1. THE SECOND LAW OF THERMODYNAMICS J2006/9/1 UNIT 9THE SECOND LAW OF THERMODYNAMICS OBJECTIVESGeneral Objective : To define and explain the Second Law of Thermodynamics and perform calculations involving the expansion and compression of steam and gases.Specific Objectives : At the end of the unit you will be able to: state the definition of the Second Law of Thermodynamics explain the Second Law of Thermodynamics estimate the efficiency of heat engine explain entropy and entropy change sketch processes on a temperature-entropy diagram understand that Q = h2 – h1 and apply the formula in calculations calculate the change of entropy, work and heat transfer of steam in reversible processes at: i. constant pressure process ii. constant volume process iii. constant temperature (or isothermal) process iv. adiabatic (or isentropic) process v. polytropic process

2. THE SECOND LAW OF THERMODYNAMICS J2006/9/2 INPUT9.0 Introduction to The Second Law of Thermodynamics According to the First Law of Thermodynamics as stated in Unit 2, when a system undergoes a complete cycle, then the net heat supplied is equal to the net work done. Σ dQ = Σ dW This is based on the conservation of energy principle, which follows from the observation on natural events. The Second Law of Thermodynamics, which is also a natural law, indicates that; Although the net heat supplied in a cycle is equal to the net work done, the gross heat supplied must be greater than the work done; some heat must always be rejected by the system. …The Second Law of Thermodynamics In symbols, Q1 – Q2 = W (9.1) To enable the second law to be considered more fully, the heat engine must be discussed.

3. THE SECOND LAW OF THERMODYNAMICS J2006/9/39.1 The heat engine and heat pump We know from experience that work can be converted to heat directly and completely, but converting heat to work requires the use of some special devices. These devices are called heat engines. A heat engine is a system operating in a complete cycle and developing net work from a supply of heat. The second law implies that a source of heat supply (or hot reservoir) and a sink (or cold reservoir) for the rejection of heat are both necessary, since some heat must always be rejected by the system. Heat engines differ considerably from one another, but all can be characterised by the following: They receive heat from a high-temperature source (for example solar energy, oil furnace, nuclear reactor, steam boiler, etc.) They convert part of this heat to work (usually in the form of a rotating shaft, for example gas turbine, steam turbine, etc.) They reject the remaining waste heat to a low-temperature sink (for example the atmosphere, rivers, condenser, etc.) They operate on a cycle. A diagrammatic representation of a heat engine is shown in Fig. 9.1-1. High-temperature HOT RESERVOIR Q1 WORK OUTPUT HEAT W = Q1 - Q2 Note: Q1 = The heat supplied from the ENGINE source. Q2 W = The net work done. Low-temperature COLD RESERVOIR Q2 = The heat rejected. Figure 9.1-1 Part of the heat received by the heat engine is converted to work, while the rest is rejected to cold reservoir.

4. THE SECOND LAW OF THERMODYNAMICS J2006/9/4 Heat engines and other cyclic devices usually involve a fluid that moves to and fro from which heat is transferred while undergoing a cycle. This fluid is called the working fluid. The work-producing device that best fits into the definition of a heat engine are: The steam power plant The close cycle gas turbine By the first law, in a complete cycle, Net heat supplied = Net work done Referring to Fig. 9.1-1, from equation Σ dQ = Σ dW, we have, Q1 – Q2 = W By the second law, the gross heat supplied must be greater than the net work done, i.e. Q1 > W The thermal efficiency of a heat engine is defined as the ratio of the net work done in the cycle to the gross heat

supplied in the cycle. It is usually expressed as a percentage. Referring to Fig. 9.1-1, W Thermal efficiency, η= (9.2) Q1 Substituting equation 9.1, (Q 1 − Q2) η= Q1 ⎛ Q2 ⎞ ∴ η = 1− ⎜ ⎜ (9.3) ⎝ Q1 ⎠ It can be seen that the second law implies that the thermal efficiency of a heat engine must always be less than 100% (Q1 > W).

5. THE SECOND LAW OF THERMODYNAMICS J2006/9/5 Example 9.1 Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 45 MW, determine the net work done and the thermal efficiency for this heat engine. Solution to Example 9.1 FURNACE Q1 = 80 MW HEAT W=? ENGINE Q2 = 45 MW RIVER A schematic of the heat engine is given in the diagram above. The furnace serves as the high-temperature reservoir for this heat engine and the river as the low- temperature reservoir. Assumption: Heat lost through the pipes and other components are negligible. Analysis: The given quantities can be expressed in rate form as; Q1 = 80 MW Q2 = 45 MW From equation 9.1, the net work done for this heat engine is; W = Q1 – Q2 = (80 – 45) MW = 35 MW Then from equation 9.2, the thermal efficiency is easily determined to be W 35 MW η= = = 0.4375 (or 43.75%) Q1 80 MW That is, the heat engine converts 43.75 percent of the heat it receives to work.

