Engineering Thermodynamics
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Lecture 42
Examples related to exergy change & exergy destruction

Hello and welcome back. Today we will be discussing few problems related to Exergy.

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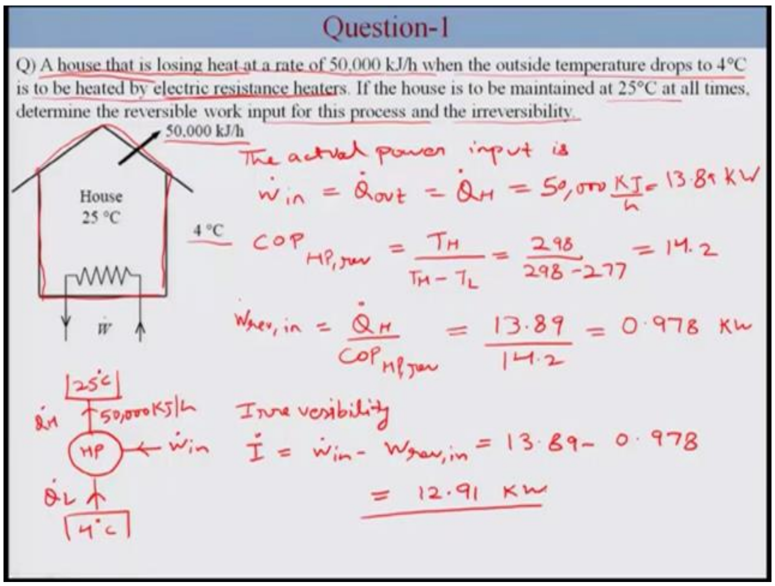

So in the first question, a house that is losing heat at a rate of 50000 kiloJoule per hour when the outside temperature drops to 4 degree Celsius is to be heated by electric resistance heaters. If the house is to be maintained at 25 degree Celsius at all the times, determine the reversible work input for this process and the irreversibility.

So uh this uh diagram shows the house which is uh maintained at 25 degree Celsius and it is losing heat at a rate of 50,000 kiloJoules per hour and the surroundings or the outside temperature is maintained at 4 degree Celsius. Now, it is heated using an electric resistance heater so the actual power input is W in dot which is also equal to the rate of energy which is going out and it is equal to QH dot and this is 50,000 kiloJoule per hour or it can be written as 13.89 kilowatt.

Now if we draw a heat pump so it is like heat pump which is used to maintain a temperature of

25 degree Celsius and this is QH dot which is equal 50,000 kiloJoule per hour and some work is being given as input and the outside temperature is 4 degree Celsius and this is QL dot.

Now, because the power which is lost by house is continuously supplied by resistance heater to maintain a constant temperature so the COP of this heat pump will be for a reversible process is TH which is 25 degree Celsius divided by TH minus TL and RL is 4 degree Celsius, so this becomes equal to 298.

So this is equal to 14.2. Thus the reversible work input is QH dot divided by COP on the heat pump so this is coming from the definition of COP so COP is QH dot divided by W reversible in dot so QH dot is 19.89 divided COP which is 14.2 so reversible work input is 0.978 kilowatt and we also need to determine irreversibility so irreversibility is I dot is equal to actual work input minus the reversible work input well this is equal to 13.89 minus 0.978 and this is equal to 12.97 kilowatt so this is the irreversibility of this process.

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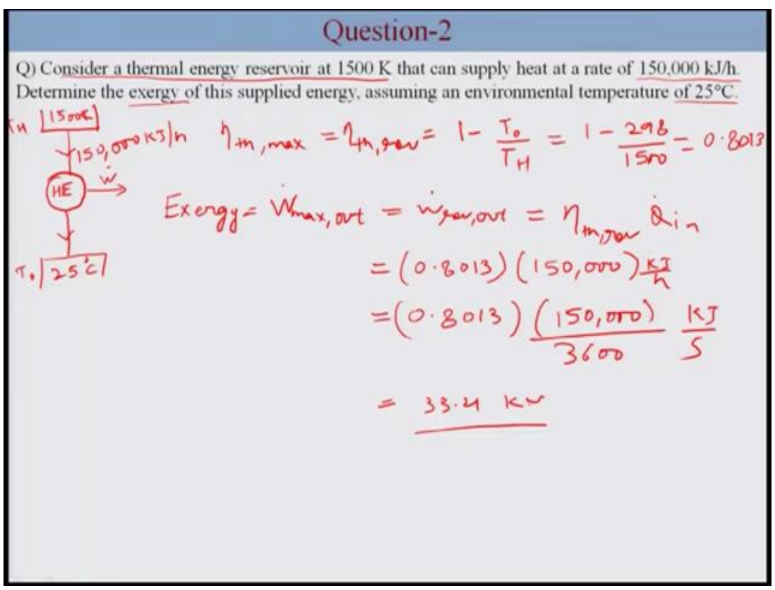

Moving onto the next question and this question, consider a thermal energy reservoir at 1500 Kelvin that can supply heat at a rate of 150000 kiloJoule per hour. Determine the Exergy of this supplied energy assuming the environmental temperature at 25 degree Celsius. So for this, if we take it as a heat engine, so it takes an energy from a reservoir which is at 1500 Kelvin and it is supplying heat at a rate of 150000 kiloJoule per hour and the environmental temperature is 25 degree Celsius and some work is being produced so we have to calculate the Exergy of this supplied energy.

Now the thermal efficiency of this heat engine is, for a reversible process is 1 minus T0 by TH so T0 is the environmental temperature and TH is the temperature of the reservoir, so this is equal to 1 minus 298 divided by 1500 so this is equal to 0.8013. Now, the Exergy of the supplied heat in the rate form is the amount of power that will be produced by reversible heat engine, so Exergy is equal to maximum work out or it is also equal to the reversible work which comes as a output and this can be written in for of efficiency.

Maximum efficiency multiplied by the heat which has given us input so this is equal to 0.8013 multiplied by Q in which is 150,000 kiloJoule per hour so this is equal to 0.8013 multiplied by converting R into second so it it will be 3600 kiloJoule per second and this comes out to be 33.4 kilowatt so this is the Exergy of the supplied energy.

