

# ENV321: Energy and the Environment

## Practical 2

### Thermodynamic Cycles

Tim Cockerill  
November 1999

#### 1.0 Introduction

During the latter part of semester 1, we have looked at a range of energy technologies and talked about the thermodynamic cycles that underlie their operation. The objective of this practical is to encourage you to think a little more about these cycles, and thereby enhance your understanding of them.

As a secondary objective, you will investigate how the performance of the technologies depends on certain parameters. We have seen the environmental effects of energy technologies depend on their design, both through a link with efficiency and therefore the quantity of resources consumed in producing energy, and through a link with combustion conditions and thence the nature of any pollutants produced.

During the practical you will investigate and compare four energy technologies:

- A gas turbine - operating on the JOULE cycle;
- A thermal power station operating on the RANKINE cycle;
- A petrol engine - operating on the OTTO cycle;
- A diesel engine - operating on the DIESEL cycle .

You will perform parameter studies using a specially prepared spreadsheet for each of the systems above. In most cases you will be asked to identify an optimum configuration for a given set of conditions.

You should note that this practical takes these subjects a little beyond what is strictly required in the course. You should not focus on the details of the numerical work involved. Instead you should concentrate on ensuring that you understand the principles of the technologies involved, and regard this practical as an exercise to help you think about the concepts. Another important lesson should be that there are a wide range of trade-offs to be balanced in the design of energy technologies - technical, economic, environmental, and practical.

## 2.0 Learning Outcomes

At the end of this practical session, in combination with the appropriate lectures, you should:

- a) be able to outline the thermodynamic principles that underlie thermal power stations, gas turbines, petrol engines and diesel engines;
- b) be able to estimate the efficiency of the energy technologies in (a);
- c) be able to explain how the efficiency of the energy technologies in (a) depends upon a range of factors;
- d) be able to outline, in broad terms, the importance of efficiency for the technical, economic and environmental performance of energy technologies;
- e) be better able to perform and interpret sensitivity studies.

## 3.0 The Thermodynamic Cycles Spreadsheet

The practical is carried out with the ENV321 Thermodynamic Cycles Spreadsheet. This spreadsheet runs under Microsoft Excel, and can be found on drive U: of the student fileserver under directory \APPS\INFO\TIM\_C\ENV321\PRAC2 with filename prac2.xls.

Start up Excel and open the spreadsheet. As with the economic spreadsheet in practical 1, the workbook consists of a number of connected worksheets, each dealing with a separate technology.

Select the worksheet labeled "Gas Turbine". This sheet performs calculations for gas turbine systems, and is shown in figure 1. We will discuss gas turbines later, as for now the objective is to teach you how to use the sheet.

