# Material and Energy Balances

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## Lecture – 44
## Energy Balances on Single-Phase Nonreactive Processes: Tutorials

Welcome to today's lecture. Today, we will have a tutorial session. We will solve multiple problems where we have single phase systems without reactions so some of these problems would be similar to the ones which we did during our exercise problems where we discussed these concepts. Here we will perform more problems so that we can actually get more familiarized and be comfortable with solving such problems.

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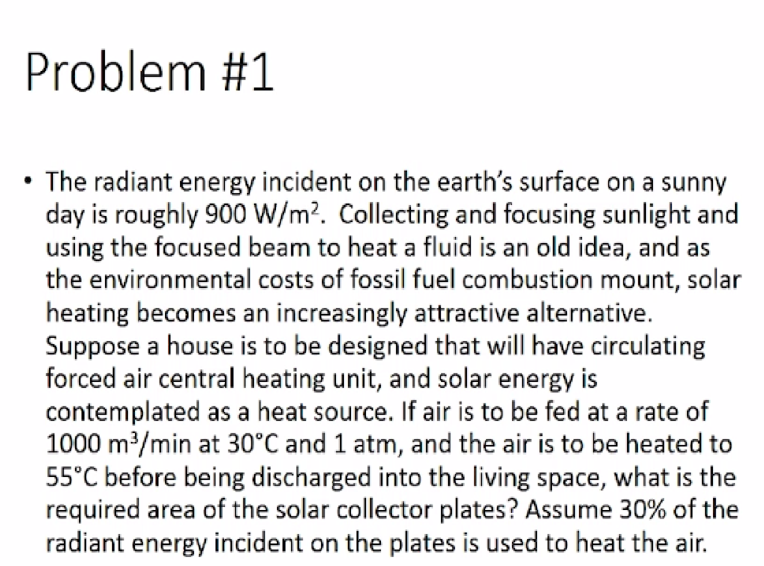

Problem #1

- The radiant energy incident on the earth's surface on a sunny day is roughly 900 W/m$^2$. Collecting and focusing sunlight and using the focused beam to heat a fluid is an old idea, and as the environmental costs of fossil fuel combustion mount, solar heating becomes an increasingly attractive alternative. Suppose a house is to be designed that will have circulating forced air central heating unit, and solar energy is contemplated as a heat source. If air is to be fed at a rate of 1000 m$^3$/min at 30°C and 1 atm, and the air is to be heated to 55°C before being discharged into the living space, what is the required area of the solar collector plates? Assume 30% of the radiant energy incident on the plates is used to heat the air.

Here is the first problem. The radiant energy incident on the earth's surface on a sunny day is roughly 900 watts per meter square. Collecting and focusing sunlight and using the focus beam to heat a fluid is an old idea and as the environmental cause of fossil fuel combustion mounts, solar heating has become an increasingly attractive alternative. Suppose a house is to be designed that will have a circulating forced air central heating unit, and solar energy is contemplated as a heat source.

If air is to be fed at a rate of 1000 meter cube per minute at 30 degree Celsius and 1 atmosphere and the air is to be heated to 55 degree Celsius before being discharged into the living space, what is the required area of the solar collector panels? Assume 30% of the radiant energy incident on the plates is used to heat the air. So here we are asked to design a solar panel. So we need to identify the area of the solar panel based on the amount of energy the heat which can be transferred to the air also accounting for the efficiency of such panels.

So let us try to see how you would solve this problem. So this problem is reasonably simple for the fact that we have only 1 component and it is a very simple heating process. So we will have to first look at whether there are any material balances that are required. Here we have been given the volume of air which is coming in. So we need to convert this volume into moles so that we can use that for calculating change in enthalpy rather than change in specific enthalpy.

So now for calculating the amount of air which is fed or converting the volume to moles we will use ideal gas law.

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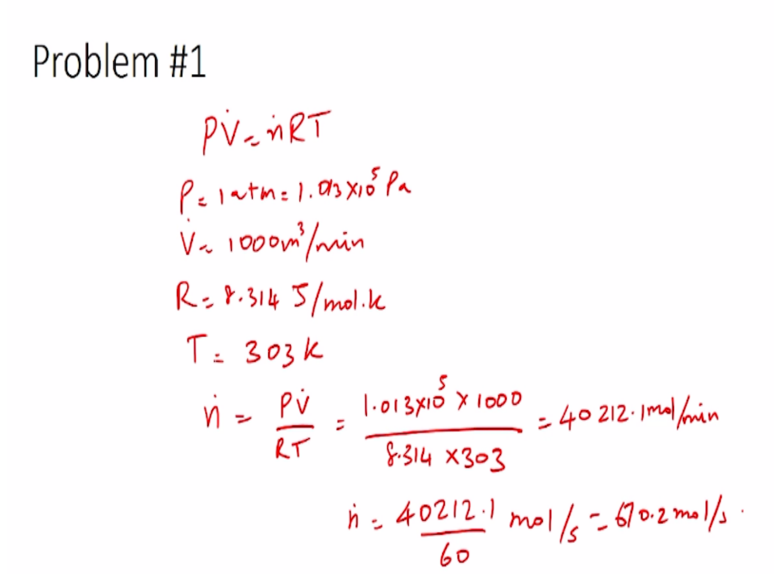

Problem #1

$$P\dot{V} = \dot{n}RT$$

$$P = 1\,atm = 1.013\times10^{5}\,Pa$$

$$\dot{V} = 1000\,m^3/min$$

$$R = 8.314\,J/mol.K$$

$$T = 303\,K$$

$$\dot{n} = \frac{P\dot{V}}{RT} = \frac{1.013\times10^{5}\times1000}{8.314\times303} = 40212.1\,mol/min$$

$$\dot{n} = \frac{40212.1}{60}\,mol/s = 670.2\,mol/s.$$

According to ideal gas law PV = nRT. So here is P is 1 atmosphere = 1.013 * 10 power 5 Pascal and volume is 1000 meter cube per minute and R would be 8.314 joules per mole Kelvin and temperature is 303 Kelvin or per degree Celsius. So this is the condition of air which is entering into the solar heater. We can calculate n. So here it will be n dot because it is molar flow rate. n dot would be = PV/RT. So we have V dot so it will be PV dot = n dot RT.

So we are calculating n dot as PV dot/RT. So 1.013 * 10 power 5 * 1000/8.314 * 303 will give you the number of moles per minute. So this value is 40212.1 moles per minute. Since the solar energy is given in terms of watts it would be useful to convert this particular term of molar flow rate * moles per second. So this would mean molar flow rate n dot = 40212.1/60 moles per second = 670.2 moles per second. We have air coming in and leaving the system which means this is an open system.

