Engineering ISSUE DATE 17 JAN 2014 SECOND YEAR

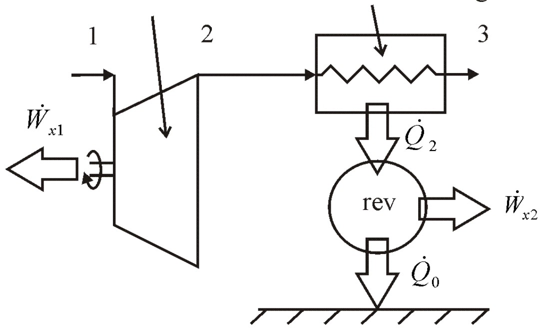
Part IB Paper 4: Thermofluid Mechanics

THERMODYNAMICS

Examples Paper 5

Maximum available power

Q1. An industrial process provides a steady flow of 1kgs^{-1} of air at 800K and 5 bar (station 1 in diagram below). The environment is at 300K, 1bar. Answer the following questions neglecting all kinetic and potential energy changes.



(a) An isentropic turbine is used to extract power from the flow. The turbine exhausts to an environmental pressure of 1bar (station 2 in the diagram above). Draw the process on a h-s diagram. Calculate the power output from the turbine, $\dot{W}_{x1}$ (NB for each part of the question think whether it requires a 1st law or 2nd law analysis). Without calculating Δb_{12} explain why the change in enthalpy across the turbine, Δh_{12}, is equal to change in availability, Δb_{12}.

(b) A heat-exchanger is used to remove a heat flux from the turbine's exit flow. The exhaust of the heat-exchanger (station 3 in the diagram above) is at the same temperature as the environment. Draw the process on the h-s diagram from part (a). Calculate the heat flux extracted from the flow. Calculate the maximum power, $\dot{W}_{x2}$, which can be extracted by a reversible heat engine receiving this heat flux. Why is the change in enthalpy across the heat-exchanger, Δh_{23}, greater than the change in availability, Δb_{23}?

(c) Compare the combined power output from part (a) and (b), $\dot{W}_{x1} + \dot{W}_{x2}$, to the difference in the availability of the air at inlet, station 1, and the availability of the fluid at the dead state. Comment on the comparison.

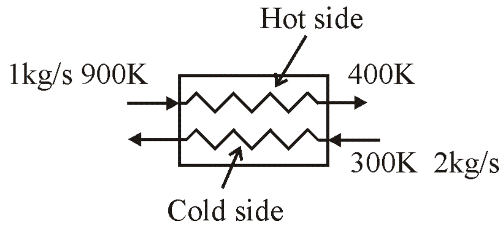
Q2. The flow in question 1, 1kgs^{-1} of air with a pressure and temperature of 800K and 5 bar, is throttled to an environmental pressure of 1bar. Answer the following questions neglecting all kinetic and potential energy changes.

(a) Calculate the lost power potential across the throttle. What is the cause of this 'energy degradation'? Draw the process on the h-s diagram from question 7.

(b) Calculate the maximum power potential which can be extracted from the exhaust of the throttle described in part (a). What type of device would be required to extract this power.

(c) Compare the lost power potential in part (a) and the power output in part (b) to the power output from Q1 part (c).

Q3. A heat exchanger, shown in the diagram below, is designed to transfer heat between two steady flows of air. There is no heat transfer to the environment. The hot flow of 1kgs^{-1} enters at 900K and leaves at 400K. The cold flow of 2kgs^{-1} enters at 300K. There is no irreversible entropy creation or pressure drop in the flow on either side of the heat-exchanger. The environment is at 300K.



(a) Calculate the temperature at the exit of the cold side.

(b) By considering a control volume around the whole heat exchanger, calculate the lost power potential within the control volume. What is the cause of this 'energy degradation'?

(c) Consider two control volumes, one around the hot side and one around the cold side of the heat exchanger. Calculate the transfer of power potential due to heat transfer to, or from, each control volume.

(d) Compare your answers from parts (b) and (c). How are they related?

Gas Turbines

Q4. A land based gas turbine power plant used for electricity generation works on an irreversible Joule cycle with an overall compression ratio of 10. The temperature of the environment and the air entering the compressor is 25°C and that of the air entering the turbine is 1250°C. Both the compressor and the turbine have isentropic efficiencies of 85%. The exhaust gases may be treated as air, taking c_p=1.01kJ/kgK and γ=1.4 throughout. Neglect the mass flow rate of fuel, pressure losses in the combustion chamber and all kinetic and potential energy changes. (NB all parts of this question can be undertaken with a 1st law analysis, i.e. availability is not required and will just take extra time). Calculate, per unit mass flow of air:

(a) The work input required by the compressor.

(b) The heat added in the combustion chamber.

(c) The turbine work output.

(d) The net work output and cycle thermal, or 1st law, efficiency.

Q5. The aim of this question is to undertake a lost power potential analysis of a gas turbine, i.e. to calculate where the power potential transferred into the cycle as heat in the combustor ends up. The gas turbine considered is the one presented in the previous question. Uses should be made of the values calculated in the previous question.

(a) Calculate the transfer of power potential due to heat transfer into the combustion chamber. Consider the combustion chamber as a simple heat addition to the air.

(b) Calculate the rational, or 2nd law, efficiency of the cycle.

(c) Calculate the lost power potential in the compressor.

(d) Calculate the lost power potential in the turbine.

(e) Calculating the lost power potential in the exhaust by considering the maximum power which could be extracted from the exhaust.

(f) By comparing the transfer of power potential into the combustor to the power output and lost power potential in the components and exhaust propose methods of improving the efficiency of the machine.

