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Boiler Efficiency Testing

Objectives:

- To understand the operation of a fire tube boiler
- To determine the operating efficiency of the boiler

Theory

Most industrial processes require heating. This is usually provided by generating steam in boilers. Steam is used as a heating fluid as water, it evaporates at temperatures much below the metallurgical limit of carbon steel (boiler construction material) and has a high heat of vaporization.

The basic processes which occur in a boiler are combustion of the fuel in the presence of air and heat transfer from the products of combustion (flue gases) to water. The generated steam is then supplied to the process. Boilers can use a variety of fuels: solid fuels (coal, lignite, bagasse, rice husk etc.), liquid fuels (furnace oil, Light Diesel Oil, High Speed Diesel oil etc.) and gaseous fuels (natural gas).

Typically, process boilers in industry are fire tube (smoke tube) boilers with the flue gases (products of combustion) flowing in the tubes enclosed by water in the shell. These boilers are also known as package boilers or shell boilers. Package boilers are usually compact. Figure 1 shows the components of a typical smoke tube package boiler. Power plants usually have water tube boilers with water in the tubes. In industries with high pressure steam generation, water tube boilers may be used.

Fire tube steam boilers may be either high or low pressure boilers. There are three types of fire tube steam boilers: (i) horizontal return tubular boiler, (ii) scotch marine boiler, and (iii) vertical fire tube boiler. The boiler studied in the present experiment is horizontal return tubular boiler. This boiler is a 3 pass fire tube boiler.

A boiler usually has fuel, air and water supply sub-systems. Figure 2 depicts the schematic of the components in these systems for an oil fired boiler. In an oil fired boiler, the oil circuit would consist of oil storage and service tanks, oil heaters (if required) and burners. The air circuit, depending on the requirement, may have a forced draught (FD) fan and/or an induced draught (ID) fan, or may operate only on the natural draught provided by the chimney. Many boiler systems include both FD and ID fans which provide a greater control on the draught. This is known as balanced draught. The water supplied to the boiler is first stored in an intermediate (day/service) tank and then is passed through a water treatment plant. The treated feed water is supplied to the de-aerator where the condensate returns from process and some low pressure steam is added. The hot water from the de-aerator is

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then pumped to the boiler by the feed water pump.

