Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

Chemical Engineering Thermodynamics

by
Prof. M.S. Ananth

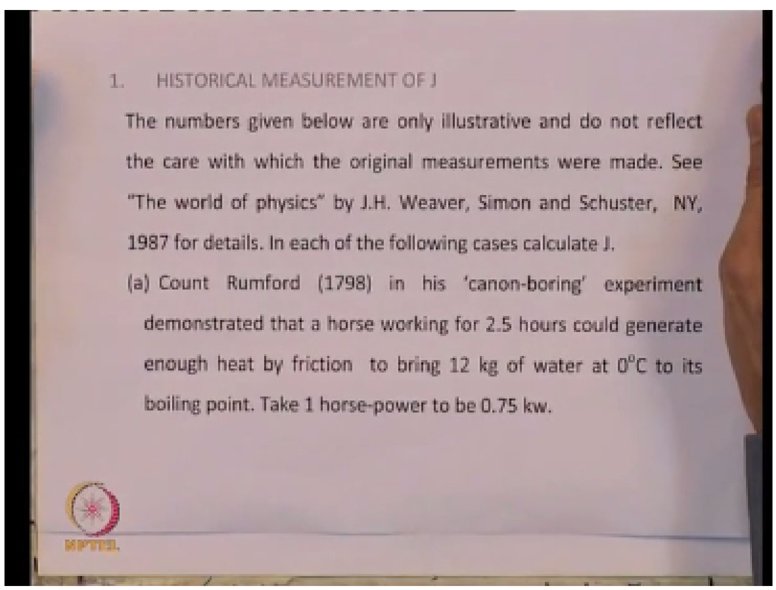
Department of Chemical Engineering
IIT Madras

Lecture 5

Illustrative Calculations 1

We can discuss the first law and second law in the class. I am going to discuss some illustrative problems. The first problem I want to discuss is about historical measurements of the mechanical equivalent of heat, the experiments that were done by Rumford, Meyer and joule.

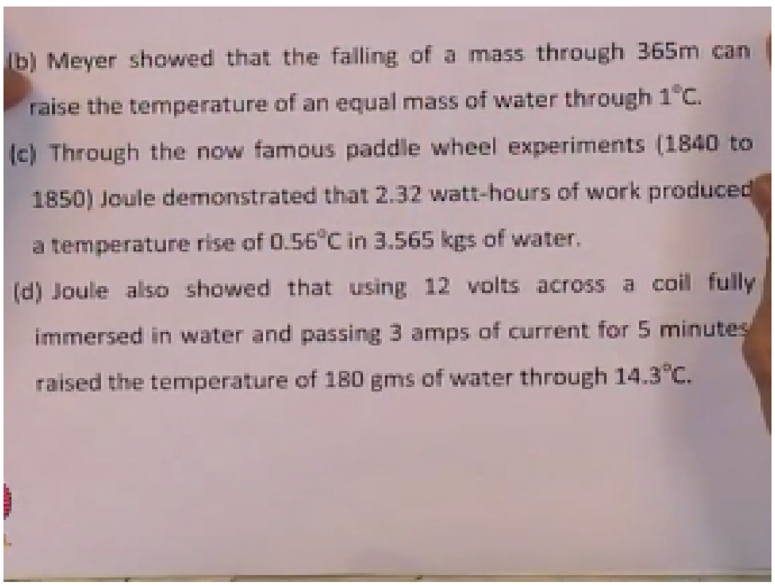
(Refer Slide Time: 00:29)



The numbers I am going to give you are equivalent numbers, and they are going to be illustrative and do not reflect the care with the original measurements were made. There is a book called the world of physics by Weaver, Simon and Schuster 1987, I would recommend that you look at it for details. In each of the cases what I want to do is to calculate the mechanical equivalent of heat.

So the first experiment was by Count Rumford in his canon-boring experiment is it is called. He demonstrated that a horse working for 2 and a half hours could generate enough heat by friction to bring 12 kg of water at 0^0 C to its boiling point. The horse power is a vague unit you can take 1 horse power to be = 0.75 kilo watts which is the current unit of measurement, current definition of horse power.

