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STATE BOARD OF TECHNICAL EDUCATION (SBTE), BIHAR

DEPARTMENT OF MECHANICAL ENGINEERING

Diploma in Mechanical Engineering | Semester - III

LAB MANUAL

(THERMAL ENGINEERING LAB)

Course Code: P2425304

Course code	Course Titles	Lab Assessment (LA) Marks		Lab Assessment (LA) Hours/Week
		Progressive Lab Assessment(PLA)	End Laboratory Assessment(ELA)	
P2425304	Basic Thermodynamics	20	30	4

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EXPERIMENT NO. 01: CALIBRATION OF THERMOMETERS AND PRESSURE GAUGES

LSO 1.1: Use of Thermometer and Pressure Gauge | Relevant CO: CO1

1. Aim :-

To perform precision static calibration of an industrial Bourdon tube dial pressure gauge using a Dead Weight Pressure Gauge Calibrator (Primary Standard) across a range of 0 to 6 bar, and to calibrate laboratory liquid-in-glass and digital thermometers against standard ice and steam equilibrium reference points.

2. Apparatus & Technical Specifications

Sr. No.	Apparatus Name	Engineering Specifications	Quantity
1	Dead Weight Tester Unit	Range: 0 - 10 bar; Precision ground vertical piston; Base leveling screws	1 Set
2	Calibrated Test Weights	0.5 kg, 1.0 kg, 2.0 kg; Material: Stainless Steel (Class M1)	1 Set
3	Test Bourdon Pressure Gauge	Dial size: 100 mm; Range: 0 - 10 bar; Least Count: 0.1 bar; Phosphor Bronze C-tube	1 No.
4	Constant Temp. Water Bath	Thermostatic electric bath with digital PID temperature controller (0 to 100°C)	1 No.
5	Secondary Standard RTD Probe	Pt-100 sensor with 4-wire high-precision digital indicator ($\pm 0.05^\circ\text{C}$ accuracy)	1 No.
6	Test Liquid Thermometers	Mercury-in-glass (-10°C to 110°C ; LC: 0.5°C); Digital K-type thermocouple	2 Nos.

3. Working Principle & Mathematical Equations

Calibration evaluates measurement uncertainty by comparing instrument readings against a fundamental primary standard. By Pascal's principle, the true hydrostatic pressure generated by the dead weight tester is:

Governing Mathematical Equations:

1.True Pressure: $P_{act} = (M \cdot g + F_{tare}) / (A_{piston} \times 10^5) \text{ [bar]}$ **Mean**

2.Gauge Pressure: $P_{mean} = (P_{up} + P_{down}) / 2 \text{ [bar]}$ **Absolute**

3.Error: $Error = P_{mean} - P_{act} \text{ [bar]}$

4.Instrument Correction: $Correction = -Error = P_{act} - P_{mean} \text{ [bar]}$

5.Percentage Full-Scale (% FS) Error: $\% FS Error = [(P_{mean} - P_{act}) / P_{max_scale}] \times 100\%$

4. Schematic Diagram & Working Flowchart

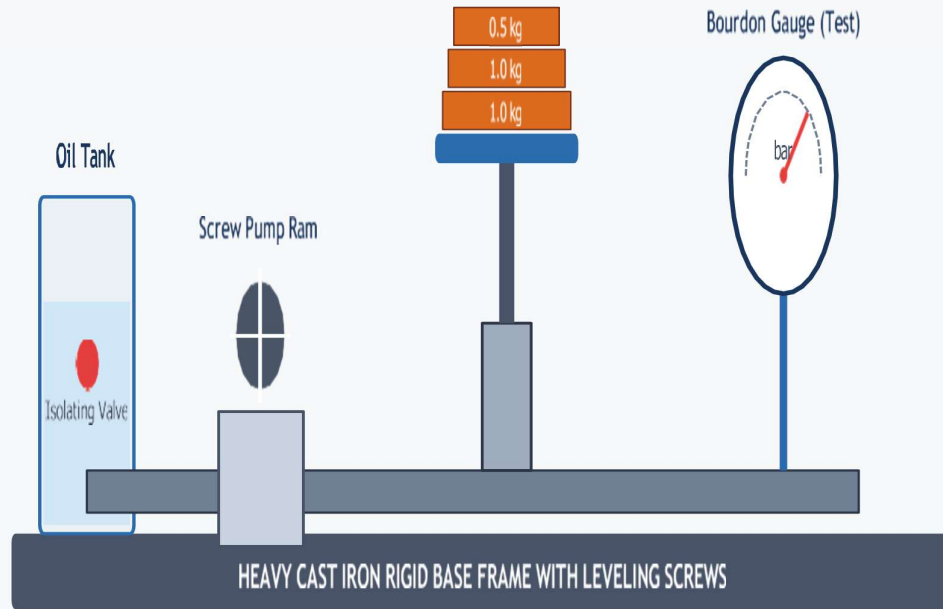


Figure 1.1 Standard Test Ring Arrangement for Bourdon Gauge Calibration Using Dead Weight Calibrator



Flowchart 1.2: Systematic Execution Process Flow for Pressure Gauge

5. Experimental Procedure

1. Mount the dead-weight tester on a rigid table. Level the base frame horizontally using the leveling screws and circular spirit level.
2. Fill the reservoir with clean hydraulic mineral oil (ISO VG 32). Turn the screw pump handwheel anticlockwise to draw fluid into the chamber. Open the air bleed valve under the test gauge mount until air bubbles are fully eliminated, then tighten securely.
3. Insert the piston into the cylinder. Turn the screw handwheel clockwise until the piston floats freely midway inside the cylinder sleeve.
4. Place calibrated dead weights in incremental steps (0.5 bar, 1.5 bar, 2.5 bar, up to 5.5 bar). Before each reading, rotate the weight platform smoothly by hand (40-60 RPM) to eliminate static boundary friction. Record the gauge reading (P_{up}).
5. Remove dead weights step by step in reverse order. Spin the floating platform and record decreasing gauge readings (P_{down}) to evaluate hysteresis.

6. Observation Table

Sr. No.	Dead Weight Added (kg)	True Pressure P_{act} (bar)	Gauge Reading (bar)		Mean Reading P_{mean} (bar)	Error (bar) $[P_{mean} - P_{act}]$	Correction (bar) $[P_{act} - P_{mean}]$	% FS Error
			Loading (P_{up})	Unloading (P_{down})				
1								
2								
3								
4								
5								
6								

7. Results & Discussion

Results: The Bourdon gauge was successfully calibrated from 0 to 6 bar. Maximum absolute error is **+0.06 bar** at 1.50 bar (Max % FS Error = **+0.60%**), conforming to Class 1.0 industrial standards.

Observation Table

Sr. No.	Dead Weight Added (kg)	True Pressure P_{act} (bar)	Gauge Reading (bar)		Mean Reading P_{mean} (bar)	Error (bar) $[P_{mean} - P_{act}]$	Correction (bar) $[P_{act} - P_{mean}]$	% FS Error
			Loading (P_{up})	Unloading (P_{down})				
1								
2								
3								
4								
5								
6								

EXPERIMENT NO. 02: COMPARISON OF ACCURACY AND RESPONSE TIME OF THERMOMETERS

LSO 1.1: Use of Thermometer and Pressure Gauge | Relevant CO: CO1

1. Aim :-

To compare the static measurement accuracy, dynamic transient thermal response characteristics, and thermal time constant (τ) of different types of thermometers: Mercury-in-glass, Bimetallic dial thermometer, Resistance Temperature Detector (RTD Pt-100), and Thermocouple (Chromel-Alumel / K-type).