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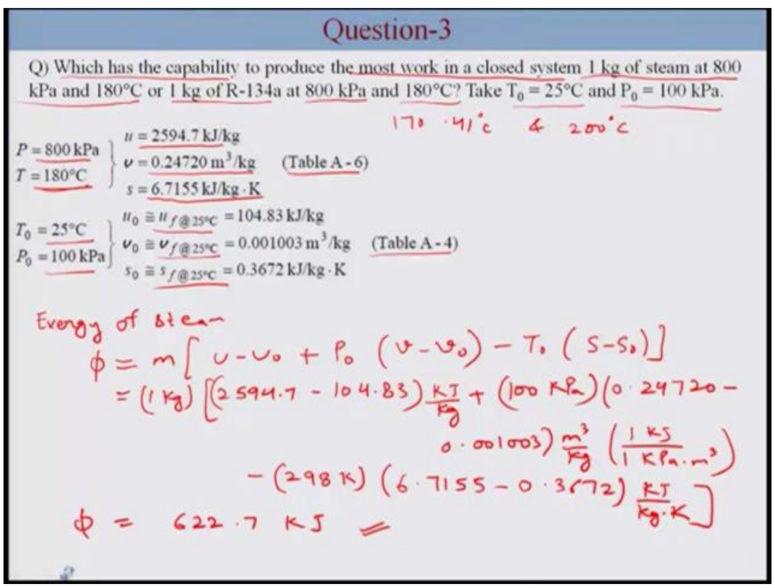

Now, in the next question, which has the capability to produce most work in a closed system? 1 kg of steam at 800 kiloPascal and 180 degree Celsius or 1 kg of R314A refrigerant at 800 kiloPascal and 180 degree Celsius. The surroundings are at 25 degree Celsius and the pressure is 100 kiloPascal so we have to compare which has the more capability, 1 kg of steam or 1 kg of refrigerant at the same conditions.

So uh first uh taking steam into consideration. So for steam the conditions are 800 kiloPascal and 180 degree Celsius so if we see from table A6 at this, we will find in the table the values are given for 170.41 degree Celsius and 200 degree Celsius. Now, to calculate the values, we need to interpolate between these 2 temperatures to get the values at 180 degree so after interpolation, we get the values as U is 2594.7, specific volume is 0.24720 and entropy as 6.7155.

For the environmental conditions uh it is at 25 degree Celsius and 100 kiloPascal, we can directly obtain these values from the table A4 at 25 degree Celsius and these are the properties of saturated liquid. Now the Exergy of the steam is a measure of the work potential, so if we calculate Exergy of steam so this equal to m (U minus Uo) plus P not which is the pressure of the surrounding into V minus V knot minus T0 (S minus S0).

Now putting all the values, mass is 1 kg, U is 2594.7 minus U0 is 104.83 plus uh pressure is 100 kiloPascal. V minus V0 is 0.24720 minus 0.001003 meter cube per kg and converting the units and making all the units consistent so 1 kiloJoule is equal to 1 kiloPascal meter cube so this will make the units consistent minus T0 which is 298 Kelvin multiplied by S minus S0 so S is 6.7155 minus S0 which is 0.3672 and this is kiloJoule per kg Kelvin so this gives a value of 5 which is equal to 622.7 kiloJoule. So this is the uh capability of the steam to produce work so this much work can be produced by the steam.

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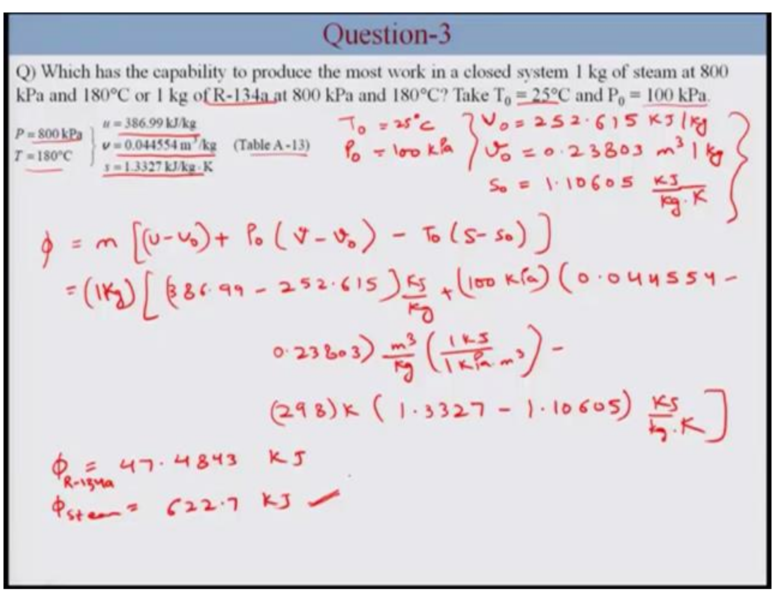

Now moving onto the refrigerant R134A so at the given conditions, 800 kiloPascal and 180 degree Celsius, the values from the table A13 are, U is this, V specific volume is his and entropy is this. Now, for the environmental conditions, that is 25 degree Celsius and 100 kiloPascal, it is again super heated so we need to see the values so at T0 is equal to 25 degree Celsius and P0 is equal to 100 kiloPascal, these values are U0 is equal to 252.615 kiloJoule per kg, V0 is equal to 0.23803 meter cube per kg and S0 is equal to 1.10605 kiloJoule per kg Kelvin.

Now these values are obtained by interpolating between 20 and 30 degree Celsius because directly the values are not given in the table A13. Similar procedure is followed as done for steam so Phi Exergy is given as m(U minus U0) plus P0(V minus V0) minus T0(S minus S0). Putting all the values so mass is 1 kg, U is 386.99 minus U0 is 252.615 kiloJoule per kg plus P0 is 100 kiloPascal multiplying this by V minus V0 so V is 0.044554 minus V0 is 0.23803 and it is meter cube per kg. Again 1 kiloJoule is equal to 1 kiloPascal meter cube minus T0 which is 298 Kelvin to S 1.3327 minus S not which is 1.10605 kiloJoule per kg Kelvin.

Um this gives a value of Phi which is equal to 47.4843 kiloJoule so if we compare the 2 values for the steam, the value is so Phi steam is equal to 622.7 kiloJoule and thus for refrigerant that is R134A this value is 47.4843 so uh for steam, the Exergy is more so it has the more potential to do work or it has a more capability to produce work.

