Concepts of Thermodynamics
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Lecture – 48
Entropy Transport for a Flow Process: Examples

In the previous lecture, we were discussing about entropy transport across the control volume. We will now start solving some problems which will illustrate those concepts that we developed in the previous lecture.

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Problem 7.1: A small turbine delivers 150 kW and is supplied with steam at 700°C, 2 MPa. The exhaust passes through a heat exchanger where the pressure is 10 kPa and exits as saturated liquid. The turbine is reversible and adiabatic. Find the specific turbine work and the heat transfer in the heat exchanger.

Ans: $w_t = 1397.05\ kJ/kg$; $\dot{Q}_{HX} = -250\ kW$

So, we start with this problem; problem 7.1. A small turbine delivers 150 kilowatt and is supplied with a steam at 700 degree centigrade 2 megapascal. The exhaust passes through a heat exchanger where the pressure is 100 kilopascal and it exits as saturated liquid. The turbine is reversible and adiabatic. Find the specific turbine work and heat transfer in the heat exchanger.

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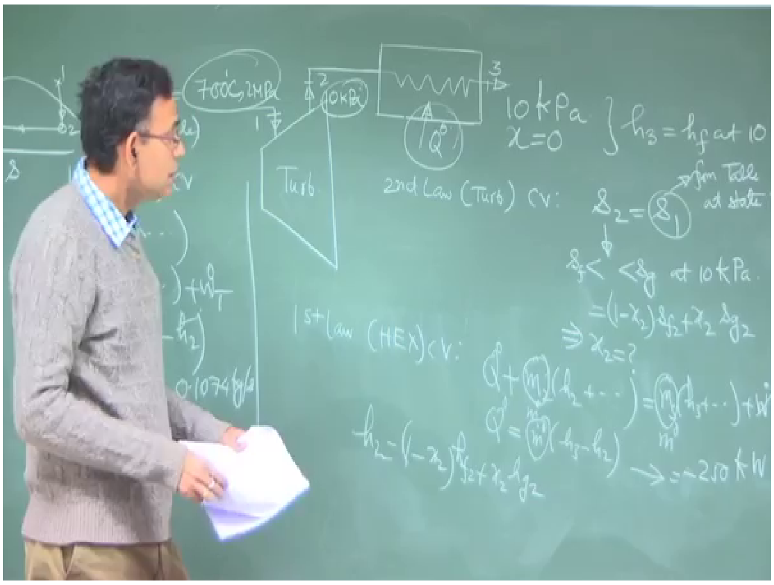

So, let me draw a schematic of this problem in the board. So, this is state 1, after expansion it comes through state 2 and then it passes through a heat exchanger and comes out at state 3. State 1 is 700 degree centigrade 2 MPa it completely defines state 1. So, this is waters I mean steam basically, state 2 it is 10 kilopascal that is known state 3 is also 10 kilopascal and quality is 0, saturated liquid ok.

The turbine is reversible and adiabatic ok. Even if it was not told that the turbine is adiabatic, we could have guessed, why? See there is a keyword in the problem statement small turbine because it is small it has maybe negligible area a surface area for heat transfer to take place and; that means, it can be approximated as adiabatic. But here explicitly in a problem it is given that it is reversible and adiabatic because it is reversible and adiabatic if we apply the second law for the turbine as the control volume.

You can write s 2 is equal to s 1, reversible and adiabatic. So, if you; so, how do you know what is s 1. So, from table of steam at state 1 ok. So, once you know this you will see that this is I mean the value s 2 this is between s f and s g at 10 kPa. So, this will be between s f and s g at 10 kPa, if you look into tha table you will get this is very common for practical for practical situation that turbine exhaust is a two phase system. So, from common engineering practice we know this you can verify this from the table. So, then you can write this s 2 as 1 minus x 2 into s f 2 plus x 2 into s g 2.

So, from here you can find out what is x 2 because s f and s g you get from the table at 10 kPa what is s f and s g. So, you get what is x 2; once you get what is x 2, you can calculate all properties at state two; for example, specific volume or whatever you require ok. So, in this case what do you require? You require is the heat transfer in the heat exchanger. So, there is a Q dot. So, you apply the first law for the heat exchanger as control volume.

