3.1 Steam Engine Trials

Engine trials are carried out for the purpose of comparing actual engine performance with theoretical or ideal performance. Trials are also carried out when the manufacturers have entered into agreement and guaranteed specified efficiency and maximum capacity (output) of the engine. The tests in this case are made to verify the guaranteed steam consumption per indicated power per hour or per brake power per hour under specified steam supply pressure and condenser vacuum.

For complete steam engine trial, it is necessary to measure losses in addition to the part of the heat converted into useful work and also to draw up a heat balance account. Such trials have been the direct cause of, and incentive to, the improvement in engines throughout the period of their development. This interest created a demand for authentic (trustworthy) records of engine performance which could only be satisfied by exhaustive trials carried out on steam plants. The measurements necessary to determine the thermal efficiency (brake and indicated) and to draw up complete heat balance sheet are:

- Indicated power (if possible),
- Brake power,
- Steam consumption in kilograms per hour,
- Pressure of steam supply at engine stop valve,
- Condition of steam supply at engine stop valve i.e. dryness fraction of steam if wet steam is used or temperature of steam if superheated steam is used,
- Temperature and pressure of exhaust steam,
- Quantity of condenser cooling or circulating water per hour, and
- Inlet and outlet temperatures of condenser cooling water.

When proper precautions are taken, it is possible to estimate the indicated power of a steam engine with great accuracy by taking indicator diagrams. In order to have the pressure inside the indicator cylinder same as the pressure inside the engine cylinder, the connecting pipe between the indicator and engine cylinder should be as short and straight as possible and of large bore. For double-acting steam engines, a separate indicator diagram should be taken for each end of the cylinder. Indicator diagrams taken from a double-acting cross-compound steam engine are shown in fig. 3-1. Before taking a diagram, the steam should be allowed to blow through freely in order to clear out condensed steam which may have collected in the pipes. Then the indicator cord is coupled up to the reducing gear. The pencil should be lightly pressed against the paper for about twenty seconds and the diagram is taken. The atmospheric line should then be drawn and the indicator cord uncoupled. The mean effective pressure is then calculated by measuring the area of the indicator diagram by means of a planimeter or by the
The brake measures the work available for use external to the engine itself, and helps to assess the useful power available known as brake power. The type of dynamometer which should be used will depend upon the size of the engine under test. For comparatively small powers, an ordinary rope brake may be used with success, but for large powers, several alternatives are possible. A very convenient method is to couple up the engine directly to an electric dynamo whose efficiency is known at all loads. The output from the dynamo is very easily measured and the brake power of the engine estimated from the known efficiency of the dynamo. If a dynamo is not available and the power is too large to be measured by a rope brake, a hydraulic brake may be used, while for large engines (marine engines) a torsional (transmission) dynamometer may be used.

The steam consumption is best measured by condensing and weighing the exhaust steam. This is very easy in case of a condensing engine, fitted with a surface condenser. For a non-condensing engine, the steam consumption can only be measured by using a boiler solely to supply the steam to the engine under test; the steam consumption is estimated by deducting from the measured boiler feed, the sum of (i) the steam condensed in the steam pipes, (ii) the steam used for driving the feed pump, and (iii) the leakage of steam from the steam pipes.

When saturated steam (or wet steam) is used, its pressure and dryness fraction should be measured close to the engine side of the stop valve. The dryness fraction can be estimated by using a combined separating and throttling calorimeter if the steam is very wet, or by using a throttling calorimeter if the steam is nearly dry. In determining the dryness fraction of steam, great care should be taken in getting a proper sample of steam supplied to the engine. If superheated steam is used, the pressure and temperature of steam should be measured close to the engine side of the stop valve.

The pressure in the condenser is measured by taking vacuum gauge and the barometer readings. The vacuum gauge reading should be taken at every five minutes and the barometer readings at the beginning and at the end of the trial. The temperature of exhaust steam is measured by taking the temperature of water discharged from the air pump. The temperature of exhaust steam is also known as the temperature of condensate or hot-well temperature.

The quantity of condenser cooling water used per hour is measured by taking reading of the hook gauge to give the head of water in the water channel every five minutes. Then for a right-angled V-notch,

\[ Q = 1.418 \frac{(h)^{5/2}}{C_d} \text{ (assuming } C_d = 0.6) \]  \hspace{1cm} (3.1)

where, \( Q = \) cubic metres of water flowing per second, and
\( h = \) head of water over the notch in metres.

The quantity of condenser cooling water also may be measured by calibrated tanks. The inlet and outlet temperatures of condenser cooling water are measured by reading...
the thermometers fitted in the inlet and outlet water pipes every ten minutes.

3.2 Heat Balance Sheet

In a trial of any heat engine, the distribution of the heat supplied per minute or per hour is required. This appears in the heat balance sheet or heat account sheet. In order to complete a heat balance sheet for a steam engine, the engine should be tested over a period of time under conditions of constant load and constant steam supply. All the measurements listed earlier should be taken at regular interval of time. On the completion of the trial, the necessary data should be averaged out and a heat account sheet should be drawn up as follows:

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>..</td>
<td>..</td>
<td>- Heat equivalent of brake power</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Heat removed by condenser cooling water</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Heat remaining in condensate</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Heat remaining in jacket drain</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Heat lost by radiation, leakage, error of measurement, etc. (by difference)</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td>Total</td>
<td>..</td>
<td>..</td>
<td>Total</td>
<td>..</td>
<td>..</td>
</tr>
</tbody>
</table>

Note: The heat equivalent of the friction power is not included in the above balance sheet on the right hand side because it is possible that some of the frictional heat will re-appear in the steam and eventually appear as heat removed from the condenser. Thus, the right hand side of the heat balance sheet should include the brake power and not the indicated power.

Various items in heat balance sheet can be estimated as follows:

Heat supplied per minute (measured above 0°C):

Let $H_I$ = Enthalpy in kJ per kg of steam at engine stop valve condition,

$m_s$ = mass of steam supplied to the cylinder per min., and

$m_j$ = mass of steam supplied to the cylinder jacket per min.

Then, gross heat supplied to the engine (measured above 0°C)

$$= (m_s + m_j) \times H_I \text{ kJ/min.} \quad \text{...(3.2)}$$

Heat expenditure per minute:

1. Heat equivalent of brake power or heat converted into useful work:

Heat equivalent of brake power per min. = brake power $\times 60 \text{ kJ/min.} \quad \text{...(3.3)}$

2. Heat removed by condenser cooling water:

Let $m_w$ = mass of condenser cooling water per min., and

$t_2 - t_1$ = rise in temperature of condenser cooling water.

Then, heat removed by condenser cooling water per minute

$$= m_w \times 4.187 \times (t_2 - t_1) \text{ kJ/min.} \quad \text{...(3.4)}$$

(where $4.187 \text{ kJ/kg K}$ is the specific heat of water (K))

3. Heat remaining in condensate or heat to hot-well (measured above 0°C):

Let $h_2$ = Enthalpy in kJ per kg of condensate (water) in the hot-well, and

$m_s$ = mass of condensate per minute.

Then, heat remaining in condensate per min.
Heat rejected in exhaust steam per minute

\[ = m_w \times 4\cdot187 \times (t_2 - t_1) + m_s \times 4\cdot187 \times (t_c - 0) \text{ kJ/min.} \quad \text{(3.6)} \]

(4) Heat remaining in jacket drain (measured above 0°C):
Let \( h_2 \) = Enthalpy in kJ per kg of water from jacket drain at the temperature measured, and
\[ m_j = \text{mass of steam supplied to jacket per min.} \]
Then, heat remaining in jacket drain per min.
\[ = m_j \times 4\cdot187 \times (t_j - 0) \text{ kJ/min.} \quad \text{(3.7)} \]

(5) Heat lost by radiation, leakage, error of observation, etc. (by difference):
This is obtained by the difference between gross heat supplied and the sum of items (1), (2), (3) and (4).

**Problem-1**: The following data was obtained during a test on a single-cylinder, double-acting steam engine having 20 cm cylinder diameter and 25 cm stroke:

- **M.E.P. (from indicator diagram)**: 250 kPa
- **Speed**: 5 r.p.s.
- **Effective radius of brake wheel**: 38 cm
- **Net brake load**: 1,360 newtons
- **Steam consumption**: 3.55 kg/min.
- **Steam supply pressure at engine stop valve**: 8 bar
- **Dryness fraction of steam at engine stop valve**: 0.97
- **Condenser cooling water**: 110 kg/min.
- **Temperature rise of condenser cooling water**: 14°C
- **Condensate temperature**: 40°C

Calculate:
(a) the brake power,
(b) the indicated power,
(c) the mechanical efficiency,
(d) the specific steam consumption in kg per kW-hr.,
(e) the brake thermal efficiency, and
(f) the indicated thermal efficiency.