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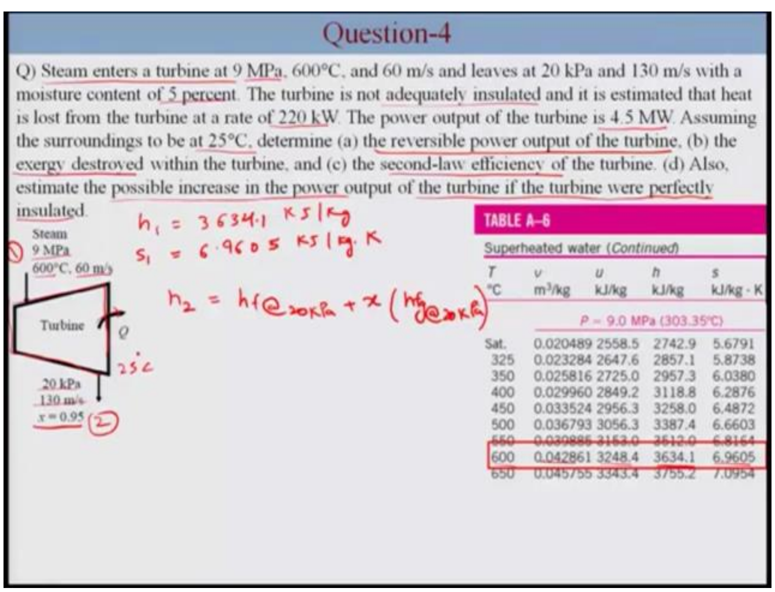

Moving onto next question, in the question, steam enters the turbine at 9 megaPascal. This is the turbine. Steam enters at 9 megaPascal, 600 degree Celsius and 60 meter per second and leaves at 20 kiloPascal 130 meter per second with a moisture content of 5%, so this 5% means X is 0.95.

The turbine is now not adequately insulated so some amount of heat is going out as it is not properly insulated and it is estimated that heat is lost from the turbine at a rate of so this is the heat loss from the turbine so Q dot is 220 kilowatt. The power output of the turbine is, so this is the work produced by the turbine 4.5 mega watt. Assuming the surroundings to be at 25 degree Celsius so outside is at 25 degree Celsius. Determine the reversible power output of the turbine so there are various quantities we need to find.

Second is the Exergy destroyed within the turbine, second law efficiency and also the possible increase in the power output of the turbine if the turbine were perfectly insulated. So moving step by step uh if we find the properties of the steam at the inlet and exit state so uh at 9 megaPascal and 600 degree Celsius from the steam table, at 600 degree Celsius as this is a super heated steam so from super heated water table at 600 degree Celsius, we can uh we know a specific volume, internal energy, enthalpy and entropy.

So h1 is is equal to this is taken as point 1, this is taken as point 2 so h1 is equal to 3634.1 from this table kiloJoule per kg. S1 is equal to 6.9605 kiloJoule per kg kelvin. Now uh for water, it is already given in the question that it is a mixture of liquid and vapor so we can find h2 from hf at 20 kiloPascal because the pressure is 20 kiloPascal plus X which is 0.95 multiplied by hfg a 20 kiloPascal.

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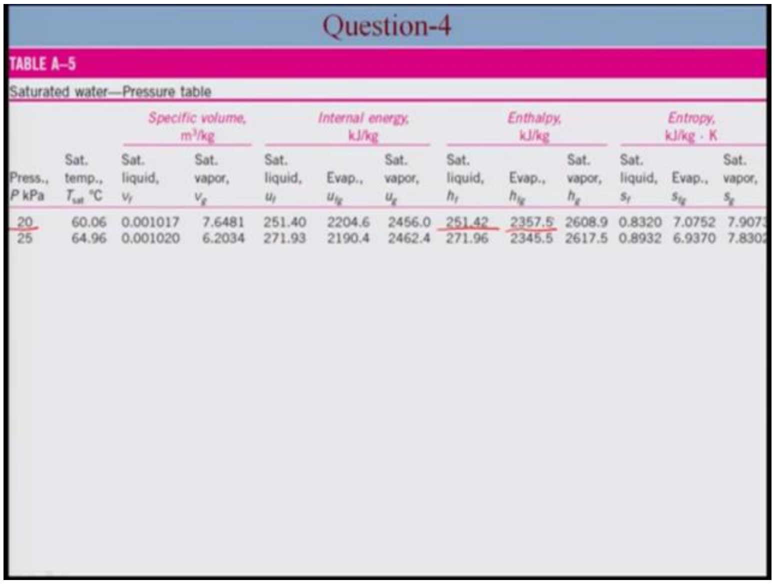

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/kg · K: Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302

Now for obtaining these values, we need to see the table of saturated water so at 20 kiloPascal, we can find that hf is 251.42, hfg is 2357.5 and also entropy Sf is 0.8320 and Sfg is 7.0752 so putting these values.

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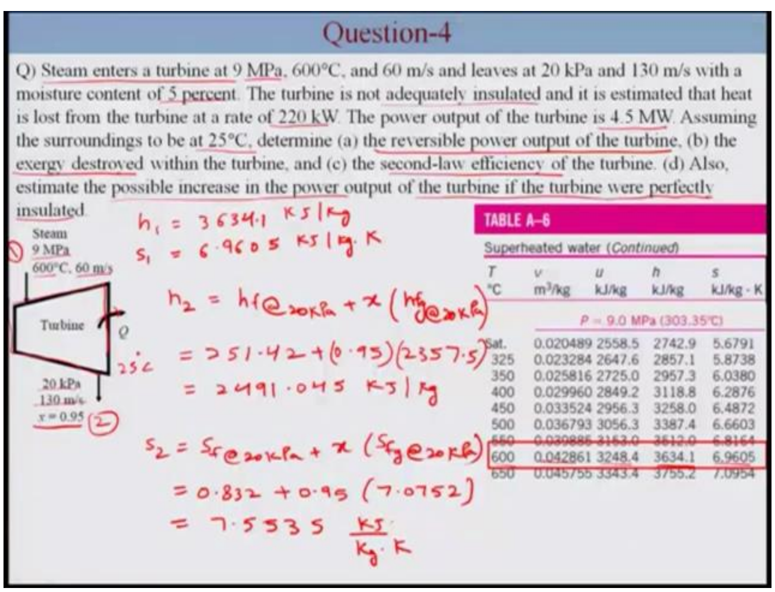

So obtain h2 so h2 is equal to 251.42 plus 0.95 multiplied by 2357.5 and this gives h2 is equal to 2491.045 kiloJoule per kg. Similarly S2 is obtained which is equal to Sf at 20 kiloPascal plus X multiplied by Sfg at 20 kiloPascal so this is equal to 0.83 to as shown earlier in the table of saturated water vapor so S2 comes out to be 7.5535 kiloJoule per kg kelvin.

