Chemical Process Control

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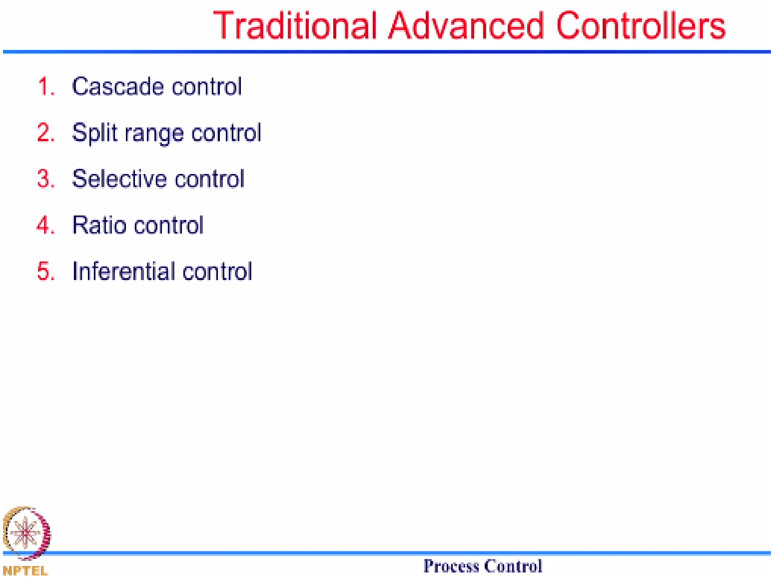
Lecture – 38
Cascade Control

Hello students. We have been talking about feedback control for the last 2-3 weeks. We started with what is the architecture of feedback control then we looked at how do we assess the stability of feedback control systems, then in the last week we looked at how do you synthesize a feedback control system, how do you select what type of a controller to use and lastly we looked at what sort of values, what are the best ways to find out values for controller parameters.

In this week we will go one step further and we will look at how do you improve the performance of these feedback controllers by using or doing some additional mechanisms, these typically are called as advanced controllers from a traditional sense. What I mean by that is these were the advancements proposed over a typical PID control long back, at that time they were considered as advanced controllers. Nowadays what we really refer to advanced control as something which uses a model-based control strategy or an optimization based control strategy. In some books, you will see that the controllers which we are going to see in this week they are sometimes called advanced controllers, sometimes they are called PID enhancements. Just to distinguish from a real state-of-the-art advanced controller, I will call them as traditional advanced controllers.

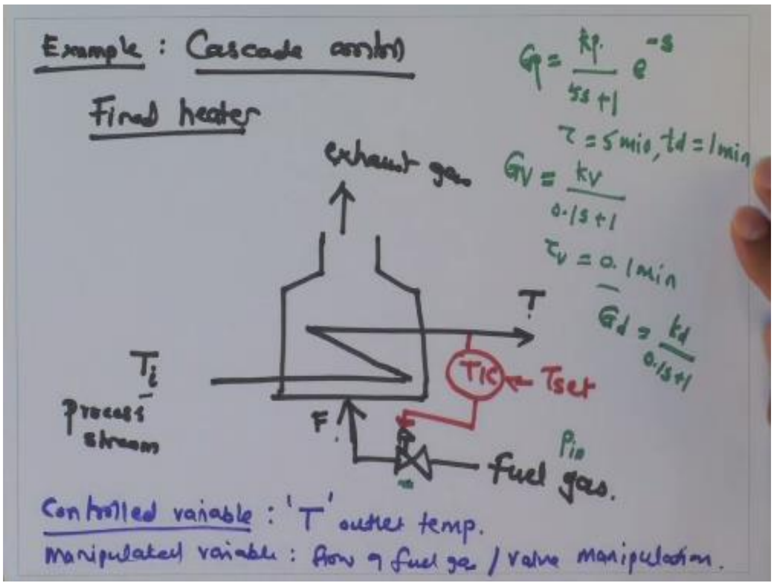
You will see that these are the controllers sometimes they use PID control logic itself; however, sometimes the architecture is different or sometimes the way the controllers are selected or the manipulated inputs are selected is slightly different. Let us look at what are these traditional advanced controllers.