**Draw up a heat balance sheet for the engine in kJ/min. and in percentages.**

(a) Brake power = \( (W - S) \times R \times 2 \times \pi \times N \)
\[ = 1,360 \times 0.38 \times 2\pi \times 5 = 16,236 \text{ watts or 16.236 kW} \]

(b) Indicated power = \( 2 \times p_m \times a \times i \times N \)
\[ = 2 \times (250 \times 10^3) \times (0.7854 \times (0.2)^2) \times 0.25 \times 5 \]
\[ = 19,635 \text{ watts or 19.635 kW} \]

(c) Mechanical efficiency, \( \eta_m = \frac{\text{Brake power}}{\text{Indicated power}} = \frac{16.236}{19.635} = 0.8268 \text{ or 82.68%} \]

(d) Specific steam consumption = \( \frac{3.55 \times 60}{16.236} = 13.12 \text{ kg/kW-hr.} \)

**Gross heat supplied per minute**:
At 8 bar, \( h = 721.11 \text{ kJ/kg and L} = 2,048 \text{ kJ/kg (from steam tables).} \)
Heat in steam supplied per min. measured above 0°C at engine stop valve

\[ m_s \times H_1 = m_s ( h + xL ) = 3.55 ( 721.11 + 0.97 \times 2.048 ) = 9,612 \text{ kJ/min.} \]

**Heat expenditure per minute:**

1. Heat equivalent of brake power per minute = 16.236 \times 60 = 974.2 \text{ kJ}
2. Heat removed by condenser cooling water per minute

\[ m_w \times ( t_2 - t_1 ) \times 4.187 = 110 \times 14 \times 4.187 = 6,448 \text{ kJ} \]
3. Heat to hot-well or heat remaining in condensate above 0°C per min.

\[ m_s \times ( t_c - 0 ) \times 4.187 = 3.55 ( 40 - 0 ) \times 4.187 = 594.6 \text{ kJ} \]

(heat rejected in exhaust steam per min. = 6,448 + 594.6 = 7,042.6 kJ)
4. Heat lost by radiation, error, etc. per minute (by difference)

\[ 9,612 \times ( 974.2 + 6,448 + 594.6 ) = 1,595.2 \text{ kJ} \]

**Heat balance sheet with 0°C as Datum**

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>9,612</td>
<td>100</td>
<td>(1) Heat equivalent of brake power</td>
<td>794.2</td>
<td>10.13</td>
</tr>
<tr>
<td>(2) Heat removed by condenser cooling water</td>
<td>6,448</td>
<td>67.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) Heat to hot-well</td>
<td>594.6</td>
<td>6.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4) Heat lost by radiation error of measurements etc. (by difference)</td>
<td>1,595.2</td>
<td>16.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9,612</strong></td>
<td><strong>100</strong></td>
<td><strong>Total</strong></td>
<td><strong>9,612</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

(e) Net heat supplied per minute = gross heat supplied per min. – heat to hot-well per min.

\[ 9,612 - 594.6 = 9,017.4 \text{ kJ} \]

Brake thermal efficiency, \( \eta_b = \frac{\text{Heat equivalent of brake power per min.}}{\text{Net heat supplied per min.}} \)

\[ \frac{974.2}{9,017.4} = 0.108 \text{ or 10.8%} \]

(f) Indicated thermal efficiency, \( \eta_i = \frac{\text{Brake thermal efficiency}}{\text{Mechanical efficiency}} \)

\[ = \frac{0.108}{0.8268} = 0.1307 \text{ or 13.07%} \]

**Problem-2**: The following readings were taken during a trial of a single-cylinder, double-acting steam engine having a cylinder diameter of 58 cm and stroke of 85 cm:

- **Piston rod diameter** .. 9 cm
- **Speed** .. 158 r.p.m.
- **Mean effective pressure (cover end)** .. 2.52 bar
- **Mean effective pressure (crank end)** .. 2.58 bar
- **Brake power developed** .. 224 kW
- **Steam supply pressure** .. 10 bar
- **Steam supply temperature** .. 234°C
- **Condenser cooling water flow** .. 1,700 kg/min.
- **Inlet temperature of condenser cooling water** .. 15°C
Outlet temperature of condenser cooling water .. 28°C
Mass of condensate collected .. 2,760 kg/hr.
Condensate temperature .. 38°C
Condenser Vacuum .. 637-5 mm Hg
Barometer reading .. 750 mm Hg
Kp of superheated steam .. 2·1 kJ/kg K

Calculate the mechanical and indicated thermal efficiencies of the engine and draw up a heat balance sheet in kJ/min. and in percentage. Also estimate the dryness fraction of the steam entering the condenser.

Piston area (cover end) = \(\frac{\pi}{4} \times (58)^2 = 2,640 \text{ cm}^2 = 0-264 \text{ m}^2\)

Piston area (crank end) = \(\frac{\pi}{4} \times (58^2 - 9^2) = 2,580 \text{ cm}^2 = 0-258 \text{ m}^2\)

Indicated power\(_{\text{engine}}\) = indicated power\(_{\text{cover}}\) + indicated power\(_{\text{crank}}\)

\[
\text{Indicated power}_{\text{engine}} = \left(2-52 \times 10^5\right) \times \frac{2-64 \times 0-85 \times 158}{60} + \left(2-58 \times 10^5\right) \times \frac{2-58 \times 0-85 \times 158}{60} = 2,979,900 \text{ watts} = 297-9 \text{ kW}
\]

Mechanical efficiency, \(\eta_m\) = \(\frac{\text{Brake power}}{\text{Indicated power}}\) = \(\frac{224}{297-9}\) = 0-7519 or 75-19%

At 10 bar, \(H_s = 2,778-1 \text{ kJ/kg, } t_s = 179-91^\circ\text{C}\) (from steam tables).

Enthalpy of 1 kg of superheated steam measured above 0°C,

\[H_1 = H_s + K_p (t_{\text{sup}} - t_s) = 2,778-1 + 2·1 (234 - 179-91) = 2,891-7 \text{ kJ/kg.}\]

Enthalpy of 1 kg condensate (water) above 0°C,

\[h_2 = (38 - 0) \times 4·187 = 159·1 \text{ kJ/kg.}\]

Net heat supplied (difference in enthalpy) per kg of steam

\[= H_1 - h_2 = 2,891-7 - 159·1 = 2,732-6 \text{ kJ/kg.}\]

Net heat supplied per minute = \(m_s \times (H_1 - h_2) = \frac{2760}{60} \times 2,732-6 \text{ kJ/min.}\)

Indicated thermal efficiency = \(\frac{\text{Heat equivalent of indicated power per min.}}{\text{Net heat supplied per min.}}\)

\[
= \frac{\text{Indicated power} \times 60}{m_s (H_1 - h_2)} = \frac{297-9 \times 60}{\frac{2760}{60} \times 2,732-6} = 0-1422 \text{ or 14-22%}
\]

Gross heat supplied per minute:

Heat in steam supplied per minute = \(m_s \times H_1 = \frac{2760}{60} \times 2,891-7 = 1,33,018 \text{ kJ}\)

Heat expenditure per minute:

(1) Heat equivalent of brake power per min. = 224 \times 60 = 13,440 \text{ kJ}

(2) Heat removed by condenser cooling water per min.

\[= m_w \times (t_c \times h) \times 4·187 = 1,700 \times (28 - 15) \times 4·187 = 92,533 \text{ kJ}\]

(3) Heat remaining in condensate above 0°C per min.

\[= m_s \times (t_c - 0) \times 4·187 = \frac{2760}{60} \times (38 - 0) \times 4·187 = 7,319 \text{ kJ}\]
(4) Heat lost by radiation, error, etc. (by difference) per min.
= 1,33,018 - (13,440 + 92,533 + 7,319) = 19,726 kJ

Heat balance sheet with 0°C as Datum

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>1,33,018</td>
<td>100</td>
<td>(1) Heat equivalent of brake power</td>
<td>13,440</td>
<td>10-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) Heat removed by condenser cooling water</td>
<td>92,533</td>
<td>69-57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) Heat remaining in condensate</td>
<td>7,319</td>
<td>5-50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4) Heat lost by radiation error of measurements etc. (by difference)</td>
<td>19,726</td>
<td>14-83</td>
</tr>
<tr>
<td>Total</td>
<td>1,33,018</td>
<td>100</td>
<td>Total</td>
<td>1,33,018</td>
<td>100</td>
</tr>
</tbody>
</table>

Condenser pressure = 750 - 637-5 = 112-5 mm of Hg = 112-5/750 = 0-15 bar.

At 0-15 bar, \( L = 2,373-1 \text{ kJ/kg} \) and \( t_s = 53-97°C \) (from steam tables).

