Chemical Process Utilities
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Lecture - 23
Boilers – Question Practice

Welcome to the remaining part of the boiler. And if you recall, we previously discussed the Loeffler boiler, and then we discussed the Schmidt Hartman boiler. We discussed the Velox boiler and performed the performance evaluation concept of the boiler. In this chapter, we will discuss a couple of numerical problems attributed to the direct method and indirect method.

So, first is, our problem attributed to the direct method. Here, we discussed a couple of equations or mathematical equations in the previous lecture attributed to the direct and indirect methods related to the performance evaluation.

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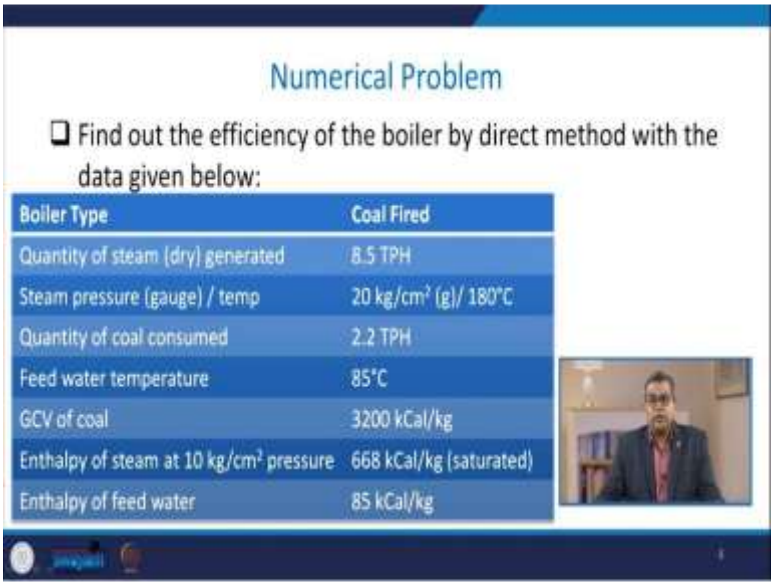

Numerical Problem

☐ Find out the efficiency of the boiler by direct method with the data given below:

Boiler Type	Coal Fired
Quantity of steam (dry) generated	8.5 TPH
Steam pressure (gauge) / temp	20 kg/cm^2 (g)/ 180°C
Quantity of coal consumed	2.2 TPH
Feed water temperature	85°C
GCV of coal	3200 kCal/kg
Enthalpy of steam at 10 kg/cm^2 pressure	668 kCal/kg (saturated)
Enthalpy of feed water	85 kCal/kg

So, in this particular problem, you need to find out the boiler's efficiency by the direct method. To support this, we have given various essential data because this particular problem numerical problem is also being used for reference purposes. So, the boiler type is a coal-fired boiler, and the quantity of steam generated on a dry basis is 8.5 tons per hour.

Steam pressure or gauge pressure per temperature is 20 kilograms per centimeter square 180 degrees Celsius. The quantity of coal consumed is almost 2.2 tons per hour. The feed water temperature is around 85 degrees Celsius. The gross calorific value of coal is 3200-kilo calories per kilogram. Enthalpy of steam at 100 kilograms per centimeter square for reference is 668-kilogram kilocalorie per kilogram on a saturation basis, and enthalpy of feedwater is again 85-kilo calorie per kilogram.

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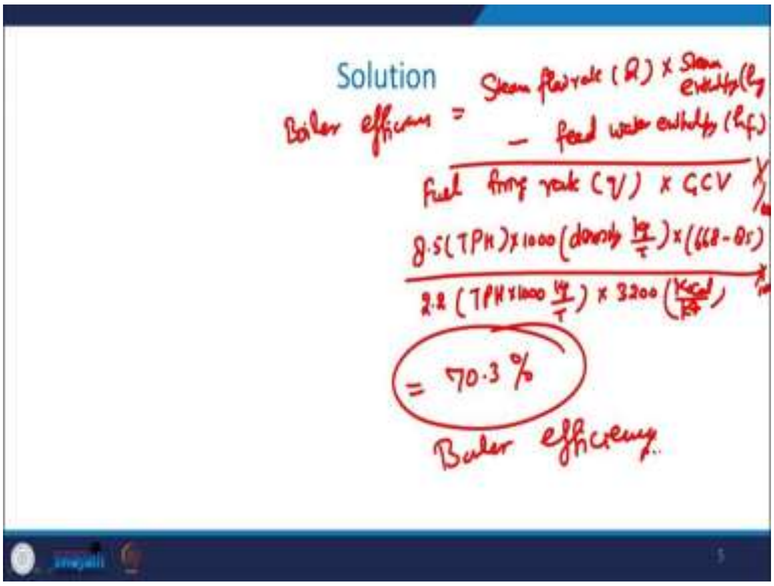

Solution

Boiler efficiency = Steam flowrate (Q) × Steam enthalpy (h_g) − feed water enthalpy (h_f) / Fuel firing rate (q) × GCV ×100

8.5 (TPH) × 1000 (density kg/T) × (668 − 85) / 2.2 (TPH × 1000 kg/T) × 3200 (kCal/kg) ×100

= 70.3 %

Boiler efficiency

So, when we talk about the efficiency,

$$Boiler\ efficiency = \frac{Steam\ flowrate(Q) \times (steam\ enthalpy(h_g) - feed\ water\ enthalpy(h_f))}{Fuel\ firing\ rate\ (q) \times Gross\ Clorific\ Value\ (GCV)} \times 100$$

$$= \frac{\left[8.5(TPH) * 1000 \left(density, \frac{kg}{T}\right) * (668 - 85)\right]}{2.2(TPH * 1000 \left(\frac{kg}{T}\right) * 3200\ \left(\frac{kCal}{kg}\right)} * 100$$

=70.3%

So, if we calculate, it comes out to be 70.3%. So, this is our boiler efficiency. So, this way is quite simple, and you may require certain you can say data which is usually given by various handbooks.

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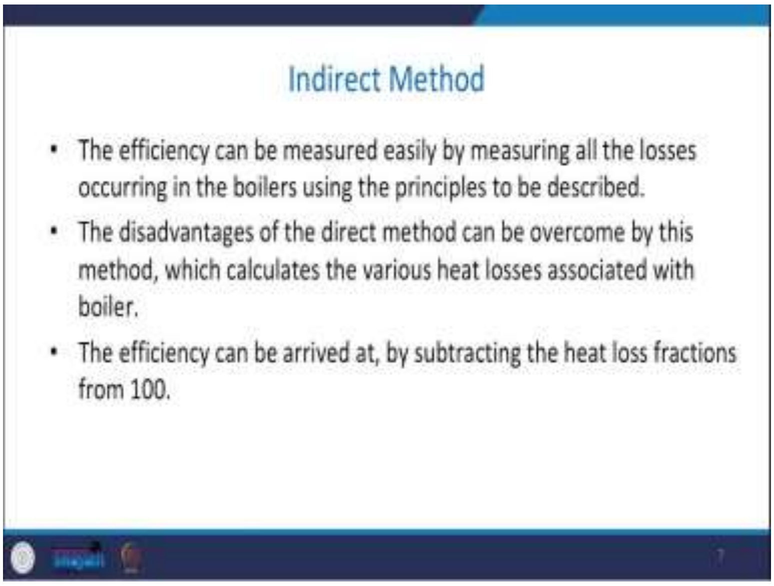

Indirect Method

- The efficiency can be measured easily by measuring all the losses occurring in the boilers using the principles to be described.
- The disadvantages of the direct method can be overcome by this method, which calculates the various heat losses associated with boiler.
- The efficiency can be arrived at, by subtracting the heat loss fractions from 100.

