2nd Proceeding of International Conference on Science and Technology UISU (ICST)
"Engineering for Sustainable Future: Innovation in Renewable Energy, Green Technology, and Circular Economy"
ISSN:3063-7929 (Online)
DOI: https://doi.org/10.30743/icst

Analysis and Effect of Steam Production Amount on Efficiency of Simple Tube Boiler Applications

Suhardi Napid[1*], Ahmad Bakhori[2], Alfaridz Hartana[3], Junaidi[4,5]
[1,2,3]Faculty of Engineering, Islamic University of North Sumatra, Medan, Indonesia
[4]Faculty of Engineering, Harapan University of North Sumatra , Medan, Indonesia
[5]Postgraduate Student of Doctor of Philosophy, Mechanical Engineering, University Malaysia Perlis
*Corresponding Author: Suhardi Napid (suhardi.napid@uisu.ac.id); junaidi@studentmail.unimap.edu.my

Abstract - Boilers, or steam boilers, are crucial components in a variety of industries and applications, from power plants and chemical plants to building heating systems. Their primary function is to generate steam by heating water using a specific energy source (e.g., fossil fuels, biomass, or electricity). The steam produced is then used to drive turbines, heat industrial processes, sterilize, and for various other purposes. This research to quantitatively analyze the effect of variations in steam production on the operational efficiency of a small-scale boiler with a nominal capacity of 12 kg/hour. The experimental method is carried out by operating the boiler (a modified gas cylinder) at various levels or variations in steam production rates achieved by adjusting the fuel combustion rate, while maintaining the appropriate operating pressure. The main equipment of the experiment is an LPG gas cylinder modified as a boiler, a gas stove, a 3 kg LPG gas cylinder. The parameters measured include the fuel consumption rate, the actual amount of steam production, the feed water temperature, and the outlet steam temperature. The boiler efficiency at each steam production level is calculated based on the comparison between the energy contained in the steam produced and the input energy from the fuel. The first test with an absolute pressure of 300 kPa obtained an absolute temperature of 133.52°C and an efficiency of 84%. While the second test with an absolute pressure of 375 kPa obtained an absolute temperature of 141.3°C and an efficiency of 87%. For the third test, with an absolute pressure of 500 kPa obtained an absolute temperature of 151.83°C and an efficiency of 77.5%. The results of the study indicate a correlation between the amount of steam production and boiler efficiency, with the identification of a range of steam production rates that produce optimum efficiency with an efficiency of 87%. This information is crucial for the efficient operation of small-scale boilers, especially in applications with varying steam demand. It is hoped that this research can provide a real contribution in efforts to save energy, reduce operational costs, and minimize the environmental impact of the use of simple tube boilers in various industries.

Keywords : Steam Production Rate, Efficiency, Boiler Tubes

1. INTRODUCTION

A boiler is a closed vessel where combustion heat is transferred to water until steam is formed, which is used as work energy [1]. Increasing boiler efficiency can result in significant energy savings and reduced exhaust emissions [2]. The fuel used in a boiler can affect performance. Boiler performance can be determined by calculating the combustion efficiency value [3]. Small-scale boilers with a nominal steam production capacity of 12 kg/hour play a crucial role in a variety of specific applications, including providing steam for sterilization in small healthcare facilities, process heating in cottage or micro-scale industries, and as a steam source for experiments and education. The operational efficiency of these steam generation systems has direct implications for energy consumption, operating costs, and the overall environmental footprint. Efficiency improvements, even on a small scale, can result in significant energy savings and contribute to more sustainable practices.

One of the fundamental operating parameters believed to have a close correlation with boiler efficiency is the steam production rate. The steam production rate directly reflects the boiler capacity utilization rate and is directly proportional to the amount of fuel consumed per unit time. Under low steam production load conditions, the proportion of constant heat losses (such as radiation and convection losses from the boiler surface) can be more significant compared to the energy effectively transferred to the water to produce steam. As a result, the overall efficiency of the boiler can decrease. Conversely,[4] at higher steam production rates, combustion dynamics, heat transfer within the boiler heat exchanger, and potential heat losses through flue gases can be determining factors for efficiency.