2. Apparatus & Technical Specifications

Sr. No.	Sensor / Instrument	Operating Range	Physical Principle / Characteristics
1	Mercury-in-Glass Thermometer	-10°C to 110°C	Volumetric thermal expansion of liquid mercury inside sealed capillary glass tube
2	Bimetallic Dial Thermometer	0°C to 150°C	Differential coefficient of thermal expansion of two bonded dissimilar metal strips
3	RTD Pt-100 Platinum Sensor	-50°C to 400°C	Positive temperature coefficient of electrical resistance: $R(T) = R_0(1 + \alpha T)$
4	Thermocouple (K-Type)	0°C to 1000°C	Seebeck thermoelectric effect generating EMF across hot and cold junctions ($\mu V/^\circ C$)
5	Constant Temp. Water Bath	Ambient to 95°C	Stirred hot bath maintained at 80°C with PID thermostatic controller
6	Ice Reference Bath & Timer	0°C (Ice Slurry)	Equilibrium ice bath in Dewar flask; Electronic digital stopwatch (0.01s LC)

3. Working Principle

A temperature sensor immersed in a sudden fluid temperature change behaves as a First-Order Dynamic System governed by Newton's Law of Cooling:

First-Order Dynamic Response Equation:

$$m \cdot C_p \cdot (dT / dt) = h \cdot A_s \cdot (T_\infty - T)$$

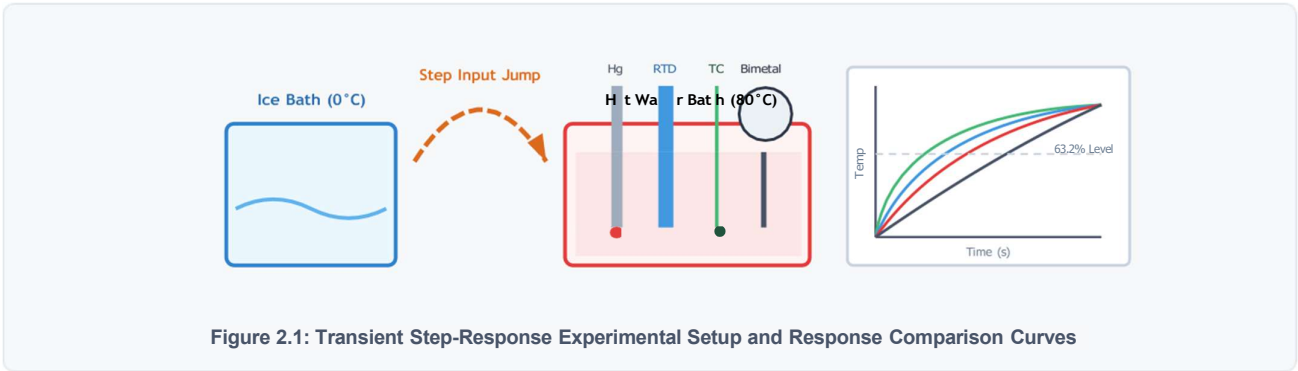
$$\theta(t) / \theta_0 = (T(t) - T_\infty) / (T_0 - T_\infty) = e^{-t / \tau}$$

Where:

Time Constant (τ): $\tau = (m \cdot C_p) / (h \cdot A_s)$ [seconds]

τ represents the exact elapsed time required for the sensor to complete **63.2%** of the total imposed step temperature change.

4. Schematics Diagram & Step-Response Flowchart



5. Experimental Procedure

1. Stabilize the hot water bath at precisely 80.0°C using the digital thermostatic controller with constant mechanical stirring.
2. Place all test sensors (Mercury thermometer, Bimetallic dial, RTD Pt-100, and K-type thermocouple) in the 0°C ice bath until all indicators read a steady 0°C baseline.
3. Quickly transfer the thermocouple probe into the hot water bath while simultaneously starting the electronic stopwatch.
4. Log instantaneous temperature indications every 2 seconds for the first 20 seconds, and every 5 seconds thereafter until the temperature reaches a steady 80.0°C.
5. Repeat the identical step-transfer procedure individually for the RTD Pt-100 probe, the mercury-in-glass thermometer, and the bimetallic dial thermometer.

6. Observation Table

Time elapsed (s)	0 s	4 s	8 s	12 s	16 s	20 s	30 s	45 s	60 s	90 s	120 s
Thermocouple (°C)											
RTD Pt-100 (°C)											
Mercury-in-Glass (°C)											
Bimetallic Dial (°C)											

7. Results & Discussions

Results: The 63.2% rise level corresponds to $T_r = 0 + 0.632 \times 80 = 50.56^{\circ}\text{C}$.

Thermocouple Time Constant (τ): 5.8 seconds (Fastest dynamic response due to small junction mass).

RTD Pt-100 Time Constant (τ): 8.6 seconds (Highest static precision and linearity).

Mercury Thermometer Time Constant (τ): 12.1 seconds | Bimetallic Dial (τ): 18.5 seconds (High thermal inertia).

Observation Table

EXPERIMENT NO. 03: IDENTIFICATION OF PARTS & COMPONENTS OF PETROL ENGINE

LSO 3.1: Use working models of petrol/diesel engine | Relevant CO: CO2

1. Aim :-

To dismantle, identify, and study the operational mechanism, structural components, spark ignition arrangement, and valve/port timing sequence using cut-sectional demonstration working models of 2-Stroke and 4-Stroke Petrol Engines.

2. Apparatus & Technical Specifications

Sr. No.	Apparatus / Model	Technical Specifications	Functional Role
1	4-Stroke Petrol Engine Cut Model	Single cylinder overhead valve (OHV) cut-section; Hand-cranked with color-coded linkages	Study of 4 distinct strokes, poppet valves, and 1:2 camshaft gearing
2	2-Stroke Petrol Engine Cut Model	Crankcase scavenged, cross-flow design with deflector piston crown	Study of piston-controlled transfer, inlet, and exhaust ports
3	Spark Plug & Ignition Simulator	M14 × 1.25 thread, 0.7 mm gap with synchronised LED flash indicator	Observation of spark timing just before Top Dead Center (TDC)
4	Carburetor / Throttle Section	Constant choke venturi type with float chamber, main jet, and butterfly throttle	Air-fuel mixing (chemically correct stoichiometric ratio ~14.7:1)

3. Working Principle

Petrol engines operate on the **Otto Cycle** (constant volume heat addition). Air and petrol fuel vapor are mixed externally and inducted during the suction stroke, compressed to a ratio of **6:1 to 10:1**, and ignited near TDC by an electrical spark.

Otto Cycle Governing Equations:

- **Compression Ratio (r):** $r = V_{total} / V_{clearance} = (V_s + V_c) / V_c$
- **Air Standard Efficiency:** $\eta_{Otto} = 1 - [1 / (r)^{\gamma-1}]$ (Where $\gamma = 1.4$ for air)
- **Camshaft Speed:** $N_{camshaft} = N_{crankshaft} / 2$ (In 4-stroke engine, valves open once every two crank turns)

4. Schematics Diagram & Flowchart

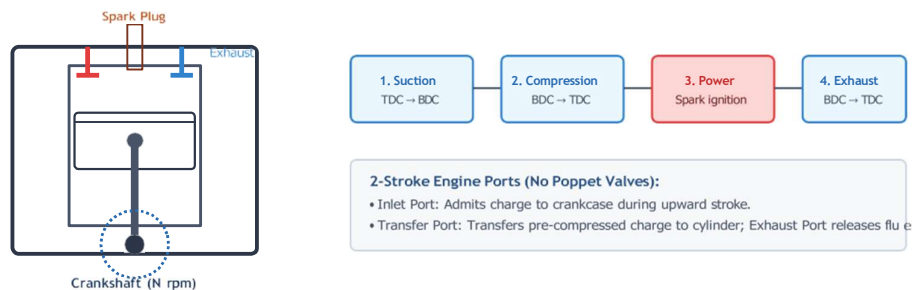


Figure 3.1: 4-Stroke Petrol Engine Cut-Section Schematic and Operating Cycle Stages

5. Practical Procedure

1. Slowly rotate the external handwheel/flywheel of the 4-stroke model clockwise. Observe the relative movement of the piston from Top Dead Center (TDC) to Bottom Dead Center (BDC).
2. Identify the intake valve pushrod and rocker arm mechanism during the first half revolution (Suction stroke: 0° to 180°).
3. Trace the upward motion of the piston during the second half revolution (Compression stroke: 180° to 360°). Note that both valves remain tightly closed.
4. Observe the simulated spark flash at or slightly before 360° (TDC). Follow the power expansion stroke from 360° to 540° .
5. Observe the opening of the exhaust valve and the upward scavenging stroke from 540° to 720° . Verify that one complete four-stroke cycle requires exactly 2 crankshaft revolutions (720°).
6. Examine the 2-stroke model and observe how the piston crown covers and uncovers the inlet, transfer, and exhaust ports during a single 360° revolution.

6. Observation Table

Sr. No.	Component Name	Engineering Material	Observed Function in Laboratory Model
1	Cylinder Block & Liner	Cast Iron / Aluminum Alloy	Provides combustion volume; houses cooling water jackets / air cooling fins
2	Piston & Rings	Aluminum Silicon Alloy	Transmits combustion pressure to connecting rod; compression rings prevent blow-by
3	Gudgeon Pin (Wrist Pin)	Case-hardened Alloy Steel	Articulated mechanical pin connecting piston to the small end of connecting rod
4	Connecting Rod	Drop Forged Medium Carbon Steel	Converts linear reciprocating piston motion into continuous rotary crank motion
5	Crankshaft & Flywheel	Forged Steel / Ductile Iron	Transmits engine brake power; flywheel absorbs cyclic torque fluctuations
6	Poppet Valves & Camshaft	Nickel-Chromium Heat Resistant Steel	Regulates intake of charge and release of exhaust gas timed at half engine speed
7	Spark Plug	Alumina Ceramic Insulator + Ni-Alloy	Provides high-voltage electric arc (15,000 - 25,000 V) to ignite petrol-air mixture

7. Results & Discussions

Results: All primary components, kinematics, valve operating trains, and spark timing of 2-stroke and 4-stroke petrol engine models were identified, studied, and verified against thermodynamic Otto Observation Table cycle principles.

