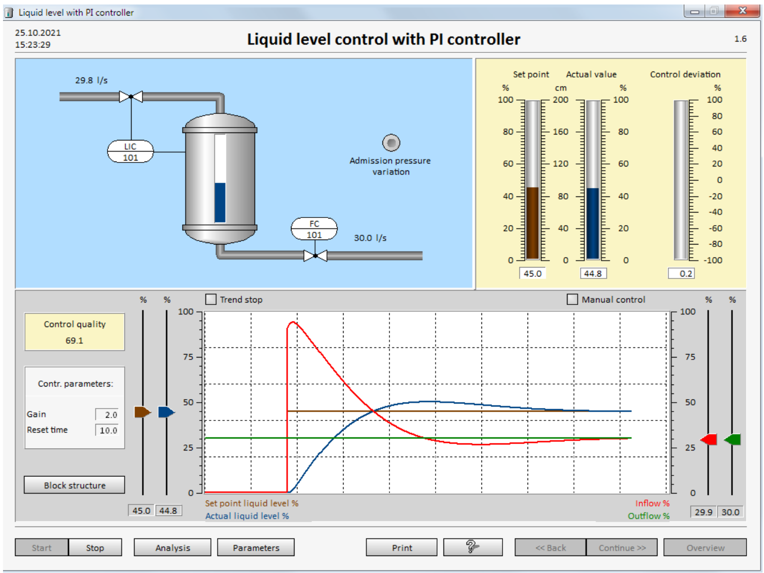
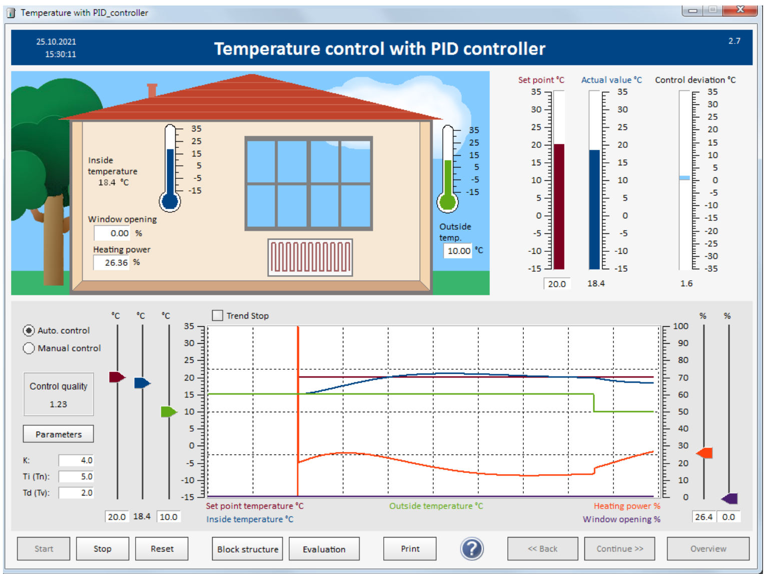
Ingenieurbüro
Dr.-Ing. Schoop

Tasks and Solutions

ControlTraining I / II





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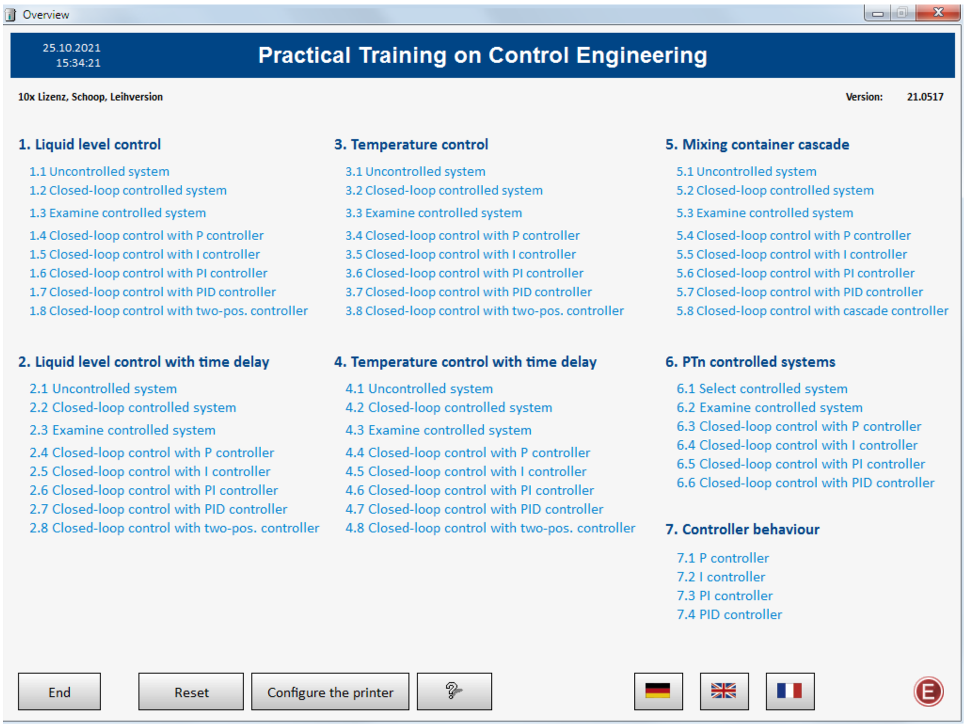
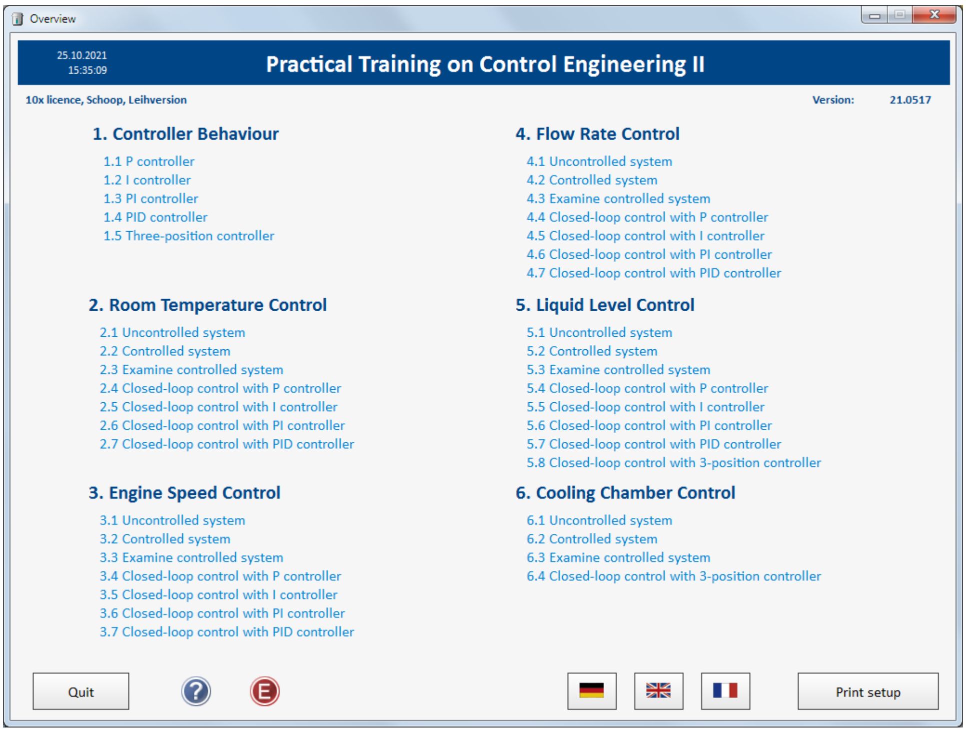
1 Introduction Control Training I / II

With the Control Training I / II the behavior of controlled systems, controllers and control loops can be examined on simulated systems.

Control Training I:



Control Training II:



2 Controller Behavior, Control Training I/II

In this section you can examine the behavior of the P, I, PI and PID controllers. The controller examinations are the same for both trainings.

The Control Training II additionally offers the option of examining the behavior of a three-position controller.

2.1 P Controller

Select in the menu under controller behavior the P controller (item 1.1 or item 7.1)

The P controller works like an amplifier.

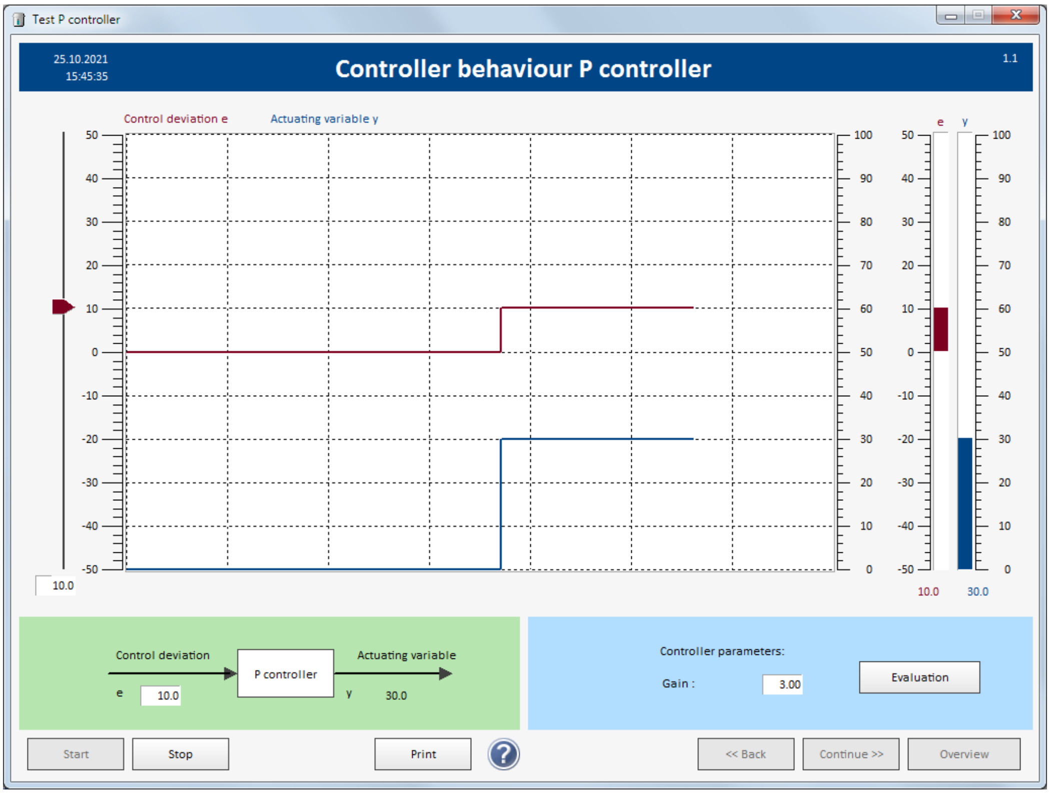
Task 1.

Click “Start”.

Set the controller parameter "Gain" to 3.

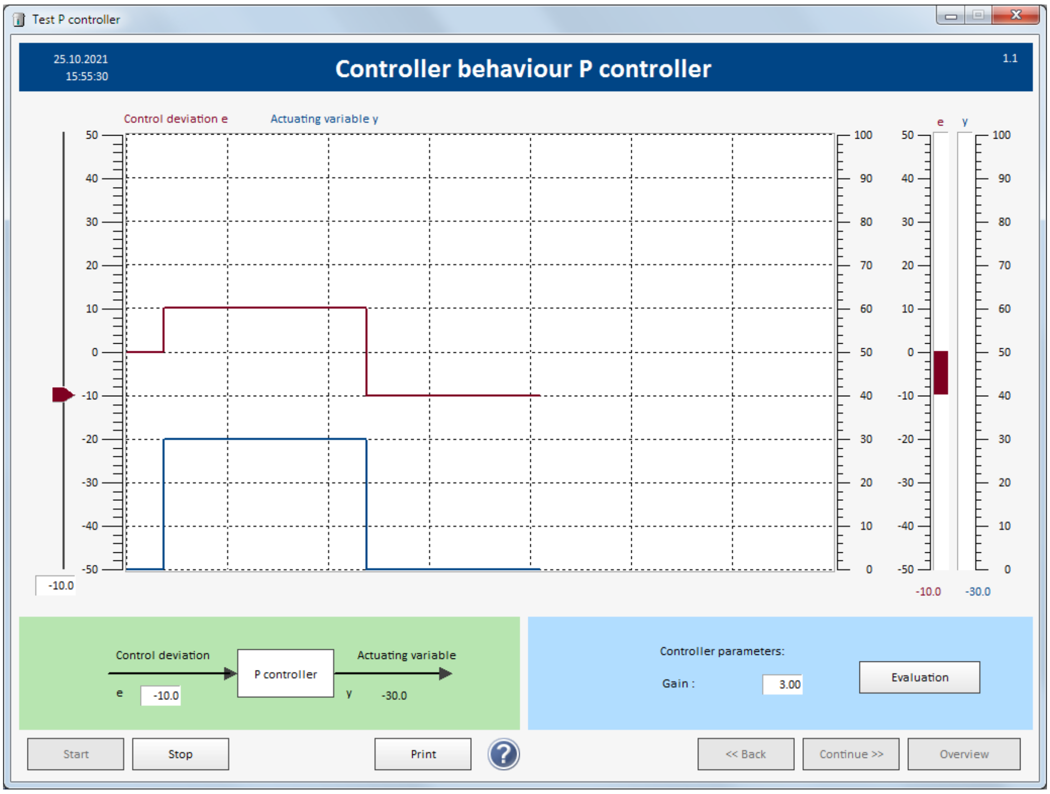
Enter the value 10 for the control deviation e.

Observe the controller output (control signal, actuating variable) y.



The input value of the controller e = 10 is amplified with gain 3. The controller output y then assumes the value y = 30.

If you enter the value -10 for e, y receives the value -30. In many cases, the controller output is limited from 0% to 100%, so that the controller output cannot have negative values. Therefore, the value 0 is displayed for y in the trend display.



2.2 I Controller

Select the I controller (item 1.2 or 7.2) under controller behavior. The I controller works like an integrator.

An integrator has following behavior:

- If the input to the integrator is positive (greater than 0), the output of the integrator increases.
- If the input to the integrator is negative (less than 0), the output of the integrator decreases.
- If the input to the integrator is equal to 0, the output of the integrator retains its value.

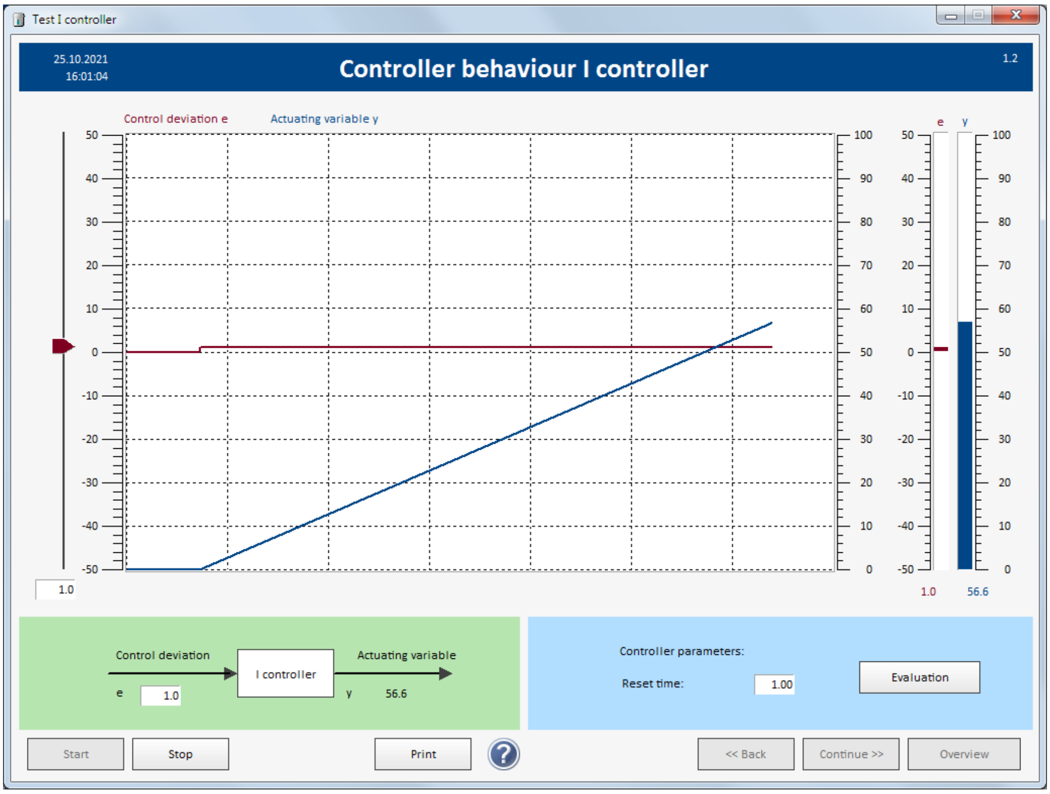
Task 2.

Click “Start”.

Set the controller parameter “Reset time” to 1.

Enter e = 1 for the control deviation (difference between set point and actual value).

Observe the behavior.



The output y of the controller begins to increase.

The slope of the increase in y is 1, i.e. the output y increases by 1 in one second.

Task 3.

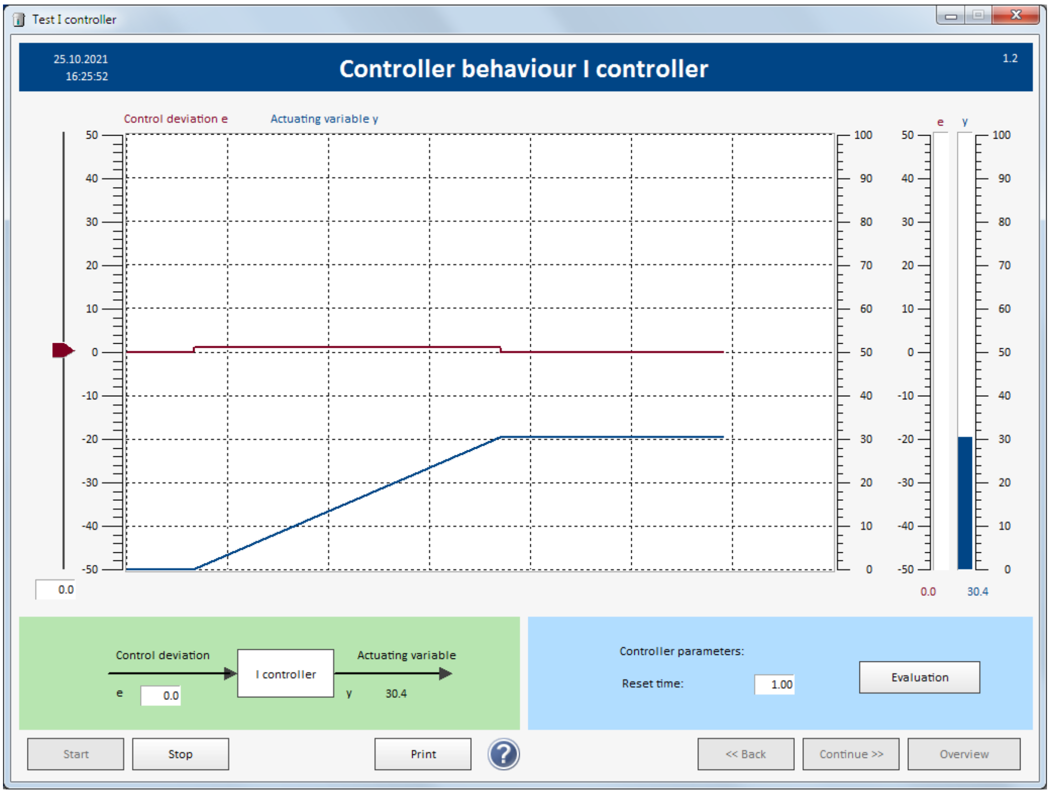
Click “Start”.

Set the controller parameter "Reset time" to 1.

Enter for e the value 1. Wait until y has exceeded 30.

Change the value from e = 1 to e = 0.

Observe the behavior.

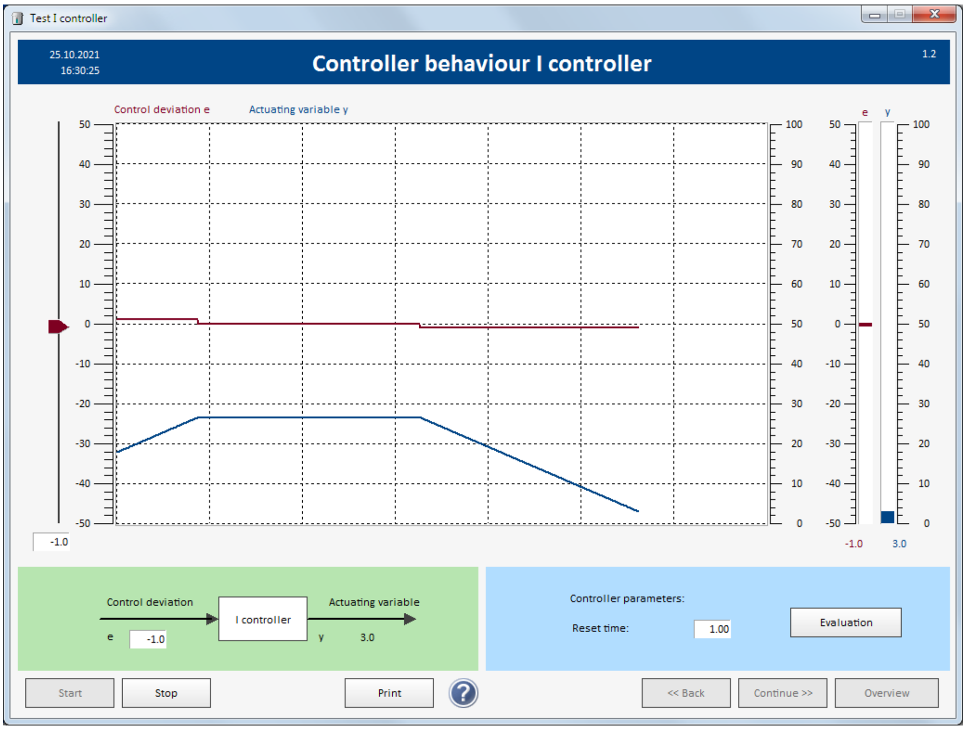


If the input e of the I controller (integrator) is 0, the output of the I controller retains its value (y remains constant).

Task 4.

Now change the input e to -1.

Observe the behavior.

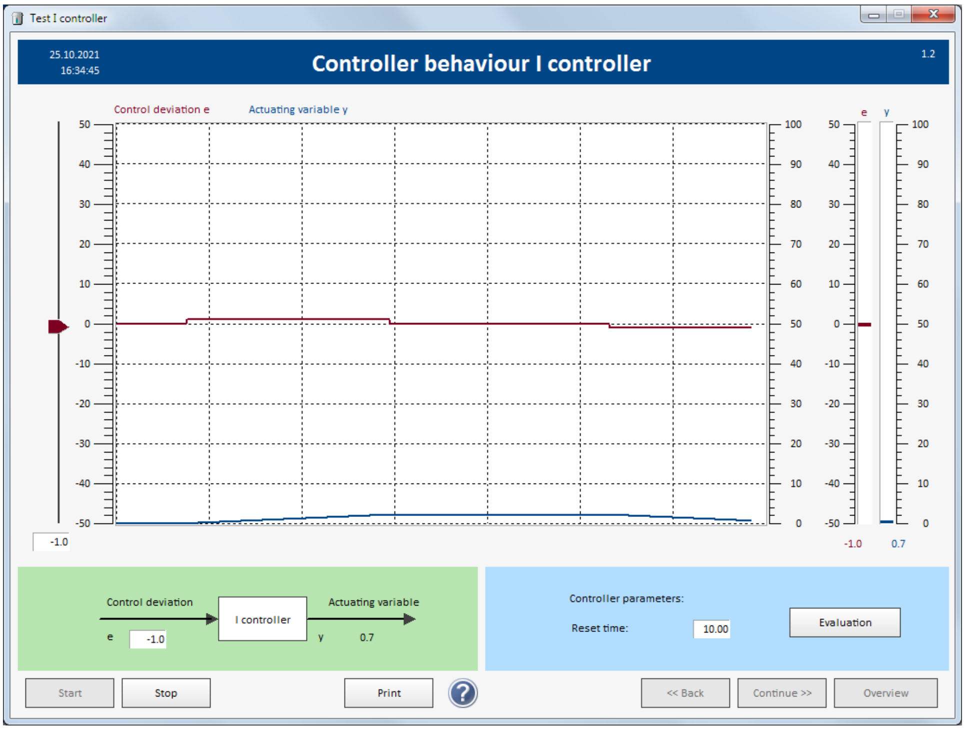


First the input e of the controller has the value 0 and y is constant. When input e is set to -1, output y decreases. It constantly drops with the slope -1, i.e. the output y decreases by 1 in one second.

Task 5.

Carry out the above experiments with the reset time 10.

Observe the behavior.



With input e = 1, output increases 10 times slower than in the previous tasks. While e = 0 the output remains constant. While the input is negative, the output drops 10 times slower.

The slope of the output y depends on the reset time. The slope of the output y is 1/(reset time) or -1/(reset time), depending on whether input e is positive or negative

If the input e is enlarged, the output increases quicker by the enlargement factor. The same applies if the input is negative.

As can be seen from these tasks, the I controller behaves like an integrator. If it´s input is positive, the output increases continuously. If the input is zero, the output retains its value. If the input is negative, the output decreases continuously.

Conclusion:

From the behavior of the I controller it can be concluded that with a controller with an I component (integrator) the actual value (control variable) is either adjusted to the set point (reference variable) after a settling phase or the control loop becomes unstable.

This is concluded from the fact that the I controller only outputs a constant value while its input e is equal to 0. The input to the controller is the difference between set point and actual value, i.e. only if the actual value is equal to the set point, the input e is equal to 0.

2.3 PI Controller

Select the PI controller (item 1.3 or 7.3) under controller behavior.

The output of the PI controller is calculated with the following formula:

$$y(t) = K \cdot (e(t) + \frac{1}{T_I} \cdot \int_0^t e(\tau) \cdot d\tau) \quad \text{K = Gain, Ti = Reset time}$$

The PI controller is therefore a combination of P and I controllers, with gain K acting on input e and on the integrator.

Task 6.

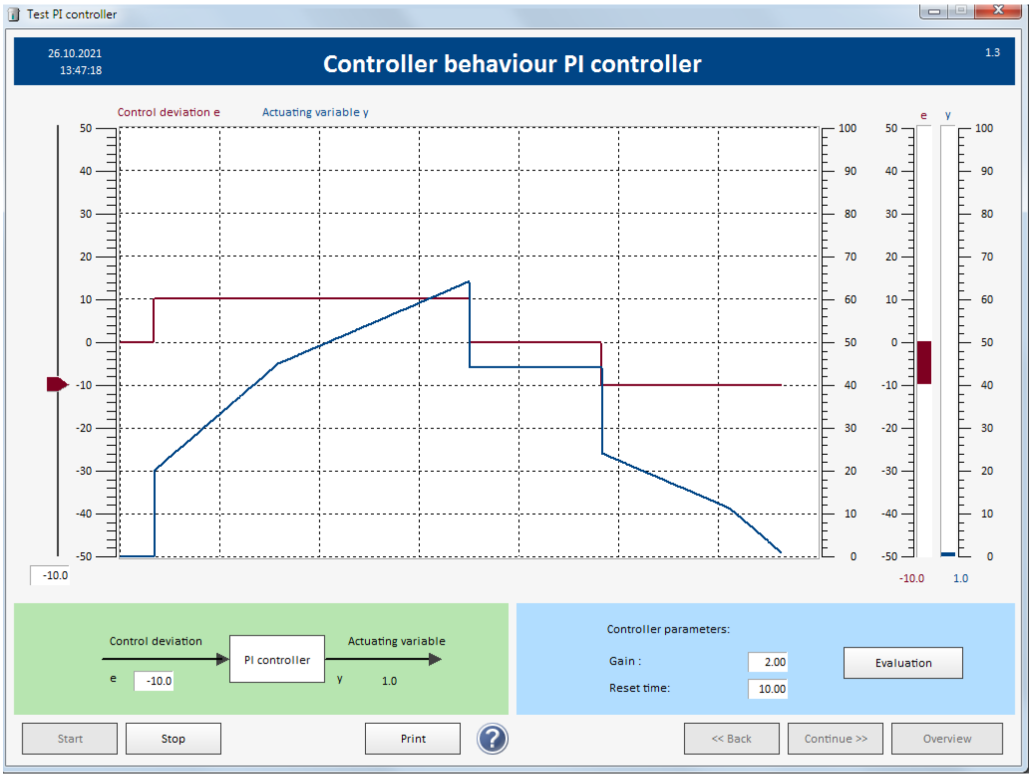
Click “Start”.

Set the following parameters: Gain K = 2, reset time Ti = 10.

Perform the following actions one after the other with a time delay:

e = 10, Ti = 20, e = 0, e = -10, Ti = 10

Observe the behavior.



You will get roughly the above trend display for e and y.

The investigation of the time behavior of the PI controller is shown in the figure above. First, the input e of the PI controller is set from 0 to 10. The input signal e (brown signal, control difference) follows accordingly. Since the gain of the PI controller is 2, the output signal y immediately assumes the value 20.
The reset time Ti (Tn) of the I component initially has the value 10. The gain 2 results in a total time constant of 10/2 = 5. The output signal y (blue signal, actuating variable, control signal) rises evenly and after 10s reaches a value increased by 20 (step e to 10).

The reset time Ti was adjusted from 10 to 20. The rise of the output signal y is slower because the time constant is now 20/2 = 10. With a time constant of 10, the output would reach the value 1 after 10 seconds with an input step of 1. Since we have specified an input step of e = 10, output y reaches the 10 after 10 seconds.

Then the input signal e is reset to 0. The P component then immediately is 0, i.e. the output signal y immediately decreases by 20. The I component of the PI controller retains its value, so that from this point in time the output has a constant value. The constant value is factor 20 smaller than the value of the output signal at the switching point.

This is followed by a step from e to -10. Due to the gain of 2 (P component), the output signal y immediately decreased by 20. Due to the I component, y then continuously decreases. Output y decreases by 10 within 10 seconds because of the reset time Ti = 20s and the gain K = 2 (calculation as above).

Changing the reset time to Ti = 10 then caused the output to decrease twice as quickly.

2.4 PID Controller

Select the PID controller (item 1.4 or 7.4) under controller behavior.

The output y of the PID controller is calculated using the following formula:

$$y(t) = K \cdot (e(t) + \frac{1}{T_I} \cdot \int_0^t e(\tau) \cdot d\tau + T_D \cdot \dot{e}(t))$$

K = Gain, Ti = Reset time,

Td = Derivative time

The PID controller is therefore a combination of P, I and D components, with the gain K acting on input e, integrator and D component.

Task 7.

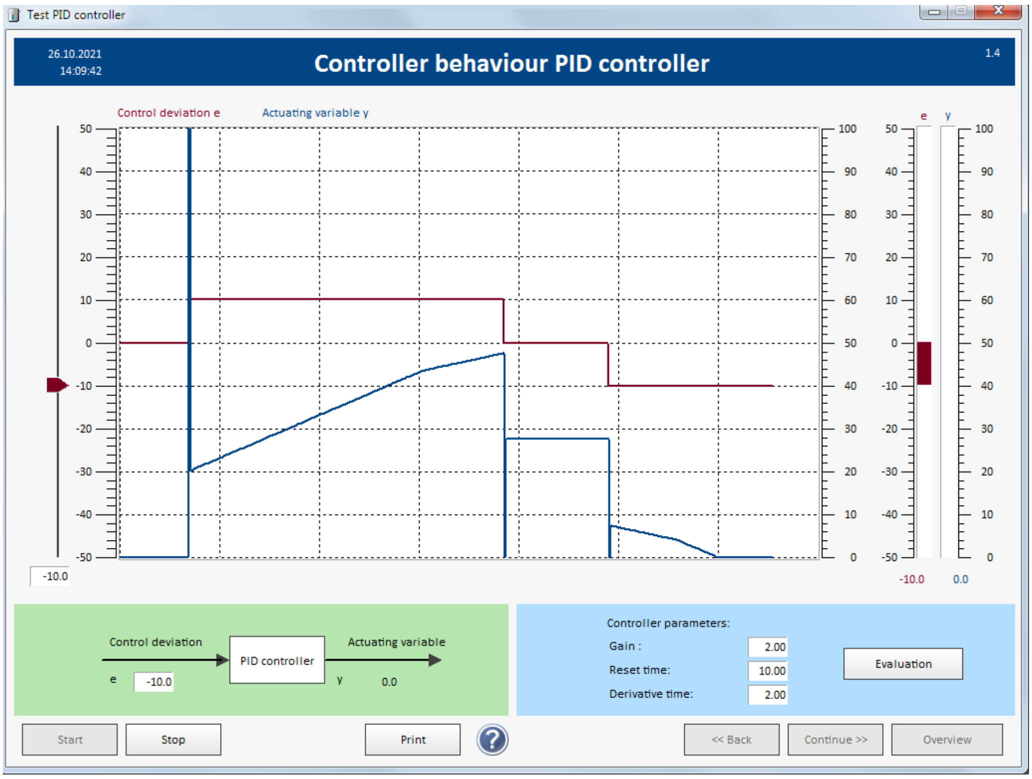
Click “Start”.

Set the following parameters: Gain K = 2, reset time Ti = 10, derivative time Td = 2.

Make the following entries one after the other with a time delay:

e = 10, Ti = 20, e = 0, e = -10, Ti = 10

Observe the behavior.



In the figure above, a control deviation step is applied. The input signal e (brown signal, control difference) steps from 0 to 10. The D component of the PID controller immediately results in a peak of the output signal y, since the derivative of a sudden change approaches infinity.

The gain of the PID controller has the value 2. As a result, the peak in the next time step resets to 2x input signal, i.e. to 20 (blue signal).

The D component has no effect while there is no change in the input signal e.

The reset time Ti of the PID controller is 10s. With the gain of 2 also affecting the I component of the PID controller, the overall time constant is 10/2 = 5. The output signal y (blue signal, actuating variable, control signal) increases steadily and after 10s it reaches a greater value by factor 20 (input step e = 10).

After a few seconds the reset time is changed from 10 to 20. The slope of the output signal y is now less steep because of the new time constant 20/2 = 10. This means with an input step from 0 to 1, the output reaches the value 1 after 10 seconds. Since we applied a step from 0 to 10, output y increases by 10 after 10 seconds.

Then the input signal e is reset to 0. Due to the sudden change in the input signal, the D component of the PID controller again immediately results in a peak downwards in output signal y. The P component immediately is 0, which results in an output signal y 20 times smaller.

The I component of the PID controller retains its value, so that the output has a constant value from this point in time. The value is 20 times smaller than the value of the output signal at the switching point.

Then e is set to -10. The D component caused a negative peak and the P component results in a sudden decrease of the output signal by 20 after the peak. The I component then continuously decreases in the reset time Ti.

By adjusting the reset time to 10s, the speed in decreasing is doubled.

The D component of the PID controller reacted three times in this example, namely always when the input signal e is changed. In general, the D component of the PID controller only outputs a value when the input signal of the controller changes, i.e. when there is a change in the difference between the set point and the actual value.

2.5 Three-Position Controller

Go to „Overview“ and under controller behavior, select the three-position controller (item.1.5).

The three-position controller is a discontinuous controller that can output three states as a control signal. Depending on the difference between set point and actual value, the first, the second or the third state is set.

An example for the use of a three-position controller is the temperature control in a cooling chamber. If the temperature is too high it must be cooled. If the temperature is too low, it must be heated. If the temperature is in a range around the set point, neither heating nor cooling is necessary.

Another example of the use of a three-position controller is a motorized valve that is used to control flow rate. If the flow rate is too high, the valve must close (motor running counter-clockwise). If the flow rate is too low, the valve must open (motor running clockwise). If the flow is in a range around the set point, the motor is not activated.

On the page for examining the three-position controller, a diagram is shown in which the control signal y is plotted against the control error e. The control error can be automatically moved between -100 and 100 using the arrow buttons. The control signal then assumes the values -1, 0 or 1 depending on the control error e and the controller parameters.

Task 8.

Click “Start”.