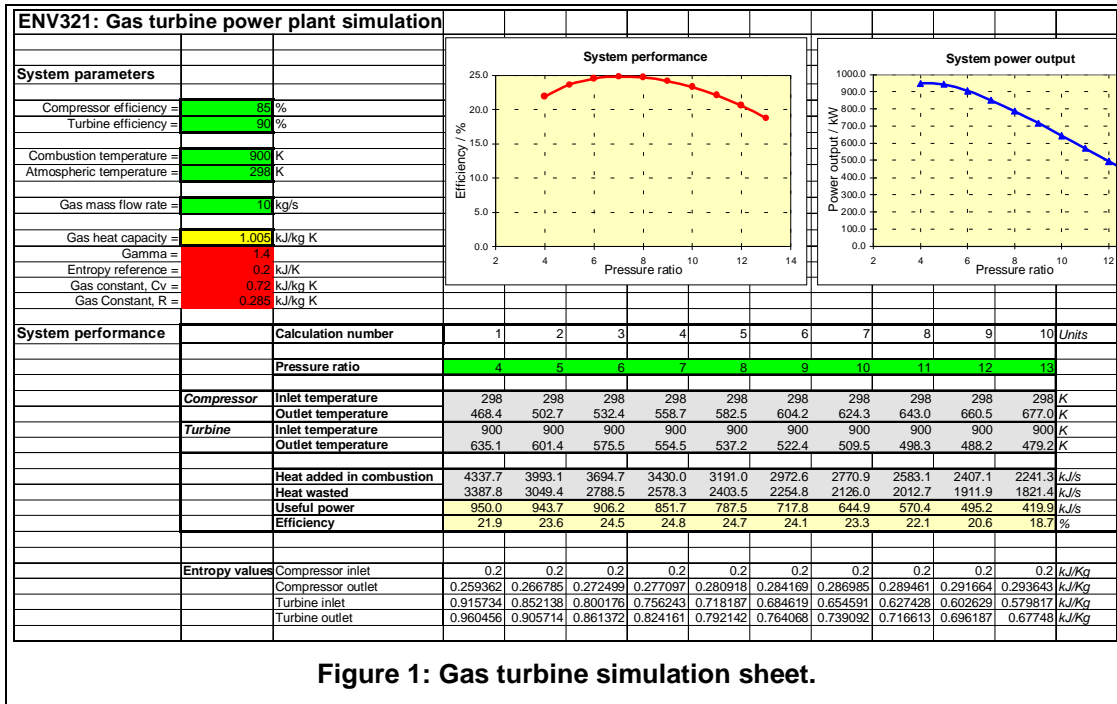


Figure 1: Gas turbine simulation sheet.

At the top left of the sheet is an area labeled "System Parameters". This contains characteristic values that influence the overall performance of the system. We will not use all of these parameters today, and those that you will need to change are highlighted in green. Be careful not to alter cells highlighted in red unless you are sure you know what you are doing.

Below the system parameters area is a region labeled "System Performance". Each column in this table represents a separate gas turbine calculation, based both on the system parameters and on information specified in the column. Once again, areas for you to change are highlighted in green, with the more important results from the calculation highlighted in yellow. There are a number of graphs scattered around the sheet which are intended to be self-explanatory and are produced automatically from data in the tables.

There are three other worksheets in the workbook that you will use:

- Otto (Petrol Engine)
- Diesel
- Rankine (Thermal Power Plant)

All are structured in a similar manner to the Gas Turbine sheet, although of course the information they contain varies.

The remaining worksheets contain information that is used for various aspects of the calculations. You are welcome to look at these sheets if you like, but do not change any of the information they contain, or you may break the calculations.

#### 4.0 The Petrol Engine - Otto cycle

We will begin by looking at the thermodynamic cycle with which you probably have most contact on a day to day basis - the Otto cycle [1] which models the performance of a petrol engine.

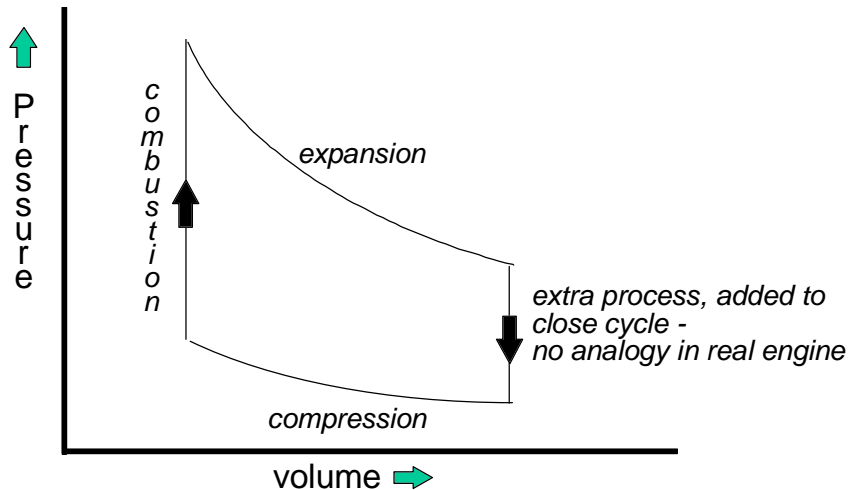


Figure 2: The Otto Cycle.

The pressure/volume diagram for the Otto cycle is shown in Figure 2. You should be able to identify the lines on the diagram that are associated with the compression and power strokes of a 4 stroke petrol engine. Note that the Otto cycle is not a very precise model of the engine and it is not possible to associate lines with the induction and exhaust strokes.