Research on boiler performance and efficiency has been a continuing focus in thermal engineering. Numerous studies have investigated the influence of operating parameters such as pressure, feedwater temperature, and fuel type on boiler efficiency at various capacity scales [5]. However, specific literature that thoroughly analyzes the effect of variations in steam production rate on boiler efficiency with very limited steam production capacities, such as 12 kg/hr, is still relatively limited. [6] Longer testing times have resulted in improved steam power and efficiency values.

A comprehensive understanding of how changes in steam production rate affect the efficiency of a 12 kg/h small-scale boiler is crucial for optimizing its operation. Identifying the most efficient operating point will allow users to adjust steam production loads as needed without sacrificing energy efficiency. Furthermore, the results of this study can provide valuable insights for small-scale boiler designers and manufacturers in their efforts to improve designs to achieve higher efficiencies at various steam production levels. A boiler is considered efficient if its efficiency falls within the range of 70-90% [7]. The value of the amount of steam produced is estimated by the amount of steam required for each device. In relation to other variables, boiler efficiency can be calculated using the

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equation [8]. The advantages of using a simple tube boiler are Low Initial Investment Cost, Simple Maintenance, Fast Response to Low Loads and the disadvantages are Limited Pressure and Steam Capacity, Slow Response to Load Fluctuations, Higher Risk of Explosion on Failure [9]. Simple tube boilers (fire tube boilers) are widely used in various applications, especially in the industrial and commercial sectors that require low to medium pressure steam with the main applications being the food and beverage industry, textile and laundry industry, small and medium industries [10].
Therefore, this research is expected to make a significant contribution to more efficient energy utilization in applications that use small-scale boilers as a steam source.

2. RESEARCH PURPOSES

1. Quantitatively analyze the effect of variations in the amount of steam production on the operational efficiency of a small-scale boiler with a nominal capacity of 12 kg/hour.
2. Calculate the amount of Steam Production (Q) and the amount of Fuel consumption (q) through the equation.
3. Determining the thermal efficiency value of a simple tube boiler after operating at various capacities or different steam production rates.

3. MATERIALS AND TOOL

3.1 Material

Materials Used

1. Water: Water is the primary material used in boilers to produce steam. The amount of water converted to steam during the test is 12 kg. Scientifically, under ideal conditions and standard atmospheric pressure, 1 kg of water heated to its boiling point and undergoing a complete phase change will produce 1 kg of steam [11].
2. Gas: Gas is the fuel source used in this test. The gas used comes from a 3 kg LPG cylinder.

3.2 Equipment

The tools used in the testing included an electric hand grinder, an electric hand drill, a vernier caliper, a welding machine, a balance, a wrench, a stopwatch, a thermometer gun, a gas stove, , a safety valve, a pressure gauge, a boiler glass tap, a boiler glass tube, a boiler valve, a boiler glass seal, a boiler seal, an iron socket, a double nipple, a measuring cup, heat-resistant paint and 12 kg gas cylinder modified as a simple tube boiler.

Boiler tabung sederhana diuji dengan alat untuk mendapatkan sifat mekanik dengan data berikut ini. The chemical composition of steel tubes material is C ≤ 0,2 %, Si ≤ 0,35 %, Mn ≤ 1 %, P = 0.04 %, S = 0,04 %. As for the mechanical properties: Yield Strength = 295 MPa, Tensile strength = 440 Mpa, Elongasition = 26 %.

