Analysis of the Impact of Boiler Performance Due to the Addition of Water Tubes in a Vertical Fire-Tube Boiler with a Steam Capacity of 100 Kg/Hour

Beni Syahputra[1,a)], Khairudin Syah[2)], Aprijal Gultom[3,b)], Abdul Gafur[4)]

[1]*Mechanical Engineering, Bengkalis State Polytechnic, Bengkalis, Indonesia*
[2]*Electrical engineering, Bengkalis State Polytechnic, Bengkalis, Indonesia*
[3]*Mechanical Engineering, Bengkalis State Polytechnic, Bengkalis, Indonesia*
[4]*Mechanical Engineering, Bengkalis State Polytechnic, Bengkalis, Indonesia*

[a)]Corresponding author: benisyahputra@polbeng.ac.id
[b)]aprijalputrajayagultom@gmail.com

Abstract. The problem with this boiler is that the steam produced is not continuous, meaning that at a pressure of 1 bar, the steam lasts for approximately 2 minutes, and the heating process of this fire-tube boiler is also prolonged, taking around 95 minutes from the start until reaching a temperature of 100°C. This results in the need for more used oil as fuel. Some initial analyses to solve these issues include increasing the heating surface area of the boiler or the combustion chamber by adding water tubes and using wood as the fuel. The objective of this research is to analyze the heating time, steam retention time, wood fuel consumption, and efficiency before and after the modification with the addition of water tubes. The method used is experimental. The tests conducted before modification showed a heating time of 45 minutes, and with the addition of water tubes, the heating time was reduced to 36 minutes. The steam retention time before modification was 4 minutes, while with the addition of water tubes, it increased to 4 minutes and 42 seconds. The total wood fuel consumption for the fire-tube boiler to reach an operating pressure of 3 bar required 33.2 kg of wood, and after the addition of water tubes, the total consumption to reach 3 bar was reduced to 27 kg of wood. The efficiency of the fire-tube boiler before modification at 1 bar pressure was 66.6%, at 2 bar pressure 59.3%, and at 3 bar pressure 51.6%. After adding water tubes to the fire-tube boiler, the efficiency increased, with the efficiency at 1 bar pressure being 74.5%, at 2 bar pressure 68.8%, and at 3 bar pressure 62.9%. This indicates that the addition of water tubes can improve the boiler's efficiency.

Keyword: Fire-tube boiler, Steam production continuity, Water tube modification, Boiler efficiency improvement

INTRODUCTION

A boiler is a closed steel vessel used to produce steam. Steam is generated by heating water inside the vessel using fuel. Typically, boilers utilize liquid fuels (such as residue or diesel), solid fuels (like coal or wood), or gas. The heat produced from the combustion of the fuel (or other heat sources) is transferred to the water inside the boiler, causing the water to heat up or convert into steam [1].

The boiler previously constructed at Politeknik Negeri Bengkalis is a vertical fire-tube type. This boiler has a steam production capacity of 100 kg/hour and is used for citronella (serai wangi) distillation. It is equipped with 17 fire tubes, each with a diameter of 40 mm, and the body of the boiler has a diameter of 500 mm [2]. The main issue with this boiler is that during the distillation process, the steam produced is not continuous. At a pressure of 1 bar, the steam lasts for only about 2 minutes, leading to suboptimal citronella distillation. Moreover, the heating process of the boiler is prolonged, taking approximately 95 minutes from start-up to reach 100°C, resulting in higher fuel consumption.

To address these issues, preliminary analyses suggest increasing the heating surface area of the boiler or combustion chamber by adding water tubes to heat the boiler feedwater. Several studies have explored similar modifications. For instance, [3] researched the design and construction of a mini steam boiler with a capacity of 30 liters/30 minutes, combining fire-tube and water-tube types. The study found that it took 30 minutes to produce wet steam at a pressure of 4 bars and a temperature of 160ºC. Similarly, [4] conducted research on the efficiency of a mini water-tube boiler with a capacity of 20 kg/hour and a pressure of 3 bars, designed for operational needs in hospitals, particularly for sterilization and laundry services. The actual steam production of this mini boiler was 14.3 kg/hour, with fuel consumption of 1.17 kg/hour at an average pressure of 3.01 bars and an average exhaust gas temperature of 251.94°C. Another study by Rispi Andra (2021) on the performance of a mini water-tube steam boiler with the same capacity and pressure also found that the actual steam produced was 14.3 kg/hour, with fuel consumption of 1.17 kg/hour, at an average pressure of 3.01 bars, and an average exhaust gas temperature of 251.94°C.

The objective of this research is to analyze the impact of heating time due to the addition of water tubes in a vertical fire-tube boiler with a steam capacity of 100 kg/hour. The study will focus on key boiler performance parameters, such as heating time, fuel consumption, and boiler efficiency. The findings are expected to improve the boiler's performance, allowing it to produce steam more continuously, ensuring a stable and reliable steam supply.

