Pearson BTEC Level 5 Higher Nationals in Engineering (RQF)

Unit 63: Industrial Services

Unit Workbook 3

in a series of 4 for this unit

Learning Outcome 3

Steam

Contents

INTRODUCTION

Discuss the provision of steam services for process and power use.

- *Steam Power Plant:*
  - Use of tables and charts to analyse wet and dry saturated steam.
  - Circuit diagrams showing steam raising plant.
  - Process steam: enthalpy of evaporation, available energy.
  - Overall plant efficiencies for process.
  - Power steam: superheated steam, turbine efficiency, Rankine cycle, cooling towers.
  - Overall plant efficiency for power.
  - Efficiencies and improvements.

GUIDANCE

This document is prepared to break the unit material down into bite size chunks. You will see the learning outcomes above treated in their own sections. Therein you will encounter the following structures;

Purpose	Explains *why* you need to study the current section of material. Quite often learners are put off by material which does not initially seem to be relevant to a topic or profession. Once you understand the importance of new learning or theory you will embrace the concepts more readily.
Theory	Conveys new material to you in a straightforward fashion. To support the treatments in this section you are strongly advised to follow the given hyperlinks, which may be useful documents or applications on the web.
Example	The examples/worked examples are presented in a knowledge-building order. Make sure you follow them all through. If you are feeling confident then you might like to treat an example as a question, in which case cover it up and have a go yourself. Many of the examples given resemble assignment questions which will come your way, so follow them through diligently.
Question	Questions should not be avoided if you are determined to learn. Please do take the time to tackle each of the given questions, in the order in which they are presented. The order is important, as further knowledge and confidence is built upon previous knowledge and confidence. As an Online Learner it is important that the answers to questions are immediately available to you. Contact your Unit Tutor if you need help.
Challenge	You can really cement your new knowledge by undertaking the challenges. A challenge could be to download software and perform an exercise. An alternative challenge might involve a practical activity or other form of research.
Video	Videos on the web can be very useful supplements to your distance learning efforts. Wherever an online video(s) will help you then it will be hyperlinked at the appropriate point.

In a steam power plant, there are three basic types of components: turbines, pumps and heat exchangers and with these different components comes a different characteristic change in the working properties of the fluid. It is important to understand that the purpose of a turbine is to extract energy from the steam and use that to do work, in most cases by rotating a shaft, leading to this work being converted to electrical energy via the generator.

The work done by a **turbine**, under steady flow conditions, is actually equivalent to the decrease in enthalpy of the steam and can be expressed in the following way:

$$W_{Turbine} = Mass\ Flow\ Rate(H_{In} - H_{Out})$$

The purpose of a **pump** is to move the steam by doing work upon it, in this case the work done of the pump is equivalent to the increase in enthalpy of the steam. As with the turbine, a pump is not 100% efficient. The key difference between this and a turbine, is that the turbine extracts energy from the steam whilst the pump increases the steam's energy.

A **heat exchanger** is quite simply a device which transfers heat between two working fluids, examples include hot gases being used to evaporate feedwater and the condenser being used to transfer heat from the working fluid to the surrounding environment.

1.1.3 Steam & Energies

Enthalpy of evaporation, sometimes known as enthalpy of vaporisation, heat of evaporation or (latent) heat of vaporisation, is a term given to the amount of energy that must be added to a substance in order to turn it from a liquid to a gas, it is dependent on the pressure at which this transformation takes place and is measured in J/kg. Some older units are still used in certain industries and in other countries, such as kcal/mol or Btu/lb.

The **Carnot cycle** is a principle which demonstrates the maximum theoretical efficiency of a heat engine, i.e. a thermodynamic system transferring heat and work, which is based on the temperature of heat input and the temperature of the heat rejected, and assuming that the process as a whole is reversible. In reality this is not the case, however a theoretical Carnot efficiency, sometimes known as ideal efficiency, can be used to show the unattainable upper limit for a real-life system's efficiency. Since the Carnot efficiency is dependent on the temperature of the heat input (source) and the temperature of the heat rejected (sink), it makes sense that to improve efficiency, one would simply increase the temperature of the heat source and decrease the temperature of the heat sink. This idea has certain limits because the ultimate heat sink is the Earth, whose temperature is fixed, whilst the heat source temperature is also somewhat limited based on the fuel that is being used and the materials that the whole system is made from. Considering these limitations, the highest possible Carnot efficiency is 73%.