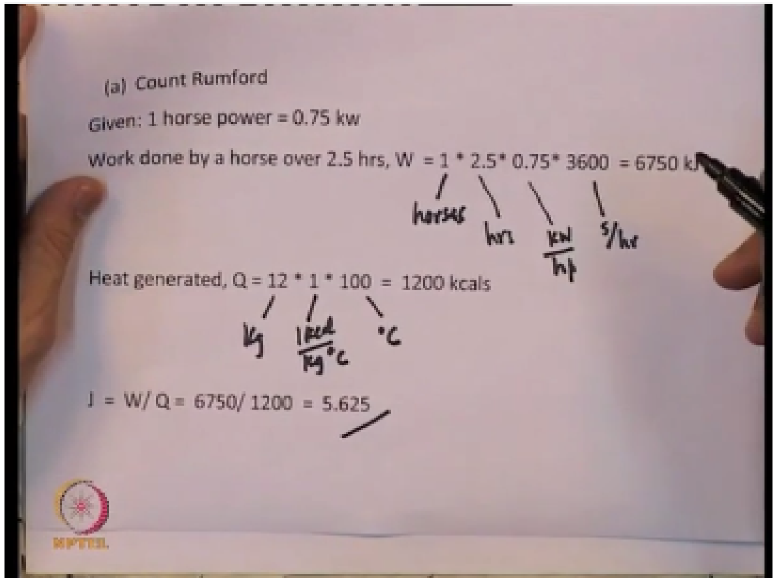
(Refer Slide Time: 01:34)



Second experiment which was to Meyer who showed that the falling of a mass through 365m can raise the temperature of an equal mass of water through 1ºC. Now the third experiment consists of the same of paddle wheel experiments by joule between 1840 and 1850 who demonstrated that on an average 2.32 watt-hours of work produced at a temperature rise of 0.56ºC in 3.565 kgs of water.

Joule also showed that using 12 volts across a coil fully immersed in water and passing 3 amps of current for 5 minutes raised the temperature of 180gms of water through 14.3˚C. So in each of these cases we calculate J the mechanical equivalent.

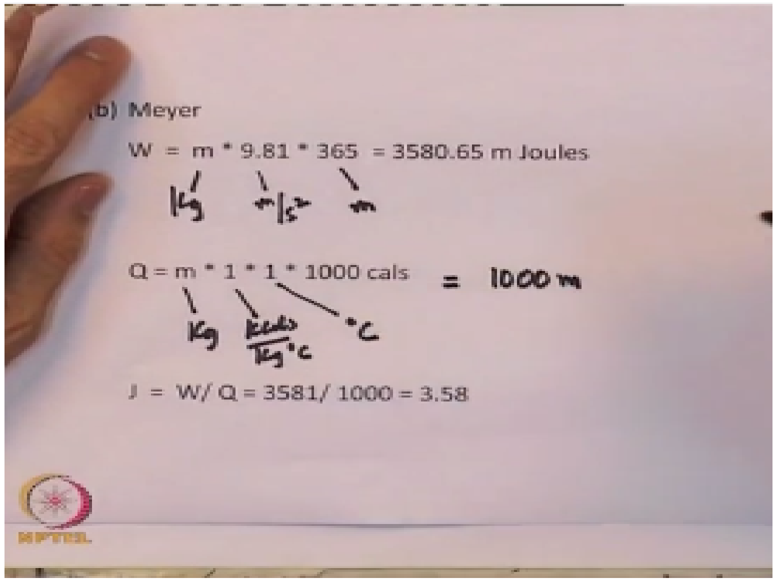
(Refer Slide Time: 02:28)



Take experiment of Count Rumford we are given that 1 horse power is 0.75 kilo watts, now I am just calculating the work done by a horse in 2 and a half hours, this is what number of horses 2.5 is hours, 0.75 is kilo watts /horse power, and this is seconds/hour. So if you multiply these out you get kilo watts seconds of kilo joules, you get 6750 kJ. Now the heat generated as a consequence was given by, in the experiment it is given to you, it is given as 12 kgs, time is 1kcal/kg°C and this is ºC.

So you get simply 1200 kcals J is simply W/Q. So if you divide this 6750 kJ/1200 you get 5.625 you can see this is a bit high, but Count Rumford himself used a little lower value than 0.75 as the conversion factor from what is now called the kilo watt unit to the horse power. And in many cases, what he got a number conceptually this is one of the first demonstrations of the equivalents of heat and work.

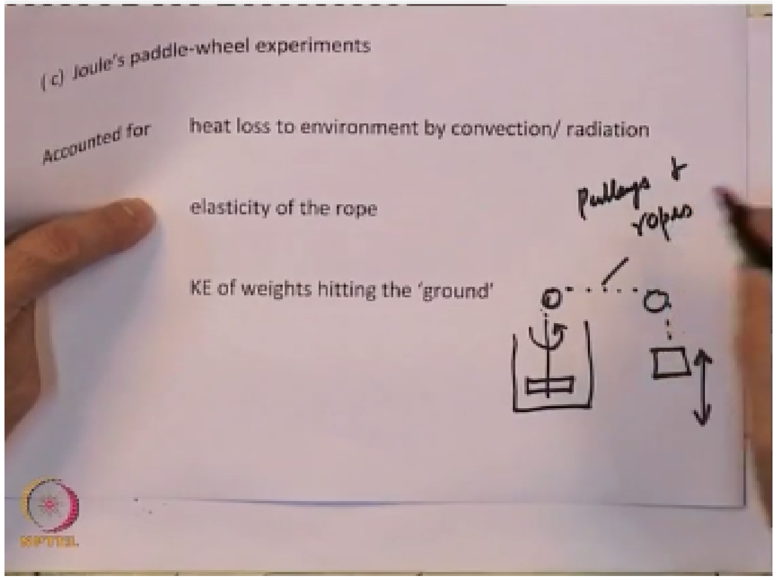
(Refer Slide Time: 04:25)