METHODS

The research to be conducted employs a quantitative research method through experimentation. This involves varying independent variables to observe their effects on dependent variables, with the aim of determining cause-and-effect relationships. Data collected from the experimental tests will be numerical and subsequently analyzed statistically to test the established hypotheses. The independent variables in this study include the design of the water tubes, and other independent variables are the pressure levels set at 1 bar, 2 bar, and 3 bar. The dependent variables measured or observed in the experiment include temperature, fuel consumption, efficiency, heating time, and steam retention time, as detailed in Table 3. The boiler used in this study is a vertical fire-tube boiler with a steam capacity of 100 kg/hour, previously constructed at Politeknik Negeri Bengkalis. Data for the boiler to be tested is presented in Table 1 and the design in Figure 1.

Table 1, Design of Vertical Fire-Tube Boiler

		Keterangan
Types of boilers	:	Vertical fire tube *boiler*
Boiler shell diameter	:	500 mm
boiler height	:	1200 mm
Fire tube diameter	:	40 mm total number of pipes: 17 units
plate thickness	:	1,2 mm
Type of plate used	:	*Carbon steel bahan SA 285 Grade V AS,E section IV*
Pipe material	:	*Seamless carbon steel SA 53 Grade B ASME Section IV*
Operating temperature	:	100 °C –150°C
Operating pressure	:	2 Bar
Fuel	:	Used oil
Type of steam	:	Saturated steam

Table 1 shows the specifications of a vertical fire-tube boiler that was previously constructed at Politeknik Negeri Bengkalis. Several tests have been conducted on this vertical fire-tube boiler, resulting in a heating time of 95 minutes and a steam duration of approximately 2 minutes when using used oil as fuel. In future research, wood will be used as the fuel, and tests will be conducted to evaluate the performance with wood fuel. Subsequently, modifications will be made by adding water tubes to enhance the performance of the boiler. The initial design of the fire-tube boiler is illustrated in **Figure 1.**

Fugure 1, Boileres vertical fire tube

The research methodology will follow several initial steps to ensure a well-structured approach. This research begins with testing an existing boiler, which may or may not have been modified, using several parameters that will be observed and have been predefined. After obtaining the initial test results, the process will proceed with modifications. The initial steps include calculating the specifications for the fire tubes that will be used. The design of the water pipes can be seen in Figure 3.

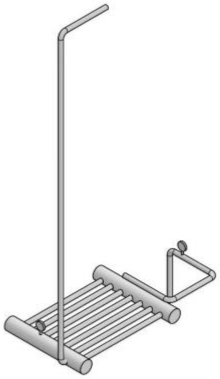

Figure 2, Design of Water Pipes

Figure 2 shows the results of the design calculations, which can be found in Table 2 below.

Table 2, Water Pipe Design

Type of Water Pipe	:	Horizontal
Volume	:	5,81 liter of air
Length of Water Pipe 1	:	3500 mm total number of pipes: 7 units
Diameter of Water Pipe 1	:	25,4 mm
Thickness of Water Pipe 1	:	3,4 mm
Length of Water Pipe 2	:	1100 mm total number of pipes: 2 units
Diameter of Water Pipe 2	:	76,2 mm
Thickness of Water Pipe 2	:	2 mm
Material of Water Pipe	:	*Seamless carbon stell* SA 53 Grade B
Operating Pressure	:	3 Bar

Next, the design is drafted using AutoCAD Inventor. After that, measurement parameter points are determined for the testing phase. Once the design is completed, tools and materials are prepared. The fabrication process is then carried out, followed by the assembly of the components into the existing fire-tube boiler. The next step is to conduct testing, with the testing scheme illustrated in Figure 3.

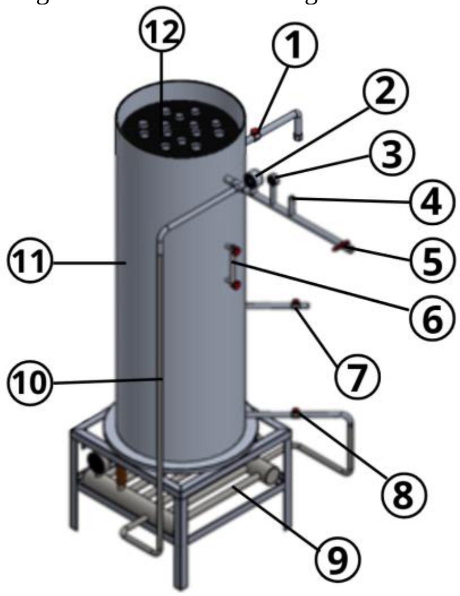

Figure 3. Vertical Fire-Tube Boiler with Addition of Water Tubes

1.	*Main steam valve*	7.	*Safety valve*
2.	Manometer	8.	*Ball valve* pipa air
3.	Thermometer	9.	Pipa air
4.	*Safety valve*	10.	Pipa keluaran uap dari pipa air
5.	*Ball velve steam*	11.	Tabung *boiler*
6.	*Sight glass*	12.	Pipa api

Figure 3 shows the testing scheme for this trial. The test conditions are conducted at atmospheric pressure during the experiment. The first step in this study is using water as the medium. Before operating the boiler, a check will be performed to ensure that all components are securely installed. Next, a leakage test will be conducted on the water pipes by closing the inlet and outlet lines. Each water pipe connection will be inspected for leaks using water.