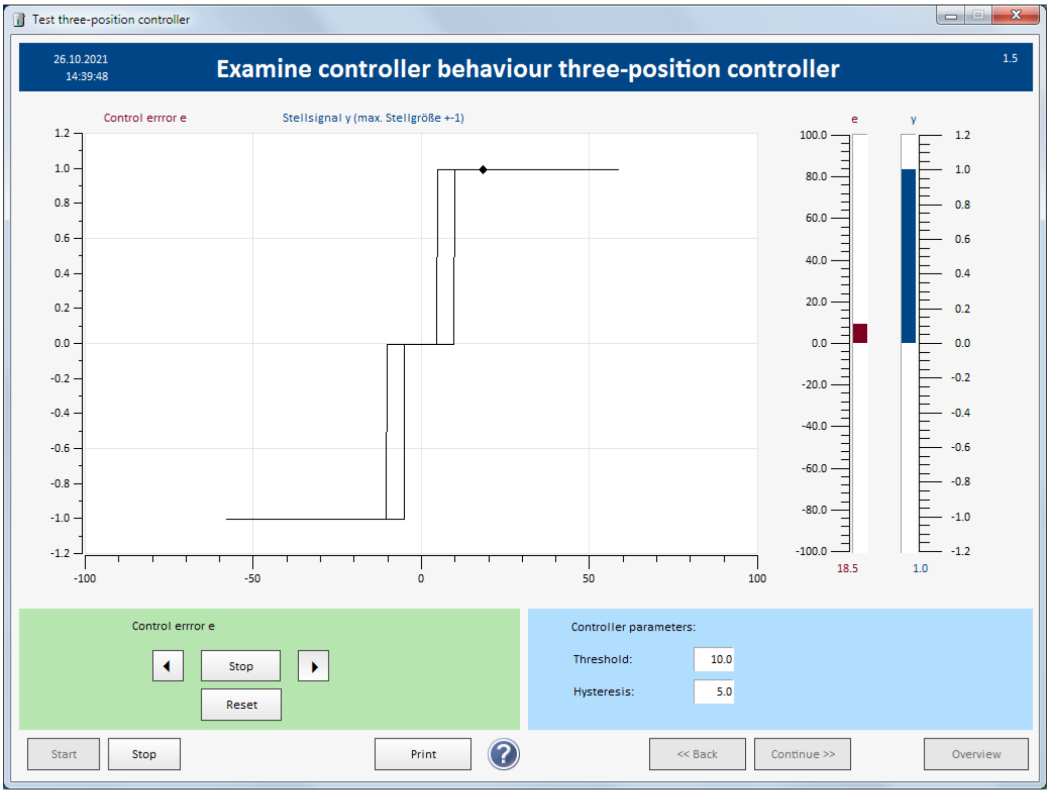
Set the controller parameters "Threshold" to 10 and "Hysteresis" to 5.

Click the arrow pointing to the right. Wait until the control error has reached approximately 50. Then click the arrow pointing to the left.

Let the control error e run to approximately -50 and then click the arrow pointing to the right again.

Monitor the diagram.

How does the control signal y behave depending on the control error with the controller parameters "threshold" and "hysteresis" and the direction (increase or decrease) of the control error e.



After clicking the arrow pointing to the right, the control error e slowly begins to increase continuously.

The control signal y remains at 0 until the control error has reached the threshold of 10. Then the control signal y steps to its maximum value 1 and remains at 1.

If the arrow pointing to the left is clicked, the control error e slowly and continuously decreases.

Only when the control error e is smaller than the hysteresis of 5, the control signal y steps to 0.

If the control error e runs below the value -10 (threshold), the control signal y steps to it´s minimum value -1.

If the control error e is allowed to increase again by clicking the arrow pointing to the right, the control signal y remains at -1 until the hysteresis -5 is reached, then y steps to 0.

The control signal y therefore assumes the values -1, 0, 1, depending on the control error (difference between set point and actual value), the chosen "threshold" and "hysteresis" and the direction (increase or decrease) from which the control error e changes.

3 Room Temperature Control (Control Training II)

The room temperature control of the control training II is the typical introductory example in control engineering. The temperature behavior in a room is known to everyone through personal experience.

The process is a room that is heated by an electric heater. The technical control task is to control the temperature of the room by changing the heating power so that it corresponds to a specified set point. The heating power is the input variable (actuating variable), the internal temperature of the room is the output variable (controlled variable) of the system. The outside temperature and the degree of window opening represent disturbance variables.

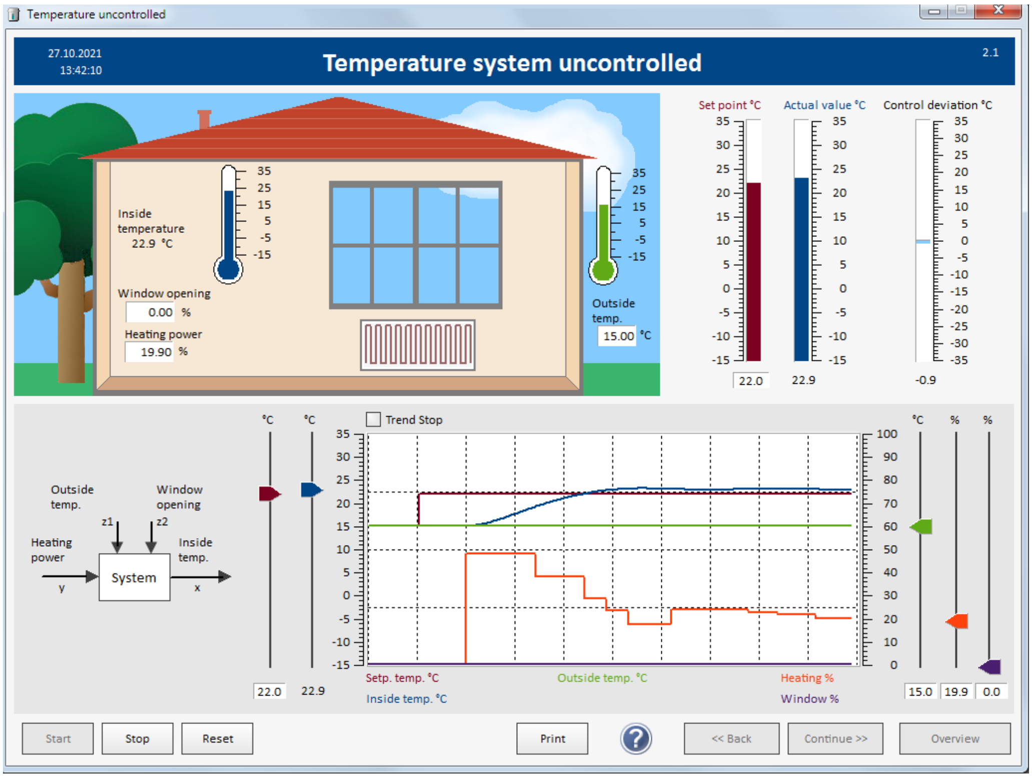
3.1 Uncontrolled System (Manual Control)

In Control Training II, select item 2.1 "Uncontrolled system".

Click “Start”. You can now change the values for the set point (Setp. temp. °C), the heating power (Heating %), the outside temperature (Outside temp. °C) and the window opening (Window %) using the slider or by entering values below the slider

Task 1.

Enter 22°C as set point (reference variable) and try to adjust the heating power (control signal, Heating) so that the actual value (controlled variable, Inside temp.) equals the set point (Setp. Temp.).



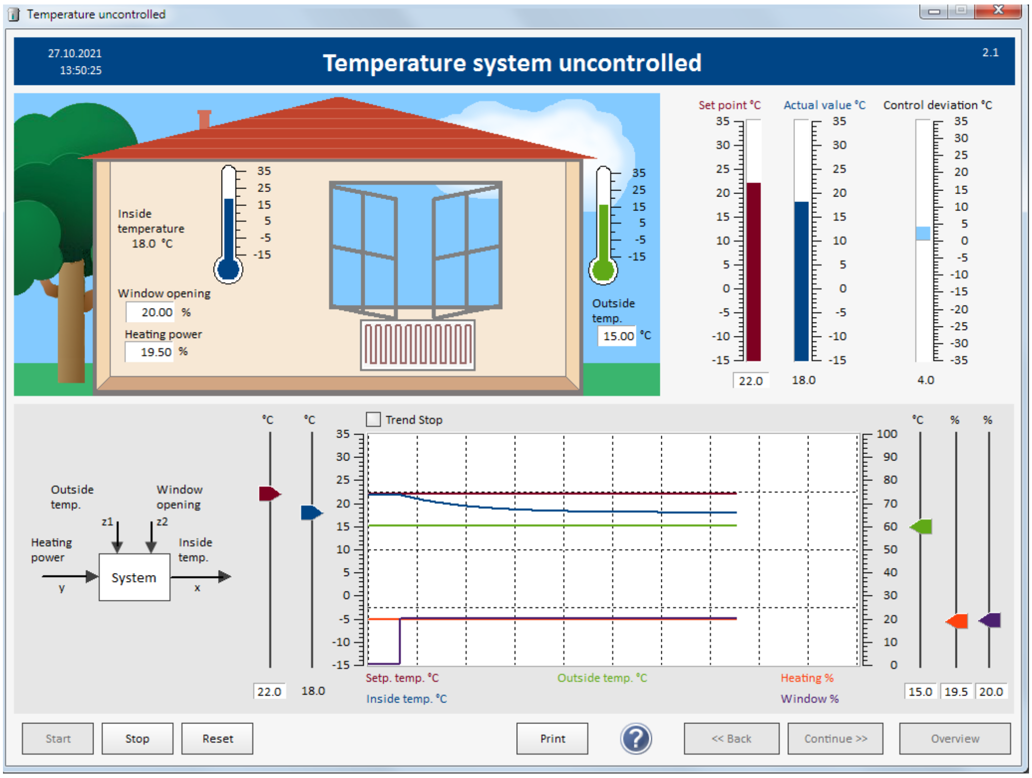
Info:

If the set point is adjusted and an attempt is made to adjust the actual value (controlled variable) to the new set point (reference variable), we speak of the command response.

Task 2.

Open the window, set the window opening to 20%.

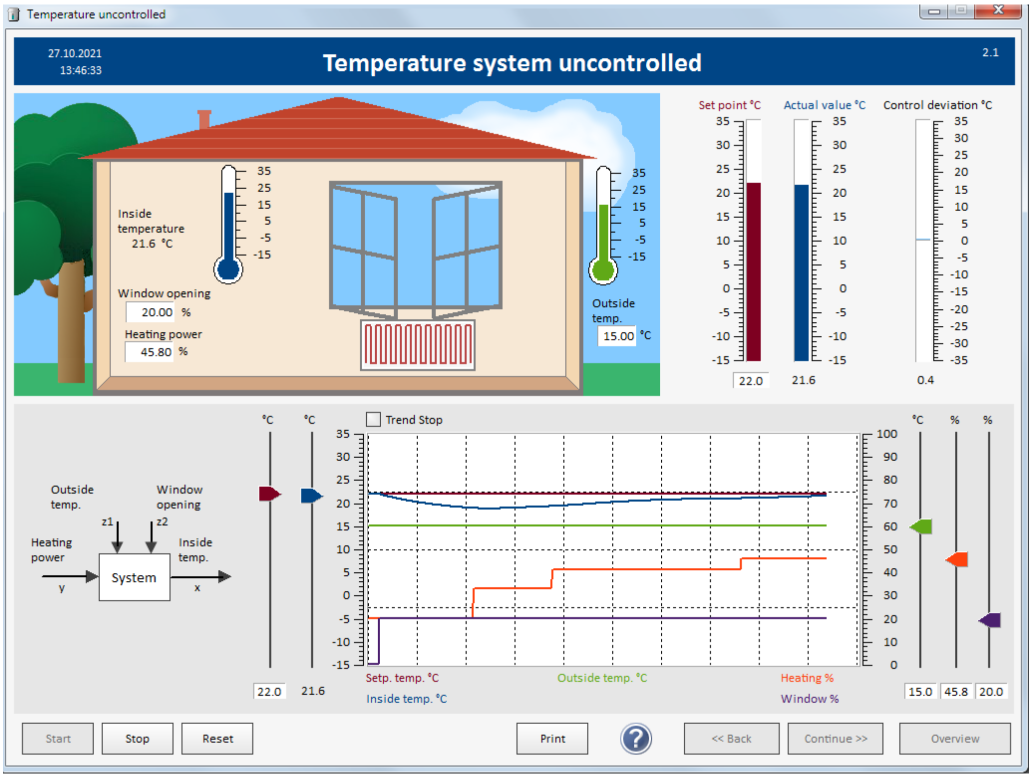
What will happen ?



Since the outside temperature is 15°C, the room temperature (inside temperature) will decrease when the window is open.

Task 3.

With the window open, try to adjust the internal temperature to the set point of 22°C by adjusting the heating power.



Due to the external disturbance, an attempt must be made to adjust the actual value (controlled variable) to the set point (reference variable) by adjusting the heating power (actuating variable).

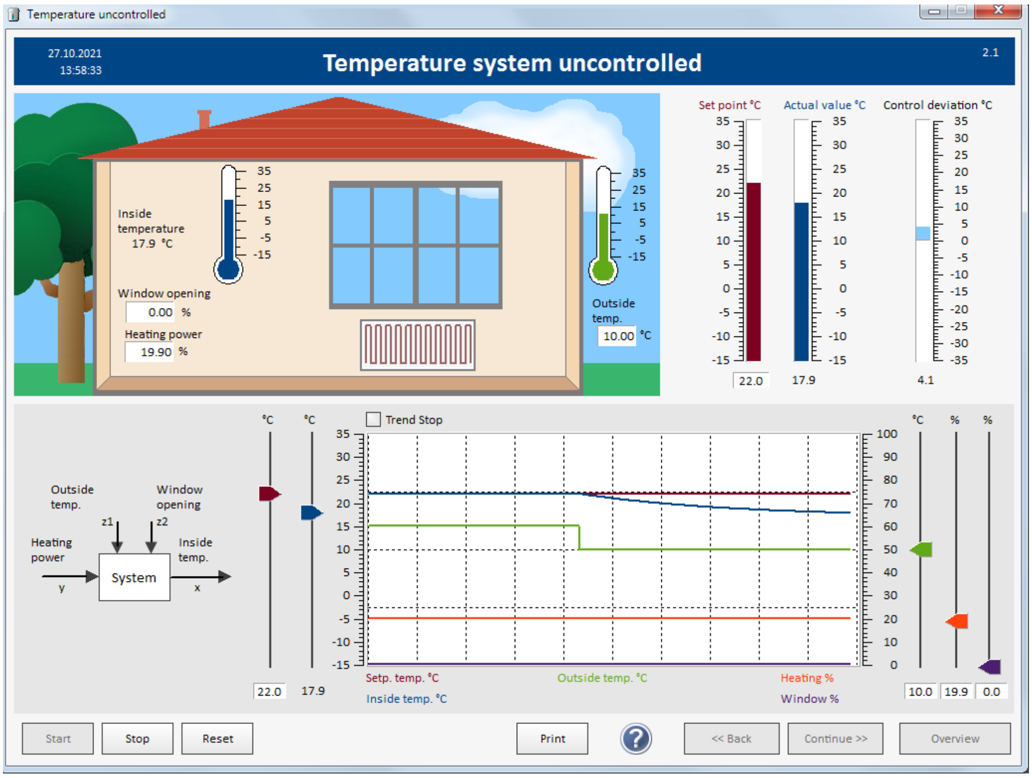
> *Info:*
>
> When responding to a disturbance in the system, one speaks of the disturbance response of the control loop.

Task 4.

Close the window and try to adjust the internal temperature to the set point value of 22°C by adjusting the heating power.

When the actual value has stabilized at the set point, change the outside temperature (Outside temp.) by setting it from 15°C to 10°C.

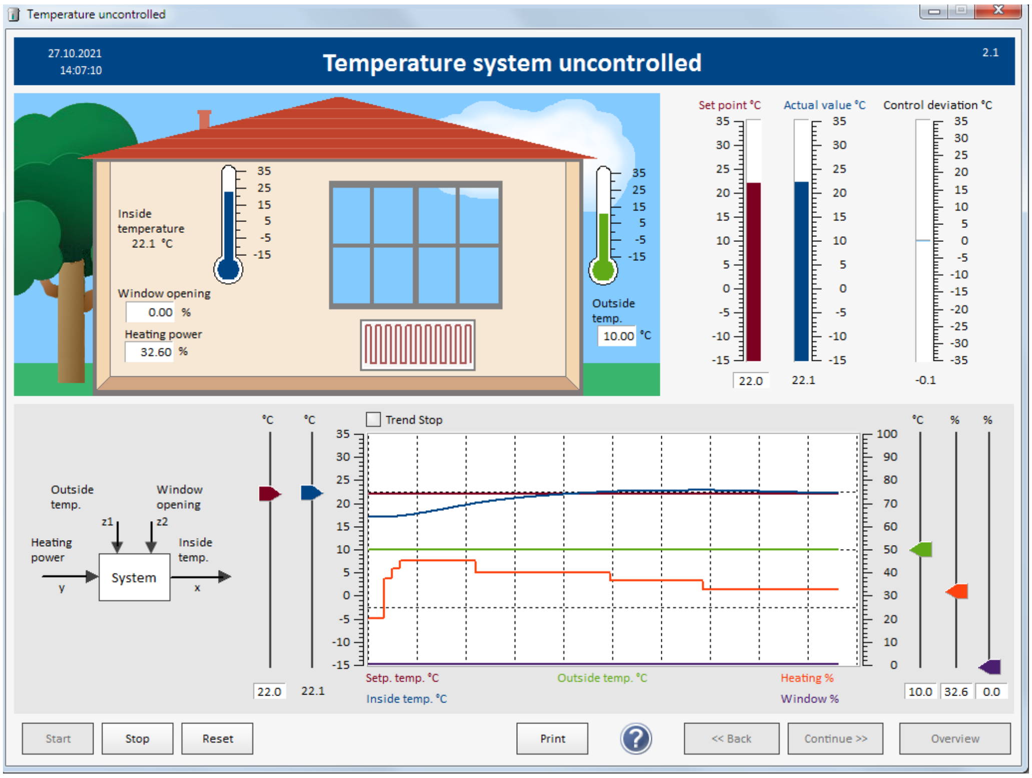
What will happen?



As the outside temperature decreases, the inside temperature in the room decreases likewise.

Task 5.

Try to correct the disturbance caused by the new outside temperature by adjusting the heating power.



The internal temperature decreases due to the disturbance occurring from the outside temperature.

In order to compensate for this disturbance, the heating power must increase. This is again about the disturbance response in the control loop.

Everyone knows from personal experience that the heating power has to be increased when the outside temperature is decreasing.

3.2 Closed-loop Control Examination

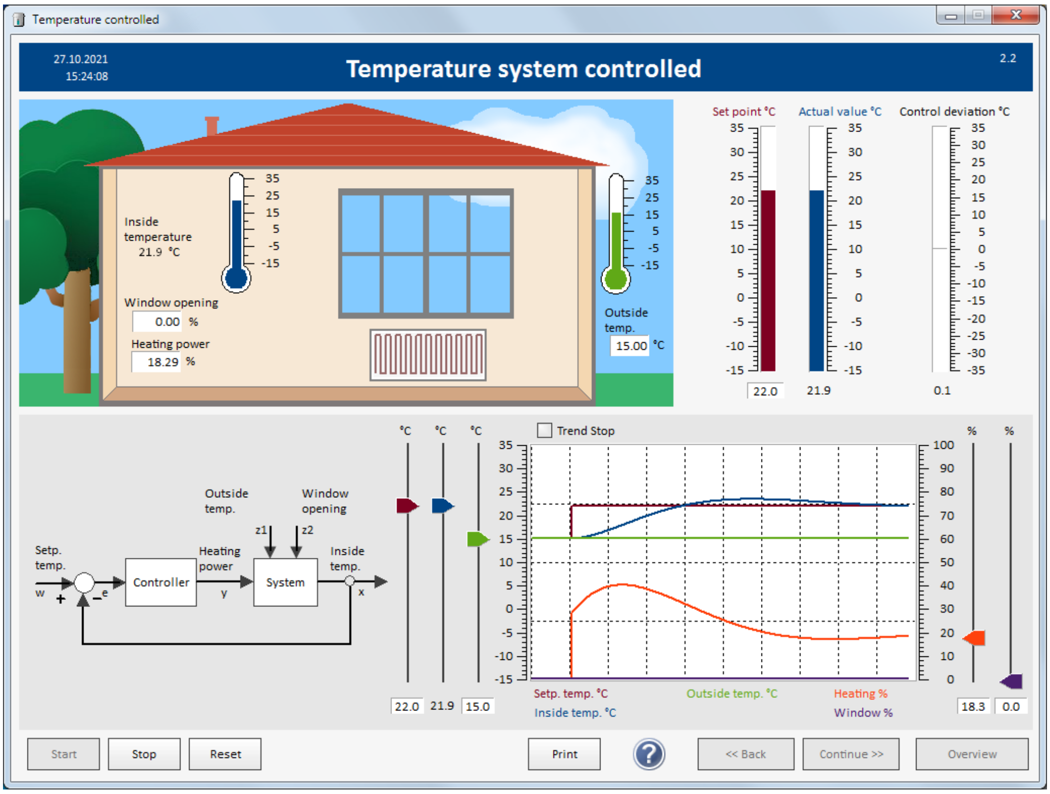
3.2.1 Closed-loop Control System

Return to „Overview“ and select item 2.2 „Controlled system“.

Here you can see how the system behaves in principle if, instead of manual control by the user, a controller takes over the task of adapting the actual value to the set point.

Task 6.

Click “Start” and enter 22°C as set point.



With overshoot, the actual value approaches the set point after a certain time.

Even if a disturbance is applied e.g. by changing the outside temperature, the controller works to adjust the actual value to the set point.

3.2.2 Closed Loop Control with P Controller

Go to "Overview" and select item 2.4 "Closed-loop control with P controller".

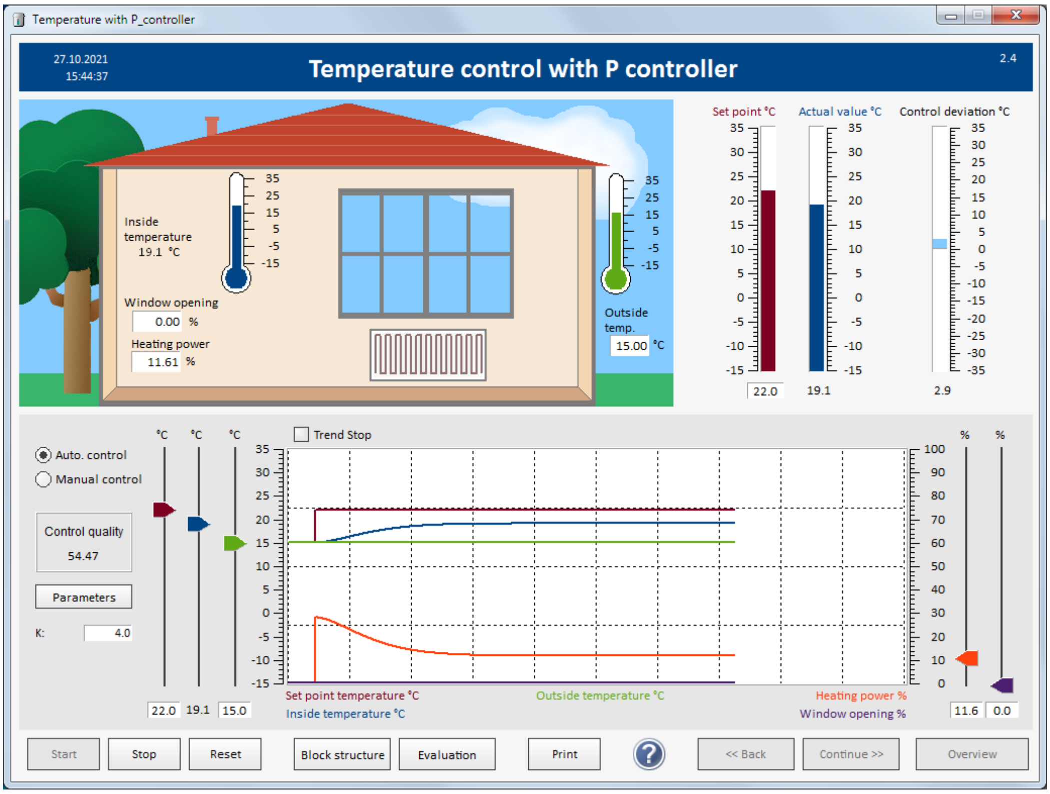
Task 7.

Click “Start”.

Since the actual value (controlled variable) and the set point (reference variable) have a value of 15°C, there is no need for heating. The controller therefore outputs 0% heating power as a control signal.

Change the set point to 22°C and wait until the control loop has settled, i.e. until the actual value no longer changes.

What will happen?



After the settling phase, the actual value (controlled variable) does not reach the set point (reference variable). We get a steady-state control error.

The control error e is defined as e = w - x, with

w = reference variable (set point) and x = controlled variable (actual value).

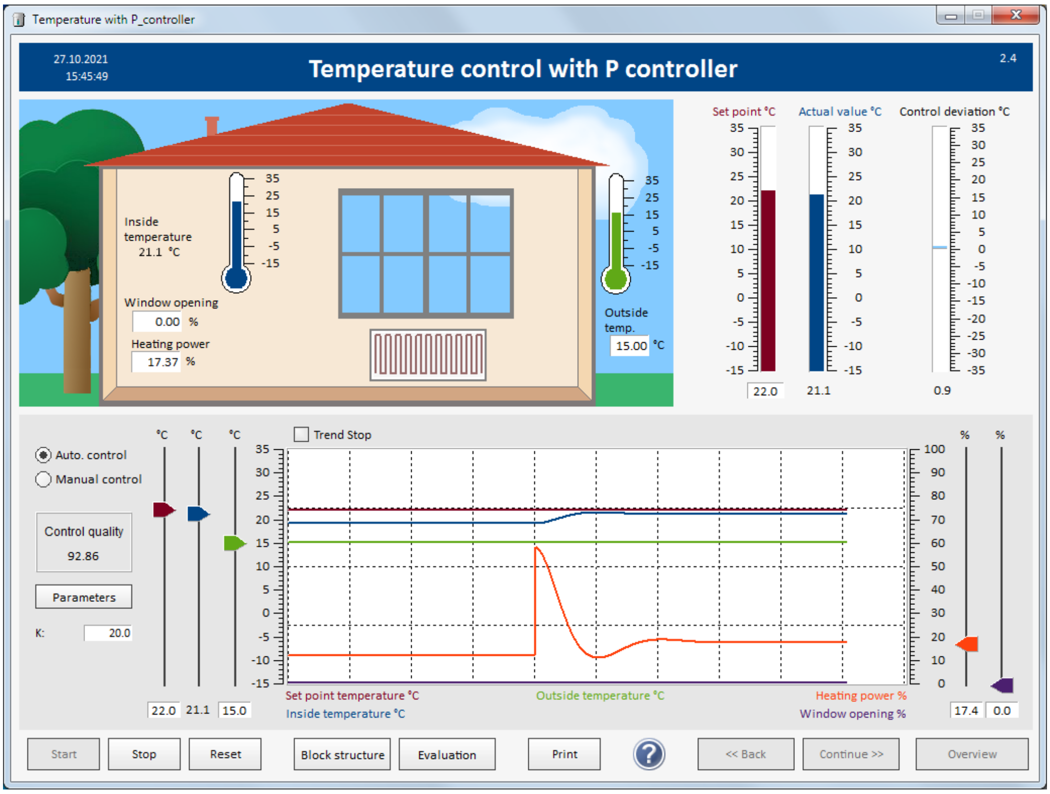
The P controller works like an amplifier. The input signal to the controller w - x (set point - actual value) is amplified with the gain K (in our case 4).

In our case, the desired set point w was 22°C. An actual value x of 19.1 ° C was achieved. The control error is therefore 2.9°C (w-x). Since the gain K of the P controller was set to 4, the control difference is multiplied by 4. This results in the value of the control signal (22-19.1) * 4 = 11.6. This value can also be read in the program.

> *Info:*
>
> In order for the P-controller to output a control signal (heating power) that is not equal to zero, the set point and actual value must be different, i.e. steady state control fault.

Task 8.

Adjust the gain of the P controller from 4 to 20 and wait until the control loop has settled again.



The control difference between set point and actual value becomes significantly smaller as the gain K is increased from 4 to 20. However, the P controller does not manage to adjust the actual value to the set point here either. For the reason described above, we also get a permanent, albeit significantly smaller, control error (e = w - x). As stated above, you can also calculate the control signal value.

The P-controller also reacts to a disturbance (e.g. change in outside temperature). Also a permanent control difference is obtained for this.

Conclusion

As can be seen from the settling time, the P controller reacts immediately and quickly to changes in the set point and disturbance variable. However, we get a steady-state control error for this system with the P controller.

3.2.3 Closed-Loop Control with I Controller

Go to "Overview" and select item 2.5 "Closed-loop with I controller".

Click “Start”.

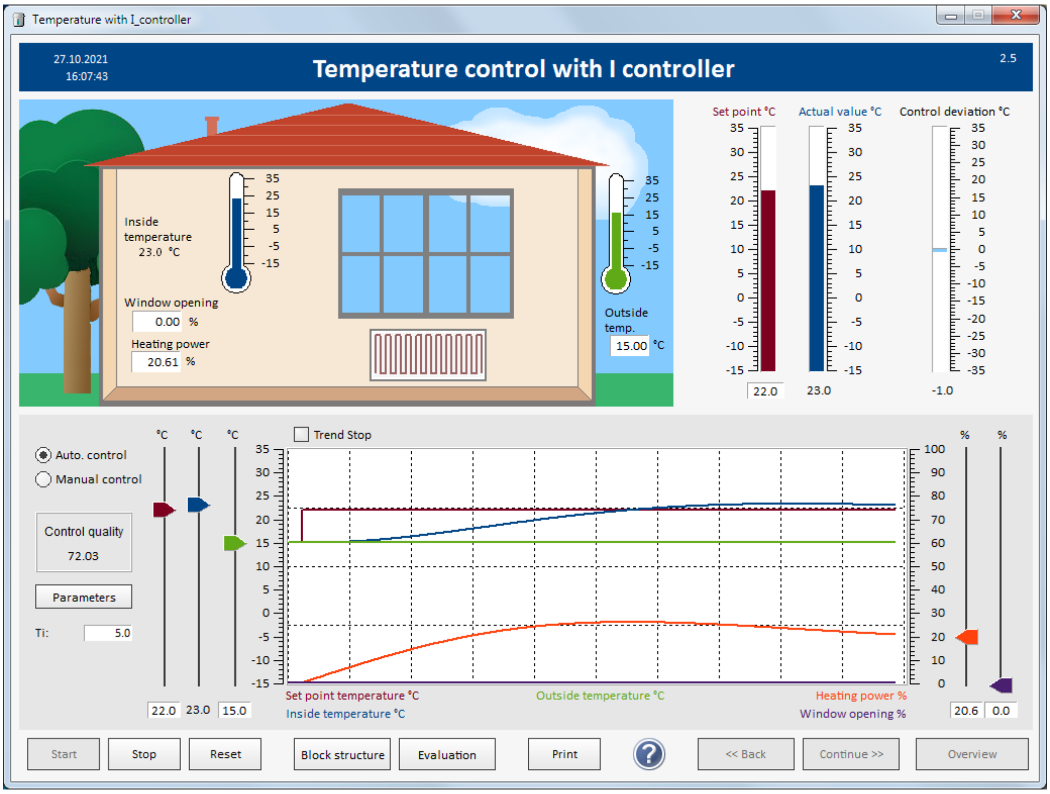
Task 9.

Since the actual value (controlled variable) and the set point (reference variable) have a value of 15°C, there is no need for heating. The controller therefore outputs 0% heating power as control signal.

Maintain the set reset time Ti of 5s.

Change the set point to 22°C and wait until the control loop has settled, i.e. until the actual value no longer changes.

Describe the behavior.



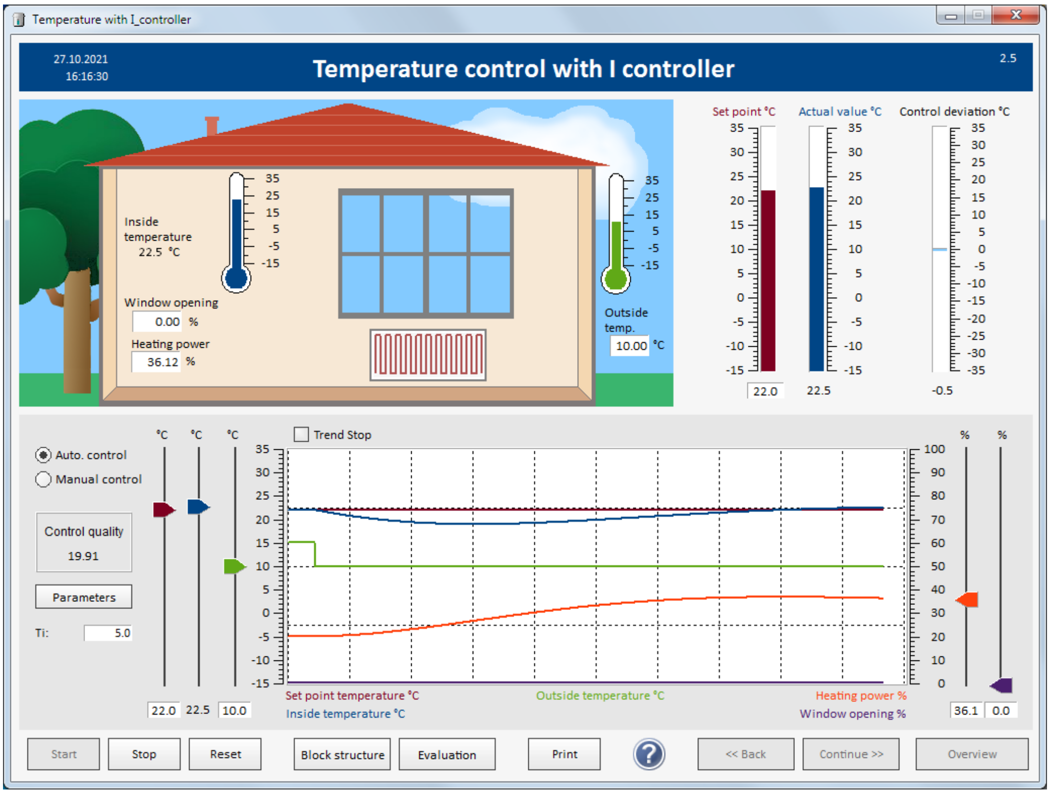
After a significantly longer settling phase than with the P controller, the actual value reaches the set point with a small overshoot. There is no steady-state control error.

However, it takes a long time for the control loop to settle.

Task 10.

Apply a disturbance, change the outside temperature to 10°C.

How does the control loop behave?



After a longer settling phase, the actual value approaches the set point.

There is also no permanent steady-state control error for the disturbance behavior.

However, settling takes a long time.

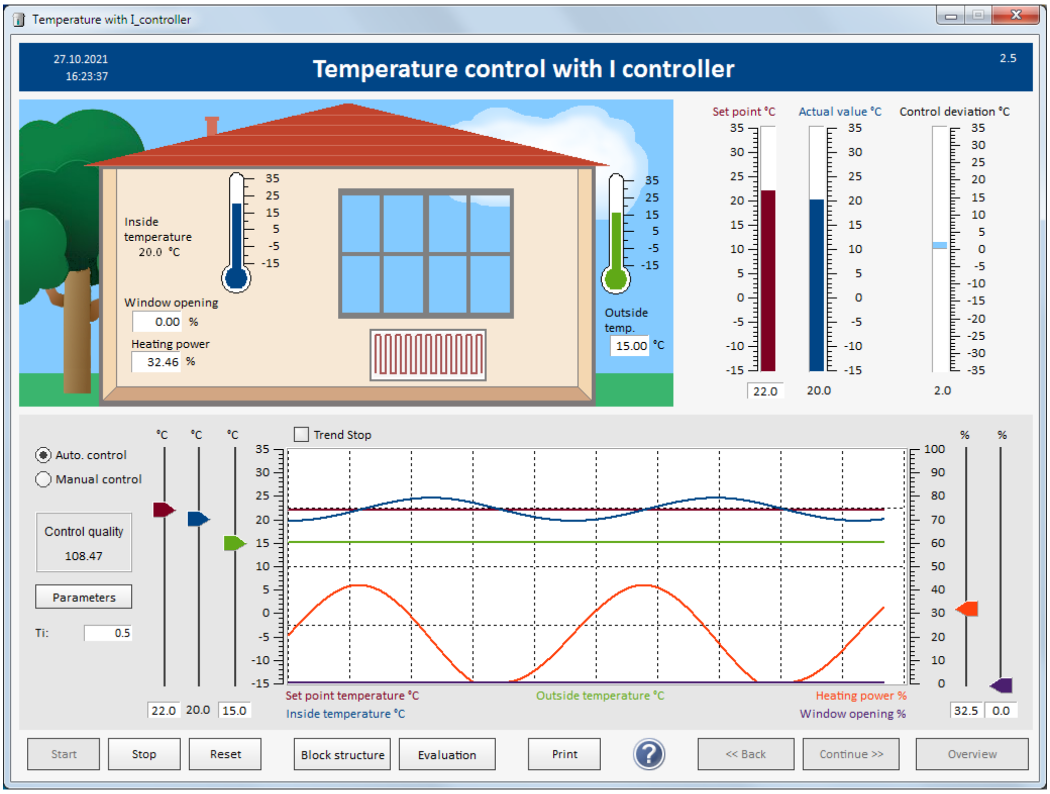
Task 11.