Now Meyer did this experiment again he reported that a given mass falling to the 365ms, so you will have mass let say in kgms this is ms/sec^2, so you get kg x m/sec^2 N and this is ms, so Nm being a J, he gets essentially 3580 m Joules as a work done. The corresponding heat generated is given by again the mass is in kgs, this kcals/kgºC, this is ºC, this is 1000 is he conversion from kcals to cals. So this gives you 1000m, because he said in equivalent mass of water.

So J according to Meyer was simply W/Q which was 3581 /1000 came to 3.58 this is lower than the current value that is expected somewhat 4.18. Then there were the experiments by Joule so Joules paddle wheel experiments are the most famous.

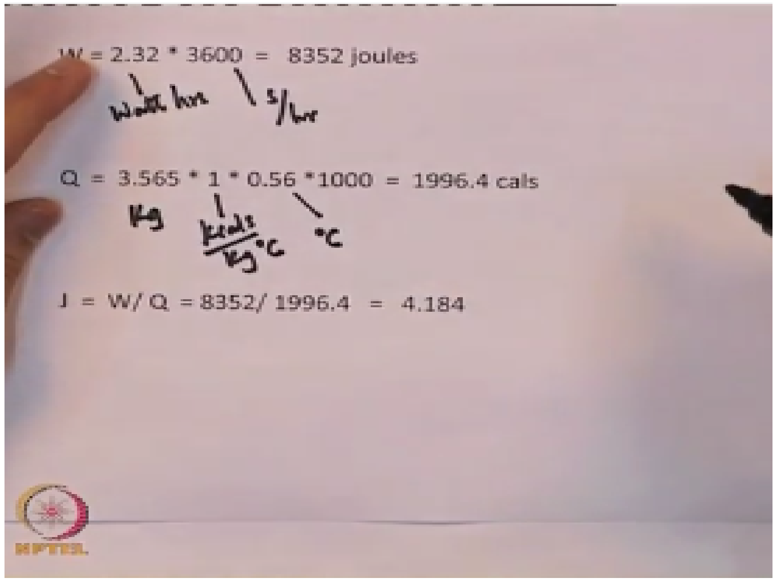
(Refer Slide Time: 05:51)



You may recall that he actually did this experiment repeatedly in the royal society till the members in the royal society actually protested and said, we are convinced do not do any more experiments, but Joule insisted that he do experiments in various mean ways. The paddle wheel experiment is essentially consisted of having a paddle wheel, a container, and a paddle wheel, this paddle wheel was rotated through a system, a complicated system of pulleys and ropes etc and a weight finally.

This weight could move up and down and you must know whether Joule did his experiments with great care he accounted for convection laws, radiation laws, in the environment accounted for elasticity of the rope, he accounted for the kinetic energy as the weights hitting the ground and so on. And that world of physics reference that I told you about these are given in detail. And this whole thing was an arrangement of pulleys and ropes. Okay, now let us get this experiment as a experiment said that.

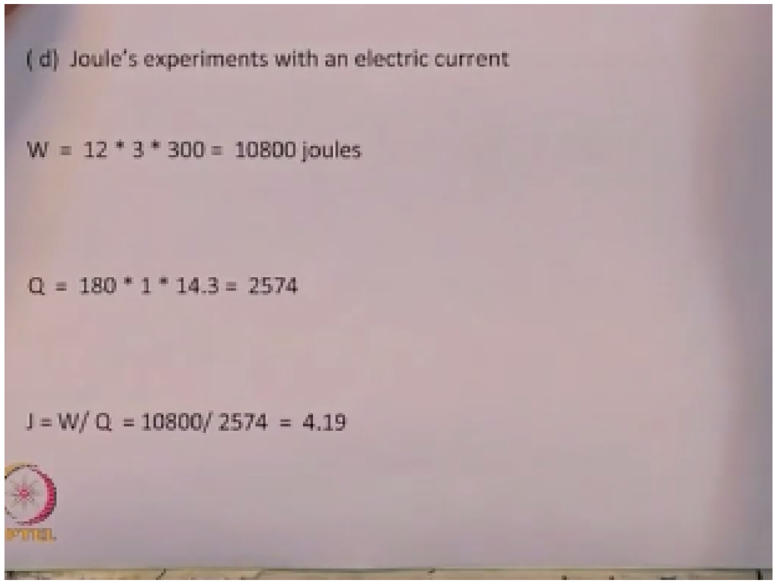
(Refer Slide Time: 07:10)