If you apply that you have Q dot plus m dot 2 into h 2 plus you know the kinetic energy, potential energy terms for almost all problems that we will be solving those terms are not important. So, to save time I will just write dot dot is equal to m dot 3 h 3 plus you know w dot is 0, heat exchanger has only heat transfer it exchanges heat with the ambient in this case.

So, Q dot is equal to an m dot 2 and m dot 3 they are all the same they are m dot. So, m dot into h 3 minus h 2. h 3 pro is nothing but h f at 10 kPa right. And, what is h 2? h 2 is 1 minus x 2 into h f 2 plus x 2 into h g 2 where h f and hg at 10 kPa. So, if you substitute these values you will get what is Q dot. So, first of all to get Q dot see there is another parameter that needs to be obtained and that is m dot right, nobody has given what is m dot here, but what is given is what is the turbine work, you can indirectly calculate m dot from here.

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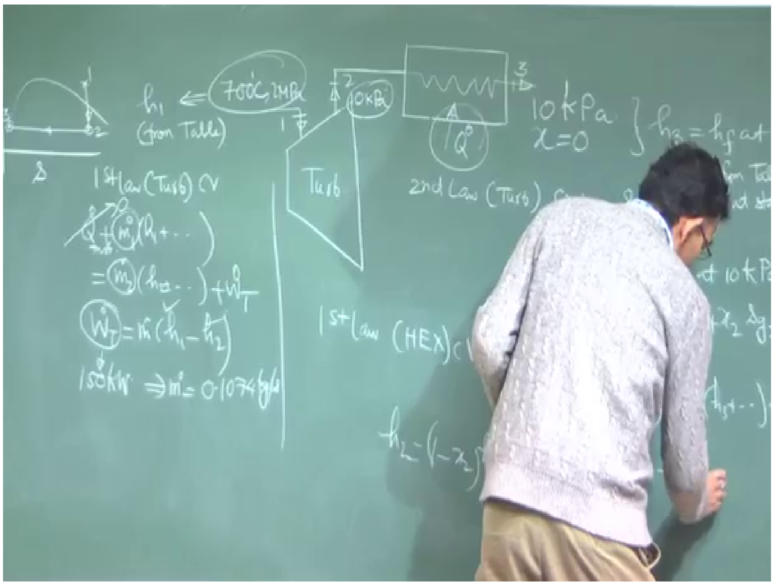

So, if you apply first law for turbine as control volume. So, you have Q dot plus m dot 1 into h 1 plus w dot turbine right, Q dot turbine is 0, m dot 1 and m dot 2 are m 1. So, w dot turbine is equal to m dot into h 1 minus h 2. So, this will let you know what is h 1 from steam table. So, h 1 you know h 2, I have just shown how to calculate and this turbine power is given as 150 kilowatt. So, this will give you what is m dot. So, m dot is 1 3 9 7 sorry, m dot is 0.1074 kg per second. So, process has to be separately drawn on a T s diagram.

Now, here there is no information on entropy transport. So, see we have to decouple the entropy considerations of turbine with the entropy considerations of the heat exchanger, nothing is told about the reversibility, reversibility everything about the heat exchanger. So, with the information given it is not possible to map the process between 2 to 3 in a T s diagram, we only know that it is a constant pressure process that much we know. But what happens to the entropy, it depends on the kind of irreversibility and whether it is isothermal and all these things there, that have to be definitely not isothermal right because you see it is; it may be isothermal it is because it changes the.

So, in this case you can assume so, this is at 10 kPa, at 10 kPa at constant pressure it changes phase from two phase to saturated liquid. So, it is therefore, a constant temperature process. So far as the process diagram in a T s diagram goes that does not take into account what is happening externally. So, external it may be reversible or irreversible you can still draw this process in a T s diagram considering only the internal part of the process. So, how you can do that? So, you have this liquid vapour dome you started with state 1 from state 1, you have a constant entropy process till you come to the saturated thing and then from here to here this one.

So, this much you can draw in the T s diagram what I wanted to mean is that from this you cannot conclude anything about the entropy transport. The reason is you have no information on the external irreversibility. So, having information on the T s diagram will not give or give you an idea of the entropy transport simply because this irreversibility associated with these therefore, that completely information is not given, but change in entropy between the states you can figure out from the T s diagram ok. So, the final answer if you put this m dot here Q dot will be minus 250 kilowatt ok.

