

## DEVELOPMENT AND COMPARATIVE STUDY OF WATER TUBE BOILER WITH VERTICAL AND HORIZONTAL TUBE ARRANGEMENTS

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### ABSTRACT

*This work sets out a comparative study of two different boiler tube arrangements. The boiler tubes were designed and constructed for horizontal and vertical arrangements. A combustor was designed and constructed to provide the required heat by burning propane gas (C<sub>3</sub>H<sub>8</sub>) through an in-house designed and developed burner. The tube arrangements were tested individually under the same thermal condition and within the same test duration. The test results showed that for horizontal tube arrangements, the steam temperature ranges between 55°C to 133°C for the duration of 1800 seconds. While that of vertical arrangements ranges between 40°C and 125°C for the same duration. The average experimental flame temperature was found as 773K with air/fuel ratio of 34.62:1.*

**KEYWORDS:** Boiler, Calorific value, Flame temperature, Heat exchanger, Gas burner

### INTRODUCTION

A steam generator or boiler is, usually, a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel (solid, liquid or gaseous) to water, and ultimately to generate steam. It consists of two principal systems namely, the furnace and the boiler heat exchanger. The furnace is the part that produces heat by burning a fuel and the heat exchanger is the device that converts water to steam and even super critical steam.

The production of steam at different dryness levels is due to certain factors such as the fuel supply, test duration, effectiveness of heat transfer, design of the tubes (tube configurations) etc.

### CLASSIFICATIONS OF BOILERS

Boilers can be classified based on different considerations like mode of operations, fuel used, capacity, tube configurations, contents in the tube etc. but, two types of boilers are most common; Fire-tube and Water-tube boilers.

### USES/ APPLICATIONS OF BOILER

Boilers found their applications in petroleum, chemical, textiles, tannery industries e.t.c. for different purposes. They are used to produce hot water for dyeing in textiles and for converting hides into leather in tannery.

### STATEMENT OF THE PROBLEMS

It was observed that sometimes a lot of fuel is wasted when used to supply heat for a certain type of boiler before it produces the required output (steam). The problem can be from the selection of the boiler to serve the purpose or from its design.

### SIGNIFICANCE OF THE RESEARCH

In many industries, extensive uses are made of boilers and other multi-phase systems like

fluidized bed combustor, incineration plant, nuclear power plants, etc.

Since the need of heat transfer equipment is in continuous rise, both in industries and at home, then there is need for extensive research for effective and efficient heat transfer devices as well as extensive analysis of the basic considerations and elements constituting them.

### AIMS, OBJECTIVES AND SCOPE

The aim of the research is to design, construct and test a water tube boiler of different tube configurations of a boiler heat exchanger to find out the most efficient.

### LITERATURE REVIEW

A boiler is simply a device for generating steam which uses the phenomenon of boiling just like power plant, rockets, refrigerators, etc. History has recorded that the use of boiling for technological purpose occurred in steam turbine by Hero Alexandria at about the first century AD /1/.

The earliest boiler recorded in the history was that of Alexandria C.130 BC, which undergone many stages of development till when Denis Papin was able to devise a boiler which might be called the First Safety Valve. /2/.

But the first truly successful boiler was that of James Watt's Waggon in 1789 which operated at 5 p.s.i. ( $3.45 \times 10^4$  N/m<sup>2</sup>) steam pressure /3/.

### THEORETICAL ANALYSIS

#### Modes of Heat Transfer

Heat flows across temperature difference and it is transferred in many ways. In boiler system, heat is transferred from hot product of combustion to the boiler heat surface through a tube wall and to water by various mechanisms.

**Boiling**

Boiling is a volume process involving evaporation of liquid with generation of bubbles. The most common types of boiling are, nucleate and film boiling.

For forced convection local boiling inside vertical tubes, the heat transfer coefficient recommended is (5).

$$h = 2.54(T_w - T_{sat})^3 \lambda^{P/1.551} \dots\dots\dots 3.1$$

Where P is the pressure in MPa (0.5, 17MPa) h is in W/m<sup>2</sup> °C

But for film boiling outside a horizontal tube, Bromley correlation is used as (6):

$$h_c = 0.62 \left\{ \frac{k^3 g P_v (P_c - P_v) h_{fg}}{\mu_v D \Delta T} \right\}^{1/4} \dots\dots\dots 3.2$$

However, when the temperature of the wall (T<sub>w</sub>) is high, we have radiation coming into play and then the global heat transfer would be (2):

$$h = h_c \left( \frac{h_c}{h} \right)^{1/3} + h_r \dots\dots\dots 3.3$$

Where hr is the radiation heat transfer given by (6):

$$h_r = \sigma \epsilon \frac{(T_w^4 - T_{sat}^4)}{\Delta T_{sat}} \dots\dots\dots 3.4$$

Where σ is the Stefan-Boltzmann constant given as 5.68696 × 10<sup>-8</sup>W/M<sup>2</sup>K<sup>4</sup> and ε is the emmissivity of the surface.