The total work done was 2.32 watt hours, this is watt hours this is s/hr, so if you convert it into watt sec which is Joules which will give you 8352 Joules from the 3.565 which is kgs of water this is kcals /kg°C this is °C and I am multiplying by 1000 in order to calculate cals. So you get 1996.4 cals is equivalent to 8352 joules or the mechanical equivalent of heat is 4.184 as close to the current the expected value as you can think of.

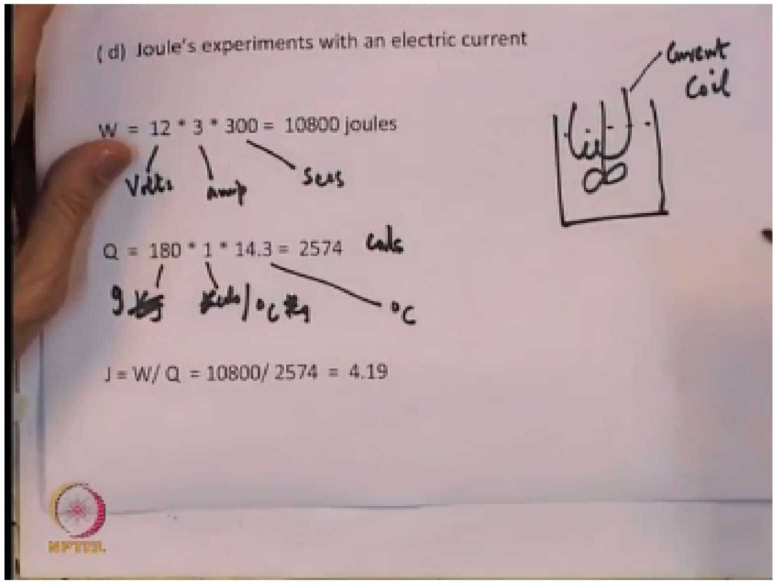
Now let us look at another experiment that joule did, but I must emphasize here that you really have to read the original experiment in the care whether joule did these experiments.

(Refer Slide Time: 08:20)



Because joule was the first one does it, that while it was known that work and heat where the only two ways in which a close system can exchange energy sorry, while it was known that work and heat were two ways of exchanging energy with the surroundings for a close system. Joule is the one who first asserted that there are only two ways to make that assertion that he needed to show that work done many form as equivalent to heat, and everything every form was given and he was actually either a heat or work.

(Refer Slide Time: 08:59)



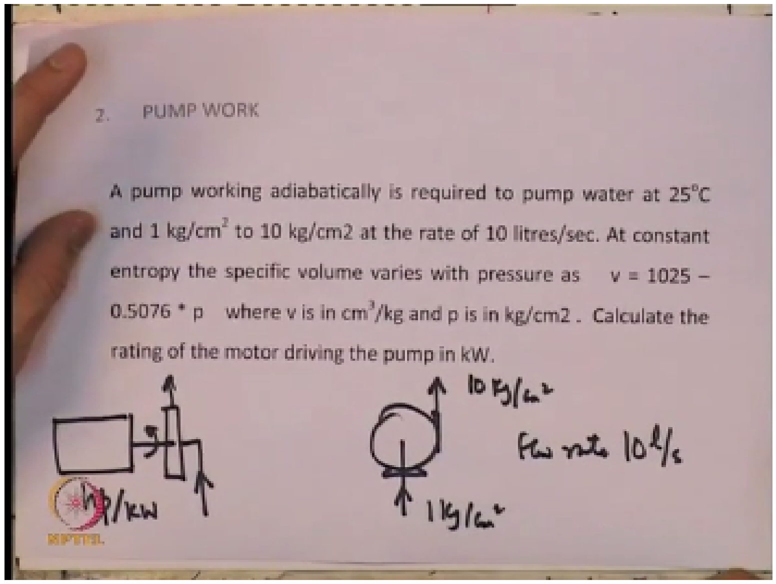
Now let us look at another experiment that joule did and this was an experiment with an electric current joule had 12 volts he had 3 amps passing through this circuit, he had essentially a container with water well stirred may be more importantly he passed a current through it. Then he passes a 3 amps through a 12 volt circuit. So you get this and this is for 5 minutes, so this is seconds.

