Pengaruh Masukan Udara Pada Ruang Bakar Boiler Tipe Pipa Api Untuk Kapasitas 100 Kg/Jam Terhadap Distribusi Suhu Di Ruang Bakar

Nurul Syafika[1], Abdul Gafur[2], Irwan Kurniawan[3], Vebrita Sari[4]

[1,2,3,4]Teknik Mesin, Politeknik Negeri Bengklais, Jl. Bathin Alam, Desa Suangai Alam, Bengkalis, 28714

E-mail: nurulbks55@gmail.com, abdulgafur@polbeng.ac.id

INFO ARTIKEL	ABSTRAK
	Banyak boiler mini yang beroperasi dengan desain ruang bakar kurang optimal, mengakibatkan pemborosan energi dan rendahnya produksi uap. Penelitian ini membahas pengaruh variasi masukan udara pada ruang bakar boiler pipa api kapasitas 100 kg/jam. Metode yang digunakan adalah eksperimen dengan variasi kecepatan aliran udara antara 3 m/s, 5 m/s, 7 m/s, 9 m/s, 11 m/s, 13 m/s, 15 m/s dan 17 m/s. Hasil menunjukkan laju aliran udara optimal adalah 11 m/s, yang menghasilkan efisiensi tertinggi sebesar 86% pada tekanan 1 bar Pada laju optimal ini, suhu ruang bakar menunjukkan stabilitas dan moderasi yang baik, mengindikasikan distribusi panas yang lebih merata. Sebaliknya, laju aliran udara yang terlalu rendah (3 m/s) maupun terlalu tinggi (17 m/s) menyebabkan fluktuasi suhu signifikan dan penurunan efisiensi akibat pembakaran tidak sempurna atau pendinginan berlebih. Studi ini menyimpulkan bahwa kontrol masukan udara yang presisi, khususnya pada 11 m/s, sangat penting untuk mencapai distribusi suhu yang seragam dan efisiensi termal maksimal di ruang bakar boiler. Implikasi dari penelitian ini menekankan peran krusial optimasi aliran udara dalam meningkatkan kinerja dan konservasi energi boiler.

Kata Kunci: Masukan Udara, Efisiensi Energi, Boiler |

ABSTRACT

Many mini boilers operate with suboptimal combustion chamber designs, leading to energy waste and low steam production. This study investigates the effect of air inlet variations in a fire-tube boiler with a capacity of 100 kg/h. The experimental method was applied by varying airflow velocities at 3 m/s, 5 m/s, 7 m/s, 9 m/s, 11 m/s, 13 m/s, 15 m/s, and 17 m/s. The results show that the optimal airflow velocity is 11 m/s, achieving the highest efficiency of 86% at a pressure of 1 bar. At this optimal velocity, the furnace temperature demonstrates good stability and moderation, indicating a more uniform heat distribution. In contrast, excessively low (3 m/s) or high (17 m/s) airflow velocities cause significant temperature fluctuations and efficiency losses due to incomplete combustion or excessive cooling. This study concludes that precise control of air supply, particularly at 11 m/s, is essential to achieve uniform temperature distribution and maximum thermal efficiency in the boiler combustion chamber. The implications highlight the crucial role of airflow optimization in improving boiler performance and energy conservation.

Keywords: Air Input; Energy Efficiency; Boiler.

1. INTRODUCTION

Energy efficiency is an important aspect in modern industry to support sustainability and reduce operational costs [1]. One of the equipment widely used for heating and small-scale steam production is the mini fire-tube boiler, such as the one utilized at the Bengkalis State Polytechnic for citronella distillation with a capacity of 100 kg/h [1]. A common issue encountered is the suboptimal design of the combustion chamber, were excessive outside air mixes with flue gases, lowering flame temperature. This condition leads to inefficient combustion, increased fuel consumption, and unstable steam production [2].

Previous studies have shown that excess combustion air absorbs heat and reduces energy efficiency [3], uneven temperature distribution inside the furnace reduces boiler performance [4], and certain design modifications can improve efficiency up to 3.2% [5]. Improvements using local materials such as bricks, cement, and sand have also been proven to increase heat resistance, reduce energy losses, and enhance combustion efficiency up to 5% [6]–[8].