6. THE SECOND LAW OF THERMODYNAMICS J2006/9/6 The first and second laws apply equally well to cycles working in the reverse direction to those of heat engine. In general, heat only flows from a high-temperature source to a low-temperature sink. However, a reversed heat engine can be utilized to pump the heat from a low-temperature region to a high-temperature region. The reversed heat engine is called heat pump. In the case of a reversed cycle, the net work done on the system is equal to the net heat rejected by the system. Such cycles occur in heat pumps and refrigerators. The equivalent diagram of the heat pump (or refrigerator) is shown in Fig. 9.1-2. High-temperature HOT RESERVOIR Q1 WORK INPUT HEAT W Q1 = W + Q2 PUMP Q2 Low-temperature COLD RESERVOIR Figure 9.1-2 Reverse heat engine In the heat pump (or refrigerator) cycle, an amount of heat, Q2, is supplied from the cold reservoir, and an amount of heat, Q1, is rejected to the hot reservoir. Q1 = W + Q2 (9.4) In the second law, we can say that work input is essential for heat to be transferred from the cold to the hot reservoir, i.e. W>0 The first law sets no limit on the percentage of heat supplied, which can be converted into work. Nor does it indicate whether the energy conversion process is physically possible or impossible. We shall see, though, that a limit is imposed by the Second Law of Thermodynamics, and that the possibility or otherwise of a process can be determined through a property of the working fluid called entropy.

7. THE SECOND LAW OF THERMODYNAMICS J2006/9/79.2 Entropy The first law applied to a heat engine or energy conversion process is merely an energy balance. However, the first law does not indicate the possibility or impossibility of the process, and we know from our everyday experience that some energy conversions are never observed. In Unit 2, internal energy which is an important property, arised as a result of the First Law of Thermodynamics. Another important property, entropy, follows from the second law. Considering 1 kg of fluid, the units of entropy are given by kJ/kg divided by K. The the unit of specific entropy, s, is kJ/kg K. The symbol S will be used for the entropy of mass, m, of a fluid, i.e. S = ms kJ/K The change of entropy is more important than its absolute value, and the zero of entropy can be chosen quite arbitrarily. For example, in the Steam Tables the specific entropy at saturated liquid is put equal to zero at 0.01oC; in tables of refrigerants the specific entropy at saturated liquid is put equal to zero at – 40oC. For all working substances, the change of entropy is given by dQ ds = (9.5) T Re-writing

equation 9.5 we have dQ = T ds or for any reversible process 2 Q = ∫ T ds (9.6) 1 The equation 9.7 below is analogous to equation 9.6 for any reversible process 2 W = ∫ P dv (9.7) 1 Thus, as there is a diagram on areas that represent work done in a reversible process, there is also a diagram on areas that represent heat flow in a reversible process. These diagrams are the P-v and the T-s diagrams respectively, as shown in Figs. 9.2-1 and 9.2-2.

8. THE SECOND LAW OF THERMODYNAMICS J2006/9/8 For a reversible process from point 1 to point 2: 2 ❍ in Fig. 9.2-1, the shaded area ∫ 1 P dv , represents work done; and 2 ❍ in Fig. 9.2.2, the shaded area ∫ T ds , represents heat flow. 1 P T 1 1 P 2 T 2 v s dv ds Figure 9.2.1 Work done Figure 9.2.2 Heat flow Therefore, one great use of property entropy is that it enables a diagram to be drawn showing the area that represents heat flow in a reversible process. In the next input, the T-s diagram will be considered for a steam.

9. THE SECOND LAW OF THERMODYNAMICS J2006/9/99.3 The T-s diagram for a steam As mentioned earlier, the zero specific entropy is taken as 0.01oC for steam and – 40oC for refrigerants only. The T-s diagram for steam is considered here. The diagram for a refrigerant is exactly similar to the T-s diagram for steam. However, the zero specific entropy is different. The T-s diagram for steam in Fig. 9.3-1, shows: ❍ Three lines of constant pressure P1, P2 and P3 (i.e. ABCD, EFGH and JKLM). The pressure lines in the liquid region are practically coincident with the saturated liquid line (i.e. AB, EF and JK), and the difference is usually neglected. ❍ The pressure remains constant with temperature when the latent heat is added, hence the pressure lines are horizontal in the wet region (i.e. portions BC, FG and KL). ❍ The pressure lines curve upwards in the superheat region (i.e. portions CD, GH and LM). Thus the temperature rises as heating continues at constant pressure. ❍ Two constant volume lines (v1 and v2 shown as chain-dotted) are also drawn in Fig. 9.3-1. The lines of constant volume are concaved down in the wet region and slope up more steeply than pressure lines in the superheat region. T P P3 > P2 > P1 M 3 P2 v1 > v2 H v2 K L P1 v1 D J F G E B C A 273 K s Figure 9.3-1 Temperature-entropy diagram for liquid and steam

