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Experimental Study on the Effect of Air Intake on Temperature Distribution in the Combustion Chamber of a Fire-Tube Boiler with a Capacity of 100 kg/hour

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Abstract

Mini fire-tube boilers with a capacity of 100 kg/h are widely used in small industries and MSMEs, yet their performance is often limited due to suboptimal furnace design and improper air supply settings. This study aims to analyze the effect of air inlet variations on temperature distribution and thermal efficiency in the furnace of a fire-tube boiler. The research was conducted experimentally using a modified energy losses in pipe apparatus as the controlled air supply system. Airflow velocities were varied from 3 to 17 m/s. Furnace temperatures were measured using Type-K thermocouples placed at five locations, and the data were analyzed through graphical comparison and temperature stability evaluation based on standard deviation. The results indicate that an airflow velocity of 11 m/s provides the best performance, achieving a thermal efficiency of 86% at 1 bar and producing a furnace temperature distribution of 720–760 °C with a ±12 °C deviation, demonstrating a more uniform heat distribution. Low airflow velocity (3 m/s) produced unstable temperatures (520–640 °C) due to incomplete combustion, while excessively high velocity (17 m/s) caused significant temperature reduction (580–610 °C) due to excessive cooling. The novelty of this study lies in determining the optimum air velocity based on furnace temperature stability rather than overall efficiency alone. This research contributes to the operational optimization of small-scale boilers to enhance performance and energy conservation. The limitation of this study is that burner configuration and furnace geometry were not varied.

Keywords : Air Inlet, Temperature Distribution, Thermal Efficiency, Fire-Tube Boiler, Combustion Optimization

1. INTRODUCTION

Energy efficiency has become a central priority in modern industrial systems to support sustainability targets and reduce operational costs [1]. Boilers are among the most widely used thermal equipment in small- to medium-scale industries, serving as the primary source of heat and steam. In particular, mini fire-tube boilers with capacities of 100 kg/h are commonly utilized for distillation, drying, and various heating applications. One such example is the fire-tube boiler operated at the Polytechnic State of Bengkalis for the steam distillation of citronella oil, where stable combustion performance is crucial to maintain continuous steam production [1].

However, many small-scale boilers still operate with non-optimized furnace designs, leading to excessive air infiltration from outside the combustion chamber. This uncontrolled air supply mixes with combustion gases, reduces flame temperature, and shifts the combustion process away from ideal stoichiometric conditions. As a result, the system often experiences incomplete combustion, fluctuating furnace temperatures, higher fuel consumption, and unstable steam production rates [2]. These operational inefficiencies not only increase the cost of fuel but also reduce the overall thermal performance of the boiler.

Several studies have explored factors affecting boiler performance, particularly those related to airflow, temperature distribution, and furnace construction. Excessive combustion air has been shown to absorb a significant amount of heat generated during burning, thereby lowering flame temperature and reducing thermal efficiency [3]. Uneven temperature distribution inside the furnace can also negatively impact heat transfer, reduce steam generation, and accelerate material degradation of boiler components [4]. Research efforts to improve furnace design—

such as adjusting burner position, modifying airflow pathways, and optimizing insulation—have demonstrated efficiency improvements of up to 3.2% in small-scale boilers [5]. Additionally, the use of locally available refractory materials, including fire bricks, cement, and sand, has proven effective in enhancing thermal resistance, minimizing heat loss, and increasing combustion efficiency by 5% [6]–[8].

Despite these advancements, many existing studies do not specifically address how variations in air inlet velocity influence the temperature distribution profile within a mini fire-tube boiler furnace. This gap is critical because temperature uniformity plays a key role in determining combustion completeness, heat transfer effectiveness, and overall thermal efficiency. Moreover, airflow optimization is often overlooked in small-capacity boilers, even though it directly affects flame stability and fuel utilization.

Based on these conditions, the present study aims to redesign and evaluate the furnace of a 100 kg/h mini fire-tube boiler by analyzing the influence of controlled air inlet variations on temperature distribution and combustion stability. This research is expected to accelerate heating time, improve fuel efficiency, and support continuous steam generation according to the operational requirements of 100 kg/h. The findings are anticipated to contribute to the optimization of small-scale boilers and to serve as a reference for future design improvements in educational and industrial applications.