Not all energy is available to be used usefully and some is rejected to the surrounding environment. Firstly, if we can consider that the working fluid is water/steam then this immediately causes efficiency restrictions, heat is added to this fluid at constant pressure and at below the maximum allowable material temperature, which means that not all of the available energy is harnessed. The following entropy-temperature graph shows the amounts of energy which are available, unavailable and additionally available:

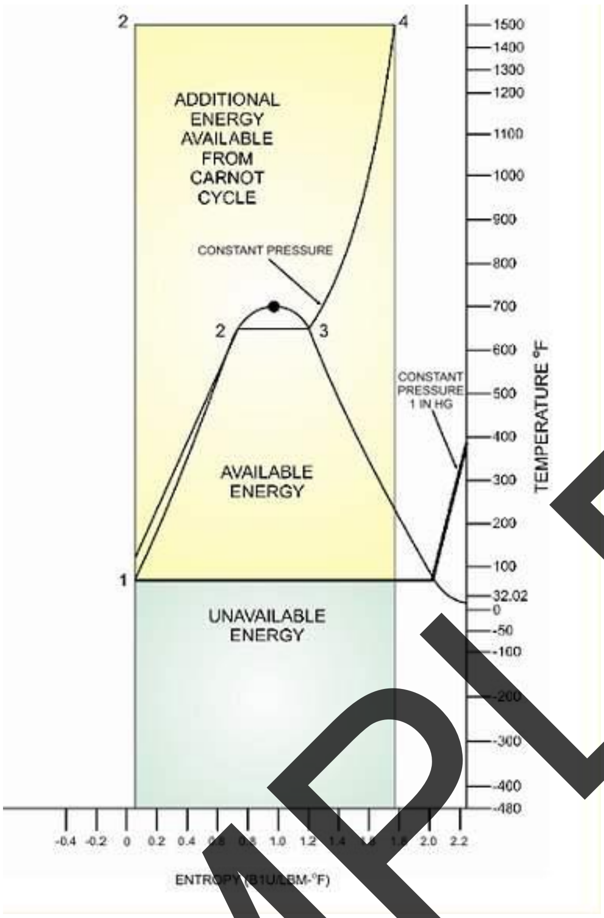


Figure 1.4: *Typical Steam Plant Cycle*

The actual energy available can be seen as the area under the 1-2-3-4 curve, whilst the available energy from an ideal Carnot cycle can be seen as the area under the 1-2-4 curve, with both operating between the exact same temperatures. The Carnot cycle is not suitable to be used practically for a few different reasons, firstly, it would require an enormous amount of pumping work, this pumping would also likely cause cavitation in the system and the ideal mixture required at point 1 would also pose insurmountable technical problems. A Carnot steam cycle on an entropy-temperature graph can be seen below:

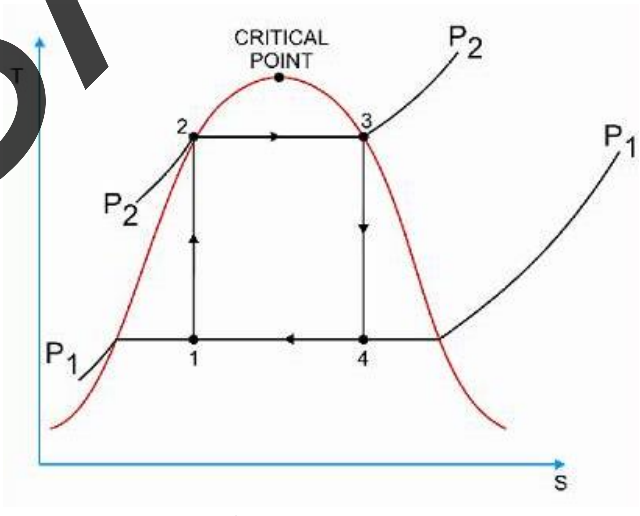
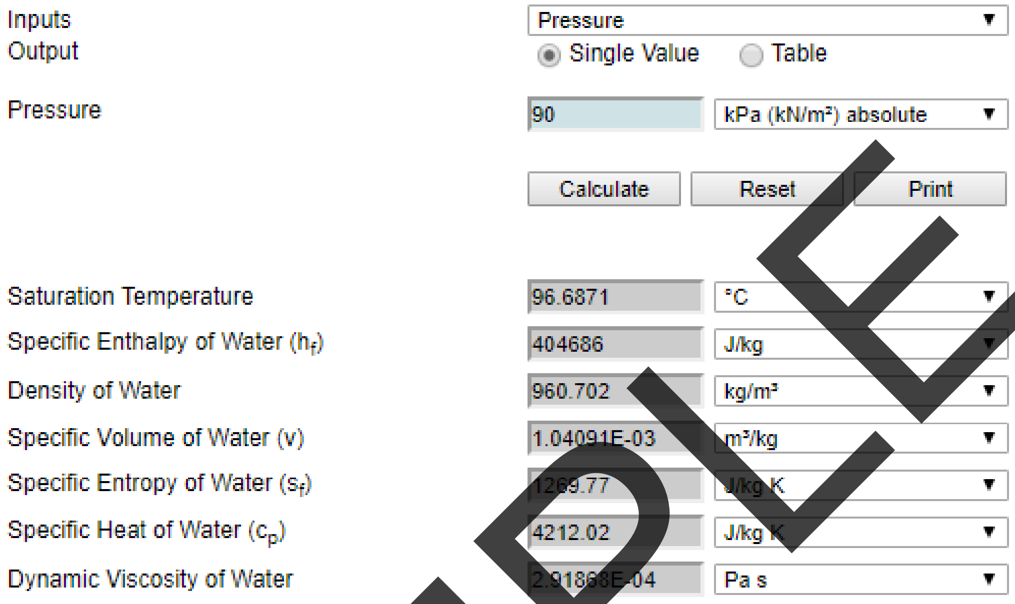