Using eqn. (1.2a),
heat lost by exhaust steam/hr. = heat gained by condenser cooling water/hr.
\[
ms \left[ xL + (t_s - t_c) K \right] = mw \times (t_2 - t_1) K
\]
i.e. \( 2,760 \left[ 2,373-1x + (53-97 - 38) \times 4-187 \right] = 1,700 \times 60 \times (28 - 15) \times 4-187 \)
\[ x = 0-82 \] (dryness fraction of exhaust steam)

Problem-3: The following data was obtained during a test on a single-cylinder, double-acting steam engine having 20 cm cylinder diameter and 25 cm stroke: Mean effective pressure from indicator diagram, 2-5 bar; speed, 5 r.p.s.; effective radius of brake wheel, 38 cm; net brake load, 1,340 newtons; steam consumption, 3-6 kg/min.; steam supply pressure at engine stop valve, 8 bar; dryness fraction of steam at engine stop valve, 0-9; condenser cooling water, 110 kg/min.; temperature rise of condenser cooling water, 14°C; condenser pressure, 0-1 bar (10 kPa); hot-well temperature, 40°C. Take specific heat of water as 4-187 kJ/kg K and calculate: (a) the brake power, (b) the indicated power, (c) the mechanical efficiency, (d) the brake thermal efficiency, (e) the indicated thermal efficiency, and (f) the brake power steam consumption in kg per kW-hour. Also draw up a heat balance sheet in kJ/min. and in percentages.

(a) Brake power = \( (W - S) R 2 \pi N \)
\[
= 1,340 \times \frac{38}{100} \times 2 \times 3-14 \times 5 = 15,990 \text{ watts or 15-99 kW}
\]
(b) Indicated power = \( p_m \times a \times l \times N \times 2 \)
\[
= 10^5 \times 2-5 \times \frac{\pi}{4} \left( \frac{20}{100} \right)^2 \times \frac{25}{100} \times 5 \times 2 = 19,635 \text{ or 19-635 kW}
\]
(c) Mechanical efficiency, \( \eta_m = \frac{\text{Brake power}}{\text{Indicated power}} = \frac{15-99}{19-635} = 0-8143 \text{ or 81-43%} \)
(d) Gross heat supplied per minute:
At 8 bar, \( h = 721-11 \text{ kJ/kg} \), \( L = 2,048 \text{ kJ/kg} \) (from steam tables).
Heat in steam supplied per min. measured above 0°C at engine stop valve
\[
= ms \times H_1 = ms \left( h + xL \right) = 3-6 \times (721-11 + 0-9 \times 2,048) = 9,231-52 \text{ kJ/min.}
\]

Heat expenditure per minute:
(1) Heat equivalent of brake power/min. = 15-99 \times 60 = 959-4 \text{ kJ/min.}
(2) Heat removed by condenser cooling water per min.
   \[= m_w \times 4,187 \times (t_2 - h) = 110 \times 4,187 \times 14 = 6,447.98 \text{ kJ/min.}\]

(3) Heat to hot-well or heat remaining in condensate above 0°C per min.
   \[= m_s \times 4,187 \times (t_c - 0) = 3,6 \times 4,187 \times (40 - 0) = 602.93 \text{ kJ/min.}\]

(4) Heat lost by radiation, error, etc. per min (by difference)
   \[= 9,231.52 - (959.4 + 6,447.98 + 602.93) = 1,221.21 \text{ kJ/min.}\]

Net heat supplied per min. = Gross heat supplied/min. - heat to hot-well/min.
\[= 9,231.52 - 602.93 = 8,628.59 \text{ kJ/min.}\]

Brake thermal effi., \(\eta_b = \frac{\text{Heat equivalent of brake power per min.}}{\text{Net heat supplied per min.}}\)
\[= \frac{959.4}{8,628.59} = 0.1112 \text{ or } 11.12\%\]

(e) Indicated thermal efficiency, \(\eta_i = \frac{\text{Heat equivalent of indicated power per min.}}{\text{Net heat supplied per min.}}\)
\[= \frac{19,635 \times 60}{8,628.59} = 0.1366 \text{ or } 13.66\%\]

(f) Brake power steam consumption in kg/kW-hr. = \(\frac{3.6 \times 60}{15.99}\) = 13.51 kg/kW-hr.

Heat balance sheet with 0°C as Datum

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>9,231.52</td>
<td>100</td>
<td>(1) Heat to brake power</td>
<td>959.4</td>
<td>10.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) Heat removed by condenser cooling</td>
<td>6,447.98</td>
<td>69.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) Heat to hot-well</td>
<td>602.93</td>
<td>6.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4) Heat lost by radiation error etc. (by difference)</td>
<td>1,221.21</td>
<td>13.23</td>
</tr>
<tr>
<td>Total</td>
<td>9,231.52</td>
<td>100</td>
<td>Total</td>
<td>9,231.52</td>
<td>100</td>
</tr>
</tbody>
</table>

Problem-4: During a test on a single-cylinder, double-acting jacketed steam engine, the following observations were made:

- Indicated power, 26 kW; brake power, 21; pressure of steam supplied, 6 bar, quality of steam supplied, 5% wet; mass of steam used in engine cylinder, 325 kg/hour; mass of steam used in Jacket, 30 kg/hour; condensate temperature, 40°C; temperature of jacket drain, 140°C; condenser cooling water, 10,200 kg/hour; temperature rise of condenser cooling water, 15°C. Taking specific heat of water as 4,187 kJ/kg K, draw up a heat balance sheet in kJ/min. and in percentage. Calculate the indicated thermal efficiency when the heat of jacket drain is not available to the boiler as feed water heat.

What will be the percentage improvement in the indicated thermal efficiency if the heat of the jacket drain is also available to the feed water?

At 6 bar, \(h = 670.56 \text{ kJ/kg, } L = 2,086.3 \text{ kJ/kg (from steam tables).} \)

Enthalpy of 1 kg of wet steam measured above 0°C,
\[H_t = h + xL = 670.56 + 0.95 \times 2,086.3 = 2,652.54 \text{ kJ/kg.}\]

Total mass of steam supplied to engine per min.
\[= \text{mass of steam used in engine cylinder/min. plus mass of steam used in jacket/min.} \]
Gross heat supplied per minute:

Heat supplied to engine per min. = \( \frac{m_s + m_j}{60} \times H_t = \frac{355}{60} \times 2,652.54 = 15,694.2 \) kJ/min.

Heat expenditure per minute:

1. Heat equivalent of brake power per min. = 21 \times 60 = 1,260 kJ/min.
2. Heat removed by condenser cooling water per min.
   \[ = m_w \times 4.187 \times (t_2 - t_1) = \frac{10,200}{60} \times 4.187 \times 15 = 10,676.85 \) kJ/min.
3. Heat remaining in condensate per min.
   \[ = m_s \times 4.187 \times (t_c - 0) = \frac{325}{60} \times 4.187 \times (40 - 0) = 907.2 \) kJ/min.
4. Heat remaining in jacket drain per min.
   \[ = m_j \times 4.187 \times (t_j - 0) = \frac{30}{60} \times 4.187 \times (140 - 0) = 293.09 \] kJ/min.
5. Heat lost by radiation, error, etc. per min. (by difference)
   \[ = 15,694.2 - (1,260 + 10,676.85 + 907.2 + 293.09) = 2,557.06 \] kJ/min.

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>15,694.2</td>
<td>100</td>
<td>(1) Heat equivalent of brake power</td>
<td>1,260</td>
<td>8.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) Heat removed by condenser cooling water</td>
<td>10,676.85</td>
<td>68.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) Heat remaining in condensate</td>
<td>907.2</td>
<td>5.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4) Heat remaining in jacket drain</td>
<td>293.09</td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(5) Heat lost by radiation error etc. (by difference)</td>
<td>2,557.06</td>
<td>16.29</td>
</tr>
<tr>
<td>Total</td>
<td>15,694.2</td>
<td>100</td>
<td>Total</td>
<td>15,694.2</td>
<td>100</td>
</tr>
</tbody>
</table>

Indicated thermal efficiency when heat of condensate and heat of cylinder jacket drain is available to boiler as feed water heat

\[
= \frac{\text{Heat equivalent of indicated power per min}}{\text{Net heat supplied per min.}} = \frac{1,560}{15,694.2 - (907.2 + 293.09)} = 0.1076 \text{ or } 10.76\%
\]

Indicated thermal efficiency when heat of condensate is only available to boiler as feed water heat

\[
= \frac{26 \times 60}{15,694.2 - 907.2} = \frac{1,560}{14,787} = 0.1055 \text{ or } 10.55\%
\]

Percentage improvement in indicated thermal efficiency when heat of jacket drain is also available to boiler as feed water heat

\[
= \frac{10.76 - 10.55}{10.55} = \frac{0.21}{10.55} = 0.019 \text{ or } 1.9\%
\]

Problem-5: The following observation were recorded during a trial on a jacketed double-acting compound steam engine supplied with dry saturated steam:
### H.P. cylinder diameter
23 cm