After checking the components and pipe leakage, water is then filled into the boiler tube. The water will flow from the boiler into the water pipes, as the water pipe valves have been opened. Next, the combustion chamber is ignited using wood. As a result, the water pipes will experience heat transfer through convection. The water pipes exposed to the heat energy from the combustion will heat the water inside the water pipes and the boiler tube through the fire tube. Once the fire is lit, the heating duration is measured from 0°C until the boiling point of 100°C using a stopwatch. Concurrently with the convection heat transfer process, the water heated in the boiler at 100°C will change phase to saturated steam. The water inside the water pipes will also boil, undergoing phase change to steam. The steam in the water pipes will rise towards the steam pipe, where the steam from both the boiler and the water pipes will converge in the steam pipe. When the pressure reaches 1 bar, the steam valve is opened to release the saturated steam. The duration for which the steam remains is then measured using a stopwatch, and parameters such as steam temperature, boiler water temperature, flame temperature, exhaust gas temperature, water temperature before entering the water pipes, and the temperature of the steam exiting the water pipes are recorded. This process is then repeated at pressures of 2 bar and 3 bar.

The conduction rate equation is known as Fourier's Law of Heat Conduction, and its mathematical expression is written as follows (Kreith, Frank, 1997).

$$q_{kond} = -k.A.\frac{dT}{dx}$$

Where Qk_ = Heat flow rate (w), K is the thermal conductivity of the pipe material (W/m·K), AAA is the surface area of the pipe (m²), dT is the temperature difference between the inside and outside of the pipe (K), and dx is the thickness of the pipe (m).

TABLE 3, Parameters Input and Output

Input Parameters		Output Parameter	
Constant Variables	Variable Changes	Measured Variables	Calculated Variable
Boiler dimensions	Fuel	Water Temperature (°C)	**Heating Time** (Minutes)
Boiler capacity	Water pipe	Steam Temperature (°C)	**Steam Retention Time** (Minutes)
Boiler material		Flame Temperature (°C)	**Fuel Consumption** (Kg)
Pressure		Flue Gas Temperature (°C)	**Efficiency** (%)
		Water Pipe Temperature (°C)	

RESULTS AND DISCUSSION

The results of the fire tube design have been calculated according to heat transfer concepts. The specifications for the water pipes are detailed in Table 4, and the design of the vertical fire tube boiler with the addition of water pipes is shown in Figure 4.

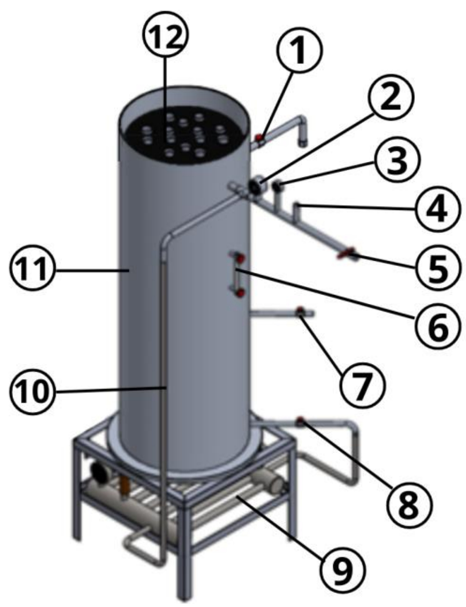

Figure 4. Vertical fire-tube boiler with the addition of water tubes

TABLE 4. Design of a Vertical Fire-Tube Boiler with Additional Water Tubes

Explanation		
Boiler Type Kapasitas	:	**Vertical combination boiler (fire-tube and water-tube)**
Capacity	:	100 kg/h
Steam Type	:	**saturated steam.**
Operating Temperature	:	100 C - 150 C
Operating Pressure	:	3 Bar
Fuel Type	:	Wood
Boiler Height	:	1120 mm = 112 cm
Fire Tube Diameter	:	40 mm (jumlah 17 pipa)
Water Tube Length	:	3500 mm (total of 7 pipes)
Water Tube Diameter	:	25,4 mm
Water Tube Thickness	:	3,4 mm
Water Tube Material	:	*Seamless carbon stell* SA 53 Grade B
Economizer Tube Length	:	1550 mm (total of 5 pipes)
Economizer Tube Diameter	:	19,05 mm
Economizer pipe diameter	:	2,7 mm
The thickness of the economizer pipe Economizer tube material	:	*Seamless carbon stell* SA 53 Grade B

3.1 Water Pipe Design Data

The design of the water pipe obtained will be based on data from the literature. The specifications for the water pipe design are derived from the data, which can be seen in Table 5, and the water pipe design is illustrated in Figure 5.