Figure 1.5: *Carnot Cycle on Temperature-Entropy Diagram*

Now we state our known conditions:

At **point 1**, Pressure (p) = 90 kPa and the working medium is fluid water which has come out of the condenser; therefore, we know that we have a saturated liquid which, in turn, means that the quality or dryness ratio (x) = 0. Now consult the steam tables or use a steam calculator to determine all of the other conditions at this point (https://beta.spiraxsarco.com/resources-and-design-tools/steam-tables):



Pressure ▼

● Single Value ○ Table

Pressure: 90 kPa (kN/m²) absolute

Saturation Temperature: 96.6871 °C

Specific Enthalpy of Water (h_f): 404686 J/kg

Density of Water: 960.702 kg/m³

Specific Volume of Water (v): 1.04091E-03 m³/kg

Specific Entropy of Water (s_f): 1269.77 J/kg K

Specific Heat of Water (c_p): 4212.02 J/kg K

Dynamic Viscosity of Water: 2.91868E-04 Pa s

The key useful characteristics here are the specific volume (v), specific enthalpy (h) and specific entropy (s) which we will subscript these with ‘1’ to signify that they apply to point 1 on the system:

$$v_1 = 1.04 \times 10^{-3} \frac{m^3}{kg}$$

$$h_1 = 404686 \frac{J}{kg}$$

$$s_1 = 1269.77 \frac{J}{kg} K$$

Let us now consider **point 2** on the system: we know that the pressure (p) is 4 MPa. From point 1 to point two on the graph is a straight line upwards, meaning that there is no change in entropy, i.e. it is an isentropic process. Therefore s_1=s_2 and the working medium is still a fluid, meaning that the specific volume is unchanged, (v_1=v_2), these can both be signified simply as the specific volume of the fluid (v_f). At this point we cannot use the steam tables to determine parameters because we do not know the quality, however we can determine the work done of the pump if we so wish, by using the formula below:

$$-W_{Pump} = v_f(p_2 - p_1)$$

$$-W_{Pump} = 1.04 \times 10^{-3}(4 \times 10^6 - 90000) = 4066 \frac{J}{kg}$$

It transpires that this is actually an incredibly useful value to determine because, in an isentropic process the work done is equivalent to the change in enthalpy, and so:

$$-W = \Delta h$$

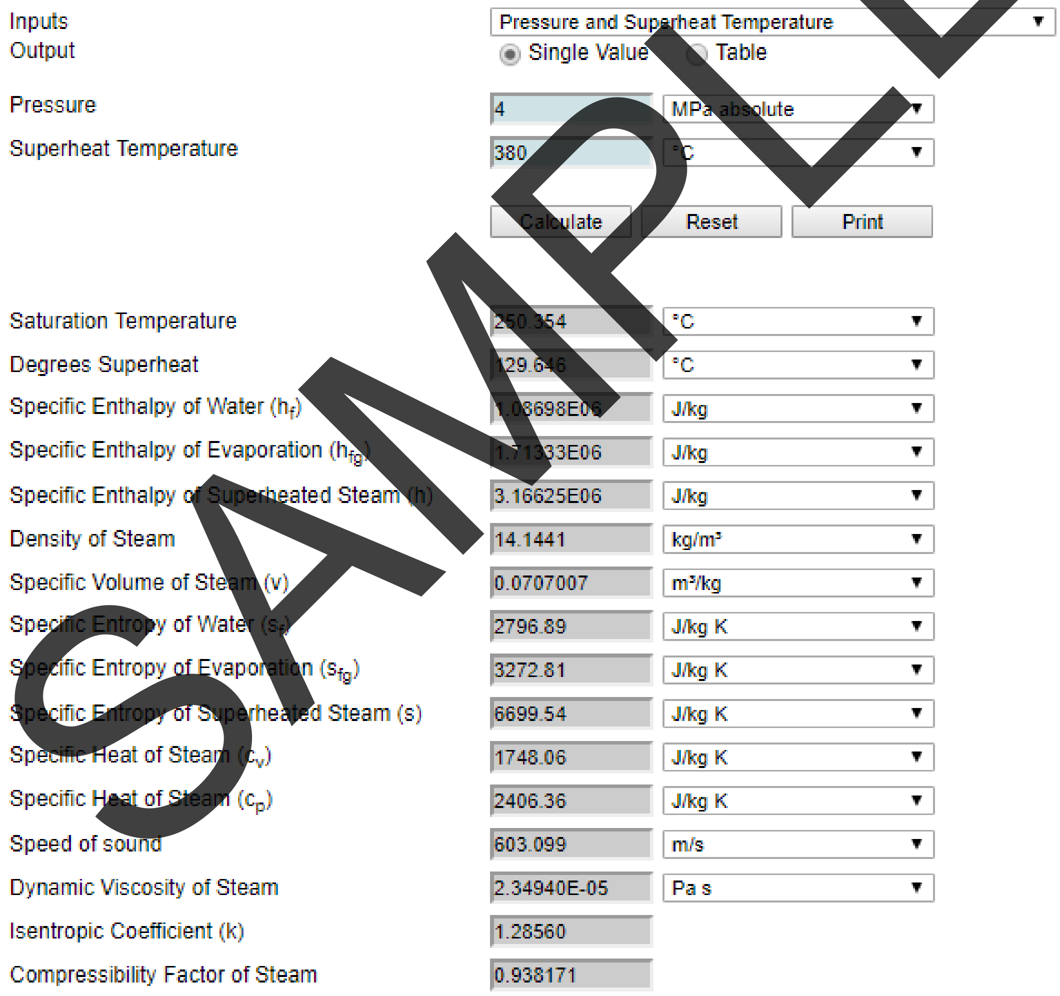
In our case, we can say specifically that:

$$-W_{Pump} = h_2 - h_1$$

$$4066 = h_2 - 404686$$

$$h_2 = 408752 \frac{J}{kg}$$

At **point 3**, there is no change in pressure, so p$_3$=p$_2$=4 Mpa but rather we are now given the temperature of 380°C, where the medium has been changed from a saturated fluid to a superheated steam. We can now use the steam tables to look up the values of its characteristics.



Inputs	Pressure and Superheat Temperature	
Output	● Single Value ○ Table	
Pressure	4	MPa absolute
Superheat Temperature	380	°C
Saturation Temperature	250.354	°C
Degrees Superheat	129.646	°C
Specific Enthalpy of Water (h_f)	1.08698E06	J/kg
Specific Enthalpy of Evaporation (h_{fg})	1.71333E06	J/kg
Specific Enthalpy of Superheated Steam (h)	3.16625E06	J/kg
Density of Steam	14.1441	kg/m³
Specific Volume of Steam (v)	0.0707007	m³/kg
Specific Entropy of Water (s_f)	2796.89	J/kg K
Specific Entropy of Evaporation (s_{fg})	3272.81	J/kg K
Specific Entropy of Superheated Steam (s)	6699.54	J/kg K
Specific Heat of Steam (c_v)	1748.06	J/kg K
Specific Heat of Steam (c_p)	2406.36	J/kg K
Speed of sound	603.099	m/s
Dynamic Viscosity of Steam	2.34940E-05	Pa s
Isentropic Coefficient (k)	1.28560	
Compressibility Factor of Steam	0.938171	