### L. P. cylinder diameter
40 cm

### Stroke
58 cm

### M.E.P. in H.P. cylinder
2.46 bar

### M.E.P. in L.P. cylinder
1.39 bar

### Average engine speed
92.4 r.p.m.

### Brake-torque
4,150 Nm

### Steam pressure during admission
6.5 bar

### Receiver pressure
2.8 bar

### Condenser vacuum
610 mm of Hg

### Barometer reading
760 mm of Hg

### Steam measured as discharged from air pump
8 kg/min.

### Discharge from cylinder jacket drain
0.86 kg/min.

### Discharge from receiver jacket drain
0.49 kg/min.

### Mass of condenser cooling water
274 kg/min.

### Temperature rise of condenser cooling water
15°C

### Temperature of condensate
53°C

**Draw up a heat balance account giving heat quantities in kJ per minute and in percentages. Estimate also the mechanical and brake thermal efficiencies of the engine.**

**Indicated power of both cylinders (engine) =**

\[
(\rho_{m1} a_1 + \rho_{m2} a_2) \times l \times N \times \pi
\]

\[
= \left[ \left( 2.46 \times 10^5 \right) \times 0.7854 \times (0.23)^2 + (1.39 \times 10^5) \times 0.7854 \times (0.4)^2 \right]
\]

\[
\times 0.58 \times \frac{92.4}{60} \times 2 = 49,462 \text{ watts} = 49.462 \text{ kW}
\]

**Brake power of the engine = Torque \times 2 \pi N = 4,150 \times 2 \pi \times \frac{92.4}{60} = 40,156 \text{ watts} = 40.156 \text{ kW}**

At 6.5 bar (from steam tables), enthalpy per kg of dry saturated steam

\( H_1 = 2,760 \text{ kJ/kg.} \)

**Enthalpy per kg of condensate (water) from condenser,**

\( h_2 = (53 - 0) \times 4.187 = 221.9 \text{ kJ/kg.} \)

**Enthalpy per kg of condensate (water) from the receiver jacket drain at 2.8 bar is 551.48 kJ/kg (from steam tables), and**

**Enthalpy per kg of condensate (water) from cylinder jacket drain at 6.5 bar is 684.28 kJ/kg (from steam tables).**

**Total mass of steam supplied = 8 + 0.86 + 0.49 = 9.35 kg/min.**

### Gross heat supplied per minute :

- **Heat in steam supplied = 9.35 \times 2,760 = 25,806 kJ/min.**

### Heat expenditure per minute :

1. **Heat equivalent of brake power = 40.156 \times 60 = 2,409.5 kJ/min.**
2. **Heat removed by condenser cooling water = 274 \times 15 \times 4.187 = 17,208.6 kJ/min.**
3. **Heat remaining in condensate above °C = 8(53 - 0) \times 4.187 = 1,775.3 kJ/min.**
4. **Heat remaining in cylinder jacket drain above 0°C = 0.86 \times 684.28 = 588.5 kJ/min.**
(5) Heat remaining in receiver jacket drain above 0°C = 0.49 x 551.48 = 270.2 kJ/min.
(6) Heat lost by radiation, error, etc. (by difference)

\[ = 25,806 - (2,409.6 + 17,208.6 + 1,775.3 + 588.5 + 270.2) = 3,554 \text{ kJ/min.} \]

### Heat Balance sheet with 0°C as Datum

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>25,806</td>
<td>100</td>
<td>(1) To useful work brake (power)</td>
<td>2,409.4</td>
<td>9.34</td>
</tr>
<tr>
<td>(2) To condenser cooling water</td>
<td>1,720.8</td>
<td>66.68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) To condensate</td>
<td>1,775.3</td>
<td>6.88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4) To cylinder jacket drain</td>
<td>588.5</td>
<td>2.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(5) To receiver jacket drain</td>
<td>270.2</td>
<td>1.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(6) To radiation error of measurement etc. (by difference)</td>
<td>3,554.0</td>
<td>13.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25,806</strong></td>
<td><strong>100</strong></td>
<td><strong>Total</strong></td>
<td><strong>25,806</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Mechanical efficiency \( \eta_m = \frac{\text{Brake power}}{\text{Indicated power}} = \frac{40.156}{49.462} = 0.8118 \text{ or } 81.18\% \)

Assuming that heat of receiver jacket and cylinder jacket drains and heat of condensate (from condenser) is available to the boiler feed water,

Net heat supplied = 25,806 - (270.2 + 588.5 + 1,775.3) = 23,172 kJ/min.

Brake thermal efficiency, \( \eta_b = \frac{\text{Heat equivalent of brake power per min}}{\text{Net heat supplied per min}} \)

\[ = \frac{2,409.4}{23,172} = 0.104 \text{ or } 10.4\% \]

### Problem-6

A steam jacketed condensing steam engine working with dry saturated steam at an initial temperature of 123.27°C, develops brake power of 74 kW. The air pump discharges 1,150 kg of water per hour to the hot-well at a temperature of 50°C. The condenser cooling water supplied per hour is 18,500 kg and its rise in temperature is 35°C. Neglecting radiation losses, find: (a) the heat received by the working steam from the jacket, and (b) assuming that the jacket to be supplied with boiler steam and only enthalpy of evaporation (latent heat) of the jacket steam to be given up to working steam, find the mass of cylinder jacket steam used per kilogram of cylinder feed.

(a) Absolute pressure of steam corresponding to the saturation temperature of 123.27°C is 2.2 bar, and enthalpy \( (H_1) \) of dry saturated steam at 2.2 bar is 2,711 kJ/kg. and enthalpy of evaporation \( L_1 = 2,193.4 \text{ kJ/kg (from steam tables).} \)

Now, heat supplied by the boiler steam entering the cylinder per min.

\[ = \frac{m_s}{60} \times H_1 = \frac{1.150}{60} \times 2,711 = 51,961 \text{ kJ/min.} \]

(1) Brake power heat equivalent = 74 x 60 = 4,440 kJ/min.

(2) Heat removed by condenser cooling water = \[ \frac{18,500}{60} \times 35 \times 4.187 = 45,185 \text{ kJ/min.} \]

(3) Heat to hot-well = \[ \frac{1.150}{60} (50 - 0) \times 4.187 = 4,013 \text{ kJ/min.} \]

\[ \therefore \text{Heat rejected in exhaust steam} = 45,185 + 4,013 = 49,198 \text{ kJ/min.} \]

(4) Neglecting radiation losses, heat received by the working steam from the cylinder
jacket steam per min.

= heat supplied by the working steam entering the cylinder minus
heat to brake power + heat rejected in exhaust steam

= 51,961 - (4,440 + 49,198) = -1,677 kJ/min.

Negative sign indicates that heat is received by the working steam from the cylinder jacket steam.

(b) Now assuming that the cylinder jacket to be supplied with boiler steam at 2.2 bar and only enthalpy of evaporation (latent heat) of cylinder jacket steam to be given up to working steam,

Mass of jacket steam used per hour, \( m_j = \frac{1,677 \times 60}{2,193.4} = 45.87 \text{ kg} \)

\((2,193.4 \text{ kJ/kg is the enthalpy of evaporation of 1 kg of steam at 2.2 bar from steam tables})\)

\[ m_j = \frac{45.87}{1150} = 0.399 \text{ kg} \]

3.3 Steam Boiler Trials

Boiler trials are carried out to determine the thermal efficiency of the boiler and to draw up the heat balance account. Boiler trials are also carried out to verify the guaranteed maximum evaporative capacity of the boiler. For complete boiler trial, it is necessary to measure losses in addition to the heat utilised in raising steam. Such trials have been the direct cause of and incentive to the improvement of boilers. The measurements necessary to determine the thermal efficiency of a boiler and to draw up the heat balance account for a boiler are:

- Rate of fuel consumption, i.e. mass of fuel burned/hr.,
- Calorific value and chemical analysis of fuel after proper sampling,
- Rate of water evaporation, i.e. mass of water evaporated/hr.,
- Pressure of steam at the boiler stop valve,
- Condition of steam at the boiler stop valve, i.e. dryness fraction of steam if there is no superheater, or temperature of steam if there is a superheater,
- Feed water temperature,
- Flue gases temperature,
- Analysis of flue gases,
- Mass of ashes and determination of their calorific value after proper sampling, and
- Measurement of pressure, temperature and humidity of air.

To obtain the best results from a trial on the steam boiler, special attention must be paid to the method of stoking. The method of starting and stopping the trial, and the duration of the trial are also of great importance. The decisions regarding these, entirely depend upon the conditions under which the boiler has to work.

The following method of starting and stopping the trial will generally be found the most convenient:

The boiler should be kept running on load for some time in order to get settled down to working conditions. About fifteen minutes before the trial commences, the fire should be cleaned and all ashes and clinker removed. Then, at the start of the trial the thickness
of the fire, the steam pressure and the temperature of the flue gases should immediately be noted. The water level be marked by tying a piece of string around the gauge glass, and the feed pump should be stopped. At the end of the trial, the thickness of the fire, the steam pressure and the temperature of the flue gases should be same as that at the start of the trial. If the water levels of the feed water tank and boiler water tank and boiler water gauge glass is the same at the end as at the start of the trial, the working of result is much simplified.