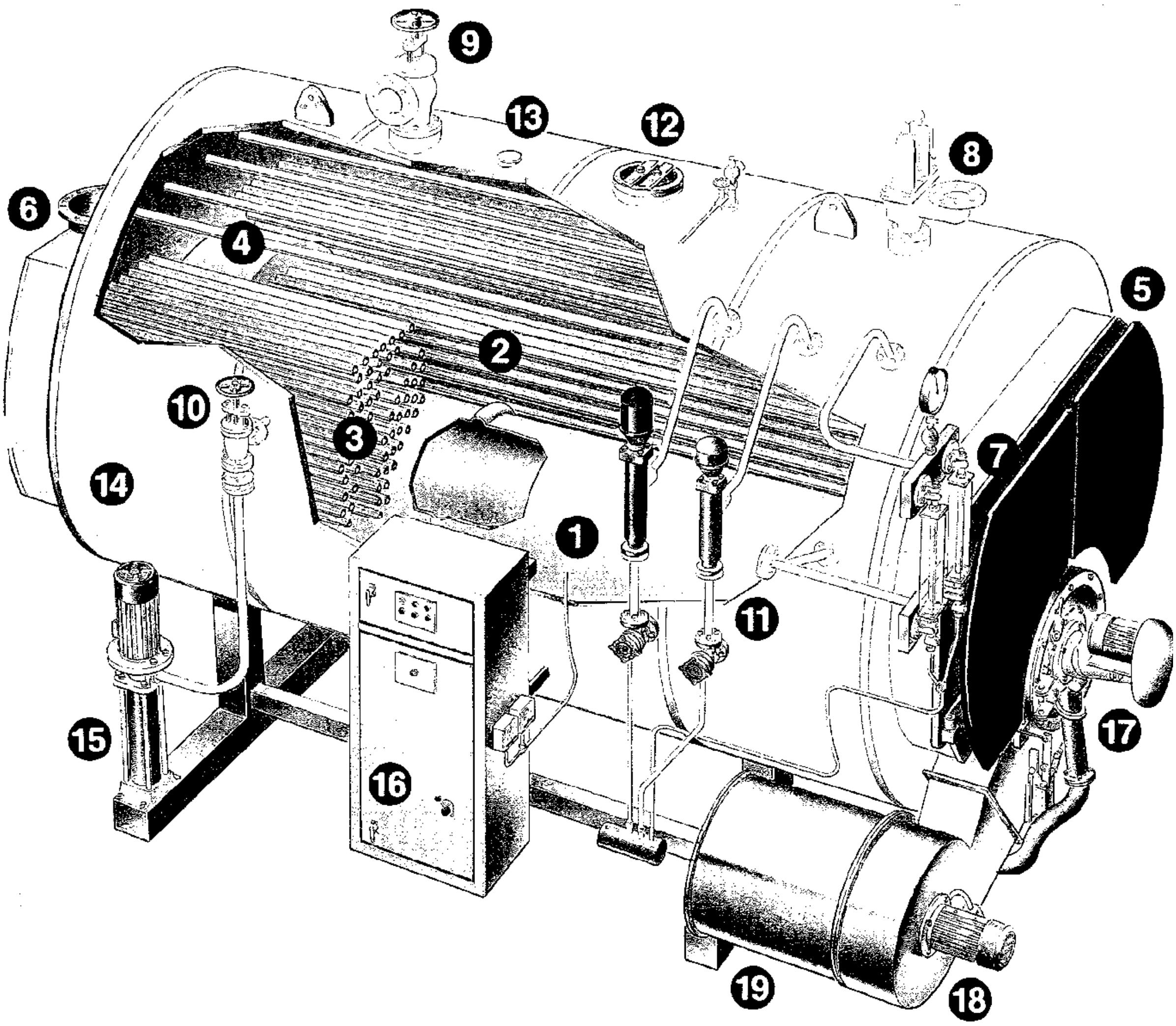

Fig. 1 A typical smoke tube package boiler

1. Furnace Tube
2. Tubes (2nd pass)
3. Tubes (3rd pass)
4. Combustion Chamber
5. Front smoke box
6. Rear outlet box
7. Sight glass
8. Safety Valve

9. Crown Valve
10. Feed Check valve
11. Level controls
12. Manhole
13. Spare Connection
14. Shell
15. Feed Pump
16. Control Panel