Now, let us talk about the indirect method whenever we go for the indirect method. So, the efficiency we can measure easily by measuring all the losses occurring in the boiler using the principle to be described. So, the disadvantage of the direct method can be overcome by this indirect method, which usually calculates the various heat losses associated with the boiler we are not encountering during the direct method. See the efficiency achieved by subtracting the heat loss fraction from one hundred.

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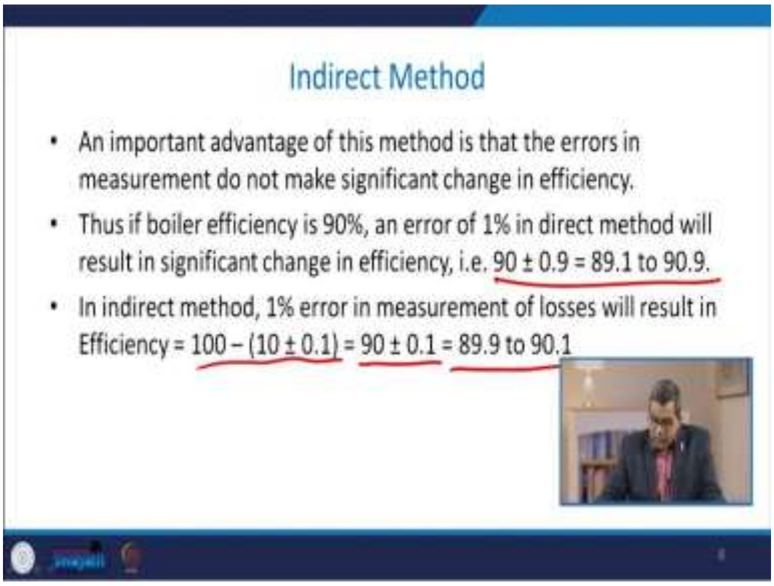

Indirect Method

- An important advantage of this method is that the errors in measurement do not make significant change in efficiency.
- Thus if boiler efficiency is 90%, an error of 1% in direct method will result in significant change in efficiency, i.e. $90 \pm 0.9 = 89.1$ to 90.9.
- In indirect method, 1% error in measurement of losses will result in Efficiency $= 100 - (10 \pm 0.1) = 90 \pm 0.1 = 89.9$ to 90.1

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Thus if boiler efficiency is 90%, an error of 1% in direct method will result in significant change in efficiency, i.e. $90 \pm 0.9 = 89.1$ to 90.9.

In indirect method, 1% error in measurement of losses will result in Efficiency = 100 – (10 ± 0.1) = 90 ± 0.1 = 89.9 to 90.1

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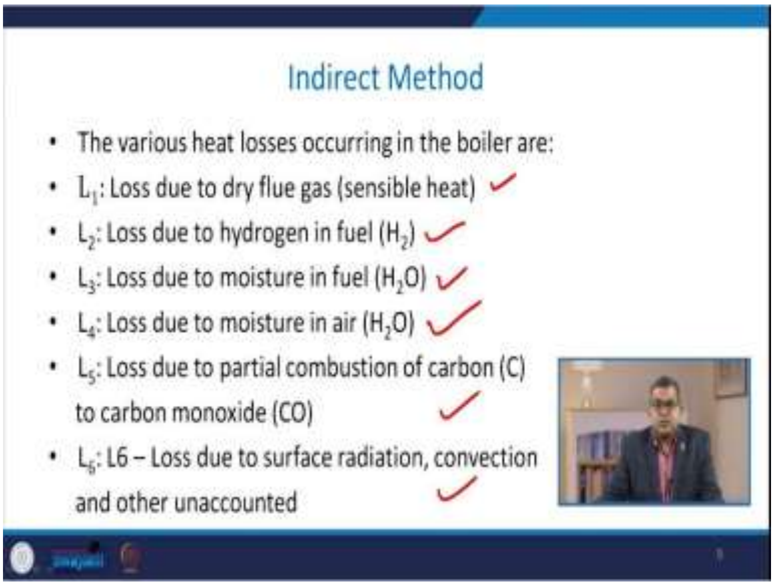

Indirect Method

- The various heat losses occurring in the boiler are:
- L_1: Loss due to dry flue gas (sensible heat) ✓
- L_2: Loss due to hydrogen in fuel (H_2) ✓
- L_3: Loss due to moisture in fuel (H_2O) ✓
- L_4: Loss due to moisture in air (H_2O) ✓
- L_5: Loss due to partial combustion of carbon (C) to carbon monoxide (CO) ✓
- L_6: L6 – Loss due to surface radiation, convection and other unaccounted ✓

The various heat losses occurring in the boiler are:

L_1: Loss due to dry flue gas (sensible heat)

L_2: Loss due to hydrogen in fuel (H_2)

L_3: Loss due to moisture in fuel (H_2O)

L_4: Loss due to moisture in air (H_2O)

L_5: Loss due to partial combustion of carbon (C)
to carbon monoxide (CO)

L_6: L6 – Loss due to surface radiation, convection
and other unaccounted

So, we tried to capture the different types of losses in due course of time; apart from this, there may be certain unburned losses in fly ash attributed to the carbon.