So you get essentially watt seconds which gives you joules, so it is 10,800 joules was the work done by the current passing through this circuit for 5 minutes. Now the corresponding increase in water temperature is given and the weight of the water is given its 180kgs, this is kcals /^{o}C /gms and this is ^{0}C. So what you get by way of Q is simply a total of I am sorry, the experiment was simply grams not kgms.

So here we are talking about cals/gm and the total amount here you get this 2574 cals and J is therefore 10,800/2.574 =4.19. Again you have to read the original expected description, the original experiments to appreciate the accuracy in the methodical way in which joule did these experiments. And when you are a pioneer it becomes that nmuch more difficult, because you have to be extra careful.

It shows a certain perseverance and faith in the scientific processes. And let me now get to a second problem we can discuss both closed and open system in class, and you can calculate the work done in different situations and here we are going to look at a pump that works adiabatically.

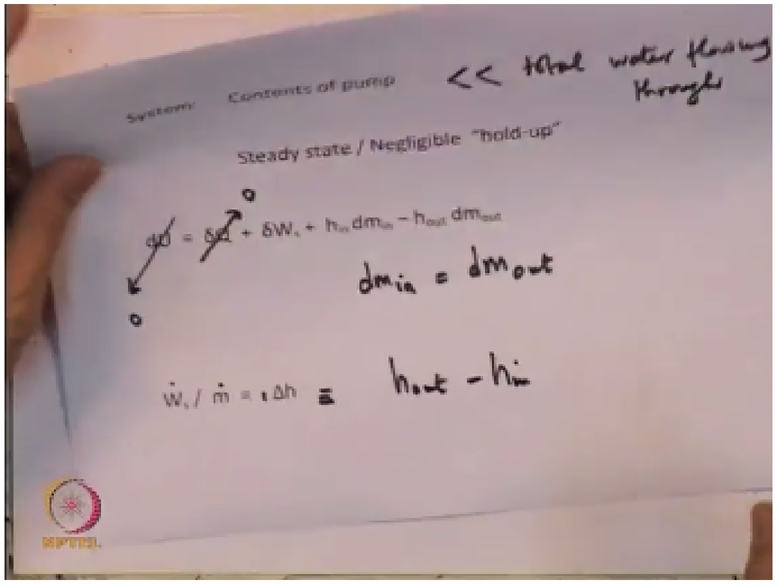
(Refer Slide Time: 11:32)



This is a pump and the inlet this is 1kg/cm^2 and the outlet is given as 10kg/cm^2, in the flow rate is given as 10litres/sec. You should realize that the pump itself if you look at it in cross section is driven by a motor, so this is the input to the pump, this is the outlet, and this is the motor working on the pump. So the question is how much horse power should the motor have in order to do this shop horse power or kilo watts. What should be the power of the motor?

So it says the pump works adiabatically is required to pump water at 250ºC and 1kg/cm^2 to 10kg/cm^2 at the rate of 10litres/sec, at constant entropy the specific volume varies with pressure, this comes from hence taking measurements of the equation of state you get an expression v=1025 - 0.5076P where v is in cm/kg, cm^3/kg and p is in kg/cm^2. So you are asked to calculate the rating of the motor pump, motor driving the pump in kilo watts. So we have to define a system we define the system and simply the contents of the pump. Here we have seen the contents of the pump.

(Refer Slide Time: 13:30)

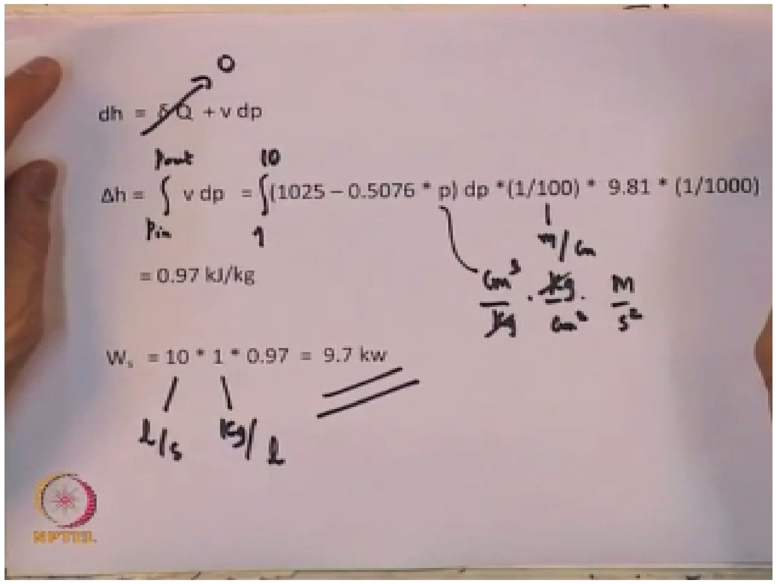


You essentially analyze the system for a time long enough, so that this is less than total water flowing through 10litres/sec. So you are talking of, even if you are talking of 10s you are talking of 100 liters going through and this is size of the pump is much smaller. So what the pump contains is small mass of water and the mass can be neglected in comparing to the mass of water flowing through during the period for which the analysis is defined or you can discuss the operation of the pump at steady-state.