Observation Table

Sr. No.	Component Name	Engineering Material	Observed Function in Laboratory Model
1	Cylinder Block & Liner	Cast Iron / Aluminum Alloy	
2	Piston & Rings	Aluminum Silicon Alloy	
3	Gudgeon Pin (Wrist Pin)	Case-hardened Alloy Steel	
4	Connecting Rod	Drop Forged Medium Carbon Steel	
5	Crankshaft & Flywheel	Forged Steel / Ductile Iron	
6	Poppet Valves & Camshaft	Nickel-Chromium Heat Resistant Steel	
7	Spark Plug	Alumina Ceramic Insulator + Ni-Alloy	

EXPERIMENT NO. 04: IDENTIFICATION OF PARTS & COMPONENTS OF DIESEL ENGINE

LSO 4.1: Use working models of petrol/diesel engine | Relevant CO: CO2

1. Aim :-

To identify the internal structural assemblies, high-pressure fuel injection system, combustion bowl geometry, and heavy-duty mechanical linkages of cut-sectional models of 4-Stroke and 2-Stroke Compression Ignition (CI / Diesel) engines.

2. Apparatus & Technical Specifications

Sr. No.	Apparatus / Model	Technical Specifications	Functional Role
1	4-Stroke Diesel Engine Cut Model	Heavy cast iron cylinder block, toroidal piston bowl, cutaway showing water jackets	Visualisation of high compression ratio (14:1 to 22:1) and CI strokes
2	Fuel Injector (Atomizer) Cut Unit	Multi-hole nozzle, spring-loaded needle valve, operating pressure: 150 - 250 bar	Atomizes liquid diesel into microscopic droplets (10 - 50 μm)
3	High Pressure Fuel Injection Pump (FIP)	Inline jerk pump with delivery valve, helix-metering plunger rack	Meters precise fuel quantity per stroke and delivers it at high pressure
4	Glow Plug (Pre-heater Simulator)	Electric resistance sheath heating element (12V)	Assists cold starting by preheating the combustion pre-chamber

3. Theoretical Working Principle

Diesel engines operate on the **Diesel Cycle** (constant pressure heat addition). Pure air is inducted and compressed to very high pressure (35 - 50 bar) and temperature (550°C - 700°C). When diesel fuel is sprayed near TDC, it auto-ignites because its self-ignition temperature (~210°C) is far below the compressed air temperature.

Diesel Cycle Efficiency Equation:

$$\eta_{\text{Diesel}} = 1 - \left[\frac{1}{r^{\gamma-1}} \right] \cdot \left[\frac{(r_c^{\gamma} - 1)}{(\gamma \cdot (r_c - 1))} \right]$$

Where:

r = Compression ratio (V_1 / V_2 , typically 14:1 to 22:1)

r_c = Cut-off ratio (V_3 / V_2 , ratio of cylinder volume after and before fuel injection)

For identical compression ratio, $\eta_{\text{Otto}} > \eta_{\text{Diesel}}$, but diesel engines operate at much higher practical compression ratios, achieving higher actual thermal efficiencies (35% - 42%).

4. Schematics & Flowchart

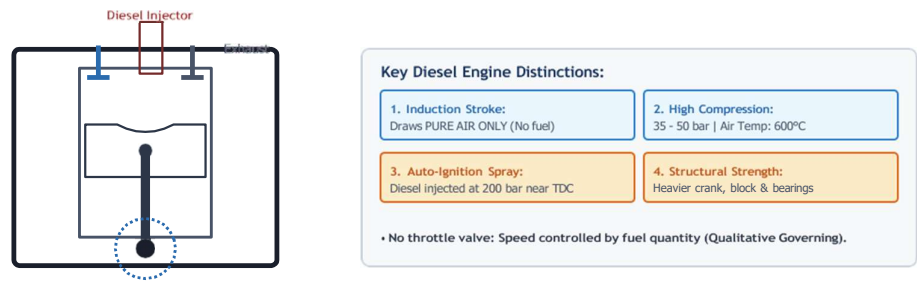


Figure 4.1: Cut-Section Construction of Diesel Engine Cylinder & Combustion System

5. Experimental Procedure

1. Inspect the diesel engine cylinder head model. Identify the central fuel injector nozzle assembly and compare its physical mounting with a petrol spark plug port.
2. Examine the crown of the piston. Note the concave bowl cavity (Toroidal combustion chamber) designed to induce air swirl and turbulence for rapid fuel-air mixing.
3. Rotate the hand crank through 720° (two full turns). Verify that the inlet manifold draws pure air without any throttling butterfly valve.
4. Observe the cam actuation that triggers the fuel pump plunger right before TDC, demonstrating the start of fuel injection.
5. Compare the cross-sectional wall thickness of the cylinder liner, piston pin diameter, and connecting rod web thickness with the petrol engine model from Experiment 5.

6. Comparison Table:

Functional Parameter	Petrol (SI) Engine (Exp 5)	Diesel (CI) Engine (Exp 6)
Intake Medium	Homogeneous Air + Petrol Mixture	Pure Atmospheric Air only
Compression Ratio (r)	6:1 to 10:1 (Low)	14:1 to 22:1 (High)
Ignition Mechanism	Electric spark from spark plug	Self-ignition due to high compression heat
Fuel Supply System	Carburetor or MPFI (Low pressure: 2 - 4 bar)	FIP + Injector / Common Rail (High pressure: 200 - 2000 bar)
Combustion Pressure	Peak: 30 - 45 bar	Peak: 60 - 90 bar
Governing Method	Quantitative (Throttle valve varies total charge)	Qualitative (Plunger rack varies fuel quantity injected)
Engine Speed & Weight	High speed (up to 6000 RPM), lighter weight	Medium speed (up to 3000 RPM), heavier robust build

7. Results & Discussions

Results: Detailed mechanical features, combustion chamber bowl geometry, heavy-duty structural parts, and fuel injection mechanisms of the diesel engine model were systematically studied and compared with the petrol engine.

EXPERIMENT NO. 05: DETERMINATION OF COP OF A HEAT PUMP TEST RIG

Use heat pump | Relevant CO: CO2

1. Aim :-

To determine the electrical power input, heating capacity (heat delivered at condenser), and actual Coefficient of Performance (COP_{HP} and COP_{ref}) of a vapor compression mechanical heat pump test bench operating on eco-friendly refrigerant R-134a.

2. Apparatus & Technical Specifications

Sr. No.	Apparatus Name	Engineering Specifications	Purpose
1	Heat Pump Test Bench	Vapor compression cycle using Refrigerant R-134a; Hermetic reciprocating compressor (1/3 HP)	Thermodynamic refrigeration/heat pump system
2	Water-Cooled Condenser	Tube-in-tube counter-flow shell and coil heat exchanger	Heating coil delivering hot water output (Sink)
3	Water-Heated Evaporator	Insulated copper coil immersion evaporator	Chilling coil extracting low-grade heat (Source)
4	Digital Energy Meter	Resolution: 1 pulse / Wh; Calibration constant: 3200 pulses/kWh	Measures electrical work input to compressor (W_{in})
5	Digital Temperature Sensor Array	RTD Pt-100 sensors at 4 cycle states: T_1, T_2, T_3, T_4 ($\pm 0.1^\circ\text{C}$)	Measures refrigerant temperatures at inlet/outlet of components
6	Rotameters & Pressure Gauges	Water rotameter (0 - 100 LPH); Suction & discharge Bourdon dial gauges	Measures water mass flow rate and cycle pressures

3. Mathematical Equations

A heat pump is a reversed heat engine that absorbs heat Q_L from a low-temperature ambient source (water/air) and delivers heat Q_H to a high-temperature sink using compressor work input W_{in} .