In this part of the week, we will try to see what is the need of going beyond a typical PID controller, single-input single-output PID controller which we have seen so far. That will also help us to motivate the need for these traditional advanced controllers and you should also be able to identify those when you see them on the field because you will see that most of these advanced controllers which we will see in this part of the week, they are very commonly utilized in chemical industry.



In this part of the week, we will go through these 5 advanced control strategies or traditional advanced control strategies. They will be cascade control, split range control, selective control, ratio control and inferential control.

So let us start with cascade control. In order to motivate the need for cascade control, let me take an example.



Let us consider an example of a fired heater. Let us say there is a furnace, which is used to heat a process stream at temperature 'T_i' to 'T'. This is the process stream which has to be heated from some initial temperature to a final very high temperature and this is done by firing a fuel gas. This fuel enters this furnace, it gets combusted and then its temperature increases and that hot gas, the combusted gas is used to heat this process stream from initial temperature 'T_i' to the final temperature 'T'.

If you apply the principles from last week, here the controlled variable, the primary control variable will be the thing for which this particular unit is set up that is to raise the temperature of the system to temperature 'T'. The controlled variable is outlet temperature and then the manipulated variable is the flow of fuel gas, which will be done through the manipulation of the valve.

For this system, let us consider some example values. Let us say that the transfer function between this flow and the temperature which is given by G_p is equal to some $K_p/(5s+1)$. The time constant is of 5 minutes and it has a dead time of 1 minute. So '**τ**' is 5 minutes and dead time is of 1 minute. After the flow changes, this is a fairly multi-capacity system where you have multiple phenomena going on when you put in the fuel gas, it will get reacted with oxygen. It will get combusted because of the heat of combustion, the temperature of this fuel gas which is inside this chamber will increase. Then it will transfer heat with the process stream and eventually, you will see that effect on the final outlet temperature. So it is a fairly multi-capacity process which can be represented as first order plus dead time, wherein here, in this case, the dead time is 1 minute and tau is of 5 minutes.

Then let us focus on how this valve operates, so that will be a valve transfer function. Again it will have some gain and the valve operates typically very fast, so the time constant of the valve is 0.1 minute. So you can see that the moment valve is opened, within let us say 0.5 minutes, the flow would be stabilized.

For this system let us consider that, we want to control this temperature. We would want to implement a control loop. You will have a measurement of temperature. Let us call your temperature indicating controller. It will have its own setpoint and it will be used to manipulate the valve. This controller will be able to reject any disturbances which are happening in the process stream inlet temperature. So accordingly it will increase or decrease the flow of fuel gas by opening or closing this valve.

Now let us consider a different type of disturbance. Let us consider there is a disturbance in the inlet pressure of this fuel gas. Now let me give you some idea about where this kind of systems are used. Typically, this fuel gas will be an off-gas from one of the reactors or some of the processing unit which may have some rich calorific value like unreacted hydrogen or unreacted methane.

In that case that gas is typically used as a heating source to provide this particular heating. Now as this is coming from some process, there may be some transportation loss so the pressure as well as there might be that unit might the pressure of operating pressure of that unit might change depending on the length of the pipeline, there will be a pressure drop. So all those things accounted, this pressure of the inlet gas may fluctuate.