2. REVIEW OF LITERATURE

Fire-tube boilers are widely used in small industrial sectors due to their simple construction, stable operation, and relatively low maintenance costs. Their design allows hot combustion gases to flow through tubes surrounded by water, making them suitable for steam capacities ranging from 100 to 500 kg/h in applications such as distillation, drying, and heating processes. Previous studies have emphasized that energy efficiency remains a crucial indicator of boiler performance, especially in small-scale operations where fuel consumption has a direct impact on operational cost and sustainability (Rahman & Siregar, 2020; Yunus & Turner, 2019). Inefficiencies in combustion, excessive heat losses, and poor airflow control are among the primary factors responsible for reduced boiler performance. In particular, an improper supply of combustion air has been identified as a significant contributor to low efficiency. Excess air beyond the required stoichiometric amount absorbs a portion of the heat released from combustion, resulting in lower flame temperatures and decreased thermal efficiency, as demonstrated in studies related to combustion control (Sari et al., 2021).

Temperature distribution within the furnace also plays a vital role in determining heat transfer effectiveness and steam generation stability. Uneven temperature profiles can lead to incomplete combustion, fluctuating steam output, and accelerated thermal stress on boiler components (Widodo, 2018; Ibrahim & Latif, 2022). These conditions highlight the importance of optimizing furnace design and airflow management. Several researchers have explored design modifications aimed at improving combustion stability and reducing heat losses. Improvements such as adjusting burner position, optimizing airflow channels, and applying appropriate refractory insulation have shown promising results, with reported efficiency increases ranging from 3.2% to 5% (Simanjuntak, 2021; Putra & Nugraha, 2022). Particularly, the use of locally sourced refractory materials—such as fire bricks, cement, and sand—has been proven effective in enhancing thermal durability and minimizing wall heat losses in small-scale boilers.

Although these studies contribute significantly to improving boiler performance, most previous research has not focused on the detailed influence of air inlet velocity on furnace temperature distribution in mini fire-tube boilers. This research gap is important because airflow directly affects flame stability, combustion completeness, and the uniformity of heat distribution, all of which determine the boiler's thermal efficiency. Addressing this gap would provide valuable insights into optimizing small-capacity boiler performance, especially in

educational and industrial settings where boilers are often operated under variable load conditions.

3. METHOD

This study employed a mixed-method experimental design that integrated computational modeling with laboratory-scale testing. The computational aspect involved redesigning the boiler's combustion chamber using SolidWorks and performing thermal simulations to evaluate heat distribution and predict improvements in combustion efficiency. The experimental aspect focused on testing multiple air input velocities supplied by a blower and measuring key performance indicators such as temperature distribution, fuel consumption, and steam output. This combination of methods ensured a comprehensive evaluation of both the structural and operational impacts of the combustion chamber redesign.

The research utilized several tools, software, and materials to support the experimental and simulation activities. A 100 kg/hour fire-tube boiler served as the primary testing unit, equipped with a redesigned combustion chamber constructed from refractory brick, cement, sand, and fire-resistant cement. SolidWorks software was used extensively for three-dimensional modeling and thermal simulation analyses. The experimental setup included an adjustable air blower for varying air input velocities, thermocouples for multi-point temperature measurements, a U-tube manometer or pressure gauge to monitor boiler pressure, and a digital scale to determine fuel consumption rates. Additional tools such as a stopwatch and combustion analyzer (where available) were used to ensure accurate and reliable data acquisition. Fuel sources such as wood or biomass were used depending on the preliminary boiler operating standards.

The methodological procedure was divided into three major phases: combustion chamber redesign, simulation, and experimental testing. The redesign phase began with identifying the existing problems in the fire-tube boiler, particularly the absence of an optimal combustion chamber, which resulted in excessive heat loss and reduced efficiency. This prompted the development of a new combustion chamber design using SolidWorks, incorporating a refractory brick lining, multilayer heat insulation with sand, cement, and fire-resistant cement, and geometric optimization to improve flame stability and heat reflection. Material selection focused on refractory materials with high thermal resistance to reduce heat loss and enhance combustion effectiveness (Tabel 1).