Set up the system parameters to model an engine specified as in Table 1:

Parameter	Value	Units
Atmospheric temperature	298	K
Atmospheric pressure	101325	Pa
Calorific value of fuel	44430	kJ/kg
Air/fuel ratio	18	by mass
Number of cylinders	4	
Cylinder capacity	0.25	l
Gamma (air)	1.4	
Cv (air)	0.72	kJ/kgK

Table 1: Petrol engine parameters.

For the calculations, use a throttle setting of 100% and an engine speed of 5000 r.p.m.

According to the Otto cycle model, the efficiency of a petrol engine depends mostly on the compression ratio, defined as

$$r_v = \frac{\text{volume of air inlet to cylinder}}{\text{volume of air after compression}}$$

according to the relationship

$$\text{Efficiency} = 1 - \frac{1}{r_v^{0.4}}$$

Use the spreadsheet to investigate how the engine efficiency varies with compression ratios in the range 2-11.

Which provides the best efficiency? \_\_\_\_\_.

Check that you can use the efficiency formula to calculate this efficiency manually \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Now investigate how the maximum temperature reached in the cylinder depends on the compression ratio.

At which compression ratio is the maximum temperature reached \_\_\_\_\_, and at which point in the operating cycle? \_\_\_\_\_.

What would be the effects on the overall engine emissions (per unit of energy output) of operating at a compression ratio that gives a high efficiency in comparison to operating at a lower compression ratio?

1. \_\_\_\_\_
- \_\_\_\_\_
2. \_\_\_\_\_
- \_\_\_\_\_

What might be the effects on the economic performance of the engine (in terms of annuitised life cycle cost per unit of useful energy produced) of operating at a compression ratio that gives a high efficiency in comparison to operating at a lower ratio?

1. \_\_\_\_\_
- \_\_\_\_\_
2. \_\_\_\_\_
- \_\_\_\_\_

Use the spreadsheet to examine the effect of the following on the engine power output:

- changing the calorific value of the fuel \_\_\_\_\_.
- changing the air/fuel ratio \_\_\_\_\_.
- changing the cylinder capacity \_\_\_\_\_.

What might be the effect of the above on the emissions produced by the engine

changing the calorific value of the fuel \_\_\_\_\_.

changing the air/fuel ratio \_\_\_\_\_.

changing the cylinder capacity \_\_\_\_\_.

## 5.0 The Diesel Cycle

The Diesel cycle is of course a thermodynamic cycle that models processes in the Diesel engine. Its pressure/volume diagram is shown in Figure 3.