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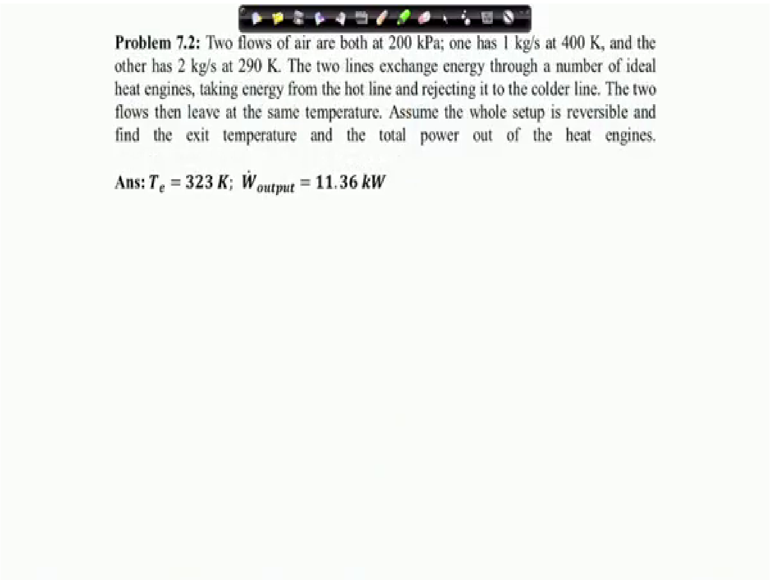

Problem 7.2: Two flows of air are both at 200 kPa; one has 1 kg/s at 400 K, and the other has 2 kg/s at 290 K. The two lines exchange energy through a number of ideal heat engines, taking energy from the hot line and rejecting it to the colder line. The two flows then leave at the same temperature. Assume the whole setup is reversible and find the exit temperature and the total power out of the heat engines.

Ans: $T_e = 323\ K$; $\dot{W}_{output} = 11.36\ kW$

So, we will move ahead to work out the next problem, let me first erase the board. Problem 7.2, two flows of air are both at 200 kilopascal one has 1 kg per second at 400 Kelvin and the other has 2 kg per second at 290 Kelvin ok. The two lines exchange energy through a number of ideal heat engines taking energy from the hot line and rejecting it to the colder line. The two flows then leave at the same temperature assume the whole set up to be reversible find the exit temperature and total power out of the heat engines. So, let me draw the schematic of the process, otherwise it may be difficult for you to follow it.

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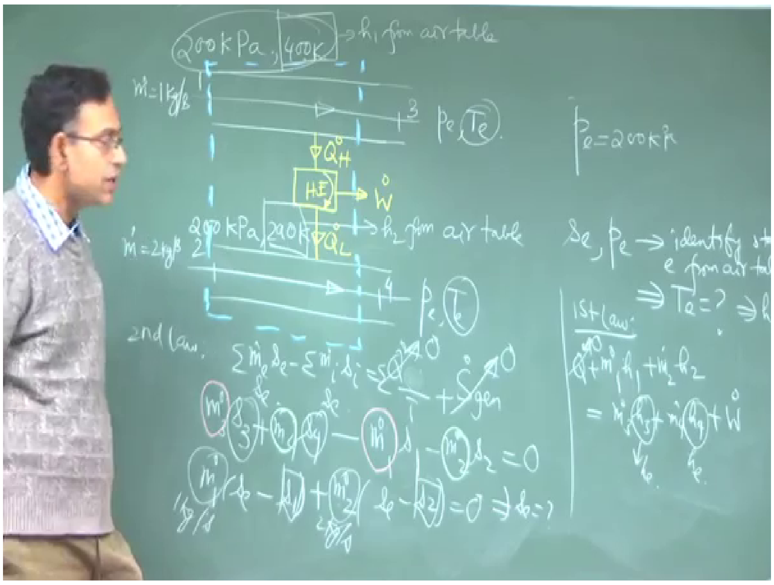

So, there are two streams of air, this is stream one and this is another stream another pipeline this is stream 2. So, here the air enters at state 1, here at the air enters at state 2. Both are 200 kilopascal, but the temperatures are different this is 400 Kelvin and this is 290 Kelvin. When the air comes out, it comes out at the common exit state which is p e T e; p e is 200 kilopascal.