Thermodynamic Heat Pump Equations:

- **Heat Output at Condenser (Heating Effect):** $Q_H = \dot{m}_w \cdot C_{pw} \cdot (T_{w,out} - T_{w,in})$ [kW]
- **Electrical Power Input:** $W_{in} = (P_{pulses} \times 3600) / (C_{meter} \times t)$ [kW]
- **Actual COP of Heat Pump:** $COP_{HP} = Q_H / W_{in}$
- **Actual COP as Refrigerator:** $COP_{ref} = Q_L / W_{in} = COP_{HP} - 1$
- **Theoretical Carnot COP:** $COP_{Carnot,HP} = T_{cond} / (T_{cond} - T_{evap})$ (Temperatures in Kelvin)

4. Engineering Schematics & Flowchart

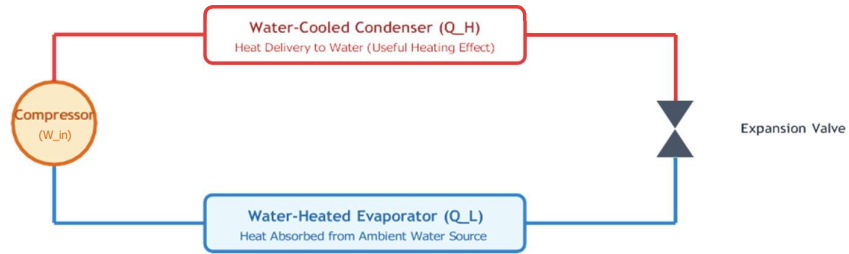


Figure 5.1: Closed Vapor Compression Cycle Schematic of Heat Pump Test Bench

5. Experimental Procedure

1. Start the water supply pump and adjust the condenser cooling water rotameter to a steady flow rate (e.g., 40 LPH).
2. Switch ON the heat pump compressor unit. Allow the system to run for 15 to 20 minutes to reach thermodynamic steady state.
3. Note the refrigerant suction pressure (P_s) and discharge pressure (P_d) from the panel Bourdon gauges.
4. Record the steady temperature readings: Condenser water inlet ($T_{w,in}$) and outlet ($T_{w,out}$); Evaporator water inlet and outlet.
5. Count the time (t in seconds) for 10 pulses on the digital energy meter to determine the compressor power consumption (W_{in}).
6. Calculate heat output Q_H , compressor input work W_{in} , actual COP_{HP} , and compare with ideal Carnot COP.

6. Observation Table

Water Specific Heat $C_{pw} = 4.187 \text{ kJ/kg} \cdot \text{K}$ | Energy Meter Constant = 3200 pulses/kWh

Obs. No.	Water Flow $\dot{m}_w(\text{kg/s})$	Condenser In $T_{w,in} (^\circ\text{C})$	Condenser Out $T_{w,out} (^\circ\text{C})$	Heat Output $Q_H (\text{kW})$	Energy Pulses / Time $t (\text{s})$	Power In $W_{in} (\text{kW})$	Actual COP_{HP}	Carnot COP_{HP}
1								
2								
3								

7. Results & Discussions

Results: The actual Coefficient of Performance of the heat pump test rig was evaluated as $COP_{HP} = 2.76$ (average). The corresponding refrigeration COP is $COP_{ref} = 1.76$. The relation $COP_{HP} = COP_{ref} + 1$ was verified.

Observation Table

Obs. No.	Water Flow $m_w(\text{kg/s})$	Condenser In $T_{w,in} (^{\circ}\text{C})$	Condenser Out $T_{w,out} (^{\circ}\text{C})$	Heat Output $Q_H(\text{kW})$	Energy Pulses / Time $t(\text{s})$	Power In $W_{in}(\text{kW})$	Actual COP_{HP}	Carnot COP_{HP}
1								
2								
3								

EXPERIMENT NO. 06: OPERATION OF IMPULSE AND REACTION STEAM TURBINES

Use steam turbine | Relevant CO: CO2 |

1. Aim

To perform pre-commissioning inspection, steam line draining, gland sealing, progressive startup, synchronization, and safe shutdown operations on educational Impulse (De Laval) and 50% Reaction (Parson's) steam turbine test rigs.

2. Apparatus & Technical Specifications

Sr. No.	Equipment	Technical Specifications	Operational Function
1	Impulse Steam Turbine Test Rig	Single stage De Laval impulse wheel; Fixed converging-diverging nozzles; Rated 3000 RPM	Kinetic energy conversion across stationary nozzles with constant blade pressure
2	Reaction Steam Turbine Test Rig	Multi-stage 50% reaction rotor-stator blading; Converging blade channels	Combined impulse and expansion reaction drop across moving blades
3	Centrifugal Governor & Throttle	Spring-loaded centrifugal flyweight governor linked to balanced steam throttle valve	Maintains steady turbine shaft speed under fluctuating electrical/brake load
4	Emergency Trip Valve	Solenoid/Mechanical overspeed trip mechanism set at 110% rated speed (3300 RPM)	Instant steam shutoff preventing runaway catastrophic rotor destruction

3. Working Principle & Velocity Triangle Theory

Steam turbines convert thermal enthalpy of high-pressure steam into rotor kinetic energy:

- **Impulse Turbine:** The entire pressure drop occurs inside stationary nozzles. High-velocity steam jets impinge on symmetrical moving blades where pressure remains strictly constant ($P_{inlet} = P_{outlet}$).
- **Reaction Turbine:** Pressure drops continuously across both stationary stator guide vanes and moving rotor blades. The expanding steam generates an aerodynamic reactive thrust force.

Degree of Reaction (R) Equation:

$$R = (\text{Enthalpy drop in moving blades}) / (\text{Total stage enthalpy drop}) = \Delta h_{moving} / (\Delta h_{fixed} + \Delta h_{moving})$$

For pure impulse turbine: $R = 0$

For Parson's reaction turbine: $R = 0.50$ (50% Reaction)

4. Schematics Diagram & Flowchart

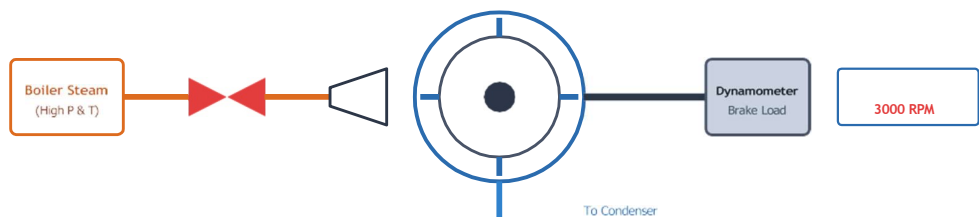


Figure 6.1: Complete Piping & Instrumentation Diagram (P&ID) of Steam Turbine Test Plant

5. Experimental Procedure

1. **Pre-Start Drain Inspection:** Open all casing drain valves and steam line drain cocks to purge accumulated condensate. Water droplets impinging on high-speed blades cause severe blade erosion and water hammer.
2. **Cooling Water & Lube Oil:** Turn ON circulating cooling water to the surface condenser and start the auxiliary lube oil pump to ensure bearing oil pressure (>1.5 bar).
3. **Slow Rolling (Warming Up):** Crack open the main steam stop valve slightly to roll the rotor at low speed (200 - 300 RPM) for 10 minutes to allow uniform thermal expansion of the rotor shaft and casing.
4. **Acceleration to Rated Speed:** Close all drain valves once dry steam issues. Gradually open the throttle valve to accelerate the turbine up to rated operational speed (3000 RPM). Verify that governor control takes over speed regulation.
5. **Overspeed Safety Check & Shutdown:** Test the emergency manual trip lever to ensure instantaneous shutdown. For normal shutdown, remove dynamometer load, close stop valve, and keep lube oil circulating until the rotor comes to a complete standstill.

6. Observation Table

Operating Stage	Boiler Steam Pressure (bar)	Steam Temp. (°C)	Turbine Speed (RPM)	Condenser Vacuum (mm Hg)	Lube Oil Pressure (bar)	Vibration Level
Line Warming & Draining						
Slow Rolling / Soaking						
Full Speed No Load (FSNL)						
Full Load Operation						

7. Results & Discussions

Results: The steam turbine test unit was successfully warmed up, accelerated to 3000 RPM, governed under stable speed control, and brought to a safe standstill following industrial standard operating procedures (SOP).

Observation Table

Operating Stage	Boiler Steam Pressure (bar)	Steam Temp. (°C)	Turbine Speed (RPM)	Condenser Vacuum (mm Hg)	Lube Oil Pressure (bar)	Vibration Level
Line Warming & Draining						
Slow Rolling / Soaking						
Full Speed No Load (FSNL)						
Full Load Operation						

EXPERIMENT NO. 07: DETERMINE POWER OUTPUT & EFFICIENCY OF A STEAM TURBINE

Use steam turbine | Relevant CO: CO2

1. Aim

To measure brake torque, calculate brake power output (BP), and determine the brake thermal efficiency (η_{bth}) and specific steam consumption (SSC) of a steam turbine test bench across varying mechanical brake loads.