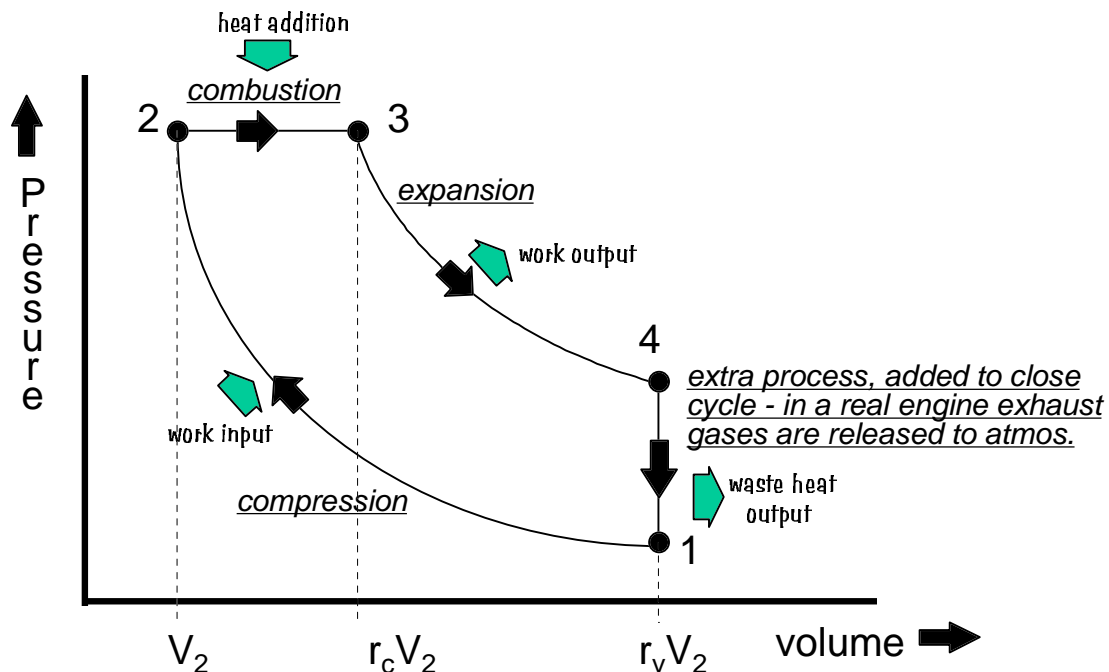


Figure 3: The Diesel cycle.

Again, you should be able to associate lines on the diagram with the compression and power strokes of the Diesel engine. The association between the other lines on the diagram and physical processes in the engine is not as clear, which is why the Diesel cycle is only a very approximate model of the Diesel engine.

The Diesel cycle can be used to show [2] that the efficiency of a Diesel engine depends on two parameters, both marked on Figure 3:

- The compression ratio  $r_v$ , which has the same meaning as for the petrol engine, and
- the so called “cut-off” ratio  $r_c$ , which is a rather contrived value related to the combustion processes within the engine.

The compression ratio is defined as

$$r_v = \frac{\text{volume of air inlet to cylinder}}{\text{volume of air after compression}}$$

and the cut -off ratio is

$$r_c = \frac{\text{volume of air at point 3 (after combustion)}}{\text{volume of air after compression}}$$

Using these definitions the efficiency of the Diesel engine is given by:

$$\eta = 1 - \frac{1}{r_v^{0.4}} \left[ \frac{r_c^{1.4} - 1}{1.4(r_c - 1)} \right]$$

Switch to the Diesel engine simulation spreadsheet and set up the system parameters to model a Diesel engine with the specifications in Table 2

Parameter	Value	Units
<b>Air properties</b>		
gamma (air)	1.4	
Cp (air)	1.01	kJ/kgK
Air density	1.01	kg/cu.m
Atmos. pressure	101325	Pa
Atmos. temp	298	K
<b>Engine parameters</b>		
Cut off ratio	3	
Cylinder volume	0.5	litres
Number of cylinders	4	
Engine speed	3000	rpm
2 or 4 stroke	4	

**Table 2: System parameters for the Diesel engine simulation.**

Investigate how the engine efficiency and power output varies with compression ratios between 5 and 14.

Which provides the best efficiency? \_\_\_\_\_.

What is this efficiency? \_\_\_\_\_.

What is the power output of the engine at this compression ratio? \_\_\_\_\_.

Look now at how the temperature in the cylinder after combustion varies with compression ratio. What might be the effect of increasing the compression ratio on the engine emissions per unit of useful energy output? \_\_\_\_\_.

\_\_\_\_\_.

### 6.0 Thermal Power plant - The Rankine Cycle

Next, we will examine the Rankine cycle [1] which underlies almost all thermal power stations, be they fossil or nuclear powered. We will focus mainly on how the efficiency of the Rankine cycle depends on the pressure in the boiler and the pressure in the condenser, but we will also consider how other factors within the equipment might be important.