Click “Reset” or restart the temperature control with the I-controller.

The actual value (controlled variable) and the set point (reference variable) again have the same value of 15°C. Therefore there is no need for heating. The controller outputs 0% as heating power (control signal).

Change the set reset time Ti to 0.5.

Set the set point to 22°C and observe the control loop.



The control loop is unstable. The actual value oscillates continuously around the set point.

> *Info:*
>
> If there is an I component (integrator) in the controller, the controller either manages to adjust the actual value to the set point after a settling phase or the control loop becomes unstable.

This is explained by the behavior of the integrator:

If the value of the input signal to an integrator is positive, the value of the output signal (control signal) increases. If the input signal is equal to zero, the integrator retains its output value (the value remains constant). If the input value is negative, the output value of the integrator decreases continuously.

In order for a control loop to settle to a value, the control signal (output of the controller) must be constant. The output value of an integrator is only constant when the input value of the integrator is equal to zero, i.e. when the set point and actual value are the same.

3.2.4 Closed-Loop Control with PI Controller:

Go to "Overview" and select item 2.6 "Closed-loop control with PI controller".

Click “Start”.

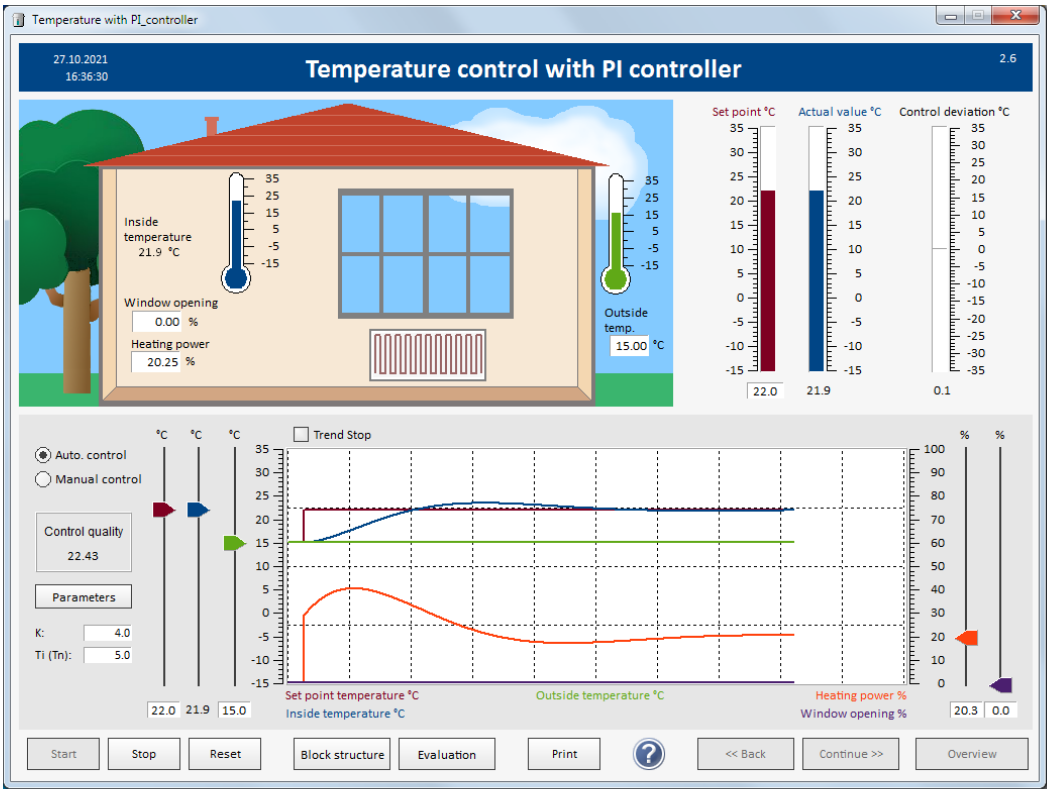
Task 12.

Since the actual value (controlled variable) and the set point (reference variable) have the same value of 15°C, there is no need for heating. The controller output (control signal, heating power) is 0%.

Keep the default parameters: K = 4, Ti = 5.

Change the set point from 15°C to 22°C.

Observe the settling behavior.



The control loop with the PI controller and the set parameters oscillates to the set point with a small overshoot. The actual value (controlled variable) reaches the set point (reference variable).

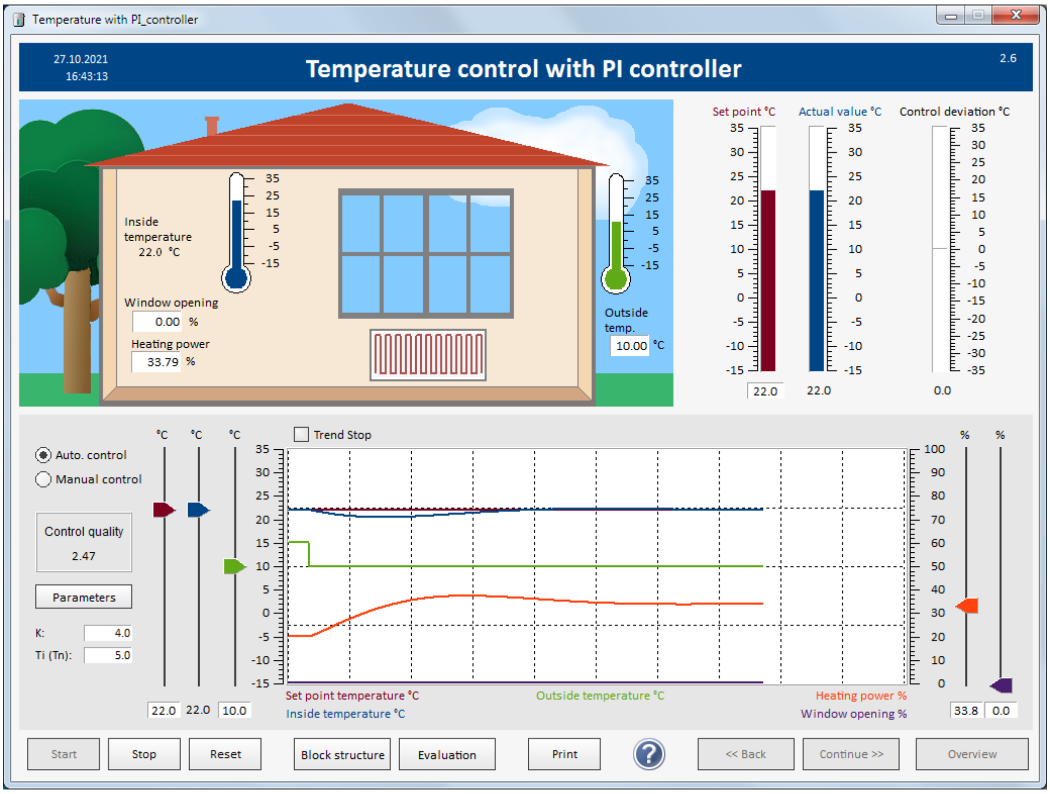
> *Info:*
>
> If the set point is adjusted and an attempt is made to adjust the actual value (controlled variable) to the new set point (reference variable), we speak of the command response.

Task 13.

Examine the disturbance response.

Let the control loop settle to the set point 22°C with the parameters K = 4 and Ti = 5.

When the control loop has settled, change the outside temperature to 10°C and observe the behavior.



The lower outside temperature causes the room temperature to decrease. The controller tries to counteract this and increases the heating power. After a settling phase, the actual value reaches the set point again.

> *Info:*
>
> When responding to a disturbance in the system, one speaks of the disturbance response of the control loop.

Task 14.

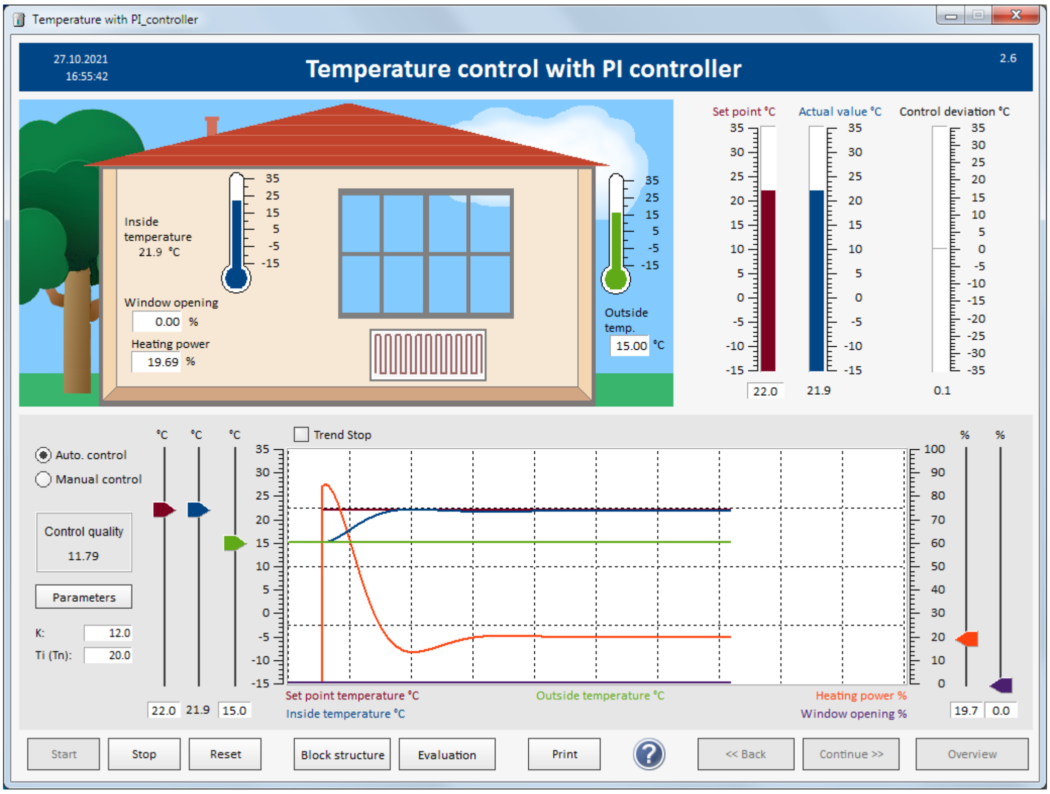
The number in the box labeled "Control quality" indicates the quality of the steady state control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the set point.

Try to reduce the value of control quality by adjusting the controller parameters.

With the controller parameters K = 4 and Ti = 5, a control quality of 22.12 was achieved.

So that the control quality is comparable in the tests, all tests must be started with the same initial states. The best way to do this is to click "Reset". This means that the set point, outside temperature and inside temperature are again default values and the window is closed.

Now change the controller parameters and then adjust the set point to 22°C. Wait until the control loop has settled.



With the parameters K = 12 and Ti = 20, a control quality of 11.8 is obtained, for example.

Carry out the experiments with further controller parameters:

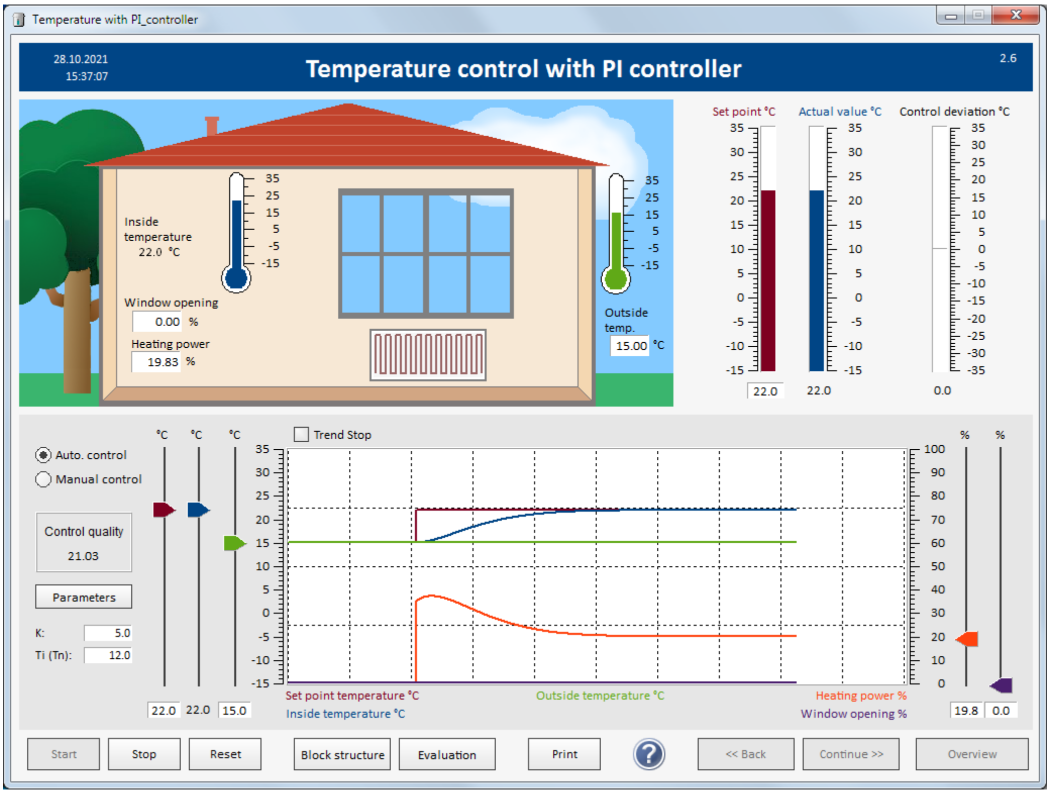
- Click reset,
- Set controller parameters,
- Change the set point to 22 ° C,
- Wait until the control loop has settled.

Task 15.

Restart the temperature control with PI controller or click "Reset".

Try to adjust the controller parameters to ensure that the actual value reaches the set point without overshooting. In this case one speaks of an aperiodic case (without overshoot).

Go back to the initial state (reset), adjust the parameters and then change the set point to 22°C.



With the parameters K = 5 and Ti = 12, for example, an aperiodic behavior is obtained.

For certain controls it can be important that the actual value reaches the set point without overshooting.

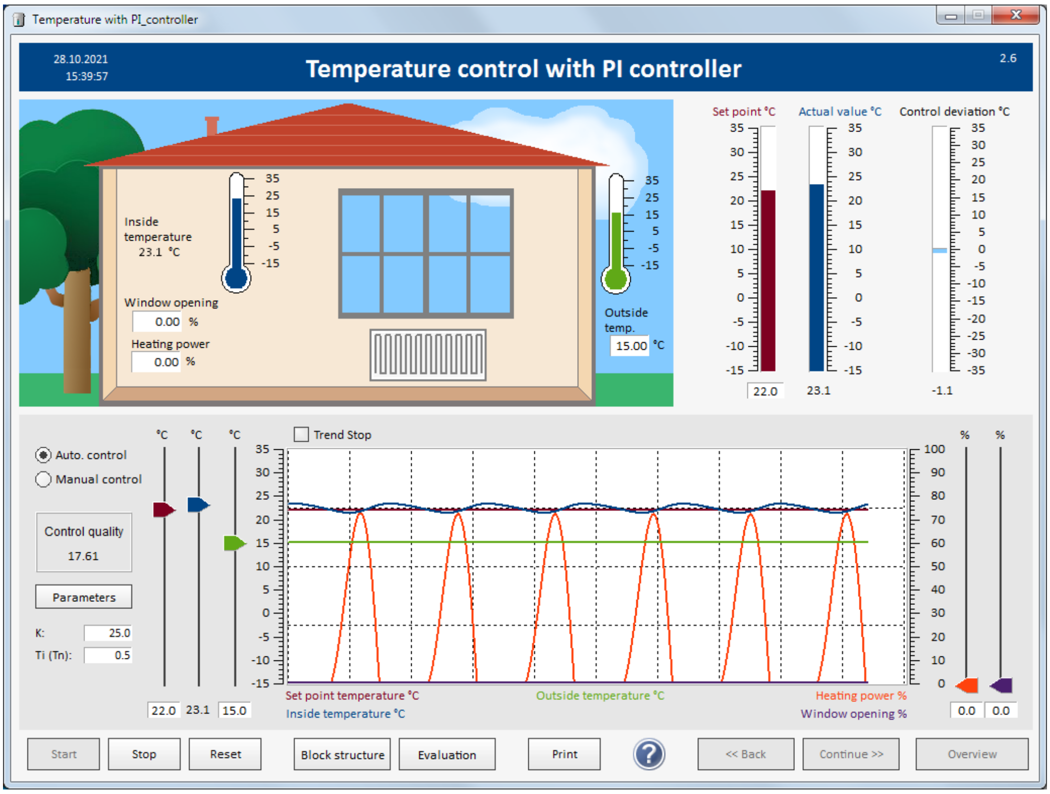
For example, it may be necessary for a bioreactor that a certain temperature is not exceeded, because otherwise it can lead to cell death.

Task 16.

Restart the temperature control with the PI controller or click "Reset".

Set the parameters: K = 25, Ti = 0.5, change the set point to 22°C.

Watch the control loop.



The system becomes unstable. The actual value oscillates around the set point.

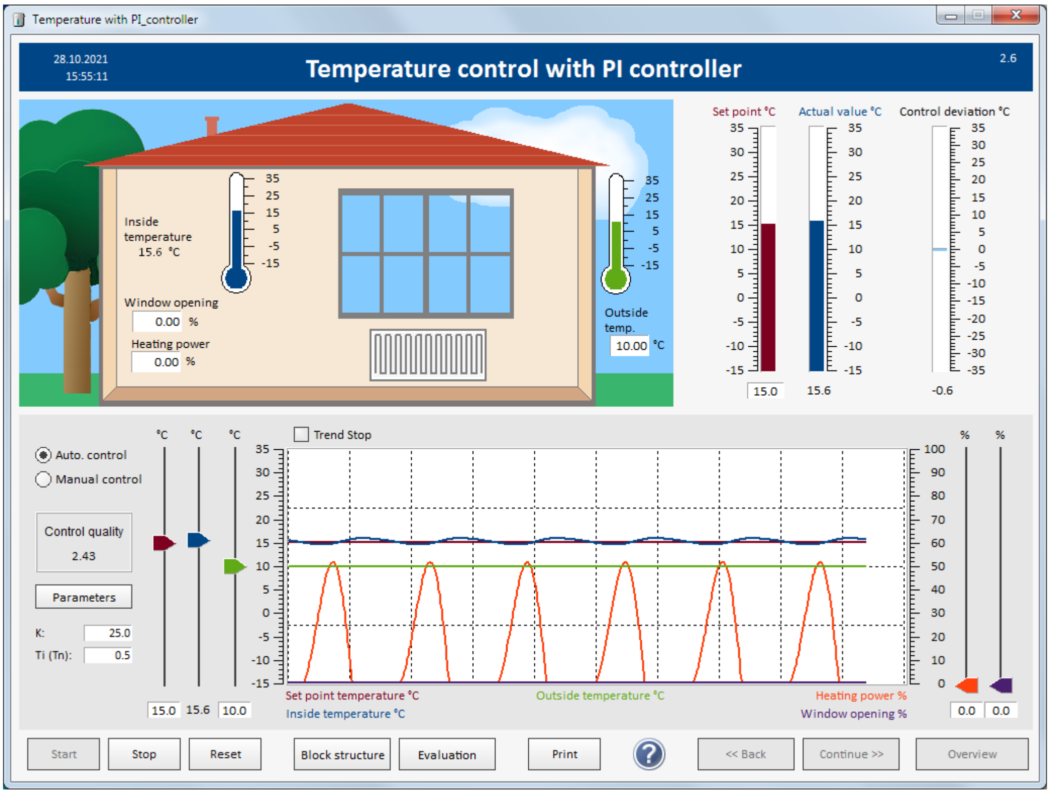
By clicking "Evaluation" you have the option of evaluating the stored signal curves and examining the settling behavior.

Task 17.

In the above task, the control behavior was examined with the parameters gain Kp = 25 and the reset time Ti = 0.5s.

Now examine the disturbance behavior with these parameters.

To do this, you have to click "Reset" again, set the controller parameters and then, for example, set the outside temperature from 15°C to 10°C.



The control loop with these parameters also becomes unstable for the disturbance behavior.

Conclusion

- With the PI controller and appropriately well set controller parameters, the control loop can be controlled quickly and easily, the actual value reaches the set point and remains at the set point.
- This applies to the command response behavior as well as to the disturbance response.
- If the parameters are poorly set, the control loop can become unstable.

3.2.5 Closed-Loop Control with PID Controller

Go to "Overview" and select item 2.7 "Closed-loop control with PID controller".

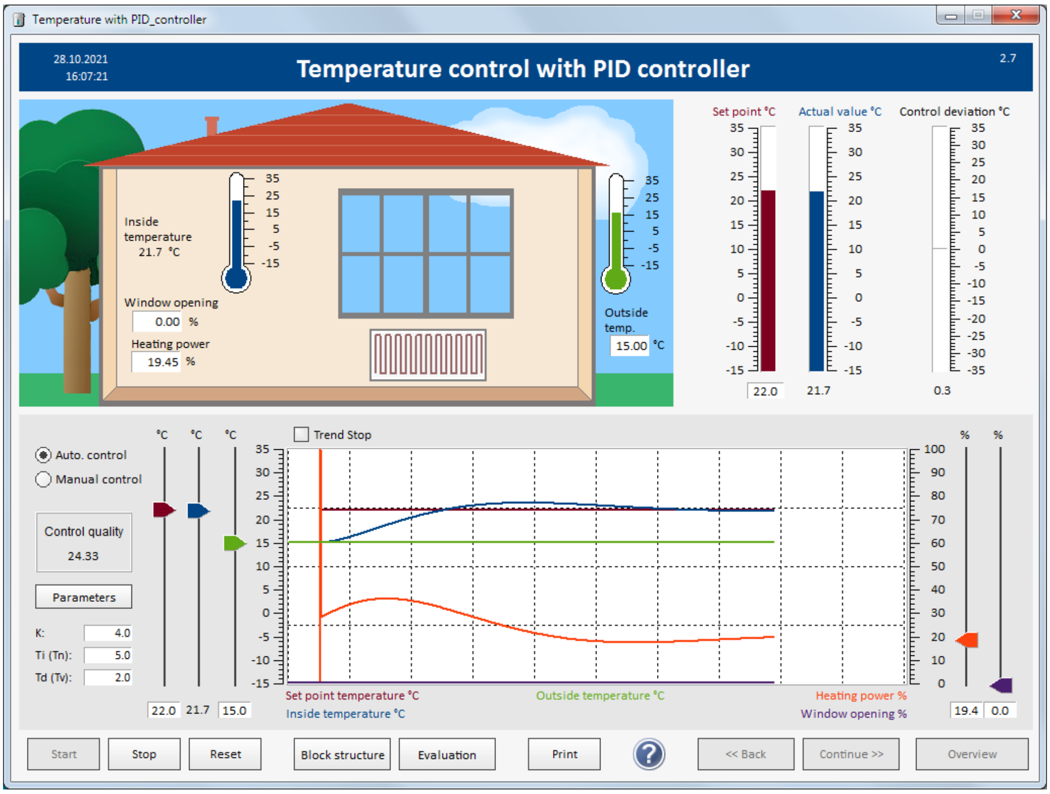
Click “Start”.

Task 18.

Examine the command response with the preset parameters.

Gain K = 4, Reset time Ti = 5, Derivative time Td = 2

Click “Reset” and change the set point to 22°C.



The control loop goes into a stable state with a small overshoot. The actual value reaches the set point.

As can be seen in the trend diagram, the sudden change in the set point causes a peak in the control signal (heating power). This peak is triggered by the D component of the controller. The derivation of a sudden change causes an (infinitely) large value.

The control quality goes to 24.3 and is therefore worse than with the PI controller with the parameters K = 4 and Ti = 5.

Note on the trend display with the PID controller:

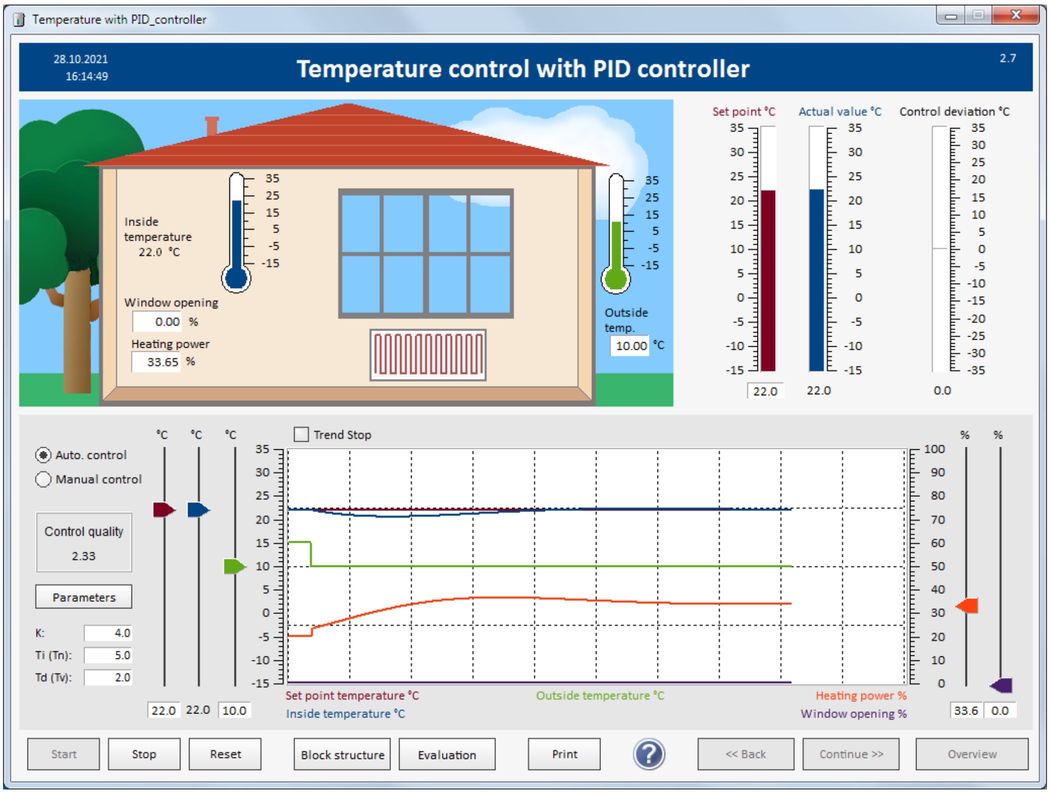
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Evaluation" (display of the stored signal values) and selection of a corresponding time range.

Task 19.

Examine the disturbance behavior with the preset parameters:

Gain K = 4, Reset time Ti = 5, Derivative time Td = 2

Click "Reset" and change the outside temperature to 10°C.

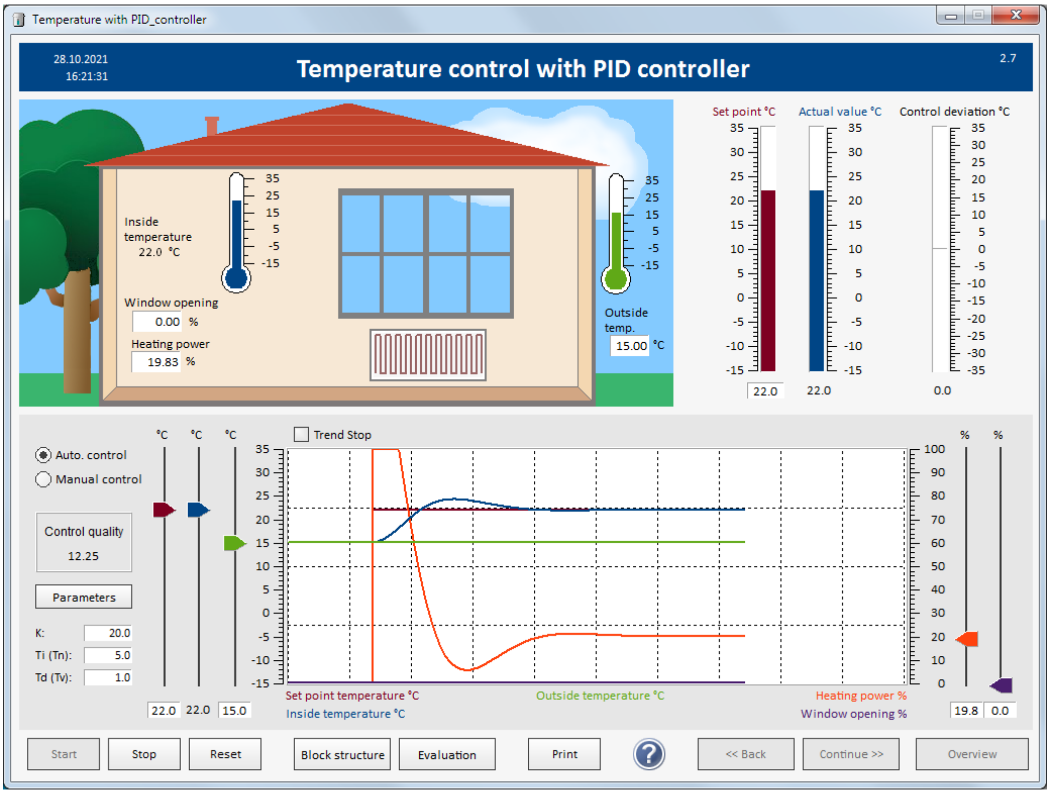


Also in the event of a disturbance, the control problem is solved with the specified controller parameters. The actual value (controlled variable) reaches the set point (reference variable) again after a period of time.

Task 20.

Try to improve the control quality by adjusting the controller parameters.

To be able to compare the experiments, you always have to start from the same initial states. Therefore click “Reset”, change the controller parameters and then adjust the set point to 22°C.



With the controller parameters K = 20, Ti = 5 and Td = 1, you get a control quality of 12.25, for example.

The experiments that were carried out with the PI controller can also be carried out with the PID controller (unstable behavior, aperiodic behavior, etc.).

Info:

In practice, the PI controller is most common. If a PID controller is used, the D component is often turned off so that the controller only works as a PI controller.

One of the reasons for this is that the D behavior in a control loop is difficult to assess. In principle, the D component gives you the option of making the control faster (which is often very difficult, however).

The D component considers the change between the set point and the actual value. If the change increases, i.e. the difference between the set point and actual value increases, the D component adds a calculated value to the control signal. If the difference between the set point and the actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend, whether the difference between the set point and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the set point and actual value decreases, the control signal is reduced.

3.3 Examine the Controlled System

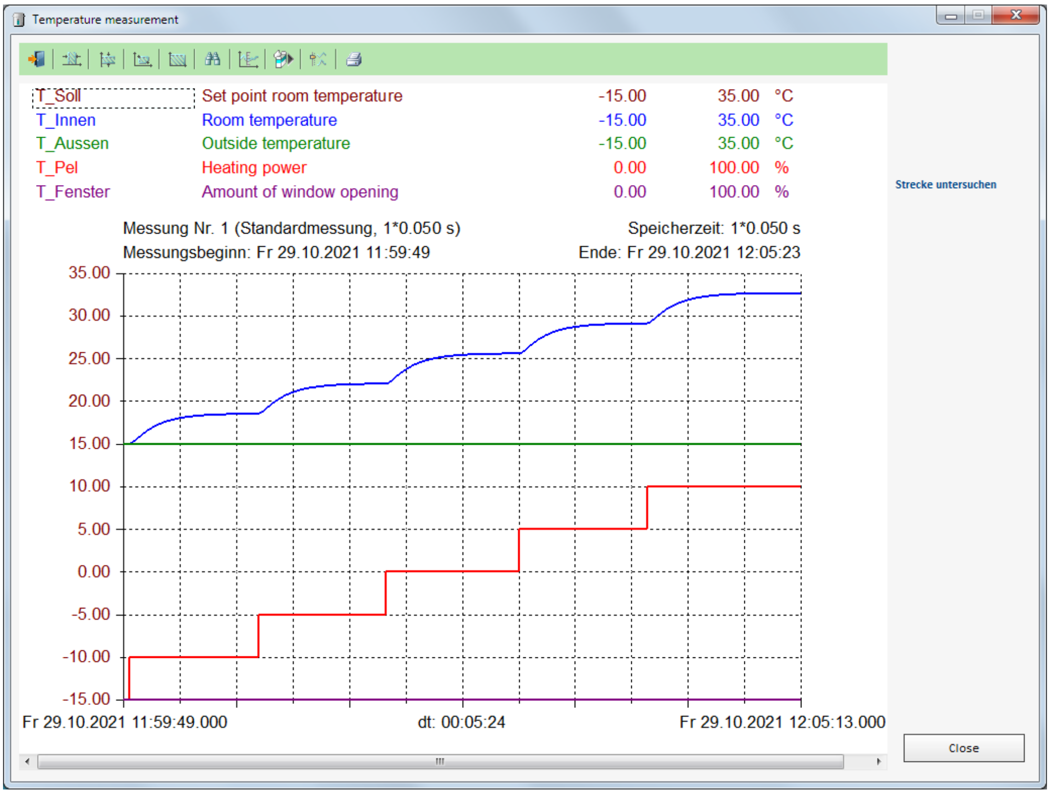
Go to "Overview" and select item 2.3 "Examine controlled system".

Click “Start”.

Task 21.

Increase the heating power in steps of 10% wait each time until the internal temperature is constant.

Observe the temperature behavior.



As can be seen from the recorded data (“evaluation”), the system behavior is similar for all steps. The actual temperature rises by approx. 3.5°C when the heating power increases by 10%. This does not always have to be the case with a controlled system.

With many controlled systems, the behavior depends on the operating point. This means that the controls will behave differently in different operating points, although the same controller and the same controller parameters.

3.4 Controller Tuning Rules

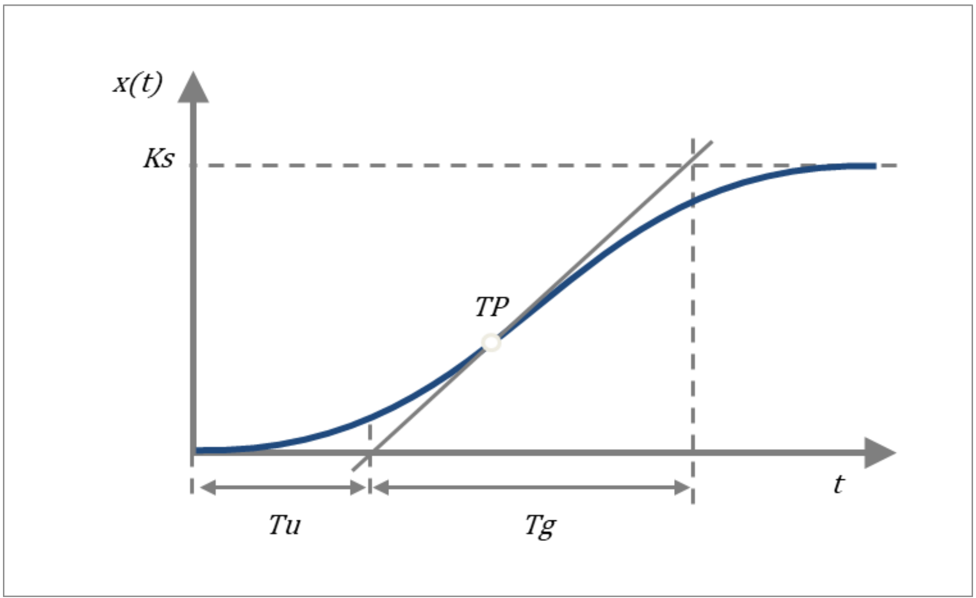
The room temperature system is a controlled system with self-regulation.