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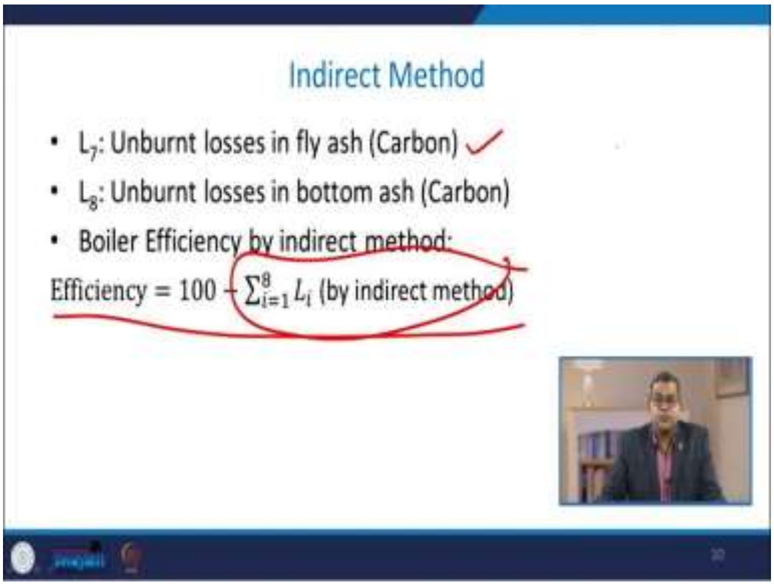

Indirect Method

- L_7: Unburnt losses in fly ash (Carbon)
- L_8: Unburnt losses in bottom ash (Carbon)
- Boiler Efficiency by indirect method:

Efficiency = 100 − $\sum_{i=1}^{8} L_i$ (by indirect method)

L_7: Unburnt losses in fly ash (Carbon)

L_8: Unburnt losses in bottom ash (Carbon)

Boiler Efficiency by indirect method:

Efficiency $= 100 - \sum_{i=1}^{8} L_i$ (by indirect method)

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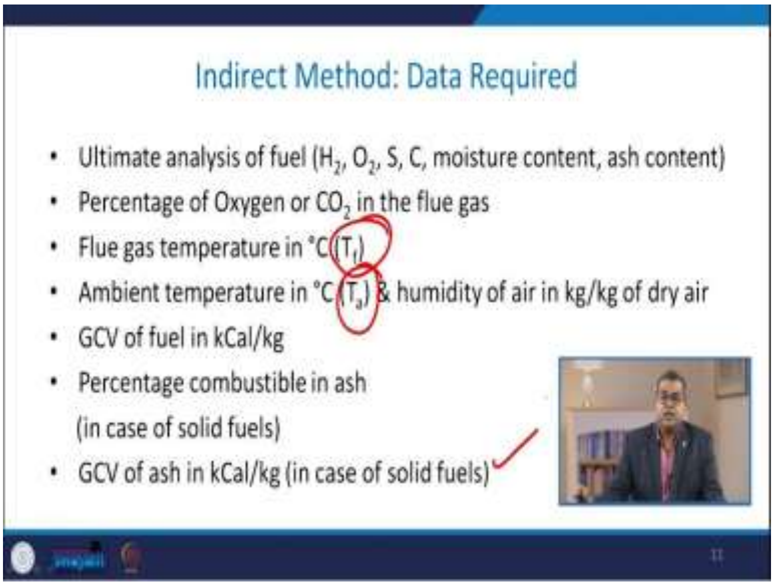

Indirect Method: Data Required

- Ultimate analysis of fuel (H_2, O_2, S, C, moisture content, ash content)
- Percentage of Oxygen or CO_2 in the flue gas
- Flue gas temperature in °C (T_f)
- Ambient temperature in °C (T_a) & humidity of air in kg/kg of dry air
- GCV of fuel in kCal/kg
- Percentage combustible in ash (in case of solid fuels)
- GCV of ash in kCal/kg (in case of solid fuels)

So, the question arises: what are the different kinds of data required in the indirect method? So, you need to carry out some more exhaustive analysis before we go for some indirect method. One is the ultimate analysis of a fuel that means hydrogen, oxygen, sulfur, carbon, moisture, ash content, etc. Another thing is that you require a percentage of oxygen or CO_2 in the flue gases.

Then obviously, you require when you are talking about the flue gases. Then you require the flue gas temperature in degrees Celsius which is sometimes referred to as a T_f. You may require the ambient temperature in degrees Celsius, and that is T_a, and the humidity of air in kilograms, a kilogram of dry air, then the gross calorific value of the fuel in kilocalorie per kilogram.

You require the percentage combustible in ashes if you are using solid fuel. Then the glass calorific values of ash in kilocalorie kilogram if you are using the solid fuel.

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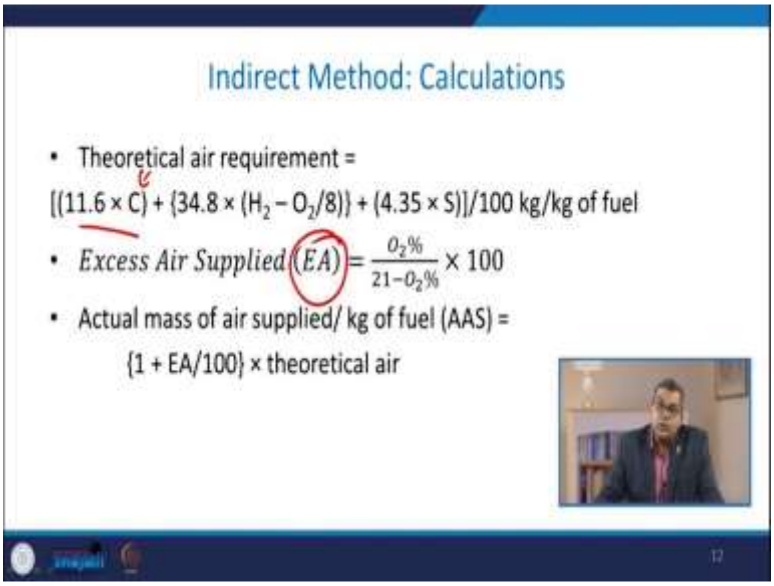

Indirect Method: Calculations

- Theoretical air requirement =

$[(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)]/100$ kg/kg of fuel

- *Excess Air Supplied* $(EA) = \frac{O_2\%}{21-O_2\%} \times 100$
- Actual mass of air supplied/ kg of fuel (AAS) =

$\{1 + EA/100\} \times$ theoretical air

So, then you have calculated the things and have the various data whatever required then, you can calculate different types of a theoretical air requirement. You see that for combustion purposes, you always require oxygen. Now, if you are using the purest form of oxygen, then the boiler would not be the economical affair because separating oxygen from the source is again a very, you can say, cumbersome and costly affair.

So, people used to supply the air. But you see that we have only 21% of oxygen in the air. So, how much air would be required? That is again a big question. So, if we are taking the 21% of oxygen in question, we can calculate the theoretical air requirement with the help of this particular mathematical correlation.