We can see that the values are as follows:

$$v_3 = 0.07 \frac{m^3}{kg}$$

$$h_3 = 3.17 \times 10^6 \ \frac{J}{kg}$$

$$s_3 = 6699.54 \ \frac{J}{kg} K$$

At **point 4** we know that p_4=p_1= 90 kPa and we can also observe on the graph that it is an isentropic process whereby there is no change in entropy, i.e. s_3=s_4= 6699.54 J/kg K. At this point after the turbine, the medium is a mixture of both a fluid and a gas. In order to determine its properties, we must first determine its quality or dryness fraction (x). This can be achieved through the use of the following formula:

$$x_4 = \frac{s_4 - s_f}{s_{fg}}$$

The values of s_f and s_{fg} are found in the steam tables in the saturated water and steam section for 90 kPa.

$$x_4 = \frac{6699.54 - 1270}{6124}$$

$$x_4 = 0.886$$

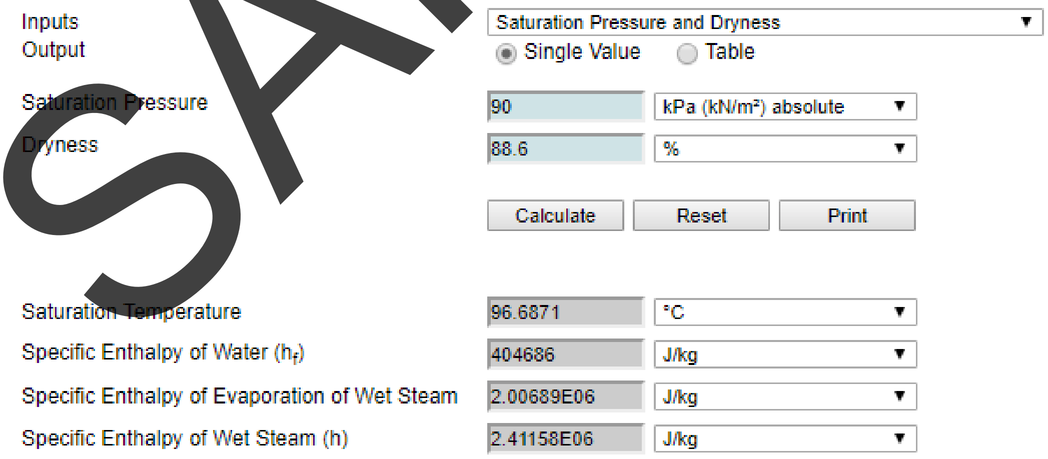
$$x_4 = 88.6\%$$

The value of h_4 can be determined by using a steam tables calculator in the wet steam section, or via the following formula:

$$h_4 = h_f + x_4(h_{fg})$$

$$h_4 = 405000 + 0.886(2266000)$$

$$h_4 = 2412676 \frac{J}{kg}$$



Inputs: Saturation Pressure and Dryness
Output: ● Single Value ○ Table

Saturation Pressure: 90 kPa (kN/m²) absolute
Dryness: 88.6 %

Saturation Temperature: 96.6871 °C
Specific Enthalpy of Water (h_f): 404686 J/kg
Specific Enthalpy of Evaporation of Wet Steam: 2.00689E06 J/kg
Specific Enthalpy of Wet Steam (h): 2.41158E06 J/kg

(Discrepancies are due to rounding differences in online calculators and hand calculations).

Finally, we may now determine the thermal efficiency, there are several different ways to accomplish this, it may be determined by dividing the net work out by the heat in to the system, as such:

$$\eta_{Thermal} = \frac{W_{net}}{Q_{in}}$$

Note that:

$$W_{net} = W_{Turbine} - W_{Pump}$$

Whilst, the work output of the turbine is calculated by:

$$W_{Turbine} = h_3 - h_4$$

We already know the value of W_{Pump} , although if we did not, then we could work this out by simply determining h_2-h_1. In addition, the heat input is determined through the following equation:

$$Q_{in} = h_3 - h_2$$

We therefore arrive at the equation:

$$\eta_{Thermal} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$$

$$\eta_{Thermal} = \frac{(3.17 \times 10^6 - 2412676) - (408752 - 404686)}{(3.17 \times 10^6 - 408752)}$$

$$\eta_{Thermal} = 0.272$$

$$\eta_{Thermal} = 27\%$$