Steam Motor and Energy Conversion

INTRODUCTION

In this session you will make use of a laboratory-scale steam plant based on the Rankine cycle to power a steam motor. The laboratory will introduce you to a number of physical constraints both in the operation on a non-ideal Rankine cycle and in the challenges in measuring enthalpy of a liquid vapour mixture.

The aim of this laboratory is to determine the performance of the steam plant and analyse it in comparison with the ideal Rankine cycle including the specific steam consumption and energy distribution. Specifically you will undertake the following steps:

1. As the steam leaving the boiler is not superheated, you will first determine the dryness fraction using a calorimeter
2. You will then calculate the efficiency of an ideal Rankine cycle to compare your measurements
3. You will collect data relating to the operation of the steam generator
4. You will analyse your results to quantify the efficiency of the motor and the efficiency of the full steam cycle

APPARATUS

TD1050 steam motor and energy conversion test set

TecQuipment Ltd's TD1050 steam motor and energy conversion test set (Figure 1) contains an electric pump, a reservoir to deliver water to an electrically-heated boiler, a two-cylinder steam motor, a mains water-cooled condenser and a waste tank (a measuring vessel). The test set can be operated at a maximum boiler pressure of 350 kPa (3.5 bar – gauge pressure).

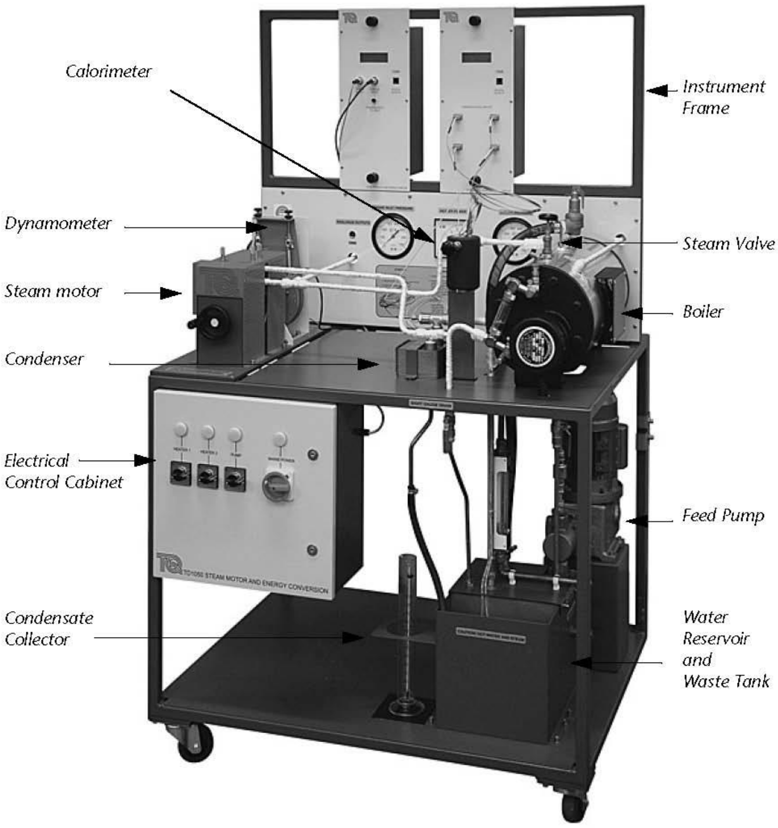


Figure 1. TD1050 steam motor and energy conversion test set.

The Test Rig Layout

The test rig layout is shown in Figure 2. Water is fed from a reservoir to the boiler via an electric pump. The boiler uses electrical heaters to generate steam which is supplied to the steam engine. The flow of steam is controlled by a valve and the enthalpy of the steam leaving the boiler is measured by a calorimeter. The steam leaving the engine passes through the condenser which is cooled by an external cold-water feed before flowing into a waste-tank. The cold-water feed is also the supply to the reservoir supplying the boiler.

