Control Engineering
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Lecture - 18
Models of Industrial Control Devices and Systems (Contd..)

Last time we were discussing about the process control applications. One application of heating of a CSTR was also given. Let me just review the process control concepts, the particular features of process control and take up another application of a heat exchanger. The process control as I said is characterized by the control of certain variables like temperature, pressure, liquid level, composition etc and I made a statement that the process control applications are characterized by factors which are large time constant factors and therefore the pneumatic devices which have characteristics of slow response they are quite adequate for these applications. And the pneumatic devices we discussed last time particularly were the control valve. Recall the schematic of the control valve; the input to the control valve is an electrical signal and the output is a pressure signal or the change of the control stem position which is going to control the fluid flow to the process.

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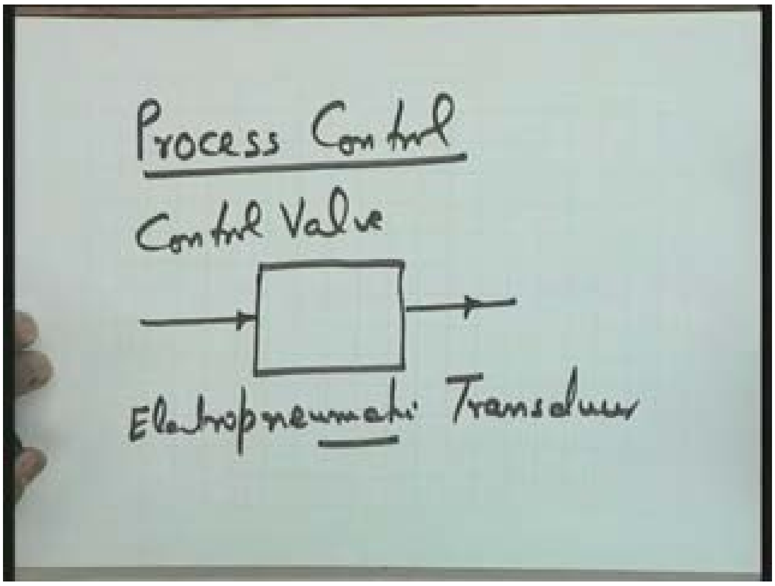

The other device we considered was the Electropneumatic Transducer. This particular device, as I said, I did not explain the device because saying that it is quite identical in construction in principle to electrohydraulic device so we can take a block diagrammatic description which says that it will act as an interface between the actuator which is the control valve and the electronic controller which maybe a digital computer based or an Op-Amp based. So this particular device will accept, as is obvious from its action, it will except an electrical signal as an input signal and will give out a suitable pressure signal which will become an input for the actuator the control valve.

Some specific features of the process control applications are in order here, the discussion on them. I say that let us consider a process and this is a measurement quantity, a signal to be measured; a temperature, a liquid level, composition or any other signal. Normally in process industry the controller is housed in a control room which is at a distance from the process. So what is required is this that the measurement signal from the process will have to be transmitted to the control room and a control signal from the control room will have to reach the process. So, transmission of signals between the process and the control room is required in a typical process control environment.

If you look at the applications prior to 1950s this communication between the control room and the process was typically through the air pressure signals that is why if you visit a typical process control industry you will find that all through the tubing is going from one place to another place because this tubing is necessitated by transmission of signal between the process and the controller and the transmission of the signal was basically going on using pneumatic signals or air pressure signals. But the scene today is changing. At least the new industry is actually adopting the electronic controllers or digital controllers, the microprocessor based controllers and the old equipment is being replaced by Op-Amp based or digital computer based controllers. So now the transmission is not through pneumatic signals it is actually through electrical signals.

So, in the 1950s I say, the typical industrial standard for transmission of signals was 3 to 15 psi of the pressure pounds per square inch. But you see that after that the standardization has taken sufficient time, the standardize prior to standardization plus minus 10 volt for example was being used for transmission standards, 1 volt to 5 volt one volt to five milliamperes 1 milliampere to 5 milliampere 4 milliampere to 5 milliampere all these are the various stages of development and equipment using these standards were in use. But now more or less industrial standardization has taken place towards 4 milliamperes to 20 milliamperes of the current for the transmission purposes.

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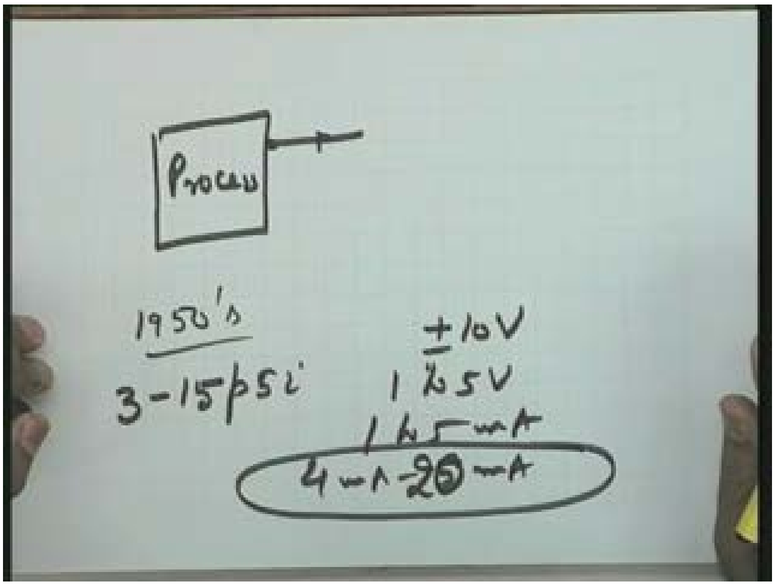

So I will say that the typical signal transmission block diagram will look like this: The process, here is a measured quantity which is a typical process variable, this measured quantity will be fed to a sensor, this sensor will generate an electrical signal now, it could be pneumatic, earlier using suitable force balance equipment pneumatic signals were being generated but now let us concentrate only on electrical signals and let us say this is a suitable electrical signal available over here and most of the sensor outputs as you know are voltage signals. But for transmission I will convert these voltage signals into current signals because current signals are less affected by noise. So it means, at this particular point I can have what is called a signal conditioning circuit or a transmitter (Refer Slide Time: 7:21) this will consist of this transmitter will consist of suitable signal conditioning plus line driving; any losses because of the transmission of the signals have to be taken care of. So this is a transmitter which will have these characteristics and the transmitted signal is going to the controller in the control room.

