

**Thermodynamics for Biological Systems:
Classical and Statistical Aspects
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**Lecture – 14
Open System**

Welcome!

As we know from earlier classes, and as we have already seen in the review, there are three kinds of systems: isolated systems, close systems and open systems. We said that isolated system is something that does not exchange either mass or energy with its environment. A closed system is something that can exchange only energy with its environment, but not mass; whereas, open systems can exchange both mass and energy with its surroundings or environment. We saw that isolated system was a good concept, and this far in this module, module 2 we have looked at closed systems.

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Let us begin with:

- one input stream
- one output stream

Rate of heat interaction across the system boundary: \dot{Q}
Rate of work interaction across the system boundary: \dot{W}



The diagram shows a dashed-line boundary representing a system. A vertical arrow labeled \dot{Q} points downwards into the system from the top. A horizontal arrow labeled \dot{W} points to the right, crossing the boundary from the system to the surroundings. A diagonal arrow labeled \dot{Q} points downwards and to the right, crossing the boundary from the system to the surroundings. A diagonal arrow labeled \dot{W} points downwards and to the left, crossing the boundary from the system to the surroundings. The NPTEL logo is in the bottom left corner.

Convention:
 \dot{Q} into the system is +ve
 \dot{W} out of the system is +ve

Now, let us start looking at open systems. To make things simple, let us begin with one input stream and one output stream. We will derive this ... we will derive the relevant expressions for one input stream and one output stream for a particular system, and then generalize it for many input streams and many output streams. Also, let us call the rate of heat interaction across the system boundary – as we have seen this heat interaction and work interaction, make sense only when they cross the system boundary. The rate of heat interaction across the system boundary, let us denote that by \dot{Q} ; dot brings in the rate aspect, the time rate; and the rate of work interaction across the system boundary is \dot{W} , this is the terminology.


So, if you use this to represent our system, so this is a system which could be anything which could cover very many real life parts, real life aspects of a plant, bioprocess plant or it could be even a conceptual one. We said we will consider one input stream and one output stream. And this is our heat interaction here and this is our work interaction; which cross the system boundaries. And as we all know there is convention to be followed, and the convention that we are following in this course is that the \dot{Q} , the heat interaction into the system is positive, and the work interaction out of the system is positive. So, as written, both these are positive.

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Energy cannot be generated or consumed. Therefore, the energy balance can be written, in terms of rates of accumulation, input, and output as:

$$\frac{dE_{sys}}{dt} = \dot{E}_I - \dot{E}_O \quad \text{Eq. 2.60}$$

Input rate: due to the streams and heat interaction
 Output rate: due to the streams and work interaction

$$\frac{dE_{sys}}{dt} = (\dot{E}_{in\ stream} + \dot{Q}) - (\dot{E}_{out\ stream} + \dot{W}) \quad \text{Eq. 2.61}$$


Now, let us write an energy balance. We had written mass balances earlier; now let us write an energy balance. Unlike mass, energy can neither be created nor destroyed – that we all know. In other words, it cannot be generated or consumed. Therefore, the generation and consumption terms need not be taken into account whenever we consider energy. The energy balance written in terms of rates of accumulation, input, and output – those are the other three remaining terms in the balance apart from the generation or consumption – can be written as this: $\frac{d}{dt}$ of the energy of the system; note that is the total energy of the system,

$$\frac{dE_{sys}}{dt} = \dot{E}_I - \dot{E}_O$$

It is quite intuitive, straight forward to see, there are no other terms that can be included in this. If you want to think about it please go ahead and do that. You will realize it there are no other terms that can be included in this. It is very fundamental, simple balance. See ... all these balances are just like accounting. Accounting in finance where you have a credit, a debit, and a balance. So, where you put in these is what makes the difference. It is as simple as that. So, we have an energy credit, and an energy debit, and the balance. Let us call this equation 2.60.

It is convenient to consider


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graph LR
    Work --> ShaftWork[Shaft work, W_s]
    Work --> PVWork[PV work]
  
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Thus

$$\dot{W} = \dot{W}_s + \dot{m}_o P_o \hat{V}_o - \dot{m}_i P_i \hat{V}_i \quad \text{Eq. 2.62}$$

\dot{m} = mass flow rate of the streams
 \hat{V} = volume per unit mass



If you look at the input rates for the system under consideration – let us take a look again at the system under consideration. The energy input could be due to the stream itself, and the heat interaction, in the system that we have written ... which we have started to consider. That is, it has one input stream, one output stream, and energy interaction of ... heat interaction of Q and a work interaction of W ; or the rates of that is \dot{Q} and \dot{W} . Therefore, the input rate is due to the streams and the heat interaction. Similarly, as you have seen in that figure, the output rate could be due to the streams itself, there is the energy that is carried by the streams and the work interaction. If you think about it, this heat interaction and work interaction can be accounted for in any place. You could account it for in the input, you could account it for in the output as long as you chose your signs appropriately.