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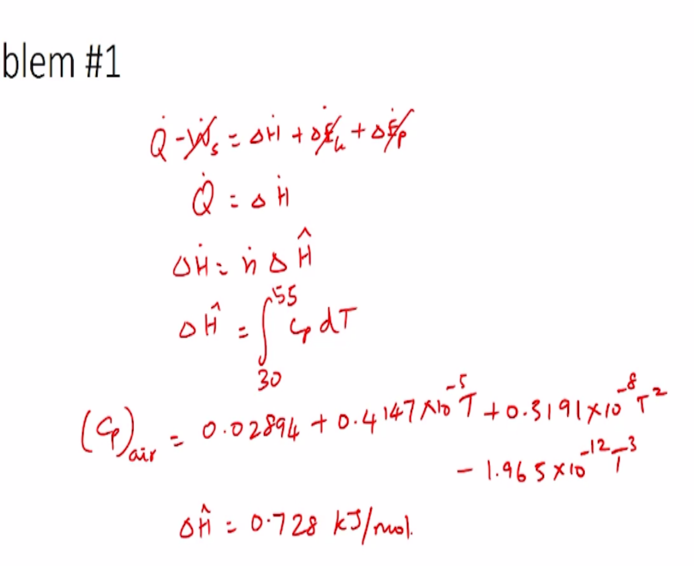

Problem #1

$$\dot{Q} - \cancel{\dot{W}_s} = \Delta\dot{H} + \cancel{\Delta\dot{E}_k} + \cancel{\Delta\dot{E}_p}$$

$$\dot{Q} = \Delta\dot{H}$$

$$\Delta\dot{H} = \dot{n}\,\Delta\hat{H}$$

$$\Delta\hat{H} = \int_{30}^{55} C_p\, dT$$

$$(C_p)_{air} = 0.02894 + 0.4147\times10^{-5}\,T + 0.3191\times10^{-8}\,T^2 - 1.965\times10^{-12}\,T^3$$

$$\Delta\hat{H} = 0.728 \text{ kJ/mol.}$$

So the energy balance equation is Q dot - Ws dot = delta H dot + delta Ek dot + delta Ep dot. So here there are no moving parts. So shaft work could be 0. So there is no change in kinetic energy or potential energy that has been given to us in the problem so we would have Q dot = delta H dot. So we just have to calculate delta H dot. So delta H dot = n dot * delta H cap. We already have calculated n dot.

We just need to calculate delta H cap. So delta H cap = integral Cp * dT and temperature here increases from 30 degree Celsius to 55 degree Celsius. So we can look up the tables or any hand book to get the CP of air. So Cp of air with Celsius as the units would be 0.02894 + 0.4147*10 power - 5*T + 0.3191*10 power - 8*T square - 1.965*10 power - 12*T cube. So integrating this Cp from 30 to 55 you would get delta H cap value as 0.728 kilo Joules per mole.

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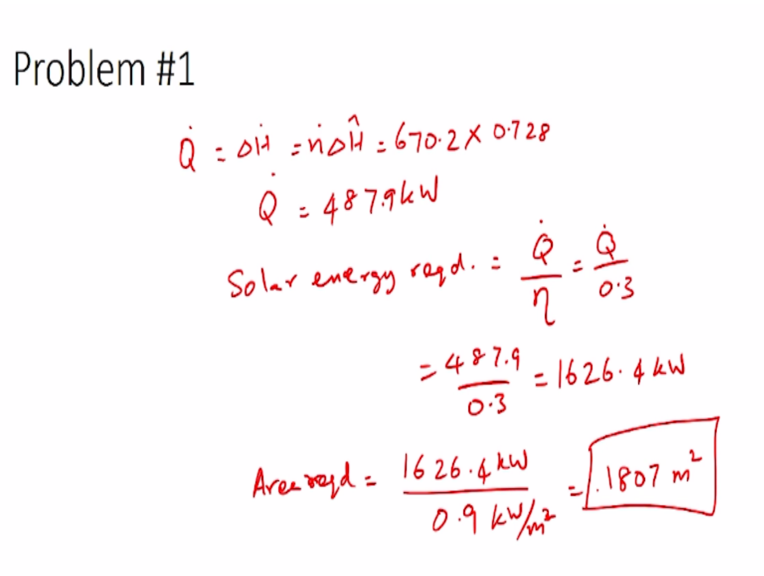

Problem #1

$$\dot{Q} = \Delta\dot{H} = \dot{n}\Delta\hat{H} = 670.2 \times 0.728$$

$$\dot{Q} = 487.9\,kW$$

Solar energy reqd. $= \dfrac{\dot{Q}}{\eta} = \dfrac{\dot{Q}}{0.3}$

$$= \frac{487.9}{0.3} = 1626.4\,kW$$

Area reqd $= \dfrac{1626.4\,kW}{0.9\,kW/m^2} = \boxed{1807\,m^2}$

So we now have delta H cap so we can calculate Q dot which = delta H dot as n dot * delta H cap which is 670.2 * 0.728. So this gives Q dot as 487.9 kilowatts. So, 487.9 kilowatts is required for heating air from 30 degree Celsius to 55 degree Celsius. We know that the solar panels are only 30% efficiency. So because they have only 30% efficiency we need to account for that. So the amount of solar energy which is actually required would be solar energy required would actually be = Q dot/efficiency which is Q dot/0.3.

So 487.9/0.3 giving you the amount of solar energy required as 1626. 4 kilowatt. We have been told that 1 meter square can actually provide 900 watts of solar energy so which means we can convert this total solar energy required and use this to calculate the area of the solar panels required. So area required would be = amount of solar energy required which is 1626.4 kilowatts/0.9 kilowatts per meter squared.

This would give us the area required as 1807 meter square. So we would require 1807 meter square of solar panels for the given problem so that we can heat air from 30 degree Celsius to 55 degree Celsius. So the amount of air heated would be 1000 meter cube per minute. So this we have actually solved the energy balance problem and we will move on to the next tutorial problem. So here is the next tutorial problem.