Based on these conditions, this research aims to redesign the combustion chamber of a mini fire-tube boiler to better suit capacity and operational needs, accelerate the heating process, improve fuel efficiency, and continuously produce steam at the target of 100 kg/h.

2. METODOLOGI

This research applied a quantitative approach with an experimental method to analyze the effect of air inlet velocity variations on the combustion chamber of a vertical fire-tube boiler with a capacity of 100 kg/h, with the goal of improving energy efficiency. Airflow velocity was varied using a blower at 3 m/s, 5 m/s, 7 m/s, 9 m/s, 11 m/s, 13 m/s, 15 m/s, and 17 m/s. The airflow velocity was measured using an anemometer to ensure the accuracy of test The observed parameters included:

a. Furnace temperature
b. Steam temperature
c. Boiler water temperature
d. Fuel consumption
e. Heating time
f. Energy efficiency (final calculation result)

The experiment was conducted at Bengkalis State Polytechnic using a modified fire-tube boiler design. The vertical fire-tube boiler was a product previously tested in earlier studies, with a heating time of 95 minutes and steam endurance of ±2 minutes when fueled with used oil. Additional components in this research included a type-K thermocouple, pressure gauge, blower, and air ducts.

The research stages consisted of:

a. Preparation of tools and materials
b. Initial testing
c. Combustion chamber modification
d. Testing with airflow variations
e. Energy efficiency calculation
   f. Statistical analysis

2.1 Alat

This research was carried out using several supporting instruments for data collection and the experimental process. The instruments included a pressure gauge to measure the steam pressure from combustion, a stopwatch to record the combustion duration, a scale to measure the weight of the fuel used, an anemometer to measure the airflow rate entering the combustion chamber, a thermocouple to measure the temperature inside the combustion chamber, and a blower to supply air into the chamber.

Tabel. 1 Alat

tool	unit
Pressure gauge	1
Stopwatch	1
Scale	1
Anomometer	1
Thermocouple	1
Blower	1

2.2 Materisls

The main materials used for constructing and supporting the performance of the combustion chamber are listed below.
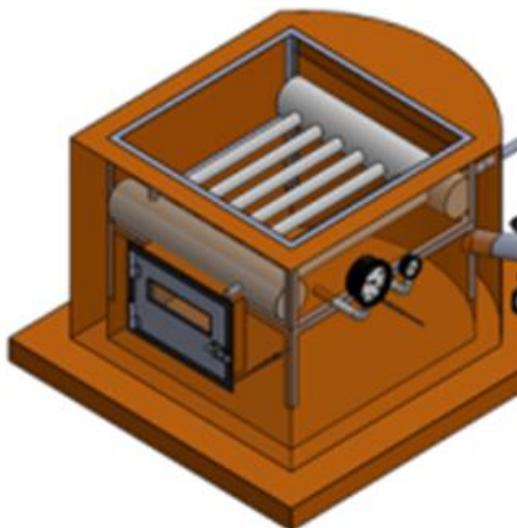
Tabel. 2 materials

materials	unit
Bricks	250 pieces
Cement	50kg
Sand	90kg
Refractory cement	50 kg

In this study, the fuel was replaced with wood, and an additional combustion chamber was built to improve efficiency. The modified design was created using SolidWorks with the following dimensions:
a. Base: length 1045 mm, width 920 mm, height 60 mm
b. Furnace: length 855 mm, width 720 mm, height 620 mm
c. Furnace rear arch: radius 460 mm

2.3 Combustion Chamber Design

The design of this boiler combustion furnace was developed based on data collected from the field. The specifications for constructing the boiler combustion chamber are as follows.
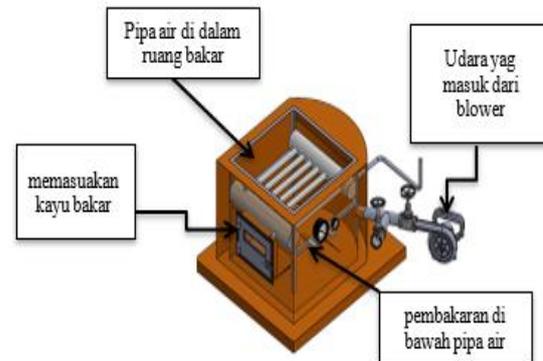

Gambar. 1 Combustion Chamber Design

Tabel. 3 Spesifikasi Ruang Bakar

Materials	:	Bricks, cement, refractory cement, and sand
Furnace length	:	855 mm = 85,5 cm
Furnace width	:	720 mm = 72,0 cm
Furnace height	:	620 mm = 62,0 cm

3. RESULTSS AND DISCUSSION

3.1 Combustion Chamber Design

The design of the fire-tube boiler was developed with additional specifications, including the incorporation of water pipes and an economizer, as well as modifications to the combustion chamber using bricks.