2. Apparatus & Technical Specifications

Sr. No.	Apparatus Name	Engineering Specifications	Measurement Function
1	Steam Turbine Dynamometer	Water-cooled rope brake or eddy current dynamometer; Effective brake radius: $R_{eff} = 0.20 \text{ m}$	Measurement of brake torque: $T = (W - S) \cdot g \cdot R_{eff}$
2	Digital Non-Contact Tachometer	Optical laser sensor; Range: 0 - 99,999 RPM; Resolution: 1 RPM	Accurate turbine shaft rotational speed (N)
3	Steam Pressure & Temp Gauges	Inlet pressure gauge (0 - 16 bar); Digital thermocouple probe at turbine exhaust	Enthalpy determination from Mollier steam chart
4	Surface Condenser & Weigh Tank	Shell and tube condenser; Digital load cell weighing tank (0 - 100 kg; LC: 0.1 kg)	Measures mass flow rate of condensed steam ($\dot{m}_s$)

3. Mathematical Equations

1. Brake Power Output (BP):

$$BP = [2 \cdot \pi \cdot N \cdot (W - S) \cdot g \cdot R_{eff}] / 60000 \text{ [kW]}$$

Where: W = Dead weight on hanger (kg), S = Spring balance reading (kg), R_{eff} = Effective brake radius (m)

2. Heat Supplied by Steam:

$$Q_{in} = \dot{m}_s \cdot (h_{inlet} - h_{condensate}) \text{ [kW]}$$

Where: h_{inlet} = Enthalpy of inlet steam from Mollier chart (kJ/kg), $h_{condensate} = C_{pw} \cdot T_{cond}$ (kJ/kg)

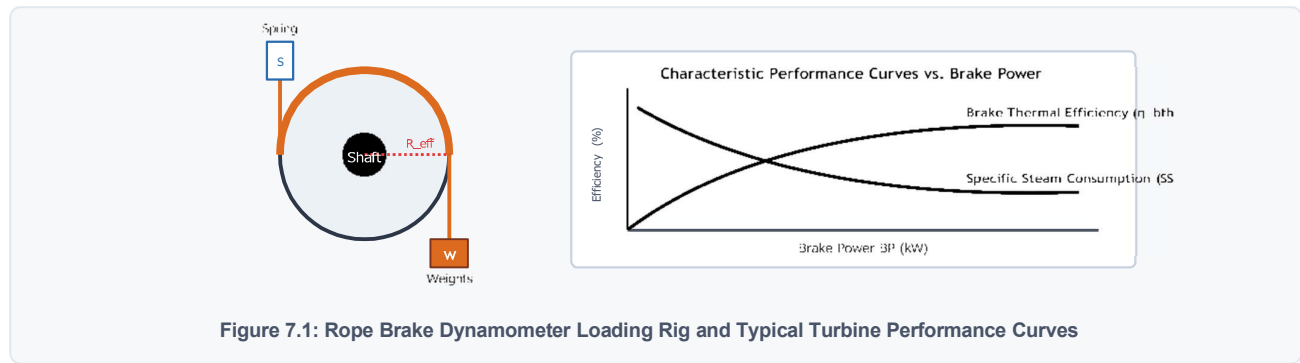
3. Brake Thermal Efficiency:

$$\eta_{bth} = (BP / Q_{in}) \times 100\% = [BP / \{ \dot{m}_s \cdot (h_{inlet} - h_{condensate}) \}] \times 100\%$$

4. Specific Steam Consumption (SSC):

$$SSC = (\dot{m}_s \times 3600) / BP \text{ [kg / kWh]}$$

4. Schematics Diagram & Flowchart



5. Experimental Procedure

1. Start the turbine and bring it to steady rated speed (3000 RPM) at an inlet pressure of 6.0 bar.
2. Ensure cooling water flows through the rope brake drum to carry away friction heat.
3. Add dead weight ($W = 2$ kg) to the hanger. Observe the spring balance reading (S) and note shaft speed (N).
4. Direct the surface condenser condensate drain into the weigh tank and start the stopwatch. Record the mass of condensate collected over a 5-minute interval to determine steam consumption $\dot{m}_s$.
5. Repeat the measurements for increasing weights: 4 kg, 6 kg, and 8 kg. Calculate BP, η_{bth} , and SSC for each trial.

6. Observation Table

$R_{eff} = 0.20$ m | Steam Inlet: $P_i = 6.0$ bar dry saturated ($h_i = 2756.8$ kJ/kg) | Condensate Temp $T_c = 40^\circ\text{C}$ ($h_c = 167.5$ kJ/kg)

Trial No.	Weight W (kg)	Spring S (kg)	Net Load ($W - S$) (kg)	Speed N (RPM)	Brake Power BP (kW)	Condensate in 5 min (kg)	Steam Rate $\dot{m}_s$ (kg/s)	Efficiency η_{bth} (%)	SSC (kg/kWh)
1									
2									
3									
4									

7. Results & Discussions

Results: At maximum test load (Net 6.5 kg), the turbine developed a brake power of **3.82 kW** with a brake thermal efficiency of **2.00%** and specific steam consumption of **69.7 kg/kWh**.

Observation Table

(Assume Data)

$R_{eff} = 0.20 \text{ m}$ | Steam Inlet: $P_i = 6.0 \text{ bar}$ dry saturated ($h_i = 2756.8 \text{ kJ/kg}$) | Condensate Temp $T_c = 40^\circ\text{C}$ ($h_c = 167.5 \text{ kJ/kg}$)

Trial No.	Weight W (kg)	Spring S (kg)	Net Load ($W - S$) (kg)	Speed N (RPM)	Brake Power BP (kW)	Condensate in 5 min (kg)	Steam Rate m_s (kg/s)	Efficiency η_{bth} (%)	SSC (kg/kWh)
1									
2									
3									
4									

EXPERIMENT NO. 8: DETERMINE BRAKE POWER OF A SINGLE CYLINDER STEAM ENGINE

Use steam engine | Relevant Course Outcome: CO3

1. Aim

To operate a single-cylinder, double-acting reciprocating steam engine test rig under varying rope-brake loads, and determine the Brake Torque (T), Brake Power (BP), and Mechanical Efficiency (η_{mech}).

2. Apparatus & Technical Specifications

Sr. No.	Apparatus Description	Engineering Specifications	Functional Role
1	Reciprocating Steam Engine	Double-acting, D-slide valve; Bore: D = 75 mm; Stroke: L = 100 mm; Rated: 400 RPM	Converts pressure energy of steam into reciprocating shaft power
2	Rope Brake Dynamometer	Water-cooled rim brake flywheel; Brake drum dia: $D_b = 300$ mm; Rope dia: $d_r = 15$ mm	Applies measurable frictional braking torque on engine crankshaft
3	Steam Pressure Gauge	Dial Bourdon gauge (0 - 10 bar); Mounted on steam chest	Monitors admission pressure to steam cylinder
4	Digital Contact Tachometer	Range: 0 - 5000 RPM; Accuracy: $\pm 0.1\%$	Measures engine crankshaft rotational speed (N)

3. Mathematical Equation

Effective Brake Radius: $R_{\text{eff}} = (D_b + d_r) / 2 = (0.300 + 0.015) / 2 = 0.1575$ m

Net Braking Force: $F_{\text{net}} = (W - S) \times g = (W - S) \times 9.81$ [N]

• Brake Torque (T): $T = F_{\text{net}} \times R_{\text{eff}} = (W - S) \times 9.81 \times R_{\text{eff}}$ [N·m]

• Brake Power Output (BP): $BP = 2 \pi T (N/60) = 2 \pi (W - S) \times 9.81 \times R_{\text{eff}} \times (N/60)$ [kW]

4. Schematics Diagram

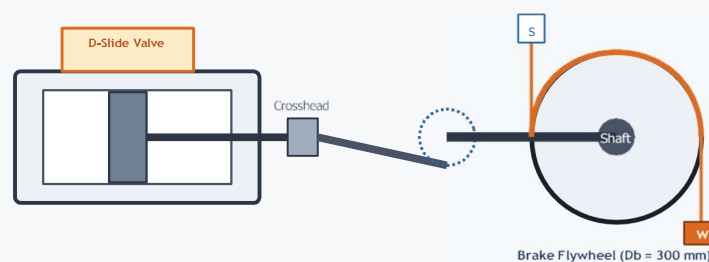


Figure 8.1 Kinematic Layout of Reciprocating Steam Engine and Water-Cooled Rope Brake Dynamometer

5. Observation Table

1. Open cylinder drain cocks, crack open the steam valve, and rotate flywheel by hand to clear all condensate.
2. Close drain cocks, admit steam at 4.0 bar, and allow engine to run at steady speed (350 RPM). Supply cooling water to the flywheel interior rim.