In the event of a sudden change in the control signal, a controlled system with self-regulation oscillates to a constant value after a finite time, while with a controlled system without self-regulation, the controlled variable (actual value) continues to rise.

The behavior of the temperature in a room is a controlled system with self-regulation, since when the heating power is suddenly adjusted, the temperature approaches to a fixed value after a certain time (outside temperature and window opening remain constant), as was shown under point 3.3.

The method according to Chien / Hrones / Reswick is used as a controller tuning procedure for a controlled system with self-regulation.

A controlled system with self-regulation has roughly the following behavior in response to a step in the control signal (sudden change in the control signal by 1):



In the new standard, the delay time is designated with Te, the compensation time with Tb and the turning point with P.

Since the terms Tu and Tg are still used in most of the literature, we keep the old terms here, or use both.

The parameters Ks, Tg and Tu can be determined from this step response, as shown in the figure above. The controlled system´s gain Ks (final value of the actual variable) results from the abrupt change in the control signal by 1. If the amount of change is greater, you have to divide the resulting system´s gain value by the amount the control step value in order to obtain Ks.

It means:

Te = Tu = Delay time

Tb = Tg = Compensation time

Ks = Gain

With the help of these three parameters, the controller parameters can then be determined from the setting table according to Chien / Hrones / Reswick:

Table 1: Equations to calculate controller parameters according to Chien/Hrones/Reswick

Controller	Quality criteria			
	With 20 % Overshoot		Aperiodic case	
	Disturbance	Command	Disturbance	Command
P	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$
PI	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.3 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 4 \cdot T_U$	$K_P \approx \frac{0.35}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.2 \cdot T_g$
PID	$K_P \approx \frac{1.2}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2 \cdot T_U$ $T_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.35 \cdot T_U$ $T_V \approx 0.47 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.4 \cdot T_U$ $T\_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$ $T_V \approx 0.5 \cdot T_U$

For systems without self-regulation use $\frac{T_g}{(K_S \cdot T_U\ )}$ instead of $\frac{1}{(K_{IS} \cdot T_U\ )}$.

The table was taken from: E. Samal, Grundriss der praktischen Regelungstechnik, Oldenbourg

Task 22.

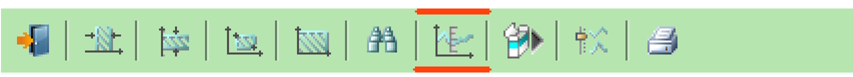
Go to "Overview" and select item 2.3 "Examine controlled system".

Click “Start”. Enter a step in the heating power from 0% to 10%.

All signal curves are saved and can be evaluated and analyzed using "Evaluation".

Determine the parameters Ks, Te (Tu) and Tb (Tg) from the stored signal curves.

By clicking on the "Evaluation" button, you will get the measurement curves. With the help of the button bar, time and value segments can be selected.



For the analysis try to choose an area of interest for the evaluation including the step in heating power and the settling of the internal temperature.

For example, you can then print out the diagram and measure the curves using a ruler to determine Te and Tb.

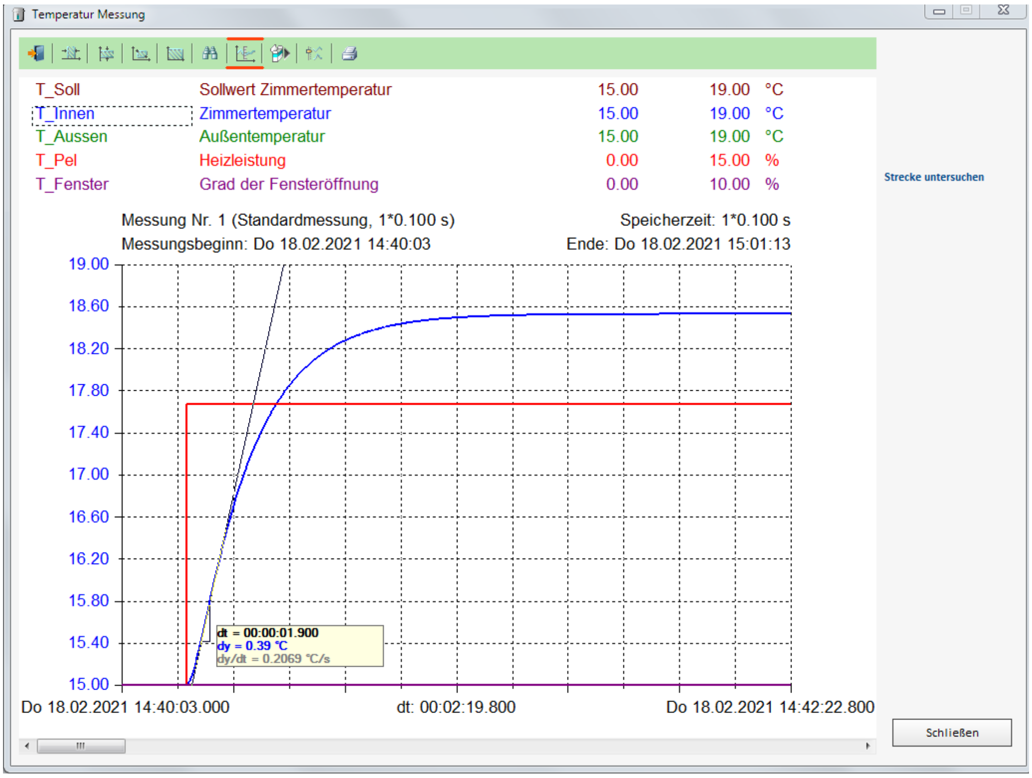


Figure: 3-1: Measurement view for the analysis of controlled system

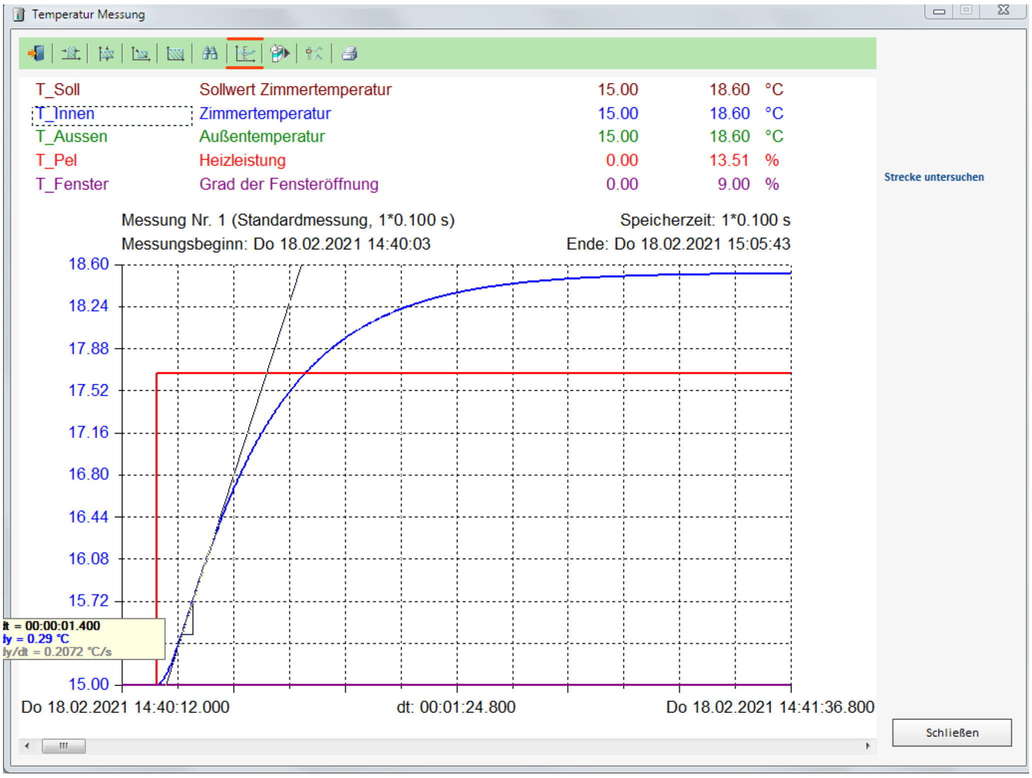


Figure 3-2: Evaluation of the controlled system by "drag and drop" in the measurement view

It is also possible to measure the values in the diagram. Click on the blue signal "T_innen" in the header. Then click on the line in the diagram, by drag and drop, the time difference and value difference as well as the slope are indicated. With this you can try to determine the slope of the blue curve at the turning point.

From the two curves shown above, the value dx/dt = 0.2°C/s for the slope of the tangent at the point of turning can be read.

After the sudden change in the heating power from 0% to 10%, the internal temperature goes from 15°C to 18.5°C after the settling phase.

This enables the compensation time Tg to be calculated (T = actual temperature):

dx/dt = (End value (T) - Start value (T)) / Tg, i.e.

Tg = (18,5°C – 15°C) / 0,207°C/s = 16,91s

Ks results from:

Ks = (End value(T) – Start value(T)) / Step height(Heating power)

= (18,5°C – 15°C) / 10% = 0,35°C/%

The delay time Tu can be measured and is approximately 1.3s.

So: Te = Tu = 1,3s Tb = Tg = 17,5s Ks = 0,35

This results in the following controller parameters from the table for the PI controller:

PI controller

Command response 20% overshoot

K = 0,6*Tb / (Ks*Te)	22,30
Tn = Tb	16,91

Command response aperiodic

K = 0,35*Tb / (Ks*Te)	13,01
Tn = 1,2 * Tb	20,29

Disturbance response 20% overshoot

K = 0,7*Tb / (Ks*Te)	26,02
Tn = 2,3 * Te	2,99

Disturbance response aperiodic

K = 0,6*Tb / (Ks*Te)	22,30
Tn = 4 * Te	5,20

Since the parameters differ significantly depending on the application, the user must decide which type of control is important for his control loop (disturbance or control behavior, with or without overshoot).

The user may have to make a compromise between the controller parameters.

The selected parameters result in the following settling response for the PI controller with a set point step from 15°C to 20°C:

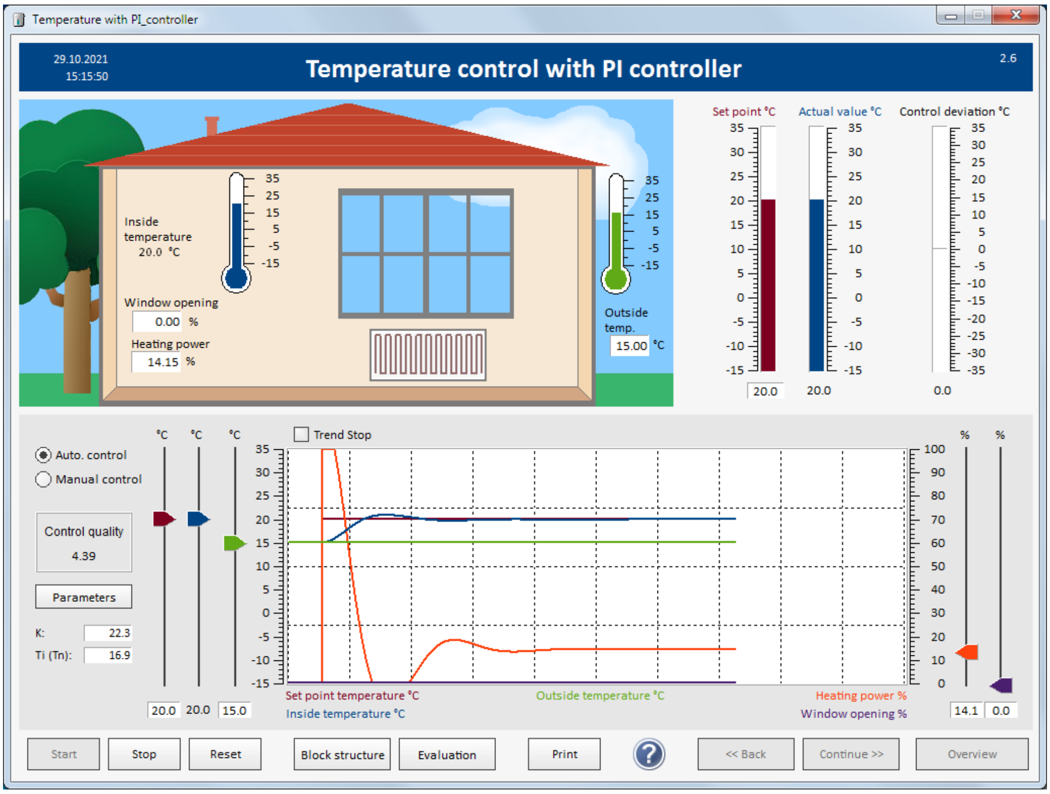


Figure 3-3: Command response with 20% overshoot

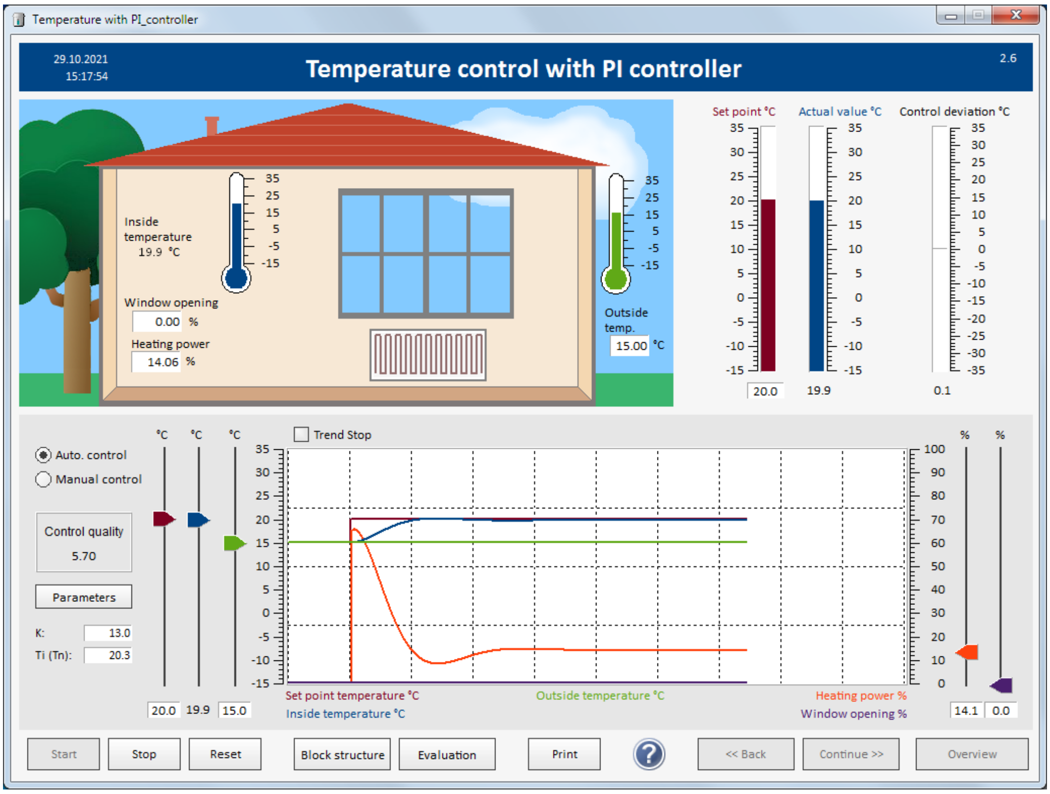


Figure 3-4: Command response aperiodic

A steady control loop with set point and actual value = 20°C was assumed for the disturbance behavior. For the disturbance, the outside temperature was set from 15°C to 10°C:

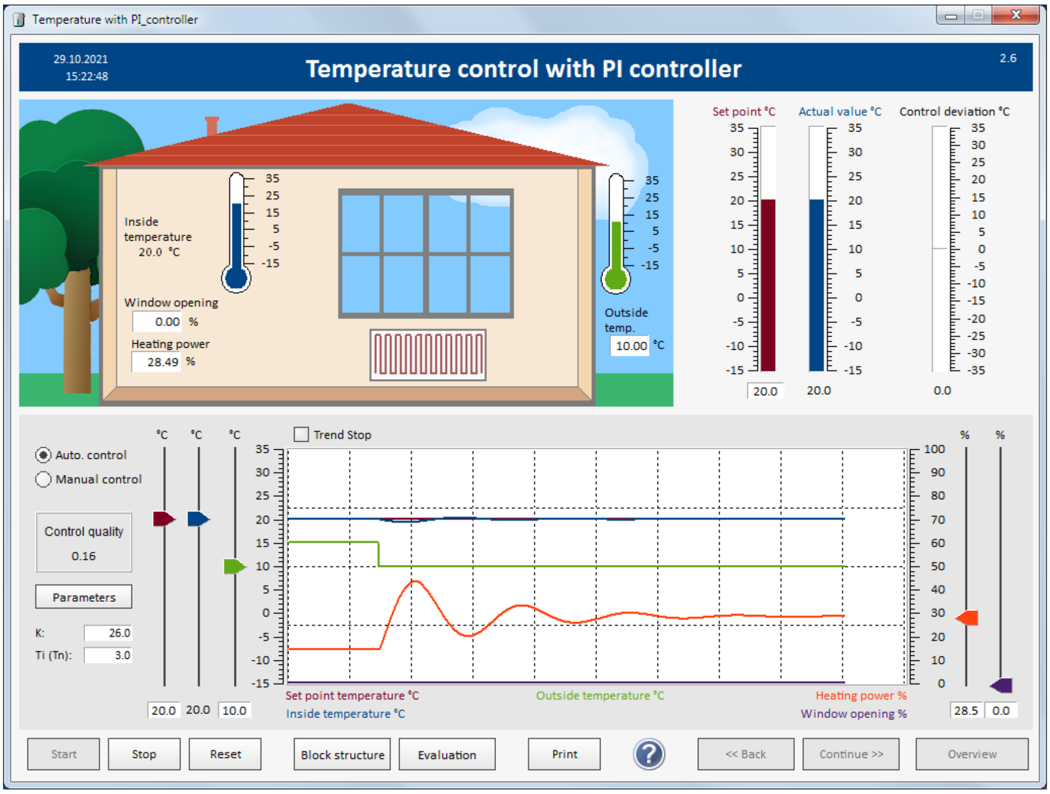


Figure 3-5: Disturbance response 20% overshoot

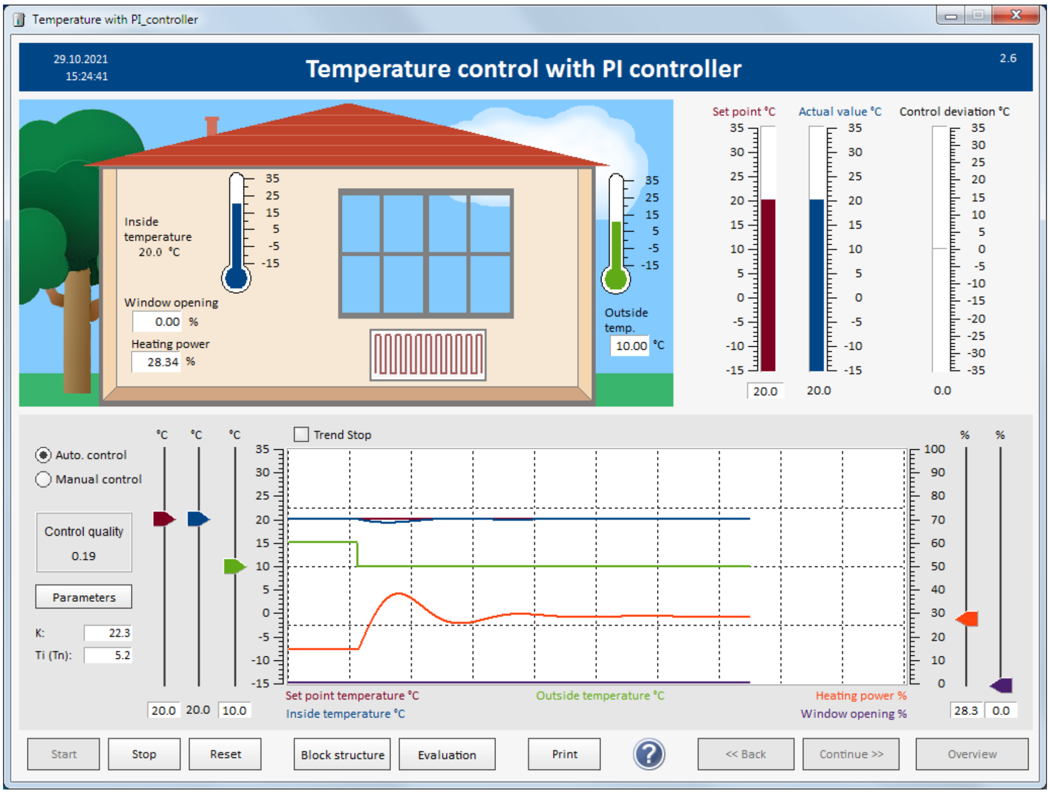


Figure 3-6: Disturbance response aperiodic

The following parameters result for the PID controller:

PID controller

Command response 20% overshoot

K = 0,95*Tb / (Ks*Te)	35,31
Tn = 1,35 * Tb	22,83
Td = 0,47 * Te	0,61

Command response aperiodic

K = 0,6*Tb / (Ks*Te)	22,30
Tn = Tb	16,91
Td = 0,5 * Te	0,65

Disturbance response 20% overshoot

K = 1,2*Tb / (Ks*Te)	44,60
Tn = 2 * Te	2,60
Td = 0,42 * Te	0,55

Disturbance response aperiodic

K = 0,95*Tb / (Ks*Te)	35,31
Tn = 2,4 * Te	3,12
Td = 0,42 * Te	0,55

Here, too, the parameters differ significantly depending on the application (disturbance or control behavior).

The user must therefore decide which type of control is important for his control loop (disturbance or control behavior, with or without overshoot).

The user may have to make a compromise and determine the controller parameters that are suitable for the necessary control applications.

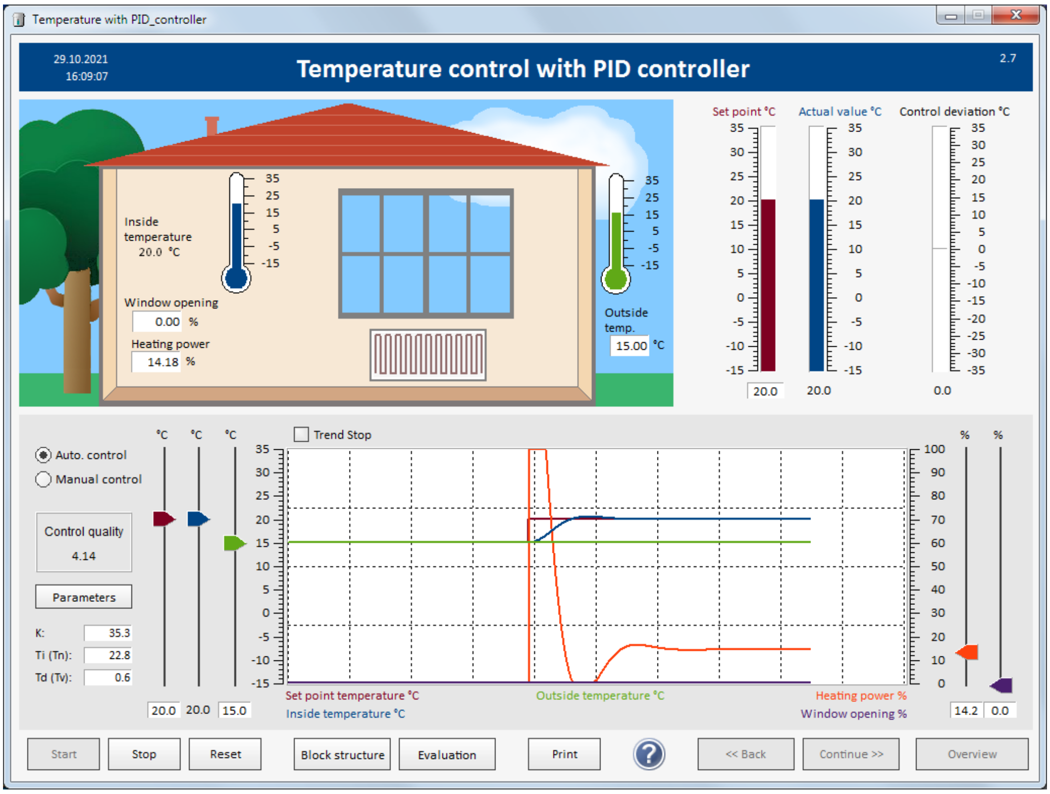


Figure 3-7: Command response 20% overshoot

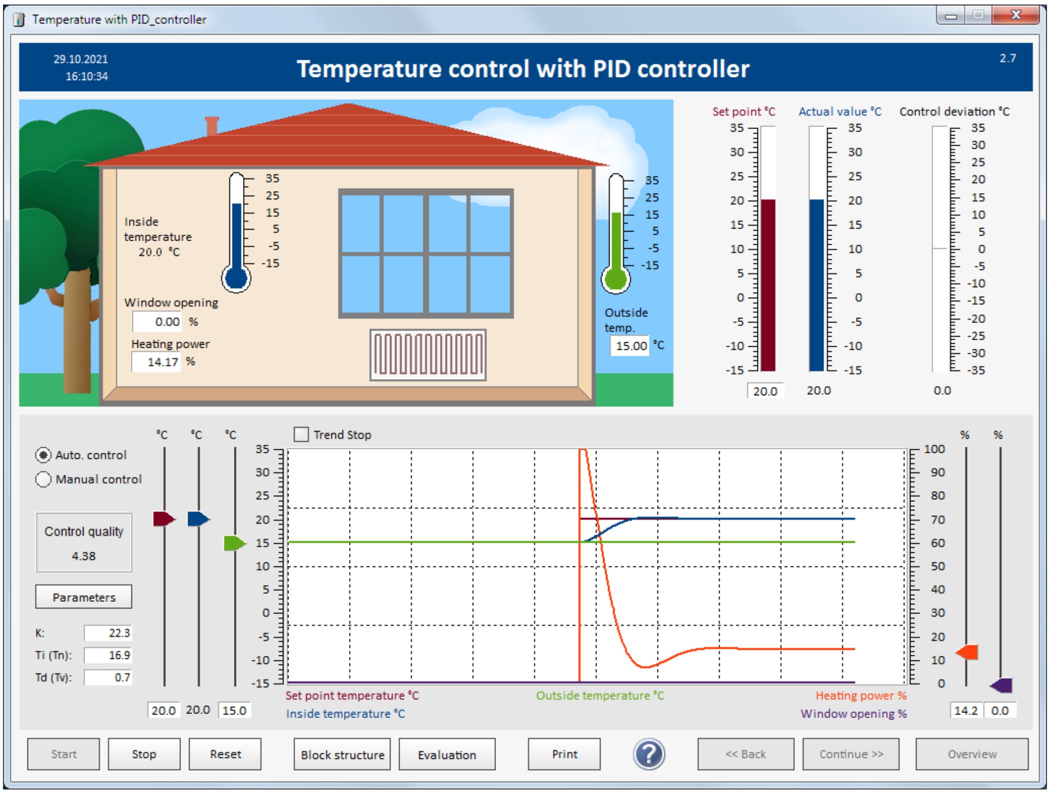


Figure 3-8: Command response aperiodic

With these settings, the control signal (red signal) exceeds the range limits of 0% and 100%. The control signal is limited to 0% or 100%. Of course, this causes a change in the originally expected settling response.

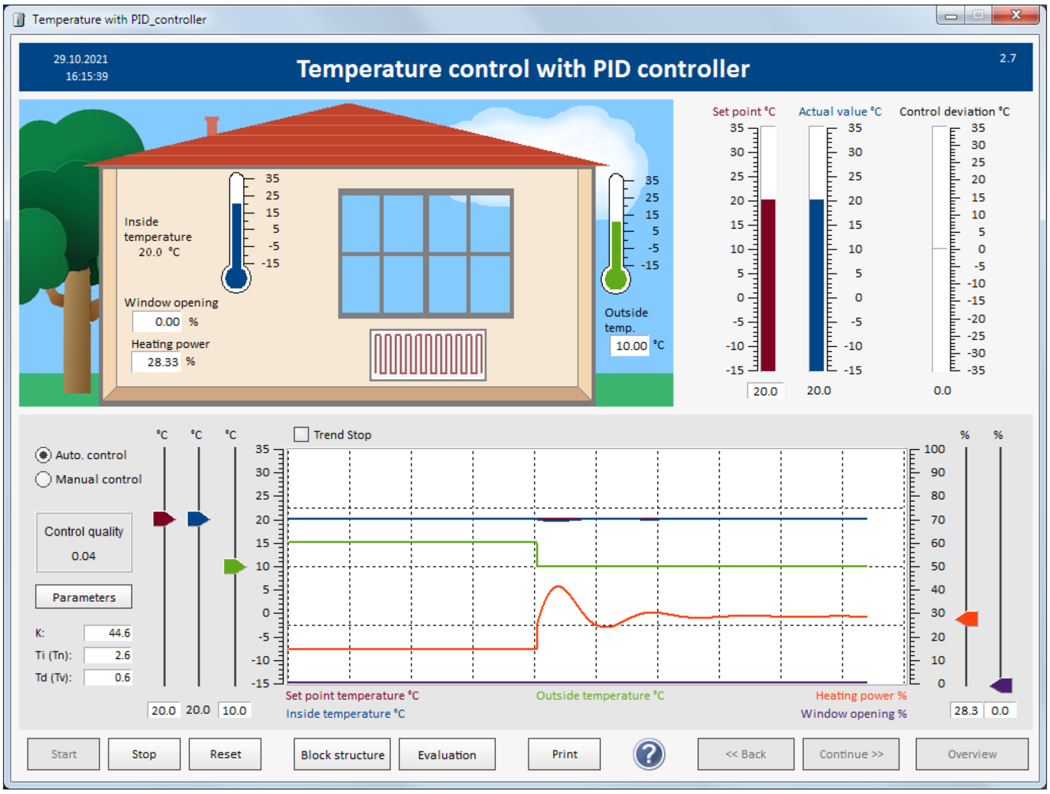


Figure 3-9: Disturbance response 20% overshoot

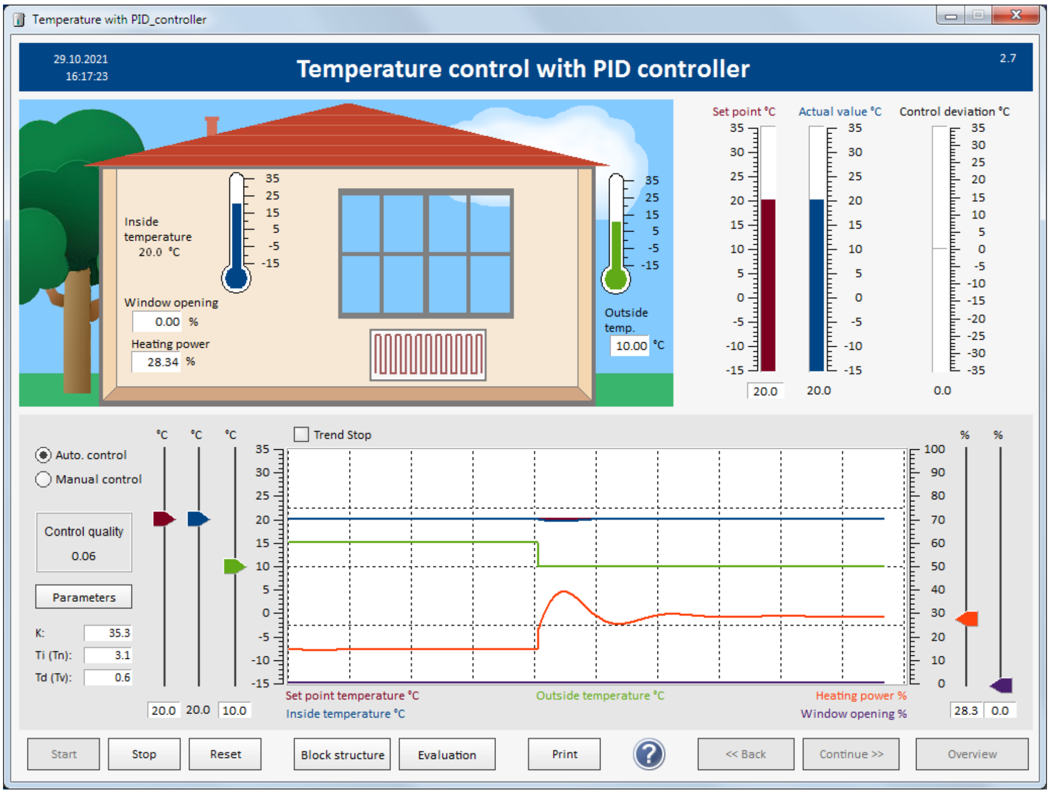


Figure 3-10: Disturbance response aperiodic

3.5 Assessment of the Controller Tuning Rules

Controller tuning rules are empirically determined methods that are often suitable for calculating good controller parameters by rule of thumb.

The settings for calculating controller parameters distinguish between disturbance and command response. Different controller parameters are calculated.

If you need controller parameters for both cases (disturbance and control behavior), you have to make a compromise between the calculated parameters of the disturbance behavior and the control behavior.

The above examples show that a reasonable control loop behavior can be obtained with the calculated controller parameters. However, the behavior does not exactly correspond to the behavior as selected in the table.

The fact that the system has not settled exactly aperiodic or with 20% overshoot is also due to the fact that the control signal has partially reached it´s limit and the time constants could not be determined exactly.

But in the examples and tasks shown, the controller parameters proposed by Chien/Hrones/Reswick were well suited for sensible control.

4 Liquid Level Control (Control Training I)

In this controlled system you can fill water into a container via inflow valve. The system is designed in such a way that the outflow is exactly 30 l/s. The system thus corresponds to the behavior of an integrator.

With real level control systems, the outflow with a fixed valve position is still dependent on the pressure of the water column in the container, i.e. on the level. Here, a constant outflow is assumed by a flow control.

The level control system of the Control Training I is a system without self-regulation.

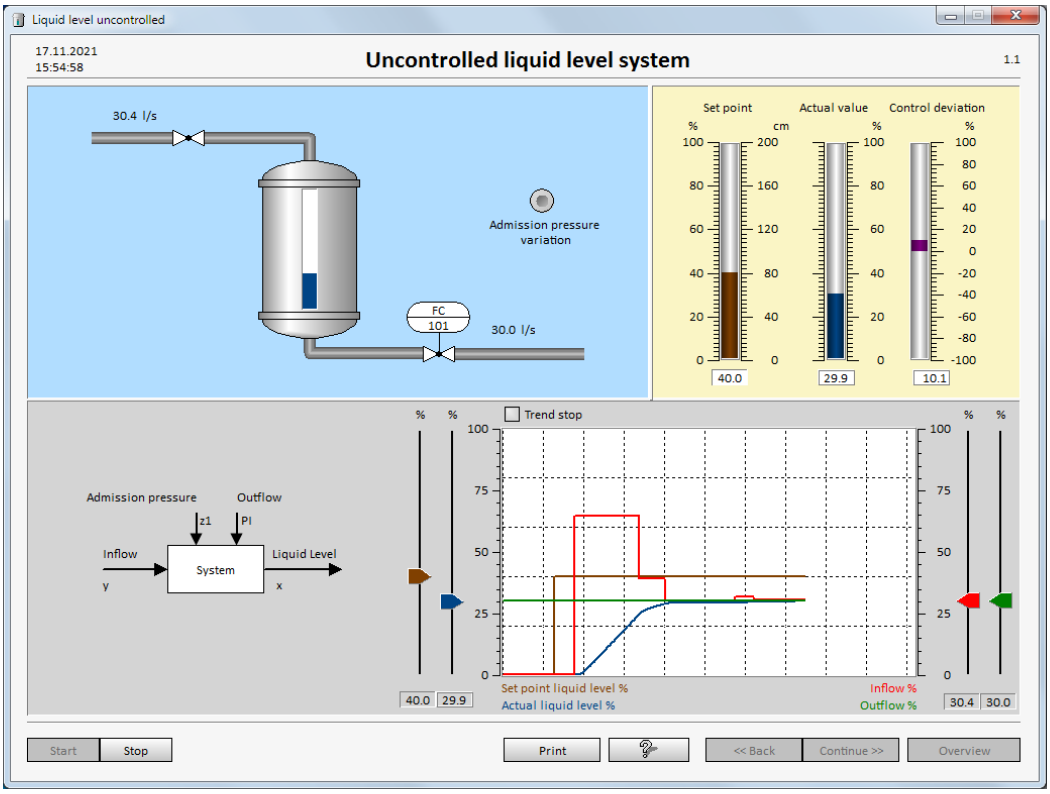
4.1 Uncontrolled System (Manual Control)

Go to overview and select item 1.1 "Uncontrolled system".

