Unit 14: Principles and Applications of Thermodynamics

NQF Level 3: BTEC National

Guided learning hours: 60

Unit abstract

We are reliant on fossil and nuclear fuels for the majority of our energy needs and this is likely to be the case for many years to come. It is also likely that resources will become more scarce and that we shall have to use them more efficiently. In addition to this, it is becoming apparent that the use of fossil fuels is contributing to global warming, giving further cause for increased fuel efficiency.

Fossil and nuclear fuels provide heat energy which is in turn converted into useful mechanical and electrical energy. Thermodynamics is the study of heat energy production, its transfer and conversion into more useful forms.

The aim of this unit is to introduce learners to the basic concepts and principles of work and heat transfer and their application. The basic laws concerned with the expansion and compression of gases and associated heat and work transfer will be introduced. These will then be then applied to quantify the heat and work transfer that occurs in closed and open thermodynamic systems.

The combustion of fuels will be examined and methods of determining calorific value explained. Learners will be introduced to the properties of steam as a working substance and to the use of thermodynamic property tables. These will then be used to determine heat and work transfer in steam-generating plant.

Learning outcomes

On completion of this unit a learner should:

1 Be able to apply thermodynamic principles to the expansion and compression of gases

2 Be able to quantify energy transfer in thermodynamic systems

3 Know about combustion processes and the calorific value of fuels

4 Be able to quantify energy transfer in steam plant.

Unit content

1 **Be able to apply thermodynamic principles to the expansion and compression of gases**

Polytropic processes: process parameters and relationships eg absolute pressure, absolute temperature, volume, universal gas constant, molecular weight, characteristic gas constant, general gas equation ($pV/T = Constant$), characteristic gas equation ($pV = mRT$), polytropic process equation ($pV^n = Constant$), value of 'n' for isobaric processes ($n = 0$), isothermal processes ($n = 1$), adiabatic processes ($n = \gamma$)

2 **Be able to quantify energy transfer in thermodynamic systems**

Closed thermodynamic systems: work transfer eg general expression for a polytropic process, isothermal work transfer; heat transfer eg specific heat capacities at constant volume and constant pressure, application of first law of thermodynamics, expression for change of internal energy, closed system energy equation, relationship between system constants c_v, c_p, γ and R; systems eg internal combustion engine cylinders, positive displacement compressors

Open thermodynamic systems: work transfer eg general expression for a polytropic process, isothermal work transfer; heat transfer eg application of first law of thermodynamics, expression for change of enthalpy, open system energy equation; systems eg gas turbines, rotary compressors, coolers

3 **Know about combustion processes and the calorific value of fuels**

Combustion process: stoichiometric equations for complete combustion of fuel elements eg hydrogen ($2H_2 + O_2 = 2H_2O$), carbon ($C + O_2 = 2CO_2$), sulphur ($S + O_2 = SO_2$), theoretical air requirements, products of combustion

Calorific value: determination of calorific value eg Schole's bomb type calorimeter to determine gross calorific value of solid fuels and fuel oil, Boys' gas type calorimeter to determine gross and net calorific value of gaseous fuels

4 **Be able to quantify energy transfer in steam plant**

Steam plant: heat and work transfer in major steam plant elements eg boiler, superheater, turbine, condenser, thermal efficiency of elements; conditions eg feed water temperature, steam temperatures and pressures, dryness fraction, steam flow rate, fuel consumption rate, power output; use of thermodynamic property tables to determine enthalpy values eg feed water, saturated water, wet steam, dry saturated steam, superheated steam

Throttling process: use of simple throttling calorimeter to determination dryness fraction of wet steam

Grading grid

In order to pass this unit, the evidence that the learner presents for assessment needs to demonstrate that they can meet all of the learning outcomes for the unit. The criteria for a pass grade describe the level of achievement required to pass this unit.

Grading criteria		
To achieve a pass grade the evidence must show that the learner is able to:	**To achieve a merit grade the evidence must show that, in addition to the pass criteria, the learner is able to:**	**To achieve a distinction grade the evidence must show that, in addition to the pass and merit criteria, the learner is able to:**
P1 determine the mass of a gas and its final condition parameters after undergoing a given polytropic process P2 determine the work and heat transfer during a thermodynamic process in a closed system P3 determine the rate of work and heat transfer during a thermodynamic process in an open system P4 use stoichiometric equations to determine the theoretical mass of air required for complete combustion of a given mass of fuel P5 determine the gross calorific value of a solid or liquid fuel from given test data obtained using a bomb type calorimeter	M1 determine the polytropic process index '*n*' from the initial and final condition parameters of a gas M2 determine the specific heat capacities at constant volume c_v, and constant pressure c_p, for a gas from given values of the adiabatic index γ, the universal gas constant and its molecular weight M3 determine the gross and net calorific values of a gaseous fuel from given test data obtained using a Boys' gas type calorimeter M4 determine the efficiency of a boiler from given feed water and output steam conditions and the fuel consumption rate.	D1 evaluate and compare the work and heat transfer that occurs when a fixed mass of gas undergoes a given increase in volume according to Boyle's law and according to Charles' law from the same initial conditions D2 prepare a complete analysis by mass of the products of combustion when unit mass of a given fuel is completely burned with an excess air supply.