The duration of the trial will depend chiefly upon the magnitude of the error likely to be made in judging the thickness and condition of the fire at the start and end of the trial, as compared to the mass of fuel fired during the trial. The duration of trial should not, as a rule, be less than six hours.

The following measurements and readings should be taken to determine the thermal efficiency and to draw up the heat balance account for the boiler:

1. The fuel should be weighted out in convenient lots of, from 20 to 400 kg depending upon the capacity of the boiler. This should be done by using two boxes. At the time of commencement of the trial, the first lot (box) should be emptied on the floor and stoking commenced. A complete record of time of emptying the boxes may be kept on a log sheet.

2. A sample should be taken from every lot of fuel weighted out and towards the end of the trial the samples should be broken up into small pieces and well mixed, and two representative samples be taken – one for the determination of its calorific value (by using the Bomb calorimeter) and the other for chemical analysis.

3. Some sort of volumetric measurement is used for measuring the feed water supplied to the boiler. Various methods may be adopted for the purpose. For small size boilers, one feed tank is used, while for large size boilers, two tanks may be used, each fitted with a gauge-glass and accurately calibrated. Just before the trial commences the feed pump should be stopped and the water level in the feed tank should be marked and recorded if only one feed tank is used. The feed pump is then started. The difference in water levels at the start and end of the trial gives the amount of feed water used. In case if two tanks are used, just before the commencement of the trial, No. 1 tank should be filled up, the boiler being fed from No. 2 tank. At the beginning of the trial the boiler is fed from No. 1 tank and No. 2 tank being filled up. The number of refilling of tanks depends totally on the size of the boiler and the duration of the trial.

4. Readings should be taken every five minutes of the steam pressure gauge.

5. Measurements regarding condition of steam at the boiler stop valve are done exactly in similar manner as for condition of steam at engine stop valve described earlier in this chapter under steam engine trial.

6. The temperature of feed water supplied to the boiler is measured at regular time interval of 10 minutes by means of ordinary mercury glass thermometer. For the purpose of calculation of feed water temperature, average reading of the temperature is considered.

7. The temperature of the flue gases is most accurately measured by a pyrometer. This should be placed at the bottom of the chimney and near the damper on the chimney side. Readings are taken at regular time interval of 10 minutes and average value is taken into account for the purpose of calculation of heat carried away by the flue gases.

8. The sample of flue gases should be taken just on the chimney side of the damper at the same place at which the temperature of flue gases is measured. When the boiler under test is fired by mechanical stokers, the flue gas sample may be drawn directly into the analysing apparatus, but when firing is by hand, continuous collection is necessary.
to secure an average sample. When great accuracy is required, the flue gases should be collected over mercury, but distilled water which has been saturated with common salt, or water with a layer of oil on the top, will give results accurate enough for most purposes. The flue gas is conveniently analysed on the spot by means of Orsat apparatus described in chapter 7 of volume I.

9. The amount of ashes formed during the trial period is obtained by weighing the ashes formed in the ash pit at the end of trial. As in the case of fuel, representative sample of the ash is obtained and its calorific value is determined by using the Bomb calorimeter.

10. Average values of temperature and pressure of the boiler house are obtained by reading a thermometer and a barometer at regular time interval of 10 minutes. In order to estimate the humidity (moisture) in the air of the boiler house, readings of the dry and wet bulb thermometers are taken at regular time interval.

3.4 Efficiency of Boiler

The thermal efficiency of boiler is expressed by the ratio:

\[
\frac{\text{Heat transferred to feed water in converting it into steam per kg of fuel}}{\text{Heat released by complete combustion of one kg of fuel}}
\]

The available heat in one kilogram of fuel as fired will not be the calorific value of one kilogram of fuel, unless of course the fuel is dry. The moisture present in the fuel has to be evaporated and superheated to the temperature of the flue gases, and the amount of heat so utilised is lost. The effect of moisture in air supply may also have an appreciable effect on the performance of a boiler, as this moisture has to be heated, evaporated and superheated, the heat so utilised being lost in the flue gases. The amount of this heat may be estimated from the readings of the wet and dry bulb thermometers. It will be found that the heat absorbed in superheating the water vapour (moisture) in the air is negligibly small and may be neglected.

The actual available heat supplied to the boiler per kilogram of coal

\[
= \text{calorific value of 1 kg of dry coal as fired} - \text{(heat absorbed by the moisture in 1 kg of dry coal as fired)} - \text{(heat absorbed by the moisture in the mass of air supplied per kg of coal)}
\]

The lower caloric value of fuel was formerly used in estimating the boiler thermal efficiency, but now the gross value (higher calorific value) is recommended.

3.5 Heat Balance Sheet for Boiler

The various items of the heat balance sheet for a boiler test are as follows:

Heat balance sheet per kg of coal fired

<table>
<thead>
<tr>
<th>Heat supplied by 1 kg of coal per kg of coal</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure per kg of coal</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head supplied</td>
<td></td>
<td></td>
<td>(1) Heat utilized in steam formation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) Heat carried away by products of combustion (dry flue gases)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) Heat carried away by excess air</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4) Heat lost in evaporating and superheating the moisture in the coal and the water vapour formed due to burning of hydrogen in coal</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(5) Heat lost by incomplete combustion</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The method of estimating the various items of heat balance sheet is illustrated by the following problems:

**Problem-7**: The following data was obtained in a steam boiler trial:

- Feed water supplied per hour 690 kg at 28°C, steam produced 0.97 dry at 8 bar,
- coal fired per hour 91 kg of calorific value 27,200 kJ/kg, ash and unburnt coal collected from beneath the fire bars 7.5 kg/hour of calorific value 2,760 kJ/kg, mass of flue gases per kg of coal burnt 17.3 kg, temperature of flue gases 325°C, room temperature 17°C, and the specific heat of the flue gases 1.026 kJ/kg K.

Estimate: (a) the boiler efficiency (b) the percentage heat carried away by the flue gases, (c) the percentage heat loss in ashes, and (d) the percentage heat loss unaccounted for.

Explain what may have actually happened to the heat included under unaccounted losses.

(a) Heat supplied to the boiler per hour = 91 x 27,200 = 24,75,200 kJ/hr.
At 8 bar, \( h = 721.1 \) kJ/kg, \( L = 2,048 \) kJ/kg (from steam tables).

Enthalpy of wet steam, \( \Delta h = h_1 + xL_1 = 721.1 + 0.97 \times 2,048 = 2,707.67 \) kJ/kg.

Enthalpy of feed water at 28°C, \( h_2 = 28 \times 4.187 = 117.24 \) kJ/kg.

:. Heat utilised in steam formation per hour

\[ = \text{mass of steam produced per hr.} \times (\Delta h - h_2) \]

\[ = 690 \times (2,707.67 - 117.24) = 17,87,396 \text{ kJ/hr}. \]

Boiler efficiency = \( \frac{\text{Heat utilised in steam formation per hr.}}{\text{Heat supplied to the boiler per hr.}} \)

\[ = \frac{17,87,396}{24,75,200} = 0.7221 \text{ bar or } 72.21\% \]

(b) Heat carried away by the flue gases = \( m_g \times K_p \times (t_g - t_r) \)
where, \( m_g = \text{mass of flue gases} = 17.3 \text{ kg/kg of coal fired}, \)
\( t_g = \text{temperature of flue gases} = 325\^\circ \text{C}, \)
\( t_r = \text{room temperature} = 17\^\circ \text{C}, \) and
\( K_p = \text{specific heat of flue gases} = 1.026 \text{ kJ/kg K}. \)

:. Heat carried away by the flue gases

\[ = 17.3 \times 1.026 (325 - 17) = 5,467 \text{ kJ/kg of coal}. \]

Hence, percentage heat carried away by the flue gases per kg of coal fired
\[
\frac{5,467}{27,200} \times 100 = 20.1\%
\]

(c) Percentage heat loss in ashes = \( \frac{\text{Heating value of ash in kJ/hr.}}{\text{Heat supplied to the boiler in kJ/hr.}} \times 100\)

\[
= \frac{7.5 \times 2,760}{24,752,000} \times 100 = 0.836\%
\]

(d) Percentage heat loss unaccounted for (by difference)

\[
= 100 - (72.21 + 20.1 + 0.836) = 6.854\%
\]

Heat loss unaccounted for, includes error of observation and unmeasured losses such as those due to radiation, escape of unburnt hydrocarbons, superheating of moisture in air and coal, loss in hot ashes, etc.