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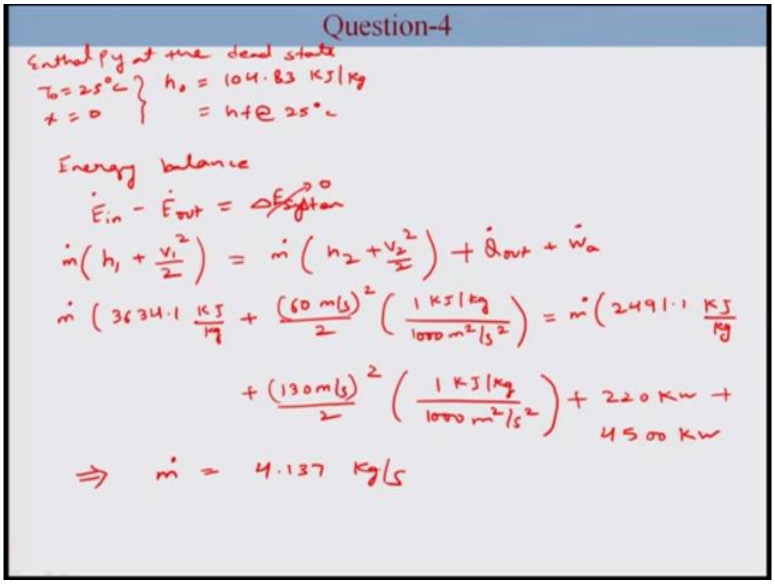

Calculating the enthalpy at the dead state so T0 is equal to 25 degree Celsius and X is equal to 0 so from table, h0 is equal to 104.483 kiloJoule per kg and this is equal to hf so this value is hf at 25 degree Celsius. The mass flow rate of steam can be determined from energy balance on turbine so energy balance on turbine will be E in dot minus E out dot is equal to delta E of the system so delta E of system is 0 for steady flow process.

Now, energy in is the energy of this steam which is entering the turbine so that is equal to mass times h1 enthalpy plus because of the velocity with which (is) it is entering so it is the kinetic energy contribution and this is equal to E out so E out is mass because mass entering is equal to mass leaving so m dot 2 multiplied by h2 plus V2 square by 2 plus uh there is some heat loss plus some work is produced by the turbine.

So putting all the values, h1 is 3634.1 kiloJoule per kg plus the velocity at the inlet is 60 meter per second. Converting the units, this is equal to m dot so h2 is 2491.1 kiloJoule per kg plus 130 meter per second which is the velocity at the exit divided by 2. Now, 1 kiloJoule per kg is equal to 1000 meter square per second square. Also uh 220 kilowatt of heat is being lost by the turbine because of uh imperfect insulation and also 4500 kilowatt of work is produced by the turbine so this equation gives a value of m dot which is the mass flow rate of steam that is 4.137 kiloJoule per second.

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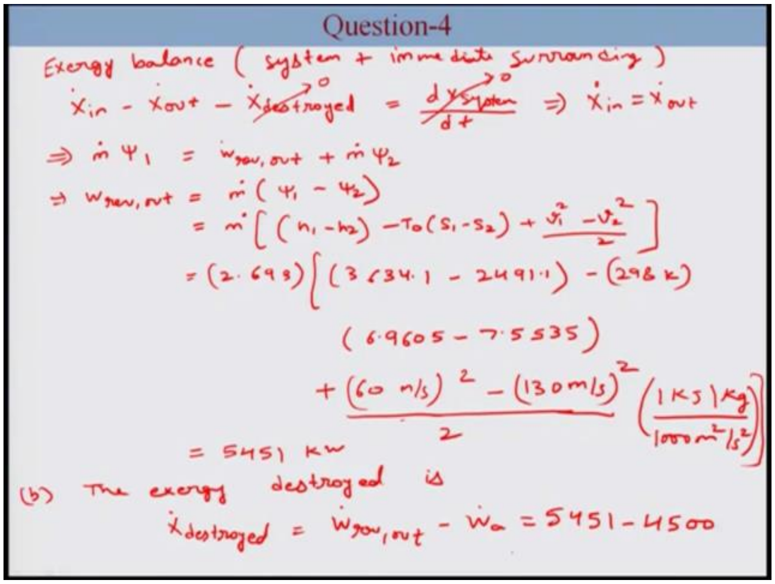

For calculating the reversible power output, we can apply an Exergy balance on the system and its immediate surrounding and setting the Exergy destruction equal to 0 so X in dot minus X out dot minus X dot destroyed is equal to dX of system divided by dT so this is 0 for a steady flow system and this is also made 0 to obtain the reversible work output so from this, we get X in dot is equal to X out dot. This can be written as mass flow rate time and this is equal to reversible work output plus.

So from here reversible work output is m dot Psi1 minus Psi2 so this is equal to h1 minus h2 minus T0 s1 minus s2 plus V1 square minus V2 square by 2. Putting all the values, m is 2.693, h1 is 3634.1 minus 2491.1 minus T0 which is 298 Kelvin multiplying this by S1 minus S2 so S1 is 6.9, 605 minus S2 is 7.5535 plus 60 meter per second divided by 130 meter per second, the out velocity at the exit so multiplying this by 1 kiloJoule per kg for converting the units which is equal to 1000 meter square per second square.

So this gives uh reversible work output of 5451 kilowatt. Now the second part is we have to calculate the Exergy destroyed within the turbine so the Exergy destroyed is that is X destroyed equal to reversible work minus the actual work so this is uh reversible work is 5451 minus the actual work produced is 4500 so this is equal to 951 kilowatt.