Gambar. 2 Hubungan Ruang Bakar dan Boiler

The relationship between the combustion chamber design and the boiler operating cycle can enhance combustion efficiency, maximize heat utilization, and support the stability of boiler operation. This design also facilitates the performance data collection process during testing, as parameters such as temperature, pressure, and airflow rate can be adjusted and monitored optimally according to the research objectives.

3.2 Test Data Results

The testing was carried out on a fire-tube boiler with a capacity of 100 kg/h using variations of inlet air velocity at 3 m/s, 5 m/s, 7 m/s, 9 m/s, 11 m/s, 13 m/s, 15 m/s, and 17 m/s. The observed parameters included furnace temperature, fuel consumption, and energy efficiency.

Tabel. 4 Experimental Data

Testing was conducted on a fire-tube boiler with a capacity of 100 kg/h at airflow velocities of 3, 5, 7, 9, 11, 13, 15, and 17 m/s. Observed parameters included furnace temperature, fuel consumption, and energy efficiency.

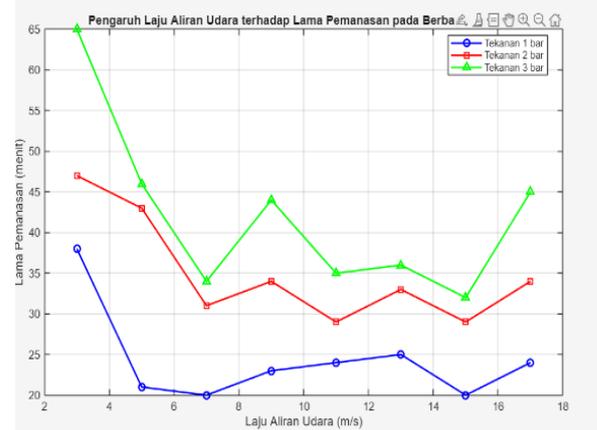| Air Velocity (m/s)	Furnace Temperature (°C)	Fuel Consumption (kg)	Efisiensi (%)
3	290	3,5	62,1
5	340	3,2	68,5
7	385	2,9	74,3
9	410	2,6	81,2
11	435	2,3	86,0
13	420	2,5	80,4
15	400	2,7	76,3
17	370	3,0	71,8

3.3 Grafik Hasil Pengujian

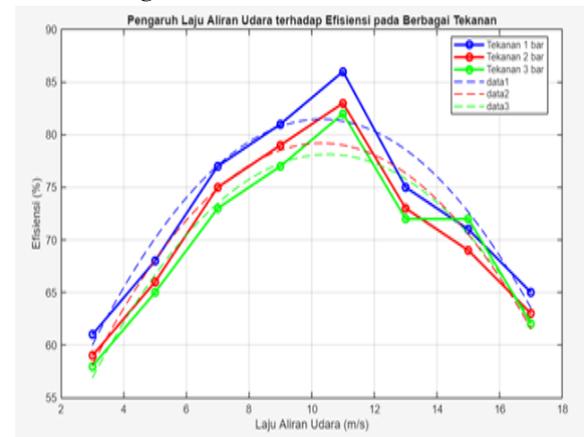*3.3.1 Laju Aliran Terhadap Suhu Ruang Bakar*
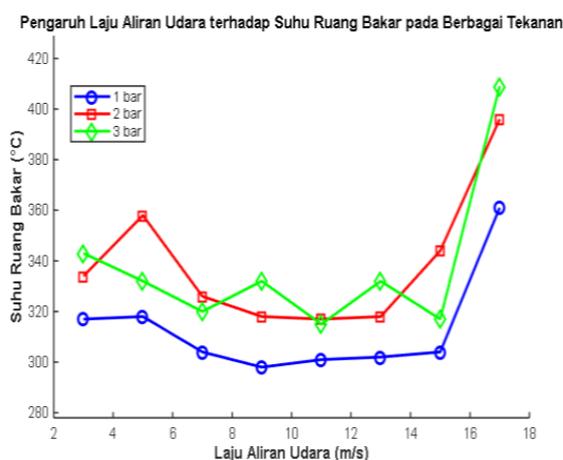
Gambar. 3 Laju Aliran Terhadap Suhu Ruang Bakar