Let us not get into that. We will take the intuitive route, and we will account for the heat interaction in the input rate ... the rate of heat interaction in the input rate, and the rate of work interaction the output rate. It is a kind of intuitive in the way we have written our system. If you take this into account, we can write equation 2.60 that we have seen here, simple energy balance, as – we are explicitly showing the various contributions

$$\frac{dE_{sys}}{dt} = (\dot{E}_{in\ stream} + \dot{Q}) - (\dot{E}_{out\ stream} + \dot{W})$$

Let us call this equation 2.61.

Now, it is convenient to consider two kinds of work. We have already ... let us assume that the other kinds of work do not exist, and only these two kinds of work exist. One is shaft work W_s .

You can go back to your earlier days of thermodynamics – you would have learnt it there – shaft work, and P V work due to pressure volume expansion, and so on. Let us consider that these are the only two work interactions. If there are other work interactions you just have to add them to this; it is quite simple. We can do that later also. For development, let us consider only these two work interactions. If we do that, then

$$W = \dot{W}_S + \dot{m}_O P_O \hat{V}_O - \dot{m}_I P_I \hat{V}_I$$

Note that this is P O V O hat. This is the mass specific volume of the streams ... you can work out the units here. If you multiply it by the mass flow rate of the outlet stream you get the rate of work interaction that crosses the system boundary due to P V work. Similarly, this is the rate of work interaction that crosses the system boundary into the system through the inlet streams. We will call this equation 2.62. As we have already ... let me state this again, m dot is the mass flow rate of the streams and V hat is the volume per unit mass. It is nice to have this in a complete form here. First time we are kind of introducing these things.

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Thus, Eq. 2.61 can be written as

$$\frac{dE_{sys}}{dt} = (\dot{E}_{in\ stream} + \dot{Q}) - (\dot{E}_{out\ stream} + \dot{W}_S + \dot{m}_O P_O \hat{V}_O - \dot{m}_I P_I \hat{V}_I)$$

Upon transposition:

$$\dot{E}_{out\ stream} - \dot{E}_{in\ stream} + \dot{m}_O P_O \hat{V}_O - \dot{m}_I P_I \hat{V}_I + \frac{dE_{sys}}{dt} = \dot{Q} - \dot{W}_S$$

Eq. 2.63

Now, this equation 2.61 that we just wrote can be written as

$$\frac{dE_{sys}}{dt} = (\dot{E}_{in\ stream} + \dot{Q}) - (\dot{E}_{out\ stream} + \dot{W}_S + \dot{m}_O P_O \hat{V}_O - \dot{m}_I P_I \hat{V}_I)$$

All this is from earlier. The only thing that we do here is expanding the \dot{W} in terms of this shaft work interaction as well as the P V work interaction. Now, if you transpose this, subtract terms or in our standard way if you take terms to one side and so on...

$$\dot{E}_{out\ stream} - \dot{E}_{in\ stream} + \dot{m}_o P_o \hat{V}_o - \dot{m}_i P_i \hat{V}_i + \frac{dE_{sys}}{dt} = \dot{Q} - \dot{W}_S$$

We will call this equation 2.63.

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E = internal + kinetic + potential + other energies

Using the regular expressions for the energies, Eq. 2.63 can be written as

$$\begin{aligned} & \dot{m}_o \left(\hat{U}_o + \frac{1}{2} u_o^2 + gz_o + \dots + P_o \hat{V}_o \right) \\ & - \dot{m}_i \left(\hat{U}_i + \frac{1}{2} u_i^2 + gz_i + \dots + P_i \hat{V}_i \right) \\ & + \frac{dE_{sys}}{dt} = \dot{Q} - \dot{W}_S \end{aligned} \quad \text{Eq. 2.63}$$