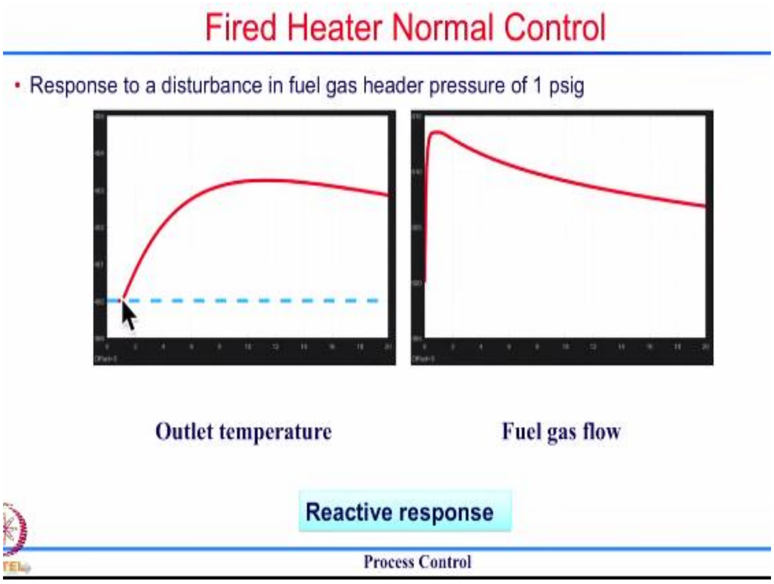
It may be that there are some other 10 different processes which are using this fuel gas as the heating source. If the input of one of those streams goes down, then this pressure might increase or vice versa depending on it is also about availability and demand. So this pressure might have fluctuations. So let us say if there is a fluctuation in this inlet pressure, what is going to cause?

Even for the same valve opening considering that the temperature is at setpoint, the valve will be at it is steady state opening. As this inlet pressure has increased, there is a net increase in the driving pressure across this valve, so it will cause an increase in the fuel gas flow. Even though the controller is not increasing the fuel flow because of a disturbance in this line, the flow of fuel gas going to the furnace increases.

It will increase according to the transfer function which will be of similar form. Let us write that transfer function as G_d. So the flow will increase and as the amount of fuel which is going into the furnace has increased, it will increase the heat of combustion and in the end, it will increase the outlet temperature.

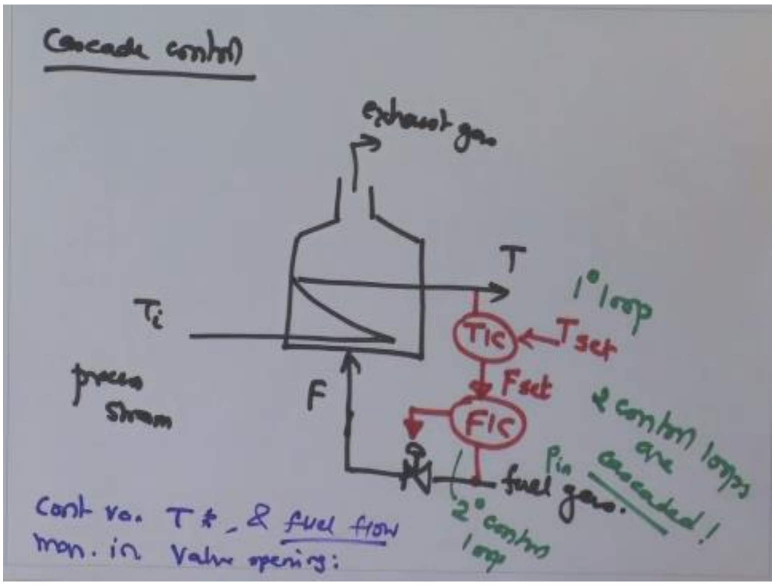
However, if you look at the process transfer function, which is the transfer function between this outlet temperature and fuel flow. Let me represent it as ‘F’. So it has a dead time of one minute. Even after the flow has increased, up to one minute this temperature will not show any effect, so the feedback controller will not take any action up to that point. Only when this temperature starts to deviate, this controller will detect that something abnormal has happened and it will try to cut down on the fuel flow by reducing the opening of this valve.