Table 1. Combustion Chamber Redesign Steps

No	Activity	Tools/Materials
1	Measuring existing boiler geometry and operating conditions.	Calipers, measuring tape, thermometer
2	Designing new combustion chamber with improved insulation layout.	SolidWorks software
3	Adding refractory layers: fire bricks, cement, sand, fireproof cement.	Refractory materials
4	Conducting thermal simulation of heat distribution.	SolidWorks Simulation
5	Finalizing design for prototype fabrication.	Computer & CAD files

The simulation phase involved conducting thermal analysis using SolidWorks to visualize temperature distribution patterns, heat transfer behavior, and potential efficiency improvements resulting from the redesigned combustion chamber. These simulations functioned as a predictive tool to assess thermal performance before physical construction, ensuring that the design met the intended operational requirements (Figure 1)

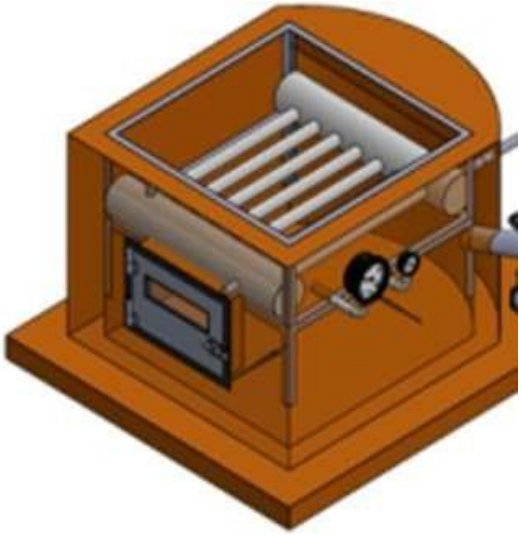


Figure 1. Modification Combustion Camber

In the experimental phase, the redesigned combustion chamber was fabricated and installed on the fire-tube boiler. An adjustable blower was configured to provide three air input velocity variations—categorized as low, medium, and high—to evaluate how airflow differences influence combustion behavior. The boiler was operated under steady-state conditions for each air input setting, and performance measurements were recorded throughout. Temperature distribution was monitored using thermocouples positioned at selected points in the chamber, while fuel consumption was measured using a digital scale. Steam production was assessed based on the mass flow rate of generated steam during operation.

Data collection focused on quantifying variables essential for evaluating boiler performance. Temperature measurements were taken at multiple strategic points to assess thermal uniformity and combustion effectiveness. Fuel consumption rates were calculated for each air input condition to determine the relationship between airflow and fuel efficiency. Steam production was recorded to assess whether the redesigned system met the expected 100 kg/hour capacity. Combustion efficiency was determined using standard boiler efficiency equations. All measurements were repeated three times to improve data reliability and minimize experimental error.

The collected data were analyzed through several steps. First, boiler efficiency was calculated by comparing the useful heat output with the total fuel heat input. The results for each air input level—low, medium, and high—were then compared to determine which airflow condition produced the highest thermal and combustion efficiency. Correlation analysis was conducted to evaluate the relationship between air velocity and performance parameters such as temperature rise, fuel savings, and steam production stability. An error analysis was also performed to identify potential sources of experimental deviation, including fluctuations in fuel quality, external airflow disturbances, and incomplete combustion events.

Finally, the conclusions were formulated based on the experimental and simulation outcomes. The study identified how variations in air input significantly affected combustion efficiency and overall boiler performance. It also evaluated the extent to which the redesigned combustion chamber contributed to efficiency improvements. The findings determined the optimal air input level that maximizes the operational efficiency of the 100 kg/hour fire-tube boiler system.

4. RESULT & DISCUSSION

4.1 Experimental Results

The results of the experimental testing on variations in air velocity and their influence on the boiler's performance are presented in Table 4. The primary parameters measured include combustion chamber temperature, fuel consumption, and overall thermal efficiency.

