Pearson BTEC Level 5 Higher Nationals in Engineering (RQF)

Unit 64: Thermofluids

Unit Workbook 2

in a series of 4 for this unit

Learning Outcome 2

Vapour Power Cycles

Sample

Contents

edexcel
Approved Centre

INTRODUCTION

Examine the operation of practical steam and gas turbines plants

- *Steam and gas turbine plant:*
    - Principles of operation of steam and gas turbine plants.
    - Use of property diagrams to analyse plant.
    - Characteristics of steam/gas turbine plant as used in energy supply.
    - Energy-saving options adopted on steam plants operating on modified Rankine cycle.
    - Performance characteristics of steam and gas power plant.
    - Cycle efficiencies: turbine isentropic efficiencies and overall relative efficiency.

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.

2.1 Power Cycles

2.1.1 The Brayton Cycle

So far, the only power cycle discussed has been the Brayton cycle, which usually considers that the working fluid moving through the system is a gas, and that it does not go through any phase change. In this workbook, power cycles that use a liquid will be analysed, and because of the high temperatures, these liquids will likely involve a phase change.

2.1.2 Second Law of Thermodynamics with Heat Engines

The second law of thermodynamics is a series of observations that concerns the way things flow as time progresses forward. Typical observations are "water flows from high to low", and "heat flows from hot to cold". In the context of heat engines, however, the second law can be summed up as: **"No heat engine can be 100% efficient"**.

2.1.3 Carnot Cycle

The Carnot cycle is a theoretical heat engine design, that is meant to be the ideal operating system of a heat engine. It consists of four closed processes:

1-2: Fig.4.1 shows the first stage of the Carnot cycle, and its effect on the $T - s$ and $P - V$ diagram. As an isentropic system $\Delta Q = \Delta s = 0$.
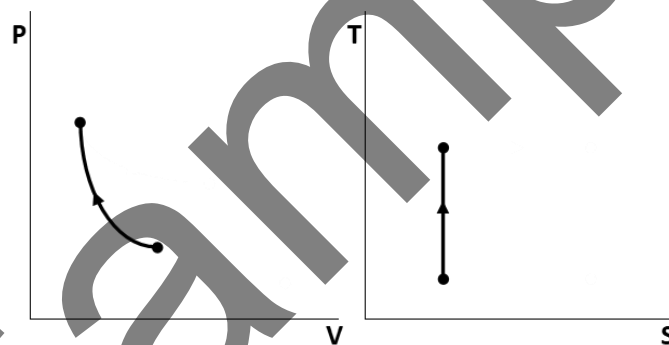

Figure 2.1: Stage 1-2 of the Carnot cycle

2-3: Fig.2.2 represents the second stage, the isothermal process means that there is a heat input, but the process also produces a work output.
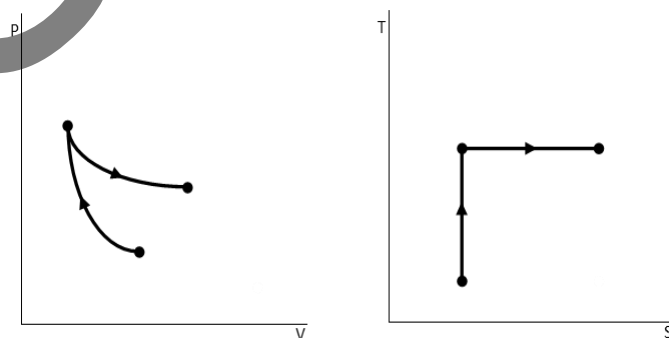

Figure 2.2: Stages 1-2-3 of the Carnot cycle

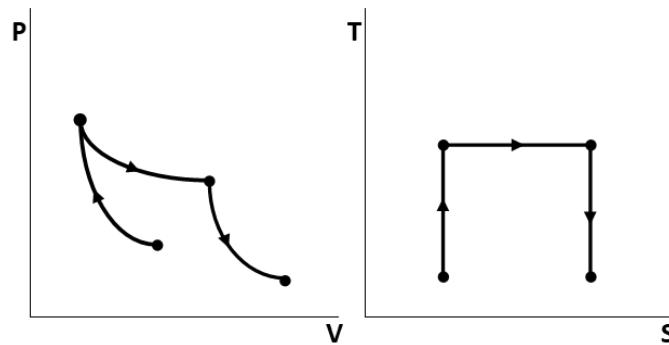**3-4:** Fig.2.3 shows the isentropic expansion of the system, as with stage 1-2, $\Delta Q = \Delta s = 0$.