Q6. An aero jet engine has a compressor with a pressure ratio of 25, a compressor inlet temperature of 0°C and a turbine inlet temperature of 1500°C. The ambient air is at 0°C. The isentropic efficiency of the compressor is 0.85 and that of the turbine is 0.90. The final nozzle may be assumed to be isentropic and the pressure in the exhaust jet is the same as that of the flow entering the compressor. Take c_p =1.01kJ/kgK for air and c_p =1.13kJ/kgK for the combustion gases, with R= 0.287kJ/kgK remaining constant throughout. Ignore any mechanical losses in the shaft connecting the turbine and the compressor, and neglect the mass flow rate of fuel and any pressure losses in the combustion chamber. Draw the jet engine on a T-s

diagram. Then, assuming that the kinetic energy is negligible everywhere except in the exhaust jet, calculate:

(a) The pressure ratio of the turbine. Note that in aero jet engines no shaft work is extracted from the shaft and so turbine work output must equal compressor work input.

(b) The kinetic energy per unit mass flow rate of the exit jet.

(c) In addition to its high kinetic energy flux does the exit jet have any other power potential? Could it be extracted in practice?

Working Fluids

Q7. A radiator in a central heating system has a volume of $0.2m^3$ and contains saturated water vapour at a pressure of 1.5 bar. The valves are closed and by cooling the pressure falls to 1.0 bar. Calculate

(a) The total mass of H_2O in the radiator;

(b) The dryness fraction in the final state;

(c) The volume and mass of liquid water in the final state;

(d) The volume and mass of steam in the final state.

Q8. Steam is bled off from a turbine at a pressure of $2.0MN/m^2$. It flows steadily and adiabatically through a throttle valve. The pressure and temperature downstream of the throttle are found to be $0.1MN/m^2$ and 125°C respectively. The change of kinetic energy across the throttle is small.

(a) Sketch the process on an *h-s* diagram.

(b) Calculate , (i) the enthalpy of the bled steam, and (ii) the dryness fraction of the bled steam.

(c) What happens if the enthalpy of the steam in the turbine is less than 2500.9kJ/kg? The h-s diagram for steam in the back of the CUED thermofluids data book may be of use.

Steam Power Plant

Q9. A steady flow steam plant works on the Rankine cycle. The cycle operates with a boiler pressure of 40 bar and a condenser pressure of 0.06 bar. At entry to the adiabatic turbine the steam is dry saturated and at entry to the adiabatic feed pump the water is wet saturated. Assume all processes making up the cycle are reversible, and that the flow velocity at inlet to and outlet from each device is small.

Sketch the cycle on a *T-s* diagram and determine per unit mass of working fluid:

(a) the work input to the feed pump (use the equation $-w_x = h_2 - h_1 = \int_1^2 v dp$);

(b) the heat supplied in the boiler;

(c) the work output from the turbine;

(d) the heat rejected in the condenser;

(e) the thermal efficiency of the cycle.

Q10. In an electricity generating power station, the working fluid is H_2O undergoes a steady flow cycle based on the Rankine cycle. The pressure in the boiler is 40 bar and the condenser pressure is 0.06 bar. Steam leaves the boiler dry saturated and the expansion in the turbine is adiabatic with an isentropic efficiency of 85%. Water leaves the condenser wet saturated and the compression in the feed pump has an isentropic efficiency of 70%. The power output from the plant is 200MW.

Draw a T-s diagram and then determine:

(a) the dryness fraction of the steam at turbine outlet;

(b) the thermal efficiency of the cycle. Compare the result with that of part (e) of the previous question and comment on the difference;

(c) the mass flow rate of water circulating.

Note: some of the results of the previous question may be used.

Q11. The cycle of the previous question is modified by using two turbines. The first turbine takes the steam from the boiler and expands it to 5 bar. The steam is then reheated (at constant pressure) to 400°C. The steam then enters the second turbine and expands to a pressure of 0.06 bar with an isentropic efficiency of 90%. The isentropic efficiency of the first turbine is unchanged at 85%.

Draw a T-s diagram and then determine:

(a) the work output from each turbine;

(b) the heat input to the steam in the reheater;

(c) the dryness fraction of the steam leaving the second turbine;

(d) the overall thermal efficiency of the cycle.

Also:

(e) explain qualitatively why the total work output and the thermal efficiency of the cycle are both improved by the re-heating of the steam.

Note: where appropriate results from the previous two questions may be used.

ANSWERS

Note: Most of the answers depend upon the use of tabulated data, and are sensitive to rounding errors. The final results here are quoted to three significant figures for convenience, but some numerical error is to be expected and is acceptable.

Q1 (a) 296.4kW, (b) 48.9kW, (c) 345.4kW.

Q2 (a) 138.6kW, (b) 206.7kW.

Q3 (a) 550K, (b) 120.9kW, (c) 258kW, -137.1kW.

Q4 (a) 329.5kJ/kg, (b) 907.7kJ/kg, (c) 630.3kJ/kg, (d) 300.8kJ/kg, 33.1%.

Q5 (a) 639.3kJ/kg, (b) 47%, (c) 25.7kJ/kg, (d) 38.3kJ/kg, (e) 274.7kJ/kg.

Q6 (a) 3.483, (b) 596.0kJ/kg.

Q7 0.173 kg, 0.684, 5.70×10^{-5} m^3, 0.0547 kg, 0.2 m^3, 0.118 kg

Q8 2730 kJ/kg, 0.962

Q9 a) 4.02kJ/kg; b) 2650kJ/kg; c) 933kJ/kg; d) 1720kJ/kg; e) 0.351

Q10 a) 0.769; b) 0.298; c) 254kg/s

Q11 a) 316kJ/kg, 784kJ/kg; b) 788kJ/kg; c) 0.968; d) 0.319; e) discussion

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