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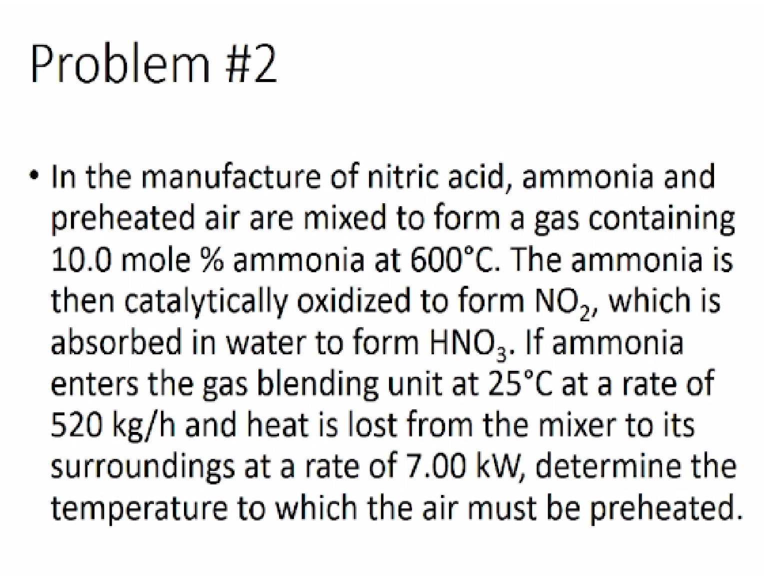

## Problem #2

- In the manufacture of nitric acid, ammonia and preheated air are mixed to form a gas containing 10.0 mole % ammonia at 600°C. The ammonia is then catalytically oxidized to form $NO_2$, which is absorbed in water to form $HNO_3$. If ammonia enters the gas blending unit at 25°C at a rate of 520 kg/h and heat is lost from the mixer to its surroundings at a rate of 7.00 kW, determine the temperature to which the air must be preheated.

In the manufacture of nitric acid, ammonia and preheated air are mixed to form a gas containing 10 mol % ammonia at 600 degree Celsius. The ammonia is then catalytically oxidized to form NO2 which is absorbed in water to form nitric acid. If ammonia enters the gas blending unit at 25 degree Celsius at a rate of 520 kilograms per hour and heat is lost from the mixer to its surroundings at a rate of 7 kilowatts determine the temperature to which the air must be preheated.

So here we have some information about heat being lost in addition to what we need to supply. So we need to account for this value of performing the calculations. So here we have also been asked to calculate temperature so if you look back at one of the problems which we did during the lectures we have actually solved such equations to get temperature so here you will again apply the same principles so let us look at how we can solve this problem.

First thing we need to identify is the composition of the air is given as 10 mol%. Combustion of the gas mixture is given as 10 mol% ammonia. So we need to convert the mass of ammonia which is being given into moles so that we can actually use them directly and also we have Q which is lost to the surroundings heat loss to the surroundings in terms of 7 kilowatts. So the flow rate should be converted to per second instead of per hour.

With these things in mind let us first convert 520 kilograms per hour to moles per second. So let us first convert 520 kilograms of ammonia per hour to moles of ammonia per second.

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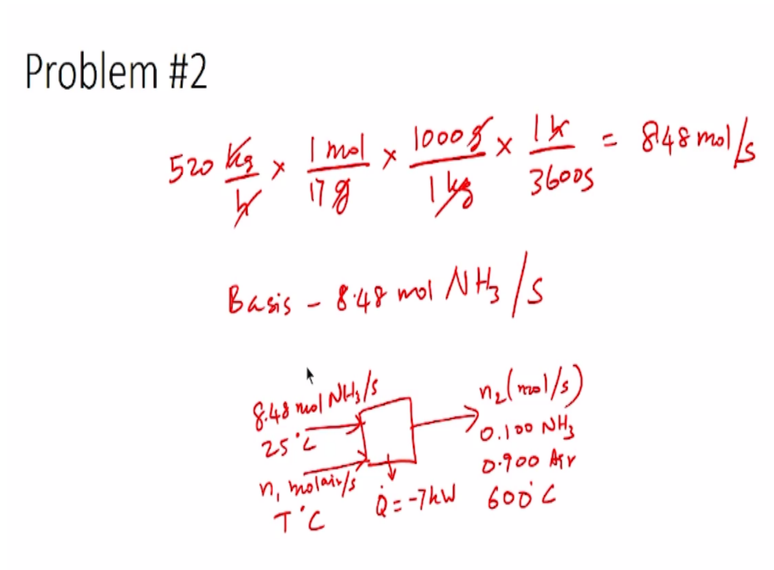

## Problem #2

$$520 \frac{\cancel{kg}}{\cancel{h}} \times \frac{1\ mol}{17\ \cancel{g}} \times \frac{1000\ \cancel{g}}{1\ \cancel{kg}} \times \frac{1\ \cancel{h}}{3600\ s} = 8.48\ mol/s$$

Basis - 8.48 mol $NH_3$/s

So this would be 520 kilograms per hour using the molecular weight of ammonia which is 17 grams per mole so you would have 1 mole/17 grams and we can convert kilogram to gram using 1000 grams are present in 1 kilogram * 1 hour contains 3600 seconds now kilograms get cancel, grams get canceled and hours get canceled and you would end up with moles per second. So the units you have is moles per second and the moles of ammonia which is coming in this 8.48 moles per second.

So the basis for this problem would be 8.48 moles of ammonia per second. So using this basis let us now draw the flowchart for the system. We have been told that there is a gas blending unit where you have 1 feed which is ammonia that is 8.48 moles of ammonia coming in per second at 25 degree Celsius and there is another stream of air which is coming in we do not know the number of moles of air which is being fed so let us call it n1 moles of air per second and we also do not know the temperature at which it is coming in so we will call that T degree Celsius.

We do know that the final mixture is going to have 10% ammonia so which is 0.1 ammonia and 0.9 air so this is the condition of the mixture. We have also been told that the temperature of this mixture is at 600 degree Celsius. We have also been told that there is heat lost which is Q dot = -

7 kilowatts. As heat is being lost from the system we will take this as a negative term. So the number of moles which would be leaving this system we can call it as n2 moles per second which would basically be the sum of moles of ammonia and the air which is entering the system.

So now that we have this flowchart we need to first perform material balances to get some of the values which have to be calculated. We will see whether material balances by themselves are sufficient to do this and then we will proceed further. To identify if material balances are sufficient to get the flow rates we need to perform a simple degree of freedom analysis using only the material balances.

Here we have 2 components 1 is ammonia other is air which means we can have 2 independent equations. In the given system, we have 2 unknown which are n1 and n2. So this means that the degree of freedom is 0 for the material balance problem in our hand. So we can perform simple material balance calculations before we start the energy balance calculations.