**Problem-8**: The following particulars refer to a boiler trial in which it was not convenient to measure the amount of water evaporated:

Percentage analysis of dry coal on mass basis: C, 85.5; H\(_2\), 3.9; O\(_2\), 3.6; Ash 7

Percentage analysis of dry flue gases by volume: CO\(_2\), 11.6; CO, 0.6; O\(_2\), 8; N\(_2\), 79.8

Percentage analysis of ash collected in ash pit: C, 15; Ash, 85

Higher C.V. of dry coal per kg ... 33,900 kJ
Moisture in coal as fired ... 2 %
Temperature of the flue gases ... 310°C
Temperature of the boiler room ... 24°C.
Mean specific heat of dry flue gases ... 1.026 kJ/kg K
Specific heat of air ... 0.997 kJ/kg K
Barometric pressure (atmospheric) ... 1 bar
Specific heat of superheated water vapour ... 2 kJ/kg K
Calorific value of carbon burnt to CO\(_2\) per kg ... 34,125 kJ
Calorific value of carbon burnt to CO per kg ... 10,175 kJ
Assuming a radiation loss of 7 per cent, draw up a heat balance sheet for the boiler and determine its thermal efficiency.

Considering one kg of coal as fired,
Gross heat supplied = 0.98 \times 33,900 = 33,222 kJ per kg.

Heat expenditure per kg of coal as fired:

(2) As one kg of coal fired contains 0.07 kg of ash, the mass of carbon in association with 0.07 kg of ash in the ash pit is \(0.07 \times \frac{15}{85} = 0.0123\) kg.

\[
\text{Mass of carbon taking part in combustion per kg of coal fired} = (0.855 \times 0.98) \times 0.0123 = 0.827\) kg.
\]
i.e. 82.7% on mass basis,

Mass of air supplied per kg of coal fired \(= \frac{NC}{33(C_1 + C_2)}\)

where, \(N\), \(C_1\) and \(C_2\) are percentages of Nitrogen, Carbon dioxide and Carbon monoxide by volume in flue gas, and \(C\) is the percentage of carbon in coal on mass basis.

\[
\text{Mass of air supplied} = \frac{79.8 \times 82.7}{33 (11.6 + 0.6)} = 16.4\) kg per kg of coal fired.
Total mass of flue gases per kg of coal fired = 16.4 + (1 - 0.07) = 17.33 kg
Minimum quantity of air theoretically required per kg of coal
\[
= (2.66C + 8H) \frac{100}{23} = (2.66 \times 0.827 + 8 \times 0.039 \times 0.98) 4.35 = 10.45 \text{ kg.}
\]
.: Excess air supplied per kg of coal fired = 16.4 - 10.45 = 5.95 kg.
Mass \((m_g)\) of moisture and water vapour per kg of coal fired.
\[
= 0.02 + (9 \times 0.039 \times 0.98) = 0.371 \text{ kg.}
\]
Mass \((m_g)\) of dry products of combustion per kg of coal fired
\[
= 17.33 - 5.95 - 0.371 = 11.01 \text{ kg.}
\]
:. Heat carried away by dry products of combustion = \(m_g \times K_p \times (t_g - t_f)\)
\[
= 11.01 \times 1.026 (310 - 24) = 3,230.6 \text{ kJ/kg of coal fired.}
\]
(3) Heat carried away by excess air.
\[
= 5.95 \times 0.997 (310 - 24) = 1,696.5 \text{ kJ/kg of coal fired.}
\]
(4) Heat carried away by water vapour in the products of combustion = \(m_s \times (H_{sp} - h_0)\)
\[
= 0.371 [2,675.5 + 2(310 - 99-63) - 24 \times 4.187] = 1,112 \text{ kJ per kg of coal fired.}
\]
(5) We next require the proportion of carbon burned to CO\(_2\) and CO respectively.
In 11.6 \times 44 parts of CO\(_2\) on mass basis, there are 11.6 \times 44 \times \frac{12}{44} = 11.6 \times 12 parts of carbon on mass basis.
.
In 0.6 \times 28 parts of CO on mass basis, there are 0.6 \times 28 \times \frac{12}{28} = 0.6 \times 12 parts of carbon on mass basis.
.
:. Proportion of carbon burnt to CO = \[
\frac{0.6 \times 12}{(11.6 + 0.6)12} = 0.0492
\]
:. Mass of carbon burnt to CO in one kg of coal fired.
\[
= 0.855 \times 0.98 \times 0.0492 = 0.0412 \text{ kg}
\]
Hence, heat lost through incomplete combustion per kg of coal fired.
\[
= 0.0412 (34.125 - 10.175) = 986.7 \text{ kJ per kg of coal fired}
\]
(6) Heat carried away by unburnt carbon in the ash pit per kg of coal fired.
\[
= 0.0123 \times 34.125 = 419.7 \text{ kJ per kg of coal fired}
\]
(7) Heat lost by radiation (assumed) = 0.07 \times 33,222 = 2,325.5 \text{ kJ per kg of coal fired.}
.
:. Total heat loss = 3,230.6 + 1,696.5 + 1,112.0 + 986.7 + 419.7 + 2,325.5
\[
= 9,771 \text{ kJ/kg of coal fired}
\]
(1) Thus, heat utilized in steam formation per kg of coal fired (by difference).
\[
= 33,222 - 9,771 = 23,451 \text{ kJ per kg of coal fired}
\]
:. Thermal efficiency of the boiler.
\[
\text{Heat utilized in steam formation per kg of coal} \div \text{Gross heat supplied per kg of coal}
\]
\[
= \frac{23,451}{33,222} = 0.7059 \text{ or 70.59%}
\]
Heat balance sheet per kg of coal fired

<table>
<thead>
<tr>
<th>Heat supplied by 1 kg of coal</th>
<th>Heat expenditure/kg of coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat supplied</td>
<td>(1) Heat utilized in steam formation (by difference)</td>
</tr>
<tr>
<td></td>
<td>(2) Heat carried away by dry products of combustion</td>
</tr>
<tr>
<td></td>
<td>(3) Heat carried away by excess air</td>
</tr>
<tr>
<td></td>
<td>(4) Heat lost in evaporating and superheated moisture in coal and water formed by combustion of hydrogen in coal</td>
</tr>
<tr>
<td></td>
<td>(5) Heat lost through incomplete combustion</td>
</tr>
<tr>
<td></td>
<td>(6) Heat carried away by unburnt carbon in ash pit</td>
</tr>
<tr>
<td></td>
<td>(7) Heat lost by radiation, error, etc. (assumed)</td>
</tr>
<tr>
<td>Total</td>
<td>Total</td>
</tr>
</tbody>
</table>

**Problem-9:** The following data was obtained during a trial of a steam boiler:

Feed water temperature, 75°C; mass of feed water supplied per hour, 4,900 kg; steam pressure, 11 bar; dryness fraction of steam, 0.9; coal fired per hour, 490 kg; higher calorific value of 1 kg of dry coal, 35,600 kJ/kg; moisture in coal, 4% on mass basis; temperature of flue gases, 300°C; boiler house temperature, 16°C; barometric (atmospheric) pressure 1 bar; analysis of dry coal on mass basis, C = 89%; H$_2$ = 3%; ash = 4%; and other matter = 4%; analysis of flue gases by volume, CO$_2$ = 10.9%; CO = 1.1%; O$_2$ = 7% and N$_2$ = 81%. Take specific heat of dry flue gases as 1 kJ/kg K and Kp of superheated steam as 2 kJ/kg K. Draw the heat balance sheet for the boiler per kg of coal fired. What is the thermal efficiency of the boiler?

Heat supplied per kg of coal = (1 - 0.04) 35,600 = 34,176 kJ per kg of coal

At 11 bar, $h = 781.34$ kJ/kg, $L = 2,000.4$ kJ/kg (from steam tables)

(1) Heat utilized per kg of steam at 11 bar and 0.9 dry = $H_1 - h_2$

$= (h_1 + x_1 L_1) - h_2 = (781.34 + 0.9 \times 2000.4) - 75 \times 4187 = 2,267.67$ kJ/kg.

Hence, heat utilized per kg of coal fired

$= \frac{4900}{490} \times 2267.67 = 22,676.7$ kJ/kg of coal.

(2) Mass of air supplied per kg of coal fired = \(\frac{NC}{33(C_1 + C_2)}\)

where, $N$, $C_1$ and $C_2$ are percentages of nitrogen, carbon dioxide and carbon monoxide by volume in flue gases, and $C$ is the percentage of carbon in coal on mass basis.

: Mass of air supplied = \(\frac{81 \times (89 \times 0.96)}{33(10.9 + 1.1)} = 17.7$ kg/kg of coal fired

Mass of dry flue gases per kg of coal fired, $m_g = 17.7 + (0.89 \times 0.96) = 18.57$ kg.

Thus, heat carried away by dry flue gases per kg of coal fired

$= m_g \times K_p (t_g - t_r) = 18.57 \times 1 \times (300 - 16) = 5,273.88$ kJ/kg of coal fired.