So it is either steady-state or negligible hold up, hold up is what it contain inside the pump. Now you can write the two laws we have written this in class for an open system it says adiabatic. So this has to be 0 you are interested in calculating this, because of the negligible holdup or the steady-state of assumption this is 0, so you simply have at steady-state 3 terms of which the dm_{in} = dm_{out}.

So if you take Ws./m the rate at which the work has done divided by the rate at which mass is flowing through the system you simply get – of Δh you take these two to the other side is h_{out} – h_{in}, so ws=+ sorry, this is defined as h_{out} –h_{in} you can calculate h_{out} –h_{in} from again the equations of the thermodynamics you have dh=Δq + vdp.

(Refer Slide Time: 15:37)



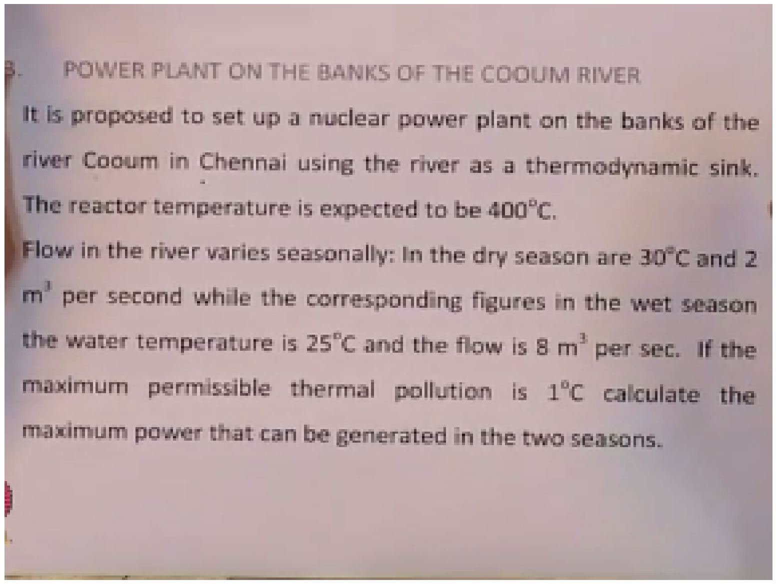
We are looking at pvt systems and here Δq is given as 0, so Δh is simply ∫vdp from p_{in} to p_{out} which is from 1 to 10. Some conversion involved, because this expression that is given to you in the problem statement gives you the volume in cm^3/kg, the pressure itself is given in kg/cm^2. So you get this is kgcm, these kg sorry, kg and kg cancel and when you do the vdp calculation this is kg/cm^2 pressure.

This is the pressure should be multiplied by 9.81 which gives you m/s^2. So this is the actual pressure kg/s^2 will give you N and will give you N/cm^2. So essentially this cm is converted to m here this is m/cm. And finally you are dividing by 1000 in order to get kJ out of this you get Joules and this is the conversion from joules to k joules. So the result you get is simply 0.97 k joules/kg.

Now this is liters/s this is the density which is kg/liter of water into the work done per unit mass which is simply 0.97. So you get 9.7 kilo watt, so this is the rating of the pump that you need for adiabatic operation to pump 10liters/s of water from 1 kg to 10 kg /cm^2. I would recommend that you get an idea of the order of magnitude of this by looking at the rating of the pump may be in your house, where the water is pumped from the tank underground to the overhead tank.

So this is the second example where we calculate the work done by the pump, and we have assumed the adiabatic effectively during the pressure pumping the time is rather short for much heat to be exchanged in the surroundings. And hence the difference is also small between the pump or its contents and the surroundings. So it is a very reasonable assumption, so you get the rating of the pump directly this is ws. like you get ws. here which is the power.