3.3.2 Laju Aliran Terhadap Konsumsi Bahan Bakar

Gambar. 4 Laju Aliran terhadap Konsumsi Bahan Bakar

3.3.3 Laju Aliran Terhadap Efisiensi Energi

Gambar. 5 Laju Liran Terhadap Efisiensi Energi

3.4 Analysis

3.4.1 Furnace Temperature

Temperature increased with airflow velocity up to 11 m/s, reaching 435°C. Above 11 m/s, the temperature decreased due to excess air absorbing combustion heat [3], [4]. This aligns with stoichiometric theory, where complete combustion occurs at an optimal fuel-air ratio [2].].

3.4.2 Fuel Consumption

Fuel consumption decreased from 3.5 kg at 3 m/s to 2.3 kg at 11 m/s, indicating improved combustion efficiency. Beyond

11 m/s, fuel consumption increased again due to excess air supply [5], [7].

3.5.3 Efisiensi Energi

Efficiency increased up to 86% at 11 m/s and then decreased at higher velocities. This value is higher than Oktaviani [1], who reported only 70% efficiency for a similar boiler. The results also support Hasibuan & Jufrizal [4], who emphasized the importance of temperature distribution in boiler performance.

3.6.4 Comparison with Previous Studies

a. Aprijal [5] reported a 3.2% efficiency increase through furnace design modifications.

b. Prasetyo [6] and Sari & Rahman [7] demonstrated that using local materials such as bricks and refractory cement improved heat resistance by up to 5%.

c. Nibras et al. [14] and Nasrullah et al. [15] found that optimal air–fuel ratios are crucial for enhancing thermal efficiency..

This study confirms the importance of air inlet control and furnace design in achieving maximum efficiency.

3.5. Discussion

From the airflow-temperature relationship, the highest recorded temperatures occurred at 17 m/s, with 361°C at 1 bar, 396°C at 2 bar, and 409 °C at 3 bar. The lowest temperatures occurred at 9 m/s, with 298 °C, 318 °C, and 332 °C, respectively. However, the most favorable condition for system stability and efficiency was achieved at 11 m/s. At this velocity, furnace temperature remained relatively stable across pressures, ranging from 302–316 °C. This indicates more controlled combustion compared to other velocities.

Heating time data showed similar trends, with 11 m/s achieving faster and more consistent heating: 24 minutes at 1 bar, 29 minutes at 2 bar, and 35 minutes at 3 bar. Although 7 m/s occasionally produced shorter heating times, 11 m/s offered better overall performance by balancing heating speed and combustion stability. This confirms that 11 m/s not only provides moderate furnace temperatures but also supports efficient heat transfer under varying pressures.

Efficiency graphs reinforced this finding, showing that 11 m/s achieved the highest efficiency across all pressures tested: 86% at 1 bar, 83% at 2 bar, and 82% at 3 bar. The decline at higher pressures was attributed to faster combustion rates and greater heat loss through exhaust gases. Nonetheless, efficiency remained high, making 11 m/s the optimal operating velocity.

Volume calculations showed that the actual furnace volume (0.381 m³) was smaller than the minimum required (0.542 m³). Consequently, the furnace's heat capacity was limited to about 38.1 kW, while the wood fuel released 54.2 kW. This imbalance could accelerate furnace wall degradation. However, field tests confirmed that operating with 11 m/s airflow at 1 bar compensated for design limitations and still produced peak efficiency of 86%.

Overall, the combination of furnace temperature, heating time, and efficiency results indicates that 11 m/s is the best operating condition. It provides combustion stability, high energy efficiency, and consistent performance across different pressures, making it the recommended airflow rate for a 100 kg/h fire-tube boiler.