The controller will start taking action only after one minute of disturbance. During that one minute, excess fuel has gone into this furnace, so the ultimate value of this temperature would be substantially higher. Let me show you what the simulation shows for this system. Here is the corresponding response in a simulation model for this system.



You can see that up to one minute, there is no effect because on the outlet temperature whereas the increase in the fuel flow is happening because of this disturbance. It increases to a high value and it remains there because of the pressure disturbance you consider as a step change. And then you can see that only after one minute, this temperature will start to show any effect. There will be a difference between actual temperature and the setpoint and accordingly the controller will try to reduce the valve opening and then you will see that the fuel gas flow reduces. However, because of this dead time of one minute, the controller did not take any action for one minute. So a substantial amount of extra fuel went into the system which caused the temperature to rise to a very high value.

Now let us see how can we improve this particular operation of this system to reduce this overshoot in temperature. The temperature here has increased by almost 5 degrees which in some cases might be detrimental. Let us see how can we improve this operation with the help of a cascade control strategy. Let us redraw the figure again.



Again our objective is still outlet temperature and then the manipulated input is still the valve opening. We are not changing the process, we are just changing the way this controller is going to react. Because the controller which we have seen earlier was reactive, it showed a reactive response, it reacted to the disturbance. Now we will see can we preempt this effect of this disturbance by taking advantage of the fact that the valve dynamics are much faster compared to the process.

If we can limit the effect of this disturbance up to the valve, then can we improve the performance of the system? So what I mean by that is here when we are saying we are controlling this temperature by manipulating this valve, actually what we are interested in is controlling the temperature by manipulating the amount of fuel which goes into the system. So what we are interested in this for a particular temperature setpoint, we want a certain flow of the fuel which goes in.

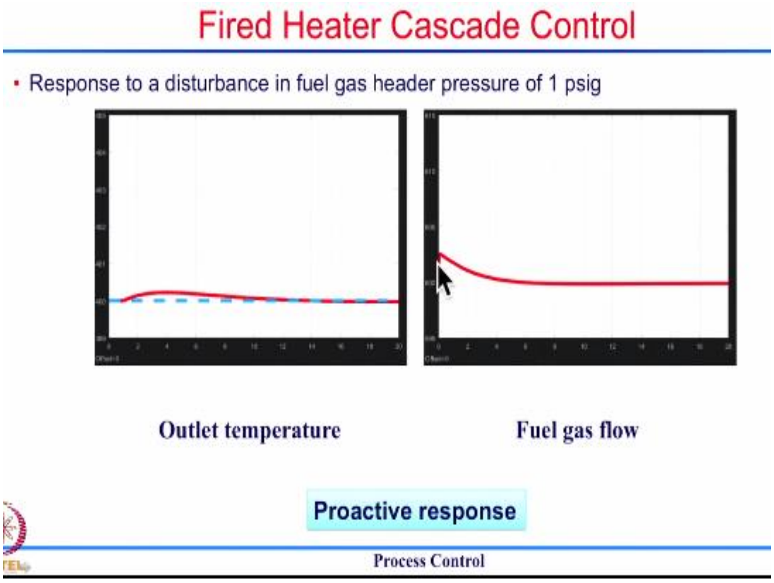
We might be interested in controlling the flow as well. We might be interested in controlling the fuel flow as well, but we have only one valve opening. Let us consider that we use the flow controller on this. We measure the fuel flow and accordingly manipulate the valve. Now as we have used this manipulated variable, now how do we control the temperature. Now we again go back to the logic of our earlier control system that when we want to control the temperature, we want to manipulate the fuel flow.

So what we are going to do is, we are to have a temperature controller which will have its own setpoint and the output of this controller will actually act as a setpoint for this flow controller. The temperature controller is going to tell me that for a particular requirement of setpoint temperature and the current temperature, what should be my flow of the fuel going into this furnace. Then that will act as a setpoint for this flow controller which is going to manipulate this valve opening.