17. Burner
18. F. D. Fan
19. Inlet fan silencer

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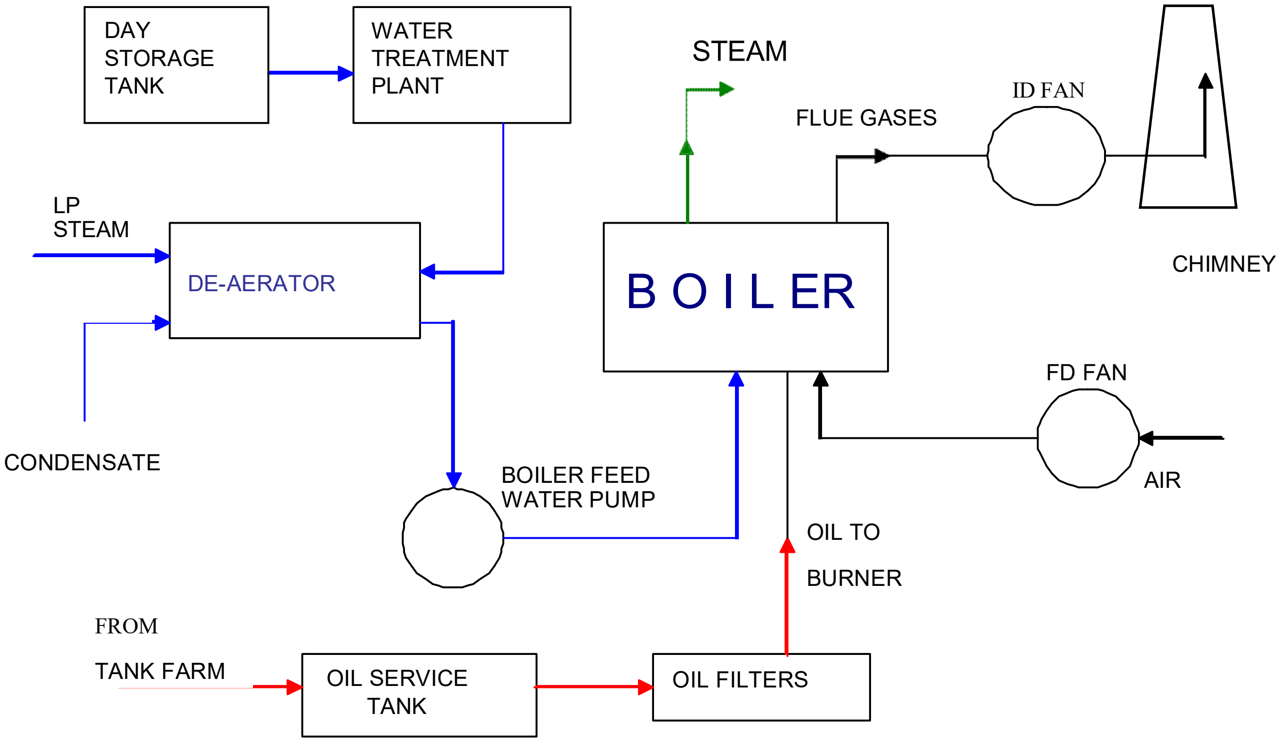

Fig. 2 Components in a boiler system

Principle of operation

When water is heated, it increases in volume and becomes lighter. This warmer water, now lighter, rises and the cooler water drops to take its place. The steam bubbles that eventually form break the surface of the water and enter the steam space.

The addition of tubes inside the drum containing the water increases the heating surface. The heating surface is the part of the boiler with water on one side and the gases of combustion on the other. By increasing the heating surface, more heat is extracted from the gases of combustion by the surrounding water. This results in a more rapid water circulation and faster formation of steam bubbles. When larger quantities of steam are released, the thermal efficiency of the boiler increases. Thermal efficiency is the ratio of the heat absorbed by the water to the heat supplied from the fuel. Modern fire tube boilers with improved design and heat transfer rates have achieved thermal efficiency as high as 80% to 85%.

Placing an internal furnace within the boiler shell greatly increases the heating surface allowing for maximum absorption of heat thus reducing the time to create steam.

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Boiler efficiency testing

Thermal efficiency of boiler is defined as the percentage of heat input that is effectively utilized to generate steam. There are two methods of assessing boiler efficiency:

1) **Direct Method:** In this method the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

2) **Indirect Method:** In this method the efficiency is the difference between the losses and the energy input.

The indirect method shall be followed in the present experiment to determine the thermal efficiency of the boiler. Indirect method is also called as heat loss method. The disadvantages of the direct method can be overcome by this method, as it determines various heat losses associated with boiler. Figure 3 depicts the typical input and output streams of a boiler, and the various heat losses from the boiler. The efficiency can be determined by subtracting the heat loss fractions from 100. An important advantage of this method is that the errors in measurement do not make significant change in the efficiency.