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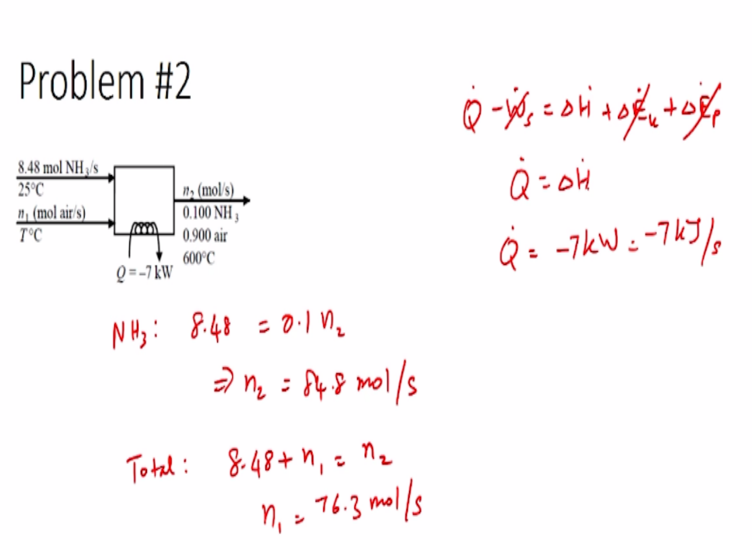

Problem #2

$\dot{Q} - \cancel{\dot{W}_s} = \Delta\dot{H} + \cancel{\Delta\dot{E}_k} + \cancel{\Delta\dot{E}_p}$

$\dot{Q} = \Delta\dot{H}$

$\dot{Q} = -7kW = -7kJ/s$

$NH_3$: $8.48 = 0.1\, n_2$

$\Rightarrow n_2 = 84.8$ mol/s

Total: $8.48 + n_1 = n_2$

$n_1 = 76.3$ mol/s

So the material balance calculation would be ammonia which is coming in at 8.48 accounts for 0.1 * n2. So from here we can calculate n2 as 84.8 moles per second. Now that we have n2 we can write an air balance or a total balance and get n1. So total balance is basically 8.48 + n1 = n2 so we already know n2 so we can calculate n1 as 76.3 moles per second. So now we have the molar flow rates of ammonia and air and the mixture which is leaving the system.

We now have to calculate the temperature at which air has been fed to the system. For this we need to perform energy balance calculations. First thing we need to do is to identify whether this is an open system or a close system. As we have air and ammonia flowing in an out of the system this is an open system. So we have the energy balance equation as Q dot - Ws dot = delta H dot + delta Ek dot + delta Ep dot. So Ek and Ep go to 0 because there is no change in kinetic and potential energies.

There are moving parts so Ws goes to 0. So Q dot = delta H dot is the energy balance equation we end up with. So now we need to calculate the delta H dot. So we can calculate delta H dot for the inlet ammonia and the outlet mixer which is leaving the system however we cannot calculate the enthalpy of the air which is fed into the system because the temperature is not known. However, the equation using this can actually be used to calculate the temperature from that.

So let us see how you would go about doing this. So we already know that Q dot for the system is - 7 kilowatts which is - 7 kilo Joules per second. So we need to now calculate delta H dot so in terms of the temperature of air which has been fed and solve for temperature. So for this we need to build an enthalpy table.

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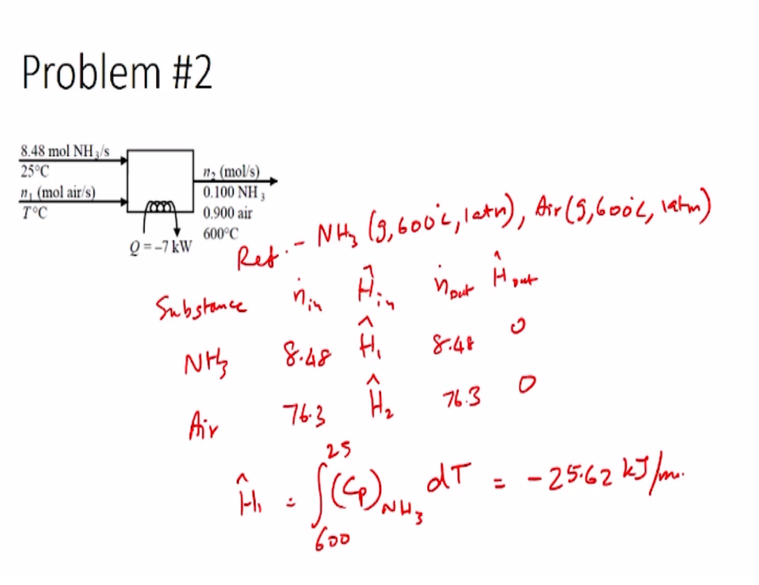

Problem #2

Ref. - $NH_3$ (g, 600°C, 1 atm), Air (g, 600°C, 1 atm)

| Substance | $\dot{n}_{in}$ | $\hat{H}_{in}$ | $\dot{n}_{out}$ | $\hat{H}_{out}$ |
|---|---|---|---|---|
| $NH_3$ | 8.48 | $\hat{H}_1$ | 8.48 | 0 |
| Air | 76.3 | $\hat{H}_2$ | 76.3 | 0 |

$$\hat{H}_1 = \int_{600}^{25} (C_p)_{NH_3} \, dT = -25.62 \text{ kJ/mol}$$

So the enthalpy table would contain substances n dot in H cap in n dot out and H cap out. So here you would have ammonia and air so ammonia entering the system is 8.48 moles per second and air entering the system is 76.3 moles per second. This is the same values which are leaving the system also. So we need to identify a reference state for which the table can be built so the reference state which we use can be based on the inlet or the outlet conditions.

So let us assume the reference state should be the outlet conditions so if you were to use that when you would have ammonia gas 600 degree Celsius and 1 atmosphere and air at 600 degree Celsius and 1 atmosphere as your reference states which means the outlet condition enthalpy should be 0. So the inlet enthalpy subshell to be calculated. So you have H1 cap and H2 cap.

So H1 cap would be = integral of 600 degree Celsius to 25 degree Celsius. Cp of ammonia dT. So this would be a numerical value which you can calculate. Using the Cp value of ammonia this can be calculated as - 25.62 kilo Joules per mole. So the next step is to calculate H2 cap. H2 cap we cannot calculate the numerical value because we do not know the inlet temperature.