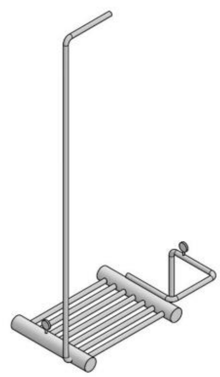

Figure 5. Vertical fire-tube boiler with the addition of water tubes.

TABLE 5. Water Pipe Installation

Keterangan		
Type of Water Pipe	:	Horizontal
Volume	:	5,81 liter of air
Length of Water Pipe 1	:	3500 mm (total of 7 pipes)
Diameter of Water Pipe 1	:	25,4 mm
Thickness of Water Pipe 1	:	3,4 mm
Length of Water Pipe 2	:	1100 mm (total of 2 pipes)
Diameter of Water Pipe 2	:	76,2 mm
Thickness of Water Pipe 2	:	2 mm
Material of Water Pipe	:	*Seamless carbon stell* SA 53 Grade B
Operating Pressure	:	3 Bars

a) Calculation of Water Volume in a Water Pipe 1:

$V_1 = \pi r_1^2$. L_1

Where:

V = Volume of the water pipe?

L_1 = 3500 mm = 3,5 m

d_1 = inner diameter (22 mm = 0,022 m)

r_1 = Inner Radius $\frac{d_1}{2}$ = 0,011 m

Thus, the volume of water in the water tube (V)

$V_1 = \pi r_1^2 . L_1$

V_1 = . $(0{,}11\ m)^2$. 2,5 m

V_1 = . 0,000121 m^2 . 3,5 m

V_1 = . 0,0004235 m^3

V_1 = 0,0013315 m^3

b) Calculation of Water Volume in a Water Pipe 2:

$V_1 = \pi r_1^2$. L_1

Where:

V = Volume of the water pipe?

L_2 = 1100 mm = 1,1 m

d_2 = inner diameter (72 mm = 0,072 m)

r_2 = Inner Radius $\frac{d_2}{2}$ = 0,036 m

Thus, the volume of water in the water tube (V)

$V_1 = \pi r_1^2 . L_1$

V_1 = . $(0{,}036\ m)^2$. 1,1 m

V_1 = . 0,001296 m^2 . 1,1 m

V_1 = . 0,0014256 m^3

V_1 = 0,0044808 m^3

$V_{total} = V_1 + V_2$

V_{total} = 0,0013315 m^3 + 0,0044808 m^3

V_{total} = 0,0058123 m^3

Because 1 cubic meter is equal to 1000 liter:

V_{total} = 0,0058123 x 1000 liter

V_{total} = 5,8123 liter

Thus, the volume of water that can be accommodated by the two pipes is 5,81 liter.

c) Calculating the Number of Water Pipes

$$L = \sqrt{\left(\pi \frac{h}{h_1} D\right)^2 + h^2}$$

Where:

L	=	Length of the water pipe (m) ?
H	=	Length of the large pipe (0,55 m)
h_1	=	Distance between the water pipe and the large pipe (0,52 m)
R	=	Radius (0,04 m)
D	=	2π r = 2 x 0,52 x 3,14 = 3,2
Pi	=	3,14

length of the water pipe

$$L = \sqrt{\left(\pi \frac{h}{h_1} D\right)^2 + h^2}$$

$$L = \sqrt{\left(3{,}14 \frac{0{,}55}{0{,}52} 3{,}2\right)^2 + 0{,}55^2}$$

$$L = \sqrt{3{,}14\ (10{,}5 . 3{,}2)^2 + 0{,}55^2}$$

$L = \sqrt{3{,}14\ (33{,}6)^2 + 0{,}30}$
$L = \sqrt{3{,}14 \,.\, 112} + 0{,}30$
$L = \sqrt{35{,}1} + 0{,}30$
$L = \sqrt{35{,}2}$
L = 3,5 m

d) Calculating the number of water pipes:

$n = \frac{\text{Pipe length}}{\text{1 Pipe distance}}$
$n = \frac{3{,}5}{0{,}52}$
n = 6,7 = 7 shaft
Therefore, the result of the calculation indicates that 7 pieces of water pipes will be required

e) Heat Transfer by Conduction:

Where :
k = Thermal conductivity of materials (55,5 W/m.K)
A = Cross-sectional area0,19635 m^2
dT = Inlet steam temperature – outlet oil temperature (375 – 120)°C
dx = Boiler plate thickness (0,003 – 0,003)m
So :
$q_{kond} = -k.A.\ \frac{dT}{dx}$
$q = 55{,}5\ W/m.K \times 0{,}19635\ m^2 \times \left(\frac{375°C - 120°C}{0{,}003\ m - 0{,}003\ m}\right)$
$q = 55{,}5\ W/m.K \times 0{,}19635\ m^2 \times \frac{255}{0\ m}$
q = 10,89742 W/m.K x 255 m/°C
q = 2772 W
So, heat transfer through conduction is = 2772 W

f) Heat Transfer by Convection

$q = h.A.\ (T_{co} - T_{ci})$
Where:
Hc = Heat Transfer Coefficient for Convection (184 $W/m^2°C$)
A = Cross-sectional Area 0,19635 $mm)^2$
ΔT = Temperature Difference Between Incoming Steam and Outgoing Steam (°C)
$q = h.A.\ (T_{co} - T_{ci})$
q = 184 $W/m^2/K$ x 0,19635 x (411°C - 119°C)
q = 184 $W/m^2/K$ x 0,19635 x 292°C
q = 105,49 W
Thus, heat transfer by conduction is = 105,49 W

g) Efficiency of Fire-Tube Boilers

Efficiency of Vertical Fire-Tube Boilers η (%)
Hg = **Saturated Steam Enthalpy**: 2675.6 kJ/kg
Hf = **Feedwater Enthalpy**: 125.74 kJ/kg
Q = **Amount of Steam Produced per Hour**: 100 kg/hr
q = **Amount of Fuel Used per Hour**: 19.5 kg/hr
HHV = **Type of Fuel and Gross Calorific Value of the Fuel**: 15,000 kJ/kg

$\eta = \frac{\text{Heat Out}}{Heat\ input}\ x\ 100\%$

$$\eta = \frac{Q\ x\ (hg - hf)}{q\ x\ HHV}\ x\ 100\%$$
$$\eta = \frac{100\ kg/hr\ \ x\ (2675{,}6\ kJ/kg - 125{,}74\ kJ/kg)}{25{,}6\ kg/hr\ \ x\ 15{,}000\ kJ/kg}\ x\ 100\%$$
$$\eta = \frac{100\ kg/jam\ \ x\ \ 2549{,}86\ kJ/kg}{384{,}00\ kg/hr}\ x\ 100\%$$
$$\eta = \frac{25498\ kJ/hr}{38400\ kJ/jhr}\ x\ 100\%$$
η = 0,666615 x 100%
η = 66,6 %

h) Efficiency of Fire-Tube Boilers with the Addition of Water Tubes

Efficiency of Vertical Fire-Tube Boilers η

Hg = **Enthalpy of saturated steam in kJ/kg:** 2706.0 kJ/kg
Hf = **Enthalpy of feedwater in kJ/kg:** 125.74 kJ/kg
Q = **Amount of steam produced per hour (kg/hr):** 100 kg/hr
q = **Amount of fuel used per hour (kg/hr):** 25 kg/hr
HHV = **Type of fuel and gross calorific value of the fuel (kJ/kg):** 15,000 kJ/kg

$$\eta = \frac{Heat\ output}{Heat\ input}\ x\ 100\%$$
$$\eta = \frac{Q\ x\ (hg - hf)}{q\ x\ HHV}\ x\ 100\%$$
$$\eta = \frac{100\ kg/hr\ \ x\ (2706{,}0\ kJ/kg - 125{,}74\ kJ/kg)}{25\ kg/hr\ \ x\ 15{,}000\ kJ/kg}\ x\ 100\%$$
$$\eta = \frac{100\ kg/hr\ \ x\ \ 2580{,}26\ kJ/kg}{375{,}00\ kg/hr}\ x\ 100\%$$
$$\eta = \frac{25802\ kJ/hr}{37500\ kJ/hr}\ x\ 100\%$$
η = 0,688053 x 100%
η = 68,8 %

3.2 Test Results and Analysis

The test data represents results obtained from an average of three tests conducted under two conditions: one with the boiler without additional water pipes and the other with the addition of water pipes. The data collection process, as described, resulted in the test data presented in Tables 6 and 7.

TABLE 6. Pengujian *boiler* vertikal pipa api

Pressure (Bar)	Steam Temperature (°C)	Flame Temperature (°C)	Boiler water temperature (°C)	Exhaust gas temperature (°C)	Heating Time (Minutes)	Time until steam is depleted (Minutes)	Fuel (Kg)	Efficiency (%)
0	0	0	0	0	45	0	0	0
1	102	340	115	135	76	1,65	25,6	66,6
2	110	380	120	140	82	3,1	28,8	59,3
3	117	405	126	148	91	4	33,2	51,6