4. CONCLUSION

This study concluded that air inlet velocity significantly influences the performance of a 100 kg/h fire-tube boiler. Among the eight tested airflow velocities, 11 m/s was identified as the optimum. At this condition, furnace temperature remained most stable, fuel consumption was minimized at 2.3 kg, and energy efficiency increased to 86%. These findings highlight that maximum efficiency is strongly affected by the stoichiometric air–fuel ratio. Too low airflow results in incomplete combustion, while excessive airflow absorbs combustion heat.

The redesigned combustion chamber using local materials such as bricks, cement, sand, and refractory cement improved heat resistance, stabilized the flame, and enhanced temperature distribution inside the furnace. Achieving higher efficiency compared to previous studies further emphasizes that precise air supply control and optimized furnace design are key factors for improving small-scale boiler performance.

Moreover, this research provides practical contributions to small and medium industries that rely on mini boilers, showing that simple design improvements and proper airflow adjustments can significantly improve energy efficiency, reduce fuel consumption, and ensure more sustainable operations.

DAFTAR PUSTAKA

[1] R. Oktaviani, "Analisis Perancangan Ulang dan Optimasi Ruang Bakar Boiler Mini Tipe Pipa Api," Politeknik Negeri Bengkalis, 2021.

[2] Bambang, "Pengaruh Kelebihan Udara Terhadap Efisiensi Pembakaran Boiler," Jurnal Energi dan Mesin, vol. 9, no. 2, pp. 45–52, 2017.

[3] A. Hasibuan and Jufrizal, "Pemodelan Numerik Distribusi Temperatur pada Ruang Bakar Boiler," Jurnal Mekanika, vol. 14, no. 1, pp. 22–29, 2023.

[4] Aprijal, "Pengaruh Modifikasi Desain Ruang Bakar terhadap Efisiensi Boiler," Jurnal Teknologi Mesin, vol. 12, no. 2, pp. 101–108, 2024.

[5] Prasetyo, "Penggunaan Material Tahan Panas pada Ruang Bakar Boiler Mini," Jurnal Material Teknik, vol. 8, no. 1, pp. 11–18, 2023.

[6] D. Sari and A. Rahman, "Efektivitas Material Batu Bata sebagai Isolasi Ruang Bakar," Jurnal Rekayasa Energi, vol. 5, no. 2, pp. 77–83, 2022.

[7] Santoso, "Optimasi Desain Geometris Ruang Bakar Boiler Mini Menggunakan Material Lokal," Jurnal Mesin Nusantara, vol. 6, no. 1, pp. 33–40, 2023.

[8] A. Rifandi, S. Anwar, and M. Ikhsan, "Redesain Tungku Pembakaran Batu Bata Menggunakan Kayu dan Sekam Padi," Jurnal Energi Alternatif, vol. 7, no. 2, pp. 89–96, 2022.

[9] T. Tamaria, R. Arsyad, and N. Hidayat, "Desain Tungku Pengering Mobile Berbahan Bakar Serbuk Gergaji," Jurnal Rekayasa Mesin, vol. 10, no. 1, pp. 55–63, 2024.

[10] Salsabila, "Efisiensi Termal Water Tube Boiler Ditinjau dari Rasio Udara–Bahan Bakar," Jurnal Teknologi Energi, vol. 4, no. 1, pp. 21–29, 2024.

[11] M. E. Simanjuntak, "Pengaruh Variasi Excess Air terhadap Kinerja PLTU Batubara," Jurnal Energi Listrik Indonesia, vol. 6, no. 2, pp. 112–118, 2019.

[12] B. Siswanto, "Pengaruh Air-Fuel Ratio pada Efisiensi Termal Boiler," Jurnal Teknik Mesin Nusantara, vol. 8, no. 1, pp. 47–54, 2019.

[13] Nibras, A. Syahputra, and R. Hidayat, "Efisiensi Termal Ruang Bakar Water Tube Boiler Ditinjau dari Rasio Udara–Bahan Bakar,"

Jurnal Mekanika Energi, vol. 9, no. 2, pp. 61–69, 2024.

[14] Nasrullah, P. Lestari, and A. Kurniawan, "Studi Kecepatan Pembakaran Laminar Premix Avgas 100 LL," Jurnal Energi & Pembakaran, vol. 7, no. 3, pp. 133–141, 2023.

[15] Graha Ilmu, Boiler dan Sistem Konversi Energi, Yogyakarta: Graha Ilmu, 2019.