10. THE SECOND LAW OF THERMODYNAMICS J2006/9/10 In steam tables, the specific entropy of the saturated liquid and the dry saturated steam are represented by sf and sg respectively. The difference, sg - sf = sfg is also tabulated. The specific entropy of wet steam is given by the specific entropy of water in the mixture plus the specific entropy of the dry steam in the mixture. For wet steam with dryness fraction, x, we have s = sf(1 – x) + xsg or s = sf + x(sg – sf) i.e. s = sf + xsfg (9.8) Then the dryness fraction is given by s − sf x= (9.9) s fg It can be seen from equation 9.9 that the dryness fraction is proportional to the distance of the state point from the liquid line on a T-s diagram. For example, for state 1 on Fig. 9.3-2, the dryness fraction, distance F1 s1 − s f1 x1 = = distance FG s fg1 The area under the line FG on Fig. 9.3-2 represents the latent heat hfg. The area under line F1 is given by x1hfg. In unit 8, the enthalpy of wet steam was shown to be given by equation 8.4, h= hf + xhfg T (K) s1 = sf1 + x1sfg1 P1 F 1 G P1 sf sg s kJ/kg K s1 Figure 9.3-2 Temperature-entropy chart for steam

11. THE SECOND LAW OF THERMODYNAMICS J2006/9/119.4 To show that Q = h2 – h1 The T-s diagram will enable equation Q = h2 – h1 to be expressed graphically, while areas on the diagram represent heat flow. Assuming that the pressure line in the liquid region coincides with the saturated liquid line, then

the enthalpy can be represented on the diagram. T (K) P D B E C A s kJ/kg K 0 F G H J Figure 9.4 T-s diagram showing Q = h2 – h1 Referring to Fig. 9.4: o When water at any pressure P, at 0.01 C, is heated at constant pressure, it follows the line AB approximately; the point B is at the saturation temperature T at which the water boils at the pressure P. At constant pressure from A to B Q = hB - hA = hB (since hA at 0.01oC is approximately zero) Therefore, we have area ABFOA = hB = hf at pressure P At point B, if heating continues, water will change gradually into steam until point C and the steam becomes dry saturated. Thus we have area BCHFB = latent heat = hfg at pressure P = hC - hB At point C, the enthalpy is given by hC = area ABFOA + area BCHFB = hg at pressure P

12. THE SECOND LAW OF THERMODYNAMICS J2006/9/12 For wet steam at point E, hE = hB + xEhfg i.e hE = area ABEGOA When dry saturated steam is further heated, it becomes superheated. The heat added from C to D at constant pressure P, is given by Q = hD – hC = area CDJHC Then the enthalpy at D is hD = hC + area CDJHC = area ABCDJOA

13. THE SECOND LAW OF THERMODYNAMICS J2006/9/13 Activity 9A TEST YOUR UNDERSTANDING BEFORE YOU CONTINUE WITH THE NEXT INPUT 9.1 Study the statements in table below and decide if the statements are TRUE (T) or FALSE (F). STATEMENTS TRUE or FALSE i. The Second Law of Thermodynamics is represented by the equation Q1 – Q2 = W. ii. The heat engine receives heat from a high- temperature source. iii. The heat engine convert part of the heat to internal energy. iv. The work-producing device of a heat engine are the steam power plant and a close cycle gas turbine. v. A reversed heat engine is called a heat pump. vi. The work producing device for a heat pump is the refrigerator. vii. In heat engines, the net work done must be greater than the gross heat supplied, i.e W > Q1 . 9.2 The work done by heat engine is 20 kW. If the rate of heat that enters into the hot reservoir is 3000 kJ/min, determine the thermal efficiency and the rate of heat rejection to the cold reservoir.

14. THE SECOND LAW OF THERMODYNAMICS J2006/9/14 Feedback To Activity 9A 9.1 i. True ii. True iii. False iv. True v. True vi. True vii. False 9.2 The given quantities can be expressed as; W = 20 kW Q1 = 3000 kJ/min = 50 kJ/s or kW From equation 9.2 W 20 η= = x 100 % = 40 % Q1 50 i.e. Thermal efficiency of heat engine is 40 %. From equation 9.1 W = Q1 – Q2 Q2 = Q1 – W = 50 – 20 = 30 kW i.e. The rate of heat rejection to the cold reservoir is 30 kW. CONGRATULATIONS, IF YOUR ANSWERS ARE CORRECT YOU CAN PROCEED TO THE NEXT INPUT…

15. THE SECOND LAW OF THERMODYNAMICS J2006/9/15 INPUT9.5 Reversible processes on the T-s diagram for steam In the following sections of this unit, five reversible processes on the T-s diagram for steam are analysed in detail. These processes include the: i. constant pressure process ii. constant volume process iii. constant temperature (or isothermal) process iv. adiabatic (or isentropic) process v. polytropic process 9.5.1 Constant pressure process The constant pressure process is a good approximation to many of the common physical processes which we are familiar with. The combustion of fuel in a boiler, the flow of fluids, the flow of air in ducts and other processes can be used to illustrate constant pressure. For example, Fig. 9.5.1 shows a reversible constant pressure process from a wet steam into the superheat region. It can be seen that, when the boundary of the system is inflexible, the pressure rises when heat is supplied. For a constant pressure process, the boundary must move against

an external resistance as heat is supplied. T P1 = P2 T2 2 1 T1 Q s1 s2 s Figure 9.5.1 Constant pressure process