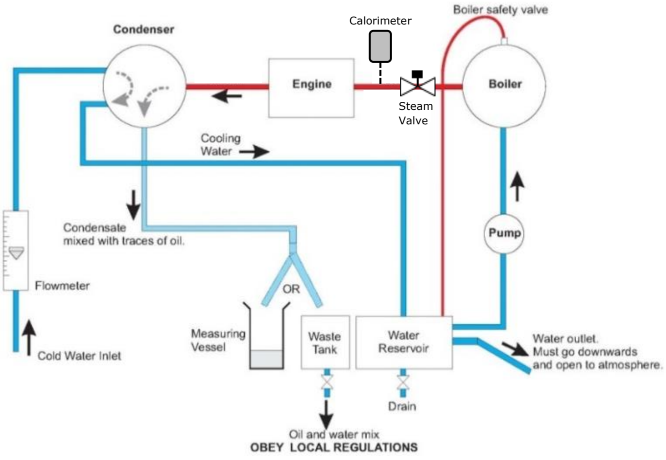


Figure 2. The water flow system.

The Pump and Boiler

An electric pump fills the boiler with water. The water passes through a non-return valve from the pump to the boiler. The steel boiler contains two electric immersion heaters. They each include a thermal cut-out, which protects against overheating due to low water level. A spring-loaded pressure relief valve protects against over pressure in the boiler. The top of the boiler has a steam valve or 'stop valve' to regulate the steam flow from the boiler to the motor.

The Steam Motor

The motor has a totally enclosed crankcase, two cast iron trunk pistons and an overhead piston valve made of stainless steel. The overhead piston is driven by an external connecting link from a vertical shaft, turned by a bevel gear at the crankshaft. The crankcase has a combined dipstick and filler, a breather and a drain plug (Figure 3). A displacement lubricator lubricates the overhead piston. A guard around the motor protects the user from moving parts and hot surfaces.

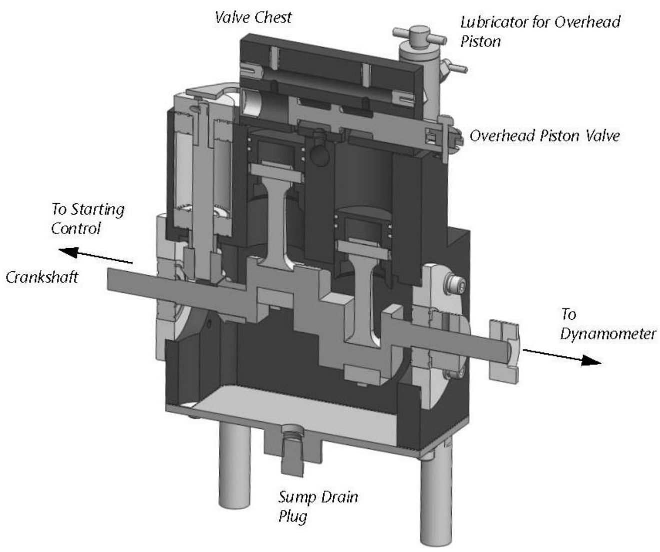


Figure 3. The steam motor.

The Condenser

The exhaust steam from the motor passes through the condenser. Cooling water circulates through the condenser, cooling the exhaust steam. The steam condenses and drains out of a connection below the condenser, to a measuring vessel or to the waste tank. When using the calorimeter for dryness fraction testing, the outlet steam of the calorimeter also passes through the condenser. The condenser cools this steam so only water passes down to the waste tank.

Brake Dynamometer with Digital Torque and Speed Display

The Brake Dynamometer is a simple friction brake instrument that fits at the back of the steam motor. As you adjust any of the two controls of the dynamometer, a cord is pulled against the dynamometer drum, applying a load. A force sensor measures the torque as you apply the load. Another sensor measures the motor speed. The product of the torque and shaft speed gives the mechanical or ***shaft power*** the steam motor absorbs from the steam flow.