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Now, let us look at E in little more detail. This E is the energy of the system, that can consist of internal energy, kinetic energy, potential energy, surface energy, electrical energy and so many other energies ... it could. And using the regular expression for energies and let us see whether we are generalizing it here; this equation 2.63 can be written as, it is reasonably general here,

$$\begin{aligned} & \dot{m}_o \left(\hat{U}_o + \frac{1}{2} u_o^2 + gz_o + \dots + P_o \hat{V}_o \right) - \dot{m}_i \left(\hat{U}_i + \frac{1}{2} u_i^2 + gz_i + \dots + P_i \hat{V}_i \right) + \frac{dE_{sys}}{dt} \\ & = \dot{Q} - \dot{W}_S \end{aligned}$$


Essentially, we have expanded the E of the outlet streams and the E of the inlet streams and then put in the various terms together. We will call this equation 2.63.

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Since $H = U + PV$ Eq. 2.64 can be written as

$$\dot{m}_o \left(\hat{H}_o + \frac{1}{2} u_o^2 + g z_o + \dots \right) - \dot{m}_i \left(\hat{H}_i + \frac{1}{2} u_i^2 + g z_i + \dots \right) + \frac{dE_{sys}}{dt} = \dot{Q} - \dot{W}_s \quad \text{Eq. 2.65}$$

If the mass flow rates of the input and output streams are the same, $\dot{m}_o = \dot{m}_i = \text{say, } \dot{m}$ and Δ indicates (output - input)

$$\dot{m} \left(\Delta \hat{H} + \frac{1}{2} \Delta u^2 + g \Delta z + \dots \right) + \frac{dE_{sys}}{dt} = \dot{Q} - \dot{W}_s \quad \text{Eq. 2.66}$$


Now, since enthalpy equals U plus P V – there is a need to bring in enthalpy here because the enthalpy values are probably easily available – enthalpy equals U plus P V. This equation 2.64, if you look at 2.64, you have \hat{H}_o plus $\frac{1}{2} u_o^2$ plus $g z_o$ plus \dots . Therefore, you have an enthalpy term right here, by the combination of this. And enthalpy values are probably more easily available ... Therefore, let us combine them and write this as

$$\dot{m}_o \left(\hat{H}_o + \frac{1}{2} u_o^2 + g z_o + \dots \right) - \dot{m}_i \left(\hat{H}_i + \frac{1}{2} u_i^2 + g z_i + \dots \right) + \frac{dE_{sys}}{dt} = \dot{Q} - \dot{W}_s$$

Let us call this equation 2.65.

Now, if the mass flow rates of the input and output streams are the same – they are typically the same, otherwise there would be accumulation – mathematically, \dot{m}_o equals \dot{m}_i . And let us call that by a simple \dot{m} after dropping the subscripts because they are the same. If that is the case, and we indicate output minus input by the delta ... you see there is an output here, there is an input here, there is a minus here. If you can indicate that by the delta, then we can write:


$$\dot{m} \left(\Delta \hat{H} + \frac{1}{2} \Delta u^2 + g \Delta z + \dots \right) + \frac{dE_{sys}}{dt} = \dot{Q} - \dot{W}_s$$

We will call this equation 2.66.

So, this is in a form that we can directly use, if you know the differences and velocity between

the inlet and outlet, the differences in heights between the ... this is outlet and inlet this is also outlet and the inlet and the differences in enthalpies of this stream at the outlet and at the inlet, then this can be computed if you know the energy interaction, the heat interaction and the work shaft work interaction. So, this is a nice form of the energy balance, a very useful form of the energy balance note that we considered only one input stream and one output stream for this particular system.

If there are multiple streams,
 c: input streams
 d: output streams
 the energy balance can be written as