Theoretical air requirement =

$[(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)]/100$ kg/kg of fuel

$$Excess\ Air\ Supplied\ (EA) = \frac{O_2\%}{21 - O_2\%} \times 100$$

Actual mass of air supplied/ kg of fuel (AAS) =

{1 + EA/100} × theoretical air

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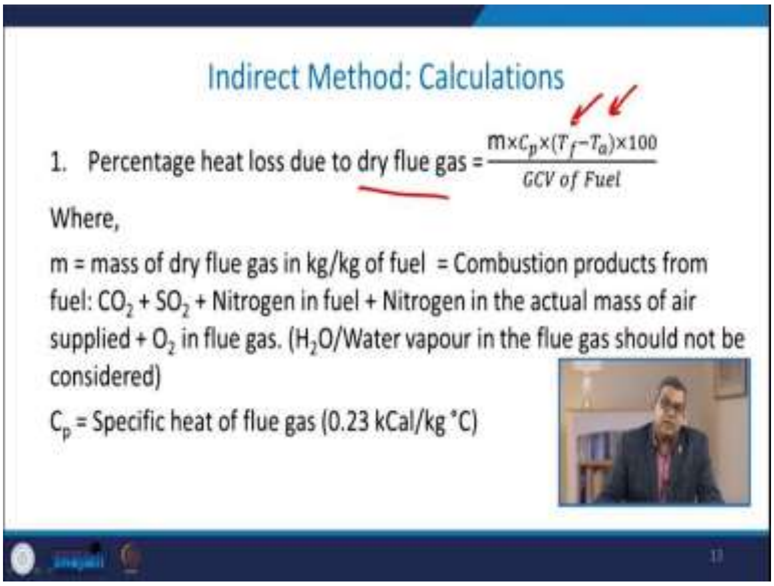

Indirect Method: Calculations

1. Percentage heat loss due to dry flue gas = $\frac{m\times C_p\times(T_f-T_a)\times 100}{GCV\ of\ Fuel}$

Where,

m = mass of dry flue gas in kg/kg of fuel = Combustion products from fuel: CO_2 + SO_2 + Nitrogen in fuel + Nitrogen in the actual mass of air supplied + O_2 in flue gas. (H_2O/Water vapour in the flue gas should not be considered)

C_p = Specific heat of flue gas (0.23 kCal/kg °C)

So, the first calculation that is we need to calculate the percentage heat loss due to dry fluid grass is equal to

1. Percentage heat loss due to dry flue gas = $m\frac{\times C_p\times(T_f-T_a)\times 100}{GCV\ of\ Fuel}$

Where,

m = mass of dry flue gas in kg/kg of fuel = Combustion products from fuel: CO_2 + SO_2 + Nitrogen in fuel + Nitrogen in the actual mass of air supplied + O_2 in flue gas. (H_2O/Water vapour in the flue gas should not be considered)

C_p= Specific heat of flue gas (0.23 kCal/kg °C)

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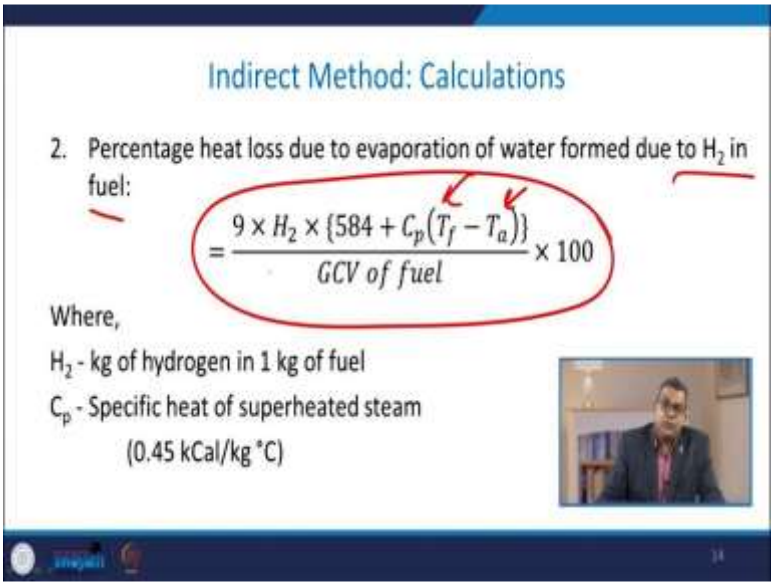

Indirect Method: Calculations

2. Percentage heat loss due to evaporation of water formed due to H_2 in fuel:

$$= \frac{9 \times H_2 \times \{584 + C_p(T_f - T_a)\}}{GCV\ of\ fuel} \times 100$$

Where,

H_2 - kg of hydrogen in 1 kg of fuel

C_p - Specific heat of superheated steam

(0.45 kCal/kg °C)

Now when we need to calculate the percentage of heat loss due to evaporation of water formed due to hydrogen in the fuel. It needs to be calculated with this particular mathematical relationship:

2. Percentage heat loss due to evaporation of water formed due to H_2 in fuel:

$$= \frac{9 \times H_2 \times \{584 + C_p(T_f - T_a)\}}{GCV\ of\ fuel} \times 100$$

Where,

H_2- kg of hydrogen in 1 kg of fuel

C_p- Specific heat of superheated steam

(0.45 kCal/kg °C)

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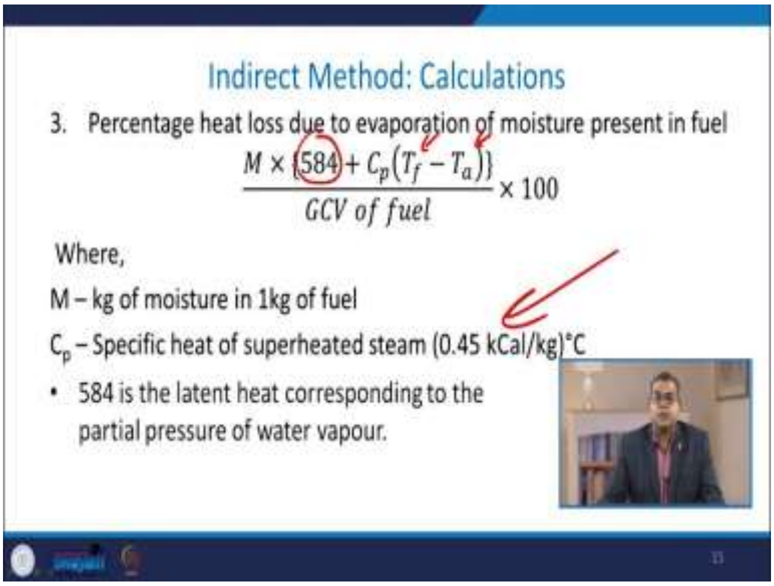

Indirect Method: Calculations

3. Percentage heat loss due to evaporation of moisture present in fuel

$$\frac{M \times \{584 + C_p(T_f - T_a)\}}{GCV\ of\ fuel} \times 100$$

Where,

M – kg of moisture in 1kg of fuel

C_p – Specific heat of superheated steam (0.45 kCal/kg)°C

- 584 is the latent heat corresponding to the partial pressure of water vapour.

Then let us look at the percentage of heat loss due to evaporation of moisture present in the fuel.