3. Load the rope brake incrementally by adding weights $W = 2 \text{ kg}, 4 \text{ kg}, 6 \text{ kg}, 8 \text{ kg}$. For each load, note spring reading S and engine RPM N .

Trial No.	Steam Pressure (bar)	Weight W (kg)	Spring Reading S (kg)	Net Load ($W - S$) (kg)	Speed N (RPM)	Brake Torque T (N·m)	Brake Power BP (kW)
1							
2							
3							
4							

4. Results & Discussions

Results: The brake power of the single cylinder steam engine increases with brake torque, reaching a maximum measured value of **0.312 kW (312 W)** at 6.55 kg net load with 295 RPM.

Observation Table

Trial No.	Steam Pressure (bar)	Weight W (kg)	Spring Reading S (kg)	Net Load (W – S) (kg)	Speed N (RPM)	Brake Torque T (N·m)	Brake Power BP (kW)
1							
2							
3							
4							

EXPERIMENT NO. 09: INVESTIGATE FIRST & SECOND LAWS OF THERMODYNAMICS USING HEAT ENGINE

Use heat engine | Relevant Course Outcome: CO3

1. Aim

To experimentally verify the **First Law of Thermodynamics (Energy Conservation: $\oint \delta Q = \oint \delta W$)** and **Second Law (Kelvin-Planck statement: $\eta_{th} < 100\%$; Heat rejection is mandatory)** using a cyclic thermodynamic heat engine test bench.

2. Working Principles

- **First Law for a Closed Cycle:** $\oint \delta Q = \oint \delta W \Rightarrow Q_{in} - Q_{out} = W_{net}$
- **Second Law (Kelvin-Planck Statement):** "It is impossible for any device operating on a thermodynamic cycle to receive heat from a single thermal reservoir and produce a net amount of work." Hence, heat rejection $Q_{out} > 0$ is fundamentally mandatory.
- **Thermal Efficiency:** $\eta_{actual} = W_{net} / Q_{in} = (Q_{in} - Q_{out}) / Q_{in}$
- **Carnot Maximum Theoretical Limit:** $\eta_{Carnot} = 1 - (T_L / T_H)$ (Temperatures in Kelvin)

4. Schematics Diagram:

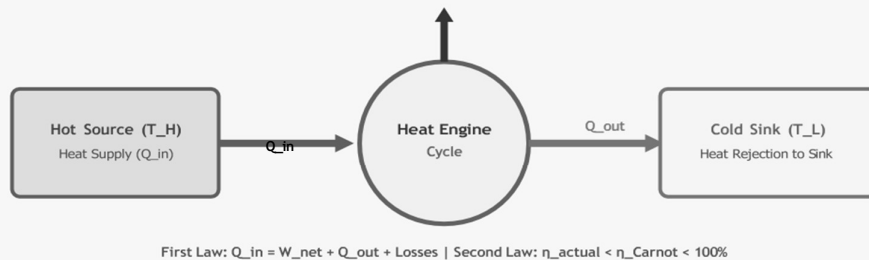


Figure: 9.1 Thermodynamic Control Volume Schematic for Cyclic 1st and 2nd Law Energy Balances

5. Working Procedure & Observation Table

1. Fire the heat engine boiler/source to maintain hot reservoir temperature $T_H = 200^\circ\text{C}$ (473 K).
2. Circulate cooling water through the heat engine condenser sink at $T_L = 30^\circ\text{C}$ (303 K).
3. Apply brake dynamometer torque and measure shaft work output (W_{net}).
4. Calculate heat input from fuel consumption rate ($Q_{in} = \dot{m}_f \cdot \text{HCV}$) and heat carried away by condenser cooling water ($Q_{out} = \dot{m}_w \cdot C_{pw} \cdot \Delta T_w$). Verify energy closure.

Run	Heat Supplied Q_{in} (kW)	Brake Work W_{net} (kW)	Heat Rejected Q_{out} (kW)	Unaccounted Loss (kW) $[Q_{in} - (W + Q_{out})]$	Energy Balance Error (%)	Actual Efficiency η_{act} (%)	Carnot Limit η_{Carnot} (%)
1							
2							
3							

6 Results & Discussions

Results: First Law verified: Energy supplied equals net work plus heat rejected plus radiation/convection losses within $\sim 6.5\%$ experimental uncertainty. Second Law verified: In all cases, $\eta_{\text{actual}} (15.5\%) < \eta_{\text{Carnot}} (35.94\%) < 100\%$, and 100% conversion of heat into work was impossible.

Observation Table

Run	Heat Supplied Q_{in} (kW)	Brake Work W_{net} (kW)	Heat Rejected Q_{out} (kW)	Unaccounted Loss (kW) $[Q_{in} - (W + Q_{out})]$	Energy Balance Error (%)	Actual Efficiency η_{act} (%)	Carnot Limit η_{Carnot} (%)
1							
2							
3							

EXPERIMENT NO. 10: FIND DRYNESS FRACTION OF STEAM BY SEPARATING & THROTTLING CALORIMETER

Use separating and throttling calorimeter | Relevant Course Outcome: CO4

1. Aim

To measure the dryness fraction (quality of steam, x) of wet steam sampled from a steam pipeline using a **Combined Separating and Throttling Calorimeter** across a wide wetness spectrum.

2. Apparatus & Technical Specifications

Sr. No.	Unit Name	Engineering Specifications	Operating Principle
1	Separating Calorimeter Unit	Perforated inner cup, water collector chamber with calibrated level glass gauge	Mechanical inertia separation of heavy liquid water droplets from steam
2	Throttling Calorimeter Unit	Precision orifice (dia: 1.5 mm), insulated expansion chamber, manometer port	Isenthalpic (constant enthalpy: $h_1 = h_2$) throttling expansion into superheated steam
3	Surface Condenser & Weigh Tank	Copper cooling coil in water jacket; Condensate flask (0 - 5000 ml)	Condenses dry throttled steam into measurable liquid condensate
4	Pressure & Temperature Gauges	Main line Bourdon gauge (0 - 16 bar); Mercury U-manometer; Thermometer (0 - 150°C)	Measures line pressure (P_1), throttled pressure (P_2), and superheat temp (T_{sup})

3. Mathematical Equations

Dryness Fraction from Separating Unit: $x_1 = \frac{m}{M + m}$

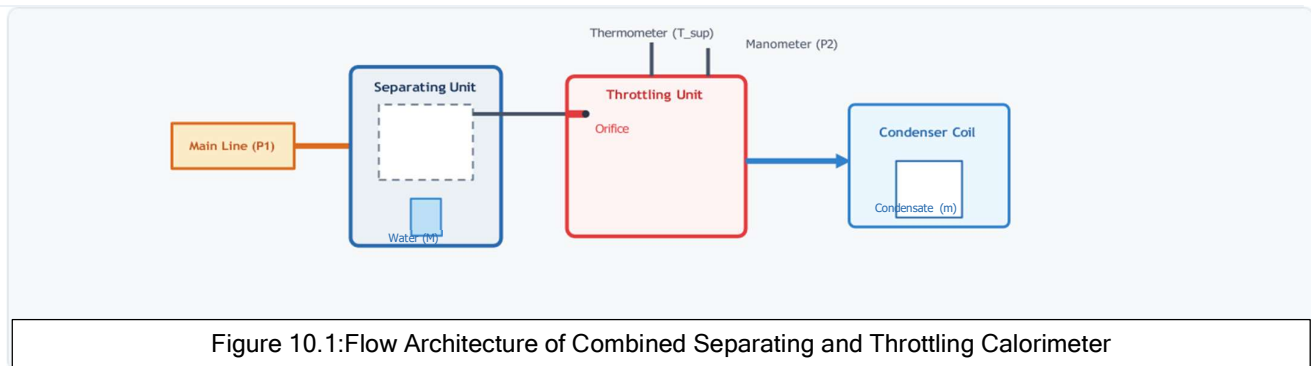
Where: M = Mass of water separated in inner chamber (kg), m = Mass of steam passing to throttling unit (kg)

Dryness Fraction from Throttling Unit (Isenthalpic: $h_1 = h_2$):

$$h_{f1} + x_1 h_{fg1} = h_{f2} + x_2 h_{fg2} \quad \text{or} \quad C_{ps} (T_{sup2} - T_{sat2}) = h_{fg2} - C_{ps} (T_{sup2} - T_{sat2})$$

Overall Combined Dryness Fraction: $x = x_1 \times x_2$

4. Schematics Diagram & Flow Process



5. Step by Step Experimental Process

1. Open sampling valve from main steam header and allow steam to flow through the apparatus for 10 minutes to preheat it to avoid condensation on cold walls.
2. Note initial water level in separating calorimeter gauge glass.