Table 4. Experimental Results at Various Air Velocities

Air Velocity (m/s)	Combustion Chamber Temperature (°C)	Fuel Consumption (kg)	Efficiency (%)
3	290	3.5	62.1
5	340	3.2	68.5
7	385	2.9	74.3
9	410	2.6	81.2
11	435	2.3	86.0
13	420	2.5	80.4
15	400	2.7	76.3
17	370	3.0	71.8

4.2 Discussion

4.2.1 Effect of Air Velocity on Combustion Chamber Temperature

The results show that increasing the air velocity initially raises the combustion chamber temperature, reaching a maximum of 435°C at 11 m/s. This indicates that adequate air supply enhances oxidation reactions and improves flame intensity, resulting in higher combustion temperatures.

These findings are consistent with Putra et al. (2019), who reported that "increasing air supply up to the optimal point enhances flame temperature due to improved mixing and oxidation." However, Putra also emphasized that excessive air can decrease temperature due to a cooling effect. This phenomenon is also observed in this study, where temperatures drop at higher velocities such as 15 m/s and 17 m/s, reaching only 370°C. The temperature distribution trend with respect to air velocity is illustrated in Figure 1, making it an appropriate placement point.

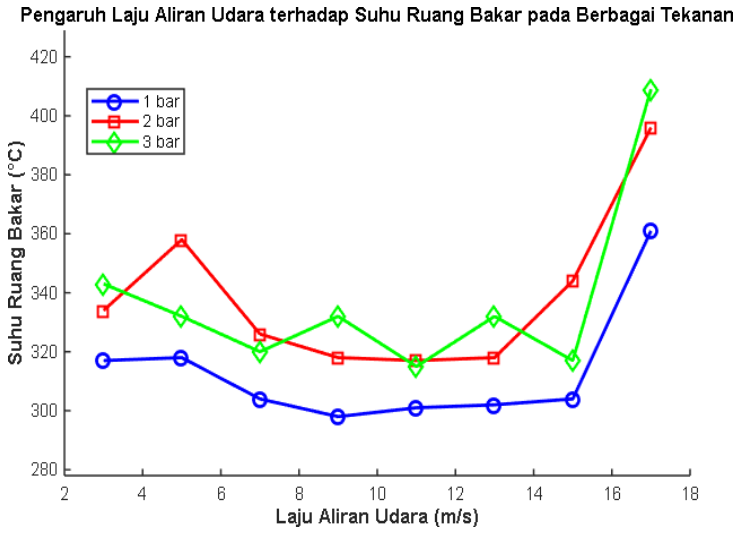


Figure 1. Effect of Air Velocity on Combustion Chamber Temperature

4.2.2 Effect of Air Velocity on Fuel Consumption

Air velocity variations also influence the amount of fuel consumed. Fuel consumption decreases significantly from 3.5 kg at 3 m/s to 2.3 kg at 11 m/s. This reduction reflects improved combustion efficiency, where more complete oxidation allows the boiler to reach the target steam output with less fuel.

This trend aligns with Siregar (2020), who noted that "fuel consumption decreases when the air–fuel ratio approaches stoichiometric conditions." After the optimum point, additional air acts as a coolant, reducing temperature and increasing fuel consumption again. This explains the rise to 3.0 kg at 17 m/s figure 2.