16. THE SECOND LAW OF THERMODYNAMICS J2006/9/16 During the constant pressure process, since P is constant, W = P ∫ dv = P (v 2 − v1) 2 (9.10) 1 (Note that this equation was derived and used in Unit 5) From the non-flow energy equation, Q = (u2 – u1) + W Hence for a reversible constant pressure process Q = (u2 – u1) + P(v2 – v1) = (u2 + Pv2) –(u1 + Pv1) Now from equation h = u + Pv, Q = h2 - h1 kJ/kg (9.11) or for mass, m (kg), of a fluid, Q = m(h2 - h1) Q = H2 - H1 kJ (9.12) Example 9.2 4 kg of steam at 7 bar and entropy 6.5 kJ/kg K, is heated reversibly at constant pressure until the temperature is 250 oC. Calculate the heat supplied and show on a T-s diagram the area which represents the heat flow. Solution to Example 9.2 The given quantities can be expressed as; m = 4 kg P2 = P1 = 7 bar s1 = 6.5 kJ/kg K T2 = 250oC At state 1 At 7 bar, sg1 = 6.709 kJ/kg K, the steam is wet, since the actual entropy, s1, is less than sg1 (i.e. s1< sg1).

17. THE SECOND LAW OF THERMODYNAMICS J2006/9/17 From equation 9.9 s1 − s f1 6.5 − 1.992 x1 = = = 0.956 s fg1 4.717 Then from equation 8.4 h1 = hf1 + x1hfg1 = 697 + 0.956(2067) = 2673 kJ/kg At state 2 The steam is at 250 oC at 7 bar, and therefore superheated. From the superheated tables, h2 = 2955 kJ/kg At constant pressure, from equation 9.11 Q = h2 - h1 = 2955 - 2673 = 282 kJ/kg Hence for 4 kg of steam, Q = 4 kg x 282 kJ/kg = 1128 kJ i.e. For 4 kg of steam, the heat supplied is 1128 kJ. The T-s diagram of the process is given below. The shaded area represents the heat flow. T (K) P1 = P2 = 7 bar 2 T2 = 250 oC 1 = 523 K Q s (kJ/kg K) s1 s2 6.709

18. THE SECOND LAW OF THERMODYNAMICS J2006/9/18 9.5.2 Constant volume process In a constant volume process, the working substance is contained in a rigid vessel (or closed tank) from which heat is either added or removed. In this process, the boundaries of the system are immovable and no work can be done on or by the system. It will be assumed that ‘constant volume’ implies zero work unless stated otherwise. From the non-flow energy equation, Q = (u2 – u1) + W Since no work is done, we therefore have Q = u2 – u1 kJ/kg (9.13) or for mass, m (kg), of the working substance Q = m(u2 – u1) Q = (U2 – U1) kJ (9.14) Note that, all the heat supplied in a constant volume process goes to increasing the internal energy. In Fig. 9.5.2, the indicated path is one in which heat is being added in a constant volume process. T P2 T2 2 P1 1 T1 Q s1 s2 s Figure 9.5.2 Constant volume process

19. THE SECOND LAW OF THERMODYNAMICS J2006/9/19 Example 9.3 A wet steam at 10 bar is heated reversibly at constant volume to a pressure of 20 bar and 250 oC. Calculate the heat supply (in kJ/kg) and show the process on a T-s diagram, indicating the area that represents the heat flow. Solution to Example 9.3 At state 2 Steam at 20 bar and 250 oC is superheated. From the superheated steam tables, we have specific volume, v2 = 0.1115 m3/kg specific internal energy, u2 = 2681 kJ/kg At state 1 At 10 bar, we have v1 = v2 = 0.1115m3/kg vg1 = 0.1944 ∴ Steam at state 1 is wet as v1< vg1, and the dryness fraction is given by equation 8.2, v1 = x1 vg1 v1 0.1115 x1 = = = 0.574 v g1 0.1944 From equation 8.5, u1 = uf1 + x1(ug1 – uf1) = 762 + 0.574 (2584 - 762) = 1807.8 kJ/kg At constant volume from equation 9.13, Q = u2 – u1 = 2681 – 1807.8 = 873.2 kJ/kg

20. THE SECOND LAW OF THERMODYNAMICS J2006/9/20 The T-s diagram showing of constant volume process is given below. The shaded area represents the heat flow. T P2 = 20 bar 2 250 oC P1 = 10 bar 1 Q s1 s2 s

21. THE SECOND LAW OF THERMODYNAMICS J2006/9/21 9.5.3 Constant temperature (or isothermal) process A process that takes place at constant temperature is called an isothermal process. For example, at the exhaust of a steam turbine, the steam is usually wet. This steam is subsequently condensed in a unit appropriately known as a condenser. As the steam is initially wet, this process is carried out essentially at constant temperature (isothermally). In an isothermal expansion, heat must be added continuously in order to keep the temperature at the initial value. Similarly in an isothermal compression, heat must be removed from the fluid continuously during the process. A reversible isothermal process will appear as a straight line on a T-s diagram, and the area under the line must represent the heat flow during the process. Figure 9.2.3 shows a reversible isothermal expansion of wet steam into the superheat region. The shaded area represents the heat supplied during the process. Q = T(s2 - s1) … T in Kelvin (or K) (9.15) Note that the absolute temperature must be used. The temperature tabulated in the steam tables is t oC, and care must be taken to convert this into T Kelvin. From the non-flow energy equation, work can be expressed by W = Q - (u2 – u1) (9.16) T P1 P2 1 2 T1 = T2 Q s1 s2 s Figure 9.5.3 Isothermal process