The flow diagram for the Rankine cycle is shown, with appropriate energy

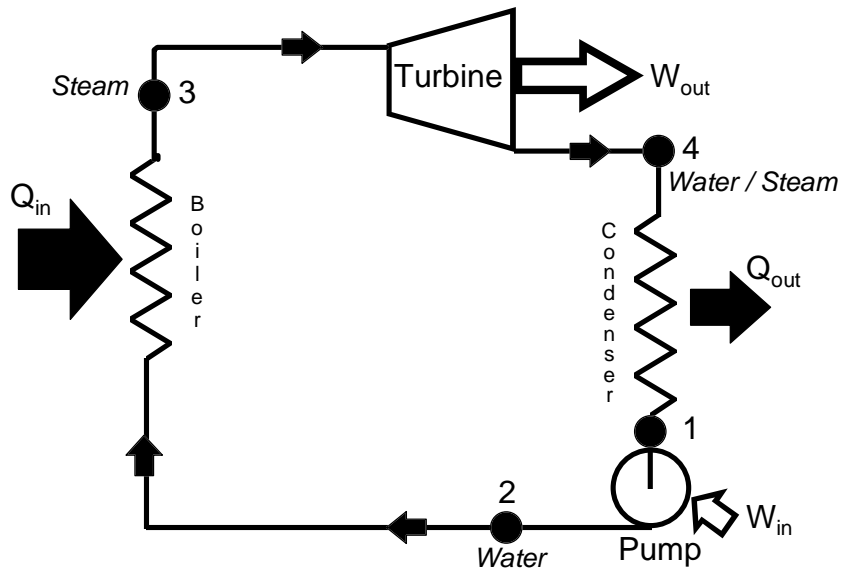


Figure 4: Flow diagram for the Rankine Cycle.

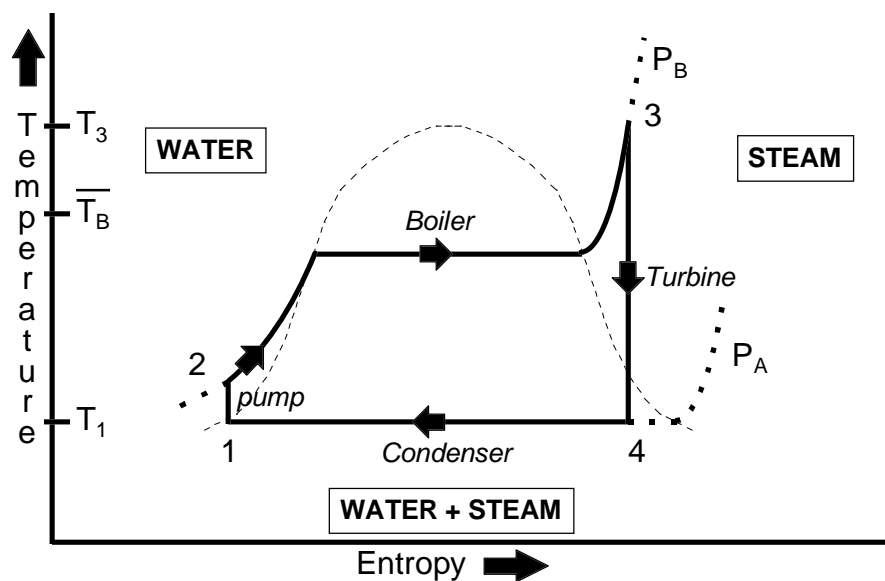


Figure 5: T-S Diagram for the Rankine Cycle.

transfers, in Figure 4. A Temperature-Entropy diagram is provided in Figure 5. In this case, unlike with the Otto and Diesel cycles, the Rankine cycle is good model of reality, and every component on the flow chart can be matched to processes on the T-S diagram. Ensure you can match the components in Figure 4 with the cycle lines in Figure 5.

We can easily write an energy balance for our thermal power station, and you should be able to work out that:

$$Q_{in} + Q_{out} = W_{out}$$

if we assume we can neglect the work input to the pump.

You should also be able to see that the efficiency of the power station would be given by the ratio of the useful work output to the heat input from combustion or from the nuclear reactor, i.e.

$$\eta = \frac{W_{out}}{Q_{in}}$$

If we were to measure both the heat input to the power station, e.g. by working out the rate of fuel consumption, and the useful work output e.g. by looking at the power output of the generator, we could work out the efficiency of our power station. The Rankine cycle spreadsheet you will be using works efficiencies out like this - by simulating the behaviour of a “real” rankine cycle power station and by “measuring” the heat input and work output. In other words, the spreadsheet deals with measure efficiencies.

You may recall from lectures we said that the Second Law of Thermodynamics dictates that the physical maximum efficiency of a thermodynamic cycle is given by:

$$\eta_{max} = 1 - \frac{T_{cold}}{T_{hot}}$$

where  $T_{hot}$  is the highest temperature reached in the cycle (“temperature of heat addition”), and  $T_{cold}$  is the lowest temperature (“temperature of heat rejection”). To apply this expression to a Rankine cycle we had to modify the expression to:

$$\eta_{RANK} = 1 - \frac{T_1}{\bar{T}_B}$$

where  $T_1$  is atmospheric temperature and  $\bar{T}_B$  is the average temperature in the boiler. You should note that this efficiency is distinct from the “measured efficiency” described above, although in some cases the two can be close in value.