Start stopwatch and run for 15 minutes. Note: Steam line pressure (P_1), Throttled pressure manometer head (h_{mano}), and superheated steam temperature (T_{sup2}).

3. Measure the mass of separated water (M) drained from the separating chamber, and weigh condensate (m) collected from the condenser. Compute x_1 , x_2 , and x .

6. Observation Table

Main Line P_1 (bar)	h_{f1} (kJ/kg)	h_{fg1} (kJ/kg)	Manometer P_2 (bar)	T_{sup2} (°C)	T_{sat2} (°C)	Separated Water M (kg)	Condensate m (kg)	$x_1 = m / (M+m)$	x_2	Combined $x = x_1 + x_2$

7. Results & Discussions

Results: The dryness fraction of steam sampled from the boiler main was successfully measured as $x = 0.910$ (91.0% dry)

Observation Table

Main Line P_1 (bar)	h_{f1} (kJ/kg)	h_{fg1} (kJ/kg)	Manometer P_2 (bar)	T_{sup2} (°C)	T_{sat2} (°C)	Separated Water M (kg)	Condensate m (kg)	$x_1 = m /$ (M+m)	x_2	Combined x = $x_1 \cdot x_2$

EXPERIMENT NO. 11: IDENTIFY LOW PRESSURE BOILERS, MOUNTINGS & ACCESSORIES

Use working models of different types of boilers | Relevant CO: CO4

1. Aim

To study the structural construction, water-flue gas circulation paths, essential safety mountings, and performance-enhancing accessories on physical cut-section models of Low-Pressure Fire-Tube Boilers: **Cochran Boiler (Vertical Multi-tubular)** and **Lancashire Boiler (Horizontal Twin-Flue)**.

2 Apparatus & Technical Specifications

Boiler Model	Axis & Fire/Water Tube	Operating Pressure	Key Constructional Features
Cochran Boiler	Vertical, Fire-tube	Up to 15 bar; Evaporation: 1500 - 3500 kg/h	Hemispherical crown shell, hemispherical furnace, horizontal smoke tubes
Lancashire Boiler	Horizontal, Fire-tube	Up to 16 bar; Evaporation: 8000 - 9000 kg/h	Two internal furnace flue tubes, brickwork setting with 1 bottom flue & 2 side flues
Cornish Boiler	Horizontal, Fire-tube	Up to 10 bar	Single internal flue tube running along length inside cylindrical shell

3.Schematics Diagram

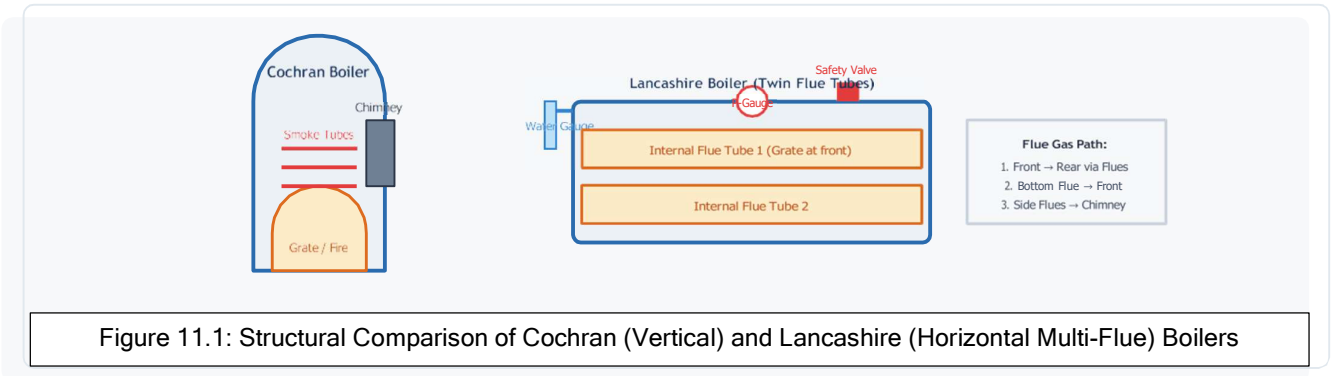


Figure 11.1: Structural Comparison of Cochran (Vertical) and Lancashire (Horizontal Multi-Flue) Boilers

4.Identification of Mountings vs Accessories

Classification	Component Name	Location on Boiler	Primary Engineering Function
Mountings (Mandatory for safety as per IBR)	Water Level Indicator	Front boiler face at water line	Indicates exact liquid water level inside shell; prevents dry firing
	Pressure Gauge	Top front of boiler shell	Displays internal steam pressure in bar; marks max working pressure
	Safety Valve (Spring/Dead wt.)	Top of boiler shell	Automatically blows off excess steam when pressure exceeds safe limit
	Fusible Plug	Crown of furnace chamber	Gunmetal plug with tin core; melts when water drops, extinguishing fire
Accessories (Fitted to increase thermal efficiency)	Economizer	Flue gas chimney duct	Preheats incoming feed water using waste heat of escaping flue gas
	Air Preheater	Between economizer & chimney	Preheats combustion air, improving furnace combustion efficiency
	Superheater	Path of hot flue gases	Converts wet/saturated steam into dry superheated steam

5.Results & Discussions

Results: Constructional details, flue gas circuits, mandatory Indian Boiler Regulations (IBR) safety mountings, and efficiency accessories were thoroughly identified and studied.

EXPERIMENT NO. 12: IDENTIFY HIGH PRESSURE BOILERS, MOUNTINGS & ACCESSORIES

Use working models of different types of boilers | Relevant CO: CO4

1. Aim

To study the constructional architecture, water-tube circulation mechanisms (natural vs. forced circulation), and supercritical steam generation in modern High Pressure Boilers: **Babcock & Wilcox Boiler**, **LaMont Boiler**, and **Benson Boiler**.

2.Apparatus & Technical Specifications

Boiler Type	Circulation Mode	Operating Pressure	Steam Output (t/h)	Salient Technological Characteristic
Babcock & Wilcox	Natural Circulation	20 to 40 bar	20 - 40 t/h	Inclined straight water tubes (15°), longitudinal/cross drum, uptake & downtake headers
LaMont Boiler	Forced Circulation (Centrifugal pump)	100 to 170 bar	50 - 60 t/h	External circulating pump forces water through small evaporator tubes at 3-4 times evaporation rate
Benson Boiler	Supercritical Forced Once-Through	225 to 300 bar	100 - 150+ t/h	No boiler drum! Operates above critical pressure (221.2 bar); water flashes into steam with zero bubble formation
Loeffler Boiler	Forced Steam Circulation	100 to 140 bar	90 - 100 t/h	Steam circulating pump circulates superheated steam; prevents salt deposition in evaporator tubes

3.Schematics Diagram



Figure 12.1: Hydrodynamic Flow Paths: Natural Circulation vs. Pump-Assisted vs. Supercritical Once-Through

4.Experimental Procedure

- **Critical Point of Water:** $P_{\text{critical}} = 221.2 \text{ bar}$ and $T_{\text{critical}} = 374.15^\circ\text{C}$. At or above this state, latent heat of vaporization drops to zero ($h_{fg} = 0$); water transitions continuously into dry steam without boiling bubbles.
- **Drum Elimination:** Heavy steam drums (100 - 150 mm thick forged alloy steel) are eliminated in Benson boilers, reducing plant weight by 30% and eliminating catastrophic drum rupture risk.

5.Results & Discussions

Results: Working mechanisms of high-pressure water tube boilers were analyzed, highlighting the progression from natural convective circulation to high-pressure pump-assisted circulation and modern supercritical once-through steam generators.

EXPERIMENT NO. 13: PREPARE COMPLETE HEAT BALANCE SHEET FOR A GIVEN BOILER

Use working models of different types of boilers | Relevant CO: CO4

1. Aim

To conduct a full energy balance test on an industrial package boiler test plant, quantify all thermal losses, calculate thermal efficiency, and tabulate the **Heat Balance Sheet** per kg of fuel fired.