Now you can see that we are now having 2 controlled variables, temperature, and flow. They both are connected together through an only single manipulated variable which is valve opening in such a way that the output of one acts as a set point for the other. So these 2 are cascaded together, so that is the name, so these 2 control loops are cascaded together. This temperature controller loop is known as a primary loop because that is what our main objective is and the secondary control loop is, this flow controller is the secondary control loop; because this is done in order to improve the performance.

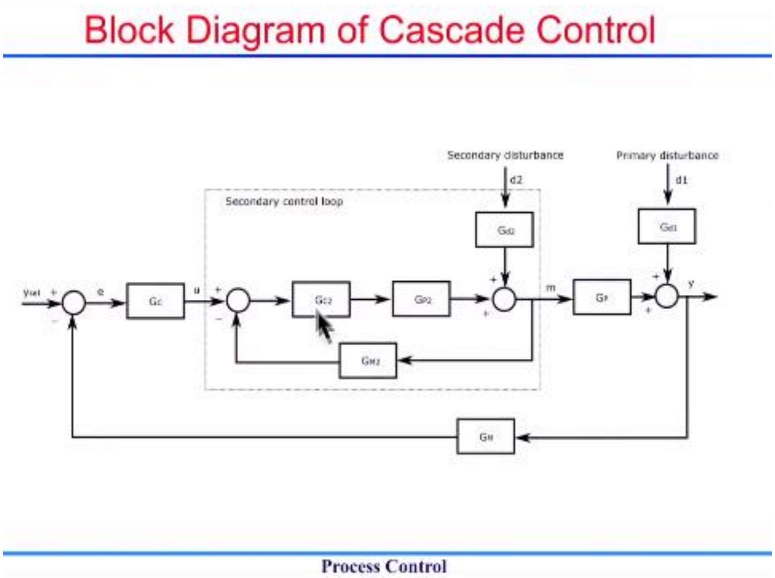
Now let us see how would it improve the performance of this system. Let us consider the same disturbance as earlier that this inlet pressure changes and the temperature are still at the setpoint. Now as the temperature is at its setpoint, the corresponding flow setpoint would be the same as the steady-state flow which in this case was 600. Because of this inlet pressure disturbance, the flow is going to increase and this flow controller will detect that change in the flow and it will try to cut down the valve opening such that the flow which goes to the furnace still remains same as the original steady-state value which was 600.

So you do not rely on this flow to make changes in terms of furnace operation, have an increase in the temperature in order for the controller to take action. The controller directly reacts with this disturbance. For this secondary controller, the process transfer function is the same as the valve transfer function which was much faster compared to the original process transfer function. This controller is going to be really fast in terms of rejecting this disturbance. So more or less this flow which goes to the furnace would remain very close to 600 and then because of that, the temperature would not go to a very high value. Let us see these responses, they are plotted on the same scale.



As you can see that on the right hand side because of this flow controller, which is very fast, the increase in the flow was very small compared to the previous case and it also got stabilized regulated back to the original value and that resulted in a very small disturbance in terms of furnace operation and you can see that the furnace temperature more or less remains very close to the setpoint value, there is very less offset in terms of temperature.

So what we can see that by using this cascade control strategy, we have effectively regulating a disturbance which was happening in the manipulated line. This is more like a proactive response to the disturbance and that is the main advantage of a cascade control strategy that it will be able to reject these disturbances which come into the secondary line.
In terms of the block diagram, I want to show how this strategy looks like.

