49	47	44	43
3	59	51	47	45	44
4	64	55	50	48	46
5	67	55	50	48	46
6	69	59	55	54	52
7	75	67	60	55	54
8	78	69	62	52	55
9	79	71	63	53	56
10	82	73	65	55	58
11	82	74	65	56	60
12	83	75	68	58	60
13	83	75	68	59	60
14	84	76	68	59	61
15	84	76	69	60	62
16	83	77	70	61	62
17	84	77	71	61	62
18	87	79	71	62	64
19	88	80	72	62	65
20	88	80	72	63	66
21	86	79	72	63	66
22	89	80	75	65	67
23	93	84	77	67	65
24	99	90	84	75	77
25	105	95	87	79	79

Data collection was performed at several predetermined points in the oven section and in the form of temperatures at the inlet, oven chamber, and outlet. This test required 9 hours to achieve dry coffee fruit conditions and obtain a moisture content of 10% to 13% (seen in Table 4). The following temperature distribution values during experimental testing under coffee bean-filled oven conditions can be seen in Table 5. Meanwhile, the moisture content of coffee beans from experimental testing results conducted on the drying equipment can be seen in Table 4.

Table 4. Coffee bean moisture content results after oven drying

Time (hours)	Air temperature at rack number (°C)								
	1	2	3	4	5	6	7	8	9
0	26	26	26	26	26	26	26	26	26
1	25	25.5	25.5	26	26	26	26	26	26
2	24	24	24.5	25	25	25	25.5	25.5	25.5
3	22	22.5	23	23.5	23.5	24	24	24	24
4	20	20	21	21	21	22	22	22	22
5	18	18.5	19	19	19	19.5	20	20	20
6	16	16.5	16.5	17	17	18	18	18.5	18.5
7	14	14	14.5	14.5	15	15	16	16	16
8	12	12.5	12.5	13	13	14	14	14.5	14.5
9	10	11	11	11.5	11.5	12	12	13	13

Table 5. Experimental test results under coffee bean-filled oven conditions

Time (minutes)	Air temperature at point (°C)				
	Inlet	A	B	C	Outlet
30	60	38	37	40	35
60	88	62	61	62	51
90	91	75	70	67	59
120	101	74	69	65	60
150	113	95	79	75	65
180	108	92	78	74	66
210	115	99	82	76	68
240	112	80	72	60	65
270	122	79	71	60	65
300	75	70	65	60	60
330	105	76	71	66	61
360	130	108	86	80	78
390	124	100	82	75	67
420	92	75	70	67	59
450	107	92	78	74	66
480	87	62	61	62	51
510	84	60	59	61	50
540	88	60	59	59	50

3.3 Discussion

From simulation data using CFD software, results in the form of temperature contours were obtained. The temperature contours obtained show that at an inlet temperature of 100°C, temperatures in the coffee drying oven of 70°C to 83°C were achieved, and 63°C at the outlet section. These simulation results show that temperatures inside the oven already meet the requirements of 60°C – 80°C. The graph of temperature distribution values occurring in the coffee drying equipment from the CFD simulation results can be seen in Fig. 10 and Fig. 11.

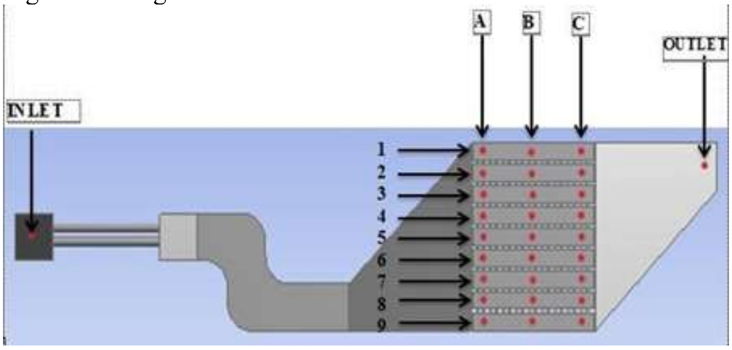


Fig. 10. CFD simulation

The CFD simulation illustrates the hot air flow entering the system through the inlet, passing through the duct, and being distributed horizontally into the oven chamber before exiting through the outlet. The airflow is directed across multiple rack levels (1–9), forming a layered heat distribution pattern inside the chamber. The results indicate that the central rack region experiences relatively stable temperatures, while variations occur near the inlet and outlet zones due to flow development, mixing behavior, and heat dissipation at the exhaust section