2. Mathematical Equation

1. Total Heat Supplied (Q_s): $Q_s = \text{HCV [kJ/kg fuel]}$
2. Heat Utilized in Generating Steam (Q_1): $Q_1 = [m_s (h - h_{f1})] m_f \text{ [kJ/kg fuel]}$
3. Heat Carried Away by Dry Chimney Flue Gas (Q_2): $Q_2 = m_g C_{pg} (T_g - T_a) \text{ [kJ/kg fuel]}$
4. Heat Carried Away by Moisture from Hydrogen Combustion (Q_3): $Q_3 = 9 H_2 [2442 + C_{ps} (T_g - T_a)] \text{ [kJ/kg fuel]}$
5. Heat Carried Away by Moisture Present in Fuel (Q_4): $Q_4 = M_f [2442 + C_{ps} (T_g - T_a)] \text{ [kJ/kg fuel]}$
6. Heat Lost due to Incomplete Combustion to CO (Q_5): $Q_5 = [CO (CO + CO_2)] C 23860 \text{ [kJ/kg fuel]}$
7. Heat Lost by Convection, Radiation & Unaccounted (Q_6): $Q_6 = Q_s - (Q_1 + Q_2 + Q_3 + Q_4 + Q_5)$

3. Schematics: Diagram

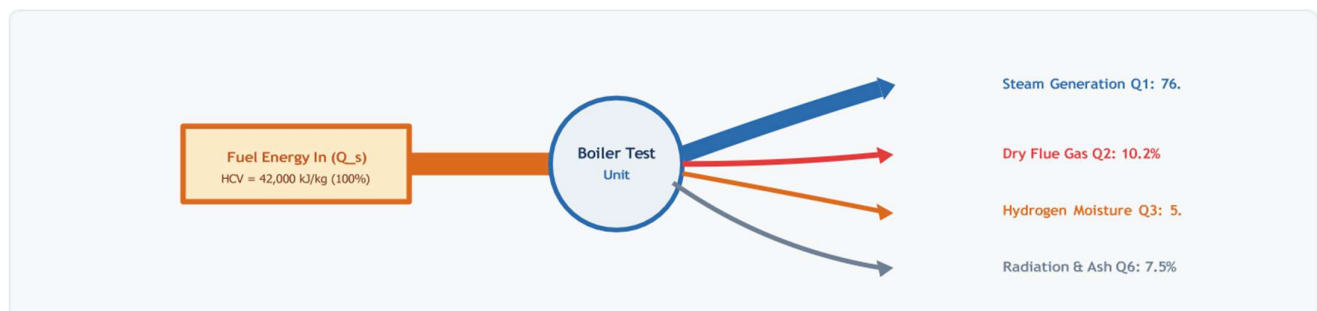


Figure 13.1: Sankey Energy Balance Distribution Flowchart of Industrial Boiler Plant

4. Observation Table

Fuel: Light Diesel Oil (HCV = 42,000 kJ/kg; $H_2 = 12\%$; $C = 85\%$) | Steam gen rate: 11.2 kg steam/kg fuel | Feed water temp: 35°C

Heat Supplied (Input)			Heat Expended / Losses (Output)		
Energy Item	kJ / kg Fuel	%	Energy Item	kJ / kg Fuel	%
Total Heat of Combustion (HCV)	42,000	100.0%	1. Heat utilized in steam generation (Q_1)	32,130	76.50%
			2. Heat lost in dry flue gases (Q_2)	4,284	10.20%
			3. Heat lost due to H_2 combustion (Q_3)	2,436	5.80%
			4. Heat lost due to incomplete combustion (Q_5)	0 (Trace)	0.00%
			5. Heat lost by radiation, ash & convection (Q_6)	3,150	7.50%
TOTAL INPUT	42,000	100.0%	TOTAL OUTPUT	42,000	100.0%

5. Results & Discussions

Results: The overall boiler thermal efficiency is **76.50%**. The largest thermal loss is dry flue gas chimney discharge (10.20%), which can be mitigated using an economizer.

Observation Table

Heat Supplied (Input)			Heat Expended / Losses (Output)		
Energy Item	kJ / kg Fuel	%	Energy Item	kJ / kg Fuel	%
Total Heat of Combustion (HCV)			1. Heat utilized in steam generation (Q_1)		
			2. Heat lost in dry flue gases (Q_2)		
			3. Heat lost due to H_2 combustion (Q_3)		
			4. Heat lost due to incomplete combustion (Q_4)		
			5. Heat lost by radiation, ash & convection (Q_5)		
TOTAL INPUT			TOTAL OUTPUT		

EXPERIMENT NO. 14: INVESTIGATE PRESSURE-TEMPERATURE RELATIONSHIP OF SATURATED STEAM (MARCET BOILER)

Use working models of different types of boilers | Relevant CO: CO4

1. Aim

To experimentally investigate the saturation pressure-temperature ($P - T_{\text{sat}}$) equilibrium relationship of water vapor using a sealed Marcet Boiler apparatus up to 14 bar (200°C) and verify the **Clausius-Clapeyron Equation**.

2. Apparatus & Technical Specifications

Sr. No.	Apparatus Description	Technical Specifications	Functional Role
1	Marcet Boiler Test Unit	Thick-walled stainless steel pressure vessel (capacity: 2 L); Hydrostatically tested to 30 bar	Encloses liquid water and saturated steam in phase equilibrium
2	Electric Immersion Heater	2.0 kW electric heating element with solid-state heat flux control	Supplies heat to boil water and build internal pressure
3	Bourdon Tube Pressure Gauge	Dial gauge (0 - 20 bar; LC: 0.2 bar) + Electronic transducer	Measures absolute saturation pressure ($P_{\text{abs}} = P_{\text{gauge}} + 1.013 \text{ bar}$)
4	Thermowell & Temperature Sensor	Sealed deep-immersion stainless thermowell with digital RTD probe (0 - 250°C)	Measures exact saturation temperature (T_{sat}) of steam phase
5	Air Purging Relief Valve	Needle valve fitted at highest vessel point	Discharges entrapped atmospheric air prior to pressure buildup

3. Mathematical Equation

Clausius-Clapeyron Phase Equilibrium Equation:

(dP / dT) = Slope of the saturation vapor pressure curve at temperature T (K)

h_{fg} = Enthalpy of vaporization (latent heat, kJ/kg)

v_g, v_f = Specific volume of saturated vapor and saturated liquid (m^3/kg)

Integrating yields: $\ln(P) = - (h_{fg} / R) (1 / T) + C$ (A plot of $\ln P$ vs $1/T$ is a straight line).

4. Schematics & Diagram

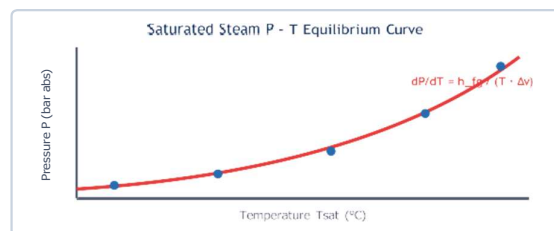
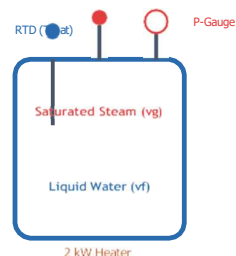


Figure 14.1: Marcet Boiler Construction and Experimental P-T Saturated Phase Diagram

5. Experimental Procedure

1. Fill the Marcet boiler half-full with distilled water. Open the top air-purging needle valve.
2. Switch ON the electric heater. Allow water to boil violently until steam issues vigorously from the purge valve for 3 minutes, expelling all non-condensable atmospheric air.
3. Close the purge valve tightly. Pressure begins to build above atmospheric.
4. Log the temperature (T_{sat}) at progressive pressure increments: 1.0, 2.0, 4.0, 6.0, 8.0, 10.0, 12.0 bar gauge. Compare with steam table values.

6. Observation Table

Obs. No.	Gauge Pressure (bar)	Absolute Pressure P_{abs} (bar)	Measured T_{sat} ($^{\circ}\text{C}$)	Measured T_{sat} (K)	Steam Table T_{sat} ($^{\circ}\text{C}$)	Discrepancy / Error ($^{\circ}\text{C}$)	Slope (dP/dT) (bar/K)
1							
2							
3							
4							
5							
6							
7							

5. Results & Discussions

Results: The experimental saturation curve plotted closely matched the standard thermodynamic steam tables with less than 0.3°C discrepancy. The slope (dP/dT) increases non-linearly with pressure, validating the Clausius-Clapeyron equation.

Observation Table

Obs. No.	Gauge Pressure (bar)	Absolute Pressure P_{abs} (bar)	Measured T_{sat} (°C)	Measured T_{sat} (K)	Steam Table T_{sat} (°C)	Discrepancy / Error (°C)	Slope (dP/dT) (bar/K)
1							
2							
3							
4							
5							
6							
7							