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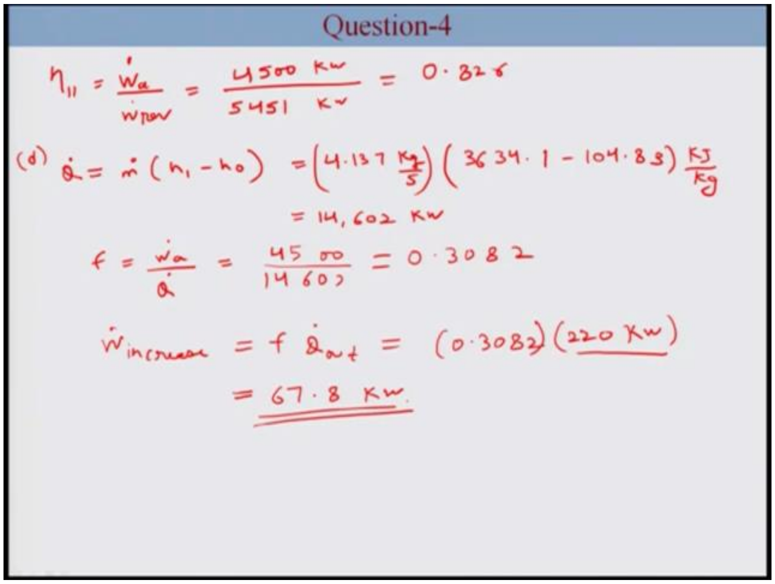

Next part is to calculate the second law efficiency of the turbine so second law efficiency is actual work divided by the reversible work so this is equal to 4500 kilowatt divided by the reversible work that is 5451 kilowatt so uh it comes out to be 0.826. In the next part, we have to calculate the possible increase in the power output of the turbine if the turbine works perfectly insulated, so to calculate the increase in the power, we know the energy of the steam at the turbine inlet at the given dead state is so X energy of the steam at the turbine inlet for a given dead state is Q dot which is equal to m mass flow rate multiplied by h1 minus h not so we know mass (flo) (ful) flow rate which is 4.137 kg per second and h1 is 3634.1 minus 104.83 kiloJoule per kg.

Now so this is equal to 14602 kilowatt so the fraction of energy at the turbine inlet that is converted to power is f is equal to actual work divided by the energy of the steam so this is equal to 14500 divided by 14602 so this is the fraction of energy which is converted to power. Now, if we assume that the same fraction of heat loss from the turbine could have been converted to work, the possible increase in the power would be, if the turbine is well insulated so increase will be this fraction multiplied Q out dot which is equal to 0.3082 into 220 so a fraction of this which is uh wasted would have been converted into a useful work, so this these many kilowatts could have been converted into useful work.

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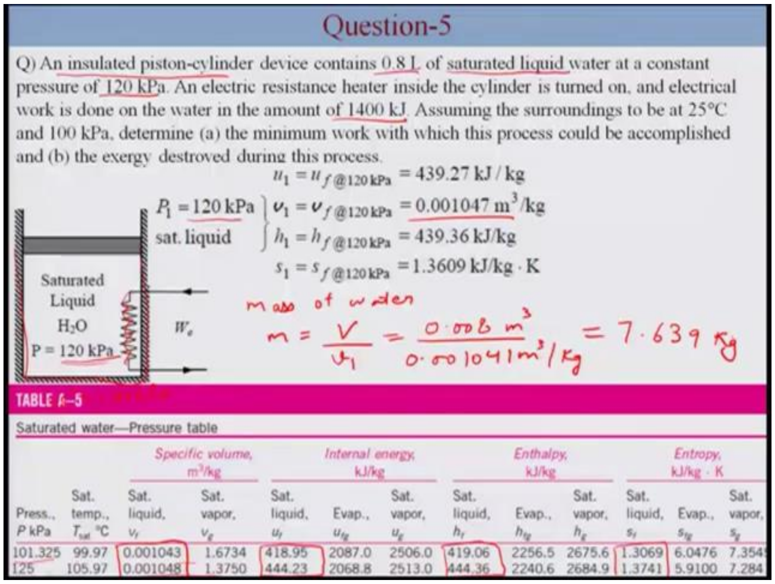

In the next question, an insulated piston cylinder device contains 0.8 liter of saturated liquid water at a constant pressure of 120 kiloPascal so this pressure is maintained and electric resistance heater, so this is the heater inside the cylinder is turned on and the electrical work is done on the water in the amount of (su) this is the amount of work done by this resistance heater, assuming a surroundings to be at 25 degree Celsius so surroundings are at 25 degree Celsius and 100 kiloPascal, determine the minimum work with which this process could be accomplish and the Exergy destroyed during the process.

So if we find the properties at the given state inside the piston cylinder device or uh in the surrounding so for both, uh from this table, saturated water pressure table, at uh 120 kiloPascal so we find the the values are not given at 120 kiloPascal rather than (val) we need we need to calculate the values at 120 kiloPascal by interpolating between 101325 and these values and at a pressure of 125 kiloPascal.

So uh after interpolating we get the values at 120 kiloPascal so as this is mentioned that this is a saturated liquid, so all the values are obtained, U1 which is obtained by interpolating between these 2 values for 120 kiloPascal. Similarly V1 is obtained by interpolating between these 2 values to obtain the value at 120 kiloPascal. Similarly h1 is obtained from these 2 values and S1 from these 2 values.

Similarly all the other properties like hfg, Sfg can be calculated by interpolating if required so the mass of the water in this device will be so mass is equal to total volume which is 0.8 liter divided by the specific volume so this is equal to 0.008 meter cube divided by specific volume which is 0.001047 meter cube per kg. So the mass of the liquid is 7.639 kg.

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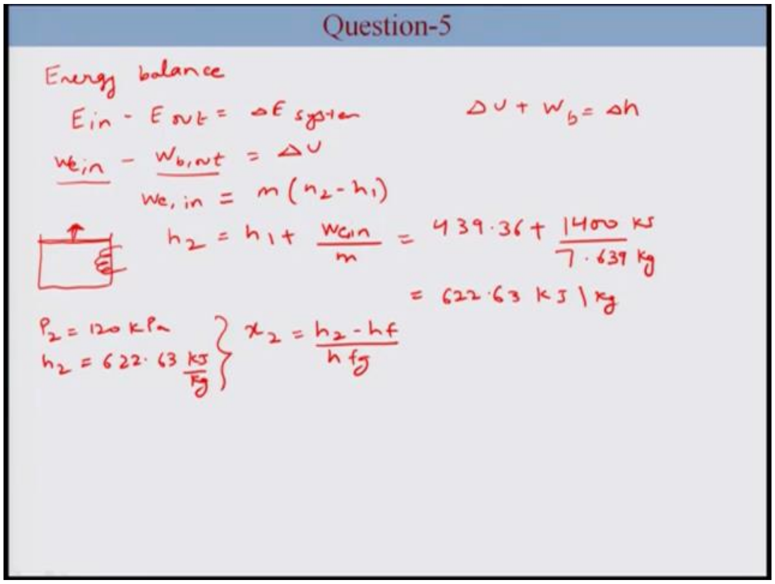

Now, we take the contents of the cylinder as the system so cylinder contents of the cylinder are taken as the system so this is a closed system. Since no mass enters and leaves so energy balance for this stationary system will be E in minus E out is equal to delta E of the system.