So, here it is m dot is equal to 1 kg per second here m dot is 2 kg per second ok, I am just trying to draw the maximum information that you get from the given data then there is a heat engine reversible which takes heat from this and rejects heat to this and in the process does some network in a cycle ok. The question is what is the power output of the heat engine.

So, the strategy to the problem will be that we will find out the power output by considering; first you have to find out what is the exit temperature. So, power output to know what is the power output if you apply the first law to the entire system you have to know what is the exit state and for that you have to appeal to the second law for entropy transport.

So, second law; so now, what is your control volume this is very important. So, control volume includes the two pipelines and the heat engines ok. So, for this control volume if you apply the second law, steady state steady flow process. Summation of m dot e s e minus summation of m dot i s i is equal to Q dot cv by T summation Q dot by T c v we may not write plus rate of entropy generation. Entropy generation is 0 because everything is reversible that is given, what is heat transfer you may have an illusion by looking into this and imagining that there is heat transfer, but these are all internal between the parts of the system. So, externally for this control volume there is no heat transfer so, it is 0.

So, m dot e s e summation is m dot 3 s 3 plus m dot 4 s 4 and m dot I s i summation is m dot 1 s 1 minus m dot 2 s 2 this is 0 and s 3 is equal to s 4 right because state 4 is; state 3 and state 4 they are at the same uniform state. So, s 3 is equal to s e s 4 is equal to s e. So, you can write at m dot 3 is same as m dot 1 that is the same stream. So, m dot 3 and m naught 1 are the same similarly, m dot 2 and m dot 4 are the same. So, what you can write is m dot 3 into s e minus s 1 plus m dot 1 sorry, yes m dot 4 and m dot 2.

So, plus m dot 2; so, m dot 3 is same as m dot 1 we can write this as m dot 1 plus m dot 2 into s e minus s 2 is equal to 0. You can put this m dot 1 as 1 kg per second and this is 2 kg per second. In fact, you could solve this problem if the absolute values are not given, but the ratios are given because what you require simply is m dot 1 by m dot 2 or m dot 2 by m dot 1. So, this will give you what is s e, you can use ideal gas law for finding out s 1 and s 2 state these states are completely given or because of such a large variation of temperature it is better that you look into air table, property table of air which takes into account variable cp cv and get s 1 and s 2 from air table.

So, if you get that, you will get what is s e and combination of s e and p e will identify state e from the air table and that will tell you what is T e, given that you already know p e. So, once you have this information on T e now, you can apply the first law because you know T e you know the enthalpy at state for first law application you need to know the enthalpy.

So, Q dot plus m dot 1 h 1 I am not writing kinetic energy, potential energy terms anymore plus m dot 2 h 2 this is a summation of m dot i h i is equal to m dot 3 h 3 plus m dot 4 h 4 plus w dot, Q dot is 0 and h 4 and h 3 are h e from T e you can calculate what is h e from the table again. If you use constant cp then you can write cp into T, but it is better to use the variable cp cv for the large temperature variation that this problem is having, m dot values you know.

So, from here you can h 1 and h 2 from the state 3. So, this will give you what is h 1 from air table will it depend on 200 kPa; no, because enthalpy of an ideal gas is a function of temperature only. So, typically this is good enough typically this is good enough to calculate h 2 from air table, but entropy of an ideal gas is both function of pressure and temperature. Enthalpy and internal energy of functions of temperature only, but entropy is a function of both pressure and temperature.

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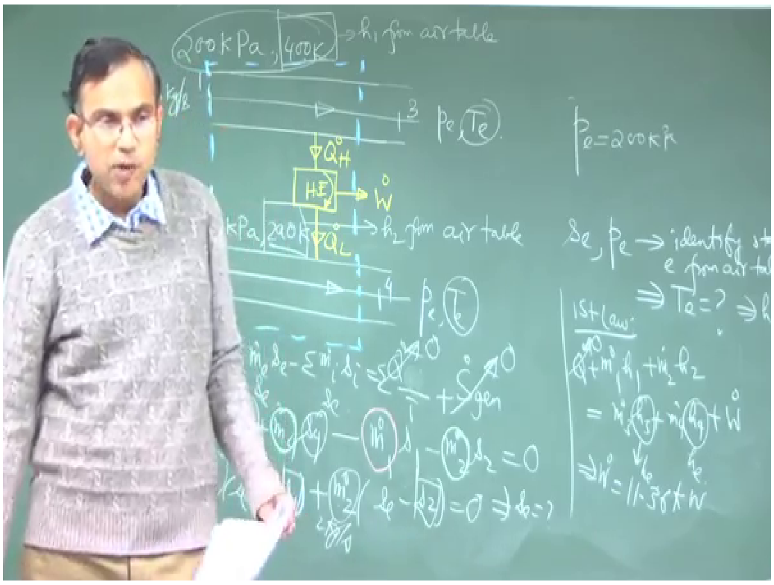