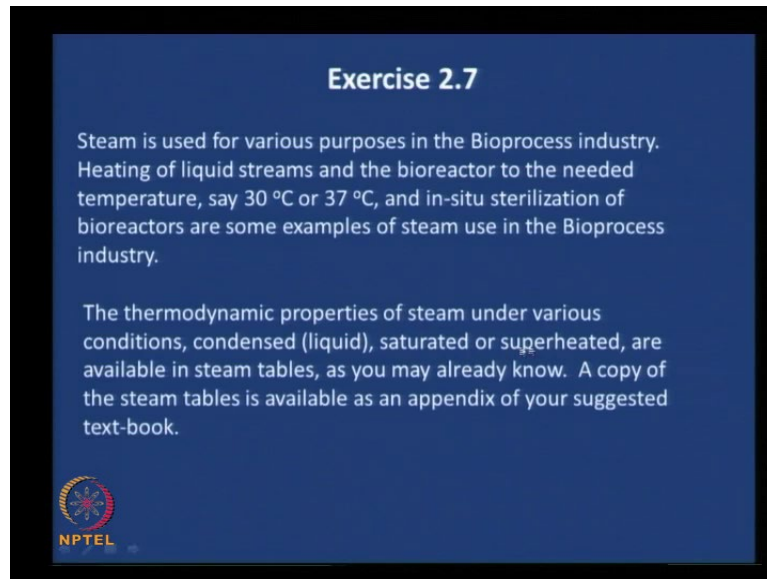
$$\sum_{\substack{d \text{ out} \\ \text{streams}}} \dot{m}_j \left(\hat{H}_j + \frac{1}{2} u_j^2 + g z_j + \dots \right) - \sum_{\substack{c \text{ in} \\ \text{streams}}} \dot{m}_k \left(\hat{H}_k + \frac{1}{2} u_k^2 + g z_k + \dots \right) + \frac{dE_{\text{sys}}}{dt} = \dot{Q} - \dot{W}_S \quad \text{Eq. 2.67}$$


Now, if we generalize things ... we have it of the form that can be easily generalized. Generalization – if there are multiple streams for example, if there are c input streams and d output streams the energy balance is nothing but, you sum over all the output streams and sum over all the input streams and subtract one from the other energy is the scalar it can be subtracted. Therefore,

$$\sum_{\substack{d \text{ out} \\ \text{streams}}} \dot{m}_j \left(\hat{H}_j + \frac{1}{2} u_j^2 + g z_j + \dots \right) - \sum_{\substack{c \text{ in} \\ \text{streams}}} \dot{m}_k \left(\hat{H}_k + \frac{1}{2} u_k^2 + g z_k + \dots \right) + \frac{dE_{\text{sys}}}{dt} = \dot{Q} - \dot{W}_S$$

Now, we have a nice general equation that can be applied to any open system that exchanges mass and energy with its surroundings. I think there is an equation number, equation number 2.67. This is a nice equation to remember.


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Exercise 2.7

Steam is used for various purposes in the Bioprocess industry. Heating of liquid streams and the bioreactor to the needed temperature, say 30 °C or 37 °C, and in-situ sterilization of bioreactors are some examples of steam use in the Bioprocess industry.

The thermodynamic properties of steam under various conditions, condensed (liquid), saturated or superheated, are available in steam tables, as you may already know. A copy of the steam tables is available as an appendix of your suggested text-book.



As usual, we would look at how to apply this equation to get more familiar and also to develop the higher level skill of application. Let us take a typical example and apply the energy balance to that. Steam is used for various purposes in the bioprocess industry as we had all know the steam is the one that is used to sterilize the central part of the bioprocess, which is a bioreactor. As you would all know, sterilization is essentially to create an environment where there is no microorganism. And then we add the microorganism of interest to us, so that only that microorganism grows. Otherwise, as we know, there are so many microorganisms present in the air all the time.

And if we do not sterilize ... if we do not eliminate all of them then, whatever is available in the air will grow along with the organism of interest. They would be competition for the food that is available, which may not be desirable for the optimal production of the product. And therefore, we sterilize things we make sure that we have a clean slate when we start out with; and under sterile conditions we add the microorganism of interest into the bioreactor and then let that organism grow and produce the product of interest. For sterilization, steam is used ... slightly higher pressure steam, and at temperatures of about 120 degrees ... 121 degrees are used.

Also steam is used for heating the various liquid streams. Sometimes the bioreactor needs to be maintained at temperatures of 37 degrees C; may be even 30 degree c when the outside is about 27, 28 in ... may be in the colder months in some parts of India ... may be standard in some other parts of India. Therefore, we need to heat these streams to get to the optimum temperature at

which the bioreactors work. So, to do that there are heat exchangers that are used to heat up these streams, and the heat exchangers predominantly use steam. To read out from here, in a formal fashion: heating of liquid streams and the bioreactor to the needed temperature say 30 to 37 degrees C and in-situ sterilization of bioreactors ... these are the two things that we talked about now ... are some examples of steam use in the bioprocess industry, So we need to get comfortable with steam.