Now, this can be written as WE in minus this is the work when the system is heated because of the this resistance heater so some work is done because this piston is being pushed up and this is the electrical work which is given as input. This is equal to delta U, change in internal energy of the system.

Now we can write delta U plus Wb is equal to delta h so this is the change in the enthalpy of the system. During a constant pressure quasi equilibrium process, from this, this is written as m(h2 minus h1) so from here so this is delta h so this is the m(h2 minus h1) so from here we can calculate h2 is equal to h1 plus electrical work given as input divided by mass. Now, we know all the values. We can put h1 is 439.36 plus electrical work input is 1400, mass is 7.639 so this comes out to be 622.63 kiloJoule per kg.

Now we know the enthalpy at state 2. It is also known the pressure at state 2 is 120 kiloPascal and h2 is 622.63 kiloJoule per kg so from here we can calculate X2 so X2 is equal to h2 minus hf divided by hfg, from the value of hfg at 120 kiloPascal from the previous table.

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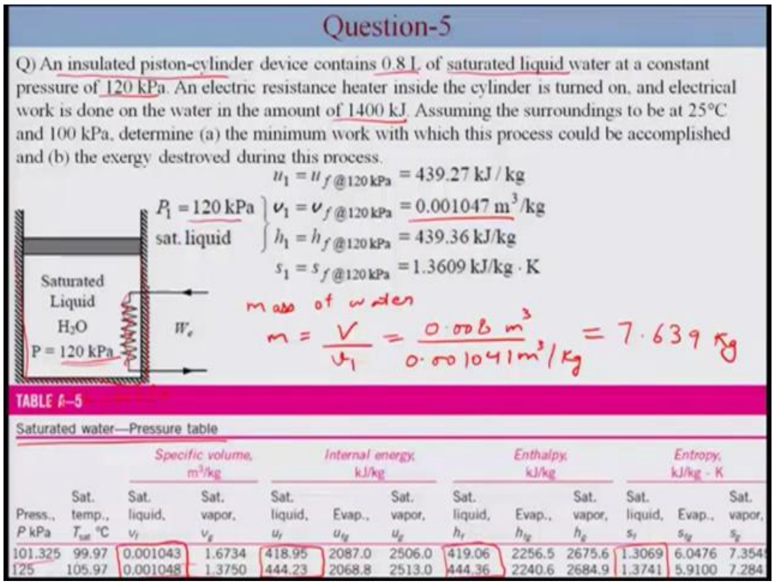

From this table by interpolation…

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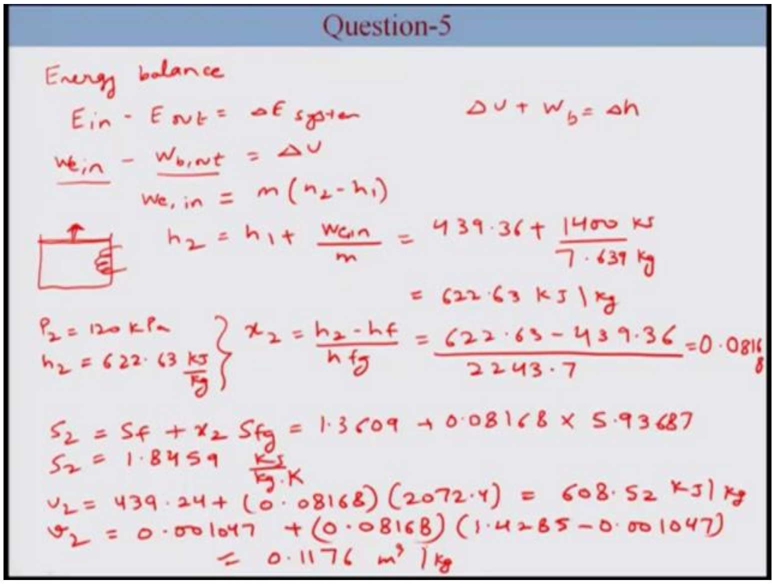

We can get the value of X2 so this is equal to 622.63 minus 439.36 divided by 2243.7 and it is equal to 0.08168. Similarly the value of S2 is equal to Sf at 120 kiloPascal plus X2 multiplied by Sfg so this is equal to 1.3609, 0.08168 multiplied by Sfg which is 5.93687 so this gives S2 is equal to 1.8459 kiloJoule per kg kelvin.

Similarly U2 is equal to Uf so I am directly writing the values plus X into Ufg which is 2072.4 so this is equal to 608.52 kiloJoule per kg and V2 is equal to Vf which is 0.001047 plus 0.08168 this is X2 multiplied by Vfg. This is equal to 1.4285 minus 0.001047 and this value comes out to be 0.1176 meter cube per kg. Now, we know the different properties at the exit state. The reversible work input which represents the minimum work input in this case can be determined from the Exergy balance by setting Exergy destruction equal to 0.

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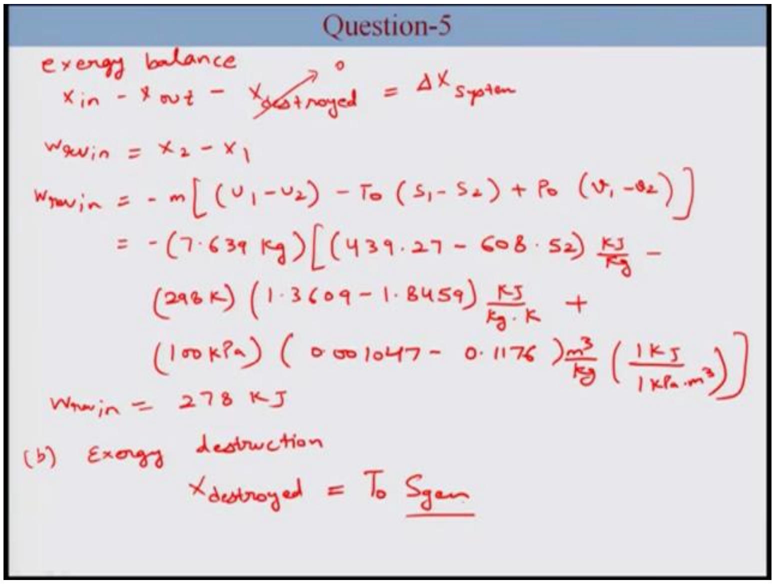

So uh applying Exergy balance uh which is X in minus X out minus X destroyed is equal to delta X of the system. Exergy destroyed is set to 0 so from here, we get work reversible input is equal to X2 minus X1. X1 represents the initial state and X2 represents the final state so work reversible input is equal to minus m (U1 minus U2) minus T0(S1 minus S2) plus P0(V1 minus V2) so this is equal to minus 7.639 kg multiplied by U1 minus U2 which is 439.27 minus 608.52 kiloJoule per kg minus 298 kelvin which is T not minus S2 minus S1 which is 1.3609 minus 1.8459 kiloJoule per kg kelvin plus P know V1 minus V2 so which is equal to 100 kiloPascal multiplied by 0.001047 minus 0.1176 meter cube per kg and making the units consistent so 1 kiloJoule is equal to 1 kiloPascal meter cube so this gives a value of reversible work input as 278 kiloJoules.