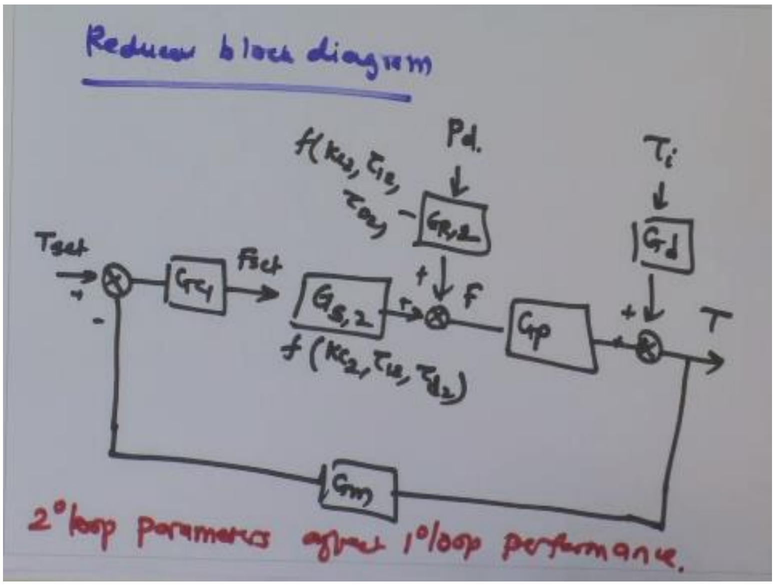


You can see that the original process is here which is the transfer function between the fuel flow and the temperature. This ‘d1’ is the disturbance transfer function where the primary disturbance, let us consider it is in the inlet temperature of the process stream. Accordingly, you get the temperature outlet of the furnace and then it gets measured through this measurement transfer function. There is a set point on this temperature and then you have a primary controller which is a temperature controller. This temperature controller is giving me, the output of this temperature controller acts as a setpoint for the secondary flow controller. So you can see that everything inside this dotted box is the secondary control loop. This is the flow control setpoint and for that, you have a transfer function which is this valve transfer function.

This ‘d2’ is the disturbance transfer function which is a transfer function between this inlet pressure of the fuel gas and outlet fuel flow, which has another measurement unit and this is the secondary controller. So you can see that this one secondary control loop is part of this bigger loop which is the primary control line.

You can see that there are 2 control loops here and if I want to analyze the response of this system, I will have to first reduce the secondary control loop, represent it as one transfer function between this disturbance and outlet and another one between this setpoint and outlet, we have seen that how do you get those, this looks like a very good, which looks like very familiar to the feedback control system.

This transfer function will be your regulatory transfer function and this transfer function between u and m will be a servo transfer function. Then accordingly we will have another transfer system of transfer functions for the primary loop. Let me show you what I just said.

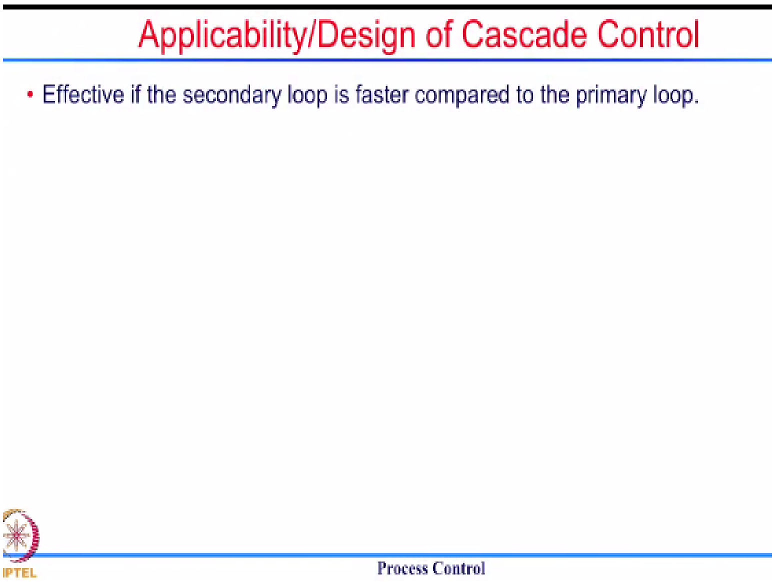


If I want to draw the reduced block diagram, so we have this temperature setpoint. We have this temperature measurement. This ‘G_{c1}’ is the primary controller and the output of this is F_{set}. And between F_{set} and flow and this is the secondary disturbance ‘Pd’. This ‘$G_{s,2}$’ is a servo transfer function for the second loop and this ‘$G_{R,2}$’ is the regulatory transfer function for the second loop, both will give me the flow and that flow will go to the process transfer function and this ‘Gd’ is the primary disturbance that will eventually give me the temperature.