Shaft power (Watts) = Shaft speed (rad/s) x Shaft torque (Nm)

Heater Power and Pressures

The electrical control cabinet contains an isolator and individual control switches with indicator lights for the two heater elements and the feed pump. A wattmeter on the back of the equipment measures electrical power input to the boiler. Two Bourdon gauges on the back panel of the equipment indicate boiler and motor inlet pressure.

Temperatures

Four thermocouples on the apparatus connect to a separate digital temperature display that fits in the instrument frame. The thermocouples measure the temperature of:

- The boiler – T_1
- The calorimeter – T_2
- Cooling water inlet – T_3
- Cooling water outlet – T_4

Cooling Water Flow Rate

A flowmeter under the boiler measures the cooling water flow rate.

Condensate (Steam) Flow Rate

A measuring cylinder and a stopwatch are used to measure the flow rate of condensate (steam flow) from the condenser. The condensate runs down a flexible pipe, so that you can direct it to the waste tank for most of the time, then direct it to the measuring vessel during experiments.

Calorimeter and Dryness Fraction

The throttling calorimeter allows a controlled expansion of steam from boiler pressure to atmospheric pressure (Figure 4). This device is necessary to determine the enthalpy of the liquid-vapour mixture leaving the boiler.

The liquid-vapour mixture enters the calorimeter with unknown enthalpy h_{in}. As it expands through the calorimeter valve, the pressure drops to atmospheric level. As no external work is done during the expansion, the enthalpy of the steam remains constant (the enthalpy of the steam that leaves the calorimeter should be equal to the enthalpy of the steam that enters).

$$h_{in} = h_{out}$$

Part of the steam enthalpy that enters the calorimeter changes into internal energy through the calorimeter and the steam can become superheated. The pressure at the outlet is atmospheric and by measuring the temperature at the outlet (T_2), you can find its enthalpy h_{out} from steam tables. You can then use this to find the dryness fraction using the temperature of the liquid-vapour mixture leaving the boiler (T_1) to determine $h_{f,in}$ and $h_{fg,in}$:

$$h_{out} = h_{in} = h_{f,in} + \left(x_{in} h_{fg,in}\right); \qquad x_{in} = \frac{h_{out} - h_{f,in}}{h_{fg,in}}$$

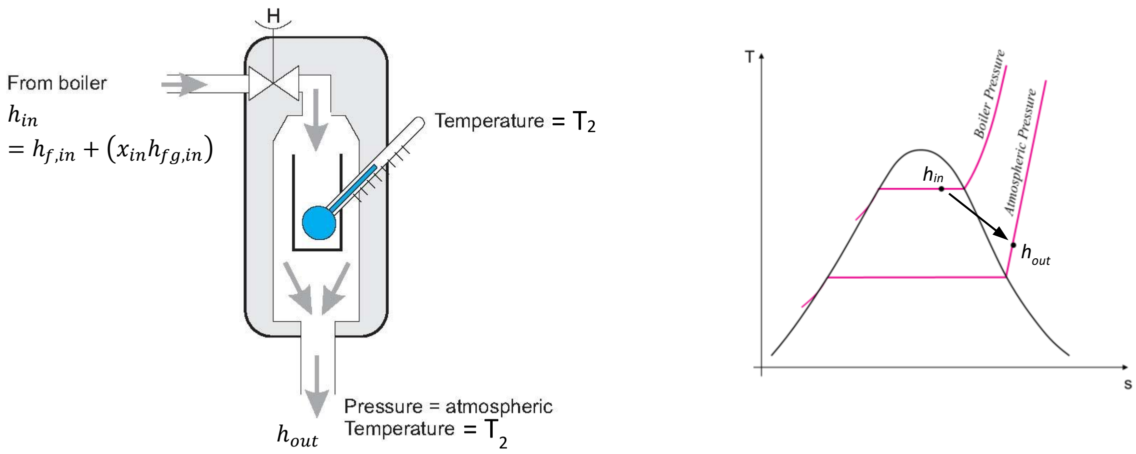


Figure 4. The throttling calorimeter.