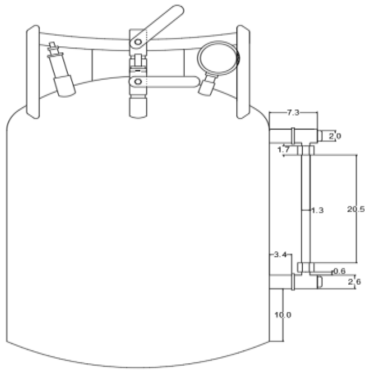

Figure 1. Modified 12kg LPG cylinder boiler design

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Figure-2.Experimental Testing with a Simple Tube Boiler

4. METHODS

This research uses an experimental approach to analyze the effect of variations in steam production rate on the efficiency of a small-scale boiler with a nominal capacity of 12 kg as a steam generator. The steps in the research methodology are explained as follows:
1. Identification of Research Variables
-Independent Variable:
-Boiler Operating Pressure (P) is varied at several levels appropriate to the boiler's capacity and design (e.g., 300 kPa, 375 kPa, and 500 kPa).
-Steam Production Amount
-Dependent Variable (Response Variable):
-Boiler Efficiency (ηboiler): Calculated based on the ratio of steam energy produced to fuel energy consumed.
-Fixed Variable (Controlled):
-Boiler Type: Boiler specifications (type, design, nominal capacity 12 kg/hour).

5. RESULTS AND DISCUSSION

First Test:
Empty boiler weight: 16.2 kg. With 18.25 liters of water used, the boiler weighs 34.45 kg after being filled with water.
The boiler weight after combustion is 30.75 kg, resulting in a mass of water converted to steam of 3.7 kg.

-Amount of Steam Production (Q)

$$Q = \frac{3{,}7\ kg}{2{,}233\ hr} = 1{,}655\ kg/hr$$

-Saturated Steam Enthalpy (h_g)($300\ kPa$) = 2724,9 kJ/kg = 650,4 $kCal/kg$

-Enthalpy of Saturated Liquid(h_f)($300\ kPa$) = 561,43kJ/kg = 134,55 $kCal/kg$
-LPG Fuel Density(ρ) = 0,55
-Total fuel consumption (q)

$$q = \frac{0{,}4\ kg}{2{,}233\ hour} = 0{,}17\ kg/hr$$
$$q = 0{,}17\ kg/hr \times 0{,}55$$
$$q = 0{,}09\ kg/hr$$

CGV from LPG gas = 11.254,61 $kCal/kg$
and then calculate the efficiency(η)

Discussion :
The equation of efficiency :

$$\eta = \frac{Q \times (h_g - h_f}{q \times CGV} \times 100\%$$

Efficiency(η) of test-1:

$$= \frac{1{,}655\ kg/hr \times (650{,}4\ kCal/kg - 134{,}55\ kCal/kg)}{0{,}09\ kg/hr \times 11.254{,}61 kCal/kg}$$

$$= \frac{1{,}655\ kg/hr \times (515{,}85\ kCal/kg)}{0{,}09\ kg/hr \times 11.254{,}61 kCal/kg}$$

$$= \frac{853{,}73}{1012{,}91} = 0{,}84$$

and so % η = 0,84 x 100 % = 84 %

Second Test:
Empty boiler weight: 16.2 kg. With 18.25 liters of water used, the boiler weighs 34.45 kg after being filled with water.
The boiler weight after combustion is 31.05 kg, resulting in a mass of water converted to steam of 3.4 kg.

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-Amount of Steam Production (Q)

$$Q = \frac{3{,}4\ kg}{2{,}17\ hr} = 1{,}566\ kg/hr$$

-Saturated Steam Enthalpy $(h_g)(375\ kPa) =$ 2735,1 kJ/kg = 653,7 $kCal/kg$
-Enthalpy of Saturated Liquid$(h_f)(375\ kPa)$ = 594,73kJ/kg = 142,14 $kCal/kg$
-LPG Fuel Density(ρ) = 0,55
-Total fuel consumption (q)

$$q = \frac{0{,}346\ kg}{2{,}17\ hour} = 0{,}159\ kg/hr$$
$$q = 0{,}159\ kg/hr \times 0{,}55$$
$$q = 0{,}087\ kg/hr$$

CGV from LPG gas = 11.254,61 $kCal/kg$
and then calculate the efficiency(η).