Click “Start”. You can now change the values for the set point value (Set point liquid level %), the control signal (inflow %) and the disturbance signal (outflow %) using the slider or by entering values below the slider.

Task 1.

Set the set point (reference variable) to 40% and try to adjust the actual value (controlled variable, actual liquid level) to the set point (Set point liquid level) by adjusting the control signal (inflow).



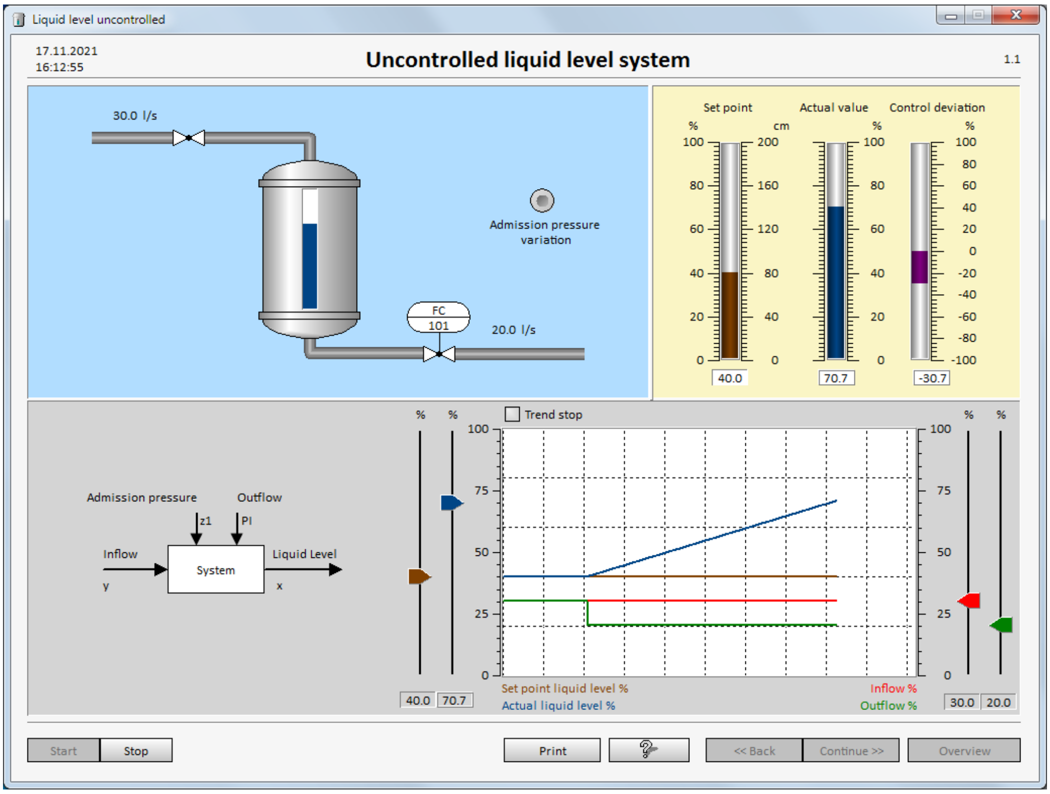
Only when the inflow has the same value as the outflow (30l/s) the level remains constant. You must therefore try to set the inflow to 30l/s (30%) when the actual value has reached the set point.

We speak of the command response, if the set point is adjusted and an attempt is made to adjust the actual value (controlled variable) to the new set point (reference variable),.

Task 2.

Change outflow to 20%.

What will happen?

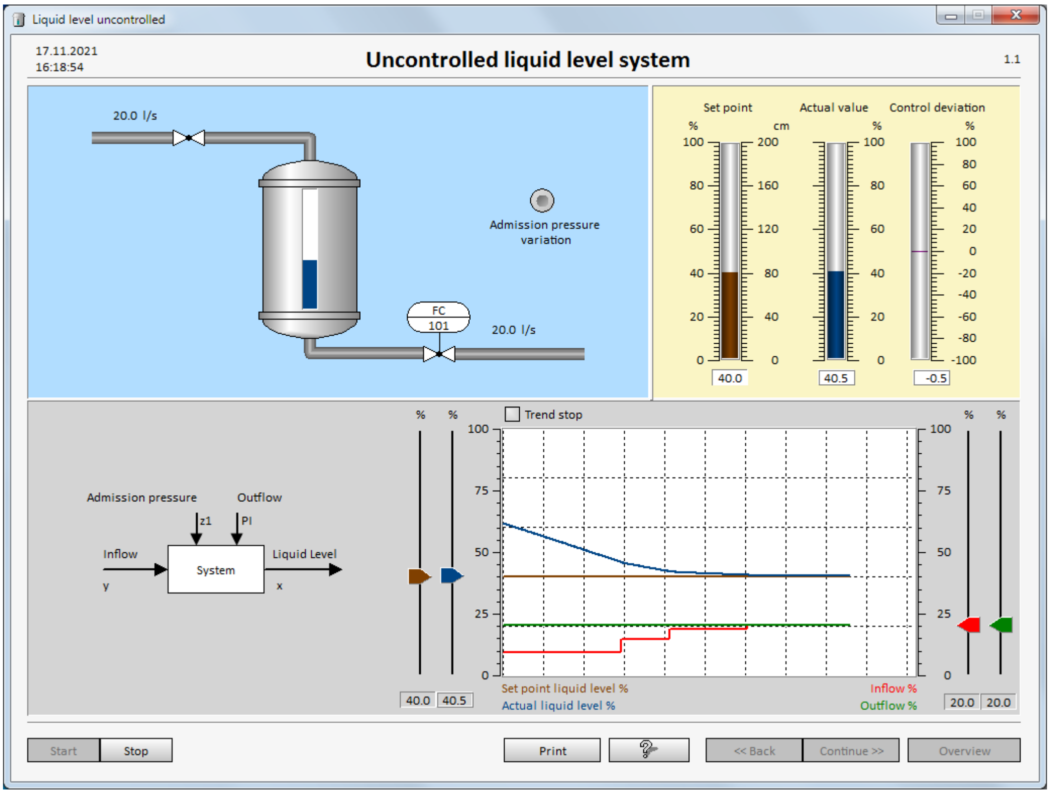


The level increases continuously, as 10l/s (10%). Inflow is greater than outflow.

(Inflow = 30l/s, outflow = 20l/s)

Task 3.

Try to adjust the level to the set point of 40% by shifting the inflow.



In this case, an attempt is made to react to a disturbance (change of outflow). Here, too, the inflow must have the exact same value as the outflow so that the level remains constant.

Since the control loop reacts to a change in the disturbance value, we speak of disturbance response in this case.

4.2 Closed-loop Controlled System

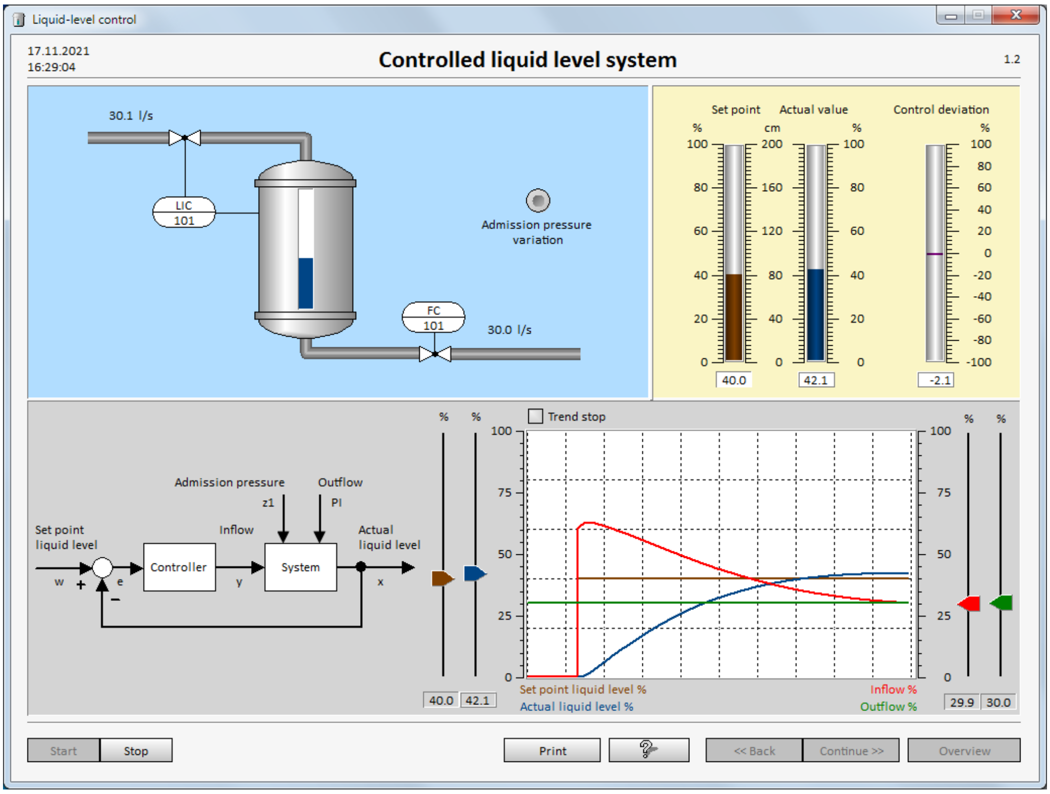
4.2.1 Closed-loop Controlled System

Return to „Overview“ and select item 2.2 „Control System“.

Here you can see how the system behaves in principle if, instead of manual control by the user, a controller takes over the task of adjusting the actual value to the set point.

Task 4.

Click „Start“ and set the set point to 40%.



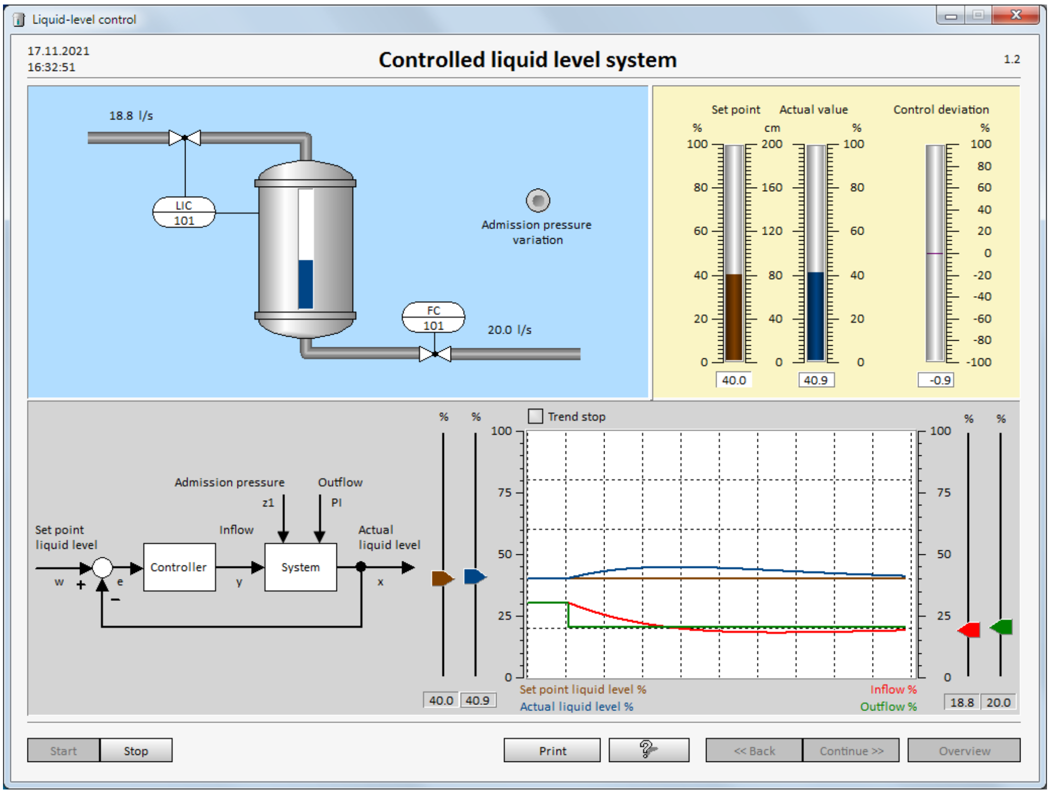
With overshoot, the actual value approaches the set point after a certain time.

Even if you specify a disturbance by changing the outflow, the controller tries to adjust the actual value to the set point.

Task 5.

Change outflow to 20%.

What will happen?



The level increases.

The controller tries to adjust the actual value to the set point by reducing the inflow. When the system has settled (the level no longer changes and the actual value has reached the set point), the inflow must be exactly the same as the outflow (20l/s).

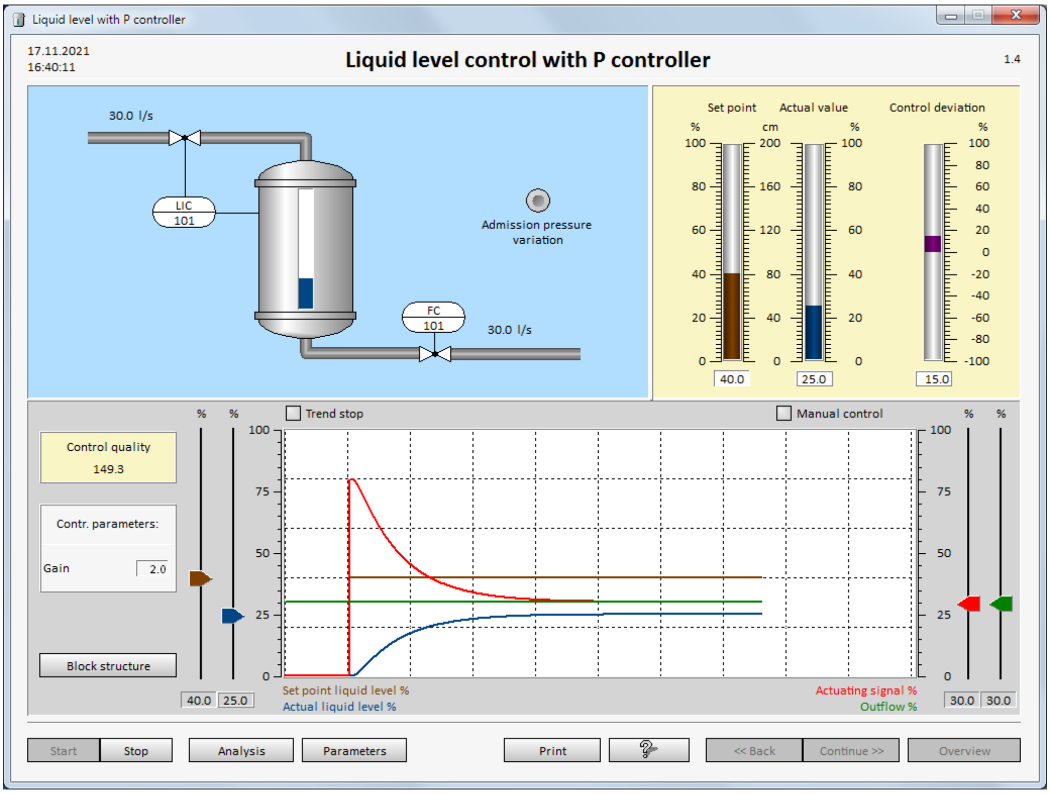
4.2.2 Closed-loop Control with P Controller

Go to „Overview“ and select item 1.4 „Closed-loop control with P controller“.

Click „Start“.

Task 6.

Change the set point to 40% and wait until the control loop system has settled, i. e. the actual value no longer changes.



After the settling phase, the actual value (controlled variable) does not reach the set point (reference variable). We get a steady-state control error.

The control error e is defined as e = w - x, with

w = reference variable (set point) and x = controlled variable (actual value).

Reason:

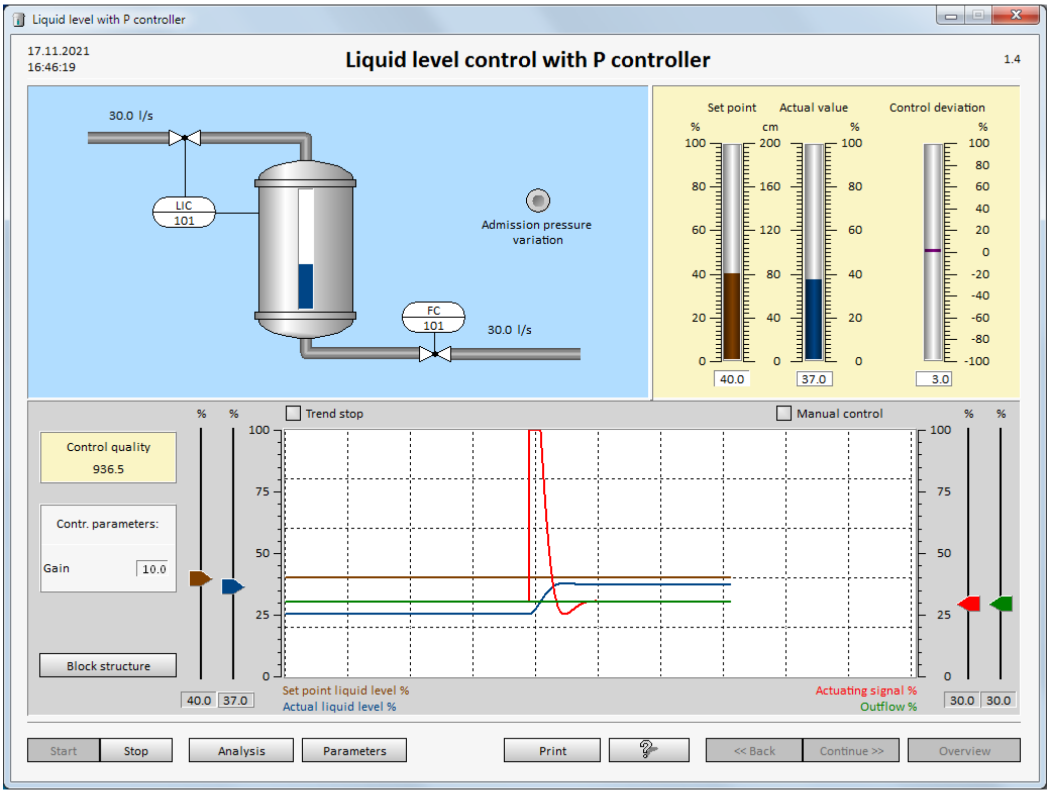
The P controller works like an amplifier. The input signal to the controller w - x (set point - actual value) is amplified with the gain K (in our case 2).

In order for the P-controller to output a control signal (an inflow) that is not equal to zero, the set point and actual value must be different, i.e. steady-state control error.

If the controller outputs 0, the input is 0 and the level drops because the outflow is 30l/s.

Task 7.

Change the gain of the P controller from 2 to 10 and then wait until the control loop system has settled.



The control difference between the set point w and the actual value x becomes significantly smaller as the gain K is increased from 2 to 10. However, the P controller does not manage to adjust the actual value to the set point here either. For the reason described above, we also get an albeit significantly smaller, steady state control error (e = w – x).

In our case the set point w was 40% and an actual value x of 37% was achieved. Therefore the control difference is 3% (w-x).

The actual value of 37 or the control difference of 3 can also be calculated. For the system to be settled (level remains constant), the inflow must be same as outflow, i.e. inflow = outflow = 30%. This results in:

Actuating variable y = 30 = K * (w - x) = 10 * (40 - x), controlled variable x = 40 – y/10 = 40 – 3 = 37.

With the gain 2 (Task 6) the controlled variable will be calculated to:

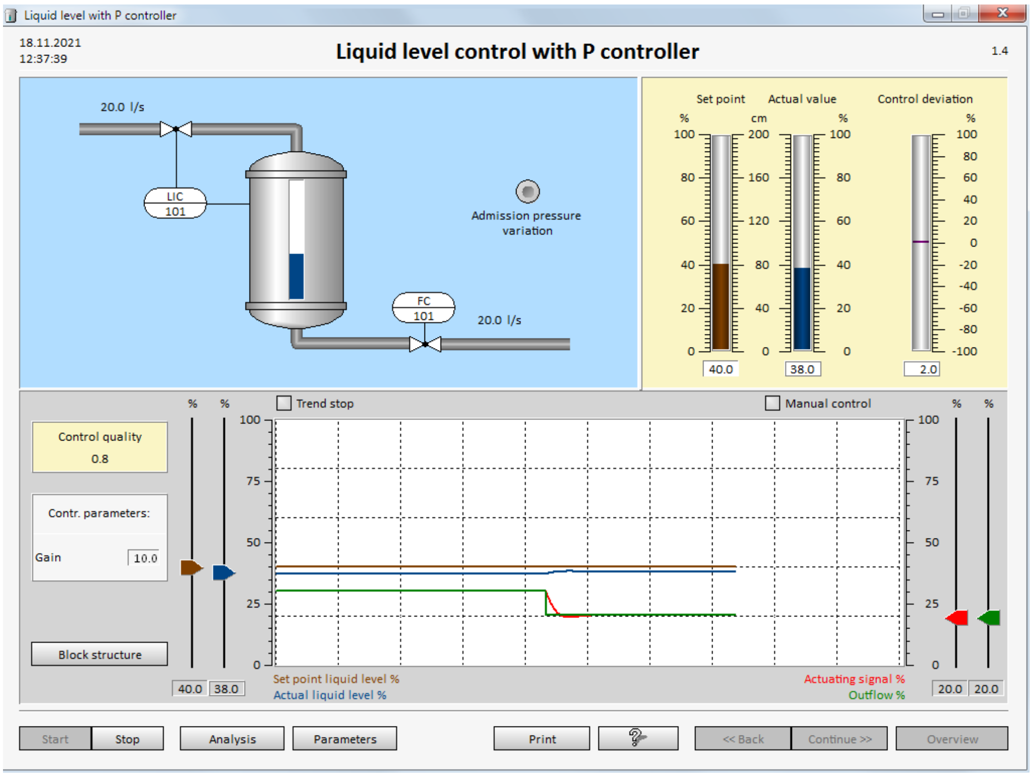
Controlled variable x = 40 – y/2 = 40 – 15 = 25.

The P-controller also reacts to a disturbance (change in the outflow). A permanent control error is also obtained for this.

Task 8.

Change outflow to 20l/s.

What will happen?



The P-controller also reacts to a disturbance (e.g. change of outflow). A steady-state control error is also obtained for this.

The actual value can also be calculated here as stated above:

Controlled variable $x = w - y/K = 40 - 20/10 = 38$

As can be seen from the settling time, the P controller reacts immediately and quickly to changes in the set point and disturbance input. However, we get a steady-state control error for this system with the P controller.

4.2.3 Closed-loop Control with I Controller

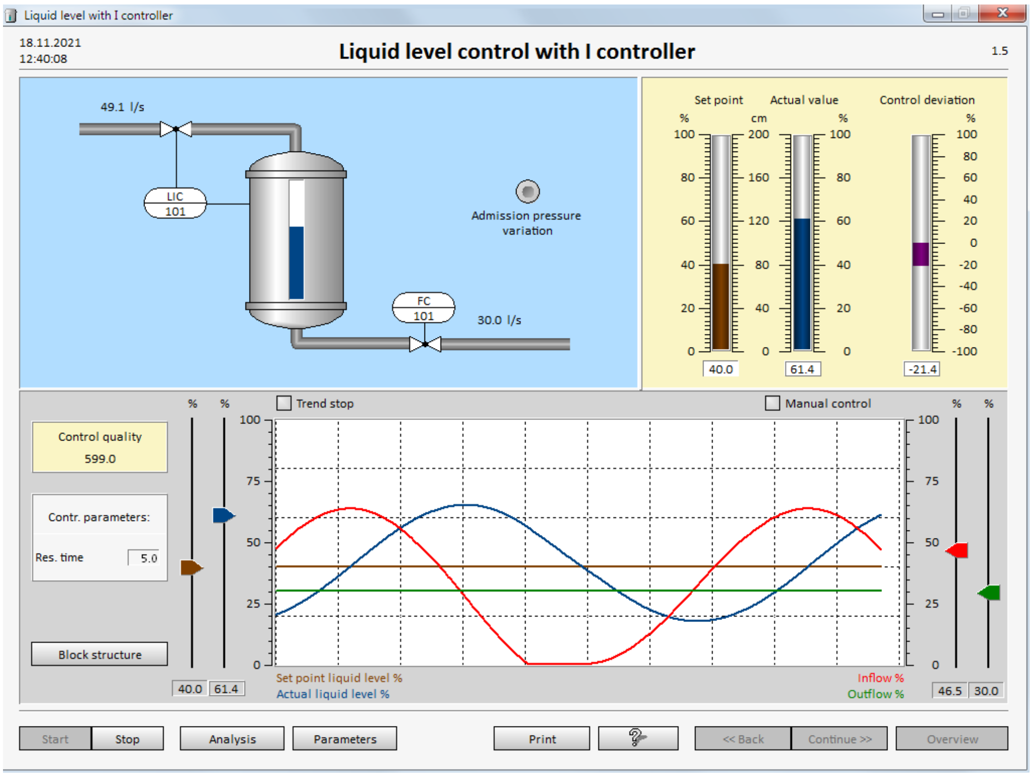
Go to „Overview“ and select item 1.5 „Closed-loop control with I controller“.

Click „Start“.

Task 9.

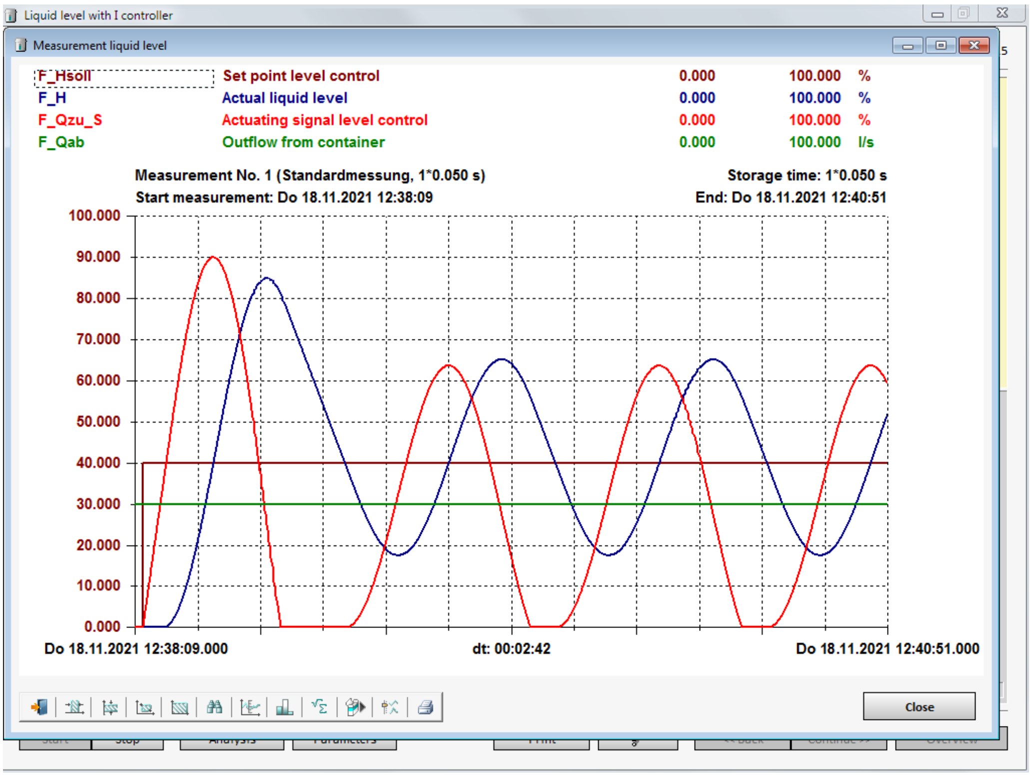
Change set point to 40%.

What will happen?



The control loop carries out a continuous oscillation. The actual value oscillates around the set point.

Even if the integration time changes, the control loop remains unstable, as does a change in the disturbance signal (outflow).



The I controller is not able to control this controlled system.

4.2.4 Closed-loop Control with PI Controller

Go to „Overview“ and select item 1.6 „Closed-loop control with PI controller“.

Click „Start“.

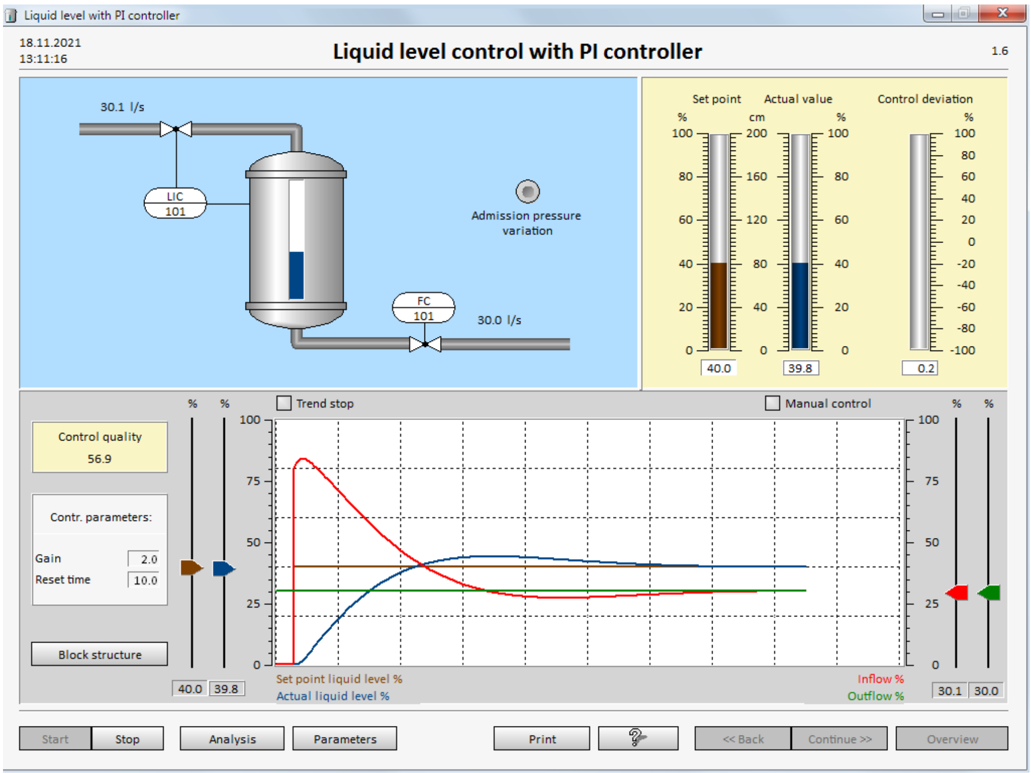
Task 10.

Keep all parameters:

Gain K = 2, Reset time Ti = 10.

Change the set point to 40%.

Observe the settling behavior.



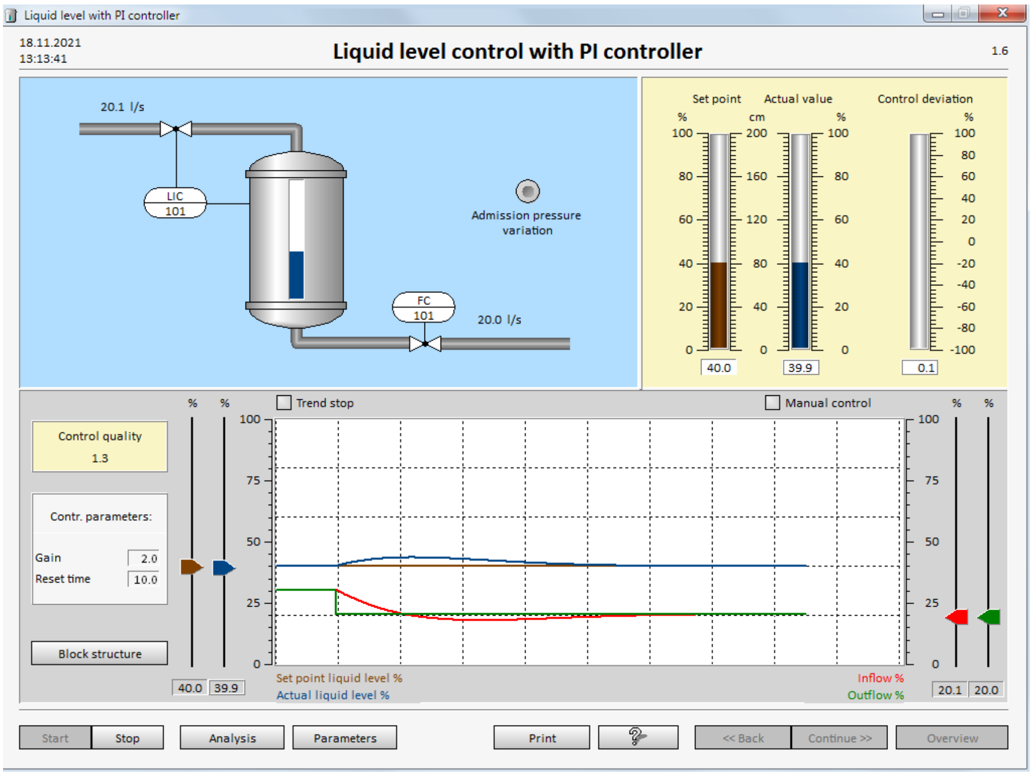
The control loop with the PI controller and the set parameters oscillates to the set point with a small overshoot. The actual value (controlled variable) reaches the set point (reference variable).

The settling of the control loop by changing the set point is referred to as the command response.

Task 11.

Investigate the disturbance response.

When the control loop has settled, change the outflow to 20% and observe the behavior.



The smaller outflow causes the level to rise. The controller tries to counteract this and reduces the inflow. After a settling phase, the actual value reaches the set point again.

Since the control loop reacts to a change in the disturbance value, we speak of disturbance response in this case.

Task 12.

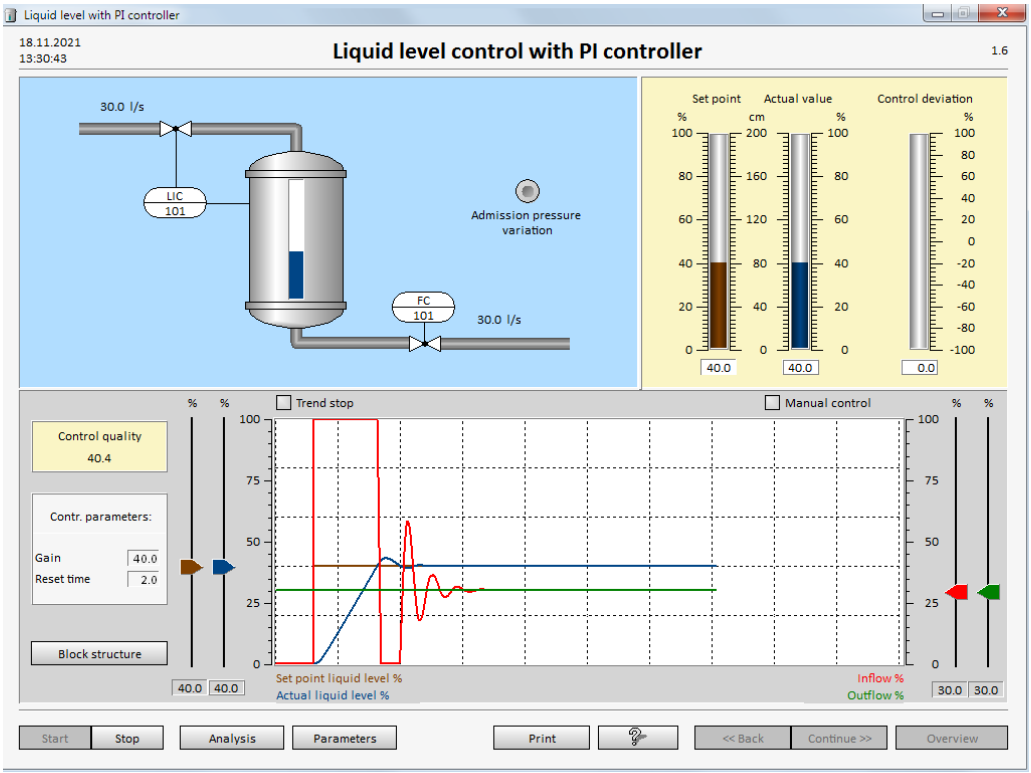
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the set point.