The Energy Balance

Figure 5 shows the key energy flows within the system. These are as follows:

- $\dot{Q}_b$ is the heat supplied to the boiler via the electric heaters
- $\dot{Q}_{loss,b}$ is the heat lost via heat transfer to the ambient from the boiler
- $\dot{Q}_{loss,eng}$ is the heat lost via heat transfer to ambient, oil and engine structure within the engine
- $\dot{Q}_{loss,cond}$ is the heat loss to ambient from the condenser
- $\dot{Q}_{cond}$ is the heat transfer from the steam to the cooling water in the condenser
- $\dot{W}_{eng}$ is the mechanical work output from the engine
- $\dot{m}h_2$ is the enthalpy of the water entering the boiler
- $\dot{m}h_1$ is the enthalpy for the water leaving the condenser

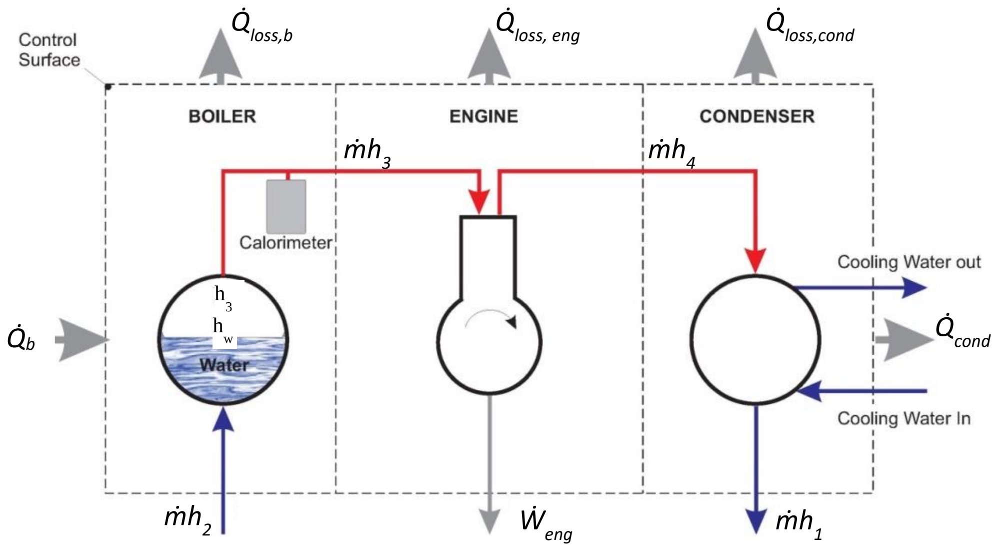


Figure 5. The Thermodynamic System of the TD1050.

The Steady Flow Energy Equation for the Steam Plant may be written as:

$$\dot{W}_{eng} = \dot{Q}_b - \dot{Q}_{loss,b} - \dot{Q}_{loss,eng} - \dot{Q}_{loss,cond} - \dot{Q}_{cond} + \dot{m}h_2 - \dot{m}h_1$$

The overall thermal efficiency of the plant is given by the ratio of the power out divided by the electrical ('fuel') power in:

$$\eta_{th} = \frac{\dot{W}_{eng}}{\dot{Q}_b}$$

For the left-hand section of the control surface, enclosing the boiler only, the Steady Flow Energy Equation becomes:

$$\dot{Q}_b + \dot{m}h_2 = \dot{Q}_{loss,b} + \dot{m}h_3$$

Assume h_2 *can be estimated as* h_f *at the boiler pressure*. Therefore the boiler efficiency is:

$$\eta_b = \frac{\dot{m}(h_3 - h_2)}{\dot{Q}_b}$$

Procedure

The students attending each lab session will be divided into sub-groups (each sub-group has 4-5 people) to use the test setup alternatively. Each sub-group needs to conduct the following tests.