Discussion :
The equation of efficiency :

$$\eta = \frac{Q \times (h_g - h_f}{q \times CGV} \times 100\%$$

Efficiency(η) of test-2:

$$= \frac{1{,}566\ kg/hr \times (653{,}7\ kCal/kg - 142{,}14\ kCal/kg)}{0{,}087\ kg/hr \times 11.254{,}61 kCal/kg}$$
$$= \frac{1{,}566\ kg/hr \times (511{,}56\ kCal/kg)}{0{,}087\ kg/hr \times 11.254{,}61 kCal/kg}$$
$$= \frac{801{,}1}{979{,}15} = 0{,}818$$

and so % η = 0,818 x 100 % = 81,8 %

Third Test:
Empty boiler weight: 16.2 kg. With 18.25 liters of water used, the boiler weighs 34.45 kg after being filled with water.
The boiler weight after combustion is 31.65 kg, resulting in a mass of water converted to steam of 2.8 kg.

-Amount of Steam Production (Q)

$$Q = \frac{2{,}8\ kg}{1{,}9\ hr} = 1{,}473\ kg/hr$$

-Saturated Steam Enthalpy $(h_g)(500\ kPa) =$ 2748,1 kJ/kg = 656,81 $kCal/kg$
-Enthalpy of Saturated Liquid$(h_f)(500\ kPa)$ = 650,09kJ/kg = 152,98 $kCal/kg$
-LPG Fuel Density(ρ) = 0,55
-Total fuel consumption (q)

$$q = \frac{0{,}285\ kg}{1{,}9\ hour} = 0{,}15\ kg/hr$$
$$q = 0{,}15\ kg/hr \times 0{,}55$$
$$q = 0{,}082\ kg/hr$$

CGV from LPG gas = 11.254,61 $kCal/kg$
and then calculate the efficiency(η).

Discussion :
The equation of efficiency :

$$\eta = \frac{Q \times (h_g - h_f}{q \times CGV} \times 100\%$$

Efficiency(η) of test-2:

$$= \frac{1{,}473\ kg/hr \times (656{,}81\ kCal/kg - 152{,}98\ kCal/kg)}{0{,}082\ kg/hr \times 11.254{,}61 kCal/kg}$$

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$$= \frac{1{,}473\ kg/hr \times (503{,}83\ kCal/kg)}{0{,}082\ kg/hr \times 11.254{,}61\, kCal/kg}$$

$$= \frac{742{,}14}{922{,}87} = 0{,}804$$

and so % η = 0,804 x 100 % = 80,4 %

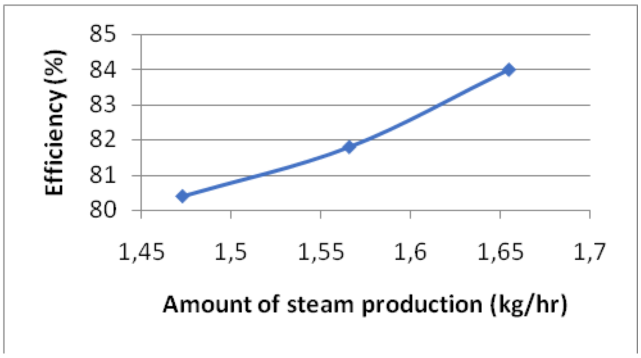

Figure 3. Efficiency as a function of the amount of steam produced

Figure 3 above is a scatter diagram that visualizes the given data. On the horizontal axis (X-axis), we place the independent variables, namely 1,473 kg/hour; 1,566 kg/hour and 1,655 kg/hour. On the vertical axis (Y-axis), we place the dependent variables, namely 80.4%; 81.8% and 84%.