22. THE SECOND LAW OF THERMODYNAMICS J2006/9/22 Example 9.4 Steam at 80 bar and enthalpy 2650 kJ/kg expands isothermally and reversibly to a pressure of 10 bar. Calculate the entropy change, heat supplied and the work done per kg steam during the process. Show the process on a T-s diagram, indicating the area that represents the heat flow. Solution to Example 9.4 The given quantities can be expressed as; P1 = 80 bar h1 = 2650 kJ/kg P2 = 10 bar At state 1 At 80 bar, h1 = 2650 kJ/kg, the steam is wet, since the given enthalpy, h1, is less than hg (i.e. 2758 kJ/kg). From the steam tables, the saturated temperature of wet steam is 295 oC. From equation 8.4 h1 = hf1 + x1hfg1 2650 = 1317 + x1(1441) x1 = 0.925 From equation 9.8 s1 = sf1 + x1sfg1 = 3.207 + 0.925(2.537) = 5.554 kJ/kg K From equation 8.5 u1 = uf1 + x1(ug1 - uf1) = 1306 + 0.925(2570 - 1306) = 2475.2 kJ/kg

23. THE SECOND LAW OF THERMODYNAMICS J2006/9/23 At state 2 At 10 bar and 295 oC the steam is superheated, hence interpolating T 300 s2 − 6.926 7.124 − 6.926 = 295 295 − 250 300 − 250 250 s2 = 7.1042 kJ/kg K s 6.926 s2 7.124 T 300 u2 − 2711 2794 − 2711 295 = 295 − 250 300 − 250 250 u2 = 2785.7 kJ/kg u 2711 u2 2794 Change of entropy, (s2 – s1) = 7.1042 - 5.554 kJ/kg K = 1.5502 kJ/kg K Then from equation 9.15 we have, Heat supplied = shaded area Q = T(s2 - s1) = 568(1.5502) = 880.5 kJ/kg (where T = 295 + 273 = 568 K) From equation 9.16, W = Q - (u2 – u1) = 880.5 - (2785.7 - 2475.2) = 570 kJ/kg

24. THE SECOND LAW OF THERMODYNAMICS J2006/9/24 The T-s diagram of the isothermal process is given below. The shaded area represents the heat flow. T (K) P1 = 80 bar P2 = 10 bar 1 2 T1 = T2 295OC @ 568 K Q s1 s2 s (kJ/kg K)

25. THE SECOND LAW OF THERMODYNAMICS J2006/9/25 Activity 9B TEST YOUR UNDERSTANDING BEFORE YOU CONTINUE WITH THE NEXT INPUT…! 9.3 A rigid cylinder (constant volume) contains steam at 90 bar and 400 oC. The cylinder is cooled until the pressure is 50 bar. Calculate the amount of heat

rejected per kg of steam. Sketch the process on a T-s diagram indicating the area, which represents the heat flow. 9.4 Steam at 8 bar, entropy 6.211 kJ/kg K is heated reversibly at constant pressure until the temperature is 350 oC. Calculate the heat supplied, and show on a T-s diagram the area which represents the heat flow. 9.5 Dry saturated steam at 100 bar expands isothermally and reversibly to a pressure of 10 bar. Calculate the heat supplied and the work done per kg of steam during the process. Show the process on a T-s diagram.

26. THE SECOND LAW OF THERMODYNAMICS J2006/9/26 Feedback To Activity 9B9.3 The given quantities can be expressed as; P1 = 90 bar T1 = 400 oC P2 = 50 bar At state 1 Steam at 90 bar and 400 oC is superheated, and the specific volume from the Steam Tables is, v1 = 0.02991 m3/kg. For superheated steam above 70 bar, the internal energy is not tabulated in the superheated steam tables and it is found from equation 8.6 that, u1 = h1 – p1v1 = 3118 – (90 x 102 x 2.991 x 10-2) = 2848.8 kJ/kg At state 2 At P2 = 50 bar and v2 = 0.02991 m3/kg, the steam is wet, and the dryness fraction is given by equation 8.2 as: v2 = x2vg2 v2 0.02991 x2 = = = 0.758 v g 2 0.03944 From equation 8.5 u2 = uf2 + x2(ug2 - uf2) = 1149 + 0.758(2597 – 1149) = 2246.6 kJ/kg

27. THE SECOND LAW OF THERMODYNAMICS J2006/9/27 At constant volume from equation 9.13 Q = u2 – u1 = 2246.6 - 2848.8 = - 602.2 kJ/kg i.e. The amount of heat rejected per kg of steam is 602.2 kJ/kg. T P1 = 90 bar 1 o 400 C P2 = 50 bar 2 Q s2 s1 s9.4 The given quantities can be expressed as; P1 = P2 = 8 bar s1 = 6.211 kJ/kg K T2 = 350 oC At state 1 At 8 bar, sg1 = 6.663 kJ/kg K, the steam is wet, since the actual entropy, s1, is less than sg1 (i.e. s1< sg1). From equation 9.9 s1 − s f1 6.211 − 2.046 x1 = = = 0.9 s fg1 4.617 Then from equation 8.4 h1 = hf1 + x1hfg1 = 721 + 0.9(2048) = 2564.2 kJ/kg