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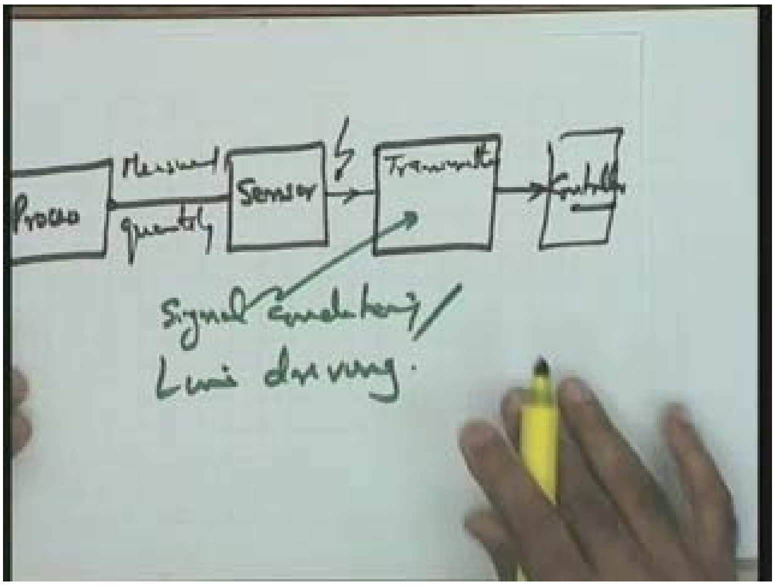

So it means what are the functions of the signal conditioning. The signal conditioning is going to convert this particular signal electrical in nature to a form which is compatible for the controller. So this particular device (Refer Slide Time: 8:10) is taking care of the distance problems also between the process and the controller because of line driving component in it. In typical process control terminology the interface between the process and the controller is typically known as a transmitter; they use the word transmitter the sensor component also embedded in it. But I may be using interchangeably the word transmitter or the sensor to give you the to characterize the function of conversion of a measured quantity to a signal compatible with the controller and for the transmission of the signal from the process to the controller.

So, for us, the word transmitter or the sensor will carry the same meaning. But please note that chemical engineers or process control engineers use the word transmitter quite frequently to describe this total block that is signal from here to the controller. So I say now that the standards for the pressure signals are going to be for our discussion 3 to 15 psi which are the normal industrial standards and for the current signal it is going to be 4 to 20 milliamperes and this current is for the transmission. Naturally voltage to current conversion at the sensor point and current to voltage conversion at the controller point will be needed to have the complete hardware.

In my block diagrammatic representation I may not be showing all the time voltage to current or current to voltage conversions. With this background I think now we can take up one complete industrial application. One mention was made in one of the classes that, well, in many situations I consider the flow variable to be constant and only temperature variable to be controlled or vice versa. Please note that in any process control environment at a time you may be interested or you are rather interested in controlling more than one variable; temperature variable, flow variable and some other the composition, the pH value and other variables you may be interested in. so it means there are number of control loops controlling all these variables.

When I am taking a particular case study or when I am taking an example over here I am taking one of these variables assuming that interaction between this control loop and the other control loops is negligibly small. So this is not really a standalone problem of a process industry; this is a control loop because here in class room we cannot have a very complex problem. So I take one control loop at a time so that we can focus on the control requirements which are going which is going to give us a base for control system design later. So the control loop being discussed now in the case study coming here is a Temperature Control Loop. So naturally this is one of the variables being controlled in a total industrial environment that point may please be noted.

The temperature control loop I take over here is through a heat exchanger. I need your attention on the schematic first and then we will take the block the block diagram description including the transfer function of each block. This is the heat exchanger schematic I am giving you, these are the tubes (Refer Slide Time: 12:05) hollow tubes in the schematic I am showing like this through these tubes the process fluid is going so here is a process fluid whose temperature you want to control it is passed through these tubes so it means this is the inlet and this is going to be the out point the outlet point of the process fluid. So this is your process now, all the other components have to be attached to it but the process should be very clear that these are the hollow tubes and through these particular tubes the process fluid with certain flow rate at a certain temperature is going.

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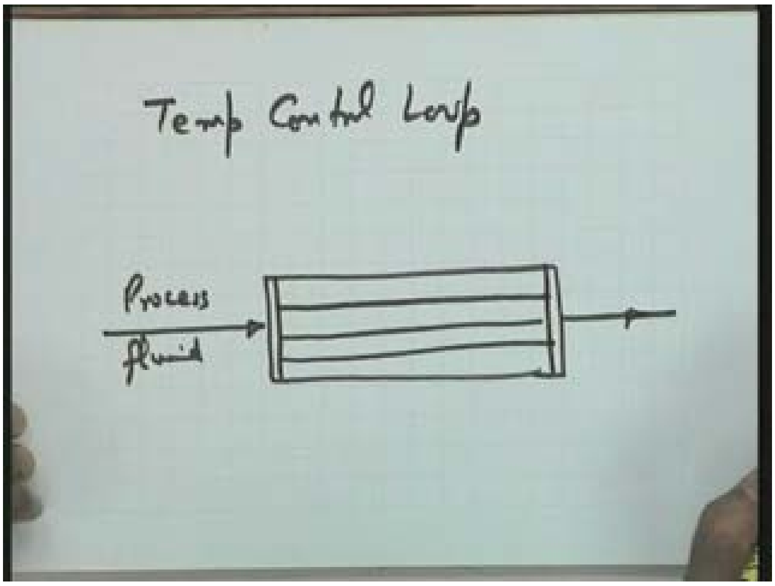

So there is a certain inlet temperature and what is the quantity to be controlled? As I said, I will be interested only in the temperature as the controlled variable and therefore the command signal is this that you want at this particular point the process fluid at a constant flow rate and at a commanded temperature. The flow rate variation is not being considered because it is another control loop which will take care of the flow rate variations. So I want the flow here to be at a constant value assuming that there are no disturbances in the flow rate but there are disturbances in the temperature and I want a control loop to be constructed so that the disturbances in the temperature are reduced to zero.

So what is the command?
The command signal is going to be the desired temperature at this particular point. You will not mind if I take the perturbations here. Let me say that theta in degree centigrade is the perturbation from the desired value. I am not writing the desire value over here. The system is operating at a steady state and theta is the perturbation in the desired value. Here I take theta i as the perturbation in the inflowing temperature with respect to the steady state value. Similarly let me take q m is the perturbation in the flow rate; why I am taking the perturbation in the flow rate is because as you will see the perturbation in the flow rate can also affect the temperature.

I need your attention here. I am not taking the control loop for the flow rate but the perturbation in the flow rate is being considered because this particular disturbance can affect the temperature and the objective of my control loop here is to keep this particular temperature at the commanded value in spite of all the perturbations acting on the process. So these are the two perturbation variables I am considering the input temperature with respect to the steady state point is changing by theta I, the flow rate with the respect to the steady state point is changing by q m and both these perturbations are affecting the output and they are perturbing it to a theta value the objective of the control will be to reduce this theta to zero.