Now the second part is we have to calculate the Exergy destroyed during this process so b is Exergy destruction so Exergy destruction can be determined from its definition as Exergy destroyed is equal to T0 into S gen where entropy generation is determined from the this term is determined from the entropy balance on the cylinder which is an insulated closed system.

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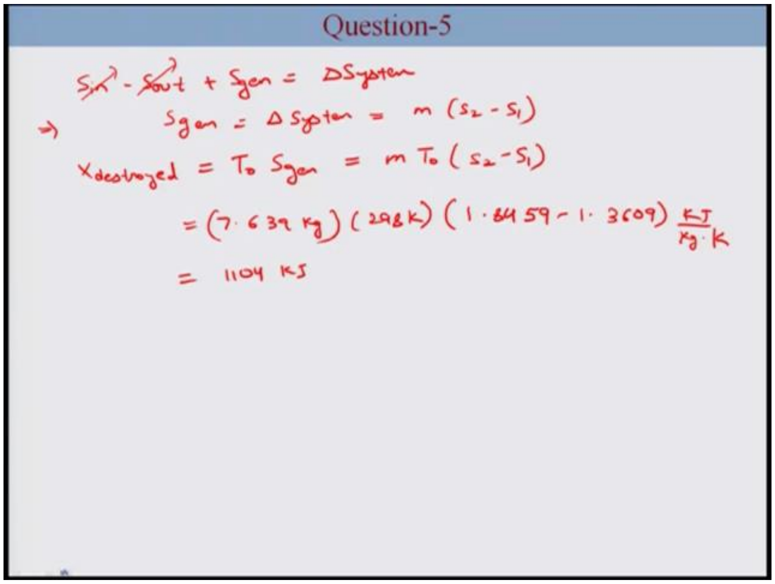

So applying entropy balance, S in minus S out plus S gen is equal to change in entropy of this system. From here uh these 2 will be 0 so we get S gen is equal to delta S of system and this is equal to m (S2 minus S1). Now substituting X destroyed is equal to T not S gen so this is equal to m T not (S2 minus S1) and putting all the values, m is 7.639 kg, T not is 298 kelvin, S2 is 1.8459 and S1 is 1.3609 that is kiloJoule per kg Kelvin, so this value comes out to be 1104 kiloJoule so Exergy destroyed is 1104 kiloJoule. (Flipping pages).

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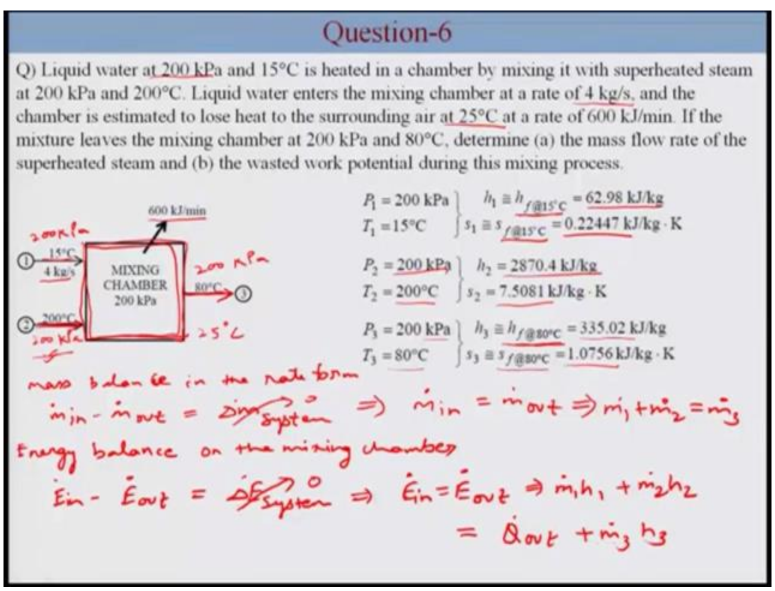

Moving onto the next question where a liquid water at 200 kiloPascal so this is a liquid water at 200 kiloPascal and 15 degree Celsius so temperature is 15 degree Celsius is heated in a chamber by mixing it so this is a mixing chamber so this water is heated in this. Mixing it with the super heated steam so this is a super heater steam at 200 kiloPascal and 200 degree Celsius.

Liquid water enters the mixing chamber at a rate of 4 kg per second so this is the mass flow rate and the chamber is estimated to lose heat to the surrounding air at 25 degree Celsius, so surroundings are at 25 degree Celsius and this heat is lost to the surrounding at this rate. If the mixture leaves the mixing chamber at 200 kiloPascal so this final mixture comes out at 200 kiloPascal and 80 degree Celsius. Determine the mass flow rate of the super heated steam so this is a super heated steam so for this we have to determine the mass flow rate and the wasted work potential during this mixing process.

So uh for the first steam, it will be uh see from the table this is a compressed liquid so we can approximate this compressed liquid from the properties of the liquid at the it's temperature that is 15 degree Celsius so enthalpy at state 1, h1 properties hf at 15 degree Celsius which is 62.98. The entropy would be the value sf at 15 degree, 15 degree Celsius which is 0.22447. Now for this state 2, uh it is uh at 200 kiloPascal and 200 degree Celsius, it is in super heated steam so from the super heated table at these conditions, h2 is 2870.4 and S2 is 7.5081.

While the uh the steam which is leaving is at 200 kiloPascal and 80 degree Celsius, it is again compressed liquid so the properties are estimated from those of the saturated liquid at the corresponding temperature which is 80 degree Celsius so h3 is hf at 80 degree Celsius which is 335.02 and entropy is entropy of the liquid at 80 degree Celsius which is 1.0756.