Try to reduce the value for the control quality by adjusting the controller parameters.

With the controller parameters K = 2 und Ti = 10 a control quality of 56,9 was achieved.

For the control quality to be comparable in the tests, all tests must be started with the same initial states. The best way to do this is to click "Stop" and then “Start”. This means that the set point, the level and the outflow are again given the initial values.

Now change the controller parameters and then adjust the set point to 40%. Wait until the control loop has settled.



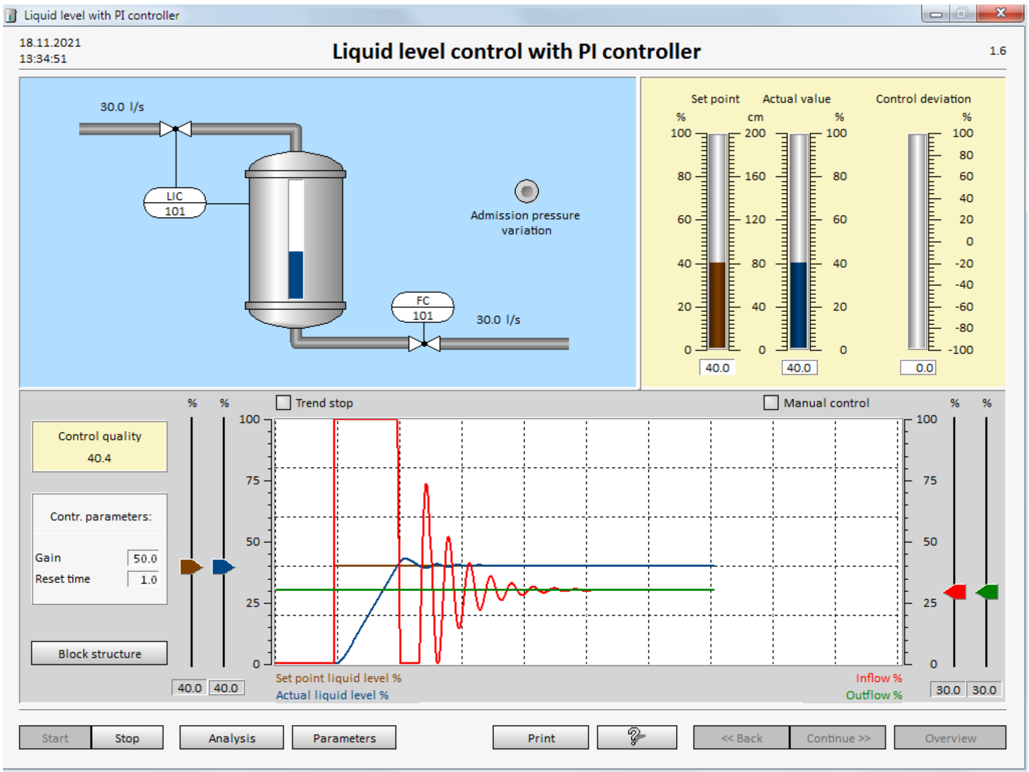
With the parameters K = 40 und Ti = 2 a control quality of 40,4 was obtained.

Carry out the experiments with further controller parameters:

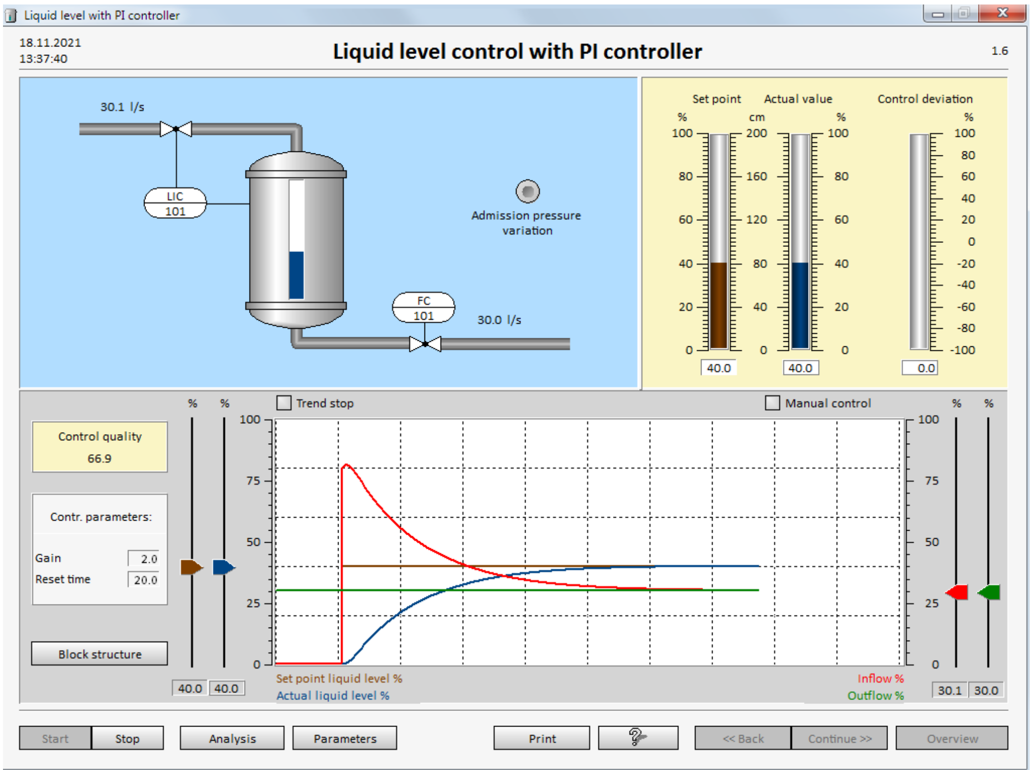
- Click „Stop“ and „Start“ again,
- Set controller parameters,
- Set the set point to 40%,
- Wait until the control loop has settled.

It is not possible to make the control loop oscillate by adjusting the parameters.

However, the control loop becomes very restless with the parameters K=50 and Ti=1.



In order to achieve an aperiodic response (without overshoot), you must select a small gain and a large reset time.



With the parameters K = 2 and Ti = 20 you get an aperiodic response.

4.2.5 Closed-loop Control with PID Controller

Go to „Overview“ and select item 1.7 „Closed-loop control with PID-controller“.

Click „Start“.

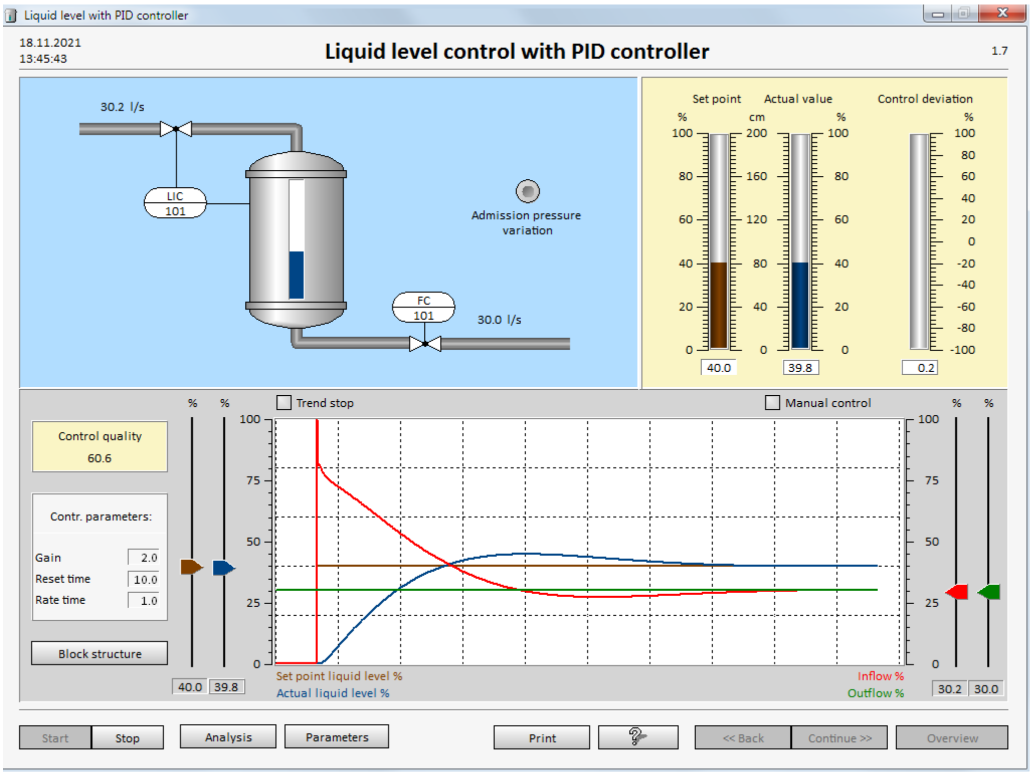
Task 13.

Examine the command response with the preset parameters.

Gain K = 2, Reset time Ti = 10, Derivative time Td = 1

Change set point to 40%.

Observe the behavior.



The control loop goes into a stable state with a small overshoot. The actual value reaches the set point.

As can be seen in the trend diagram, the sudden change in the set point causes a peak in the control signal (heating power). This peak is triggered by the D component of the controller. The derivation of a sudden change causes an (infinitely) large value.

The control quality goes to 60,6 and is therefore worse than with the PI controller with the parameters K = 2 and Ti = 10.

Note on the trend display with the PID controller:

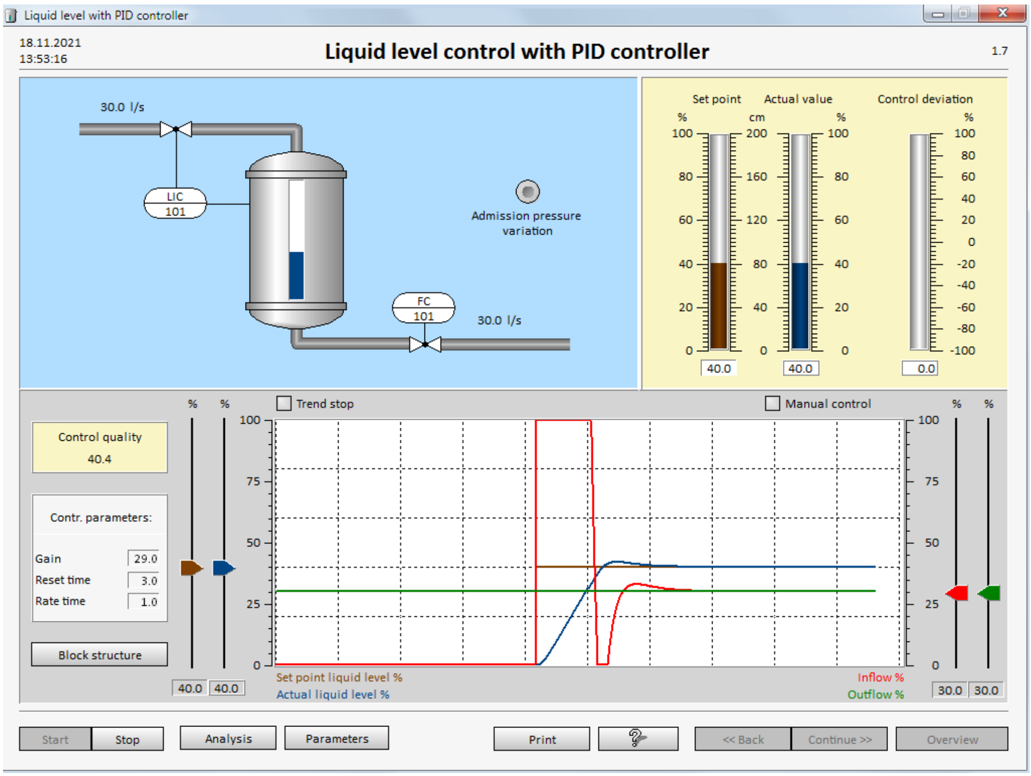
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Analysis" (display of the stored signal values) and selection of a corresponding time range.

Task 14.

Try to improve the control quality by adjusting the controller parameters.

So that you can compare the experiments, you always have to start from the same initial states:

- Click “Stop” and “Start” again
- Change the controller parameters
- Adjust the set point to 40%
- Wait until the control loop system has settled.



With the controller parameters K = 29, Ti = 3 and Td = 1 you get a control quality of 40.4 for example.

4.2.6 Closed-loop Control with Two-position-Controller

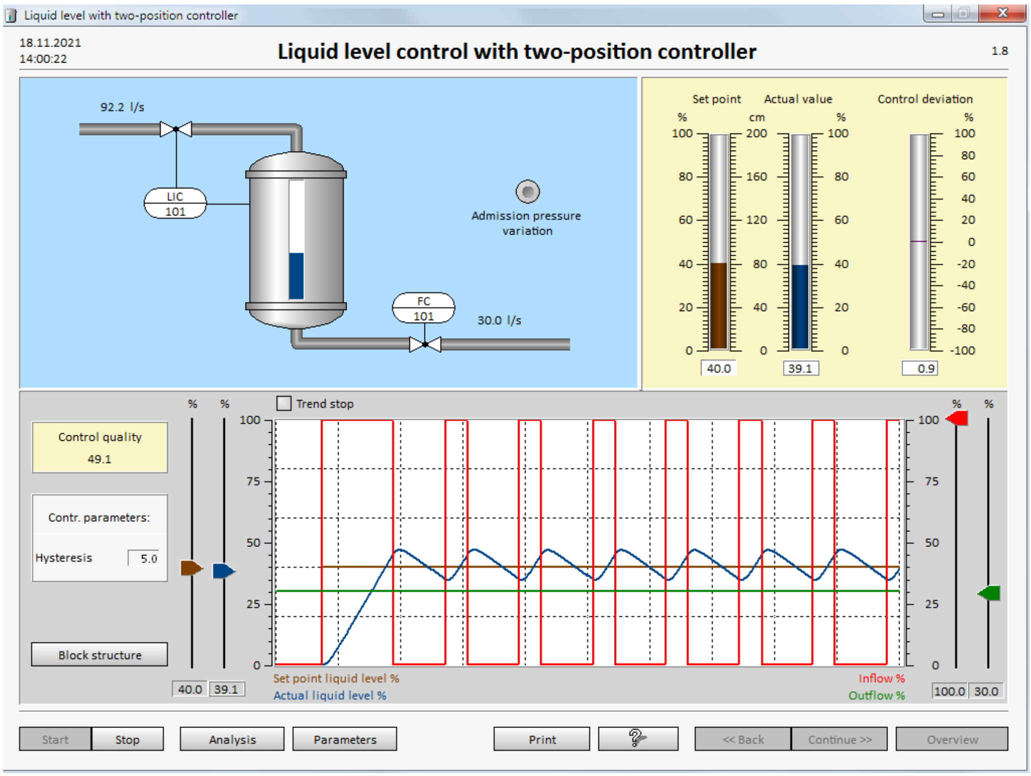
Go to „Overview“ and select item 1.8 „Closed-loop control with two-pos. controller“.

Click „Start“.

Task 15.

Investigate the command response with the preset parameter:

Hysteresis = 5



The level (actual value) oscillates around the set point. The amplitude of the oscillation depends on the parameter (hysteresis).

As can be seen, the level rises faster (valve to 100%) than it falls (valve to 0%). This is due to the fact that with the valve position 100% the inflow rate assumes the value 100l/s - 30l/s = 70l/s, while the outflow volume (valve at 0%) is only 30l/s.

Info:

In practice, the PI controller is most common. If a PID controller is used, the D component is often turned off so that the controller only works as a PI controller.

One of the reasons for this is that the D behavior in a control loop is difficult to assess. In principle, the D component gives you the option of making the control faster (which is often very difficult, however).

The D component considers the change between the set point and the actual value. If the change increases, i.e. the difference between the set point and actual value increases, the D component adds a calculated value to the control signal. If the difference between the set point and the actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend, whether the difference between the set point and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the set point and actual value decreases, the control signal is reduced.

4.3 Examine Controlled System

Select item 1.3 „Examine controlled system".

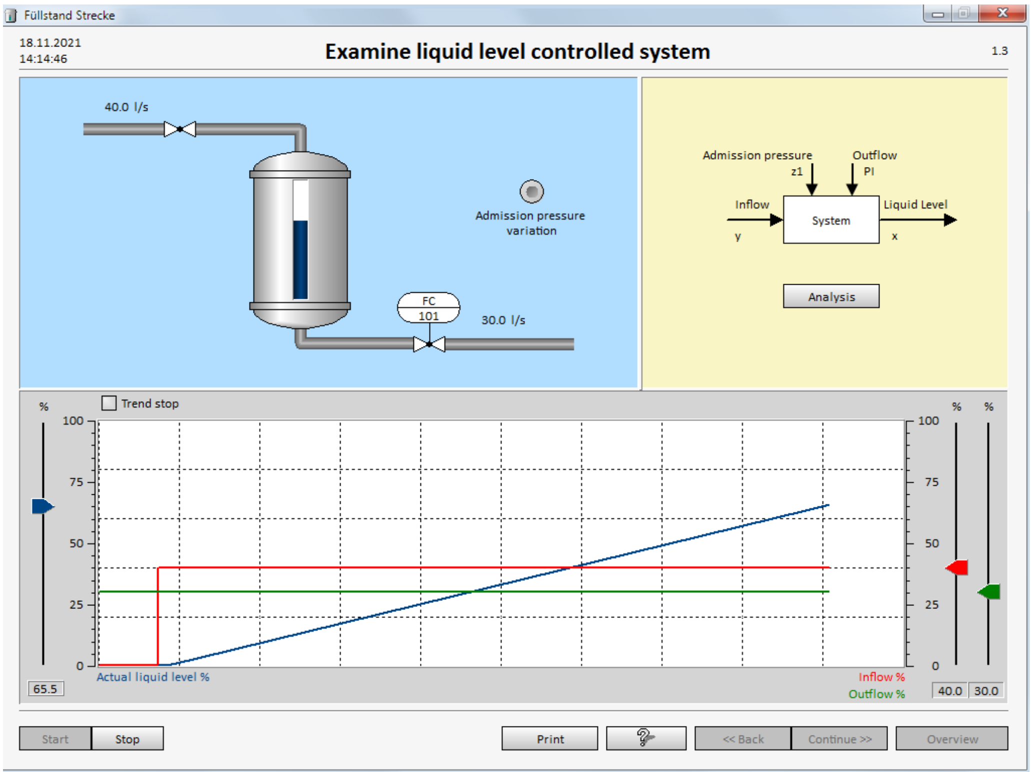
The level system is a controlled system without self-regulation. In the event of a sudden change in the control signal (inflow> outflow), the controlled variable (actual level) begins to increase. The output variable of the system (controlled variable) does not assume a permanent final state.

Task 1:

Click „Start" and set inflow to 40%.

The inflow must be set greater than 30% so that the level rises because the outflow is set to 30%.

Observe the level behavior.



Because the inflow is greater than the outflow, the level begins to rise until the container overflows.

4.4 Controller Tuning Rules

In order to use controller tuning rules, e.g. according to Chien/Hrones/Reswick, the controlled system must be examined.

A step in the control signal (sudden change in the control signal by 1)is applied to the controlled system. The behavior of the output signal of the system (controlled variable) can then be measured.

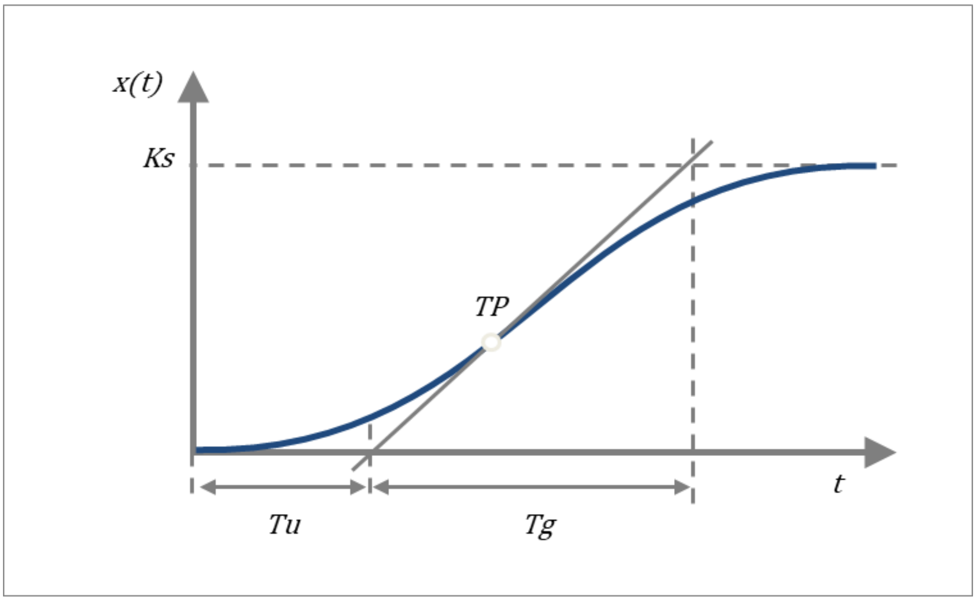
The parameters Tu, Tg and Ks are determined for the controller tuning rules for the controlled systems with self-regulation, as shown in the figure below.

It means:

Te = Tu = Delay time

Tb = Tg = Compensation time

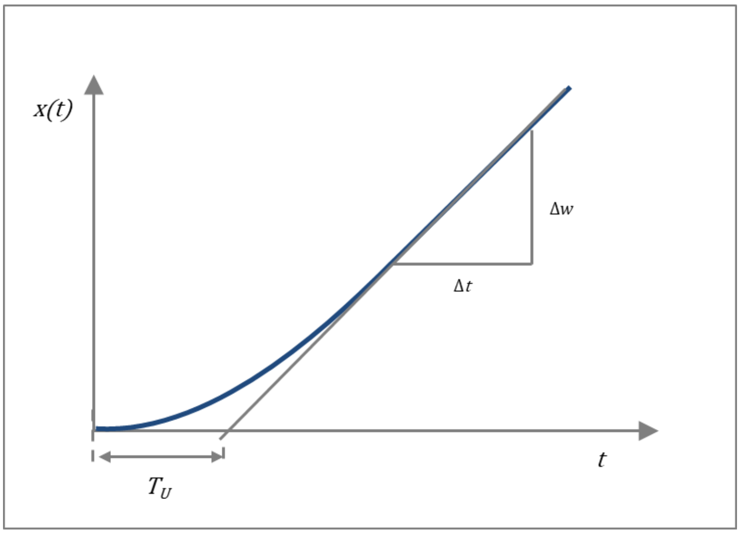
Ks = Gain



In the new standard, the delay time is designated with Te, the compensation time with Tb and the turning point with P.

Since the terms Tu and Tg are still used in most of the literature, we keep the old terms here, or use both.

For controlled systems without self-regulation, the following behavior will occur in response to a standard step change in the control signal:



Here you can define Kis as the gradient of the tangent ($\frac{\Delta w}{\Delta t}$) and Tu as the intersection of the tangent with the time axis.

Calculate the time constant Ti from Kis using Ti = 1 / Kis.

It means:

Tu	Delay time
Tg = Ti	Compensation time
Ks	Gain
Kis	Gain of controlled system without self-regulation

You can then calculate the controller parameters from the setting table according to Chien / Hrones / Reswick:

Table 2: Equations to calculate controller parameters according to Chien/Hrones/Reswick

Controller	Quality criteria			
	With 20 % Overshoot		Aperiodic case	
	Disturbance	Command	Disturbance	Command
P	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$
PI	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.3 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 4 \cdot T_U$	$K_P \approx \frac{0.35}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.2 \cdot T_g$
PID	$K_P \approx \frac{1.2}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2 \cdot T_U$ $T_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.35 \cdot T_U$ $T_V \approx 0.47 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.4 \cdot T_U$ $T\_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$ $T_V \approx 0.5 \cdot T_U$

For systems **without self-regulation** use $\frac{T_g}{(K_S \cdot T_U\ )}$ instead of $\frac{1}{(K_{IS} \cdot T_U\ )}$.

The table was taken from: E. Samal, Grundriss der praktischen Regelungstechnik, Oldenbourg

Please note that according to the new standard, the following terms are used: Tu = Te, Tg = Tb

The Liquid level system is a controlled system without self-regulation.

Since the change would be too small to determine the parameters with a unit step of 1%, a step of 10% is used here.

In the case of the liquid level system, the step is set to 40% because the outflow is set to 30%.

When determining Kis, the step height of 10% must be taken into account by dividing the change in level by 10.

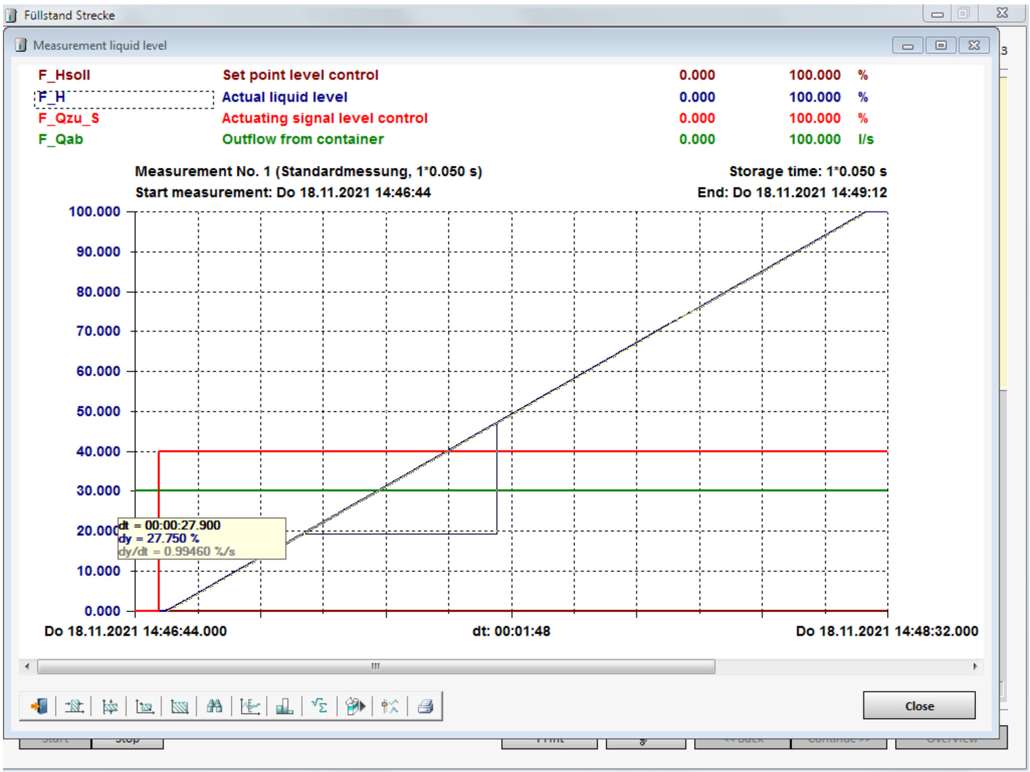
Select item 1.3 „Examine controlled system“.

Task 16.

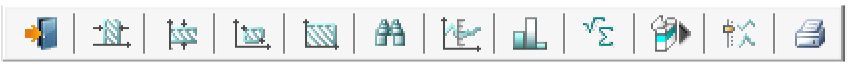
Click „Start“ and set inflow to 40%.

The inflow must be selected greater than 30% because the outflow is set to 30%.

Click "Analysis" and try to measure the recorded system behavior.



With the help of the button bar in the window, select time and value ranges.



To measure the system behavior, you can click on the blue signal (actual level) in the header and try to determine the gradient of the level curve by drag and drop.

The gradient of the straight line is approximately 1%/s. Since the step difference was 10% (40% - 30%), Kis as the gradient of the tangent on a unit step must be divided by 10, so:

Kis = 1/10 = 0,1/s

Ti calculates to: Ti = 1/Kis = 10s

The delay time Tu (Te) can be roughly determined from the diagram Tu = 2s.

Inserting the values in the table results in the following parameters:

PI controller

Command response with 20% overshoot

K = 0,6*1 / (Kis*Te)	3,00
Tn = Tb = Ti	10,00

Command response aperiodic

K = 0,35 / (Kis*Te)	1,75
Tn = 1,2 * Ti	12,00

Disturbance response with 20% overshoot

K = 0,7 / (Ks*Te)	3,50
Tn = 2,3 * Te	4,60

Disturbance response aperiodic

K = 0,6 / (Ks*Te)	3,00
Tn = 4 * Te	8,00

Since with a step in the set point from 0% to 40% the control signal reaches the upper limit and thus falsifies the transient oscillation, only a step from 0% to 20% is specified.

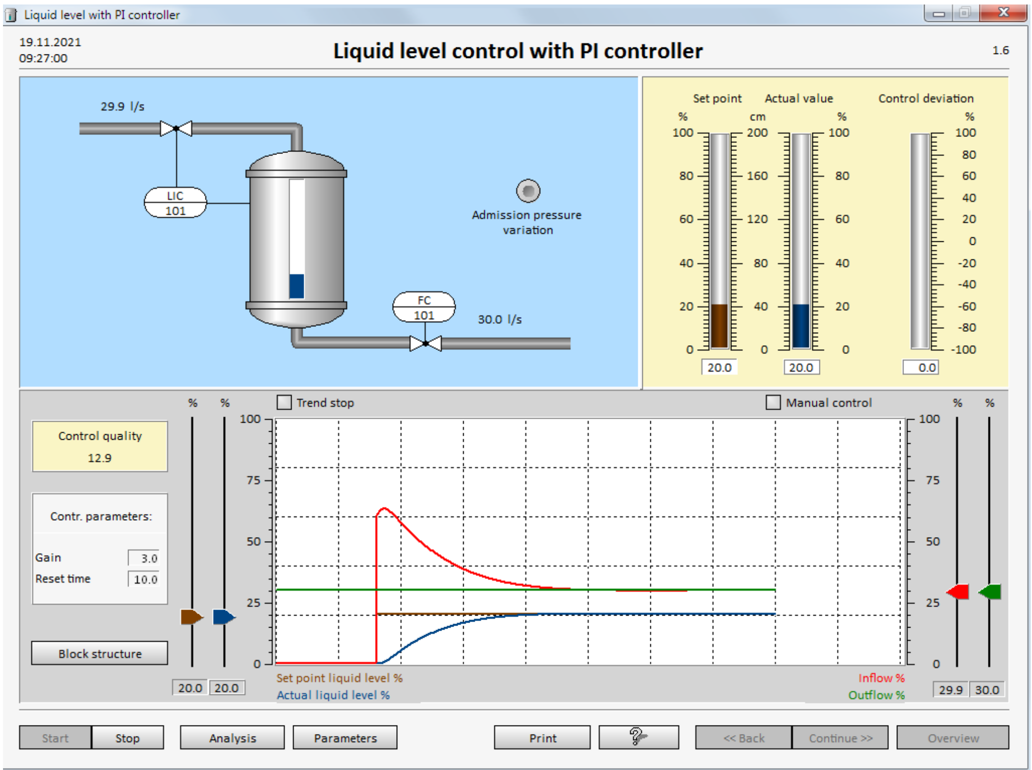


Figure 11: Command response 20% overshoot

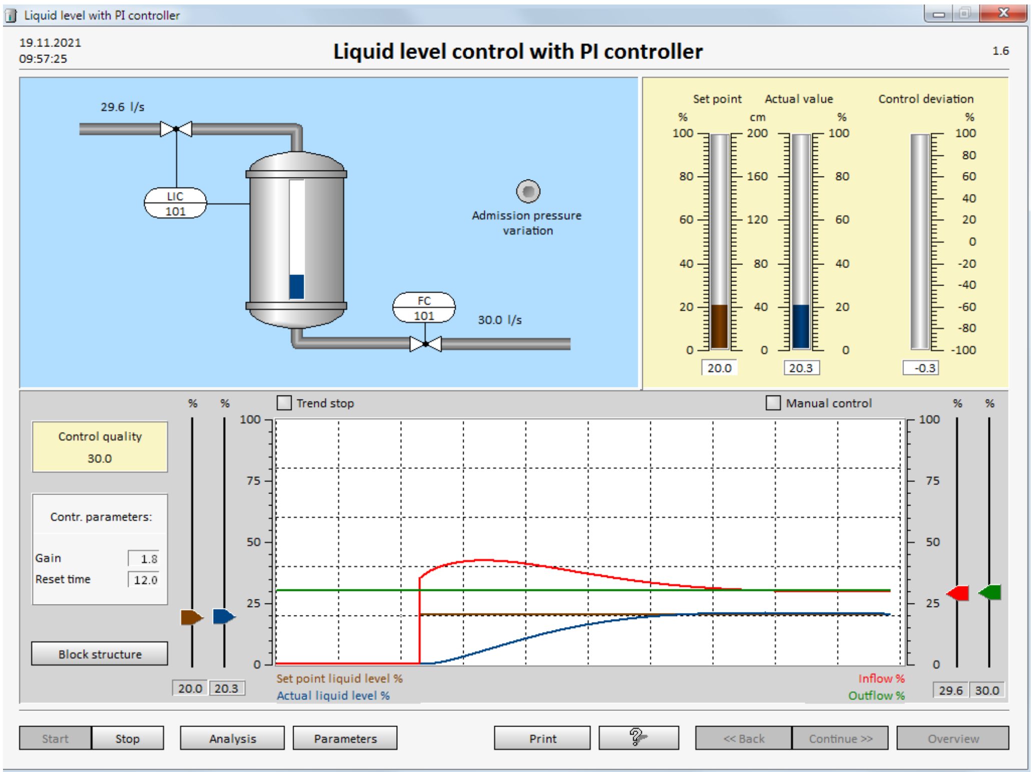


Figure 12: Command response aperiodic

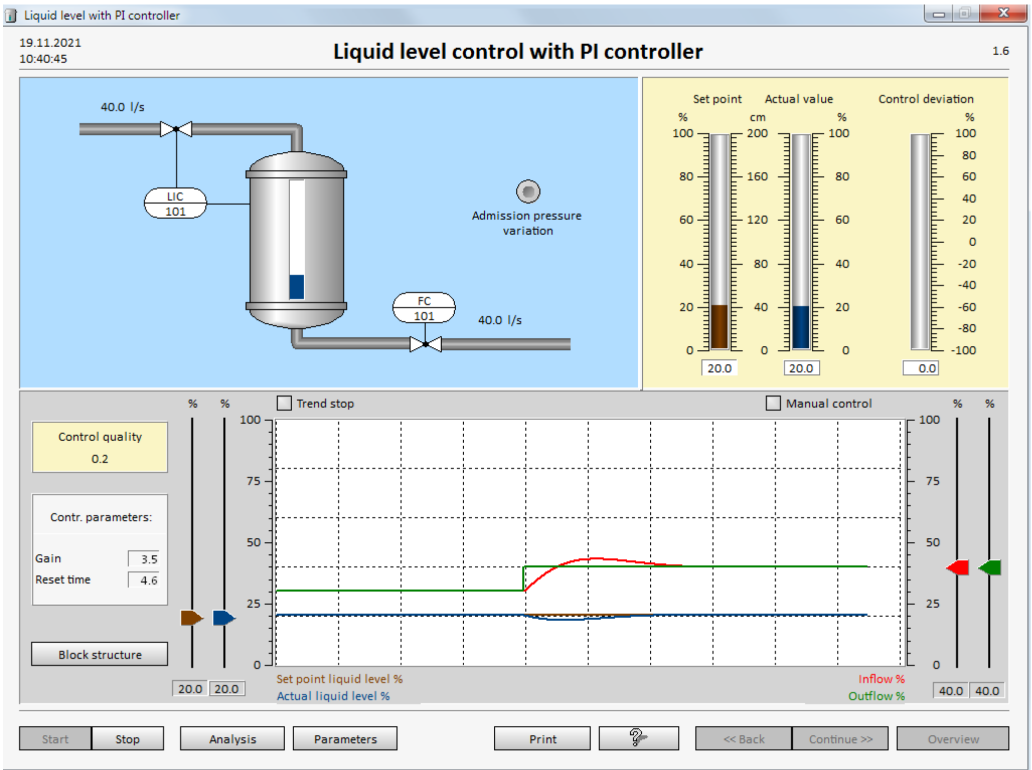


Figure 13: Disturbance response with 20% overshoot

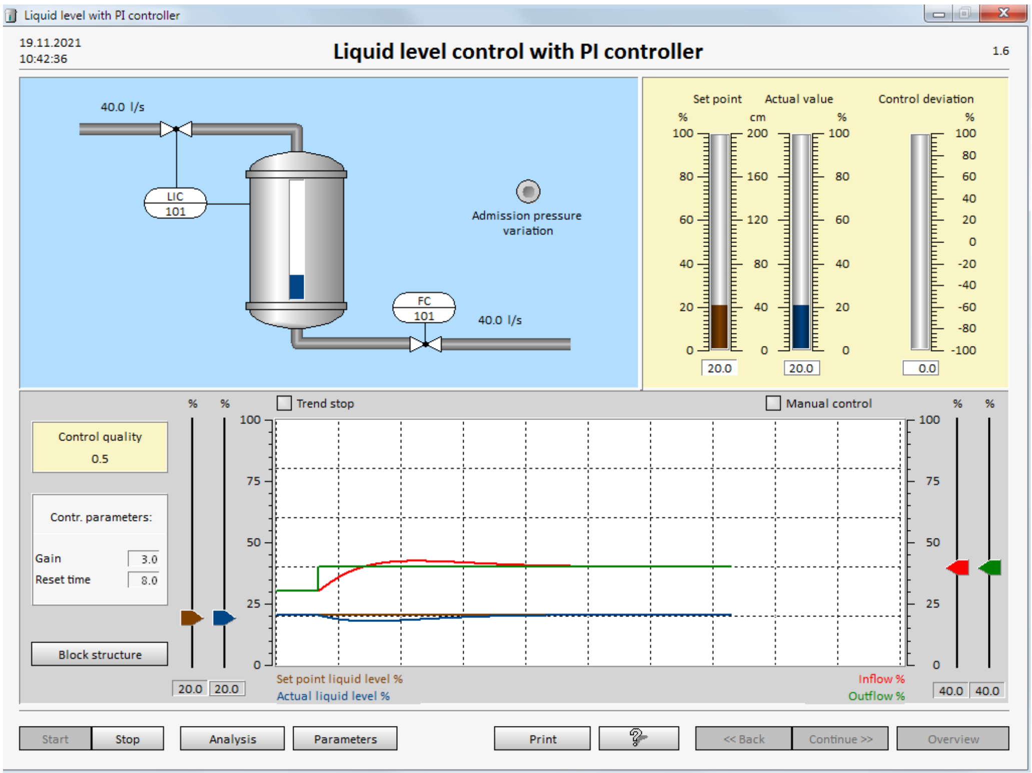


Figure 14: Disturbance response aperiodic

According to the table, the following parameters result for the PID controller:

PID controller

Command response with 20% overshoot

K = 0,95 / (Kis*Te)	4,75
Tn = 1,35 * Tb	13,50
Td = 0,47 * Te	0,94

Command response aperiodic

K = 0,6 / (Kis*Te)	3,00
Tn = Tb	10,00
Td = 0,5 * Te	1,00

Disturbance response with 20% overshoot

K = 1,2 / (Kis*Te)	6,00
Tn = 2 * Te	4,00
Td = 0,42 * Te	0,84

Disturbance response aperiodic

K = 0,95 / (Ks*Te)	4,75
Tn = 2,4 * Te	4,80
Td = 0,42 * Te	0,84

Command response from 0% to 20%:

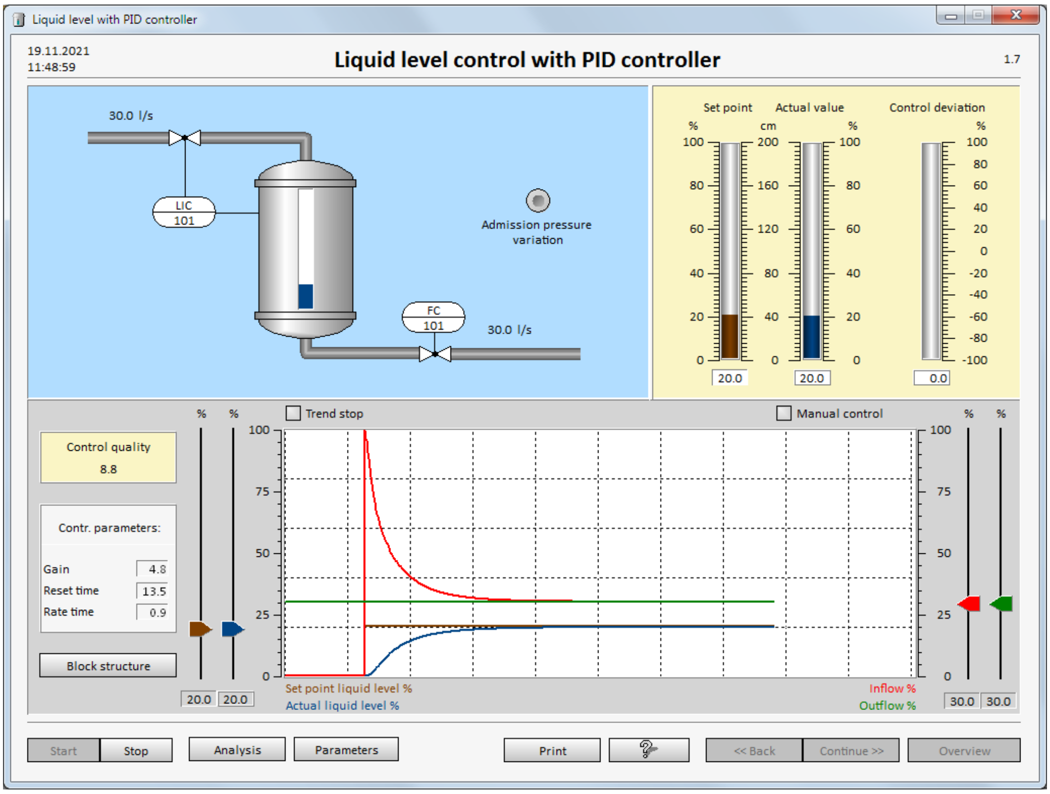


Figure 15: Command response with 20% overshoot

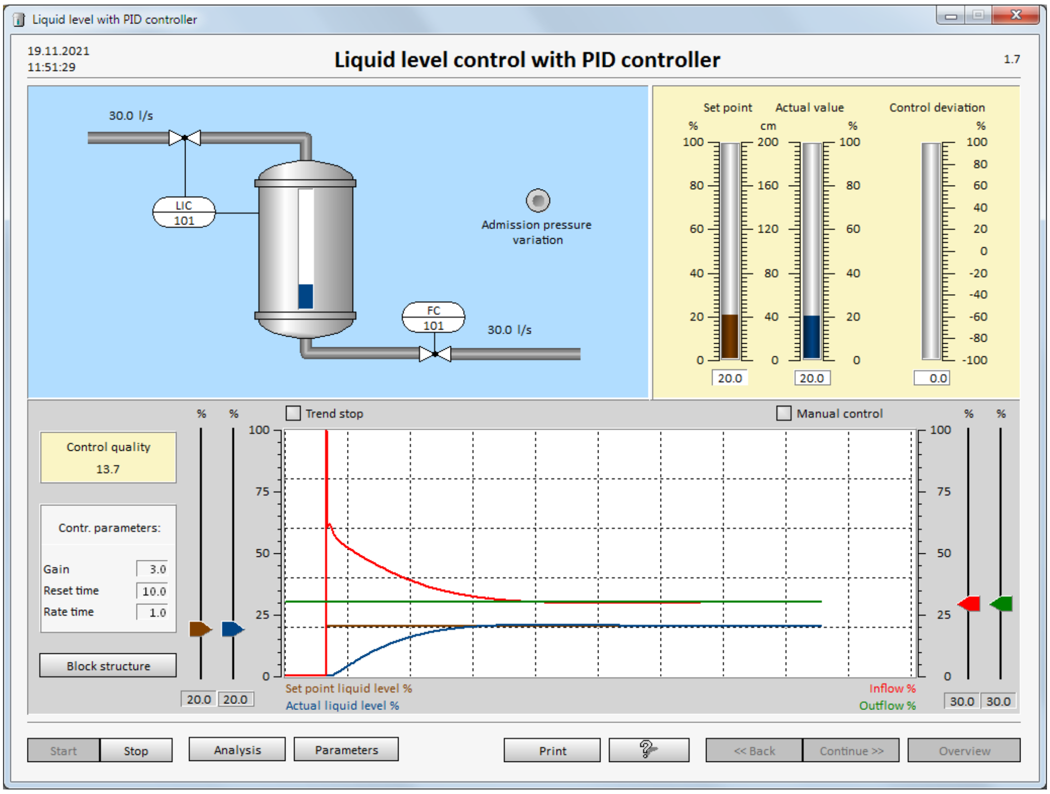


Figure 16: Command response aperiodic

Disturbance response from 30% to 40%:

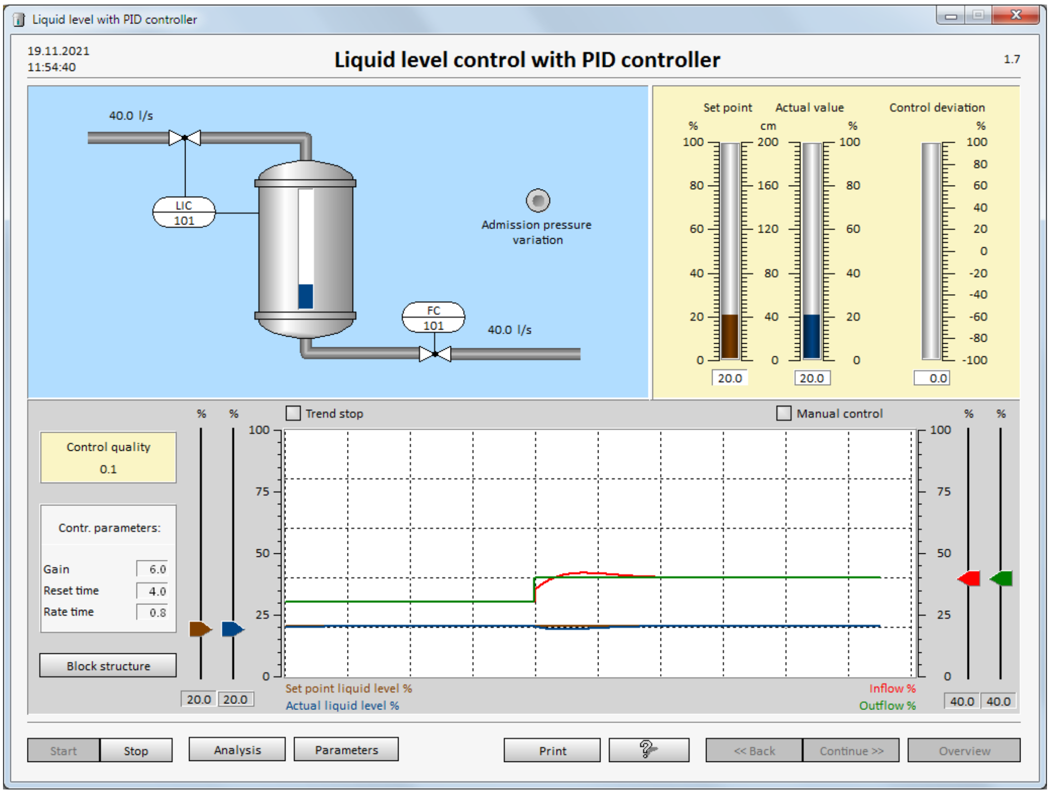


Figure 17: Disturbance response with 20% response

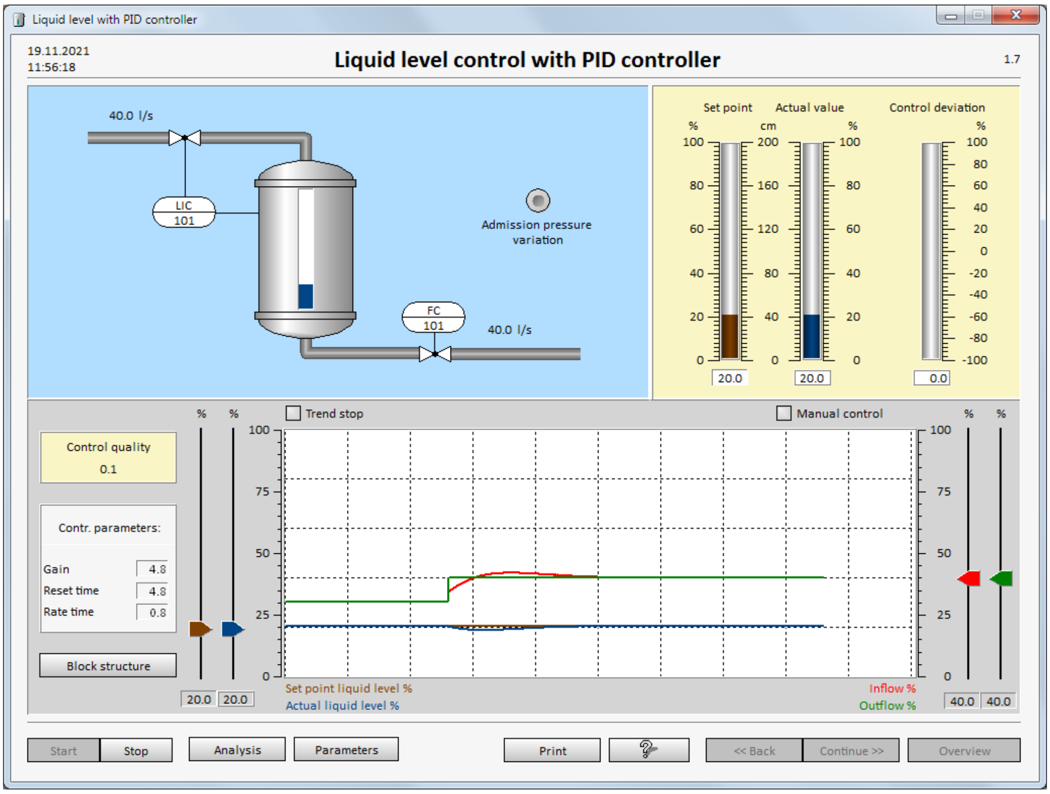


Figure 18: Disturbance response aperiodic

4.5 Assessment of the Controller Tuning Rules

Controller tuning rules are empirically determined methods that are often suitable for calculating good controller parameters by rule of thumb.

The settings for calculating controller parameters distinguish between disturbance and command response. Different controller parameters are calculated.

If you need controller parameters for both cases (disturbance and control behavior), you have to make a compromise between the calculated parameters of the disturbance behavior and the control behavior.

The above examples show that a reasonable control loop behavior can be obtained with the calculated controller parameters. However, the behavior does not exactly correspond to the behavior as selected in the table.

The fact that the system has not settled exactly aperiodically or with 20% overshoot is also due to the fact that the control signal has partially reached its limit and the time constants could not be determined exactly.

But in the examples and tasks shown, the controller parameters proposed by Chien/Hrones/Reswick were well suited for sensible control.

5 Flow Rate Control (Control Training II)

The process involves a water flow in a pipe with a valve. The pressure in the pipe is adjusted and measured. The technical control task is to control the flow through the pipeline by changing the valve position so that the actual flow corresponds to the specified set point. The pipe line pressure is the disturbance variable, the valve position the input variable (control signal) and the flow rate the output variable (controlled variable) of the system. The flow is determined via a differential pressure measurement.

The flow control system is a controlled system with self-regulation, since after a sudden change in the valve position a constant flow is established again after a period of time.

5.1 Uncontrolled System (Manual Control)

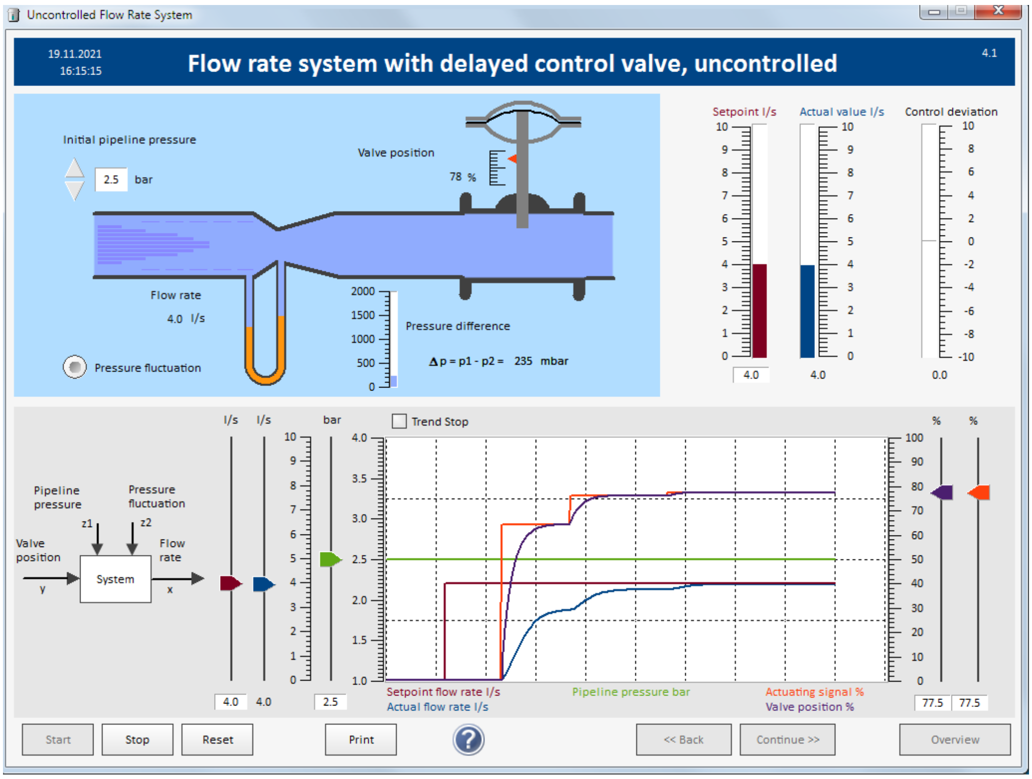
Go to „Overview“ and select item 4.1 „Uncontrolled system“.

Click „Start“.

You can now change the values for the set point (Set point flow rate [l/s]), the control signal (Actuating signal [%]) and the disturbance signal (Pipe line pressure [bar]) using the slider or by entering values below the slider

Task 1.

Set the set point (reference variable, Set point flow rate [l/s]) to 4 l/s and try to adjust the control signal (Actuating signal [%]) to adjust the actual value (controlled variable, Actual flow rate [l/s]) to the set point (Set point flow rate [l/s]).

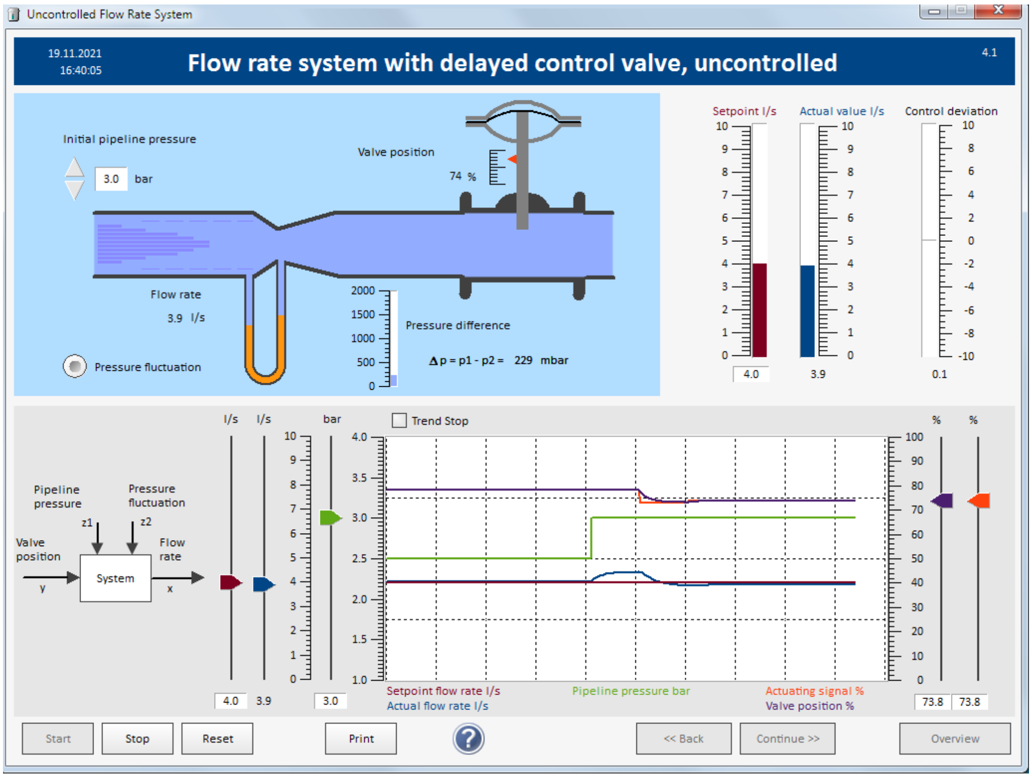


This type of control is known as command response. The set point (reference variable) is adjusted and an attempt is made to adjust the actual value (controlled variable) to the new set point (reference variable).

With this system it can be observed that the actual valve position is delayed after the control signal. If the control signal is changed (red signal), it takes until the valve position adopts the value specified by the control signal. The valve needs time to move to the desired valve position.

Task 2.

Change the pipe line pressure to 3 bar and try to correct the disturbance by adjusting the control signal.



As the pipe line pressure increases, the flow rate increases.

To compensate for this, the control signal and thus the valve opening must be reduced. Here, too, it can be seen that the actual valve position is delayed after the control signal.

The change in the pipeline inlet pressure is a disturbance for the system. That is why one speaks here of the investigation of the disturbance response.

5.2 Controlled System

5.2.1 Closed-loop Controlled System

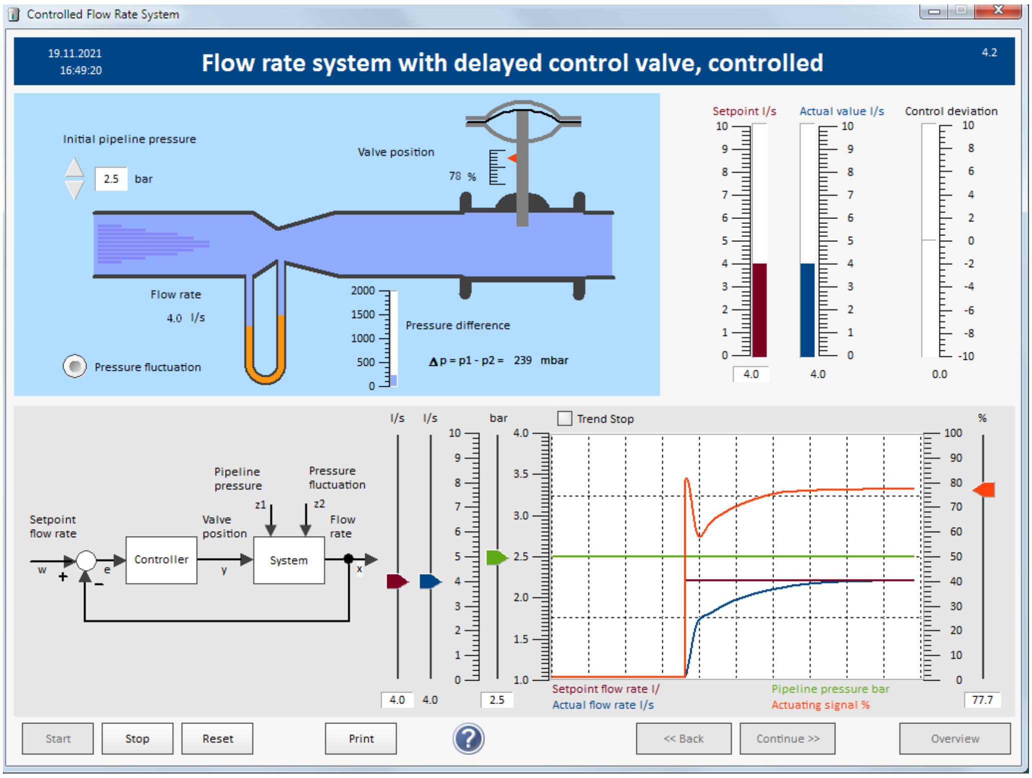
Go to „Overview“ and select item 4.2 „Closed-loop controlled system“.

Here you can see how the system behaves in principle if, instead of manual control by the user, a controller takes over the task of adjusting the actual value to the set point.

Task 3.

Click „Start“ and set the set point to 4l/s.

What will happen?

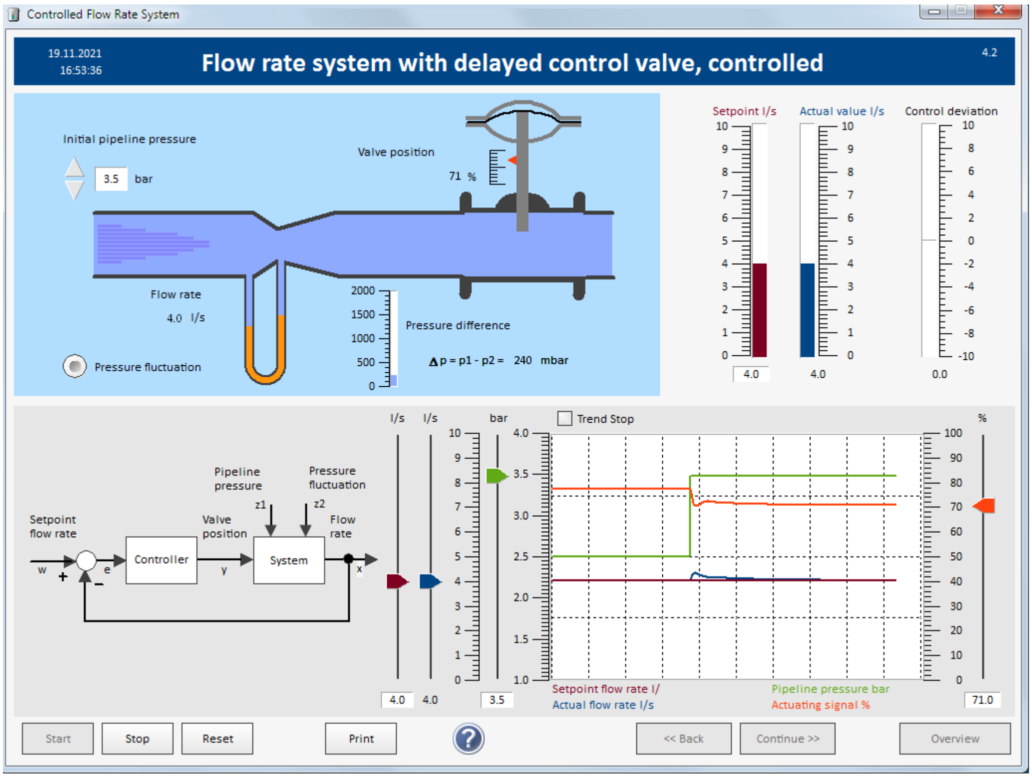


The actual value (flow rate) adjusts to the new set point (reference variable) after a certain time without overshooting. This is again a matter of examining the command response, since the set point (reference variable) has been adjusted.

Task 4.

Change the pipe line pressure to 3.5 bar.

What will happen?



The flow begins to increase.

The controller tries to adjust the actual value (actual flow rate) to the set point by closing the valve further (control signal reduced).

After a certain time, the controller has corrected the disturbance. This is about the investigation of the disturbance response, since it reacts to a disturbance.

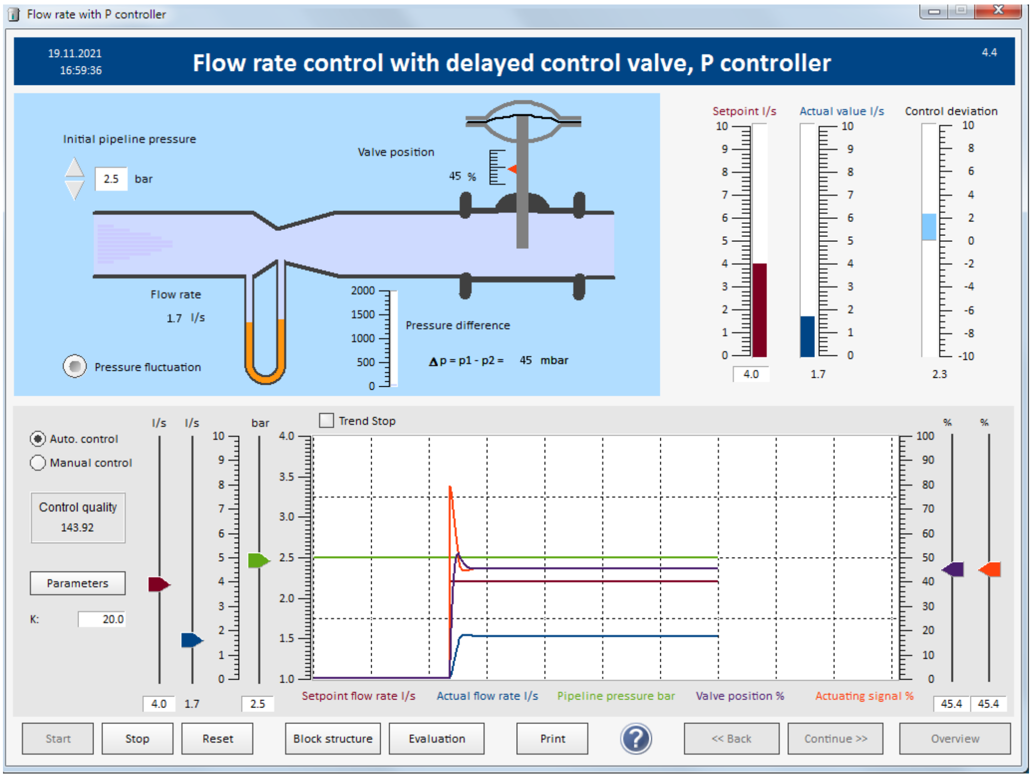
5.2.2 Closed-loop Control with P Controller

Go to „Overview“ and select item 4.4 „Closed-loop control with P controller“.

Click „Start“.

Task 5.

Change the set point to 4 l/s and wait until the control loop has settled, i.e. until the actual value no longer changes.



After the settling phase, it can be clearly seen that the actual value (controlled variable, actual flow rate) does not reach the set point (reference variable, set point flow rate). We get a steady-state control error.

The steady-state control error is defined as e = w – x, with

w = Reference variable (set point) and x = controlled variable (actual signal).

Reason:

The P controller works like an amplifier. The input signal to the controller w - x (set point - actual value) is amplified with the specified amplification factor (in our case 20). In order for the P controller to output a control signal (a valve position) that is not equal to zero, the set point and actual value must be different, i.e. permanent control difference.

If the controller outputs 0, the valve closes and the flow rate goes to 0.

The size of the control signal y can be calculated. In the steady state, the actual value x goes to approximately 1.7 l/s. The set point w was set to 4l/s. This results in a control error of e = w - x = 4 - 1.7 = 2.3.

The control signal can be calculated with the set gain K = 20 of the P controller:

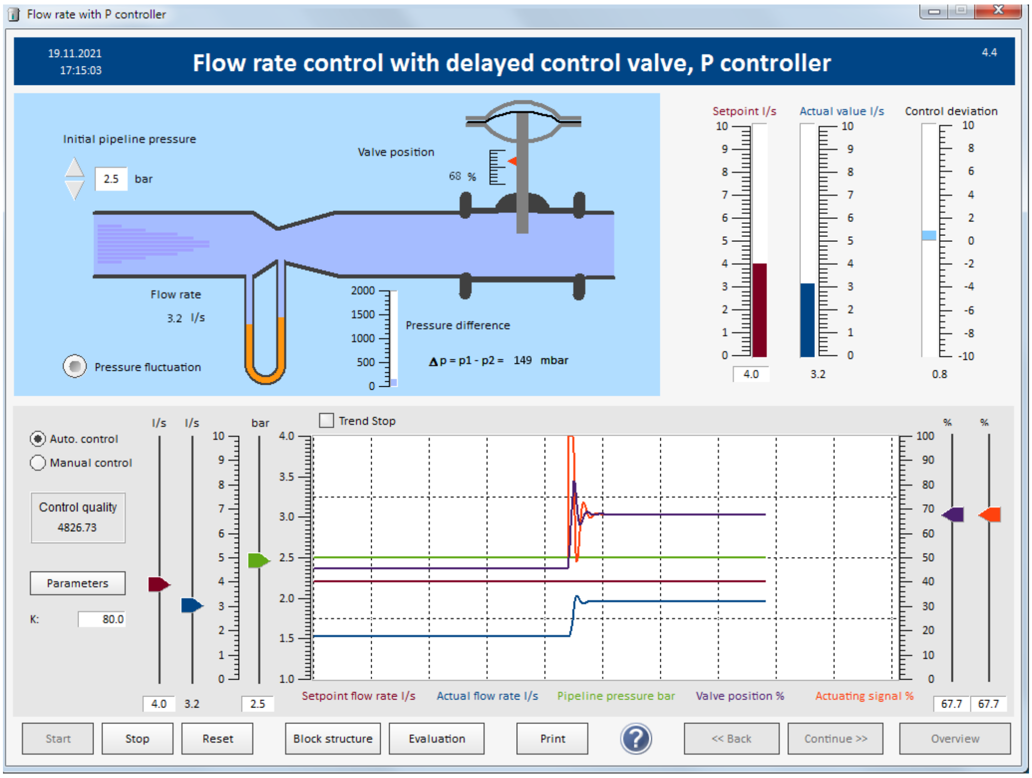
Control signal y = K * (w – x) = 20 * (4 – 1,7) = 46.

This corresponds roughly to the displayed value of the control signal of 45.4.

Task 6.

Change the gain of the P controller from 20 to 80 and wait until the control loop has settled again.

What will happen?



The control difference between the set point and the actual value becomes significantly smaller when the gain K is increased from 20 to 80. However, the P controller does not manage to adjust the actual value to the set point here either. For the reason described above, we also get a permanent, albeit significantly smaller, control difference (e = w - x).

The calculation results in y = K * (w - x) = 80 * (4 - 3.2) = 64.

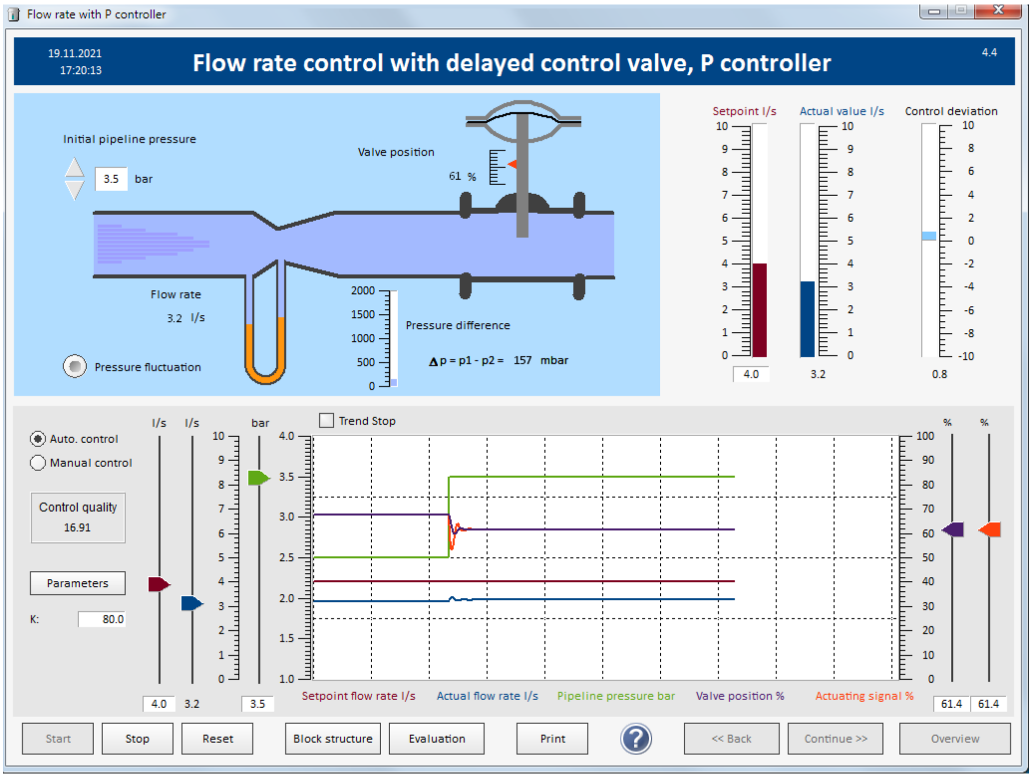
The value corresponds approximately to the displayed value of the control signal.