**Rate of Heat Release by Fuel**

The rate of heat release by a fuel can be calculated by the relationship:-

$$Q = m C_v \dots\dots\dots 3.5$$

Where m is the mass flow rate of the fuel and C<sub>v</sub> it's calorific value.

**Theoretical air requirement**



44 ..... 160

2 ..... 2X160/44 = 7.27 kg of Oxygen.

Since air contains 21% Oxygen by volume, then

21% ..... 100%

7.27 ..... 7.27 X100/21 = 34.62 kg of air per hour for the 2kg of the fuel per hour.

**DESIGN AND CONSTRUCTION**

**Design Specifications**

As initial design parameters, the incinerator was designed to burn 2kg/h (5.56 × 10<sup>-4</sup>kg/s) of the propane gas and the heat generated is to be transferred through a boiler composed of 10 tubes of diameter 10mm and 500mm long.

The exchanger was to heat water (of velocity 1m/s) from 25°C to saturated steam at 5 bars. The choice of the fuel (propane) was made so that the tests would be done under clean condition.

**Thermal and Water Flow Design**

Based on the stated values, design calculations were carried out where many parameters were obtained such as the rate of heat release by the

fuel (as 25.74kW), the theoretical air requirement (as 34.62kg/2kg of the fuel) and the average theoretical flame temperature found as 833.54K, which was found using two methods (using heat of formation and sensible heat).

The data also calculated include the heat transfer coefficient (9294.94W/m<sup>2</sup> °C) and the heat transferred (2572.84W) on the vertical tube. While on the horizontal tube it was calculated as 3432.46W/m<sup>2</sup> °C) and 950.10W respectively, as well as the heat transfer due to radiation as 0.29W/m<sup>2</sup> °C).

Furthermore, water flow design was carried out, from which the volume flow rate was calculated as 7.85 × 10<sup>-5</sup> m<sup>3</sup>/s, water flow area as 7.85 × 10<sup>-5</sup> m<sup>2</sup> and the diameter of the feeder pipe was also determined as 0.03m.

**DESIGN CALCULATIONS OF THE GAS BURNER**

Initial Data

$P = 5 \text{ bar}$   
 $R = 287 \text{ J/kg K}$   
 $T_{\infty} = 25^{\circ}\text{C} = 298\text{K}$

$d = 20\text{mm}$

$\rho_{\infty} = 5.85\text{kg/m}^3$   
 $U_{\infty} = 20\text{m/s}$   
 $A = 3.14 \times 10^{-4} \text{ m}^2$

$T_w = 165.64^{\circ}\text{C}$   
 $T_{\infty} = 25^{\circ}\text{C}$

$U_{\infty} = 20\text{m/s}$   
 $d = 0.5\text{mm} = 0.0005\text{m}$   
 $\nu_f = 2.244 \times 10^{-5} \text{ m}^2/\text{s}$

Ref = 446  
 Appendix B  
 $c = 0.683$   
 $n = 0.466$

$m = 3.67 \times 10^{-2} \text{ kg/s}$   
 $c_p = 1.009 \text{ kJ/kg K}$   
 $h_b = 661 \text{ W/m}^2 \text{ K}$   
 $dw = 0.5\text{mm}$   
 $Lw = 3.0\text{m}$

$T_w = 165.64^{\circ}\text{C}$   
 $T_{\infty} = 25^{\circ}\text{C}$

Calculations and sketches

AIR HEATER

Calculation of density of free air stream:

$$\rho_{\infty} = \frac{P_{\infty}}{RT_{\infty}} = \frac{5 \times 10^5}{287 \times 298} = 5.85 \text{ kg/m}^3$$

Calculation of flow area of air

$$A = \frac{\pi d^2}{4} = \frac{\pi (0.020)^2}{4} = 3.14 \times 10^{-4} \text{ m}^2$$