Switch to the Rankine cycle spreadsheet, and set the system parameters to model a Rankine cycle powerstation with the parameters in Table 3.

Parameter	Value	Units
Pump efficiency	100	%
Turbine efficiency	100	%
Steam mass flow rate	600	kg/s

**Table 3: System parameters for Rankine Cycle.**

Set the condenser pressure in every column to 0.004 MPa, and then do a parameter study to found out how the efficiency and power output varies with boiler pressures in the range 7MPa to 16MPa (take steps of 1MPa).

What is the maximum efficiency achieved? \_\_\_\_\_

What Boiler pressure is it achieved at? \_\_\_\_\_

What is the power output of the station under these conditions? \_\_\_\_\_

For the conditions of maximum efficiency you have identified, what is the power input required by the pump? \_\_\_\_\_

Does it seem to be a reasonable assumption to ignore the power input required by the pump in comparison to the power output of the entire power station? \_\_\_\_\_

Check that the power station obeys the first law of thermodynamics, and that all the energy is fully accounted for. We already have the useful power output, and pump work input for the case giving maximum efficiency, so determine:

The boiler heating power \_\_\_\_\_

and, the heat rejection rate \_\_\_\_\_

First, work out the net rate of heat transfer to the station, which is equal to the boiler heating power added to the rate of heat rejection (NB this latter term is negative because heat is leaving the power station). This gives: \_\_\_\_\_  
 \_\_\_\_\_ (value1).

Now work out the net rate of work transfer to the station. This gives \_\_\_\_\_  
 \_\_\_\_\_ (value2).

(Note: Treat work coming out of the power station as positive, and work going in as negative)

Is the first law satisfied? Are values 1 and 2 equal? \_\_\_\_\_.

Take a look at the enthalpy and entropy values listed for the conditions of maximum efficiency. Note them for future reference \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Now investigate the effect that small changes in the condenser pressure have on the efficiency of the power station. Try changing the condenser pressure for the calculation that gave maximum efficiency above. Use condenser pressures of 0.002, 0.003, 0.005, and 0.006 MPa. *What effect do these changes have?* \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_.

*What effect would reducing the condenser pressure have on the emissions from the power station, per unit of energy produced?* \_\_\_\_\_  
\_\_\_\_\_.

*What constrains the lowest possible condenser pressure in a real power station?* \_\_\_\_\_  
\_\_\_\_\_.

Now return all the condenser pressures to 0.004 MPa.

So far, we have been working with a Rankine cycle using a turbine with an efficiency of 100% - in other words a reversible turbine that does not introduce any entropy into the system. Any real turbine will have an efficiency of less than 100%, so let's look at the effect of reducing the turbine efficiency (in the system parameters) to 90%.

For the configuration that gives maximum overall efficiency, what is:  
*the overall efficiency?* \_\_\_\_\_  
*the power output?* \_\_\_\_\_

*How do these compare with the values obtained using a turbine efficiency of 100%?* \_\_\_\_\_  
\_\_\_\_\_.

*Now note down the enthalpy and entropy values for the configuration that gives maximum overall efficiency* \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_.

*How do these values compare with those obtained using a 100% efficient turbine?* \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_.

What do you think might limit the efficiency of turbines used in practice?\_\_

---

---

## 7.0 Gas Turbines - The Joule Cycle

This part of the practical will investigate how the overall efficiency of a gas turbine system depends on:

- The pressure ratio of the system
- The individual efficiencies of the turbine and compressor

The flow diagram and temperature-entropy diagram for a gas turbine working on the Joule cycle [1] are shown in Figure 6 and Figure 7 respectively.