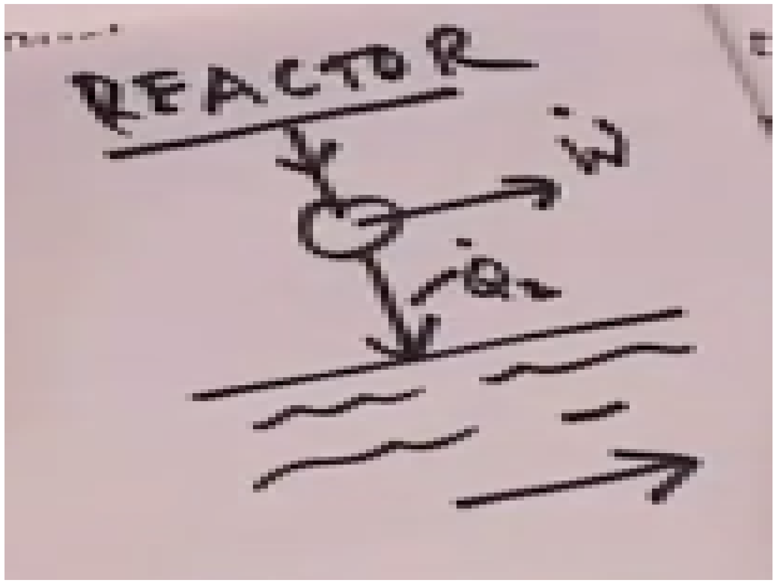
(Refer Slide Time: 19:02)



And we take a third example, all of our big cities are short of power and one suggestion is that you could set up the power plant on the banks of a river. In this case we are talking of Chennai and looking at a river Cooum in order to set up our power plant, because Carno has told you that if you start energy at temperature T1 you need a temperature T2 to which you have to reject heat you draw heat at T1 reject heat T2.

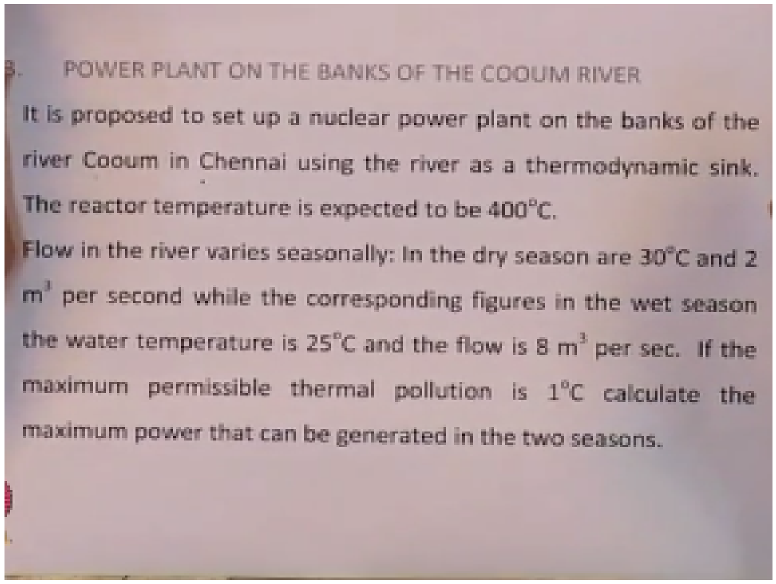
And you can get work at most= T1-T2 /T1 into the amount of heat drawn. Now the amount of heat drawn is 1 constraint, another constraint could be the amount of heat rejected. So if you have for example.

(Refer Slide Time: 19:58)



Let us say you have a river flowing, you have a nuclear reactor. So you are drawing heat from it, you are rejecting heat here, and you are doing work here. And this W is related to this amount of heat rejected here or W. is related to Q2 part.

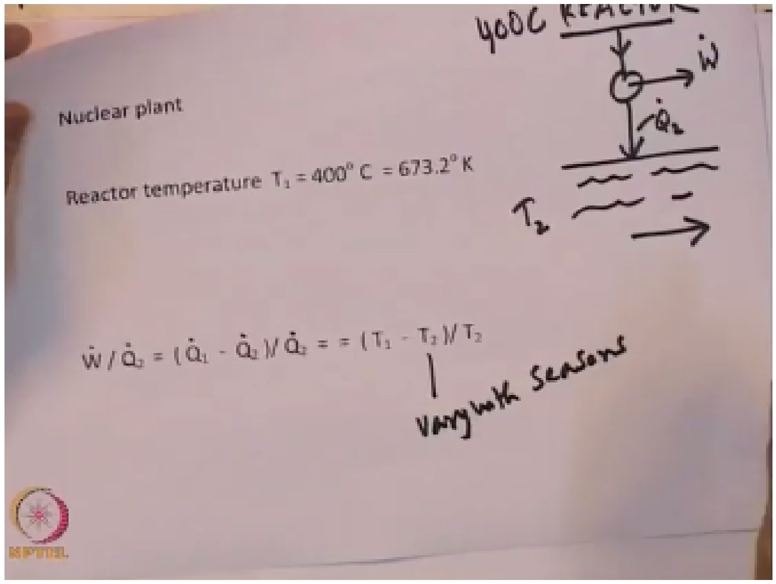
(Refer Slide Time: 20:31)



Now what you are asked is, because of pollution considerations you are told that there is the river here, the Cooum river in this case in which the flow varies seasonally and in all seasons you are allowed to pollute the river thermally to the extent of 1^0C. For example, in the dry season it runs at 30^0C and $2m^3$ per second, so you can go from 30 to 31^o, beyond that it will affect the life in the river.