Grading criteria

To achieve a pass grade the evidence must show that the learner is able to:	To achieve a merit grade the evidence must show that, in addition to the pass criteria, the learner is able to:	To achieve a distinction grade the evidence must show that, in addition to the pass and merit criteria, the learner is able to:
P6 determine the rates of heat transfer in a boiler and superheater from given feed water and output steam conditions and steam flow rate P7 determine the thermal efficiency of a steam turbine from given input and output steam conditions, steam flow rate and power output P8 determine the dryness fraction of a steam sample from test data obtained using a simple throttling calorimeter.		

Essential guidance for tutors

Delivery

There is some overlap between learning outcome 1 of this unit and *Unit 6: Mechanical Principles and Applications*. Unless the units are delivered consecutively, some time will be required to revise this material and revisit problems involving use of the general and characteristic gas equations. The general gas constant and concept of the kilogram-molecule can then be considered and used to determine values of the characteristic gas constant for common gases.

Learners should be made aware of the range of polytropic processes by which the expansion and compression of a gas can occur. In introducing the polytropic process equation $pV^n = Constant$, it should be explained that the value of the index 'n' is dependent on the extent and direction of the heat transfer taking place. The values of the index for isobaric, isothermal and adiabatic processes should be identified. Problems on the expansion and compression of gases with a higher degree of complexity can then be considered. If time permits and the facilities are available, it might be profitable to demonstrate determination of the adiabatic index γ, for air, using Clement and Desormes' method.

Delivery of learning outcome 2 could start with the definition of closed and open thermodynamic systems. Integral calculus should be applied to derive the general expression for work transfer in a closed system together with the particular expression for an isothermal process. Definition of the specific heat capacities of a gas at constant volume c_v, and constant pressure c_p, can be given followed by the concept of internal energy.

The first law of thermodynamics can then be introduced and applied to derive the expression for heat transfer during a thermodynamic process in a closed system and the expression for change of internal energy. It might be appropriate at this point to show proof of the relationships $R = c_p - c_v$ and $\gamma = c_p / c_v$ from a consideration of isobaric and adiabatic expansion in a closed thermodynamic system. Some time may then be spent on the solution of closed system problems that involve the calculation of work and heat transfer.

Consideration of open thermodynamic systems could start with derivation of the general expression for work transfer and comparison with that obtained for a closed system. It should be explained why the particular expression for isothermal work transfer is the same for closed and open systems. The concepts of pressure-flow energy and enthalpy can then be introduced followed by application of the first law of thermodynamics to derive the full steady flow energy equation. Neglecting potential and kinetic energy terms will then provide the expression for heat transfer in an open system. Some time may then be spent on the solution of open system problems that involve the calculation of work and heat transfer rates.

The delivery sequence for learning outcomes 3 and 4 is a matter of personal preference. Ideally, the consideration of calorific value in learning outcome 3 should be reinforced by practical investigations but it is unlikely that many centres will have the range of equipment required. This being the case, the apparatus and experimental procedure should be described and exemplary data presented to enable calculation of calorific value for a range of common fuels.

It is likely that learners will have scant knowledge of chemistry and some time will probably be required to explain the reason why certain elements have an affinity for oxygen resulting in an exothermic reaction. In particular, its combination with hydrogen, carbon and sulphur should be explained and their calorific values compared. The basic chemical reaction equations may then be applied to determine the theoretical amount of oxygen and air required for complete combustion of a given mass of fuel, whose constituents are known. Problems should also include analysis of the products of combustion, including excess oxygen and nitrogen from the air supply and any incombustible constituents.

Delivery of learning outcome 4 should start with an explanation of the terminology used in steam generation. The major elements in a steam generating plant should be described and a visit to an electricity generating station would be of value. It should be explained that the steam generating circuit is in theory a closed system, made up of a number of linked open systems. The general open system energy equation derived in learning outcome 2 may be applied separately to these, but it should be explained that the enthalpy values are now obtained from thermodynamic property tables. Some time will be required to explain the layout of the tables and the notation used.

Problems on work and heat transfer in steam plant elements can then be considered. Delivery of learning outcome 4 might be concluded with an explanation of the throttling process and use of the simple throttling calorimeter to determine the dryness fraction of a wet steam sample. The limitations of this apparatus should be explained.

Note that the use of ‘eg’ in the content is to give an indication and illustration of the breadth and depth of the area or topic. As such, not all content that follows an ‘eg’ needs to be taught or assessed.