Now taking this um this mixing chamber as a system, the mass and energy balance can be applied so if we apply mass balance in the rate form, so mass which is entering minus mass which is going out is equal to change in mass of the system so this is a steady flow system so this is equal to 0, so it gives m in dot is equal to m out dot so from here a mass entering is this steam 1 is entering and this 2 is entering so m1 dot plus m2 dot is equal to m3 dot.

Now, applying energy balance on this mixing chamber in the rate form so E in dot minus E out dot is equal to rate of change of energy of the system so again this rate of change of energy is 0 because of steady flow system. E in is equal to E out so this gives m1 dot h1 which is the enthalpy of steam 1 plus m2 dot h2 which is the enthaply of steam 2 so these 2 are entering so this is equal to E in and E out is equal to heat which is being wasted or uh lost to the surrounding plus enthaply of the steam which is coming out that is m3 dot h3.

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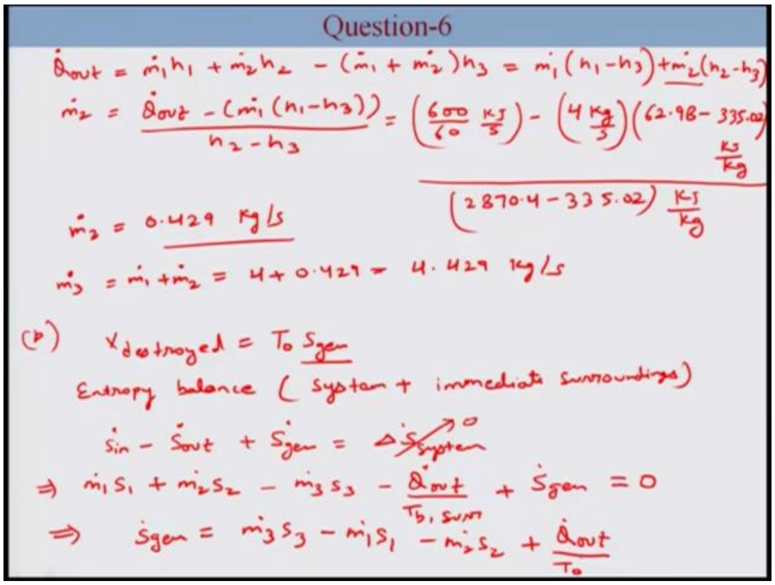

Now combining these above 2 relations of mass and energy balance, from here we can Q out dot is equal to m1 dot h1 plus m2 dot h2 minus m1 dot plus m2 dot h3 so this is equal to m1 dot h1 minus h3 plus m2 dot h2 minus h3. From here, solving for m2, so we will get m2 is equal to Q out dot minus m1 dot h1 minus h3 divided h2 minus h3, so putting uh all the values Q out is 600 by 60 kiloJoule per second minus mass flow rate which is (4) m1 dot which is 4 kg per second uh multiplying this by 62.98 minus 335.02 so this is in kiloJoule per kg.

Dividing the entire expression by h2 minus h3 which is 2870.4 minus 335.02 and this is in kiloJoule per kg so this gives a value of m2 dot which is equal to 0.429 kg per second, so this is the flow rate of the super heated steam which is entering. From this we can also determine the final mass which is coming out of the mixing chamber that is m3 dot which is equal to m1 plus m2 dot and this is equal to 4 plus 0.429 which comes out to be 4.429 kg per second.

Now in the second part, we have to determine the wasted work potential during this mixing process so in part B, so the Exergy destroyed during a process can be determined from the

Exergy balance or directly from its definition that is Exergy destroyed is equal to T0 S gen which is the entropy generated so this entropy generated can be determined from the entropy balance so entropy balance on the system and its immediate surrounding uh it gives S in dot minus S out dot plus entropy which is generated is equal to delta S dot of the system so again this will be 10 because of the steady flow conditions.

Now entropy in is m1 dot S1 plus m2 dot S2 minus which is leaving is m3 dot S3 minus because of the heat which is going out, Q out dot this is temperature of the surrounding plus S dot gen entropy generator is equal to 0 so from here, we can get entropy generated is equal to m3 dot S3 minus m1 dot S1 minus m2 dot S2 plus Q dot out divided by T not which is the outside temperature.

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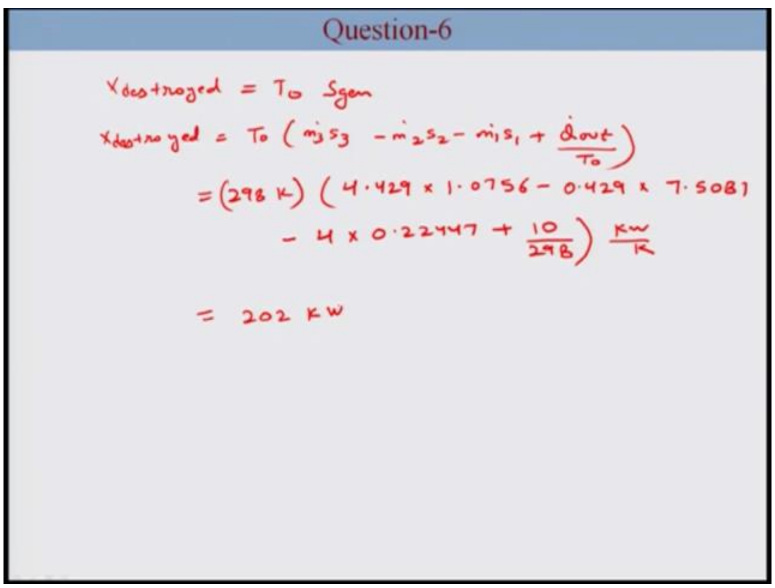

Now, substituting all the values and uh as Exergy destroyed is equal to (2) (ze) T not S gen so substituting the value of S gen from here (flipping pages) we can calculate X destroyed as T0 m3 dot S3 minus m2 dot S2 minus m1 dot S1 plus so this is 298 kelvin T not minus m3 4.429 into uh S3 which is 1.0756 minus m2 0.429 into S2 which is 7.5081 minus m1 is 4 into S1 is 0.22447 plus Q dot out is 10 when it is converted into kiloJoule per second divided by T not which is 298. So, so this comes out to be 202 kilowatt so the total Exergy (des) destroyed or the work wasted work potential during this mixing process is 202 kilowatt so this ends this lecture and we will see you in the next lecture. Thank you.