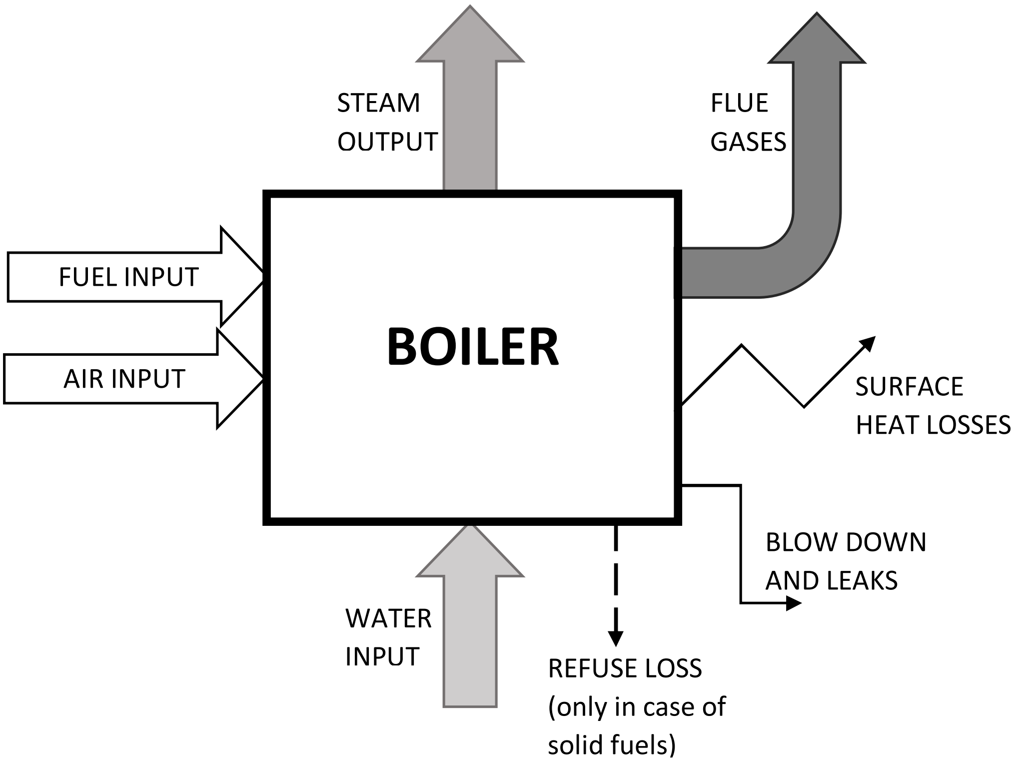

Fig. 3 Input and output streams and the heat losses of a boiler

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The following losses are accounted while estimating the thermal efficiency of the boiler: flue gas losses, blow down losses, surface losses, and refuse losses. Thus,

Boiler efficiency, η = 100 – Flue gas Losses – Blow down Losses – Surface Losses – Refuse Losses ... (1)

Here blow down losses shall be neglected. Since the fuel used is liquid, refuse losses shall be neglected.

Flue gas losses

In order to calculate flue gas losses, the air supplied for the combustion needs to be estimated. The oxygen content in the flue gas is measured. The amount of oxygen present in the flue gas is the excess oxygen supplied assuming complete combustion of the fuel occurs.

The theoretical air requirement for the combustion of the fuel can be calculated as follows. The reactions that occur during the combustion are:

$$\underset{(12)}{C} + \underset{(32)}{O_2} \rightarrow \underset{(44)}{CO_2} \quad \text{... (2)}$$

$$\underset{(2)}{H_2} + (1/2)\,\underset{(16)}{O_2} \rightarrow \underset{(18)}{H_2O} \quad \text{... (3)}$$

$$\underset{(32)}{S} + \underset{(32)}{O_2} \rightarrow \underset{(64)}{SO_2} \quad \text{... (4)}$$

Where the values in the parentheses denote molar weight of the respective element. Thus, 12 kg of carbon requires 32 kg of oxygen to form 44 kg of carbon dioxide. Therefore 1 kg of carbon requires 32/12 kg i.e. 2.67 kg of oxygen. Similarly, 1 kg of H_2 requires 8 kg of oxygen to form water and 1 kg of sulphur requires 1 kg of oxygen to form sulphur dioxide.