TABEL 7. Pengujian *boiler* vertikal pipa api dengan penambahan pipa air

Pressure (Bar)	Steam Temperature (°C)	Flame Temperature (°C)	Boiler Water temperature (°C)	Exhaust gas temperature (°C)	Water temperature before entering the water pipe (°C)	Water temperature after entering the water pipe (°C)	Heating Time (Minutes)	Time until steam is depleted (Minutes)	Fuel (Kg)	Efficiency (%)
0	0	0	0	0	0	0	36	0	0	0
1	114	375	124	146	114	124	74	4.42	23	74,5
2	119	427	129	136	117	126	82	4.17	25	66,8
3	126	432	134	138	120	128	90	2.15	27	62,9

Boiler testing graphs of fire-tube boilers, along with the addition of water pipes, were then used to observe the duration of heating, steam retention time, fuel consumption, and efficiency. The observational data can be seen in graphs 6, 7, 8, and 9 below.

a) Effect of Heating Duration on Fire-Tube Boilers and the Addition of Water Tubes

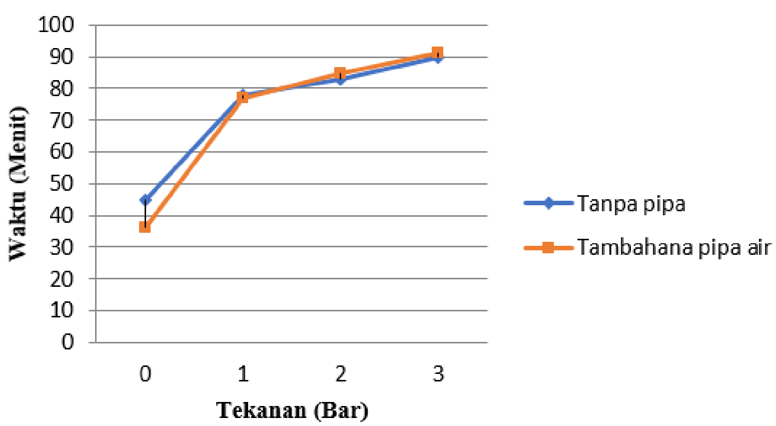

FIGURE 6. Graph of the previous heating level

In the graph shown, data from the previous heating duration tests is presented. These results were obtained from an average of 3 tests under conditions with the boiler both without and with the addition of water pipes. The heating duration of the fire-tube boiler before modification took 45 minutes to reach the boiling point of 0-100°C. After installing the water pipes in the fire-tube boiler and conducting tests, it was found that the heating duration with the additional water pipes was actually faster, taking only 36 minutes to reach the boiling point of 0-100°C.

b) The Effect of Steam Retention Time on Fire-Tube Boilers and the Addition of Water Tubes

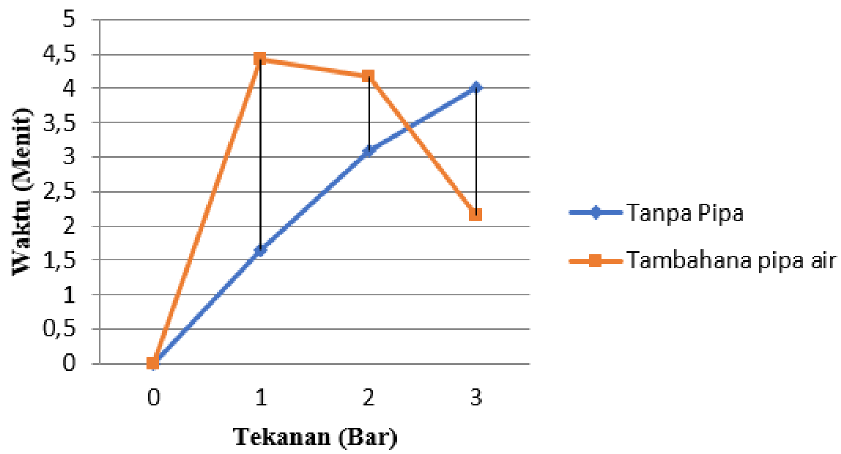

FIGURE 7. Old Steam Graph Endurance

In the graph shown the data on steam retention time represents the results obtained from an average of 3 tests conducted under two conditions: the boiler without pipes and the boiler with the addition of water pipes. For the fire-tube boiler before modification, at a pressure of 1 bar, the steam retention time was 1 minute and 65 seconds. At an operating pressure of 3 bar, the steam retention time increased to 4 minutes. This increase is due to the maintained flame temperature, which contributes to the extended steam retention time. When testing with the addition of water pipes, the steam retention time improved: at 1 bar pressure, it increased to 4 minutes and 42 seconds; at 2 bar pressure, it was 4 minutes and 17 seconds; and at 3 bar pressure, it was 2 minutes and 15 seconds.