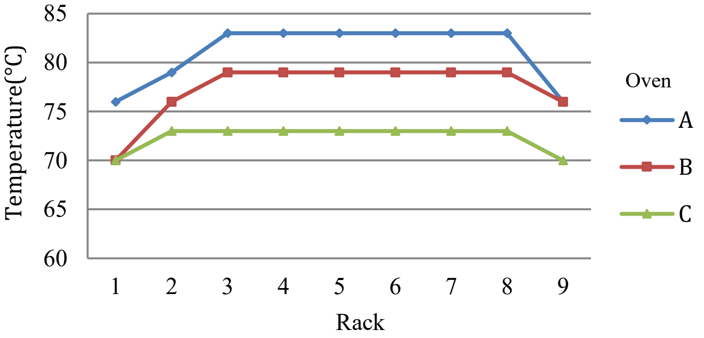


Fig. 11. Graph of the temperature distribution results in the coffee dryer from the CFD simulation

Points A, B, and C represent temperature monitoring locations at different horizontal positions across the oven chamber. Point A (left region) shows higher temperatures due to direct exposure to incoming hot airflow. Point B (central region) exhibits more uniform and stable temperatures, indicating effective heat distribution and mixing in this zone. Point C (right region, near the outlet) shows a slight temperature reduction caused by heat losses and airflow discharge toward the outlet. This distribution confirms the presence of a spatial temperature gradient from inlet to outlet, which is critical for understanding thermal uniformity and optimizing rack loading patterns for consistent heating performance.

In experimental testing under empty oven conditions, results showed temperatures at each predetermined point reached the expected range within 25 minutes of heating time. The graph of temperature distribution values during experimental testing under empty oven conditions can be seen in Fig. 12.

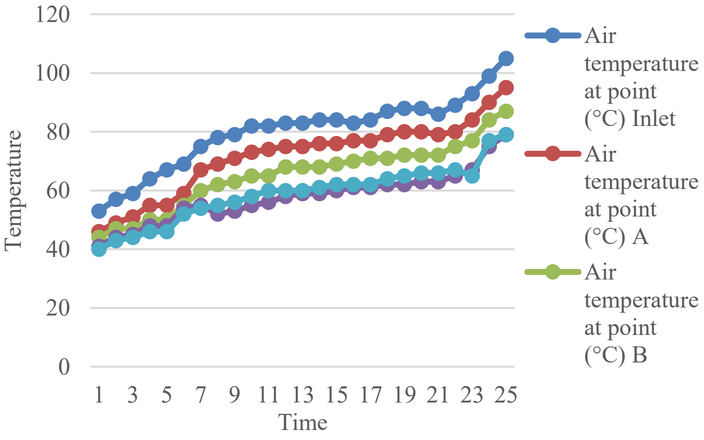


Fig. 12. Graph of the experimental test results in the oven under empty conditions

From the graph, it can be seen that the temperature distribution has a uniform temperature increase each minute, with values in the first minute of 53°C at the inlet, 46°C at point A, 44°C at point B, 41°C at point C, and 40°C at the outlet. At the 25th minute, the oven temperature had reached expectations, with an inlet temperature of 105°C, 95°C at point A, 87°C at point B, 79°C at point C, and 79°C at the outlet.

Subsequently, testing was conducted on the heated oven. Testing was performed by placing wet coffee beans in the oven while maintaining the heating process. Results of data collection in experimental testing under coffee fruit-filled oven conditions can be visualized in the graph shown in Fig. 13. Experimental testing under coffee-filled oven conditions for 9 hours achieved a moisture content in coffee beans of 10%-13% with an average inlet temperature of 100°C, an average of 87°C at point A, an average of 78°C at point B, an average of 73°C at point C, and an average of 67°C at the outlet.