So you see that what is the command signal or what is the desired value; the desired value is this theta in spite of these two perturbations should be reduce to zero. I am not showing the steady state point on my plant model. I hope you are equipped with this now and you can visualize this picture directly in term of perturbation variables. So now, first of all, before going to the control loop let me see what type of manipulation I will be using. What I do is, to raise the temperature of the process fluid, on these particular tubes, on the outside surface of these particular tubes a steam flow at a higher temperature will be passed will be allowed to go. Let us say that this is my valve controlled valve, this is the steam over here and well sorry since I have taken a line I could have shown a line over here itself but does not matter I will redraw this diagram.

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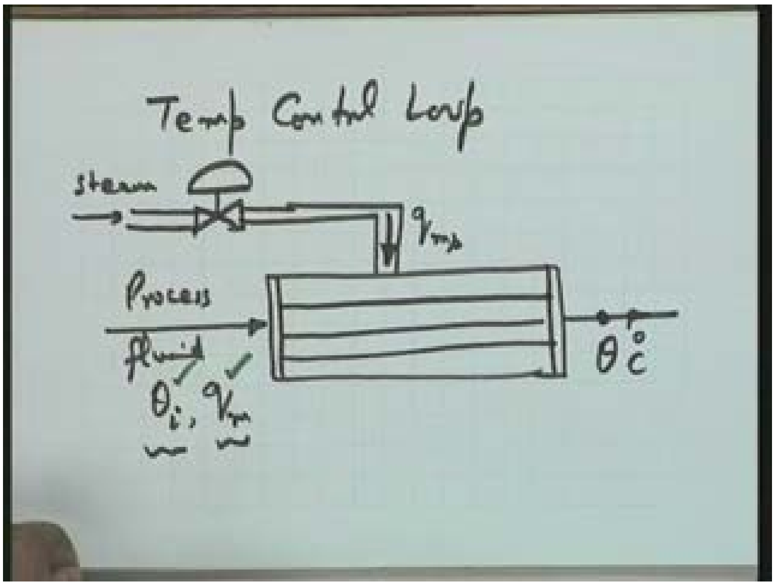

This is the steam flow (Refer Slide Time: 16:23) and let me say q ms is the perturbation in the steam flow. This s subscript in comparison to this q m is showing that it is the steam flow perturbation with respect to the steady state value. So this particular steam is flowing over these particular tubes and heat exchange is taking place. So, naturally after doing the useful work there will be a condensate here. From the steam the heat is stripped off you have a condensate. So now this is the manipulated variable; q ms is the manipulated variable which you want to control which you want to manipulate with the help of your controller and how are you going to manipulate this you are going to manipulate this by controlling this control valve the type of valve we have discussed; the opening of the control valves will suitably be controlled so that the steam going into this particular through this particular pipe the flow rate of this steam is controlled and hence q ms is my variable the perturbation manipulated variable which is going to realize the objective of reducing theta to zero.

Well, now I think you should be able to help me to make a control loop with the information we have about the equipment. please see, I redraw the diagram over here: q m and theta i are the perturbation variables, theta is the controlled variable, tubes over here, q ms is the perturbation variable here, steam and here is the control valve actuator. Come on please; let us now complete the loop. The very first thing I will require is a suitable sensor. Let me assume that I am going to use a thermocouple but alternative sensors are also possible and through some of the tutorial problems I will try to convey the message on the alternative sensors used in industry. But now for this particular diagram let me take the thermocouple. So degree centigrade is the input and here is a suitable signal conditioner. Signal conditioner output should be, I am taking now milliamperes directly, voltage to current conversion circuit is also embedded in this particular block which is the signal conditioner, the current conversion.

For my transmission I need a current signal so milliampere is the output of my signal conditioning block so now I have an error detector; the reference signal naturally should be in milliamperes because this signal is in milliamperes. Let me say that I have a suitable scale factor here; you note that, by now you very well understand my point that this is not a physical device, the scale factor should have suitable correspondence with this particular factor here for the signal conditioner.

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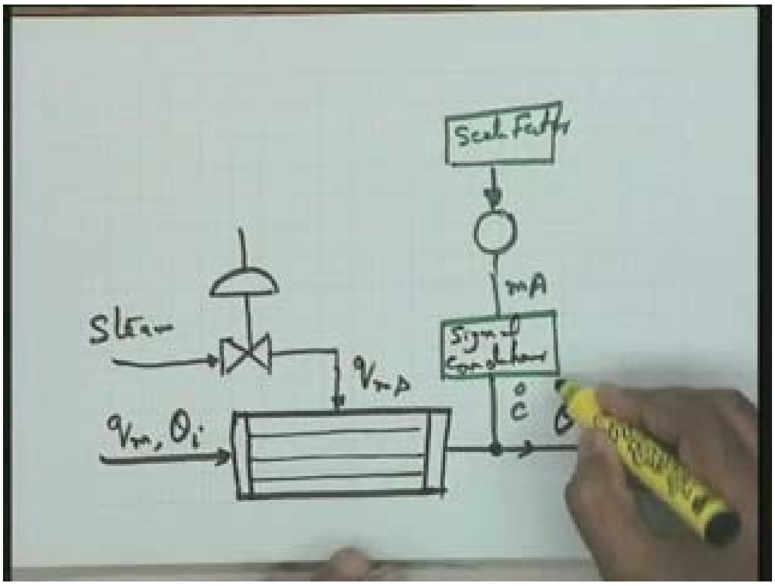

The transfer function or the gain factor of the signal conditioner should be same as the scale factor over here so that the two temperatures can be directly compared in terms of these two signals that is these two current signals so I assume that theta r degree centigrade is my reference and I am assuming milliamperes to be generated as the reference signal. So naturally the error signal is in milliamperes this error signal is now to actuate my controller.

A simple controller is a proportional controller an amplifier only but as I mentioned the typical controller may consist of derivative integral another controller actions. So let me say that this particular signal going to the controller (Refer Slide Time: 21:00); the controller output also is going to be electrical signal because basically I want that the powers of Op-Amp circuits or digital computers must be utilized. So therefore in my configuration the present day control configuration I am assuming that the controller is a suitable electrical controller and therefore here I have an electrical signal.

Since here the actuator is a control valve which is pneumatically operated I need an interface between the output of the controller and this particular actuator. So let me say here, let me put a block over here valve actuator. You know that the output of the valve actuator is going to be stem movement and the input valve actuator is going to be a pressure signal and the pressure signal you know is going to be 3 to 15 psi industry standard and the controller is 4 to 20 milliamperes and hence I have inbetween here since the block is too short to write the complete name you please complete it is Electropneumatic Transducer or Electropneumatic valve which is going to convert this 4 to 20 milliamperes input signal to 3 to 15 psi signal and hence this is your complete schematic of a temperature control loop.