The thermodynamic properties of steam under various conditions, condensed which is also the liquid – this we need not worry about too much. Typically we need to look at saturated or superheated. What does saturated mean? Recall the phase diagrams that we reviewed in the first module we had a P – T diagram, pressure versus temperature diagram. And there we had the fusion line, the vaporization line. Let us focus on the vaporization line. The points on the vaporization line correspond to ... saturated conditions. And, if steam is in that state, it is called saturated steam. ...Or, if you look at a P V diagram ... pressure versus specific volume – we had a dome, and the conditions inside the dome correspond to the saturated conditions. And superheated of course, we know, it is completely a vapor. Therefore, these two are the ones that are usually of interest to us.

The thermodynamic properties of steam under various conditions, saturated or superheated are available in steam tables. And a copy of the steam tables is available as an appendix of your suggested textbook, Smith, Van Ness and Abbott. Please take a look at that appendix and ... familiarize yourself with the various values that are given there as functions of pressure, temperature, or may be one variable. Why don't you take about 5 minutes to familiarize yourself with these steam tables? Go ahead, please go to the appendix and take a look at these two tables, the saturated tables and the superheated tables of steam. Go ahead.

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Please pause the video here. You can pause it as long as you want. The time mentioned is only a guideline

For the above uses, generated steam that is available at 100 KPa in a saturated condition, is compressed to 300 KPa, using an equipment called a compressor. The compressor, when well designed, can be approximated to work under adiabatic conditions.

Also, such compressors do not have much difference in the entry and exit elevations; the pipes are also so sized to equalize entry and exit velocities. The compressor efficiency, that is defined as the maximum (isentropic) work to the actual work is 0.8. Estimate the work needed to operate the compressor per Kg of steam compressed, for steady-state operation.

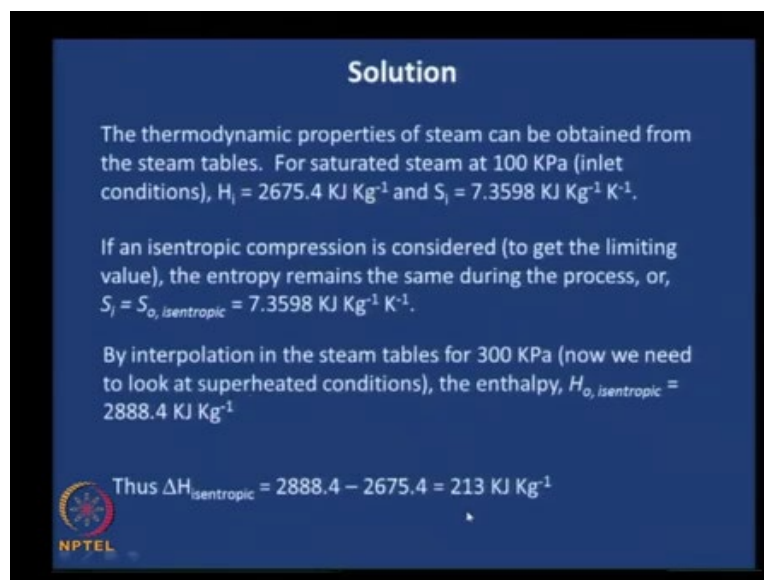


Now, that you are familiar with these steam tables, how it looks like; what are the various values there, and so on, for the above uses, the generated steam that is available at 100 kilopascals in a saturated condition is compressed to 300 kilopascals, using an equipment called a compressor. You might have already heard of a compressor; compressor essentially does compression – increases the pressure; here it is gone from 100 kilopascals to 300 kilopascals. The compressor, the equipment, when well designed can be approximated to work under adiabatic conditions, which means it can be assumed that there is no heat interaction between the compressor and the surroundings.

Also, such compressors do not have much difference in the entry and exit elevations. I said ... Z_i and Z_o this not much of a difference. The pipes are also, sized to equalize entry and exit velocities. Therefore, u_o , that is the small u_o equals the small u_i . The compressor efficiency that is defined as the maximum or the isentropic work to the actual work is 0.8, and what we are expected do to do here in this exercise is to estimate the work needed to operate the compressor per Kg of steam compressed for steady state operation. This is a very typical calculation that is done. The work that is needed to operate the compressor per Kg of steam compressed or work that is needed to operate the compressor itself translates directly to the energy costs that are required for the compressor.

Some compressors are huge energy guzzlers. So it is good to have an idea of the energy that goes into compressor operation. So, thermodynamic ... application of thermodynamic principles is going to tell us that. Especially, the final equation that we derived for open systems is going to tell us that. Let me start you out with the solution, and then probably you can take about some time to work it out. Then I will give you the final solution.