So, from here you can calculate what is w dot and that is equal to 11.36 kilowatt; we will work out one more problem before we call it a day in this lecture.

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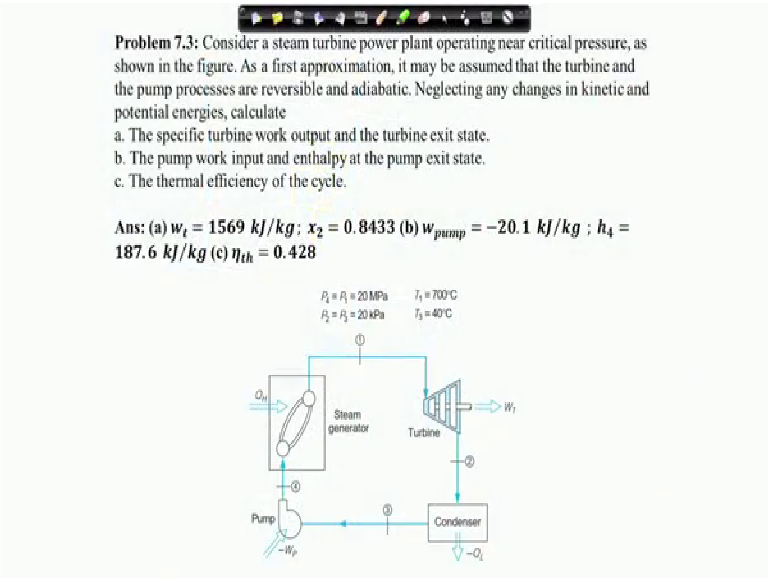

Problem 7.3: Consider a steam turbine power plant operating near critical pressure, as shown in the figure. As a first approximation, it may be assumed that the turbine and the pump processes are reversible and adiabatic. Neglecting any changes in kinetic and potential energies, calculate

a. The specific turbine work output and the turbine exit state.
b. The pump work input and enthalpy at the pump exit state.
c. The thermal efficiency of the cycle.

Ans: (a) $w_t = 1569\ kJ/kg$; $x_2 = 0.8433$ (b) $w_{pump} = -20.1\ kJ/kg$; $h_4 = 187.6\ kJ/kg$ (c) $\eta_{th} = 0.428$

So, consider a steam turbine power plant. So, this is a very basic introduction to power plant engineering for you and see how we have slowly graduated or developed from the basics of thermodynamics to come to a stage where we are now able to analyze thermal power plants. So, look into this. So, you have a system where there is a boiler steam generator is like a boiler. So, you supply heat to water which is converted into steam in the steam generator. The exit state in the steam generator is given as state 1 then that steam enters the turbine.

So, from boiler it enters the turbine, there is some work that is extracted from a stream and steam and it rejects heat to the condenser, by second law of thermodynamics this heat rejection must take place in the condenser to make the turbine work in a cycle. Then the condenser in the condenser is pumped to the boiler pressure by a pump, you have to find out the specific turbine work output and the turbine exit state specific work means work done rate of work done per unit mass and the pump work input and enthalpy at the pump exit state and the thermal efficiency of the cycle.

So, I have discussed these kind of cycle in the context of the Carnot cycle applied for a flow process and you can see a kind of application of that an extension of that to more realistic cycles. This is not a Carnot cycle a more realistic cycle where the compressor is replaced by a pump and we will try to analyze this cycle.