(3) Mass of moisture in coal and water vapor formed due to combustion of hydrogen in coal per kg of coal fired

$= m_s = m + (9 \times H_2) = 0.04 + (9 \times 0.03) = 0.31$ kg.

Heat carried away by moisture in coal and water vapour formed in flue gases due to burning of hydrogen in the coal = $m_s (H_{sup} - h_0)$
where, \( m_s \) = mass of steam (0.31 kg) formed per kg of coal fired,

\[ H_{\text{sup}} = \text{enthalpy of 1 kg of superheated steam at the temperature of flue gases (300°C) and at atmospheric pressure of 1 bar, and} \]

\[ h_0 = \text{Enthalpy (sensible heat) of 1 kg of water at the boiler room temperature (16°C).} \]

Now, \( m_s \times (H_{\text{sup}} - h_0) = m_s \left[ \{H_s + Kp (t_{\text{sup}} - t)\} - h_0 \right] \]

\[ = 0.31 \left[ \{2,675.5 + 2 \times (300 - 99.63)\} - 16 \times 4.187 \right] = 932.87 \text{ kJ/kg of coal fired}. \]

(4) Heat lost by radiation, error, etc. (by diff.)

\[ = 34,176 - (22,676.7 + 5,273.88 + 932.87) = 5,292.55 \text{ kJ/kg of coal fired}. \]

### Heat balance sheet per kg of coal fired

<table>
<thead>
<tr>
<th>Heat supplied by 1 kg of coal</th>
<th>kJ</th>
<th>Heat expenditure per kg of coal</th>
<th>kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat supplied</td>
<td>34,176</td>
<td>(1) Heat utilized in steam formation</td>
<td>22,676.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) Heat carried away by dry flue gases.</td>
<td>5,273.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) Heat lost in evaporating and superheating</td>
<td>932.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>moisture in coal and water vapour formed</td>
<td>due to combustion of hydrogen in coal.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) Unmeasured losses such as those due</td>
<td>5,292.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to radiation, escape of unburnt hydrocarbons,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>losses in hot ashes error of observation etc. (by difference)</td>
<td></td>
</tr>
</tbody>
</table>

Total 34,176 Total 34,176

Thermal efficiency of the boiler = \( \frac{\text{Heat utilized in steam formation per kg of coal}}{\text{Gross heat supplied per kg of coal}} \)

\[ = \frac{22,676.7}{34,176} = 0.6638 \text{ or } 66.38\% \]

### Tutorial - 3

1. Delete the phrase which is not applicable from the following statements:

(i) Steam engines are generally single/double acting.

(ii) Live steam from the boiler/exhaust steam is passed through cylinder jacket.

(iii) Indicated power of a steam engine is estimated by taking indicator diagram/using a dynamometer.

(iv) Mean effective pressure on cover end and crank end of a double-acting steam engine are/are not the same.

(v) Thermal efficiency of steam engine is/is not improved when heat of jacket drain is also available to boiler feed water in addition to heat of condensate.

[(i) Single, (i) Exhaust steam, (iii) Using a dynamometer, (iv) are, (v) is not]

2. Fill in the blanks to complete the following statements:

(i) Brake specific steam consumption is expressed as _____.

(ii) The rate of steam consumption of a condensing engine is best measured by condensing the exhaust steam and _____ the condensate.

(iii) Thermal efficiency of a boiler is defined as the ratio of heat utilized in steam formation per kg of coal and _____.

(iv) Boiler house instruments may be broadly divided into: (a) those which give information about performance, and (b) those which help — the performance.

[(kg/kW-hr, (ii) weighing, (iii) gross heat supplied per kg of coal, (iv) to control]

3. Indicate the correct phrase out of phrases given in the following:

(i) Thermal efficiency of a well maintained boiler will be of the order of

(a) 20%  (b) 40%  (c) 60%  (d) 75%  (e) 90%

(ii) Maximum energy loss in a boiler occurs due to
(a) flue gases (b) ash content (c) radiation losses (d) incomplete combustion.

(iii) The temperature of the flue gases is most accurately measured by
(a) a thermometer (b) a thermocouple (c) a pyrometer.

(iv) The object of steam boiler trial is
(a) to estimate steam raising capacity of the boiler when working at a definite pressure.
(b) to determine the thermal efficiency of the boiler when working at a definite pressure.
(c) to draw up a heat balance sheet for the boiler.
(d) all the three objects mentioned above.

4. In a test on single-cylinder, double-acting condensing steam engine, the following observations were made:
Indicated power, 24 KW; brake power, 20 kW; steam supply at 5-5 bar with 12°C superheat; KP of
superheated steam, 2-3 kJ/kg K; condenser vacuum, 647-5 mm of Hg when barometer reads 760 mm of
Hg; steam used per hour, 300 kg; temperature of condensate; 40°C; cooling water for condenser, 7,800
kg per hour; temperature rise of condenser cooling water, 20°C.

Estimate: (a) the indicated thermal efficiency and (b) the dryness fraction of steam entering the
condenser. Assume that all the heat given up by steam in the condenser is gained by condenser cooling
water.
Also draw up a heat balance sheet for the engine in kJ/min.

<table>
<thead>
<tr>
<th>Heat supplied/min. kJ</th>
<th>Heat expenditure/min. kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied 13,903</td>
<td>(1) To brake power 1,200</td>
</tr>
<tr>
<td></td>
<td>(2) To condenser cooling water 10,886-2</td>
</tr>
<tr>
<td></td>
<td>(3) To condensate 837-4</td>
</tr>
<tr>
<td></td>
<td>(4) To radiation etc. 979-4</td>
</tr>
<tr>
<td>Total                13,903</td>
<td>Total 13,903-0</td>
</tr>
</tbody>
</table>

5. The following data relate to a test on a compound double-acting steam engine:

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Cylinder diameter cm</th>
<th>Stroke cm</th>
<th>M.E.P. bar</th>
<th>Inlet steam</th>
<th>Exhaust steam pressure bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>H. P.</td>
<td>21</td>
<td>15</td>
<td>3</td>
<td>14</td>
<td>205</td>
</tr>
<tr>
<td>L. P.</td>
<td>33</td>
<td>15</td>
<td>0.9</td>
<td>—</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Steam consumption 9-3 kg/min.; condensate temperature, 66°C; speed 550 r.p.m.; brake torque, 750
N.m; condenser cooling water flow, 470 kg/min.; temperature rise of condenser cooling water, 10°C.

Ignoring piston rod areas, calculate: (a) the indicated power, (b) the mechanical efficiency, and (c) the
efficiency ratio on the indicated power basis. Also draw up a heat balance sheet in kJ/minute.

<table>
<thead>
<tr>
<th>Heat supplied/min. kJ</th>
<th>Heat expenditure/min. kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied 26,140-9</td>
<td>(1) To brake power 2,591-8</td>
</tr>
<tr>
<td></td>
<td>(2) To condenser cooling water 19,678-9</td>
</tr>
<tr>
<td></td>
<td>(3) To condensate 2,570-0</td>
</tr>
<tr>
<td></td>
<td>(4) To radiation etc. 1,300-2</td>
</tr>
<tr>
<td>Total                26,140-9</td>
<td>Total 26,140-9</td>
</tr>
</tbody>
</table>

6. The following observation were made during a trial of jacketed steam engine:
Supply steam pressure ... 13 bar
Dryness fraction of steam supplied ... 0.98
Mass of steam supplied to the cylinder ... 20 kg/min.
Mass of steam supplied to the cylinder jacket ... 2-5 kg/min.
Brake power ... 130 kW
Indicated power ... 160 kW
Condenser cooling water ... 450 kg/min.
Rise in temperature of condenser cooling water ... 22°C
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Temperature of condensate: ... 50°C
Temperature of cylinder jacket drain: ... 185°C

Draw up a heat balance sheet in kJ/min. and determine the indicated thermal efficiency of the engine assuming that the heat of condensate and cylinder jacket drain is available to the feed water.

\[ \eta = 17.23\% \]

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>61,834</td>
<td>(1) To brake power</td>
<td>7,800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) To condenser cooling water</td>
<td>41,451</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) To condensate</td>
<td>4,187</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) To cylinder jacket drain</td>
<td>1,937</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5) To radiation etc.</td>
<td>6,459</td>
</tr>
<tr>
<td>Total</td>
<td>61,834</td>
<td>Total</td>
<td>61,834</td>
</tr>
</tbody>
</table>

7. During a test on a jacketed steam engine, the following observations were made:

Indicated power, 90 kW; brake power, 72 kW; pressure of steam supplied 14 bar; quality of steam supplied 10% wet; mass of steam used in the engine cylinder 900 kg/hour; mass of steam used in jacket, 100 kg/hour; condensate temperature, 60°C; cooling water for condenser, 15,500 kg/hour; inlet temperature of cooling water for condenser, 26°C; outlet temperature of cooling water for condenser, 55°C. Taking specific heat of water as 4.187 kJ/kg K, draw a heat balance sheet in kJ per minute and on percentage basis.