3. Percentage heat loss due to evaporation of moisture present in fuel

$$\frac{M \times \{584 + C_p(T_f - T_a)\}}{GCV\ of\ fuel} \times 100$$

Where,

M – kg of moisture in 1kg of fuel

C_p– Specific heat of superheated steam (0.45 kCal/kg)°C

You may think that from where this 584 figure comes out; 584 is the latent heat corresponding to the partial pressure of water vapor.

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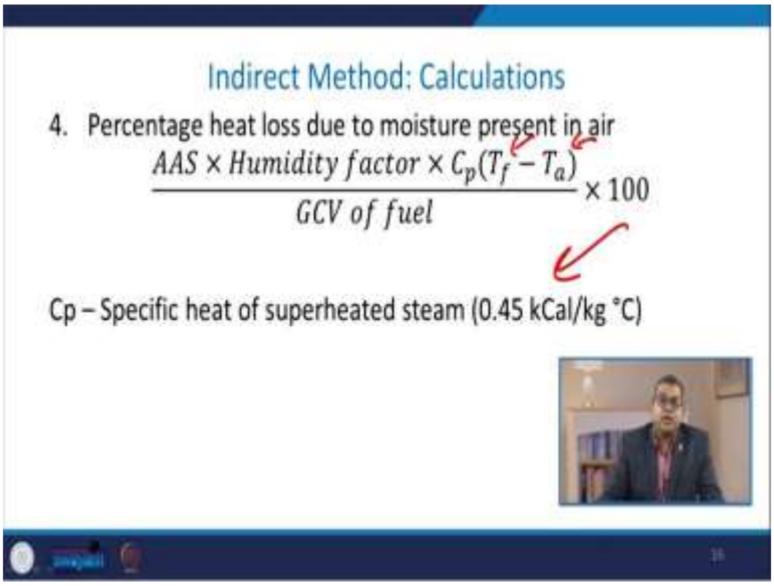

Indirect Method: Calculations

4. Percentage heat loss due to moisture present in air

$$\frac{AAS \times Humidity\ factor \times C_p(T_f - T_a)}{GCV\ of\ fuel} \times 100$$

Cp – Specific heat of superheated steam (0.45 kCal/kg °C)

Now, let us talk about the percentage of heat loss due to the moisture present in the air.

4. Percentage heat loss due to moisture present in air

$$\frac{AAS \times Humidity\ factor \times C_p(T_f - T_a)}{GCV\ of\ fuel} \times 100$$

Cp– Specific heat of superheated steam (0.45 kCal/kg °C)

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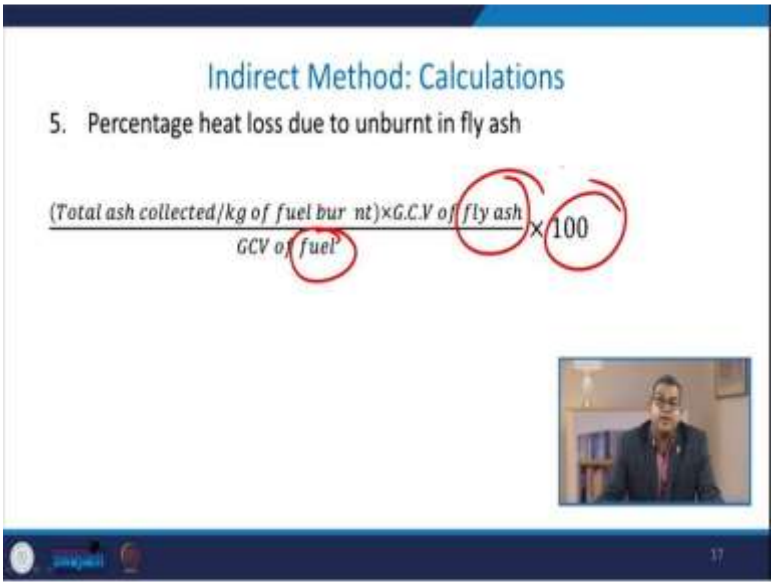

Indirect Method: Calculations

5. Percentage heat loss due to unburnt in fly ash

$$\frac{(Total\ ash\ collected/kg\ of\ fuel\ bur\ \ nt) \times G.C.V\ of\ fly\ ash}{GCV\ of\ fuel} \times 100$$

How about this percentage of heat loss due to unburnt fly ash? And that is a straight forward formula.

5. Percentage heat loss due to unburnt in fly ash

$$\frac{(Total\ ash\ collected/kg\ of\ fuel\ burtnt) \times G.C.V\ of\ fly\ ash}{GCV\ of\ fuel} \times 100$$

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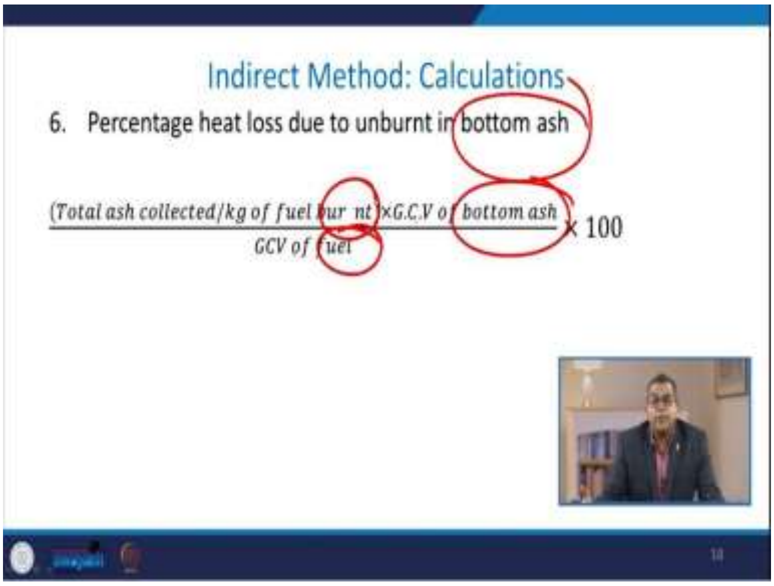

Indirect Method: Calculations

6. Percentage heat loss due to unburnt in bottom ash

$$\frac{(Total\ ash\ collected/kg\ of\ fuel\ bur\ \ nt) \times G.C.V\ of\ bottom\ ash}{GCV\ of\ fuel} \times 100$$

Then if you recall that we discussed the bottom ash, now you can calculate the percentage heat loss due to unburnt bottom ash.