Calculation of mass flow rate of air:

$$M = \rho_{\infty} U_{\infty} A$$

$$= 5.85 \times 20 \times 3.14 \times 10^{-4}$$

$$= 3.67 \times 10^{-2} \text{ kg/s}$$

Calculation of film temperature

$$T_f = \frac{T_w + T_{\infty}}{2} = \frac{165.64 + 25}{2}$$

$$= 95.32^{\circ}\text{C} = 368.32\text{K}$$

$$\approx 368\text{K}$$

Air properties at film temperature from the steam table the properties are evaluated at the film temperatures as follows (17)

$K_f = 3.186 \times 10^{-5} \text{ kW/mk}$   
 $\nu_f = 2.244 \times 10^{-5} \text{ m}^2/\text{s}$   
 $Pr = 0.693$   
 $C_p = 1.0099 \text{ kJ/kg K}$

Calculation of Reynolds number at film temperature:

$$R_{ef} = \frac{U_{\infty} d}{\nu_f}$$

$$= \frac{20 \times 0.0005}{2.244 \times 10^{-5}} = 445.63$$

Calculation of convective heat transfer coefficient,  $h_b$

$$h_b = K_f C \frac{(U_{\infty} d)^n Pr^{1/3}}{\nu_f}$$

$$\therefore h_b = \frac{3.186 \times 10^{-5} \times 10^3 \times 0.683 \times (446)^{0.466} \times 6.693^{1/3}}{2.244 \times 10^{-5}}$$

$$= 660.992 \text{ W/m}^2\text{K}$$

Calculation of burner air inlet (Air heater outlet) temperature

$$T_{ib} = \frac{2T_w - T_{\infty}(1 - \delta)}{1 + \delta}$$

Where  $\delta = \frac{2mc_p}{hA} = \frac{2mc_p}{h \times \mu dwLw}$

$$= \frac{2 \times 3.67 \times 10^{-2} \times 1.009 \times 10^3}{661 \times 0.0005 \times 3.0}$$

$$\approx 24$$

$$T_{\infty} = \frac{2 \times 165.64 - 25(1 - 24)}{1 + 24}$$

$$= 36.25^{\circ}\text{C}$$

Results

$\rho_{\infty} = 5.85\text{kg/m}^3$

$A = 3.14 \times 10^{-4} \text{ m}^2$

$m = 3.67 \times 10^{-2} \text{ kg/s}$

$T_f = 368\text{K}$

$K_f = 3.186 \times 10^{-5} \text{ kW/mk}$

$\nu_f = 2.244 \times 10^{-5} \text{ m}^2/\text{s}$

$Pr = 0.693$

$C_p = 1.0099 \text{ kJ/kg K}$

$R_{ef} = 446$

$h_b = 661 \text{ W/m}^2\text{k}$

$T_{ib} = 36.25^{\circ}\text{C}$

Convergent - Divergent Air nozzles

Properties are evaluated using data for one-dimensional compressible flow for perfect gas with constant specific heat (Appendix C)