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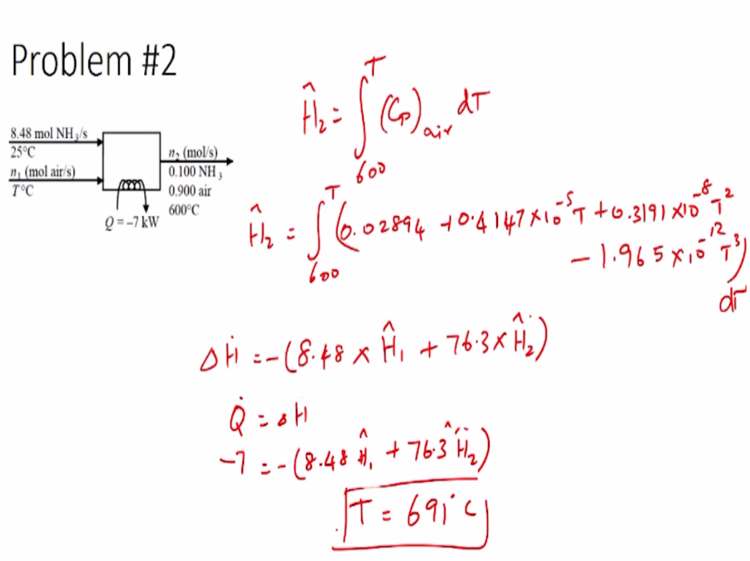

Problem #2

$$\hat{H}_2 = \int_{600}^{T} (C_p)_{air}\, dT$$

$$\hat{H}_2 = \int_{600}^{T} \left(0.02894 + 0.4147\times10^{-5}T + 0.3191\times10^{-8}T^2 - 1.965\times10^{-12}T^3\right) dT$$

$$\Delta\dot{H} = -(8.48 \times \hat{H}_1 + 76.3 \times \hat{H}_2)$$

$$\dot{Q} = \Delta\dot{H}$$

$$-7 = -(8.48\,\hat{H}_1 + 76.3\,\hat{H}_2)$$

$$\boxed{T = 691^\circ C}$$

So our problem would be given us H2 cap = integral 600 degree Celsius to temperature T Cp of air dT. So we have already identified the Cp of air for the previous problem as well so we can actually use the Cp and end up with a polynomial which would be a fourth order polynomial of temperature. So using the Cp of air you would end up with a fourth order polynomial for this equation.

So H2 cap would then be integral 600 to T Cp of air which is 0.02894 + 0.4147 * 10 power - 5 * T + 0.3191 * T power - 8 * T square - 1.965 * 10 power - 12 * T cube and this would be dT. So this would be solved by integration to get the fourth order polynomial. So now this fourth order polynomial can be brought into calculate delta H dot. Delta H dot = - 8.48 * H1 cap + 76.3 * H2 cap. So with this particular equation we can substitute it back into the general energy balance equation we had which was Q dot = delta H dot so Q dot which was identified as - 7 = - 8.48 H1 cap + 76.3 H2 cap.

So from here we can solve for the temperature using the fourth order polynomial which we arrived. So that would be temperature of 691 degree Celsius. I am not going to go into the details of the integration and how the polynomial is going to be solved. I expect you to practice it and actually be able to solve it on your own. So please do try to solve this and confirm whether you are able to get the same temperature that I have arrived at, which is 691 degree Celsius.

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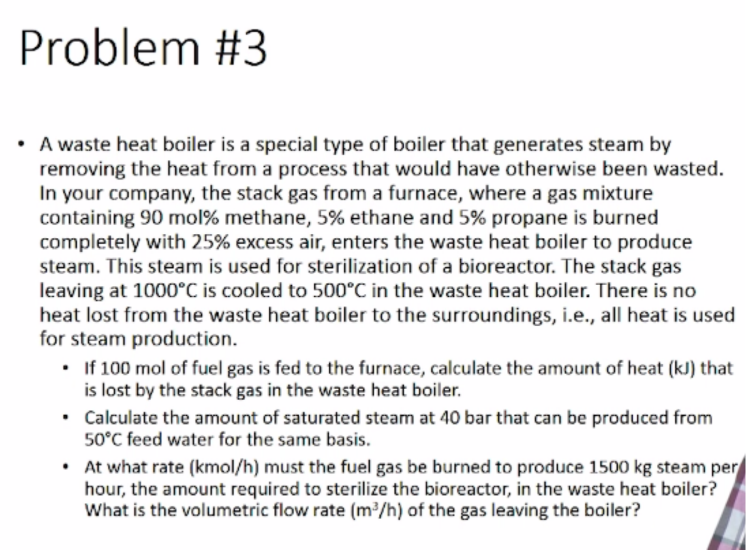

# Problem #3

- A waste heat boiler is a special type of boiler that generates steam by removing the heat from a process that would have otherwise been wasted. In your company, the stack gas from a furnace, where a gas mixture containing 90 mol% methane, 5% ethane and 5% propane is burned completely with 25% excess air, enters the waste heat boiler to produce steam. This steam is used for sterilization of a bioreactor. The stack gas leaving at 1000°C is cooled to 500°C in the waste heat boiler. There is no heat lost from the waste heat boiler to the surroundings, i.e., all heat is used for steam production.
  - If 100 mol of fuel gas is fed to the furnace, calculate the amount of heat (kJ) that is lost by the stack gas in the waste heat boiler.
  - Calculate the amount of saturated steam at 40 bar that can be produced from 50°C feed water for the same basis.
  - At what rate (kmol/h) must the fuel gas be burned to produce 1500 kg steam per hour, the amount required to sterilize the bioreactor, in the waste heat boiler? What is the volumetric flow rate ($m^3/h$) of the gas leaving the boiler?

Here is the third tutorial problem. A waste heat boiler is a special type of boiler that generates steam by removing the heat from a process that would otherwise be wasted. In your company the stack gas from a furnace, where a gas mixture containing 90 mol% methane, 5% ethane and 5%

propane is burned completely with 25% excess air, enters the waste heat boiler to produce steam. This steam is used to sterilize a bioreactor.

The stack gas leaving at 1000 degree Celsius is cooled to 500 degree Celsius in the waste heat boiler. There is no heat lost from the waste heat boiler to the surroundings. All heat is used for the steam production only. If 100 moles of fuel gas are fed to the furnace, calculate the amount of heat that is lost by the stack gas in the waste heat boiler. Calculate the amount of saturated steam at 40 bar that can be produced from 50 degree Celsius feed water for the same basis.

At what rate in kilo moles per hour must the fuel gas be burned to produce 1500 kg of steam per hour, the amount required to sterilize a bioreactor in the waste heat boiler. What is the volumetric flow rate in meter cube per hour of the gas leaving the boiler? So now we have a problem where we are asked to calculate the amount or masses of substances. So here we can actually perform these calculations, but first we need to look at the material balance which is required.

So although we are worried about energy balances only for the waste heat boiler the feed to the waste heat boiler is from a furnace and this information is required so that we can have the information about the gases which are present in the gas which is entering the waste heat boiler. So we first need to perform material balances which will help us identify the composition of the gas which is being fed to the waste heat boiler. So let us start performing the material balance calculations first.