6. Percentage heat loss due to unburnt in bottom ash

$$\frac{(Total\ ash\ collected/kg\ of\ fuel\ burtnt) \times G.C.V\ of\ bottom\ ash}{GCV\ of\ fuel} \times 100$$

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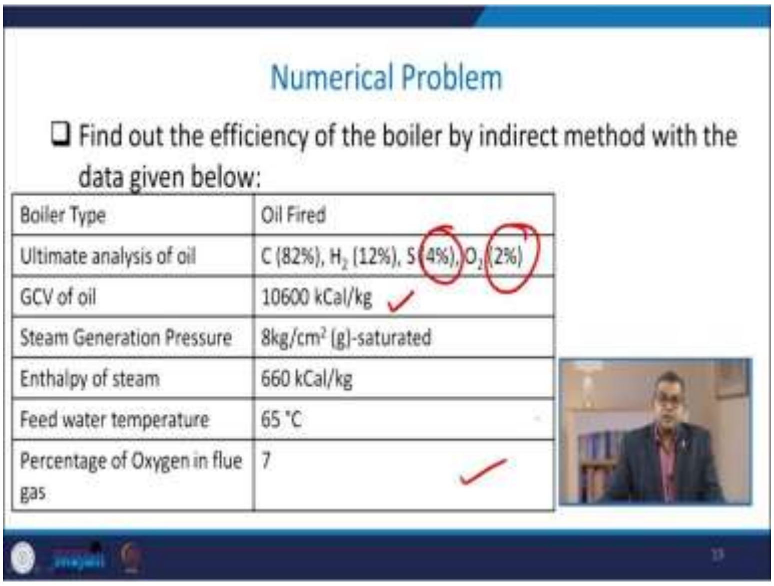

Numerical Problem

- ❑ Find out the efficiency of the boiler by indirect method with the data given below:

Boiler Type	Oil Fired
Ultimate analysis of oil	C (82%), H_2 (12%), S (4%), O_2 (2%)
GCV of oil	10600 kCal/kg
Steam Generation Pressure	8kg/cm^2 (g)-saturated
Enthalpy of steam	660 kCal/kg
Feed water temperature	65 °C
Percentage of Oxygen in flue gas	7

Now, see, we discussed the indirect method for performance evaluation and previously discussed the direct method of performance evaluation. We discussed one numerical problem related to the direct method. Now here is one standard numerical problem related to the indirect method. Now, here some specific data are given that is you need to find out the efficiency of a boiler by indirect method with the data given.

Again, we are having the boiler type oil-fired, whereas we had coal-fired in the previous problem. The ultimate oil analysis suggests that carbon is 82%, hydrogen is 12%, sulfur is 4%, and oxygen is 2%. And the gross calorific value of oil is 10600-kilo calories per kilogram. The steam generation pressure is 8 kilograms per centimeter square on a gram basis of saturated one.

Enthalpy of steam is 660-kilo calories per kilogram. Whereas feed water temperature is 65 degrees Celsius and the percentage of oxygen in flue gas is 7.

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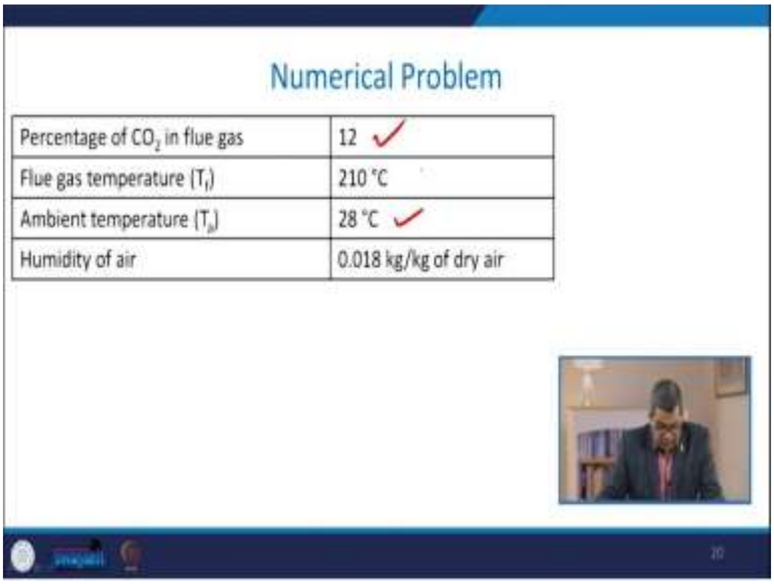

Numerical Problem

Percentage of CO_2 in flue gas	12 ✓
Flue gas temperature (T_f)	210 °C
Ambient temperature (T_a)	28 °C ✓
Humidity of air	0.018 kg/kg of dry air

Whereas if we; talk about the percentage of carbon dioxide in the flue gas, it is 12%. Of course, we are all looking for the flue gas temperature. So, flue gas temperature T f is 210 degrees Celsius, whereas ambient temperature T a is 28 degrees Celsius. We have the humidity of the air, which is 0.018 kilogram per kilogram of dry air.

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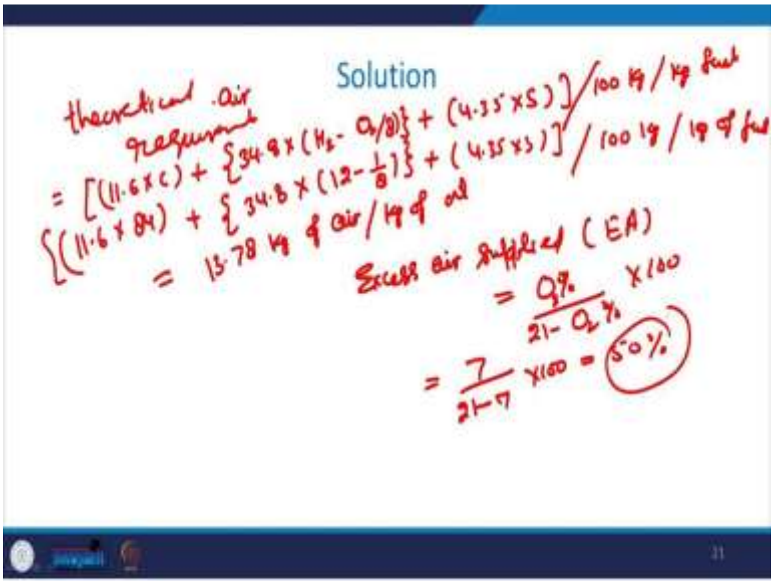

Solution

theoretical air requirement

$= [(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)]/100$ kg/kg fuel

$[(11.6 \times 84) + \{34.8 \times (12 - \frac{1}{8})\} + (4.35 \times 3)] / 100$ kg/kg of fuel

$= 13.78$ kg of air/kg of oil

Excess air supplied (EA)

$= \frac{O_2\%}{21 - O_2\%} \times 100$

$= \frac{7}{21-7} \times 100 = \boxed{50\%}$

So, let us try to solve this particular problem. Now, first, you need to find out the theoretical air requirement.