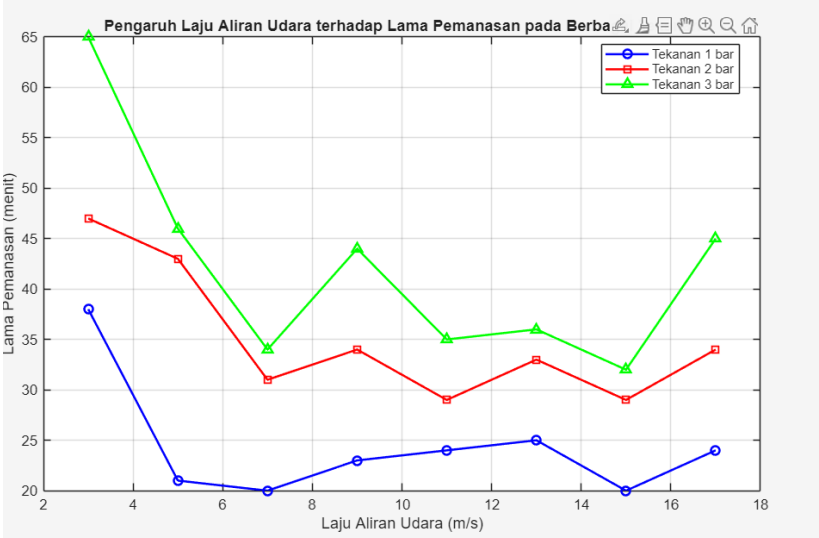


Figure 1. Effect of Air Velocity on fuel consumtion

4.2.3 Effect of Air Velocity on Boiler Efficiency

Boiler efficiency increases consistently with air velocity until reaching a peak efficiency of 86.0% at 11 m/s. This performance improvement corresponds with both the rising combustion temperature and decreasing fuel consumption at that optimal point.

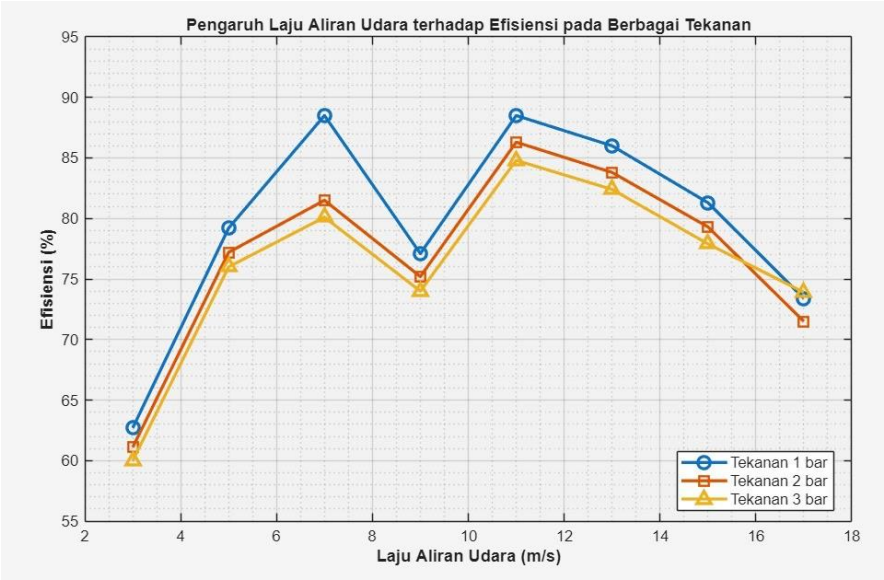


Figure 3. Effect of Air Velocity on Heating Time

Rahman and Hidayat (2020) similarly reported that optimizing air supply could increase boiler efficiency by 3–5%. Interestingly, the improvement in this study is more substantial, with an efficiency gain of approximately 23.9% between minimum and optimal conditions. The observed trend also agrees with Prasetyo et al. (2021), who stated that "maximum efficiency occurs at medium air flow rates, and efficiency declines at higher flow rates due to excessive

air dilution." A clearer representation of heating time at various air velocities is shown in Figure 3, making this section the appropriate placement for the third figure.

5. CONCLUSION

The experimental analysis of air velocity variation on the redesigned fire-tube boiler demonstrates that airflow significantly affects combustion temperature, fuel consumption, and thermal efficiency. Efficiency consistently increases from 62.1% at 3 m/s to its optimum value of 86.0% at 11 m/s, accompanied by the highest combustion temperature (435°C) and the lowest fuel consumption (2.3 kg). This confirms that an air velocity of 11 m/s provides the most complete and stable combustion. At higher velocities (13–17 m/s), efficiency decreases to as low as 71.8%, caused by excessive cooling and reduced residence time in the combustion chamber. These results align with previous studies indicating that boiler performance improves with increasing air supply until an optimum point is reached. Overall, the redesigned combustion chamber combined with controlled air velocity enhances combustion quality, reduces fuel consumption, and significantly improves boiler thermal efficiency, with 11 m/s identified as the optimal operating condition.

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