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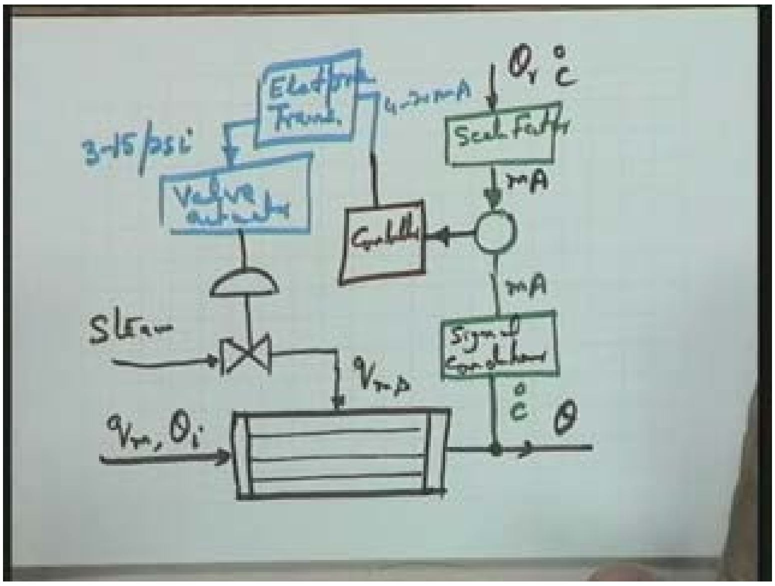

It is not just a schematic, please see, through this schematic I have made an attempt to give you information on the present trends of the hardware used in process industry. So now I want a mathematical model for this. I have been using all the time, physical principles to make a block diagrammatic description. Now, in this particular case let us use experimental methods to make a block diagrammatic description and there from I will be using the total math taking the total mathematical model for the process, the experimental methods, please see that.

You can conduct exp….. Suppose this equipment is available in the lab you can conduct experiments in the lab to identify the transfer function models of various components various blocks over here. I get started with the process itself. So, from the process I will move on to signal conditioner scale factor will be automatically given I will move on to Electropneumatic Transducer and valve actuator to get appropriate mathematical models. Please help me; I take up the process itself.

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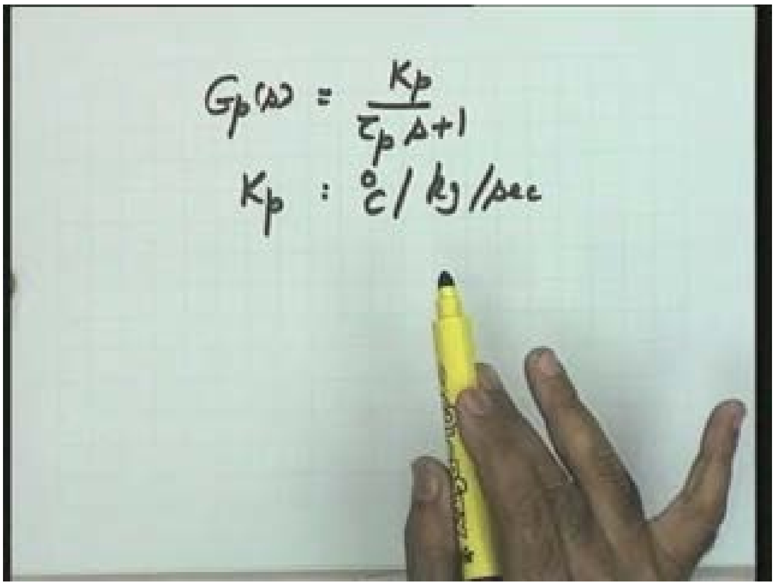

Let me assume that the parameters K p and tau p of this model can be experimentally determined and to determine experimentally these values let us say that q ms the steam flow rate is A kilograms per second let us take this as the input. in that particular case the output can be experimentally obtained and a typical output curve theta verses tau will look like this (Refer Slide Time: 24:29) wherein I show this particular input as dotted whose value is A and the output curve may look like this, this being a typical first-order process.

Now, as far as the steady state value is concerned let me say theta steady state is experimentally obtained and it can easily be established from these curves that the value of K p will be equal to theta ss over A. So naturally if I know the value of theta ss experimentally obtained and if I know the magnitude of A the value of the gain constant of the transfer function has been determined.

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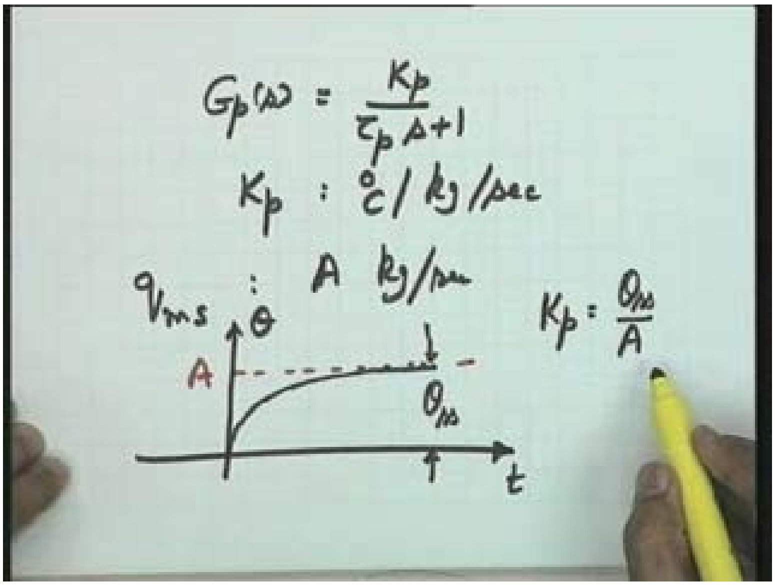

Now let me go for the transfer function the time constant. I have to obtain the time constant which I can easily obtain from the transient of this particular process reaction curve the response curve of the system and to do that what I do is I take the response theta s over Q ms s equal to K p over tau p s plus 1 you know this is the transfer function; for a unit step input or for a input of magnitude A theta s will become equal to K p into A divided by s into (tau p s plus 1) inverse transform of the this gives me theta t equal to this can easily be determined K p into A (1 minus e to the power of minus t over tau p) and you can find K p into A is your theta steady state so it is theta steady state 1 minus e to the power of minus t over tau p. This is the value of theta t.