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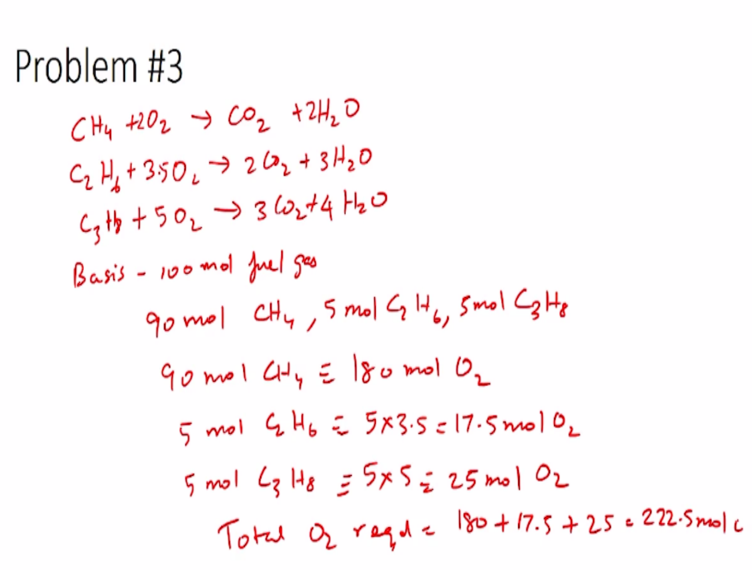

Problem #3

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$

$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

Basis - 100 mol fuel gas

90 mol $CH_4$, 5 mol $C_2H_6$, 5 mol $C_3H_8$

90 mol $CH_4$ ≡ 180 mol $O_2$

5 mol $C_2H_6$ ≡ $5 \times 3.5 = 17.5$ mol $O_2$

5 mol $C_3H_8$ ≡ $5 \times 5 = 25$ mol $O_2$

Total $O_2$ reqd = $180 + 17.5 + 25 = 222.5$ mole

The fuel gas which is burned in the furnace contains methane, ethane, and propane. So all these are burnt to produce only carbon dioxide you have been told that it is complete combustion so no carbon monoxide would be formed. So we first need to write down the combustion reactions for this particular system so you have methane reacting with oxygen to form carbon dioxide and water vapour so balancing this equation you would get 2 O2 and 2 H20.

So similarly the balance equation for combustion of ethane would be ethane + 3.5 oxygen gives 2 Co2 + 3 H20 and for propane it would be for 5 O2 it forms 3 Co2 + 4 H2O. So we are asked to assume a basis of 100 moles of fuel gas so we will do that. So, basis is 100 mol of fuel gas so this would contain 90 moles of methane, 5 moles of ethane, and 5 moles of propane. We have been told that 25% excess air is supplied. So for that we need to know how much air is actually required so that you can calculate how much air was actually supplied.

So we know that for 90 mol of methane would require 180 moles of oxygen for complete combustion. 5 moles of ethane would require 5 * 3.5 which is 17.5 moles of oxygen and 5 moles of propane requires 5 * 5 which is 25 moles of oxygen. So, total oxygen requirement would be 180 + 17.5 + 25 = 225.5 moles of oxygen. We have been told that air is supplied at 25% excess so we can assume that air is 21% oxygen and 79% nitrogen.

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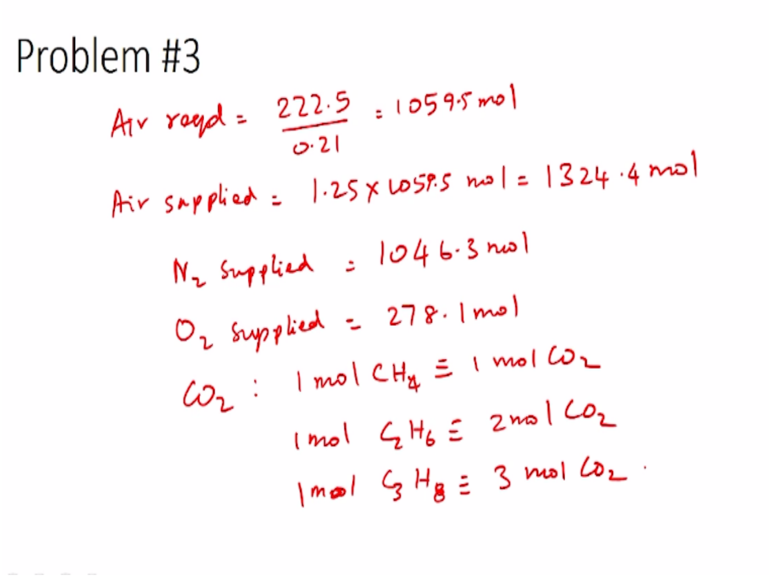

Problem #3

Air reqd = $\frac{222.5}{0.21}$ = 1059.5 mol

Air supplied = 1.25 × 1059.5 mol = 1324.4 mol

$N_2$ supplied = 1046.3 mol

$O_2$ supplied = 278.1 mol

$CO_2$ : 1 mol $CH_4$ ≡ 1 mol $CO_2$

1 mol $C_2H_6$ ≡ 2 mol $CO_2$

1 mol $C_3H_8$ ≡ 3 mol $CO_2$ .

So you would have air required as 222.5 moles/0.21 which is 1059.5 moles of air so air supplied would be 25% excess of what is required so which would be 1.25 * 1059.5 moles which = 1324.4 moles. So nitrogen supplied would be = 1046.3 moles which is basically 79% of the total air and oxygen supplied would be = 278.1 moles. The stack gas composition would not just contain oxygen and nitrogen it would also contain carbon dioxide and water vapour.

We have also been told that the reaction goes to completion which means none of the hydrocarbons are actually present in the stack gas. So the stack gas will only have carbon dioxide and water vapour. To calculate the moles of carbon dioxide we will use the stoichiometry and 1 mole of methane produces 1 mol of carbon dioxide and 1 mole of ethane produces 2 moles of carbon dioxide and 1 mol of propane produces 3 moles of carbon dioxide.