c) The Effect of Fuel Consumption on Fire-Tube and the Addition of Water Tubes

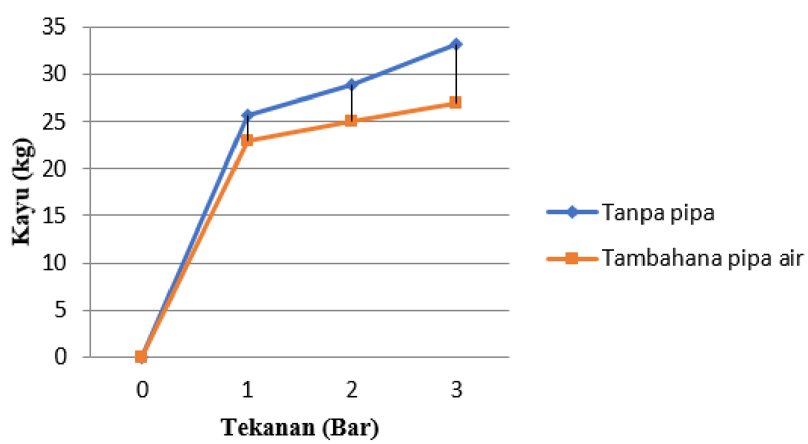

FIGURE 8, Old Steam Retention

In the graph shown, the data on the heating rate is presented. This data represents results obtained from an average of three tests, comparing the boiler's performance with and without the addition of water pipes. The fuel consumption used in the initial testing of the fire-tube boiler, before modification, required a total of 33.2 kg of wood fuel to reach an operational pressure of 3 bar. After the addition of water pipes, the total fuel consumption to reach the same pressure of 3 bar was reduced to 27 kg. This demonstrates that adding water pipes to the vertical fire-tube boiler significantly lowers the operational cost by reducing fuel consumption.

d) The Impact of Efficiency on Fire-Tube Boilers and the Addition of Water Tubes

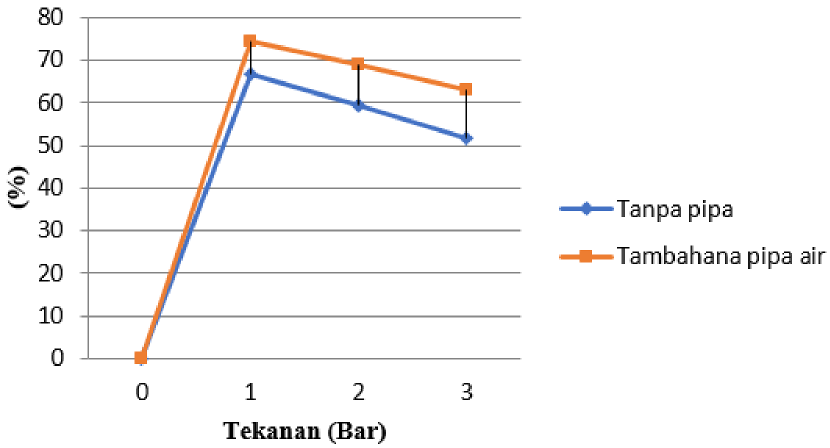

FIGURE 9, Efficiency Graph

In the graph shown, the data shows the results of the heating level tests, which were conducted with an average of three tests under different conditions: the boiler without the addition of water tubes, the boiler, and the tests with the addition of water tubes. The efficiency of the fire-tube boiler before modification, at a pressure of 1 bar, was 66.6%, at 2 bar was 59.3%, and at 3 bar was 51.6%. Subsequently, testing with the addition of water tubes to the fire-tube boiler showed an improvement in efficiency compared to before the addition. With the addition of water tubes, the efficiency at 1 bar was 74.5%, at 2 bar was 68.8%, and at 3 bar was 62.9%. This is consistent with the research conducted by [3], which indicated that the addition of water tubes enhances the efficiency of the boiler.

3.2 Discussion

By adding water pipes, the surface area for heat exchange between the hot flue gases and the water inside the pipes will increase. This allows more heat from the flue gases to be transferred to the water, enhancing the heating of the water and converting it into steam. Improved combustion efficiency results in lower flue gas temperatures exiting the boiler, as more heat is absorbed by the water. Consequently, less heat is wasted to the environment. Improving the thermal efficiency of the boiler can reduce fuel consumption and operational costs.

The testing performed on the vertical fire-tube boiler and the vertical fire-tube boiler with the addition of water tubes revealed the following data: The vertical fire-tube boiler required 45 minutes to heat from 0°C to the boiling point of 100°C. In contrast, with the addition of water tubes, the heating time decreased to 36 minutes from 0°C to 100°C, which is significantly faster than before the addition of the water tubes. The steam retention time in the vertical fire-tube boiler at 1 bar pressure was 1 minute 65 seconds, at 2 bar pressure was 3 minutes 1 second, and at 3 bar pressure was 4 minutes. After adding the water tubes, the steam retention time improved to 1 bar pressure 4 minutes 42 seconds, 2 bar pressure 4 minutes 17 seconds, and 3 bar pressure 2 minutes 15 seconds. The fuel consumption of wood during the test of the vertical fire-tube boiler up to 3 bar operating pressure was 33.2 kg. After adding the water tubes, the total fuel requirement up to 3 bar operating pressure was reduced to 27 kg, showing a significant decrease compared to before the addition of water tubes.The efficiency observed during the test of the vertical fire-tube boiler at 1 bar pressure was 66.6%, at 2 bar pressure was 59.3%, and at 3 bar pressure was 51.6%. After the addition of the water tubes, the efficiency significantly increased to 74.5% at 1 bar pressure, 68.8% at 2 bar pressure, and 62.9% at 3 bar pressure. The decrease in efficiency with higher pressures is attributed to the increased consumption of wood fuel.