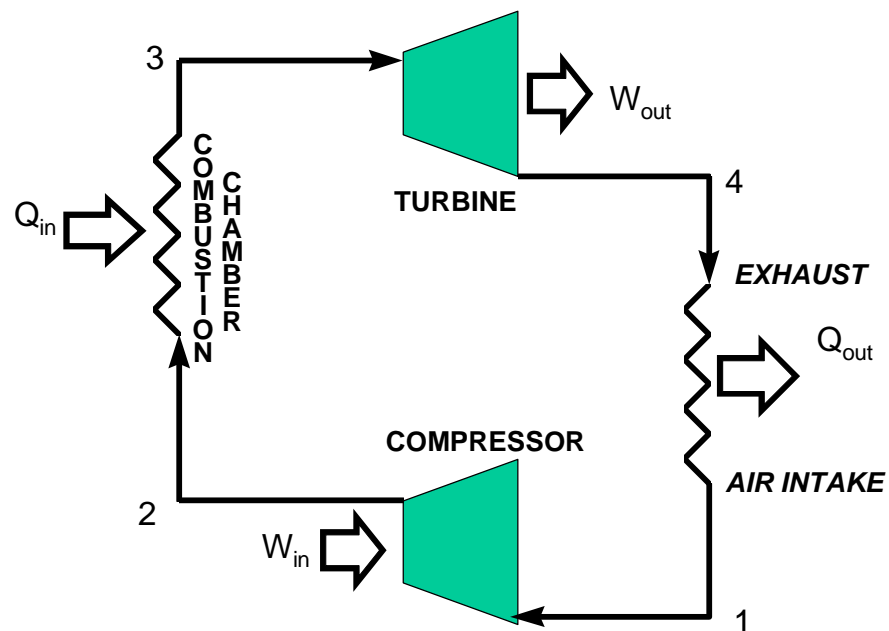
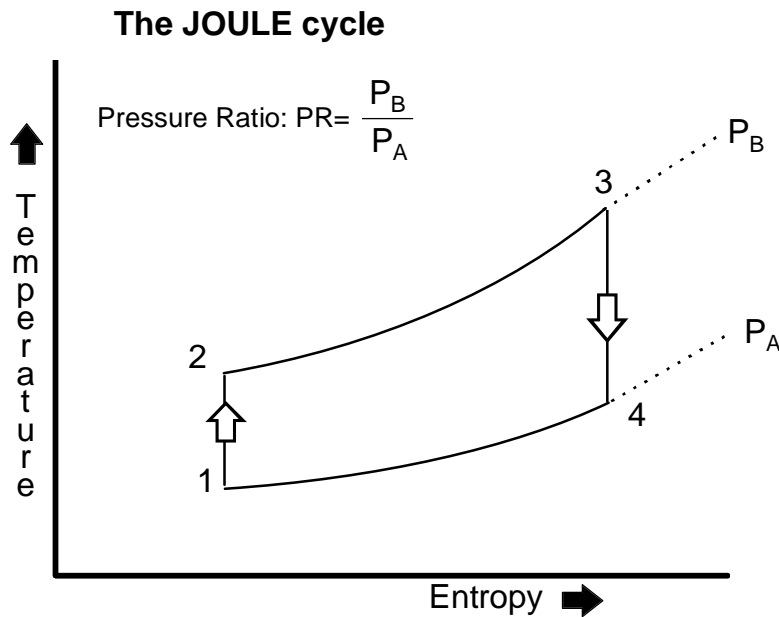


Figure 6 : Flow diagram for a gas turbine.



**Figure 7: T-S Diagram for the Joule cycle employed by the Gas Turbine.**

As with the Otto and Diesel cycles, one of the processes in the cycle is only loosely related to a real gas turbine. In this case it is process 4-1. In a real gas turbine this would be where the combustion products are exhausted to the atmosphere and fresh air and fuel brought into the system. However, to turn the process into a cycle, the Joule cycle pretends that the waste heat in the exhaust gases is got rid of to the environment and that by some magical means the exhaust gases are turned back into fresh air and fuel. This assumption makes the analysis of the Joule cycle easier and has a negligible effect on the results of the calculations.

The processes in the combustion chamber, between nodes 2 and 3, are also simplified, although to a lesser extent. In a real gas turbine, the fuel is burnt in the combustion chamber to convert its stored chemical energy into thermal energy and thence raise the temperature and enthalpy of the gas flowing through the system. Rather than model these complex combustion processes, we treat the combustion processes as though heat was added to the flowing gases from outside of the system. The amount of heat added per kilogramme of flowing gas is taken to be equal to the energy that would be released by combustion, per kilogramme of flowing gas. This simplification makes no difference to the results calculations, but makes them easier to do.