You can see that this is the function of K_{C2}, tau$_{I2}$ and tau$_{d2}$ considering it is a PID controller and same way this is the function of K_{C2}, tau$_{I2}$, tau$_{d2}$. If I want to now look at the effect of this disturbance, this disturbance or this disturbance on the final temperature, we will have to look into this closed-loop transfer function which is a function of this $G_{S,2}$. The way my secondary controller is tuned, those parameter values will decide the stability as well as the performance of this primary control loop.

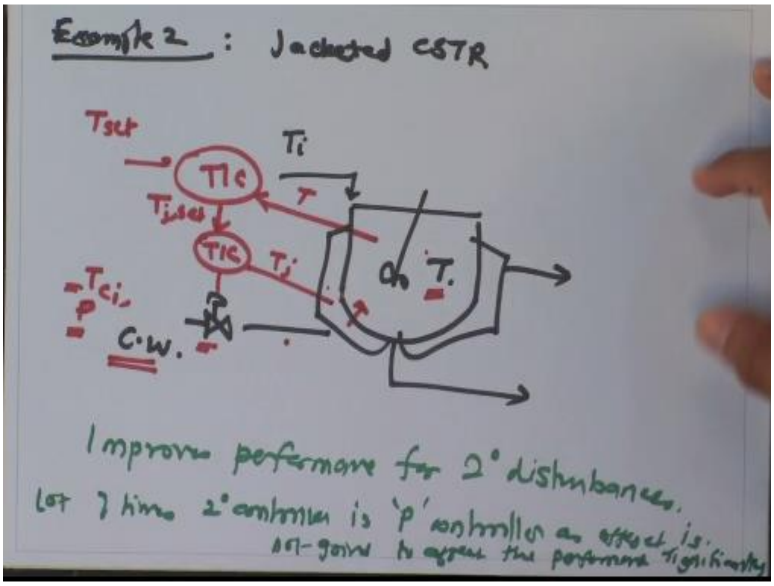
The conclusion here is secondary loop parameters affect the primary loop performance. So that is why if I want to tune this cascade control scheme, what I would have to do is I would have to first tune the secondary loop, make sure it is perfectly tuned the way we want and then once you have a good enough understanding or a good enough satisfaction about the performance of secondary loop, then only you will go with tuning of the primary control loop.

Now if you see when this cascade control strategy will be effective, the motivation for going with a cascade strategy was to reject the disturbance much faster before the process of that disturbance affects the process. All we want is that this secondary control loop should take action much faster compared to the primary control loop. So your cascade control strategy will be very effective or it will only be effective if your secondary control loop is very fast.



If your secondary loop is also of the same time constant, has the same dynamics as the primary control loop then your cascade control strategy will not be effective and it will work almost similar to your original with the traditional control strategy of controlling temperature or the variable by directly manipulating the valve.

Now we have seen only one example, there are a lot of examples about cascade control strategy wherein we would want to identify this intermediate secondary control objectives which will improve the performance of the control system. Let me take another a very commonly used example of a cascade system.

