Engineering **SECOND YEAR**

Part IB Paper 4: Thermofluid Mechanics

THERMODYNAMICS

Examples Paper 6

Advanced Steam Power Plant

S1. 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?

Q1. 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.

Refrigerators and Heat Pumps

Q2. 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.

Q3. 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?

Q4. 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?

Gas Mixtures and Psychrometry

S1. A gas mixture consists of 3kg of nitrogen and 5kg of carbon dioxide at a pressure of 3 bar and a temperature of 300K. Calculate:

(a) the mass fraction and mole fraction of each constituent

(b) the partial pressure of each constituent

(c) the equivalent molar mass and specific gas constant of the mixture

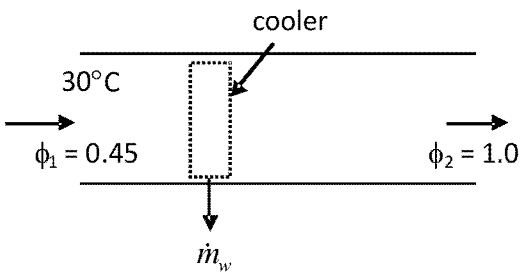
(d) the volume and density of the mixture.

Q5. A sample of moist air at an atmospheric pressure of 1.013 bar and a temperature of 35°C has absolute humidity 0.007kgw/kga. Calculate the partial pressure of the water vapour in the air, the relative humidity and the dewpoint temperature.

Q6. A dehumidifier, shown below, operates by passing $1 kgs^{-1}$ of moist air over a cooling coil which removes water vapour by condensation. The inlet air is at an atmospheric pressure of 1.013 bar, a temperature of 30°C and has a relative humidity of 45%. 30% of the mass flow of water vapour at inlet to the dehumidifier leaves as liquid water, $\dot{m}_w$. The outlet air is saturated (relative humidity 100%). The liquid water, water vapour and air leave the dehumidifier at the same temperature, T_{exit}.

(a) Calculate T_{exit}.

(b) Calculate the rate of heat transfer in the cooler. (NB consider the enthalpy of air, water vapour and liquid water entering and leaving the device.)



Combustion

Q7. Write down the chemical equation, complete with all coefficients, for the following reactions

(a) Combustion of propane C_3H_8 at an air-fuel ratio of 16:1

(b) Combustion of benzene C_6H_6 at an equivalence ratio of 1.05

(c) Combustion of ethanol C_2H_5OH at stoichiometric conditions

Q8. The combustion chamber of a space rocket operates in a steady flow. The fuel, saturated liquid hydrogen at 20K, flows at a rate of 24 kg/s. The oxidant is saturated liquid oxygen at 88 K, which is supplied at a rate of 72 kg/s. At these temperatures, hydrogen and oxygen require 452 kJ/kg and 214 kJ/kg respectively of heat input to vaporise. Below 298 K, the specific heat capacities of gaseous hydrogen and oxygen may be assumed constant and equal to the perfect gas values given in the Thermofluids Tables. All of the oxygen is consumed before the products leave the combustion chamber.

(a) What is the chemical equation for this process?

(b) Assuming that heat losses and kinetic energies of all streams are negligible, show that an exit temperature of 2443K satisfies the SFEE for the combustion chamber. NB remember to include the latent heats for hydrogen and oxygen.

(c) The combustion products pass from the combustion chamber, where the velocity is negligible, into a nozzle where they are accelerated to produce thrust. Calculate the velocity of the products at the point in the nozzle where the temperature has fallen to 1000K. Why do you think the combustion process is rich (i.e. an excess of hydrogen)?

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.

S1. 51.25MW, 51.25%

Q1. a) 5.8; b) 7°C; c) 1.265

Q2. a)42.0kJ/kg; b) 52.5kJ/kg

Q3. 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.

Q4. a) 11.6 bar, 1.33 bar; b) 3.13; c) 7.6kJ/kg; d) 3.61.

S2. CO_2 value, N_2 value,

(a) 0.375, 0.625, 0.515, 0.485,

(b) 1.544 bar, 1.456 bar,

(c) 36.24 kg $kmol^{-1}$, 229 $Jkg^{-1}K^{-1}$,

(d) $1.84m^3$, $4.36kgm^{-3}$.

Q5. 1130 Pa, 20.1%, 8.75ºC.

Q6. (a) 11.4°C, (b) - 27.67kW.

Q7. (a) $C_3H_8 + 5.128\,(O_2 + 3.762\,N_2^*) \rightarrow 3CO_2 + 4H_2O + 0.128O_2 + 19.29\,N_2^*$,

(b) $C_6H_6 + 7.143\,(O_2 + 3.762\,N_2^*) \rightarrow 5.286CO_2 + 3H_2O + 0.714CO + 26.87\,N_2^*$,

(c) $C_2H_5OH + 3\,(O_2 + 3.762\,N_2^*) \rightarrow 2CO_2 + 3H_2O + 11.28\,N_2^*$,

Q8. (a) $12H_2 + 2.25O_2 \rightarrow 4.5H_2O + 7.5\,H_2$, (c) $3744ms^{-1}$.

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