1. Direct the flexible condensate pipe into the waste tank.
2. Switch on both heaters. When the boiler pressure has reached approximately **300 kN/m^2**, slowly open the boiler steam valve about one quarter turn until the motor inlet pressure reaches about 80 kN/m^2***.***
3. Turn the motor starting control clockwise to start the motor.
4. Use the steam valve to control the motor speed and run the motor at ~1600 rev.min^{-1}. (**Never let the motor speed exceed 2500 rev.min^{-1}**)
5. Switch off one of the heaters. The boiler pressure will stabilize at around **240 kN/m^2**.
6. Use the steam valve to maintain a constant speed of 1600 rev.min^{-1} (±50 rev.min^{-1}) while you use the dynamometer to load the motor in at least six equal steps (steps of increasing torque of around 0.05 Nm). Continue loading the motor until it cannot maintain its speed.

   *For best results, always **increase** the load gradually during the experiment (tightening the dynamometer controls). Do not try to go backwards (loosening the control). If you miss a test point, reduce the load back to the previous known setting and then slowly increase the load again. This helps to avoid any hysteresis errors.*

7. At each step, record the **heater power**, the **boiler pressure** and **temperature**, **motor inlet pressure**, **motor speed**, **motor power (on the dynamometer display)**, **condenser cooling water temperatures** and **flow rate** and **condensate flow rate** using the attached form in Page 8.
8. For each step, measure the condensate flow rate by directing the flexible pipe into the measuring cylinder and measure the amount of condensate collected over intervals of 60 seconds. This allows you to directly convert the flow into LPM.
9. At the end of the experiment when the motor is still running, use the calorimeter to measure the dryness fraction and assume it is constant throughout the tests. Fully open the calorimeter valve to allow a small amount of steam to pass through for about 10 seconds (or until the calorimeter temperature stabilizes). Record the **boiler steam pressure**, **temperature** and **calorimeter temperature**. Assume the ambient pressure is 1 bar.

Calculate the cycle efficiency of an ideal Rankine cycle (ignore feed pump work) operating with a boiler pressure of 240 kN/m^2 and ambient condenser pressure.

10. Shut down the rig properly.
11. Finish all the **calculations** in the attached sheets in Pages 9-11 and get it signed by one of the PGs running the lab **before you leave**.
12. You will need to submit the completed sheets in Page 8-11 with your lab report as Appendix.

Results Analysis

1. **Dryness fraction**
   You need to calculate the dryness fraction of the steam leaving the boiler to determine the enthalpy at this point. Calculate the dryness fraction of the steam at the boiler pressure of approximately 300 kN/m^2 (gauge pressure). You will then assume that the dryness fraction is constant throughout all subsequent tests.

2. **Ideal Rankine cycle**
   You will then calculate the performance of an ideal Rankine which can be used as reference for the real cycle that will be measured on the test rig. Calculate the cycle efficiency of an ideal Rankine cycle (ignore feed pump work) operating with the boiler pressure of 240 kN/m^2 (gauge pressure) and the condenser pressure which is at ambient.

3. **Willans line and engine performance**
   In this section you will analyse the performance of the stem motor by estimating its frictional losses and efficiency.
   - Frictional losses will be estimated using a Willans line which extrapolates to the hypothetical negative engine power with zero steam flow.
   - Efficiency will be quantified using the specific steam consumption (i.e. the mass of steam required to generate a unit of power).

   Convert your condensate (steam) flow into kg/h and your motor power into kW. Assume water density is constant. Calculate the specific steam consumption in kg/kWh.

   Create two charts, steam flow rate and motor inlet pressure against power output (horizontal axis) and specific steam consumption against power output (horizontal axis).

   Specific Steam Consumption (kg/kWh) = Steam Flow (kg/h) / Power Output (kW)

   Extend the steam flow line down to the horizontal axis to find an approximate value of mechanical losses in the motor.

4. **Steady flow analysis (energy balance)**
   Here you will compare your measured efficiency to the ideal Rankine cycle efficiency. Choose one point in your results where you are confident that the system was in equilibrium and use steam tables to find enthalpies, analyse the individual energy flows. Plot a bar chart of $\dot{W}_{eng}$, $\dot{Q}_{loss,b}$, $\dot{Q}_{loss,eng}$ + $\dot{Q}_{loss,cond}$, $\dot{Q}_{cond}$ and $\dot{m}h_1$. Calculate the boiler efficiency. Calculate the overall thermal efficiency and compare it to the ideal Rankine cycle.