Let the weight fractions of carbon, hydrogen, oxygen and sulphur in the fuel oil be denoted by $\mathbf{C}$, $\mathbf{H_2}$, $\mathbf{O_2}$ and $\mathbf{S}$ respectively. Then, the theoretical oxygen required for complete combustion of 1 kg of fuel oil is given by

$$O_{2(th)} = (\mathbf{C} \times 32/12) + (\mathbf{H_2} \times 16/2) + (\mathbf{S} \times 32/32) - \mathbf{O_2} \text{ kg/kg of fuel oil} \quad \text{... (5)}$$

From molar balance for flue gas obtained per kg of fuel oil combusted,

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44 kg of CO_2 ≡ 1 kmol of CO_2 => No. of kilo moles of CO_2 in flue gas = (**C** × 44/12)/44= (**C** /12)
Similarly, no. of kilo moles of SO_2 in the flue gas = (**S** /32)
and no. of kilo moles of H_2O in the flue gas = (**H_2** /4)

No. of kilo moles of N_2 in the flue gas due to theoretical O_2= (79/21) × ($O_{2(th)}$ /32)
Let x be the kilo moles of O_2 in the flue gas.
Then, no. of kilo moles of associated N_2 = (79/21) × (x)

$$\text{Volume \% of excess } O_2 \text{ in flue gas } (O_2\%) = \frac{x \times 100}{\left[\left(\frac{\mathbf{C}}{12}\right)+\left(\frac{\mathbf{S}}{32}\right)+\left(\frac{\mathbf{H_2}}{4}\right)\right]+\left[\left(\frac{79}{21}\right)\times\left\{\left(\frac{\mathbf{C}}{12}\right)+\left(\frac{\mathbf{S}}{32}\right)+\left(\frac{\mathbf{H_2}}{4}\right)-\left(\frac{\mathbf{O_2}}{32}\right)\right\}\right]+\frac{79x}{21}+x} \quad \ldots (6)$$

$$\text{or} \quad O_2\% = \frac{x \times 100}{\left[\left(\frac{\mathbf{C}}{12}\right)+\left(\frac{\mathbf{S}}{32}\right)+\left(\frac{\mathbf{H_2}}{4}\right)\right]+\left[\left(\frac{79}{21}\right)\times\left\{\left(\frac{\mathbf{C}}{12}\right)+\left(\frac{\mathbf{S}}{32}\right)+\left(\frac{\mathbf{H_2}}{4}\right)-\left(\frac{\mathbf{O_2}}{32}\right)\right\}\right]+\frac{x}{0.21}} \quad \ldots (7)$$

In Eq. (7), O_2% is known from flue gas analysis, hence x can be deduced. Now, x kmol of O_2 in flue gas per kg of fuel oil combusted ≡ (32x)(100/23) = 3200x/23 kg of excess air per kg of fuel oil combusted ($Air_{(ex)}$)

As air contains 23% by weight of O_2, the amount of theoretical air requirement can be calculated as:

$Air_{(th)}$ = $O_{2(th)}$ / 0.23 kg/kg of fuel oil ... (8)

From Eqs. (5) and (6), we obtain

$Air_{(th)}$ = (11.59 × **C**) + (34.78 × **H_2**) + (4.35 × **S**) – (4.35 × **O_2**)

or

$Air_{(th)}$ = (11.59 × **C**) + [34.78 × {**H_2**– (**O_2**/8)}] + (4.35 × **S**) kg/kg of fuel oil ... (9)

∴Total air supplied for combustion/kg of fuel oil, TA= $Air_{(th)}$ + $Air_{(ex)}$
∴ Mass of dry flue gas, m_f = Mass of (CO_2 + SO_2 + O_2) in flue gas + N_2 in the air supplied

$$= \frac{\mathbf{C} \times 44}{12} + \frac{\mathbf{S} \times 64}{32} + (32x) + \frac{TA \times 77}{100} \text{ kg/kg of fuel oil} \quad \ldots (10)$$

$$\text{Now, \% Heat loss in dry flue gas, } L_{flue} = \frac{m_f \times C_{p(flue)} \times (T_{out} - T_{in})}{\text{GCV of fuel oil}} \times 100 \quad \ldots (11)$$

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Where $C_{p(flue)}$ = specific heat of flue gas in kJ/kg-K

T_{out} = outlet temperature of flue gas (°C)

T_{in} = inlet temperature of supply air (°C) = T_a (ambient temperature)

Surface losses

To calculate the heat loss from the surface, the following relation is employed[1]:

Surface convection and radiation heat loss, $Q_{surface}$ =

$$0.548 \times [(T_s/55.55)^4 - (T_a/55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{\frac{(196.85\ V_m + 68.9)}{68.9}} \quad \text{W/m}^2$$

... (12)

where T_s = Surface temperature (K)

T_a = Ambient temperature (K)

and V_m = Wind velocity in m/s

Now, % Heat loss from the surface, $L_{surface} = \frac{Q_{surface} \times A_s}{\text{GCV of fuel oil} \times \text{Fuel firing rate}} \times 100$... (13)

where A_s = surface area of the boiler vessel (m^2)

Finally, the boiler efficiency from equation (1) can be calculated as:

$\eta = 100 - L_{flue} - L_{surface}$ ... (14)

Procedure:

1. Initially check the water level in the vessel & diesel level present in the overhead tank using the level indicator provided at the side.
2. Measure the surface area of the boiler and note down its value. Use vane anemometer to measure wind velocity around the boiler. Note down its value.
3. Ensure that the diesel valve is open to regulate the diesel supply to the boiler. Note the ambient temperature.
4. Taking help from the boiler operator, run the boiler system.
5. Set the feed water pump system to "Automatic" mode.

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[1] *https://beeindia.gov.in/sites/default/files/4Ch1.pdf*

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6. Allow the boiler to run until the set value of steam pressure is attained, then close the steam vent.
7. After the pressure of 3 kg/cm^2 (as indicated on the pressure gauge) is reached, open the steam vent and note the steam condition, flue gas condition and oil flow rate from the EffiMax Digital Display.
8. Measure the surface temperature of the boiler at 6 different locations with the help of Infrared Gun thermometer.
9. Wait for some time and note down another set of observations after varying the fuel flow rate.
10. If the steam pressure in the boiler becomes very low, close the steam vent and let the pressure in the boiler again built up to 3 kg/cm^2, then open the steam vent and note the observations.
11. At the end of the experiment, shut down the boiler system properly taking help from the boiler operator.

Observations:

Ambient temperature, T_a= ______________ °C

Surface area of the boiler exposed to the ambient, A_s = ______________ m^2

Wind velocity, V_m = ______________ m/s

S. No.	Oil Flow Rate (kg/h)	Surface Temperature (°C)						Steam Condition		Flue Gas Condition	
		T1	T2	T3	T4	T5	T6	Pressure (kg/cm^2)	Temp. (°C)	O_2 (%)	Temp. (°C)
1											
2											
3											
4											
5											

Calculations:

Specific heat of the flue gas = __________________

GCV of the fuel oil = _________________________

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Use Eqs. (11) to (14) to calculate the indirect efficiency of the boiler for each set of reading.

Results:

S. No.	Oil Flow Rate (kg/h)	% Heat loss due to dry flue gas, L_{flue}	% Heat loss from the surface, $L_{surface}$	Indirect efficiency of the boiler, η =100 – L_{flue} – $L_{surface}$
1				
2				
3				
4				
5				

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Standard Operating Practice(SOP)

Experimental Setup- Boiler and Heat Exchangers

Use of following SOP while operating the setup is mandatory to avoid damage to equipment or user and for longer equipment life:

1. Check the water level and oil level in the tank. Close all the outlet valves and the steam vent, and open the air vent initially to remove the air inside the boiler drum till the steam pressure rises.
2. Switch ON the boiler feed pump, burner and oil pump.
3. Wait for 50 to 60 minutes till the steam pressure inside the boiler drum rises to 1 kg/cm^2, then close the air vent.
4. Wait for another 10 to 15 minutes till the steam pressure inside the boiler drum reaches to 3 kg/cm^2, thereafter start taking readings from the digital display and attached measuring instruments.
5. The steam pressure inside the boiler drum builds up fast, hence the corresponding readings from all the measuring instruments for a particular pressure should be recorded simultaneously.
6. The readings can be taken till the steam pressure reaches the cut-off pressure i.e. 8 kg/cm^2.
7. In order to take further readings, after the boiler cuts-off, the steam pressure should be reduced to 5 $kg/cm^2$by venting the steam and/or blowing down. This takes around 20 minutes. Then stop venting the steam.
8. The boiler takes around 15 minutes to reach the cut-off pressure again. Within this time period, readings should be taken at the corresponding pressure values.
9. Once the boiler reaches the peak pressure and is at steady state, the steam outlet valves can be opened and steam can be allowed in the heat exchangers one by one.
10. For each heat exchanger, the readings can be taken at various coolant flow rate. Reading must be taken at 3 minutes’ interval and 5 to 6 readings should be taken for each heat exchanger.
11. The total time required for the heat exchanger experiments is around 45 to 50 minutes.