Determination of stagnation air pressure,  $P_{\infty}$

$M_e = 2.80$	$\frac{P_e}{P_o} = 0.317$	
$P_e = 0.1585$	$\frac{P_e}{P_o} M_e = 2.9$	$P_o = 5.0 \text{ bar}$
	$\therefore P_o = \frac{0.1585}{0.0317} = 5 \text{ bar}$	
	Determination of throat air pressure, $P_e$	
	$\frac{P_e}{P_o} = 0.5283$	
$P_o = 5.0 \text{ bar}$	$\frac{P_e}{P_o} M=1$	$P_e = 2.6415 \text{ bar}$
	$\therefore P_e = 0.5283 \times 5.0 = 2.641 \text{ bar}$	
	Determination of throat air temperature, $T_t$	
$T_o = 36.25\%$	$\frac{T_t}{T_o} = 0.8333$	
$= 309.25\text{k}$	$\frac{T_t}{T_o} M=1$	$T_t = 257.7\text{k}$
	$\therefore T_t = 0.8333 \times 309.25 = 257.7\text{k}$	
	Determination of throat air density, $\rho_t$	
	$P_t = \rho_t RT_t$	
$R = 287\text{j/kg k}$	$\rho_t = \frac{P_t}{RT_t} = \frac{2.6415 \times 10^5}{287 \times 257.7}$	$\rho_t = 3.57\text{kg/m}^3$
$P_t = 2.6415 \text{ bar}$	$= 3.57\text{kg/m}^3$	
$T_t = 257.7\text{k}$		
$Cp_a = 1.0173\text{kJ/kgk}$	Determination of air velocity at throat:	
$T_o = 309.25\text{K}$	$V_a = \sqrt{2Cp (T_o - T_t)}$	
$T_t = 257.7\text{K}$	$= \sqrt{2 \times 1017.3 (309.25 - 257.7)}$	$V_a = 323.86 \text{ m/s}$
	$= 323.86\text{m/s}$	
	Determination of air nozzle exit area	
$d_e = 19.5\text{mm}$	$A_e = \frac{\pi d_e^2}{4} = \frac{\pi \times (0.0195)^2}{4}$	$A_e = 2.97 \times 10^{-4} \text{ m}^2$
	$= 2.97 \times 10^{-4} \text{ m}^2$	
	Determination of nozzle area	
$M_e = 2.9$	$\frac{A^*}{A_e} = 3.850$	
	$\frac{A^*}{A_e} M_e = 2.9$	
	$\therefore A^* = \frac{A_e}{3.85} = \frac{2.97 \times 10^{-4}}{3.85}$	$A^* = 7.76 \times 10^{-5} \text{ m}^2$
	$= 7.76 \times 10^{-5} \text{ m}^2$	
	Determination of nozzle throat diameter	
$A^* = 7.76 \times 10^{-5} \text{ m}^2$	$A^* = \frac{\pi d^{*2}}{4}$	
	$\therefore d^* = \frac{\sqrt{4A^*}}{\pi} = \frac{\sqrt{4 \times 7.76 \times 10^{-5}}}{\pi}$	
	$= 9.938 \times 10^{-3} \text{ m}$	$d^* \approx 0.01 \text{ m}$
	$= 0.009938 \text{ m}$	
	$\approx 0.01 \text{ m}$	

**Construction of the Units**

The parameters and the specifications obtained in the design were used as guide for the construction and assembly of the parts.

**Materials Selection**

The selection of the materials for the fabrication was based on the design considerations such as suitability, availability, cost, workability and efficiency. Also a gas burner was adopted which has approximately the same dimensions as the designed one in terms of nozzle area, nozzle throat diameter, air nozzle exit area, etc.

**Fabrication Procedure**

**(i) The Combustion Plant**

This consists of the incinerator (which incorporates the exchanger), feed water tank and the steam receiving tank. The incinerator was fabricated from mild steel sheet of length 110cm each and the frame from angle iron 0.6mm thick.

**(ii) The boiler heat exchanger**

Using the specifications made earlier, boiler heat exchanger was fabricated for vertical and horizontal tube arrangements.

**WORKING PRINCIPLE OF BOILER**

The feed water flows out of the tank through control valve under gravity to the hose connected to the feed water pipe. The feed water pipe is blocked at the end so that the water flows into the various tubes (in case of one pass configuration). For the two and three pass, the water flows through the single pipe crossing the combustion based on the number of the pass. he propane gas is supplied from a cylinder through a hose to the burner inlet, which is ignited directly through the combustor door.

The steam generated is to flow through a steam collection pipe which carries it to the steam tank against gravity. The steam tank is placed on a stand at the top of the combustor, so that only steam can be received in the tank.

**EXPERIMENTAL METHODS AND RESULTS  
 PRELIMINARY TEST (NO LOAD TEST)**

No load tests were carried out on each configuration in order to detect air or water leakage, thus:

- a) For water leakage: water was fed to the exchanger and the leakages were detected and subsequently corrected.
- b) For air leakage; compressed air at 6bar was passed through each tube configuration.

**Measurement of Experimental Flame Temperatures**

The results of the flame temperatures measured are given in table 5.1

**Table 5.1 Flame temperatures**

Tube Configuration	Flame Temperature °C
Vertical arrangement	500
Horizontal arrangement	500

Average flame temperature was 500°C (773 K)

**TEMPERATURE PROFILE OF THE STEAM  
 MEASURING PROCEDURE**

The temperature of the steam is measured at the interval of 300s and the results were recorded in tables 5.2 (a and b) with the corresponding pressures read from the steam table.