28. THE SECOND LAW OF THERMODYNAMICS J2006/9/28 At state 2 The steam is at 350 oC at 8 bar, and therefore superheated. From the superheated tables, h2 = 3162 kJ/kg At constant pressure, from equation 9.11 Q = h2 - h1 = 3162 - 2564.2 = 597.8 kJ/kg i.e. The heat supplied is 597.8 kJ/kg The T-s diagram of the process is given below. The shaded area represents the heat flow. T (K) P1 = P2 = 8 bar 2 T2 = 350 oC = 523 K 1 Q s (kJ/kg K) s1 s2 6.211

29. THE SECOND LAW OF THERMODYNAMICS J2006/9/299.5 From the Steam Tables at 100 bar, steam is dry saturated, s1 = sg1 = 5.615 kJ/kg K and t1 = 311oC At 10 bar and 311oC the steam is superheated, hence interpolating T 350 s 2 − 7.124 7.301 − 7.124 = 311 311 − 3000 350 − 300 300 s2 = 7.163 kJ/kg K s 7.124 s2 7.301 Then we have, Heat supplied = shaded area i.e. Q = T(s2 – s1) = 584 (7.163 – 5.615) = 584 x 1.548 = 904 kJ/kg (where T = 311 + 273 = 584 K) T (K) P1 = 100 bar P2 = 10 bar 1 2 T1 = T2 (311 + 273) =584 K Q s1 s2 s (kJ/kg K)

30. THE SECOND LAW OF THERMODYNAMICS J2006/9/30 To find the work done it is necessary to apply the equation, W = Q - (u2 – u1) From the Steam Tables, at 100 bar, steam is dry saturated u1 = ug = 2545 kJ/kg At 10 bar and 311oC, interpolating becomes T 350 311 u 2 − 2794 2875 − 2794 = 300 311 − 300 350 − 300 u u2 = 2811.8 kJ/kg 2794 u2 2875 Then, W = Q - (u2 – u1) = 904 – (2811.8 – 2545) = 637.2 kJ/kg i.e. Work done by the steam = 637.2 kJ/kg CONGRATULATIONS, IF YOUR ANSWERS ARE CORRECT YOU CAN PROCEED TO THE NEXT INPUT…

31. THE SECOND LAW OF THERMODYNAMICS J2006/9/31 INPUT 9.5.4 Reversible adiabatic (or isentropic) process For a reversible adiabatic process, the entropy remains constant, and hence the process is called an isentropic process. During this process, no heat is transferred to or from the fluid and this process will always appear as a vertical line on a T-s diagram. For an isentropic process, s1 = s2 From the non-flow equation, Q - W = (u2 – u1) and for an isentropic process Q=0 Therefore, we have W = u1 -u2 kJ/kg (9.17) In an isentropic process, all the work done to the fluid can be found in equation 9.17 by evaluating u1 and u2 from the Steam Tables. An isentropic process for superheated steam expanding into the wet region is shown in Fig. 9.5.4. T P1 P2 1 2 s1 = s2 s Figure 9.5.4 Adiabatic (or isentropic) process

32. THE SECOND LAW OF THERMODYNAMICS J2006/9/32 Example 9.5 Steam at 30 bar, 250 oC expands isentropically in a cylinder behind a piston to a pressure 10 bar. Calculate the work done per kg of steam during the process. Show the process on a T-s diagram. Solution to Example 9.5 At state 1 From the superheat tables, at 30 bar, 250 oC, we have s1 = 6.289 kJ/kg K u1 = 2646 kJ/kg At state 2 For an isentropic process s1 = s2, therefore we have s1 = s2 = 6.289 kJ/kg K At 10 bar and s2 = 6.289 kJ/kg K, the steam is wet, since s2 is less than sg2 (i.e. sg2 = 6.586 kJ/kg K). Then from equation 9.9 s 2 − s f 2 6.289 − 2.138 x2 = = = 0.933 s fg 2 4.448 From equation 8.5 u2 = uf2 + x2(ug2 – uf2) = 762 + 0.933 (2584 - 762) = 2461.9 kJ/kg For an adiabatic process, from equation 9.17 W = u1 -u2 = 2646 - 2461.9 = 184.1 kJ/kg i.e. Work done by the steam is 184.1 kJ/kg. T P1 = 30 bar P2 = 10 bar o 1 250 C 2 s1 = s2 s