CONCLUSIONS

Based on the calculations according to the ASME (American Society of Mechanical Engineers) Section IV standards and the design of the economizer and water pipes using SolidWorks software version 2017, the following conclusions are drawn:

1. Based on the design and planning results, the length of the first water pipe used is 500 mm (7 pieces) with an inner diameter of 22 mm, an outer diameter of 25.4 mm, and a wall thickness of 3.4 mm. The length of the second pipe is 1100 mm, with an outer diameter of 76.2 mm and a wall thickness of 2 mm. Therefore, the total volume of water that can be contained in both tubes is 5.8 liters.
2. The heating time for the fire-tube boiler was 45 minutes, but after modification with the addition of water tubes, it was reduced to 36 minutes, which is significantly faster than before the modification.
3. The duration of steam retention in a fire-tube boiler at 1 bar pressure was 1 minute and 65 seconds. At 2 bar pressure, it increased to 3 minutes and 1 second, and at 3 bar pressure, it further increased to 4 minutes. After the addition of the water pipes and economizer pipes, the steam retention duration at 1 bar pressure improved to 1 minute and 65 seconds, and at 2 bar pressure to 3 minutes and 1 second.
4. The efficiency of a fire-tube boiler at 1 bar pressure is 67.3%. At 2 bar pressure, it decreases to 60.6%, and at an operating pressure of 3 bar, it further drops to 53.2%. When additional water tubes are introduced, the efficiency at 1 bar pressure increases to 79.5%, at 2 bar it is 75.4%, and at 3 bar pressure, the efficiency decreases to 70.8%. The decrease in efficiency with increasing pressure is due to the increased fuel consumption, which results in reduced efficiency.

ACKNOWLEDGMENTS

We extend our gratitude to Politeknik Negeri Bengkalis and P3M for the grant provided from the PNBP 2024 fund of Politeknik Negeri Bengkalis. We also appreciate the Mechanical Engineering Department of Politeknik Negeri Bengkalis for facilitating the necessary facilities and infrastructure.

REFERENCES

[1] SUGIHARTO, Agus. Tinjauan Teknis Pengoperasian Dan Pemeliharaan Boiler. (*Swara Patra: Majalah Ilmiah PPSDM Migas*, 2016) hlm 56.
[2] OKTAVIANI, Eva, dkk. Rancang Bangun Boiler Vertikal Destilasi Minyak Serai Wangi dengan Kapasitas Uap 100 Kg/Jam. (*INOVTEK-SERI MESIN*, 2021) hlm vi.
[3] PRASTIYO, V. O. E. Rancang Bangun Mini Ketel Uap Kapasitas 30 Liter/30 Menit Dengan Penggabungan Jenis Pipa Api Dan Jenis Pipa Air. (*Simki*, 2014) hal 7.
[4] FADILLAH, Nurul, dkk. PENGUJIAN EFISIENSI KETEL UAP PIPA AIR MINI KAPASITAS 20 KG/JAM TEKANAN KERJA 3 BAR. (*Prosiding Konferensi Nasional Social & Engineering Polmed (KONSEP)*, 2021) hlm 200.
[5] B. Hasan, "Bahan Ajar Termodinamika". Politeknik Negeri Ujung Pandang, 2015.
[6] A. Khuriati, "Buku Ajar Termodinamika." Universitas Diponegoro, 2007.
[7] ruce E. Ball, Will J. Carter, "Buku Panduan ASME Bagian III, Edisi 2001". CASTI Inc, Kanada, 2001.
[8] Haryadi, A. Mahmudi, "Perpindahan Panas". Politeknik Negeri Bandung, 2012.
[9] ASWAN, Arizal. ANALISIS ENERGI BOILER PIPA AIR MENGGUNAKAN BAHAN BAKAR SOLAR. (*KINETIKA*, 2017) hlm 11.
[10] INDRIYANI, dkk. ANALISIS EFISIENSI KETEL UAP PIPA AIR DENGAN KAPASITAS MAKSIMUM 10 TON PER JAM DENGAN BAHAN BAKU BATU BARA. (*Teknika Sains: Jurnal Ilmu Teknik*, 2017) hlm 52.