Engineering **SECOND YEAR**

Part IB Paper 4: Thermofluid Mechanics

THERMODYNAMICS

Examples Paper 4

Working Fluids

Q1. 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.

Q2. 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

Q3. 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.

Q4. 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.

Q5. 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.

Q6. In a combined gas turbine-steam turbine cycle the gas turbine has a heat input of 100MW and a thermal efficiency of 35%. It rejects all of its heat to a steam cycle which has a thermal efficiency of 25%.

What is the power output and thermal efficiency of the combination?

Q7. The exhaust gas from the gas turbine of a combined cycle power plant enters the heat recovery steam generator (HRSG) at a temperature of 600°C and leaves at 140°C. The gas may be assumed to have the same properties as air with a value of cp appropriate to a temperature midway between these limits. The steam in the steam generator is at a uniform pressure of 20 bar. It enters as a sub-cooled liquid at 100°C and leaves as superheated steam at a temperature of 400°C. The flow in the steam generator is steady throughout.

(a) Draw a T-x diagram of the HRSG. Calculate the ratio of the mass flow rates of exhaust gas and steam.

(b) Use the result of (a) to calculate the temperature difference between the steam and the gas at the point where the water first reaches its boiling point (called the pinch point)

(c) Calculate the ratio of the rate of entropy increase of the steam within the steam generator to the rate of entropy decrease of the gas, and comment on the significance of its value.

<u>Refrigerators and Heat Pumps</u>

Q8. Calculate the shaft work required to compress 1 kg of dry saturated R-134A at 0.15MPa in a steady flow compressor to a pressure of 1MPa, for each of the following types of process:

(a) adiabatic and reversible;

(b) adiabatic and with an isentropic efficiency of 80%.

(c) Neglect any changes in kinetic or potential energy. Also, sketch each process on a *p-h* and a *T-s* diagram.

Q9. A vapour compression refrigerator uses R-134A as the working fluid. The pressure in the condenser is 10 bar and in the evaporator it is 1.5 bar.

(a) What are the saturation temperatures in the condenser and the evaporator?

The refrigerator operates in steady flow, the refrigerant leaves the condenser as saturated liquid and is throttled adiabatically to the evaporator pressure. It leaves the evaporator as saturated vapour and is compressed adiabatically to the condenser pressure, leaving the compressor with a temperature 20K above the saturation temperature in the condenser (i.e. with 20K of superheat).

(b) Sketch the cycle on a *p-h* and a *T-s* diagram.

(c) Calculate the heat absorbed in the evaporator per unit mass of fluid.

(d) Calculate the heat rejected in the condenser per unit mass of fluid.

(e) Calculate the COP_R of the plant.

(f) Compare the COP_R with that for a Carnot cycle working between the temperature in the evaporator and that in the condenser and suggest reasons for the difference.

(g) If the refrigerator has to remove 250 Watts from the cold space, what must be the mass flow rate of refrigerant around the cycle?

Q10. A heat pump is required to operate on a vapour compression cycle with a temperature of -20°C in the evaporator. The refrigerant is R-134A, which enters the compressor as saturated vapour and leaves at a temperature of 65°C. On exit from the condenser the refrigerant is a saturated liquid at 45°C. It then passes through a throttle valve back into the evaporator.

(a) Find the pressure in (i) the evaporator and (ii) the condenser.

(b) Calculate the COP_P of the heat pump.

(c) The throttle valve is replaced by a turbine having an isentropic efficiency of 70%. Calculate the work output of the turbine per unit mass of refrigerant.

(d) If this work is used to help drive the compressor what is the COP_P of the modified plant?

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.

1. 0.173 kg, 0.684, 5.70×10^{-5} m^3, 0.0547 kg, 0.2 m^3, 0.118 kg
2. 2730 kJ/kg, 0.962
3. a) 4.02kJ/kg; b) 2650kJ/kg; c) 933kJ/kg; d) 1720kJ/kg; e) 0.351
4. a) 0.769; b) 0.298; c) 254kg/s
5. a) 316kJ/kg, 784kJ/kg; b) 788kJ/kg; c) 0.968; d) 0.319; e) discussion
6. 51.25MW, 51.25%
7. a) 5.8; b) 7°C; c) 1.265
8. 42.0kJ/kg; b) 52.5kJ/kg
9. a) 39°C, -18°C; b) diagrams; c) 133kJ/kg; d) 187kJ/kg; e) 2.5; f) 4.47; g) 1.88×10^{-3}kg/s.
10. a) 11.6 bar, 1.33 bar; b) 3.13; c) 7.6kJ/kg; d) 3.61.

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