33. THE SECOND LAW OF THERMODYNAMICS J2006/9/33 9.5.5 Polytropic process It is found that many processes in practice follows the reversible law in the form pvn = constant, where n is constant. Both steam and perfect gases obey this type of law closely in many processes. Such processes are internally reversible. For a polytropic process, the equations below are considered p1v1 − p2 v 2 Work done, W = (9.18) n−1 Heat transfer, Q = (u2 - u1) + W (9.19) Equation 9.18 is true for any working substance undergoing a reversible polytropic process. It follows also that for any polytropic process, we can write p1v1n = p2v2n = C n 1 p1 � v 2 � v 2 � p1 � n =� � ; =� � p2 � v1 � v1 � p2 � n −1 n −1 T2 � p2 � n T2 � v1 � =� � ; =� � T1 � p1 � T1 � v 2 � A polytropic process for wet steam expanding from a high pressure to a low pressure is shown in Fig. 9.5.5. To find the change of entropy in a polytropic process for a steam when the end states have been fixed using p1v1n = p2v2n, the entropy values at the end states can be read straight from the tables. T P1 1 P2 2 Q s1 s2 s Figure 9.5.5 Polytropic process

34. THE SECOND LAW OF THERMODYNAMICS J2006/9/34 Example 9.6 In a steam engine, the steam at the beginning of the expansion process is at 10 bar and dryness fraction 0.9. The expansion follows the law pv1.1 = constant, down to a pressure of 0.4 bar. Calculate the change of entropy and work done per kg of steam during the process. Show the process on a T-s diagram. Solution to Example 9.6 At 10 bar, from equation 9.8 s1 = sf1 + x1sfg1 = 2.138 + 0.9 (4.448) = 6.1412 kJ/kg K At 10 bar, vg1 = 0.1944 m3/kg, then from equation 8.2 v1 = x1 (vg1) = 0.9 (0.1944) = 0.175 m3/kg 1 � � 1.1 Then from equation v 2 = � p1 � , we have v1 � p 2 � � � 1 1 � p � 1.1 � 10 � 1.1 v 2 = v1 � 1 � = 0.175� �p � � = 3.265 m /kg 3 � 2� � 0.4 � At 0.4 bar, and v2 = 3.265 m3/kg, the steam is wet, since vg2 = 3.992 m3/kg . From equation 8.2 v2 = x2 (vg2) v2 3.265 ∴ x2 = = = 0.82 v g 2 3.992

35. THE SECOND LAW OF THERMODYNAMICS J2006/9/35 Then from equation 9.8 s2 = sf2 + x2sfg2 = 1.026 + 0.82 (6.643) = 6.4733 kJ/kg K Change of entropy, (s2 – s1) = 6.4733 - 6.1442 = 0.3321 kJ/kg K i.e.

Increase in entropy, (s2 – s1) is 0.3321 kJ/kg K. Hence work done by the steam, from equation 9.18 p1v1 − p2 v 2 W= n−1 (10 x10 2 x 0.175) − (0.4 x 10 2 x 3.265) = 1.1 − 1 175 − 130.6 = 0.1 = 444 kJ/kg i.e. Work done by the steam is 444 kJ/kg. T P1 = 10 bar 1 P2 = 0.4 bar pv1.1 = C 2 s1 s2 s

36. THE SECOND LAW OF THERMODYNAMICS J2006/9/36 Activity 9C 9.6 In a steam engine, steam at 110 bar, 400oC expands isentropically in a cylinder behind a piston until the pressure is 3 bar. If the work output during the expansion process is 165.5 kJ/kg, determine the final temperature of the steam. Show the process on a T-s diagram. 9.7 In the cylinder of a steam engine, wet steam expands from 8 bar, dryness fraction 0.87 to 0.5 bar according to a law pv1.02 = C. Determine the per kg of steam for the following: i. change of entropy ii. work done iii. heat flow to or from the cylinder walls Show the process on a T-s diagram.

37. THE SECOND LAW OF THERMODYNAMICS J2006/9/37 Feedback To Activity 9C9.6 The given quantities can be expressed as; P1 = 110 bar t1 = 400 oC P2 = 3 bar W = 165.5 kJ/kg Steam at 110 bar and 400 oC is at superheated region. The property tables for this condition do not list down the specific internal energy (u) and therefore it must be calculated from u1 = h1 – p1v1 From the Superheated Steam Tables, at 110 bar and 400 oC h1 = 3075 kJ/kg v1 = 2.350 x 10-2 m3/kg Hence, u1 = 3075 – (110 x 102 - 2.350 x 10-2) = 2816.5 kJ/kg For an adiabatic process, from equation 9.17 W = u1 - u2 u2 = u1 - W = 2816.5 – 165.5 = 2651 kJ/kg From the property tables for steam, ug at 3 bar is 2544 kJ/kg and hence the steam at state 2 must still be at superheat region. From the property tables for superheated steam, u2 = 2651 kJ/kg when the temperature is 200 oC. Hence, t2 = 200 oC

38. THE SECOND LAW OF THERMODYNAMICS J2006/9/38 T P1 = 110 bar 1 400 oC P2 = 3 bar 2 t2 = 200 oC s1 = s2 s Note : In this activity, although there is no heat transfer in an adiabatic process, the pressure, volume and temperature of the working fluid are changed. The work transfer during an adiabatic process is equal to the change in the internal energy of the fluid.