Report

Attendance is compulsory. Any students who missed the practical lab sessions without notified mitigating circumstances or who did not participate in the report writing-up will be awarded zero marks. The report will be an individual effort, while the session will be carried out in groups. You are encouraged to discuss the measurements, data post-processing and report-writing within your group as well as with peer students in other groups.

There is a word limit of 2500 which encompass everything except diagrams and tables and the appendix. A concise *Summary* should precede the introduction. The *Introduction* of your report should explain the importance of Steam power/Rankine Cycle in engineering science, leading to the objectives of the test. The *Experimental Apparatus and Procedure* section should provide a brief account of how the experiments were conducted. The data should be tabulated clearly, and the plots illustrated in the *Results* section, including a brief discussion of experimental uncertainty. Four Figures/sketches should be presented: (i) *T-s diagrams of the ideal Rankine cycle and the actual Rankine cycle of the test set,* (ii) *The Willans Line and Pressure Curve*, (iii) *Specific Steam Consumption and (iv) bar chart of Energy distribution*. The Figures should then be described and analysed in a separate *Discussion* section. Please give some thought to your graphs and don't let your computer plotting package dictate terms. The evidence, observations and explanations collected throughout the laboratory should be used and developed in this section. The *Conclusions* should be succinct, relating back to the objectives.

The assessment criteria are provided on the back page of the handout. Please read it through to make certain you are not missing any obvious points.

Once you have done the lab, you will need to submit the report via Moodle within **TWO WEEKS**. We will be endeavouring to return the marks and feedback sheet to you via Moodle within **THREE WEEKS** of the submission deadlines.

October 2024

Name: **Lab date:** **Group:**

Atmospheric pressure: 1 bar **Cooling water flow rate (LPM):**

Dryness fraction

Boiler steam pressure (kN/m^2):

Boiler steam temperature (°C):

Calorimeter temperature (°C):

No.	**Torque**	**Motor Speed**	**Motor Power**	**Heater Power**	**Condensate Flow**	**Pressures (kN/m^2)**		**Temperatures (°C)**		
	Nm	**(rev.min^{-1})**	**(W)**	**(kW)**	**LPM**	**Boiler**	**Motor inlet**	**T_1** (The boiler)	**T_3** (Cooling Water Inlet)	**T_4** (Cooling water Outlet)
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

1. Dryness fraction

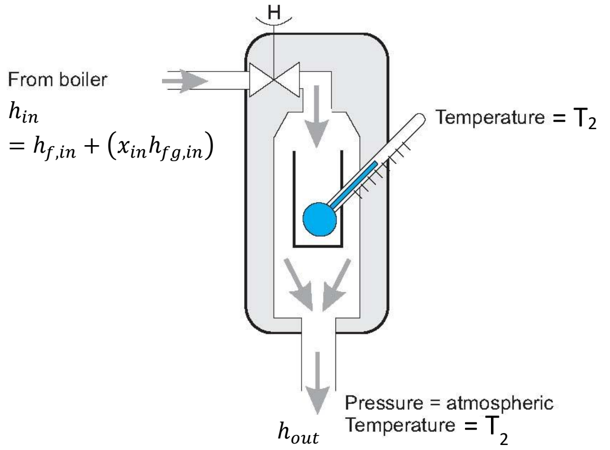
Boiler steam pressure (absolute) (bar):
Calorimeter temperature (°C):

$h_{f,in} = \quad kJ/kg$

$h_{fg,in} = \quad kJ/kg$

$h_{out} = \quad kJ/kg$

$$x_{in} = \frac{h_{out} - h_{f,in}}{h_{fg,in}} =$$



2. Ideal Rankine cycle

Sketch the *T*-*s* diagram of an ideal Rankine cycle (ignore feed pump work) operating with a boiler pressure of 240 kN/m^2 (gauge pressure) and a condenser pressure equal to ambient, and the actual *T*-*s* diagram of the steam plant including the effects of dryness fraction and engine efficiency. For your report you will need to identify the following:

- Condensate temperature (assume saturated)
- The water temperature at boiler inlet (ignore pump work)
- The boiler steam temperature
- The temperature at condenser inlet

Ideal Rankine cycle	Enthalpy (kJ/kg)	Absolute Pressure (kN/m^2)
Condenser outlet (assume saturated)		
Boiler inlet (ignore pump work)		
Boiler outlet / engine inlet		
Engine outlet / Condenser inlet		

$$\eta_{th} = \frac{work\ output}{heat\ supplied} =$$

3. Willans Line and Performance

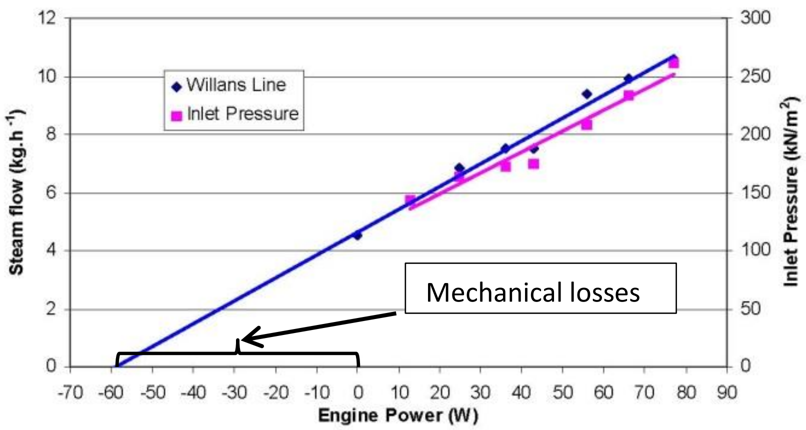
No.	Motor Power	Motor Power	Condensate		SSC	Pressure (kN/m^2)
	(W)	(kW)	Flow (L/min)	Flow (kg/h)	(kg/kWh)	Motor inlet
1						
2						
3						
4						
5						
6						
7						
8						
9						

Specific Steam Consumption (kg/kWh) = Steam Flow (kg/h)/Power Output (kW)

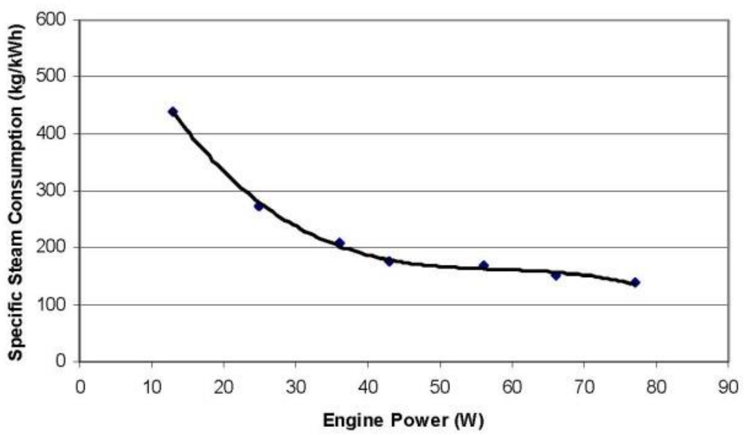
Plot Willans Line (use linear fit), inlet pressure and SSC similar to these two examples to the right.

Estimate mechanical losses for the steam motor from the Willans line.