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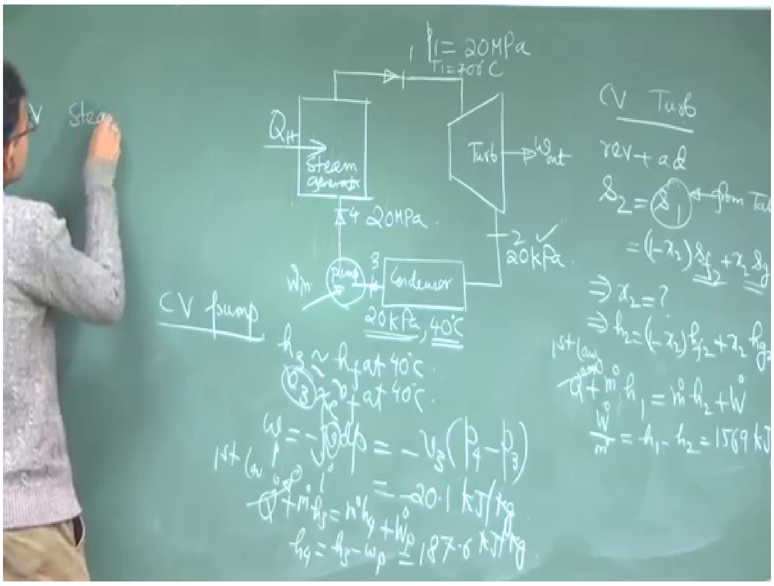

So, I am just drawing the schematic you have the steam generator then, it enters the turbine so, this is steam generator, then it enters the turbine, then it enters the condenser and then there is a pump. So, this is 1, this is 2, this is 3, this is 4. So, at one you have p 1 is equal to 20 mPa and T 1 is equal to 700 degree centigrade, this is superheated steam. At 2 you have 20 kPa you do not know any other property as yet, at 3 you have 20 kPa and you do not and 40 degree centigrade right; and 40 degree centigrade yes it is given somewhere and then at 4 you have 20 MPa and no more information is required.

So, you have first you start with control volume as turbine. So, we will start with; so, you have four different entities each will be four different control volumes to get unknowns in the properties. So, control volume turbine, we assume that it is reversible and adiabatic. So, you have s 2 is equal to s 1, s 1 from table. So, once you get s 1 from table, s 2 now it is in the two phase region we have solved a similar problem. So, this is 1 minus x 2 into s f 2 plus x 2 into s g 2, s f and s g are calculated at 20 kPa from the table.

So, that will give you what is x 2. Once you calculate what is x 2, you can calculate what is h 2 which is 1 minus x 2 into h f 2 plus x 2 into hg 2 h f and hg are again from the table. So, h 2 you can calculate, now the specific work output you can apply the first law of thermodynamics for that turbine. Q dot plus m dot 1 h 1, here all m dots are same in the cycle same fluid is circulating. So, we will just write m dot into h 1 neglect changes in kinetic energy and potential energy.

So, specific work output is w dot by m dot is equal to h 1 minus h 2. So, this is 1 5 6 9 kilo joule per kg this is a turbine specific water. So, control volume turbine. So, next we will apply control volume pump, 20 kPa 40 degree centigrade. This if you look into the table, this is very close to saturated liquid it may be little bit compressed also. Ideally it is supposed to be saturated liquid or close to that it can even be compressed liquid and that is what is desirable because the pump handles only liquid, but not two phase mixture.

So, it is liquid. So, enthalpy at state 3 you can say roughly it is h f at 40 degree centigrade, not h f at 20 kPa because the enthalpy at this state is very close to enthalpy of saturated liquid at this temperature right. Because if you now change the state little bit from the saturated liquid state, the pressure dependence may be more severe.

So, this state if you approximate it as a saturated liquid state, the property from which you calculate that should be primarily from temperature and not from pressure ok. So, h 3 is h f. So, if even if it deviates a little bit from the saturated liquid then this it will still be approximately this and v 3 is again will be roughly v f at 40 degree centigrade, this is roughly like 1 by density of water at 40 degree centigrade. Now, the work done for the pump see this is single inlet, single exit, reversible steady state steady flow this formula we have derived not pdv, vdp.

So, this is per unit mass so w pump. So now this v is roughly a constant because the pump is handling liquid because it is happening liquid, the liquid is roughly incompressible. So, its density is not changing, true from here to here its density is changing, but this is what is the engineering approximation, for all practical purposes the density is not changing substantially so that you can approximate this by this v 3, the negative work indicates that you are inputting work. So this pump work so, what you require; so, this is minus 20.1 kilo joule per kg. And then if you apply first law for the pump Q dot plus m dot h 3 is equal to m dot h 4 plus w dot pump.