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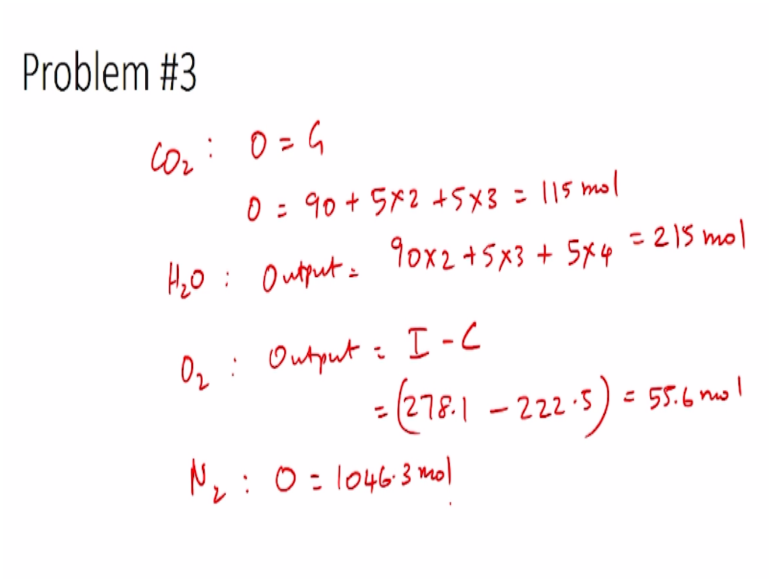

Problem #3

$CO_2$ : $O = G$

$O = 90 + 5\times2 + 5\times3 = 115$ mol

$H_2O$ : Output $= 90\times2 + 5\times3 + 5\times4 = 215$ mol

$O_2$ : Output $= I - C$

$= (278.1 - 222.5) = 55.6$ mol

$N_2$ : $O = 1046.3$ mol

So writing a balance for carbon dioxide we would actually have output equals generation. There would not be any consumption terms or input terms and that steady state accumulation goes to 0 giving as output equals generation so output would be = 90 which is the number of moles of carbon dioxide generated by combustion of methane + 5 * 2 which is the number of moles of carbon dioxide generated by combustion of ethane + 5 * 3 which is the number of moles of carbon dioxide generated by combustion of propane.

So the total number of moles of carbon dioxide present in the stack gas would be 115 moles and similarly we can do the calculations for water and the output for water would be 90 * 2 + 5 * 3 + 5 * 4 giving us the total number of moles of water as 215 moles. So we already know how much oxygen is fed. We also know how much oxygen is consumed during these reactions so we can calculate the output for oxygen as input - consumption which would be 278.1 moles - 222.5 moles giving you 55.6 moles.

Nitrogen does not take part in the reaction so whatever is coming in would also be leaving. So output for nitrogen would be 1046.3 moles. So with this we have the composition of the stack gas which is entering the waste heat boiler. We know that the stack gas is coming in at 1000 degree Celsius. So now our next step is to perform the energy balance calculations for the waste heat boiler.

So since all these gases are combustion gases we can actually use tables from the text books or from reference books where we can get information about the enthalpies for these gases. Table B8 in Felder Rousseau which is one of the prescribed text books actually has these values and we can directly use them for performing these calculations.

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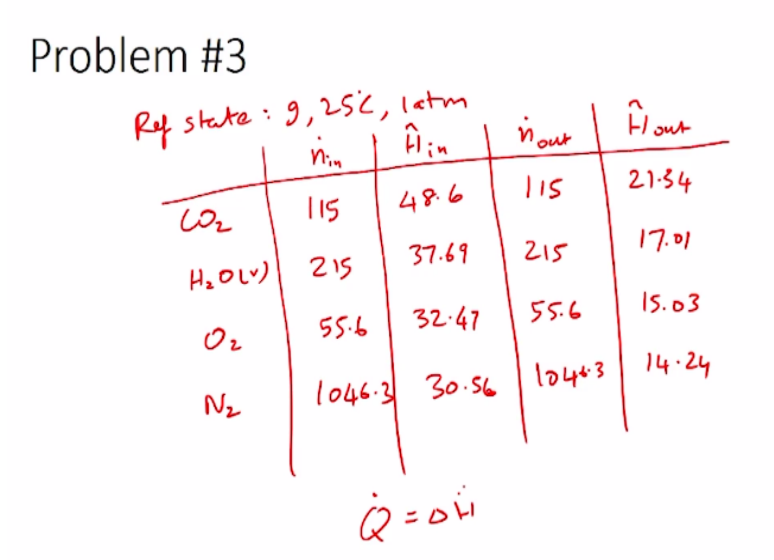

## Problem #3

Ref state: g, 25°C, 1atm

| | $\dot{n}_{in}$ | $\hat{H}_{in}$ | $\dot{n}_{out}$ | $\hat{H}_{out}$ |
|---|---|---|---|---|
| $CO_2$ | 115 | 48.6 | 115 | 21.34 |
| $H_2O(v)$ | 215 | 37.69 | 215 | 17.01 |
| $O_2$ | 55.6 | 32.47 | 55.6 | 15.03 |
| $N_2$ | 1046.3 | 30.56 | 1046.3 | 14.24 |

$\dot{Q} = \Delta \dot{H}$

So for using the table B8 we need to use the appropriate reference state so the reference state used for that table is gas 25 degree Celsius and 1 atmosphere and this is applied for all the components in the system. So the components you have would be carbon dioxide, water vapour, oxygen, and nitrogen so you would have n in dot, H cap in, n out dot and H cap out. n dot in for carbon dioxide is 115 and for water vapour is 215 and for oxygen it is 55.6 and for nitrogen it is 1046.3.

So the output of the furnace which is the stack gas is the input for the waste heat boiler. So the composition of the stack gas which we calculated as output has been used as the input in these terms. Inside the waste heat boiler there is no reactions so the number of moles of all these components will still remain the same so the outlet condition would also have the same components 115 moles of carbon dioxide, 215 moles of water vapour and 55.6 moles of oxygen with 1046 moles of nitrogen.

So we now have to find out the enthalpy values for all these terms. So you have carbon dioxide and water vapour, oxygen, and nitrogen all entering at 1000 degree Celsius. So all these values have to be looked at the enthalpy table for combustion gases. So if were to look up these values these values are given us 48.6, 37.69, 32.47, 30.56, and 21.34, 17.01, 15.03, and 14.24.

So this gives us the enthalpy table. So now that we have the enthalpy table completed we can perform the energy balance calculations for this open system. Your Q dot = delta H dot because there are no moving parts in a waste heat boiler so shaft work goes to 0 and kinetic and potential energy changes are also 0.