- Find the theoretical air requirement

= [(11.6 × C) + {34.8 × (H_2 – O_2/8)} + (4.35 × S)]/100 kg/kg of fuel

= [(11.6 × 84) + {34.8 × (12-1/8)} + (4.35 × 3)]/100 kg/kg of fuel

= **13.78 kg of air/kg of oil**

- $Excess\ Air\ Supplied\ (EA) = \frac{O_2\%}{21 - O_2\%} \times 100$

$= \frac{7}{21-7} \times 100 = \mathbf{50\%}$

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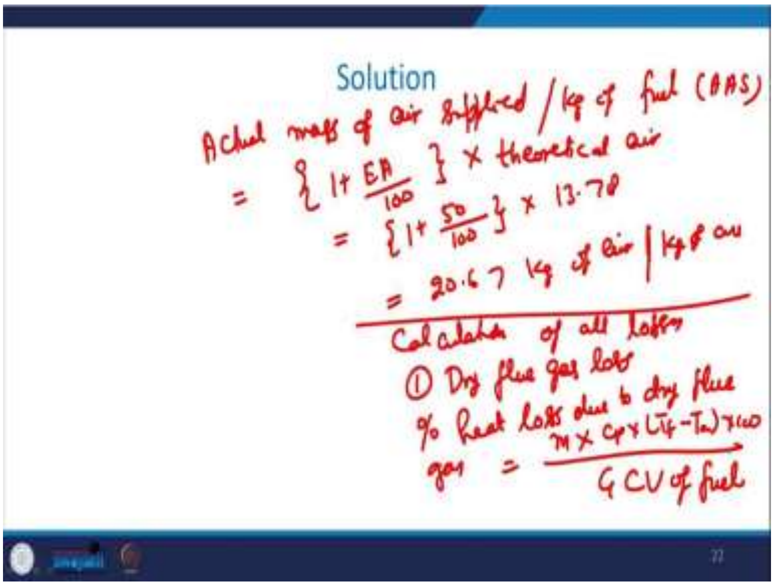

Solution

Actual mass of air supplied / kg of fuel (AAS)

$= \left\{1 + \frac{EA}{100}\right\} \times$ theoretical air

$= \left\{1 + \frac{50}{100}\right\} \times 13.78$

= 20.67 kg of air / kg of oil

Calculation of all losses

① Dry flue gas loss

% heat loss due to dry flue gas $= \frac{m \times C_p \times (T_f - T_a) \times 100}{GCV \text{ of fuel}}$

- Actual mass of air supplied/ kg of fuel (AAS)

= {1 + EA/100} × theoretical air

= {1 + 50/100} × 13.78

= 20.67 kg of air/kg of oil

- **Calculation of all losses**
- Dry flue gas loss:

Percentage heat loss due to dry flue gas = $\frac{m \times C_p \times (T_f - T_a) \times 100}{GCV\ of\ Fuel}$

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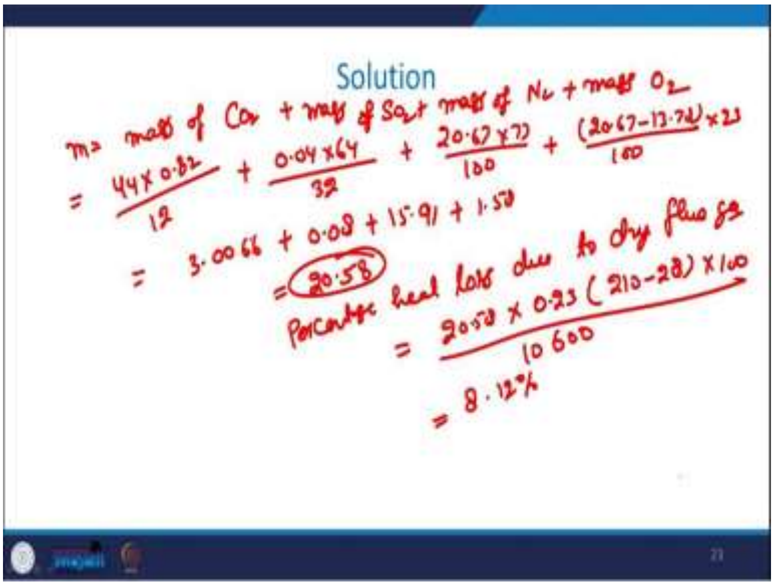

Solution

$m = \text{mass of } CO_2 + \text{mass of } SO_2 + \text{mass of } N_2 + \text{mass } O_2$

$$= \frac{44 \times 0.82}{12} + \frac{0.04 \times 64}{32} + \frac{20.67 \times 77}{100} + \frac{(20.67 - 13.78) \times 23}{100}$$

$$= 3.0066 + 0.08 + 15.91 + 1.58$$

$$= \boxed{20.58}$$

Percentage heat loss due to dry flue gas

$$= \frac{20.58 \times 0.23\,(210 - 28) \times 100}{10600}$$

$$= 8.12\%$$

m = mass of CO_2 + mass of SO_2 + mass of N_2 + mass of O_2

$$= \frac{44 \times 0.82}{12} + \frac{0.04 \times 64}{32} + \frac{20.67 \times 77}{100} + \frac{(20.67 - 13.78) \times 23}{100}$$

$$= 3.0066 + 0.08 + 15.91 + 1.58$$

$$= 20.58$$

- Dry flue gas loss:

Percentage heat loss due to dry flue gas =

$$= \frac{20.58 \times 0.23 \times (210 - 28) \times 100}{10600}$$

$= \mathbf{8.12}$ **%**

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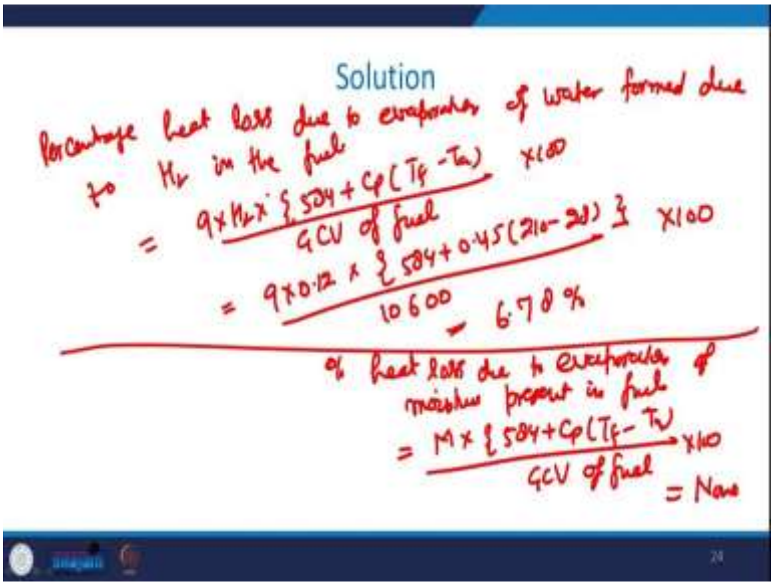