So, there is negligible heat transfer. So, h 4 is equal to h 3 minus w p, w p is w dot p by m dot because w p is already negative, negative negative makes it positive. So, h 4 is greater than h 3. So, h 4 will be 187.6 kilo joule per kg.

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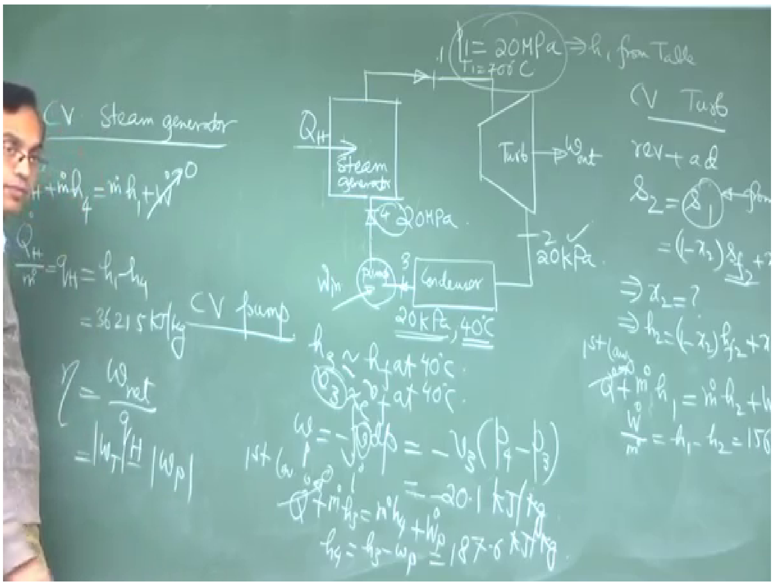

Then you apply control volume for steam generator. So, you know enthalpy here, you know enthalpy here. So, Q dot H plus m dot h 1 is equal to m dot sorry, m dot h 4 your inlet is 4, exit is one work is 0 for boiler. So, Q dot H by m dot. So, this is specific heat transfer to the boiler that is h 1 minus h 4.

So, p 1 and T 1 means you can get h 1 from table. So, this is 3621.5 kilo joule per kg. So now, for efficiency of the cycle, what you require? For efficiency of the cycle you require, the network output by q H right, this is the definition of efficiency of a cycle. So, what is the network output? Network output is w turbine minus w pump this is output power, this is the input power; mod of output power minus mod of input power that is the net power or network divided by q H.

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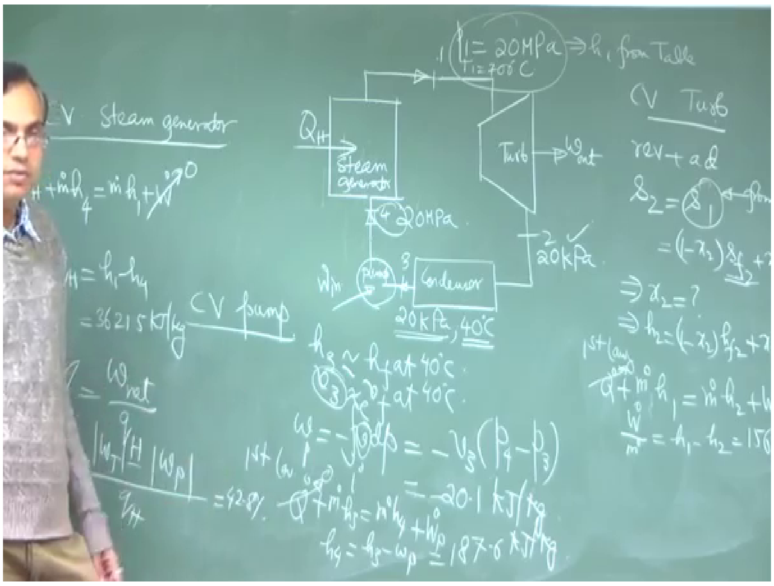

So, this will be 42.8 percent for this problem. So, you get an idea. So, this is a very practical problem, typical efficiency of thermal power plants will be around 40 percent thermal efficiency and this is what the you get from the numerical data here.

Thank you very much we will continue with more problem solving in the next lecture.