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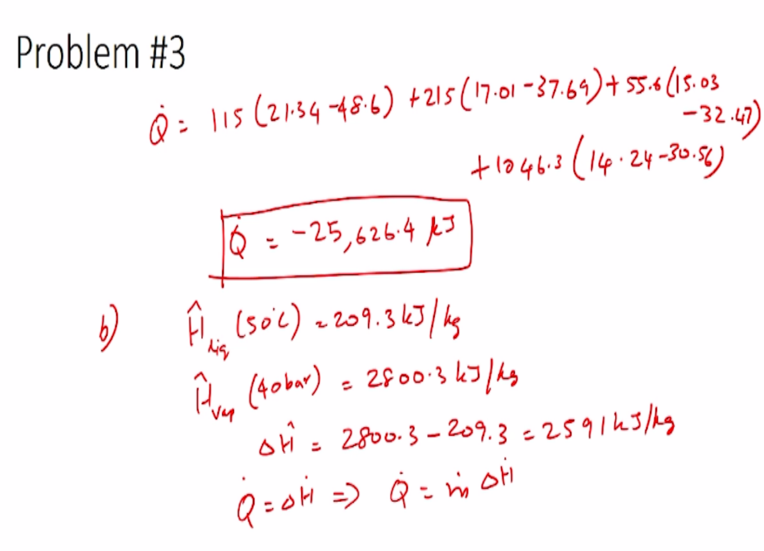

## Problem #3

$$\dot{Q} = 115(21.34 - 48.6) + 215(17.01 - 37.69) + 55.6(15.03 - 32.47) + 1046.3(14.24 - 30.56)$$

$$\boxed{\dot{Q} = -25{,}626.4 \text{ kJ}}$$

b) $\hat{H}_{liq}(50^\circ C) = 209.3 \text{ kJ/kg}$

$\hat{H}_{vap}(40 \text{ bar}) = 2800.3 \text{ kJ/kg}$

$\Delta\hat{H} = 2800.3 - 209.3 = 2591 \text{ kJ/kg}$

$\dot{Q} = \Delta\dot{H} \Rightarrow \dot{Q} = \dot{m}\,\Delta\hat{H}$

So Q dot can be calculated as delta H dot which is = 115 * 21.34 - 48.6 + 215 * 17.01 - 37.69 + 55.6 * 15.03 - 32.47 + 1046.3 * 14.24 - 30.56 giving us Q dot as - 25626.4 kilo joules. So this is the amount of heat which is lost by the stack gas in the waste heat boiler. The next part of the problem asks us to calculate the amount of saturated steam at 40 bar that can be produced from 50 degree Celsius feed water for the same basis.

So now you need to perform the energy balances for the water so whatever this heat is lost by the stack gas would be gained by the water which is being fed at 50 degree Celsius and we have to calculate it as outlet condition as saturated steam at 40 bar. So for part B we can use steam tables and the H cap of water liquid at 50 degree Celsius can be looked up (()) (33:38) table to get

209.3 kilo Joules per kilogram as the enthalpy with reference to its reference (()) (33:46) in the steam tables and similarly H cap for water vapour at 40 bar which is saturated vapour at 40 bar is 2800.3 kilo Joules per kilogram.

So these values can be obtained from the steam tables. So the total change in enthalpy specific enthalpy for the water which is coming in at 50 degree Celsius and leaving as water vapour saturated at 40 bar would be 2800.3 - 209.3 which is 2591 kilo Joules per kilogram. So now the energy balance for this system would have be Q dot = delta H dot and we have to calculate delta H dot so delta H dot is basically m dot * delta H cap.

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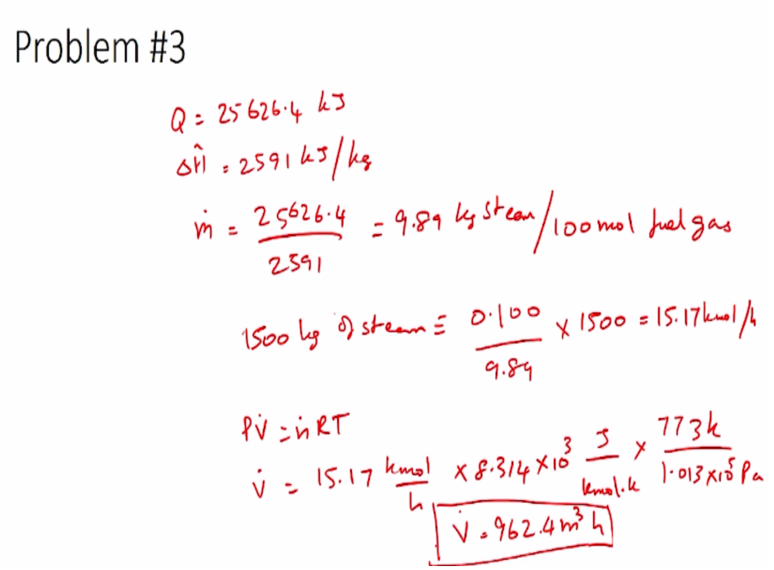

## Problem #3

$Q = 25626.4 \text{ kJ}$

$\Delta\hat{H} = 2591 \text{ kJ/kg}$

$\dot{m} = \frac{25626.4}{2591} = 9.89 \text{ kg steam/100 mol fuel gas}$

$1500 \text{ kg of steam} \equiv \frac{0.100}{9.89} \times 1500 = 15.17 \text{ kmol/h}$

$P\dot{V} = \dot{n}RT$

$\dot{V} = 15.17 \frac{\text{kmol}}{\text{h}} \times 8.314 \times 10^{3} \frac{\text{J}}{\text{kmol.K}} \times \frac{773\text{K}}{1.013 \times 10^{5} \text{ Pa}}$

$\boxed{\dot{V} = 962.4 \text{ m}^3 \text{h}}$

So we know that the heat which is gained by the steam would be equal to the heat lost by the stack gas. So Q = 25626.4 kilo Joules and delta H cap we just been calculated to be 2591 kilo Joules per kilogram. So your m dot which would be mass of steam generated would be 25626.4/2591 giving you a value of 9.89 kilogram of steam per 100 moles of fuel gas burnt. The final part of the problem requires us to calculate the rate at which fuel gas must be burnt to produce 1500 kilogram of steam per hour.

So here we already calculated that 9.89 kilograms of steam can be produced per 100 moles of fuel gas. So to calculate the amount of fuel gas which needs to be burnt to produce 1500 kilograms of steam we would just have to perform simple calculations which would be 1500 kilograms of steam can be produced by 0.1/9.89 so 0.1 is the number of kilomoles of fuel gas burnt/9.89 * 1500 giving us 15.17 kilomoles per hour.

So 15.17 kilomoles of fuel gas has to be burnt per hour to get the required steam output which is 1500 kilograms per hour. We are also been asked to calculate the volumetric flow rate for this so using PV dot = n dot RT we can calculate V dot which is 15.17 kilomoles per hour * 8.314 * 10 power 3 Joules per kilomole Kelvin * temperature is 773 Kelvin which is 500 degree Celsius/pressure which is 1 atmosphere or 1.013 * 10 power 5 Pascal.

So V dot would be = 962.4 meter cube per hour. So 962.4 meter cube of fuel gas has to be burnt per hour for us to get 1500 kilograms of steam with the given conditions. With this, we have performed enough energy balance calculations for systems which do not have any reactions. So even the phase changes which have happened we have only used steam tables so we have not accounted for phase changes explicitly.

So in the next few lectures we will look at phase change operations and how the energy associated with phase change has to be accounted for while performing energy balance calculations. Thank you and good bye.