Steam flow and Willans line



Specific Steam Consumption



4. Steady flow analysis (Energy balance)

Quantity	Symbol	Reading	Absolute values
Pressures			
Atmospheric (absolute)	p_a	1 bar	100 kN/m^2
Boiler	p_1	kN/m^2	kN/m^2
Flow Rates			
Condensate (Steam)	$\dot{m}$	LPM	kg/s
Cooling water	$\dot{m}_w$	LPM	kg/s
Temperatures			
Boiler steam	T_1	°C	K
Cooling water inlet	T_3	°C	K
Cooling water outlet	T_4	°C	K
Motor Power and Speed			
Motor Power	$\dot{W}_{eng}$	Watts (kW)	
Motor speed	N	$rev.min^{-1}$	
Boiler Power			
Electrical power input to boiler	$\dot{Q}_b$	kW	

For the boiler steam and water (T_1):

Enthalpy of the saturated water (h_f) =

Enthalpy of evaporation (h_{fg}) =

Dryness fraction (x_{in}) =

Enthalpy of the boiler steam (h_3) = $h_{in} = h_f + x_{in} h_{fg}$ =

The heat energy flow rate: $\dot{m}h_3$ =

Assume: $\dot{m}h_2 = \dot{m}h_f$ =

So $\dot{Q}_{loss,b} = \dot{Q}_b + \dot{m}h_2 - \dot{m}h_3$ =

Boiler efficiency: $\eta_b = \frac{\dot{m}h_3 - \dot{m}h_2}{\dot{Q}_b} =$

The specific heat of water c_w = 4.18 kJ/(Kg.K):

$$\dot{Q}_{cond} = \dot{m}_w \times c_w \times (T_4 - T_3) =$$

The enthalpy of the condensate leaving the condenser is kJ/kg (assume saturated water at 1 bar):

$$\dot{m}h_1 = \quad \times \quad =$$

$$\dot{Q}_{loss,eng} + \dot{Q}_{loss,cond} = \dot{Q}_b - \dot{Q}_{loss,b} - \dot{Q}_{cond} - \dot{W}_{eng} + \dot{m}h_2 - \dot{m}h_1$$

$$= \quad - \quad - \quad - \quad + \quad - \quad =$$

The overall thermal efficiency: $\eta_{th} = \frac{\dot{W}_{eng}}{\dot{Q}_b}$ =

ME22009 Steam Laboratory Assessment Sheet 2024/25

Assessor: _______

Student:____ **Date: ____________**

	A	B	C	D	E	Comments
Summary						☐ No reference to significant conclusions ☐ Too short ☐ Overview of report not provided ☐ Unclear and/or not succinct ☐ Focussed on unimportant or irrelevant content
Introduction						☐ Lacks interest or originality ☐ Objectives not stated ☐ Importance of steam power to engineering not explained ☐ Writing is unclear or lacks structure ☐ Focussed on unimportant or irrelevant content
Expt / Procedure						☐ No use of a diagram/schematic to explain the set-up ☐ Detail out of proportion with remainder of report ☐ No explanation of how the calorimeter works ☐ Writing is unclear or lacks structure
Results/ Discussion						☐ Discussion of graphs lacks coherent structure ☐ Inadequate explanation of SSC graph & Willans line ☐ Inadequate explanation of the main losses and inefficiencies ☐ No discussion of energy distribution ☐ No discussion of how to improve the **ideal** cycle efficiency ☐ No discussion of how to improve the **real** cycle efficiency and reduce losses ☐ No discussion of experimental uncertainties
Conclusions						☐ Unclear and/or not succinct ☐ Main conclusions incorrect ☐ No link to objectives ☐ Focussed on unimportant or irrelevant content
Figures and Tables						☐ Graphs not numbered or have inappropriate titles ☐ Some/all figures and tables not referred to in the text ☐ Graph axes labelled inappropriately ☐ Scales on graphs not appropriate ☐ Graphs not plotted clearly, or symbols poorly chosen ☐ Inappropriate number of significant figures in data ☐ Poorly presented data
Clarity						☐ Not written in the 3rd person, past tense ☐ Writing is unclear or lacks structure ☐ Your work has not been adequately proof-read ☐ Poor grammar
Appendix						☐ Appendix of calculations not attached

Mark:

A:70+ B: 60-69 C: 50-59 D: 40-49 E: 39-