The overall efficiency of a gas turbine system, with a reversible (100% efficient) turbine and compressor is given by

$$\eta = 1 - \frac{1}{(\text{P.R.})^{0.286}}$$

where P.R. is the ratio of the pressures in the combustion chamber ( $P_B$ ) to the lowest pressure in the cycle ( $P_A$ , often atmospheric pressure).

Now switch to the gas turbine section of the spreadsheet. Set the system parameters as follows:

Parameter	Value	Units
Compressor efficiency	100	%
Turbine efficiency	100	%
Combustion temperature	900	K
Atmospheric temperature	298	K
Gas mass flow rate	10	kg/s
Gas heat capacity	1.005	kJ/kg K
Gamma	1.4	
Entropy reference	0.2	kJ/K
Gas constant, Cv	0.72	kJ/kg K
Gas Constant, R	0.285	kJ/kg K

Notice that we have set the individual efficiencies of the turbine and compressor to 100%, in other words we are assuming that these components do not generate any entropy.

Investigate how the efficiency of the gas turbine system varies between pressure ratios of 5 and 14. *Can you find an optimum pressure ratio, that produces maximum efficiency?* \_\_\_\_\_  
*What is this maximum efficiency?* \_\_\_\_\_  
*What is the system power output at the pressure ratio?* \_\_\_\_\_  
*What is the maximum power output of the system?* \_\_\_\_\_

Take a look at the T-S diagram lower down the spreadsheet, which is plotted for the first calculation column in the sheet. Compare it to the sketch diagram in Figure 7, noting that the spreadsheet is only able to plot straight lines and cannot reproduce the curves in the sketch. *Investigate the effect of changing the pressure ratio (in the first calculation column) on the T-S diagram* \_\_\_\_\_

\_\_\_\_\_

Now let's set the individual efficiencies of the turbine and compressor to a more realistic 90% for the former and 80% for the latter.

*What effect does this have on the optimum efficiency?* \_\_\_\_\_

*What effect would this in turn have on the fuel consumption of the gas turbine and therefore on the level of emissions from a power plant?* \_\_\_\_\_

\_\_\_\_\_

How does the maximum power output of the plant differ from the previous case? \_\_\_\_\_

How does the T-S diagram differ with these new component efficiencies? \_\_\_\_\_

Why does it differ in this way? \_\_\_\_\_

Now try increasing the combustion temperature by 200 K. How does the optimum efficiency differ now? \_\_\_\_\_

Investigate with further parameter studies the effect that other component efficiencies and combustion temperatures would have on the performance (power output and overall efficiency) of a gas turbine? \_\_\_\_\_

\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

## 8.0 Questions to consider

Before finishing the practical, let's re-cap on the learning objectives.

8.1 Can you outline the principles that underlie:

- A Diesel Engine \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
- A Petrol Engine \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
- A Gas turbine \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
- The Rankine cycle \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

8.2 Can you write down, or calculate, an estimate of the efficiency for

- A Diesel Engine \_\_\_\_\_
- A Petrol Engine \_\_\_\_\_
- A Gas turbine \_\_\_\_\_
- The Rankine cycle \_\_\_\_\_

8.3 Can you explain briefly what parameters influence the efficiency of the following technologies, and perhaps give an indication of how they effect the efficiency:

- The Petrol Engine \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
- The Gas Turbine \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
- The Thermal Power Station \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

8.4 What are some of the major differences between a petrol and a Diesel engine? \_\_\_\_\_

---

---

---

---

8.5 What in broad terms is the importance of efficiency for the technical, economic and environmental performance of energy technologies \_\_\_\_\_

---

---

---

---

---

---

## 9.0 References

1. Culp A.W.; *Principles of Energy Conversion (2nd Edition or later)*; McGraw-Hill International ISBN 0-07-100991-4; Hutton Library Shelf Ref: HB 621.47 C84
2. Stone, R, *Introduction to Internal Combustion Engines*, section 2.2.2, pp.28-31; Macmillan, Second Edition 1992, ISBN 0-333-55084-6.