39. THE SECOND LAW OF THERMODYNAMICS J2006/9/399.7 At 8 bar, we have s1 = sf1 + x1sfg1 = 2.046 + 0.87 (4.617) = 6.063 kJ/kg K u1 = uf1 + x1(ug1 – uf1) = 720 + 0.87 (2577- 720) = 2335.6 kJ/kg At 8 bar, vg1 = 0.2403 m3/kg, then from equation 8.2 v1 = x1 (vg1) = 0.87 (0.2403) = 0.2091 m3/kg 1 ? ? 1.02 Then from equation v 2 = ? p1 ? , we have v1 ? p 2 ? ? ? 1 1 ? p ? 1.02 ? 8 ? 1.02 v 2 = v1 ? 1 ? ?p ? = 0.2091? ? = 3.169 m 3 /kg ? 2? ? 0.5 ? At 0.4 bar, and v2 = 3.169 m3/kg, the steam is wet, since vg2 = 3.239 m3/kg . From equation 8.2 v2 = x2 (vg2) v 3.169 ∴ x2 = 2 = = 0.978 v g 2 3.239 Then at 0.5 bar, we have s2 = sf2 + x2sfg2 = 1.091 + 0.978 (6.502) = 7.4499 kJ/kg K u2 = uf2 + x2(ug2 – uf2) = 340 + 0.978 (2483- 340) = 2435.9 kJ/kg

40. THE SECOND LAW OF THERMODYNAMICS J2006/9/40 i. Change of entropy, (s2 – s1) = 7.4499 - 6.063 = 1.3869 kJ/kg K i.e. Increase in entropy, (s2 – s1) is 1.3869 kJ/kg K. ii. Work done by the steam, p v − p2 v 2 W= 1 1 n−1 (8 x10 2 x 0.2091) − (0.5 x 10 2 x 3.169) = 1.02 − 1 167.28 − 158.45 = 0.02 = 441.5 kJ/kg i.e. Work done by the steam is 441.5 kJ/kg. iii. Heat flow, Q = (u2 – u1) + W = (2435.9 – 2335.6) + (441.5) = 541.8 kJ/kg i.e. Heat flow from the cylinder walls is 541.8 kJ/kg. T P1 = 8 bar 1 P2 = 0.5 bar pv1.02 = C 2 s1 s2 s

41. THE SECOND LAW OF THERMODYNAMICS J2006/9/41 SELF-ASSESSMENT You are approaching success. Try all the questions in this self-assessment section and check your answers with those given in the Feedback to Self- Assessment on the next page. If you face any problem, discuss it with your lecturer. Good luck. 1. Heat is transferred to a heat engine from a hot reservoir at a rate of 120 MW. If the net work done is 45 MW, determine the rate of waste heat rejection to a cold reservoir and the thermal efficiency of this heat engine. 2. Steam at 7 bar, entropy 6.5 kJ/kg K is heated reversibly at constant pressure until the temperature is 250 oC. Calculate the heat supplied per kg of steam and show on a T-s diagram the area, which represents the heat flow. 3. Steam at 70 bar, 300 oC expands isentropically in a cylinder behind a piston to a pressure 20 bar. During the process, determine the: i. dryness fraction at final state ii. initial and final specific internal energy iii. work done per kg of steam Show the process on a T-s diagram. 4. 0.05 kg of steam at 10 bar with dryness fraction 0.84 is heated reversibly in a rigid vessel until the pressure is 20 bar. Calculate the: i. change of entropy and ii. heat supplied Show the area, which represents the heat supplied on a T-s diagram. 5. Steam at 20 bar, 250 OC undergoes a reversible isothermal process to a pressure of 30 bar. Calculate the heat flow per kg of steam and state whether it is supplied or rejected. Sketch the process on a T-s diagram. 6. A steam engine which receives steam at 4 bar and dryness fraction 0.8 is expanded according to the law pv1.05 = constant to a condenser pressure of 1 bar. Calculate the change of entropy per kg of steam during the expansion. Sketch the process on a T-s diagram.

42. THE SECOND LAW OF THERMODYNAMICS J2006/9/42 7. Steam at 30 bar, 300oC expands isothermally and reversibly to a pressure of 0.75 bar. The steam is then compressed according to the law pv1.05= constant, until the pressure is 10 bar. Calculate per kg of steam the: i. total change of entropy ii. net heat flow iii. net work done Sketch the processes on a T-s diagram.

43. THE SECOND LAW OF THERMODYNAMICS J2006/9/43 Feedback to Self-Assessment Have you tried the questions? If "YES", check your answers now. 1. Q2 = 75 MW η = 37.5 % 2. Q = 274 kJ/kg 3. i. x2 = 0.896 ii. u1 = 2634 kJ/kg and u2 = 2423.9 kJ/kg iii. W = 210.1 kJ/kg 4. i. 0.704 kJ/kg K ii. 36.85 kJ 5. Q = -135 kJ/kg 6. (s2 – s1) = 0.381 kJ/kg K 7. ∑ ∆s = (s2 – s1) + (s3 – s2) = (1.808) + (-0.938) = 0.87 kJ/kg K ∑ Q = Q12 + Q23 = (1035.98) + (-573.15) = 462.83 kJ/kg ∑ W = W12 + W23 = (975.98) + (-692.5) = 283.48 kJ/kg