**Table 5.2 a: Steam Temperatures of Horizontal tube arrangement**

S/N	TIME (S)	STEAM TEMPERATURE (°C)	APPROXIMATE CORRESPONDING PRESSURE (bar)
1	300	55	0.1574
2	600	85	0.5780
3	900	100	1.01325
4	1200	115	1.7000
5	1500	125	2.300
6	1800	133	3.000

**Table 5.2 b: Steam Temperatures of Vertical Tube arrangement**

S/N	TIME (S)	STEAM TEMPERATURE (°C)	APPROXIMATE CORRESPONDING PRESSURE (bar)
1	300	40	0.07375
2	600	70	0.3116
3	900	90	0.7011
4	1200	105	1.2000
5	1500	115	1.7000
6	1800	125	2.4000

**DISCUSSION OF RESULTS**

**i) Flame temperature**

The measured flame temperatures for each are presented in table 5.1. From the results obtained, it can be observed that the temperatures are almost the same. The closeness of the temperatures is possible because almost the same fuel flow rate was maintained in order to ease the comparative analysis. The average flame temperature of the whole work was found to be 500°C (773k) which is a little bit lower than the adiabatic temperature. This small difference between theoretical and experimental is due to unavoidable losses and the excess air used.

**ii) Steam Temperature**

The results of the steam temperature measured in the interval of 5 minutes (300s) are given in tables 5.2 a and b. The results showed that the horizontal arrangement attained a temperature of 133°C (3.00 bar) after 1800 seconds while

vertical arrangement attained a temperature of 125°C (2.4 bar) after the same duration.

Also from the figures 5.1 and 5.2, it can be seen that for all the configurations, the temperature continued increasing with time, but the increase was rapidly before it reached 100°C.

**6.0 CONCLUSION AND RECOMMENDATION**

The arrangements of boiler tubes have significant and strong relationship to boiler efficiency. This work has studied the performance of vertical and horizontal tube arrangements, the findings revealed that;

- i. The steam temperature in each arrangement increases with the time of the experiment, with the vertical tube configuration attaining the highest.
- ii. The vertical tube arrangement performed better than the horizontal.
- iii. The vertical tube arrangement produced higher volume of steam.

## RECOMMENDATION

In view of the great benefit which can be derived if a proper tube arrangement is employed, as revealed by this work, the following recommendations are made for further investigations into working improvement, and efficiency of the boiler plant

i. An integral design of vertical tube arrangement coupled with an economizer is recommended.

ii. It is recommended that the various tube arrangements to be tested using various fuels to further clarify the efficiency differences.

iii. Also it is recommended that the same work is to be carried out on fire tube boiler to study any possible difference from the present work.

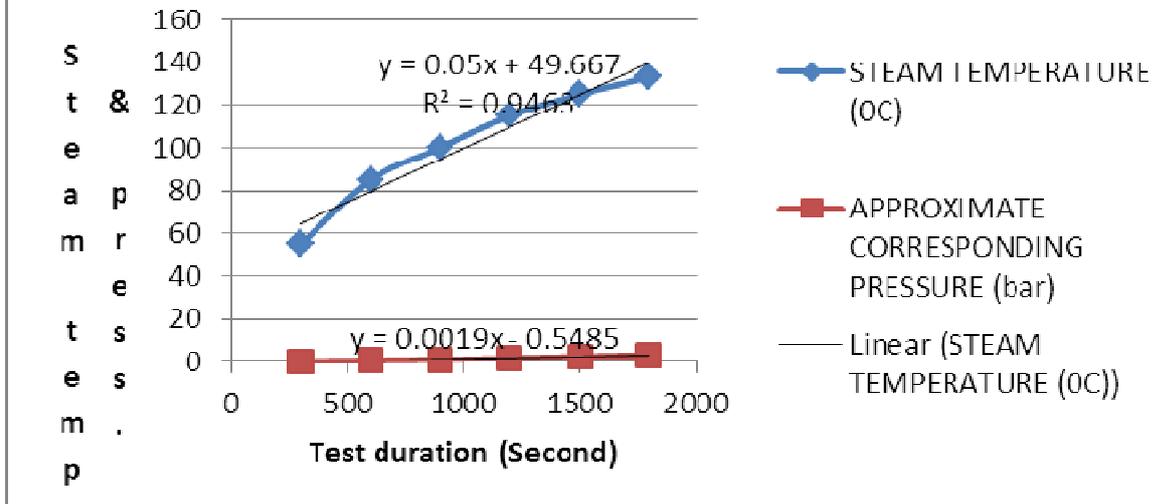
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**Figure 4.1: The Combustion Plant**

**Fig. 5.1 Graph of steam temp & pressure against test duration**



**Fig. 5.2: Steam temperature/pressure Vs Test duration**