The steam production rate of 1,655 kg/hour obtained an efficiency of 84 percent during the first test and experienced a decrease in the amount of production of 1,566 kg/hour with an efficiency of 81.8 percent in the second test, then the efficiency decreased with a value of 80.4 percent followed by a decrease in the amount of steam production of 1,473 kg/hour in the third test.

From the graph above, it can be observed that there is a positive relationship between the independent variables and the dependent variable. This means that along with the increase in the value of the independent variable, the value of the dependent variable tends to increase as well. The data points appear to follow a pattern that tends to climb from the bottom left to the top right. Specifically, the following:

• When the independent variable is 1,473 kg/hour, the dependent variable is 80.4%.
• When the independent variable increases to 1,566 kg/hour, the dependent variable also increases to 81.8%.
• And when the independent variable reaches 1,655 kg/hour, the dependent variable continues to increase to 84%.

This pattern indicates a positive correlation, where both variables move in the same direction. Although with only three data points, we cannot draw strong conclusions about the type of mathematical relationship (for example, whether it is perfectly linear), this graph provides a clear visual depiction of the trend.

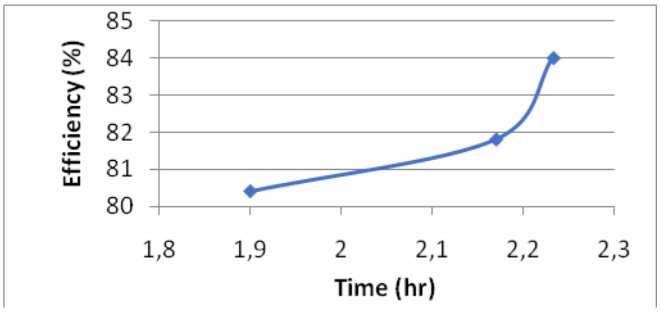

Figure 4. Efficiency as a function of Combustion time

Graph 4 above is a scatterplot that visualizes the given data. On the horizontal axis (X-axis), we plot the independent variables: 1.9 hours, 2.17 hours, and 2.233 hours. On the vertical axis (Y-axis), we plot the dependent variables: 80.4%, 81.8%, and 84.0%. Specifically, the following data are shown:

• When the independent variable is 1.9 hours, the dependent variable is 80.4%
• When the independent variable increases to 2.17 hours, the dependent variable also increases to 81.8%.
• And when the independent variable reached 2.233 hours, the dependent variable continued to increase to 84%.

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Figure 4 shows that 84 percent efficiency was achieved in 2.233 hours during the first test, and experienced a decrease in efficiency of 81.8 percent with a time of 2.17 hours in the second test. Then, efficiency decreased to 80.4 percent followed by a decrease in time of 1.9 hours in the third test.

6. CONCLUSION

Based on the analysis of the effect of steam production rate on the efficiency of a small-scale boiler with a nominal capacity of 12 kg/hour, the following conclusions can be drawn:

There is a significant correlation between steam production volume and boiler efficiency. This correlation pattern can vary depending on the boiler design characteristics and operational conditions. Generally, boiler efficiency tends to increase with increasing steam production volume until it reaches an optimal point, after which efficiency can decrease at higher steam production rates.

This research successfully identified the range of steam production volumes at which the boiler operates at maximum efficiency. This optimal point is crucial to ensure boiler operation can be tailored to steam demand without sacrificing energy efficiency.

At low steam production volumes, the proportion of constant heat losses (such as radiation and convection) becomes more dominant compared to input energy, resulting in reduced efficiency. Conversely, at high steam production volumes, the potential for heat loss through flue gas or incomplete combustion can become efficiency-limiting factors.

Understanding the effect of steam production volume on efficiency has practical implications for small-scale boiler operation. Operators can adjust steam production loads as needed to achieve higher efficiency, ultimately reducing fuel consumption and operational costs.

According to Figure 3, steam production volume increases as efficiency gradually increases until it reaches a maximum of 84%.

Figure 4 shows that the boiler combustion time increases as efficiency gradually increases from 80.4% to 81.8% to 84%.

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