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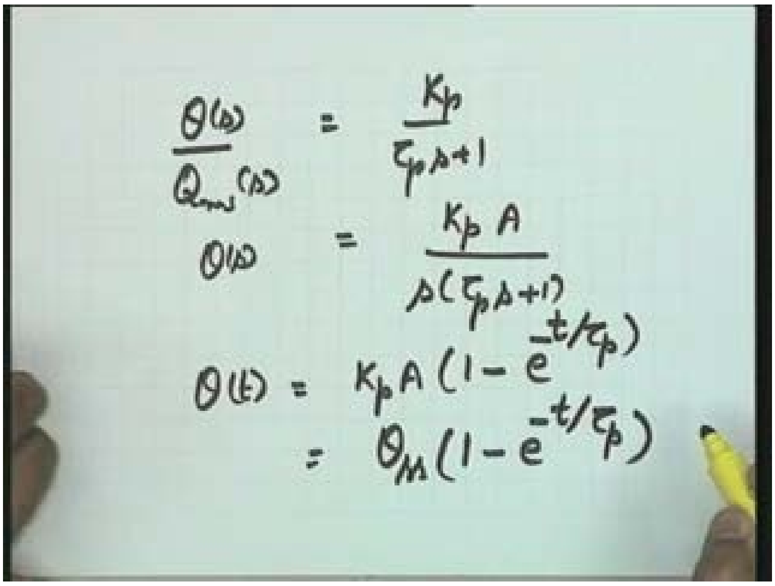

Now let me take the slope at t is equal to 0. This gives me d theta by dt at t equal to 0 is equal to theta ss by tau p at t is equal to 0.

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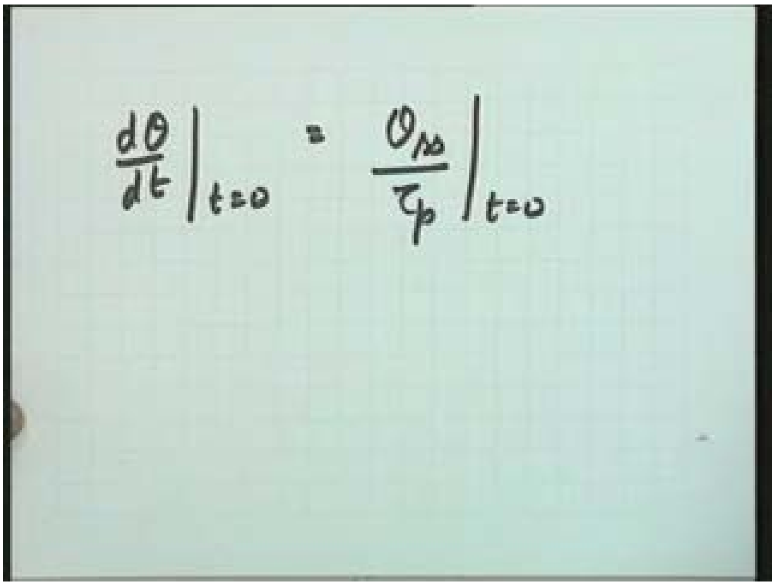

I have written this expression by simply taking derivative of this (Refer Slide Time: 26:48); this can easily be established that the derivative of this at t is equal to 0 is given by this expression. Now theta ss over tau p is the slope. Look at the process reaction curve again; I can redraw here: t verses theta, this is the A, this is the response curve. Now if the slope of this curve at t is equal to 0 is given by theta ss over tau p please let us make a slope line here; the slope line if I make, so naturally this is nothing but tau p and hence from this response curve which has been experimentally obtained the value of tau p can easily be established. So that way I have seen, by conducting a simple experiment the two parameters of the process transfer function Kp and tau p can be obtained.

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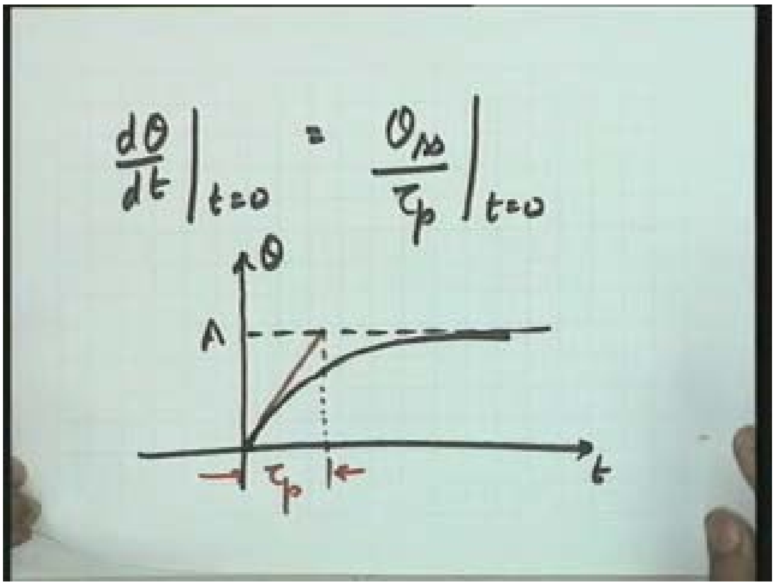

So let me rewrite this: G p(s) equal to K p over tau p s plus 1. now as a typical industrial example let me give you the parameters the parameters of a particular heat exchanger on which the experiment was conducted are as follows: K p was found to be equal to 50 and tau p was equal to 30 and therefore for that typical heat exchanger G p(s) the model becomes 50 over 30 s plus 1. Please keep this in mind that this is the model when you take the temperature theta as the output and the steam flow rate as the input. That is, it is a process model between the input output pair taken as steam flow rate and the temperature theta of the heat exchanger output.

What are the other inputs acting on the process?

You know that the other inputs acting on the process are the disturbance inputs, q m is the disturbance in the process fluid flow, theta i is the disturbance in the temperature of the process fluid inflow. So naturally, exactly, identical way can be utilized to determine a transfer function between theta the output and the disturbance q m between theta the output and the disturbance theta i.