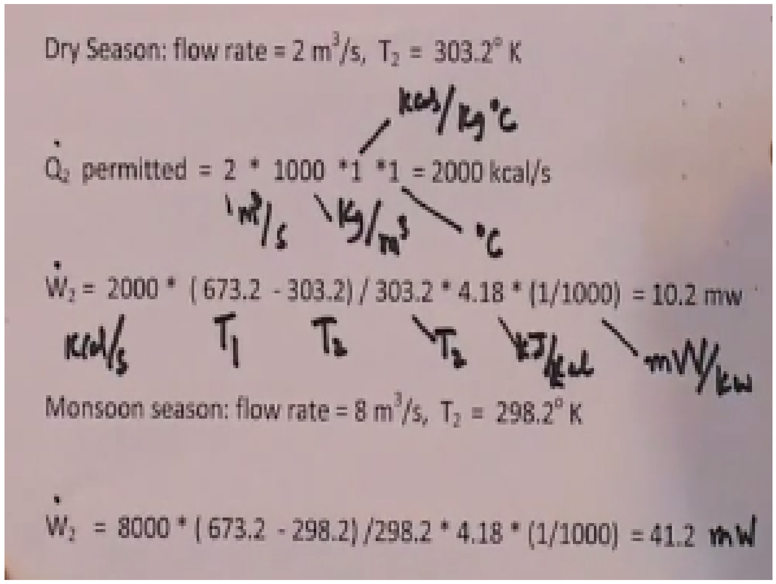
Similarly in the wet season for example the water is at 25^0 and the flow is $8m^3$ per sec, again you are allowed to pollute it to the extent of 1^0C, you are asked to calculate what is the maximum power.

(Refer Slide Time: 21:31)



And you go back to Carno, Carno tells you that this reactor here in this case there is 4000C and this temperature varies with the season here this is T2, so if the reactor temperature is T1 it is equal to 673ºk. Now W./Q2. Is if you like Q1.-Q2./Q1., but this is equal to T1-T2/T2, that is what Carno has told. Now T2 can vary with season, so you are asked to calculate in two seasons what is the amount of work that power you can produce. The dry season flow rate is given as 2m3 per sec.

(Refer Slide Time: 22:25)



And the temperature you already being told 30º which is 303.20k. So you can use this formula you know W./Q. is simply Q1-Q2 IS W./Q2 which is T1-T2 /T2. So if Q2. permitted is now given to you it is given as 2x1000x1 this is simply m^3/sec this is kg/m^3 for water, this is the specific heat which is kcal /kgºC in the thermal pollution allowed is 1ºC. So if you multiply these out you get 2000kcal/s this is the permitted thermal pollution.

If this is all the heat you can reject to the river, then the work produces automatically constraint by the formula that we already showed, you have this is T1, this is T2, and this is T2. T2 actually increases by a degree, but it does not make a difference here. So you put and ask what is the work you can get with this is joules conversion joules per cal or k joules per k cal. So you get out of this you get power and you have to divide by 1000 to get mega watts.

This is joules per sec, because this is kcal/sec. So if you like it is k joules per k cal, so if you convert this mega watts, conversion to mega watts or if you like its mw/ kw which is 1/1000. So you get 10.2mw. In the monsoon season the flow rate is 8 and your temperature T2 changes to 298.2. So you get the same figure it is slightly different 8000 instead of 2000 same formula, the temperature T1 is the same, T2 is now replaced, 303.2 is replaced by 298.2, then you have 4.18 the same conversion factors you get 41.2 mw.

So it is a fairly straightforward calculation we have seen three illustrative problems one is to follow the measurements of the masters to see what conclusions they came to. The second we looked at problem pumping water that is a normal day-to-day problem, in this case under adiabatic conditions. The third problem that we looked at a simply the problem of power generation using both the laws.

What is the maximum power you can generate, if you are constrained by the thermal pollution of the sink. So I hope these problems have illustrated for you in the power of the thermodynamic theory that we did in class. I will stop there and in the next class we will discuss next session on tutorials, we will discuss some on more of the theory that we discussed in class. Thank you very much.

This Lecture Series Edited by

Kannan Krishnamurty

Online Recording &
Post Production team

Subhash
Soju Francis
Selvam
Pradeepa
Robert
Karthikeyan
Ram Kumar
Ram Ganesh
Sathiaraj

Producers

K R. Ravindranath
Kannan Krishnamurty

Recorded at NPTEL Video Studios
IIT Madras