Assessment

Opportunity to achieve criteria P1 and M1 could be provided through a short, timed test or individual assignment. If the latter method is chosen, steps should be taken to ensure that the criteria are achieved autonomously and independently. A task to achieve P1 should require use of the characteristic gas equation, the polytropic process equation and the general gas equation to determine the mass of a given quantity of gas and its final condition parameters after undergoing an expansion or compression process.

A second task to achieve the M1 criterion would require determination of the process index ‘*n*’, from the initial and final condition parameters of a gas and manipulation of the polytropic process equation.

A second timed assessment or assignment could contain tasks to enable P2, P3, M2 and D1 to be achieved. It will be appropriate for the tasks to achieve P2 and P3 to require calculation of final condition parameters prior to the determination of work and heat transfer. The task to achieve M2 will require calculation of the characteristic gas constant prior to manipulation of the relationship formulae to determine the specific heat capacities c_v and c_p. The final task to achieve D1 should lead learners to conclude that the additional heat supplied during isobaric expansion enables the pressure to be maintained and more external work to be done.

The criteria P4, P5, M3 and D2 relate to learning outcome 3. These could be assessed by means of a third timed assignment in which a task to achieve P4 would require calculation of the theoretical amount of air needed for complete combustion of a given mass of fuel. A mass analysis of the fuel will need to be provided and ideally this should contain the range of combustible constituents.

The distinction criterion D2 will require the preparation of a full analysis of the products of combustion when a mass of fuel is completely burned with a given percentage of excess air. In addition to the range of combustible elements, the given mass analysis of the fuel might contain an oxygen content and a quantity of incombustible material. Ideally, the data required to determine calorific value for achievement of P5 and M3 should be obtained from experimental investigations. Where this is not possible, exemplary data will need to be obtained and provided. In the case of the Schole’s bomb type calorimeter this should include mass of fuel, mass of water heated, water equivalent of the calorimeter and temperature versus time data. In the case of the Boys’ gas type calorimeter this should include gas supply pressure and temperature, prevailing atmospheric pressure, volume of gas metered, water inlet and exit temperatures, mass of water collected and mass of condensate collected.

A final timed assignment to achieve criteria P6, P7, P8 and M4 could enable learners to demonstrate an understanding of steam generation, steam plant elements and the use of thermodynamic property tables. Although separate tasks might be set to cover the criteria they might relate to data provided in a single steam plant scenario. Exemplary test data for the throttling calorimeter should include wet steam supply pressure and the temperature and pressure immediately after throttling.

Links to National Occupational Standards, other BTEC units, other BTEC qualifications and other relevant units and qualifications

This unit builds on the material covered in *Unit 6: Mechanical Principles and Applications* and can be linked to *Unit 13: Principles and Applications of Fluid Mechanics*.

The unit provides some of the underpinning knowledge for the SEMTA Level 3 NVQ in Mechanical Manufacture, Level 3 NVQ in Engineering Maintenance and Level 3 NVQ in Engineering Technical Support.

Essential resources

Ideally centres should be equipped with a bomb type calorimeter and a Boys' gas type calorimeter to determine the calorific value of fuels. Failing this, exemplary simulation material and test data will need to be provided. Clement and Desormes' apparatus for determination of the adiabatic index γ might also be of value in the delivery of learning outcome 1. Learners will need to be provided with, or be encouraged to purchase, a set of thermodynamic property tables.

Indicative reading for learners

Textbooks

Darbyshire A — *Mechanical Engineering BTEC National Option Units* (Newnes, 2003) ISBN 0750657618

Joel R — *Basic Engineering Thermodynamics* (Prentice Hall, 1996) ISBN 0582256291

Moran M — *Fundamentals of Engineering Thermodynamics* (John Wiley and Sons, 2006) ISBN 0470030372

Sonntag R and Bourgnakke C — *Introduction to Engineering Thermodynamics* (John Wiley and Sons, 2006) ISBN 0471737593

Key skills

Achievement of key skills is not a requirement of this qualification but it is encouraged. Suggestions of opportunities for the generation of Level 3 key skill evidence are given here. Staff should check that learners have produced all the evidence required by part B of the key skills specifications when assessing this evidence. Learners may need to develop additional evidence elsewhere to fully meet the requirements of the key skills specifications.

Application of number Level 3	
When learners are:	**They should be able to develop the following key skills evidence:**
• determining the gross calorific value of a solid or liquid fuel from given test data using a bomb type calorimeter.	N3.1 Plan an activity and get relevant information from relevant sources. N3.2 Use this information to carry out multi-stage calculations to do with: a amounts or sizes b scales or proportion c handling statistics d using formulae. N3.3 Interpret the results of your calculations, present your findings and justify your methods.

Problem solving Level 3	
When learners are:	**They should be able to develop the following key skills evidence:**
• determining the work and heat transfer during a thermodynamic process in a closed system.	PS3.1 Explore a problem and identify different ways of tackling it. PS3.2 Plan and implement at least one way of solving the problem. PS3.3 Check if the problem has been solved and review your approach to problem solving.