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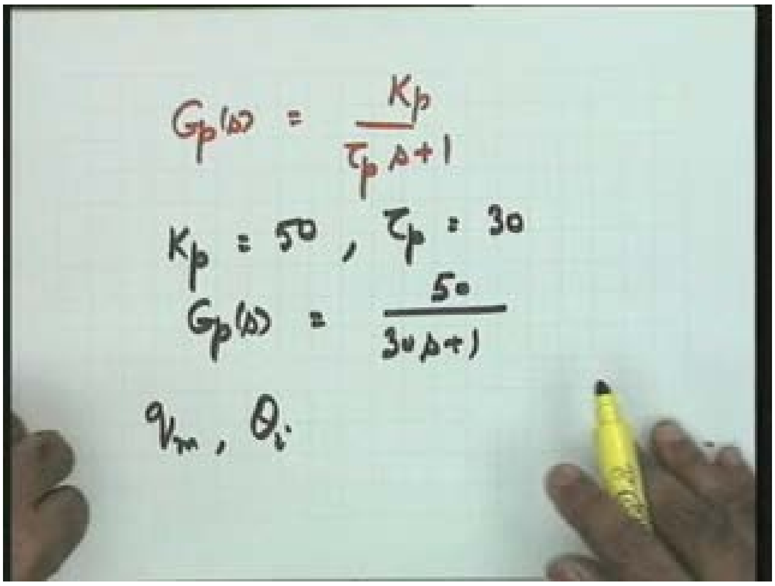

Now for the same typical heat exchanger I refer to the parameters were obtained and the transfer functions between theta and Q m was obtained as this is equal to 1 over 30 s plus 1. So it means in this particular case the gain is 1 degree centigrade per kilogram per second of the input. and how about the time constant; time constant is thirty again because it is the process time constant and the value between theta and theta i(s) that is when the input is in variation with the temperature this was obtained typically as 3 over 30 s plus 1. Let me verify this. Please, this being the experimental results what were the experimental values, I like to give these values, fine. These are correct. So 3 is the gain here degree centigrade per degree centigrade and 30 the time constant of the process.

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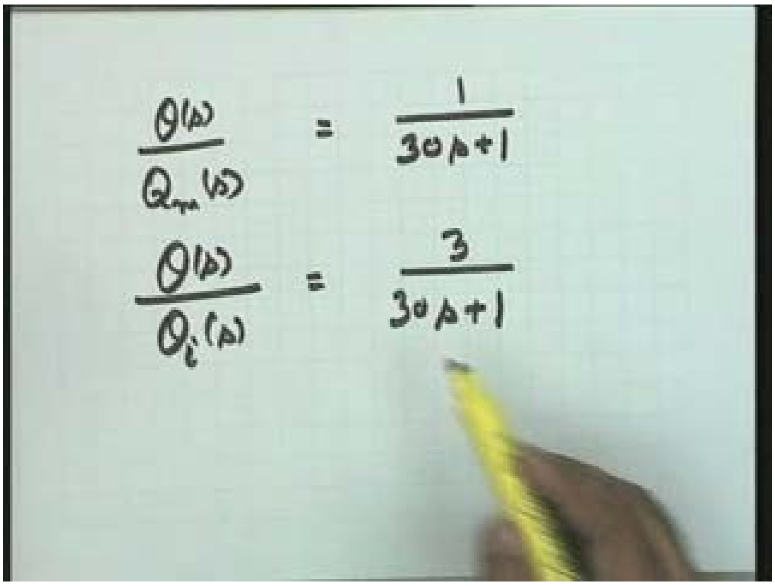

Hence that way we have come to a situation where the process model has been experimentally identified fully. Let me put it here: 50 over 30 s plus 1 is the process transfer function in response to q m(s) the steam flow and here is the output theta. Now the transfer function in response to q m the disturbance in process fluid has been determined to be 1 over 30 s plus 1 this is the disturbance transfer function. the transfer function to the third value the third input which is theta i(s) or theta i let me take it only has been taken has been determined to be 3 over 30 s plus 1 and this is the total transfer function as far as the process is concerned; three inputs, two disturbances and one manipulatable input and one output that is theta.

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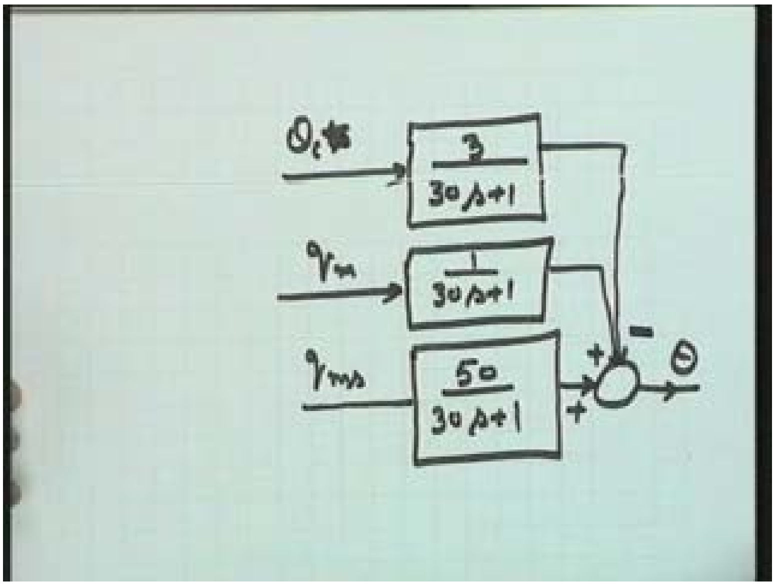

Now, after taking up the process let us pay attention to the other components of the system. I like to next go to Electropneumatic Transducer plus Control Valve.

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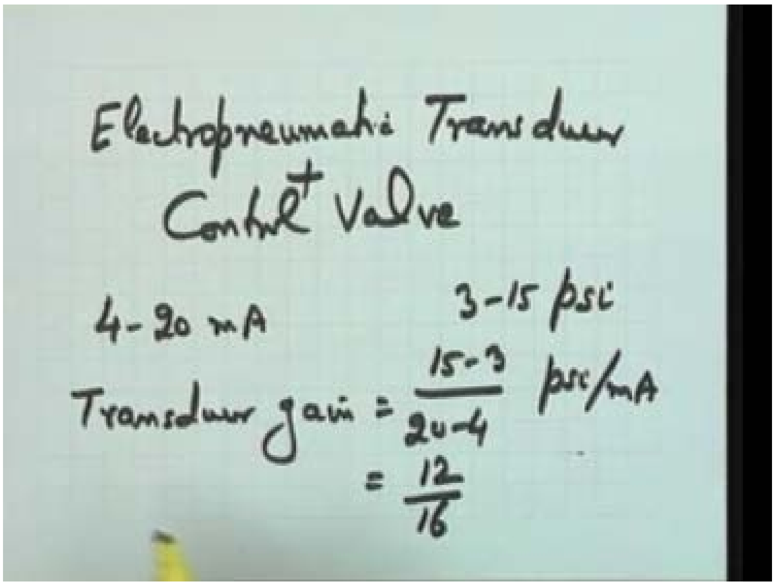

Let me take the two components together and establish a model for this. Please help me. What we will do as far as model of….. we will do the same thing; experimental identification of the transfer function of various components we will do. So, as far as the Electropneumatic

Transducer is concerned, you recall please, the input is current and the output is pressure. As far as the current range is concerned 4 to 20 miliamperes is the current range as far as the input is concerned and 3 to 15 psi is the pressure output. so assuming that the device under consideration is a linear device in this particular range so please see that I can take up the transducer gain; how much is the gain; assuming this to be linear it is 15 minus 3 divided by 20 minus 4 psi per milliamperes let me take this to be 12 by 16; for a typical device under consideration it is 12 by 16 as far as transducer gain is concerned.