Figure 2.3: Stages 1-2-3-4 of the Carnot cycle

4-1: The final stage, isothermal compression, completes the Carnot cycle, illustrated by Fig.2.4
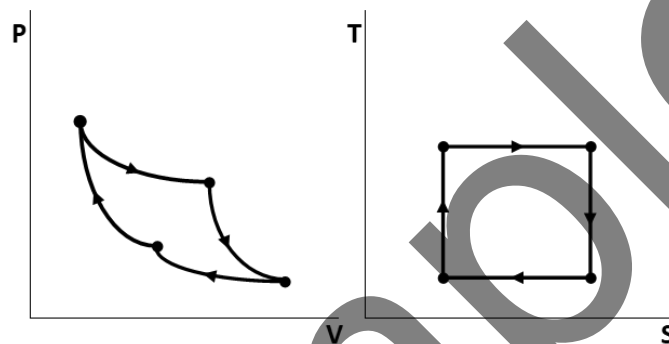

Figure 2.4: The complete Carnot cycle

We know, from the previous learning objectives, that $Q_{net} = W_{net}$, we can calculate the thermal efficiency of the system as Eq.2.1:

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{T_{cold}\Delta s_{cold}}{T_{hot}\Delta s_{hot}} \qquad \text{(Eq.2.1)}$$

Since $\Delta s_{cold} = \Delta s_{hot}$, then thermal efficiency can be reduced to Eq.4.2:

$$\eta_{th} = 1 - \frac{T_{cold}}{T_{hot}} \qquad \text{(Eq.2.2)}$$

This gives the **Carnot efficiency**, the ideal efficiency of an engine that cannot be attained in practical systems.

Example 1

What is the maximum possible efficiency of an engine where $T_{cold} = 50K$ and $T_{hot} = 320K$?

$$\eta_{th} = 1 - \frac{50}{320} = 0.844$$

Example 2

A claim that a new engine has been developed with a thermal efficiency of 75%. It draws in air at $10°C$ and its exhaust releases gas at $680°C$. Comment on whether a system such as this is possible.

Answer: **Remembering to convert the temperatures to K**

$$\eta_{th} = 1 - \frac{273 + 10}{273 + 680} = 0.703 = 70.3\%$$

The maximum possible efficiency is 70.3%, the claim cannot possibly be true.

2.1.3 Vapour Cycles

The most common fluid used in power cycles is water, due to its abundancy, price and chemical stability, and while open cycle steam engines are outdated and obsolete; closed cycle steam turbines are one of the largest contributions to electricity generation. A steam power generator is shown in Fig.2.5.
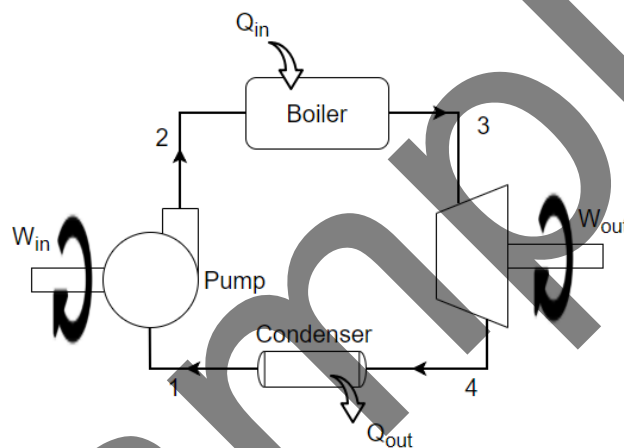

Figure 2.5: A steam power cycle

Starting at point 1 in Fig.2.5, water enters the pump to be compressed before it enters the boiler, where it is heated to steam (phase change) before moving to the turbine. The steam is then expanded in the turbine, which will output work to turn the shaft (which will be connected to a generator to produce electricity). The steam is then sent to the condenser, where it is turned back into water before moving back to the pump.

The advantages of using water/steam vapour systems compared to that of just gas is the higher energy density of the vapour, it also requires less work to increase the pressure of a liquid than a gas, meaning that less work is required at the pump. Together, amongst other factors, contributes to a higher thermal efficiency, closer to that of the Carnot cycle.