Calculate the indicated thermal efficiency when the heat of jacket drain is not available to the boiler feed water. What will be the percentage improvement in the indicated thermal efficiency if the heat of the jacket drain is also available to the feed water?

\[ \eta = 13.68\%; \eta_A = 3.65\% \]

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>43,233-83</td>
<td>100</td>
<td>(1) To brake power</td>
<td>4,320</td>
<td>9.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) To condenser cooling water</td>
<td>31,360</td>
<td>72.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) To condensate</td>
<td>3,768-3</td>
<td>8.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4) To jacket drains</td>
<td>1,383-83</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(5) To radiation etc.</td>
<td>2,401-7</td>
<td>5.55</td>
</tr>
<tr>
<td>Total</td>
<td>43,233-83</td>
<td>100</td>
<td>Total</td>
<td>43,233-83</td>
<td>100</td>
</tr>
</tbody>
</table>

8. The following observations were made in a trial on a jacketed, double-acting compound steam engine supplied with dry saturated steam at 11 bar:

Cylinder | Piston stroke | Cylinder diameter | Mean effective pressure
---|---|---|---
H. P. | 60 cm | 23 cm | 2.8 bar
L.P. | 60 cm | 40 cm | 1.1 bar

Speed, 87.5 r.p.m.; Brake torque, 4,300 N.m; Water from cylinder jacket drain, 1 kg/minute; Condensate, 8.5 kg/minute; Temperature of condensate, 45°C; Condenser cooling water, 160 kg/minute; Rise in temperature of condenser cooling water, 30°C.

Calculate: the brake power, the indicated power, the brake thermal efficiency, and indicated thermal efficiency assuming the heat of condensate and cylinder jacket drain in available to the feed water, and make out a heat balance sheet in kJ/min.

\[ \text{Brake power} = 39.4 \text{ kW}; \text{Indicated power} = 44.548 \text{ kW}; \eta_B = 9.83\%; \eta_I = 11.12\% \]

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>26,426</td>
<td>(1) To brake power (useful work)</td>
<td>2,364</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) To condenser cooling water</td>
<td>20,098</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) To condensate</td>
<td>1,601-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) To cylinder jacket drain</td>
<td>781-34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5) To radiation, etc.</td>
<td>1,581-16</td>
</tr>
<tr>
<td>Total</td>
<td>26,426</td>
<td>Total</td>
<td>26,426</td>
</tr>
</tbody>
</table>
9. The following are the average readings taken during a trial on a double-acting steam engine:

- Stroke, 30 cm; Cylinder diameter, 21.6 cm; Mean speed, 123.9 r.p.m.; Area of indicator diagram, 6.52 cm²; Length of indicator diagram, 6.6 cm; Strength of indicator spring, 85 kPa per cm; Coal consumption, 0.252 kg/min.; Calorific value of coal, 35,200 kJ per kg; Condenser cooling water, 46.2 kg/min.; Rise in temperature of condenser cooling water, 28.9°C; Load on brake, 457 newtons; Spring balance reading, 66 newtons; Radius of brake wheel, 60 cm; Steam used per min., 2.51 kg; Steam pressure, 3 bar; steam supply, dry saturated; Condenser pressure, 0.2 bar.

   Calculate the indicated power, brake power, mechanical and indicated thermal efficiencies of the engine, and overall efficiency of the steam plant from coal to brake. Draw up a percentage heat balance sheet for the engine cylinder.

10. What are the purposes of steam engine trials? What measurements are necessary in engine trials to determine the thermal efficiency and to draw up heat balance sheet? Draw up a typical heat balance sheet on percentage basis of an average steam engine.

11. The following observations and deductions are taken from a report of a trial of a boiler plant, consisting of six Lancashire boilers and an economiser:

   Calorific value of coal per kg, 30,000 kJ; mass of feed water per kg of dry coal, 9.1 kg; Equivalent evaporation from and at 100°C per kg of dry coal, 9.6 kg; Temperature of feed water to economiser, 12°C; Temperature of feed water to boiler, 105°C; Air temperature, 13°C; Temperature of flue gases entering the economiser, 370°C; Mass of flue gases entering economiser 18.2 kg per kg of dry coal; Mean specific heat of the flue gases, 1.05 kJ/kg K.

   Find: (a) the efficiency of the boilers alone, (b) the efficiency of the economiser alone, and (c) the efficiency of the whole boiler plant.

12. In a boiler trial the following quantities were obtained: Coal burned per hour, 48 kg; Calorific value of coal, 31,200 kJ/kg; Feed water per hour, 387 kg; Temperature of feed water, 20°C; Pressure of steam, 8.5 bar; Dryness fraction of steam, 0.99; Ash and unburnt coal collected from beneath fire bars, 4 kg/hour of the calorific value, 2,850 kJ/kg; Mass of flue gases per kg of coal burned, 17.3 kg; Temperature of flue gases, 340°C; Room temperature, 16°C; Specific heat of flue gases, 1.026 kJ/kg K.

   Estimate: (a) the thermal efficiency of the boiler, (b) the percentage heat carried away by the flue gases, (c) the percentage heat loss in ashes, and (d) the percentage heat loss unaccounted for.

13. In a boiler trial, 445 kg of coal were consumed per hour. The mass of water evaporated per hour was 4,150 kg. The steam pressure was 10 bar and dryness fraction of steam was 0.98. The coal contained 4 per cent of moisture on mass basis. The feed water temperature was 50°C. Calorific value of one kilogram of dry coal was 35,000 kJ. The boiler house temperature was 15°C and the temperature of the chimney gases was 280°C. Take specific heat of dry flue gases as 1.005 kJ/kg K and Kp of superheated steam as 2 kJ/kg K.

   Analysis of dry coal on mass basis: C = 86%; H₂ = 4% ash = 5%; and other matter = 5%.

   Analysis of dry flue gases by volume:
   
   CO₂ = 10.4%; CO = 1.2%; O₂ = 9.1%; and N₂ = 79.3% (by difference)

   Determine the thermal efficiency of the boiler and draw up a heat balance sheet for the boiler per kg of coal fired on percentage basis.

   [(indicated power = 3.814 kW; Brake power = 3.044 kW, ηₘ = 78.76%; ηᵢ = 3.68%; 2.06%]

<table>
<thead>
<tr>
<th>Heat supplied/min.</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure/min.</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in steam supplied</td>
<td>6,840.5</td>
<td></td>
<td>(1) To Brake power</td>
<td>182.6</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) To condensing cooling water</td>
<td>5,590.4</td>
<td>81.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) To condensate</td>
<td>626.4</td>
<td>9.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4) To radiation etc.</td>
<td>441.1</td>
<td>6.45</td>
</tr>
<tr>
<td>Total</td>
<td>6,840.5</td>
<td>100</td>
<td>Total</td>
<td>6,840.5</td>
<td>100</td>
</tr>
</tbody>
</table>
14. The following particulars relate to a boiler trial in which it was not convenient to measure the amount of water evaporated:

Percentage analysis of dry coal on mass basis: C, 83; H₂, 5; O₂, 4; Ash, etc., 8

Percentage analysis of dry flue gases by volume:
CO₂, 10.1; CO, 0.3; O₂, 9.3 and N₂ (by difference), 80.3

Percentage analysis of ash collected in ash pit: C, 14; ash, 86

Higher calorific value of dry coal per kg
... 34,000 kJ

Moisture in coal as burned
... 2%

Temperature of the flue gases
... 330°C

Temperature of boiler room
... 17°C;

Mean specific heat of flue gases
... 1.005 kJ/kg K

Specific heat of air
... 1 kJ/kg K

Specific heat of superheated water vapour
... 2 kJ/kg K

Calorific value of C burnt to CO₂ per kg
... 33,830 kJ

Calorific value of C burnt to CO per kg
... 10,130 kJ

Assuming radiation loss of 6%, draw up a percentage heat balance sheet for the boiler and determine its thermal efficiency.

<table>
<thead>
<tr>
<th>Heat supplied by 1 kg of coal</th>
<th>kJ</th>
<th>%</th>
<th>Heat expenditure per kg of coal</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat supplied</td>
<td>33,600</td>
<td>100</td>
<td>(1) To steam</td>
<td>23,580</td>
<td>70.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) To dry flue gases</td>
<td>4,774</td>
<td>14.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) To water vapour in flue gases</td>
<td>654</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4) To radiation unmeasured losses etc. (By difference)</td>
<td>4,592</td>
<td>13.66</td>
</tr>
<tr>
<td>Total</td>
<td>33,600</td>
<td>100</td>
<td>Total</td>
<td>33,600</td>
<td>100</td>
</tr>
</tbody>
</table>

[Thermal efficiency = 68.68%]