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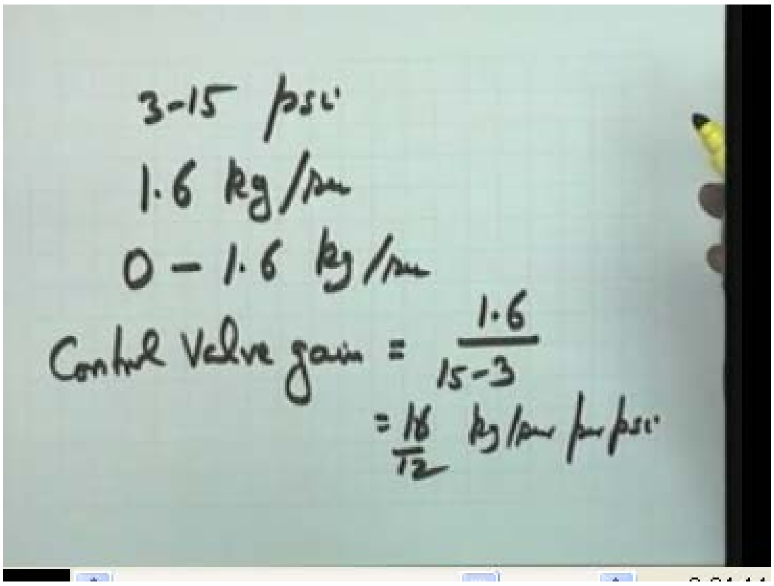

Go to the control valve now, the pressure, 3 to 15 psi is applied to the control valve; what is the output of the valve; it is the flow and again let me give you some quantitative values. For the heat exchanger system under consideration let me say that the maximum flow is 1.6 kilograms per second; this is the maximum value the hardware constrain, I give you this information based on the experimentation done on a particular equipment. Since this is the maximum flow it means variation from 0 to 1.6 kilograms per second is possible. So what is the control valve gain? The control valve gain, in this case I can say is 1.6 divided by 15 minus 3 is equal to 1.6 divided by 12; this (Refer Slide Time: 34:06), what is the units; kilograms per second per psi this becomes the controller gain now if control valve gain I am sorry.

Now if I take the two units together if I take the electropneumatic transducer and the control valve as a single unit with input as current and the output as the flow rate you will find that the gain K v will be equal to, how much please, it is initially we determined out to be 16 by or it was 12 by 16 now it will become 1.6 by 12 and what about the units; you can say it will become kilogram per second per milliamperes because the input noise is in milliamperes and the output I am taking directly is kilogram per second; if the two units are clubbed together so this becomes equal to as you see 0.1 this is K v.

Now if I assume the dynamics of this particular unit to be of the nature that it can be neglected; that is, if the time constant is too small compared to the process time constant I can neglect that value and I can take the model for Electropneumatic Transducer plus control valve as a zero-order model. But if I want to go for a more precise model in that particular case the dynamics of this unit should also be considered and let me say, experiment conducted on this unit gives you a time constant of about 3 seconds and therefore the transfer function can be written as G v(s) equal to 0.1 which is the gain divided by 3 s plus 1 where 3 is the time constant of the system.

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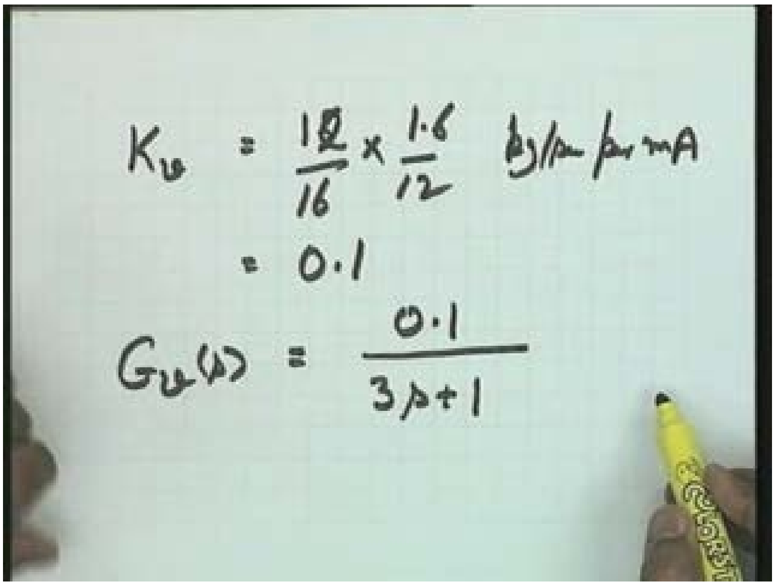

You may say that compared to the time constant 30 seconds it is negligible in that case the model becomes only 0.1 that is the gain that is the zero-order model but if you consider this is quiet appreciable, you consider it in your model and in that particular case the model of electropneumatic transducer plus control valve is a first-order model that is it is a simple lag.

Well, the next unit I will like to consider is the sensor. We are going to build up the models of the individual components and the total model of the system will then be considered. Now come on; help me please. About the sensor what is the input to the sensor; the input is the temperature and the output of course is milliamperes; this is what we have taken in our system. So temperature range you will have to establish; what is the range for which the system is being designed. And let me say that for a typical application the range is 50 to 150, the output of the sensor you know it is 4 to 20 milliamperes. So naturally the sensor gain assuming this to be linear i over this particular input output range if I consider this to be linear over this range in that particular case the sensor gain as you see will become, the output is 16 and the input is 100 this becomes equal to 0.16.

How about the units?
You can say that it is milliamperes per degree centigrade, this is the sensor gain. Now again the same logic you see. In many applications the dynamic of the sensor is neglected. But, well, if a sensor has got appreciable time constant then neglecting the dynamics is a poor approximation on modelling. Let me say in this particular case, the sensor used has an appreciable time constant.