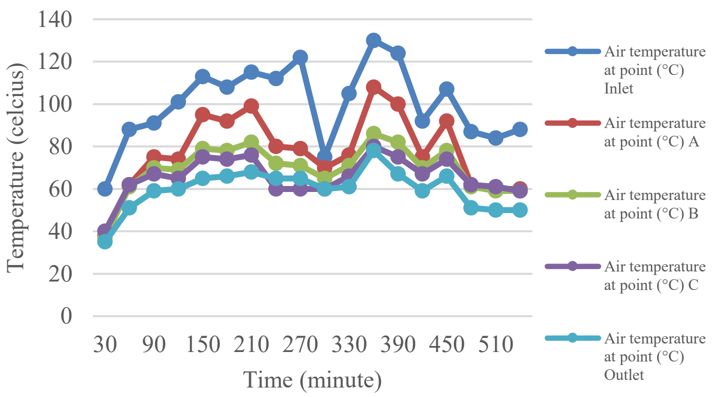


Fig. 13. Graph of the experimental test results in the oven containing coffee beans

It can be seen in Fig. 9 that the highest temperature at the 360th minute was 130°C at inlet, 108°C at point A, 86°C at point B, 80°C at point C, and 78°C at outlet. In the presented graph, a temperature decrease occurs at the inlet caused by the wood fuel used. The average temperature at the 30th minute was very low, caused by the process of inserting coffee fruit to be dried into the oven, resulting in a temperature decrease at the 30th minute.

It can also be seen in Fig. 9 that oven temperature is not uniform. The non-uniform temperature distribution observed during experimental testing is mainly caused by buoyancy-driven airflow and geometric constraints inside the oven, which result in higher temperatures at the upper racks, caused by hot air predominantly rising upward even though air flow enters from below, and there are air circulation obstacles so that hot air blown into the oven predominantly rises upward, so that lower racks receive less hot air [30], [31], [32]. The mentioned obstacles are perforated plates located on the left and right walls of the oven section, and the temperature of the coffee fruit itself drops downward because it is overcome by the conducting hot air.

Using a drying oven with a dual heater results in faster drying time, evenly dried coffee beans, and can be used during the rainy season or at night, thus greatly helping coffee collectors in achieving uniform and better coffee bean drying quality [33], [34], [35]. A temperature setting averaging 73°C to 87°C in the oven chamber, with coffee fruit arranged at 6.25 kg per rack for 8 racks for 9 hours, achieved an average moisture content of 11.5%. Using a drying oven produces faster drying, almost evenly dried coffee fruit, and can be used during the rainy season or at night, thus greatly helping coffee farmers in the coffee fruit drying process. This study primarily focuses on thermal performance and moisture content reduction. Other quality parameters such as aroma, color, and sensory characteristics, were not evaluated and are suggested for future studies.

4 Conclusion

This study demonstrated the design and validation of a 50 kg capacity biomass-fired coffee drying oven using an integrated CFD and experimental approach. The simulation results predicted chamber temperatures ranging from 67°C to 87°C, with an inlet temperature of approximately 100°C, confirming that the designed system meets the thermal requirements for coffee drying. Experimental validation was conducted through systematic testing. The experimental data show that coffee bean moisture content was reduced from an initial range of 45–55% to 10–13% within approximately 9 hours under controlled thermal conditions. These results confirm that the drying performance of the manufactured oven is consistent with the simulation predictions. Minor discrepancies observed during testing are attributed to environmental influences and unavoidable heat losses during operation. Overall, the integration of CFD-based design and experimental validation proves effective for optimizing temperature distribution and improving drying efficiency. Therefore, the developed biomass-fueled coffee drying oven can be considered a practical, energy-efficient, and low-cost solution for small-scale coffee processing, particularly in rural areas with abundant biomass resources. The findings of this study are limited to the investigated operating conditions and dryer configuration, and further research is recommended to evaluate performance under different capacities and operating parameters.

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