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Solution

The thermodynamic properties of steam can be obtained from the steam tables. For saturated steam at 100 kPa (inlet conditions), $H_i = 2675.4 \text{ kJ kg}^{-1}$ and $S_i = 7.3598 \text{ kJ kg}^{-1} \text{ K}^{-1}$.

If an isentropic compression is considered (to get the limiting value), the entropy remains the same during the process, or, $S_j = S_{o, \text{isentropic}} = 7.3598 \text{ kJ kg}^{-1} \text{ K}^{-1}$.

By interpolation in the steam tables for 300 kPa (now we need to look at superheated conditions), the enthalpy, $H_{o, \text{isentropic}} = 2888.4 \text{ kJ kg}^{-1}$

Thus $\Delta H_{\text{isentropic}} = 2888.4 - 2675.4 = 213 \text{ kJ kg}^{-1}$

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The thermodynamic properties of steam can be obtained from the steam tables. For saturated steam, no ... you need to look at the saturated steam tables; either the on the line ... on the P T diagram, or under the dome for the P V diagram. You need to have this idea in mind when you

look at steam tables. For saturated steam at 100 kilopascals, which is the inlet condition, the enthalpy values are given in the table for the 100 kilopascal condition, that turns out to be 2675.4 kilojoules per kilogram. This specific value, per mass value. And the specific entropy is 7.3598 kilojoules per kilogram per Kelvin.

So, this is some data for you to start out with. Take a look at the equation that we have developed and see what values can be obtained from the steam tables. Substitute the values and get the final solution. Maybe some help might be required towards the final solution in terms of how to get the work done and so on. We will come to that. At least look at the steam tables now and substitute the values that are available there into the energy balance expression. Go ahead, take about ten minutes do it.

Let us move forward. If ... an isentropic compression is considered, this is the limiting value, we know in an isentropic process the entropy remains constant. So, we will make use of that point. Therefore, the entropy at the outlet must be the same as the entropy at the inlet. Therefore, we have a value for the entropy at the outlet as the same 7.3598 kilojoules per kilogram per Kelvin as at the inlet.

Now, by interpolation in the steam tables ... we are going to linearly interpolate. This happens to be in between the values that are given in the steam tables. Therefore, we will assume in that narrow range the variation of the values of enthalpy and entropy are going to be linear. Therefore, if we interpolate ... in other words you take the value above 300, below 300 take the entropy value. In this case, enthalpy values and then, for this much amount of a change in temperature, you have this much amount of a change in entropy or enthalpy in this case. Therefore, for the difference that corresponds to 300 kilopascals from its previous value, what would be the change in enthalpy that needs to be added to the value that is before or below 300 kilopascals? That is a way we need to go about it. Please do that if you have any difficulty you can always clarify later.


So, we linearly interpolate to get the value. And for 300 kilopascals, we need to look at superheated conditions. It is no longer saturated, and we need to look at superheated conditions. In that case, by interpolation we get the enthalpy of the outlet stream as 2888.4 kilojoules per kilogram ... 2888.4 kilojoules per kilogram. Therefore, the change in enthalpy for an isentropic process is the outlet minus the inlet value. That turns out to be 213 kilojoules per kilogram.

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application of Eq. 2.66 to our system (the compressor is chosen as our system), with the realization that $\Delta u^2 = 0$ (equal velocities of the entry and exit streams), $g \Delta z = 0$ (no appreciable difference in elevations of the entry and exit streams), $\frac{dE_{sys}}{dt} = 0$ (steady-state conditions, all time derivatives are zero), $\dot{Q} = 0$ (compressor works adiabatically), we get,

$$\dot{m} (\Delta \hat{H}) = - \dot{W}_S \quad \text{Eq. 2.68}$$

Dividing both sides of the above equation by \dot{m} we get

$$(\Delta \hat{H}) = - W_S \quad \text{Eq. 2.69}$$


Now, application of equation 2.66 to our system. We need to very clearly identify what our system is? As we have said earlier also when we reviewed, if we do not identify a system clearly then it could be a mess. The application of balances ... to one system at one time, the other system at other time in the same problem can lead to a lot of confusion. Applying equation 2.66 to our system, which happens to be the compressor ... the compressor is chosen as a system with the realization that $\Delta u^2 = 0$ because the condition is given is that equal velocity of entry and exit streams. If you recall the problem statement it said that the pipes are sized such that there is no velocity difference between the inlet and outlet.