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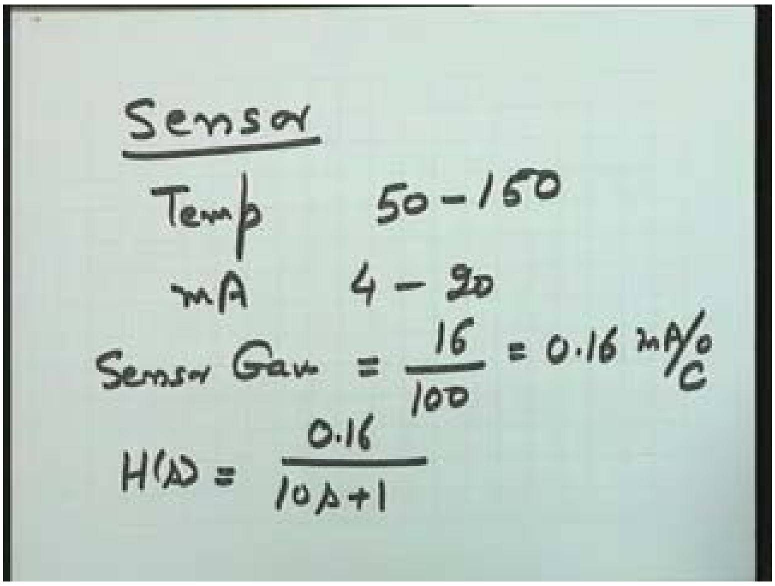

Well, again the similar experiment can be conducted and the result of the experiment, well, let us say it gives you a time constant of 10 seconds so naturally 10 seconds time constant of the sensor cannot be neglected with respect to the process time constant of 30 and therefore a model of only gain that is a zero-order model will not really be good as far as the heat exchanger system is concerned. In that case I like to consider the dynamics of the sensor and therefore the sensor transfer function H(s) could be taken as 0.16 over 10 s plus 1, now it is a first-order factor. therefore if I take the total situation now it may look like this: G p(s) the process transfer functions, let me fill it up rather, in this transfer function we have taken it as 50 over 30 s plus 1 this we have taken as the transfer function of the process plus plus here disturbance transfer function, the disturbance is q m, here the manipulated signal is q ms minus another disturbance we have taken theta I (Refer Slide Time: 39:29) these two transfer functions I have taken to be equal to 1 over 30 s plus 1 and here I have taken 3 over 30 s plus 1 these are the transfer functions I have taken.

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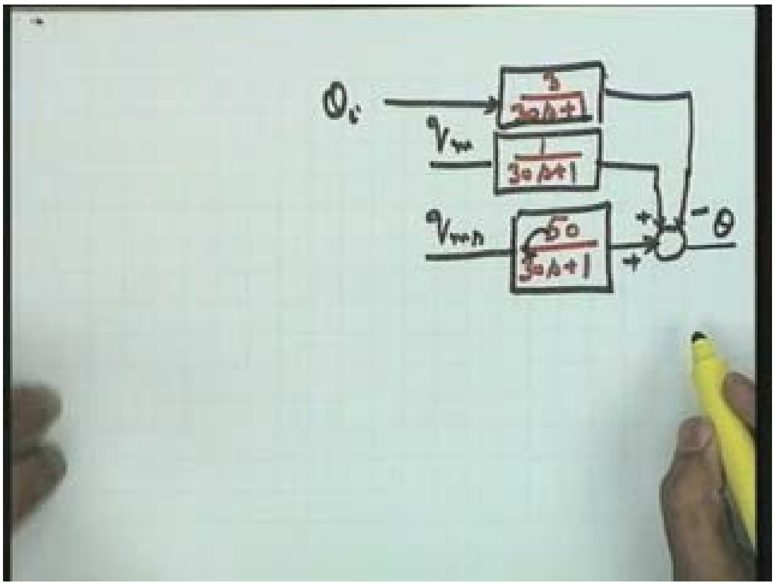

Now this theta here, I can take it on this side, this is the output. Now this output is being sensed and here is my sensor and the sensor transfer function has been taken as 0.16 over 10 s plus 1. This gives me the output here, the sensor output. Here is the control valve, the control valve transfer function we have determined I will recall it 0.1 over 3 s plus 1 where 3 is the time constant of this.

Now let me complete the system, please help me; this is the error detector, the comparison of the feedback signal will take place with the reference signal plus minus, yes, now at this stage I need your help please, what will be my scale factor here, you help me please, a scale factor. You know that this particular signal is a current in milliamperes so, for the error detection this signal has to be milliampere it cannot be any other unit other than milliamperes. So it means, the command temperature the temperature which I want to give as a command signal has to be appropriately converted into milliamperes.

You will please note that, as far as the sensor is concerned its steady state gain is 0.16, it is 0.16 milliamperes per degree centigrade, at steady state the output of the sensor is 0.16 milliamperes per degree centigrade and you want the theta to follow this particular command at steady state. So I hope you will agree with me that it looks quite appropriate if the scale factor is taken as 0.16. Naturally, because at the steady state value of the commanded signal will be corresponding to this particular factor 0.16 into theta r theta r being the reference temperature gives me the steady state value of the current which is being compared with the steady state value of the sensor output. So it means at steady state when these two signals match surely theta will follow the command signal and hence this becomes my total control model a feedback control system whose objective is to follow this particular command.

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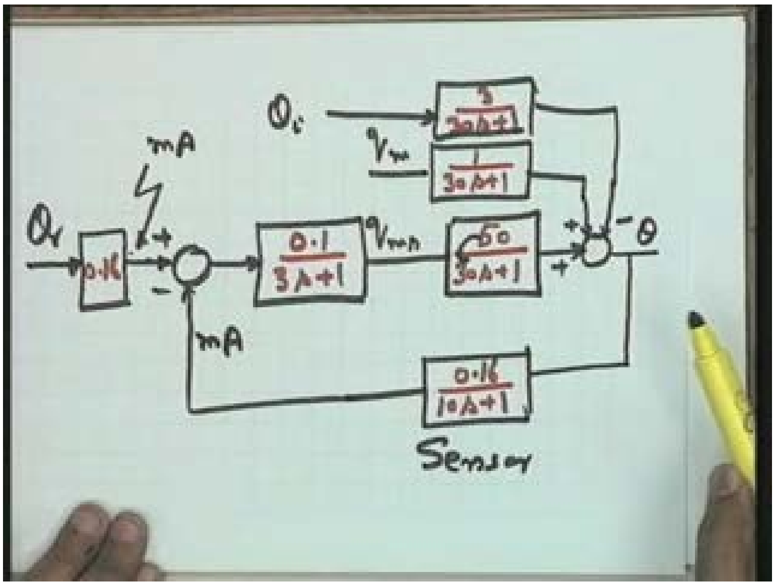

So you will please note that the numerical values which I have taken they pertain to a typical industrial process. Given any situation we can follow the exact procedure and by this procedure of experimental identification of various transfer functions we can build up the total model of the system. And now, depending upon the performance requirements I can really introduce, in this particular loop I can introduce in the forward path a controller D(s) and my objective is to design this particular controller D(s) so that the output theta which is the temperature of the outflowing process fluid it follows the command theta r in spite of disturbances acting on the process the disturbances are theta i the change in the inlet temperature and q m the change in the flow rate of the in inflowing fluid. Thank you very much.