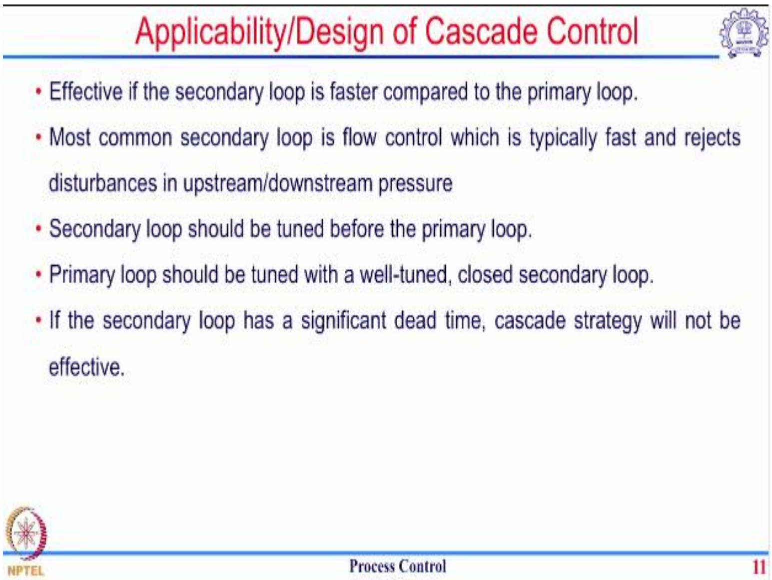


Let us say a jacketed CSTR. Let us consider that we are conducting a reaction which is exothermic and we are interested in controlling the temperature here by changing the flow of the coolant. This is cooling water, you want to control the temperature of the reactor by changing the flow of the cooling water through this valve and you can see that it is a multi-capacity process that when you change this coolant valve, it is going to first change the flow of the cooling water. Once that flow of the cooling water changes it will act as a change into this jacket, so the jacket temperature will change and once that jacket temperature changes, through heat transfer the reactor temperature will change.

If there is any disturbance upstream of this cooling water which may be that the inlet temperature of the cooling water has changed or it is the inlet pressure of the cooling water which has change which has a minor effect. In that case, in order to reject those disturbances, you will have to wait for this reactor temperature to show any effect. In order to avoid that or you can again make use of cascade control strategy. Here the objective is in order to control the temperature of the reactor, we want to maintain a certain temperature of the jacket. So what you will have is a primary temperature controller, which is going to give a jacket setpoint.

You will have another temperature controller which will control the jacket temperature by manipulating the valve. It will measure the jacket temperature and then this is our temperature setpoint. By using a temperature-temperature cascade, we can improve the performance of this cascade control strategy for disturbances which are happening in the manipulated line.

Cascade control strategy works or it improves performance for secondary disturbances like the disturbance in the fuel flow line or here the disturbances in the coolant line. Now if there was a disturbance in the inlet temperature, there is no additional benefit which you are going to get because of a cascade control strategy. It will have its own transfer function to affect the temperature and the performance will be similar whether you use a cascade control strategy or not. So keep that in mind that cascade control strategy is going to improve the performance only for secondary disturbances.



One last point which I would like to make is this secondary control loop which we are using is merely to take some action or to move the valve in the correct direction in anticipation or based on the disturbance. It is just a way to improve the performance, you do not necessarily need an offset-free response here. As long as the valve takes an action before the disturbance affects the process, the objective of improving the speed of response or improving the response of the cascade control strategy is satisfied.

So in the secondary control loop, even the offset in the secondary control loop is acceptable. A lot of time what you would see is the secondary control loop is typically taken as a P controller so that it has a faster response. Even if there is offset, that is not your main controlled objective. As long as your final control objective which is a primary control objective is maintained without any offset, we are okay with the operation.

A lot of times the secondary controller is a P controller or positional controller as the offset is not going to affect the performance significantly. And as we have seen that this cascade control strategy will work effectively when the secondary loop is faster than the primary loop, so obviously if your secondary loop has a dead time or it is slow, then definitely our cascade control strategy would not at all be effective, so in such a case it should not be used.

That was about the cascade control strategy. If you visit any industry, you will see that lot of times these elevated temperature reactors which have a jacket, those will have a cascade control strategy or any process which has a higher dead time and he chooses a very common utility like steam or fuel gas. The performance of those systems will be improved by using a cascade control strategy. So we will take a break here and when we come back we will look at the other advanced control strategies. Thank you.