By using the steady flow energy equation (SFEE), and assuming that there is negligible change in Kinetic and Potential energy means that each process can be simplified to Eq.2.3.

$$q + w_x = h_{out} - h_{in} \qquad \text{(Eq.2.3)}$$

Applying Eq.2.3 to each process in the system, and assuming the turbine and pump are isentropic gives Eq.2.4 to 2.7.

$$q_{in} = h_3 - h_2 \qquad \text{(Eq.2.4)}$$

$$w_{out} = h_3 - h_4 \qquad \text{(Eq.2.5)}$$

$$q_{out} = h_4 - h_1 \qquad \text{(Eq.2.6)}$$

$$w_{in} = h_2 - h_1 \qquad \text{(Eq.2.7)}$$

Using Eq.2.8:

$$T ds = dh - v dP \qquad \text{(Eq.2.8)}$$

And the assumption that the pump is isentropic, Eq.2.8 simplifies to Eq.2.9.

$$dh = v dP \qquad \text{(Eq.2.9)}$$

Substituting Eq.2.9 into 2.5 gives Eq.2.10:

$$w_{in} = \int_1^2 v dP \qquad \text{(Eq.2.10)}$$

In the case of a vapour power cycle, the working fluid will often stay in the liquid phase throughout the compression stage. If this is the case, then the specific volume is small enough to neglect and Eq.2.10 simplifies further to Eq.2.11.

$$w_{in} = v(P_2 - P_1) \qquad \text{(Eq.2.11)}$$

The thermal efficiency of the heat engine is given as Eq.2.12:

$$\eta_{th} = \frac{w_{out} - w_{in}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{1_{out}}{q_{in}} \qquad \text{(Eq.2.12)}$$

2.1.4 Whole Plant Efficiency

While the thermal efficiency of the heat engine has been calculated, this is not the overall efficiency of the plant. Taking a closer look into the boiler in Fig.2.6, q_{in} is dependent on the heat transfer between the combustion products and the working fluid. So, the efficiency of the boiler also needs to be calculated.
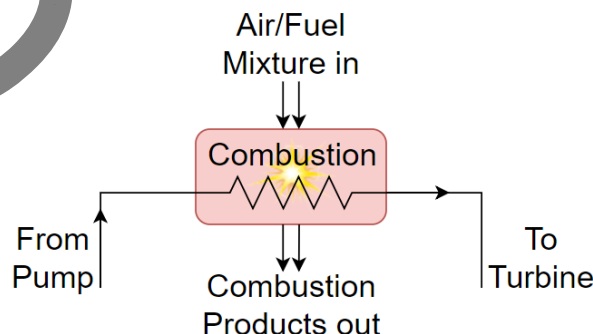

Figure 2.5: An expanded view of a power plant boiler

Calculating the efficiency of the boiler requires analysing the *ideal* boiler and the *real* boiler.

2.1.4.1 Ideal Boiler

The ideal boiler assumption is that the fuel and air enter the boiler at the standard state temperature $T_0 = 25°C$, and once complete combustion occurs the products leave the boiler at $25°C$. From the SFEE, the heat into the cycle for an ideal scenario is given as Eq.2.13, where $h_{a|0}$, $h_{f|0}$ and $h_{p|0}$ are the enthalpies at $25°C$.

$$\dot{Q}_{in|ideal} = \dot{m}_f h_{f|0} + \dot{m}_a h_{a|0} - (\dot{m}_a + \dot{m}_f)h_{p|0} = \dot{m}_f[-\Delta H_0] \qquad \text{(Eq.2.13)}$$

Under these conditions, the heat in per unit mass is simplified to the Lower Calorific Value ($LCV = -\Delta H_0$) of the fuel.

2.1.4.2 Real Boiler

The real boiler does not assume that the products of combustion leave the boiler at $25°C$ and instead leave at a higher temperature $T_{exhaust}$, the heat into the system is calculated as Eq.2.14:

$$\dot{Q}_{in|real} = \dot{m}_f h_{f|0} + \dot{m}_a h_{a|0} - (\dot{m}_a + \dot{m}_f)h_{p|exhaust} \qquad \text{(Eq.2.14)}$$

The equation no longer simplifies to the LCV, this is because some of the heat produced is used to warm the unburnt air in the boiler to $T_{exhaust}$, instead of all the heat moving into the working fluid of the heat engine. The efficiency of the boiler is given as a ratio of heat in under the real condition to the heat in under the ideal condition. The boiler efficiency is given as Eq.2.16, where AFR is the air-fuel ratio that is put into the boiler and $c_{p|p}$ is the specific heat for constant pressure of the products.

$$\eta_B = \frac{\dot{Q}_{in|real}}{\dot{Q}_{in|ideal}} = \frac{\dot{Q}_{in|real}}{\dot{m}_f[-\Delta H_0]} = 1 - \frac{AFR + 1[h_{p|exhaust} - h_{p|0}]}{[-\Delta H_0]}$$

$$\cong 1 - \frac{c_{p|p}(AFR+1)(T_{exhaust}-T_0)}{[-\Delta H_0]} \qquad \text{(Eq.2.15)}$$

The overall efficiency of the plant can be calculated as Eq.2.16:

$$\eta_{plant} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{m}_f[-\Delta H_0]} = \eta_{th}\eta_B \qquad \text{(Eq.2.16)}$$