Solution

Percentage heat loss due to evaporation of water formed due to H_2 in the fuel

$$= \frac{9 \times H_2 \times \{584 + C_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

$$= \frac{9 \times 0.12 \times \{584 + 0.45(210 - 28)\}}{10600} \times 100$$

$$= 6.78\%$$

% heat loss due to evaporation of moisture present in fuel

$$= \frac{M \times \{584 + C_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

$= \text{None}$

Now, the next step is to calculate the percentage of heat loss due to evaporation of water formed due to hydrogen in the fuel, and that is

- Percentage heat loss due to evaporation of water formed due to H_2 in fuel:

$$= \frac{9 \times H_2 \times \{584 + C_p(T_f - T_a)\}}{GCV\ of\ fuel} \times 100$$

$$= \frac{9 \times 0.12 \times \{584 + 0.45(210 - 28)\}}{10600} \times 100 = \mathbf{6.78}\%$$

- Percentage heat loss due to evaporation of moisture present in fuel

$= \frac{M \times \{584 + C_p(T_f - T_a)\}}{GCV\ of\ fuel} \times 100$ = **None**

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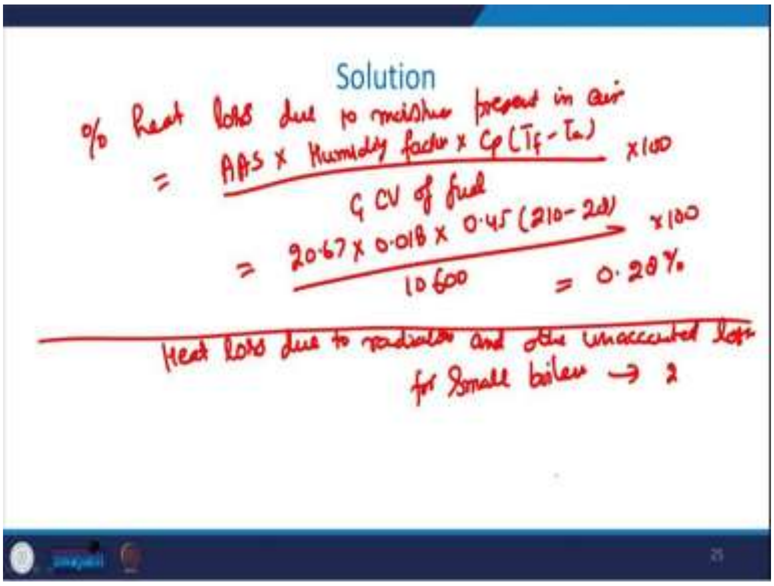

Solution

% Heat loss due to moisture present in air

$$= \frac{AAS \times Humidity\ factor \times C_p(T_f - T_a)}{GCV\ of\ fuel} \times 100$$

$$= \frac{20.67 \times 0.018 \times 0.45(210 - 28)}{10600} \times 100 = 0.28\%$$

Heat loss due to radiation and other unaccounted loss for small boiler → 2

- Percentage heat loss due to moisture present in air

$$= \frac{AAS \times Humidity\ factor \times C_p(T_f - T_a)}{GCV\ of\ fuel} \times 100$$

$$= \frac{20.67 \times 0.018 \times 0.45(210 - 28)}{10600} \times 100 = \mathbf{0.287}\%$$

- Heat loss due to radiation and other unaccounted losses:

For a small boiler it is estimated to be **2%**

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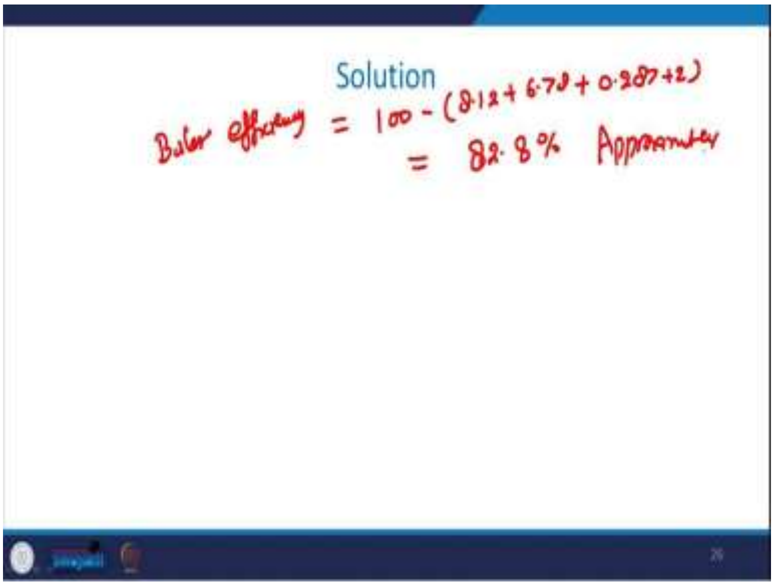

Solution

Boiler efficiency = 100 - (8.12 + 6.78 + 0.287 + 2)
= 82.8% Approximately

So, when we talk about boiler efficiency.

- **Boiler Efficiency =** 100 – (8.12 + 6.78 + 0.287 + 2) = **82.8 % Approx.**

So, this is how we can calculate the indirect method, which is applicable for performance evaluation attributed to the indirect method. So, you see that in this particular lecture, we have discussed the numerical issue of the direct method for performance evaluation of boiler.

Then we discussed all spectrums of or rather all parameters of the indirect method attributed to the performance evaluation of the boilers. And we carry out one comprehensive example of this performance evaluation attributed to the indirect method.

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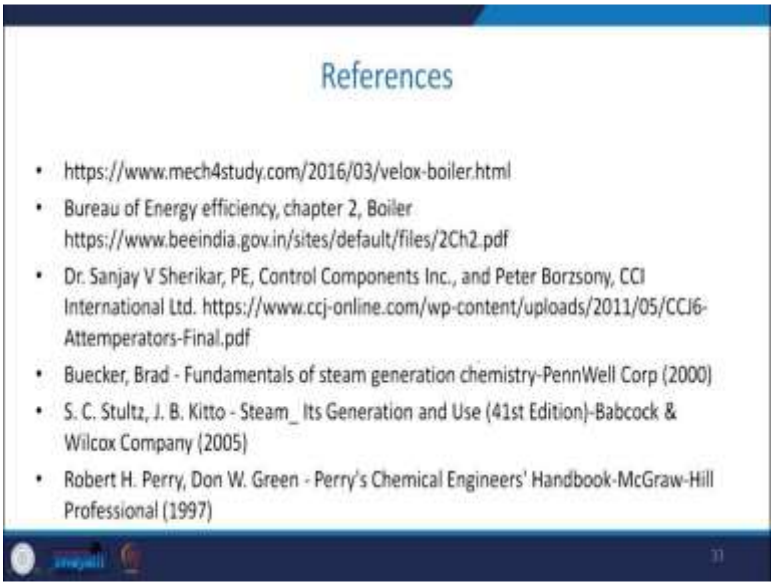

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Thank you very much.