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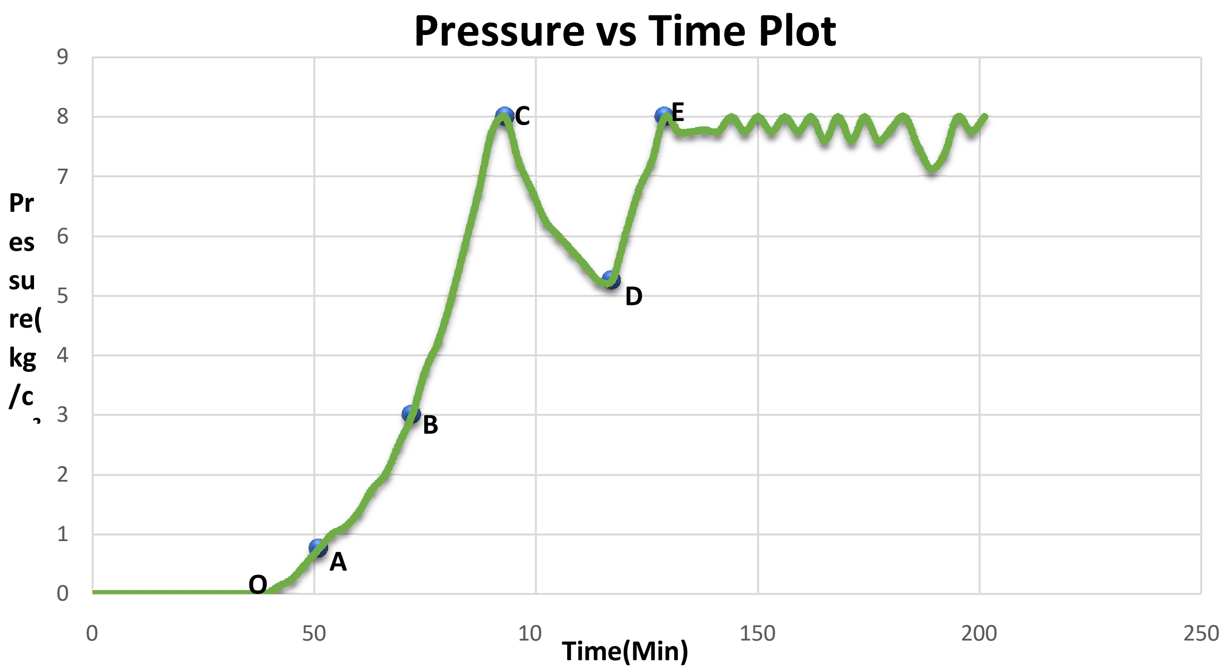
12. After completion of all heat exchanger experiments, close the steam supply valve to the heat exchangers.
13. Switch OFF the burner and water supply. Vent the steam to ambient till the pressure inside the boiler reaches to the near ambient condition.
14. Allow the water to be completely drained off from all the pipes of the heat exchangers through water outlet, and wait 5 to 10 minutes to completely close the test setup safely.



Point-O: Pressure starts building inside the boiler

Point-A: Boiler pressure reached to 1 kg/cm^2

Region BC: Start taking reading for the experiment

Point-C: Boiler cut off pressure

Region CD: Steam vent and Blow down of boiler to reduce pressure

Region DE: Second set of reading

Point E: Boiler at the cut off pressure, Steady state steam supply for heat exchanger experiments