And also, this $\Delta Z \dots g \Delta Z$ equals 0. Because the Z_2 or Z_O equals Z_I ; no appreciable difference in the elevations of the entry and exit streams – this was given. Therefore; we can take this term to be equal to 0. And since it is a steady state process, this term automatically goes to 0. $\frac{d}{dt}$ of any quantity in a steady state process can be taken to be 0. That is the definition of a steady state process – there is no variation with time at a particular point. All time derivatives are 0. And \dot{Q} equals 0, because the compressor works adiabatically; there is no heat exchange between the compressor and its surroundings. Therefore, \dot{Q} equals 0.

Now, there are so many 0 terms. If you cancel out all those terms, what will remain of the balance is $\dot{m} \Delta \hat{H}$ at the kinetic energy term has gone to 0, potential energy term has gone to 0. We are assuming no other energies in the streams and $\frac{d}{dt}$ of E_{system} is gone to 0; \dot{Q} is gone to 0. So, the only thing that remains on the right hand side is minus \dot{W}_S . So,

$$\dot{m} (\Delta \hat{H}) = - \dot{W}_S$$

We will call this equation 2.68.

Now, if we divide both sides of the above equation by \dot{m} , we get $\Delta \hat{H}$ – this is minus \dot{W}_S – note, and if we divide by the \dot{m} we automatically get minus \dot{W}_S .

$$(\Delta \hat{H}) = - \dot{W}_S$$

The rate part goes away. This is per unit mass, of course. ... You need to recognize that this is the shaft work per unit mass.

Let us call that equation 2.69.

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Thus, the compressor efficiency, η can also be expressed in terms of the changes in mass specific stream enthalpies, i.e.

$$\eta \equiv \frac{W_{S, isentropic}}{W_S} = \frac{\Delta \hat{H}_{isentropic}}{\Delta \hat{H}} \quad \text{Eq. 2.70}$$

Since we know $\Delta \hat{H}_{isentropic}$ for our case, we can find $\Delta \hat{H}$.

$$\Delta \hat{H} = \frac{\Delta \hat{H}_{isentropic}}{\eta} = 213/0.8 = 266.3 \text{ KJ Kg}^{-1}$$

From equation 2.69, the shaft work required =

$$- (\Delta \hat{H}) = - 266.3 \text{ KJ Kg}^{-1}$$

The negative sign indicates that work is done *on* the system, our convention: work done *by* the system is positive.

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The compressor efficiency, which was defined as the rate of isentropic work, the maximum work possible to the actual work. This is the efficiency, compressor efficiency definition that we saw in the problem statement, can therefore, be expressed in terms of the enthalpies.

$$\eta \equiv \frac{W_{S, isentropic}}{W_S} = \frac{\Delta \hat{H}_{isentropic}}{\Delta \hat{H}}$$

As we know these values ... we can get from the steam tables; we got these values already. So,

let us substitute them. We know ΔH isentropic for our case, we can find ΔH , and therefore, the work requirement.

$$\Delta \hat{H} = \frac{\Delta \hat{H}_{\text{isentropic}}}{\eta} = 213/0.8 = 266.3 \text{ KJ Kg}^{-1}$$

The efficiency of the compressor that is given as 0.8, and ΔH isentropic hat, we have already calculated as 213. Therefore, 213 by 0.8 turns out to be 266.3 kilojoules per kilogram.

This is ΔH hat. And from equation 2.69, we have already seen that the shaft work required W_s , ... W_s , that is shaft work by unit mass is minus ΔH hat, which is minus 266.3 kilojoules per kilogram.

$$- (\Delta \hat{H}) = - 266.3 \text{ KJ Kg}^{-1}$$

You might wonder about this minus here, why are we, you know even looking at this minus here, what sense does it make? That minus comes in because of our convention. Note that negative sign indicates that work is done on the system, which make sense; work needs to be done on the compressor for it to work; and therefore, this minus just indicates that work is done on the system. We do not have to worry about that any more. Our work, our convention has been that the work done by the system is positive. Therefore, work done on the system is negative. That is all this indicates. Therefore, an amount of 266.3 kilojoules per kilogram of steam work needs to be done on the compressor.

With this, we complete module 2. In the next class, we will begin with module 3.