The P-controller also reacts to a disturbance (change in the pipe line pressure). A permanent control difference (steady-state control error) is also obtained for this.

Task 7.

Change the pipe line pressure to 3.5 bar.

What will happen?



The P-controller reacts to the disturbance, the steady-state error remains.

As can be seen from the settling response of the control, the P controller reacts immediately and quickly to set point and disturbance value changes (command response and disturbance response).

5.2.3 Closed-loop Control with I Controller:

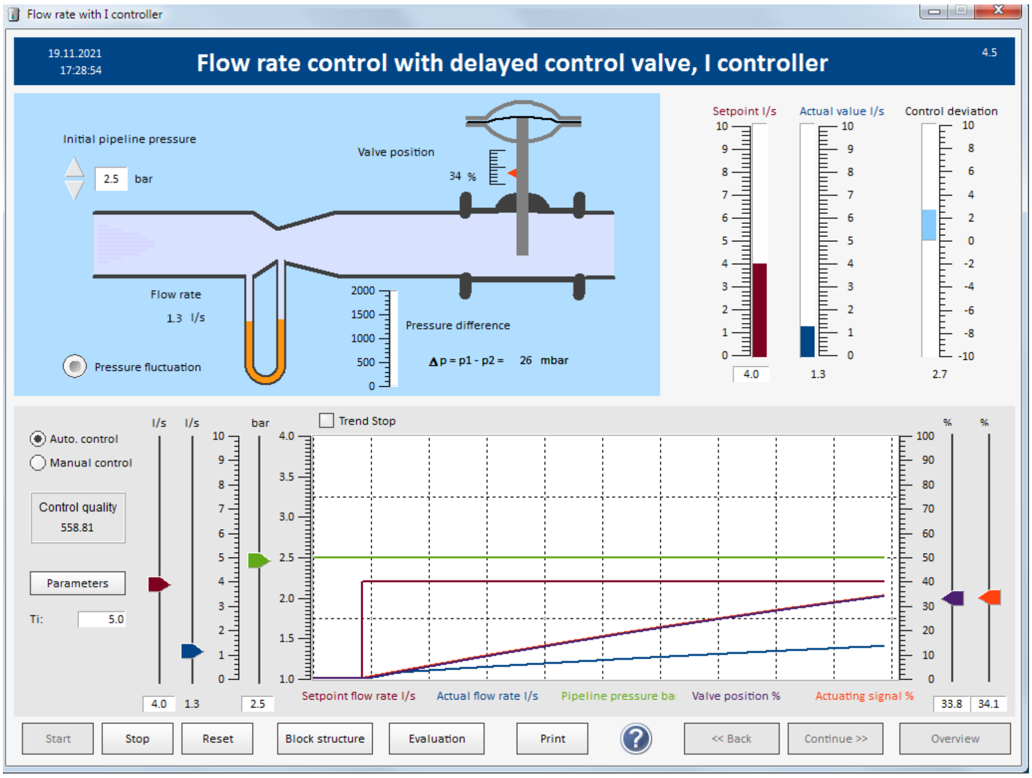
Go to „Overview“ and select item 4.5 „Closed-loop control with I controller“.

Click „Start“.

Task 8.

Change set point to 4l/s.

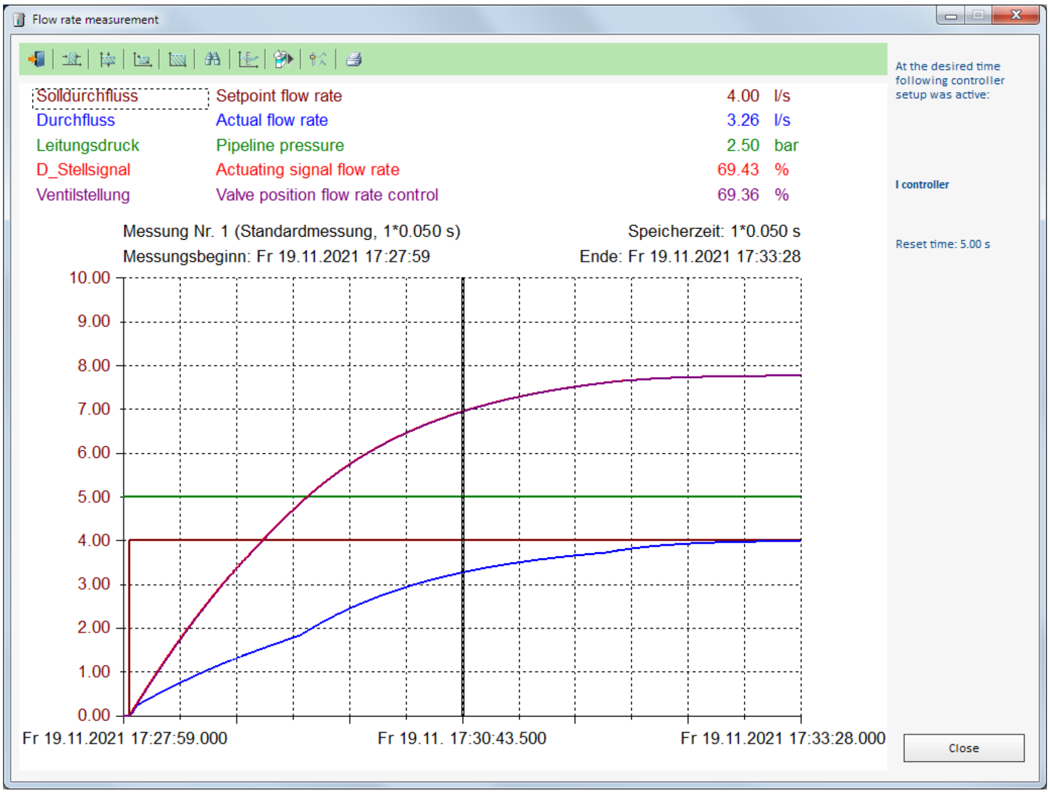
What will happen?



The valve is slowly opened by the I controller. After a long period of time, the actual value reaches the set point.

By reducing the integration time (e.g. to 1), the actual value reaches the set point faster.

But even then the settling is very slow.



The I controller is not suitable for this flow control because the settling takes too long.

5.2.4 Closed-loop Control with PI controller:

Go to „Overview“ and select item 4.6 „Closed-loop control with PI controller“.

Click „Start“.

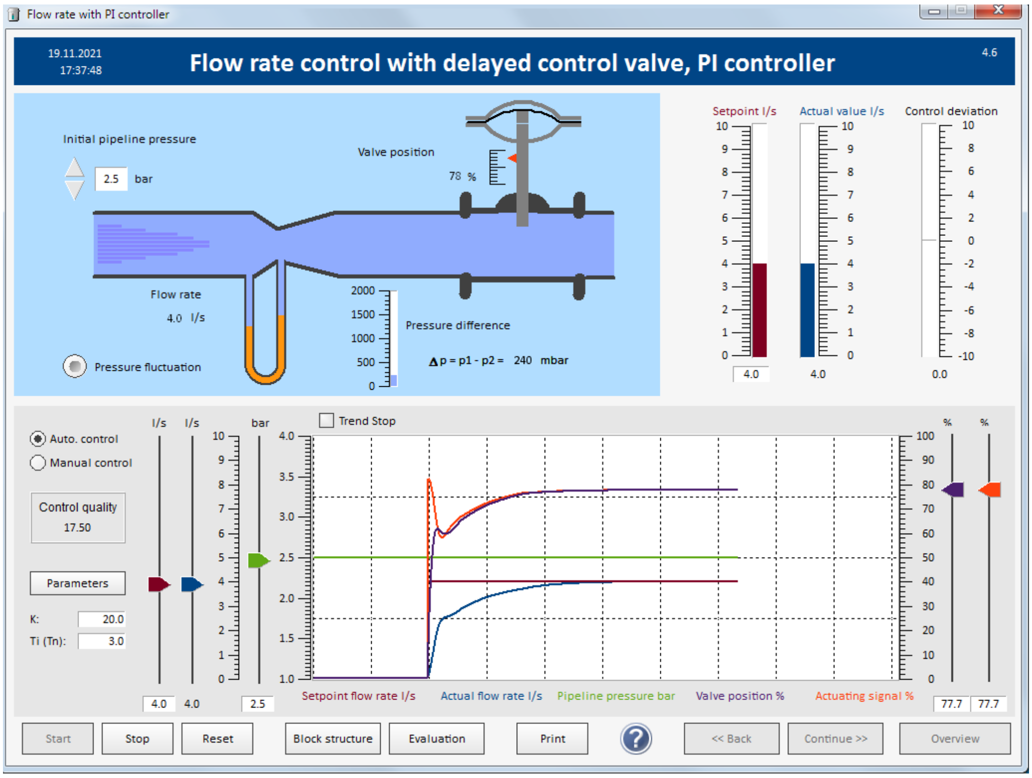
Task 9.

Keep the preset parameters:

Gain K = 20, Reset time Ti = 3.

Change the set point to 4l/s.

Observe the settling behavior.



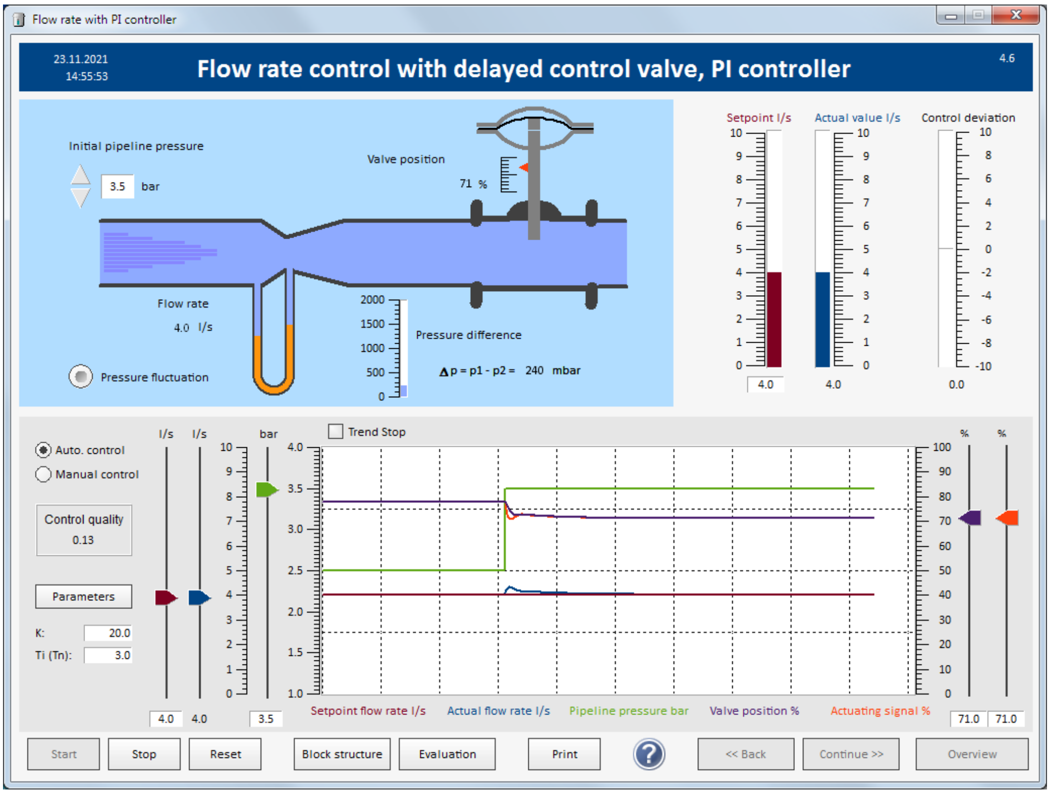
The actual value (controlled variable, actual flow rate l/s) of the control loop with the PI controller and the set parameters reaches the new set point (reference variable, set point flow rate l/s) after a short time without overshooting.

Since the set point has been changed, this is about the investigation of the command response.

Task 10.

Investigate the disturbance response.

When the control loop has settled to 4l/s, change the pipe line pressure to 3.5 bar and observe the behavior.



The higher pipe line pressure causes an increase in the flow. The controller tries to counteract this and reduces the valve opening. After a short settling phase, the actual value reaches the set point again.

The behavior of the control loop to a change in the disturbance value is referred to as disturbance response.

Task 11.

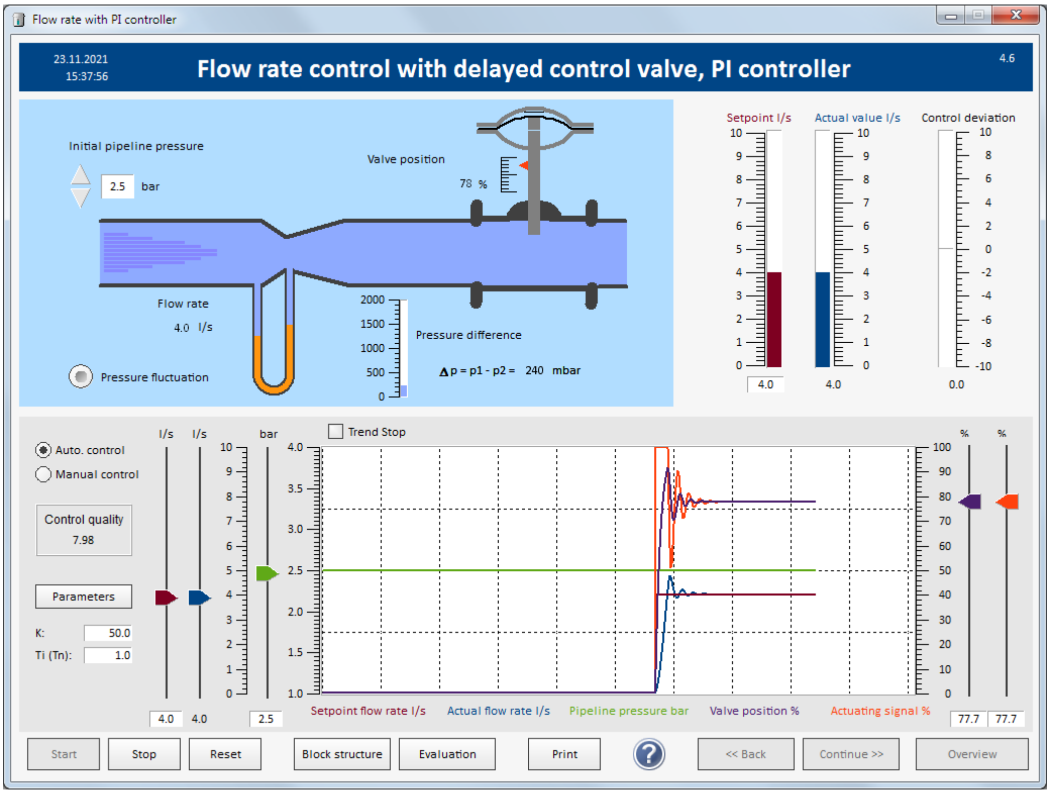
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the set point.

Try to reduce the value for the control quality by adjusting the controller parameters.

With the controller parameters K = 20 und Ti = 3, a control quality of 17.5 was achieved.

So that the control quality is comparable in the tests, all tests must be started with the same initial states. The best way to do this is to click "Reset". This means that the set point flow rate, pipe line pressure and actual flow rate are again given the initial values.

Now change the controller parameters and then adjust the set point flow rate to 4l/s. Wait until the control loop has settled.



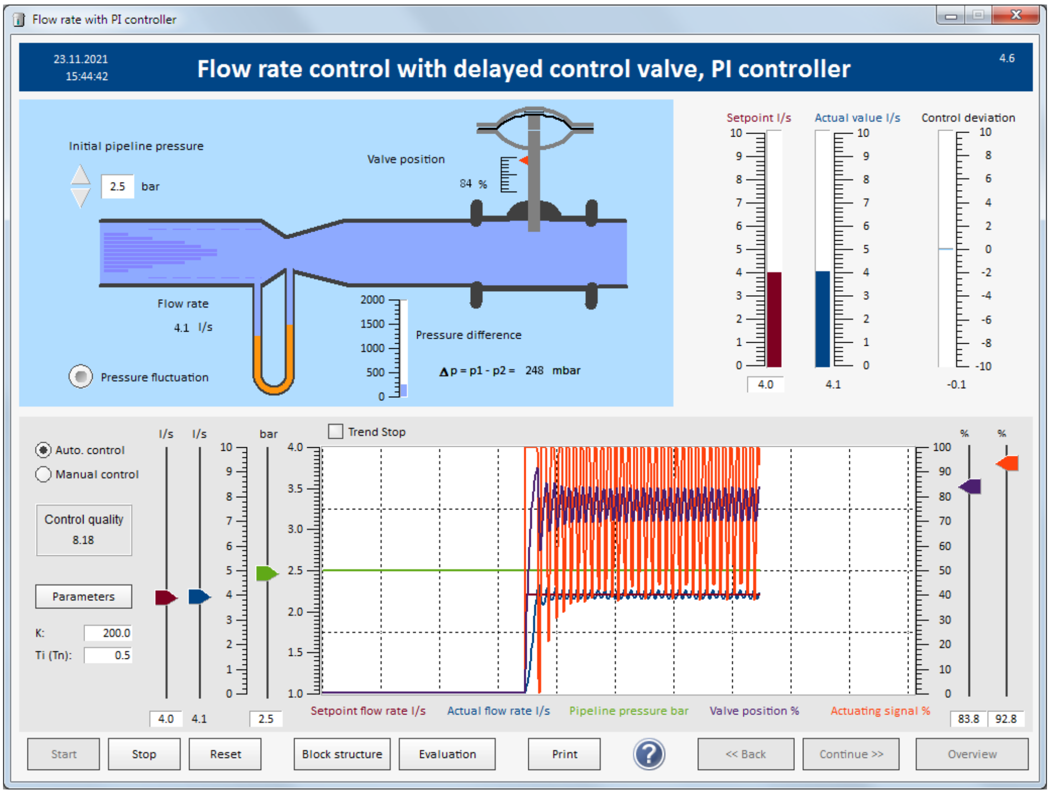
With the parameters K = 50 und Ti = 1, a control quality of 7,98 is obtained.

However, the control loop becomes very restless and the control signal and actual value begin to oscillate before they settle.

Carry out the experiments with further controller parameters:

- Click reset
- Set controller parameters
- Set the set point to 4l/s
- Wait until the control loop has settled..

By adjusting the parameters e.g. to K = 200 and Ti = 0.5, the control loop becomes unstable and carries out a continuous oscillation.



In order to achieve an aperiodic response (without overshoot), you can use the preset parameter values.

5.2.5 Closed-loop Control with PID Controller:

Go to „Overview“ and select item 4.7 „Closed-loop control with PID controller“.

Click „Start“.

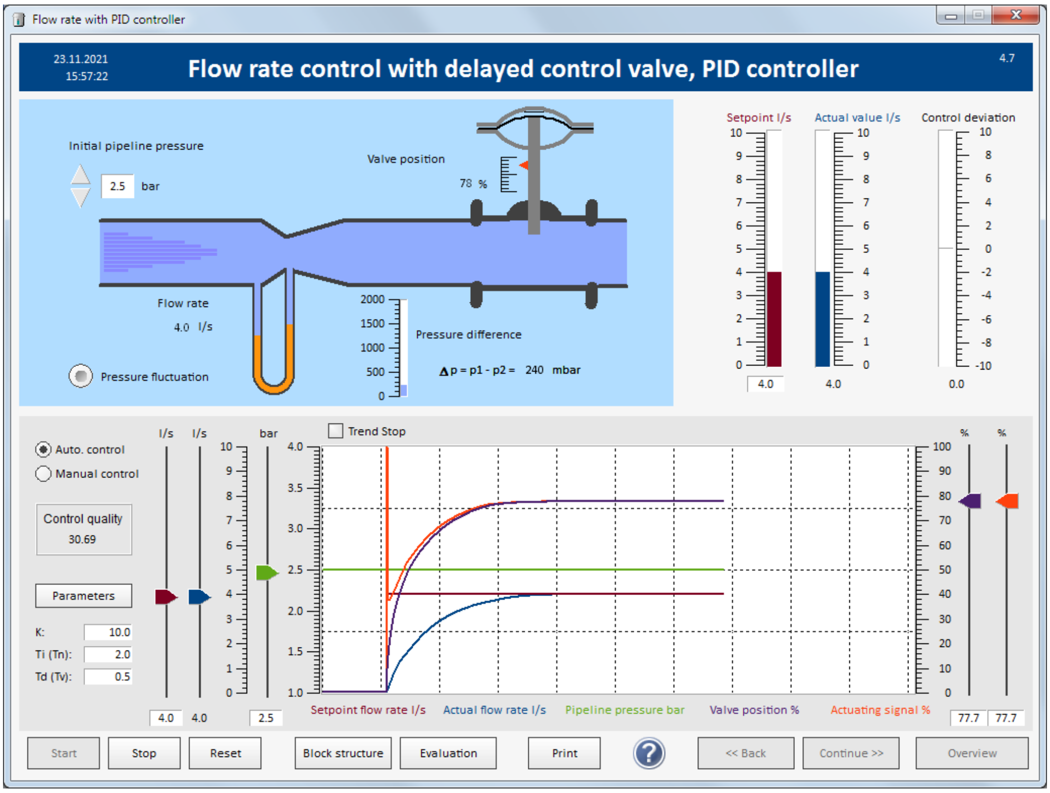
Task 12.

Investigate the command response with the preset parameters:

Gain K = 10, reset time Ti = 2, derivative time Td = 0,5

Change set point to 4l/s.

What will happen?



The control loop reaches a stable state aperiodically (without overshoot). The actual value reaches the set point.

As can be seen in the trend diagram, the sudden change in the set point causes a peak in the control signal. This peak is triggered by the D component of the controller. The derivation of a sudden change causes an (infinitely) large value.

The control quality goes to 30,69 and is therefore worse than with the PI controller with the parameters K = 20 and Ti = 3.

Note on the trend display with the PID controller:

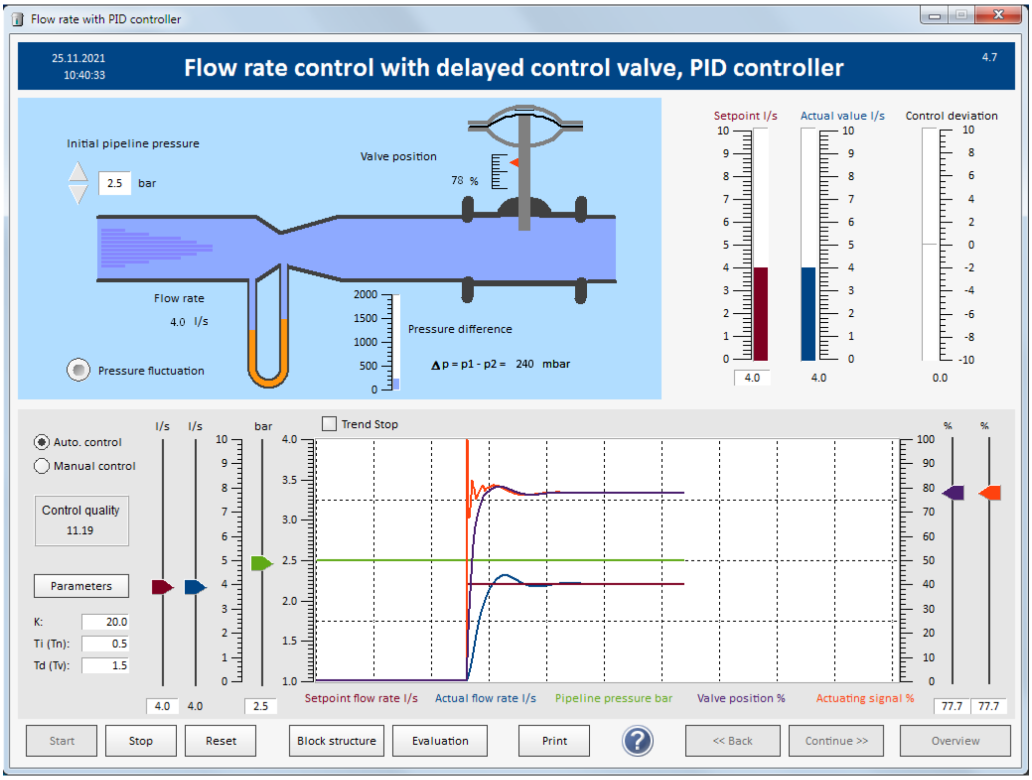
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Evaluation" (display of the stored signal values) and selection of a corresponding time range.

Task 13.

Try to improve the control quality by adjusting the controller parameters.

So that you can compare the experiments, you always have to start from the same initial states. Therefore

- Click “Reset”
- Change the controller parameters
- Adjust the set point to 4l/s
- Wait until the control loop has settled



With the controller parameters K = 20, Reset time Ti = 0,5 and derivative time Td = 1,5 you get a control quality of 11,19.

Info:

In practice, the PI controller is most common. If a PID controller is used, the D component is often turned off so that the controller only works as a PI controller.

One of the reasons for this is that the D behavior in a control loop is difficult to assess. In principle, the D component gives you the option of making the control faster (which is often very difficult, however).

The D component considers the change between the set point and the actual value. If the change increases, i.e. the difference between the set point and actual value increases, the D component adds a calculated value to the control signal. If the difference between the set point and the actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend, whether the difference between the set point and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the set point and actual value decreases, the control signal is reduced.

5.3 Examine Controlled System

For flow rate control, choose the item 4.3 „Examine controlled system“.

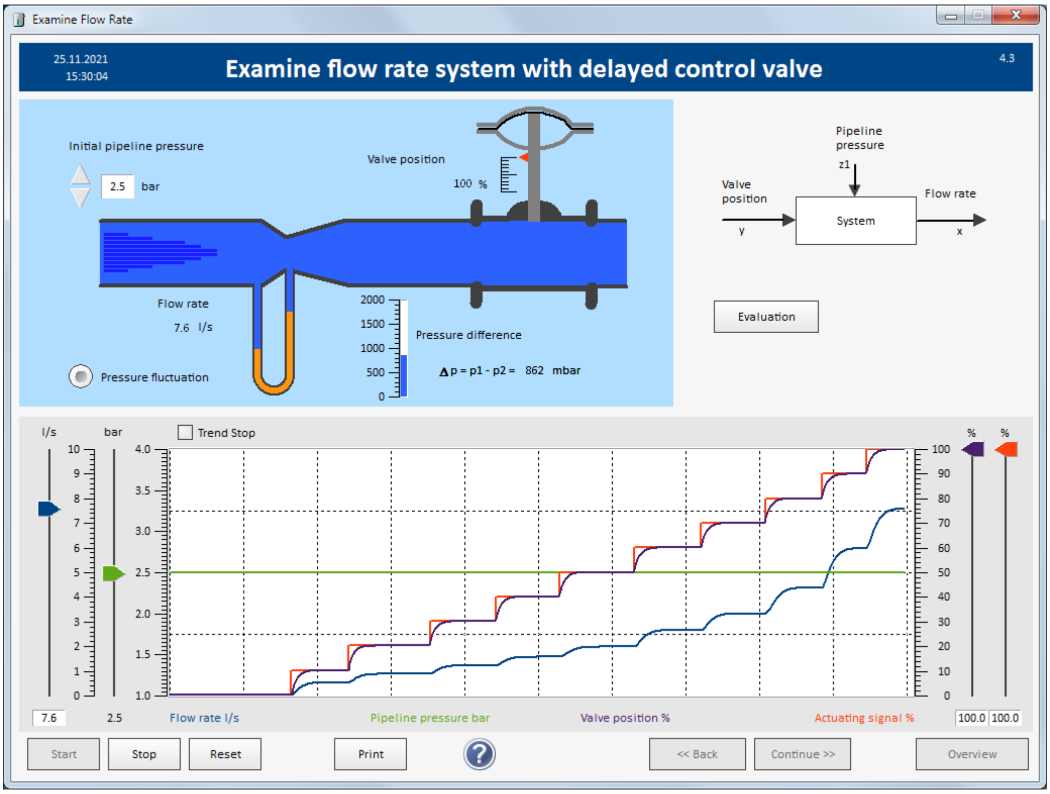
The flow rate control is a system with self-regulation. In the event of a sudden change in the control signal, the actual value (controlled variable, actual flow rate) settles to a constant value after a finite time.

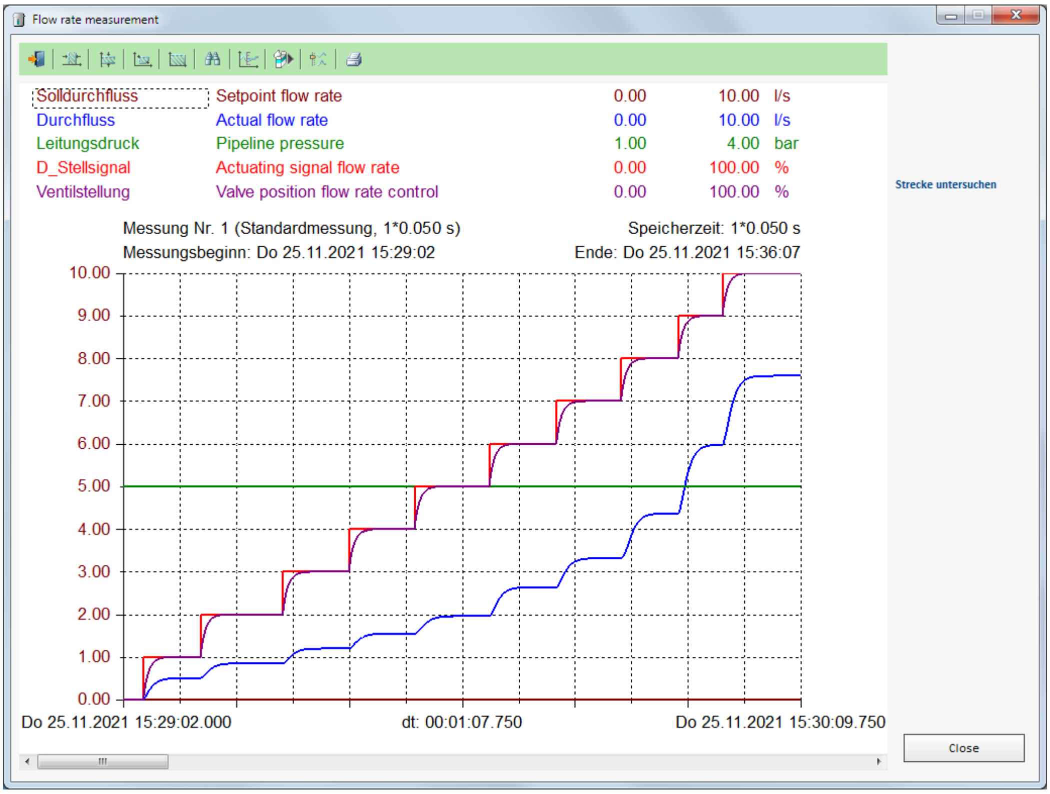
Task 14.

Click „Start“.

Increase the actuating signal in steps of 10% wait each time until the flow rate is constant.

Observe the flow rate behavior.





As can be clearly seen, the flow rate behaves differently depending on the operating point, i.e. a change in the control signal from 10% to 20% results in a smaller change in the actual flow rate than a step in the control signal from 80% to 90%.

This means that the control loop will also behave differently depending on the operating point. Therefore, in the case of control, it must be taken into account at which operating point the control is to be operated.

In the following, the operating point at round about 2l/s (between 1.5l/s and 2.5l/s) is considered; the control signal for this range is between 40% and 60%.

5.4 Controller Tuning Rules

The flow rate system is a controlled system with self-regulation.

In the event of a sudden change in the control variable, a controlled system with self-regulation oscillates to a constant value after a finite time, while with a controlled system without self-regulation, the controlled variable (actual value) continues to increase.

In order to use the controller tuning rules. e.g. according to Chien/Hrones/Reswick, the system has to be examined.

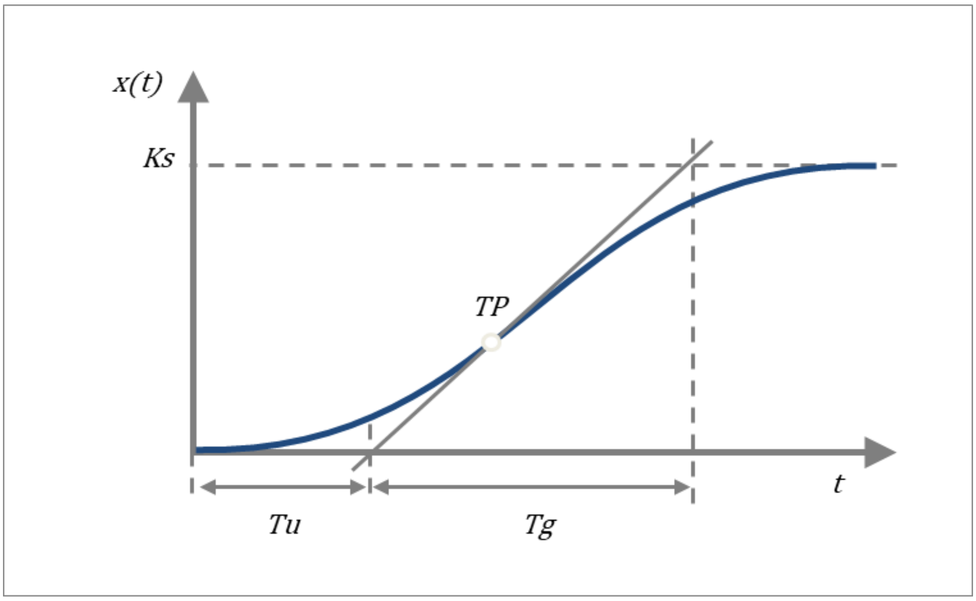
A step in the control signal (sudden change in the control signal by 1)is applied to the controlled system. The behavior of the output signal of the system (controlled variable) can then be measured.

For the controller setting procedures for systems with self-regulation, the parameters Tu, Tg and Ks are determined as shown in the figure below.

Te = Tu = Delay time

Tb = Tg = Compensation time

Ks = Gain



In the new standard, the delay time is designated with Te, the compensation time with Tb and the turning point with P.

Since the terms Tu and Tg are still used in most of the literature, we keep the old terms here, or use both.

With the help of these three parameters, the controller parameters can then be determined from the setting table according to Chien / Hrones / Reswick:

Table 3: Equations to calculate controller parameters according to Chien/Hrones/Reswick

Controller	Quality criteria			
	With 20 % Overshoot		Aperiodic case	
	Disturbance	Command	Disturbance	Command
P	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$
PI	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.3 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 4 \cdot T_U$	$K_P \approx \frac{0.35}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.2 \cdot T_g$
PID	$K_P \approx \frac{1.2}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2 \cdot T_U$ $T_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.35 \cdot T_U$ $T_V \approx 0.47 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.4 \cdot T_U$ $T\_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$ $T_V \approx 0.5 \cdot T_U$

For systems without self-regulation use $\frac{T_g}{(K_S \cdot T_U\ )}$ instead of $\frac{1}{(K_{IS} \cdot T_U\ )}$.

The table was taken from: E. Samal, Grundriss der praktischen Regelungstechnik, Oldenbourg

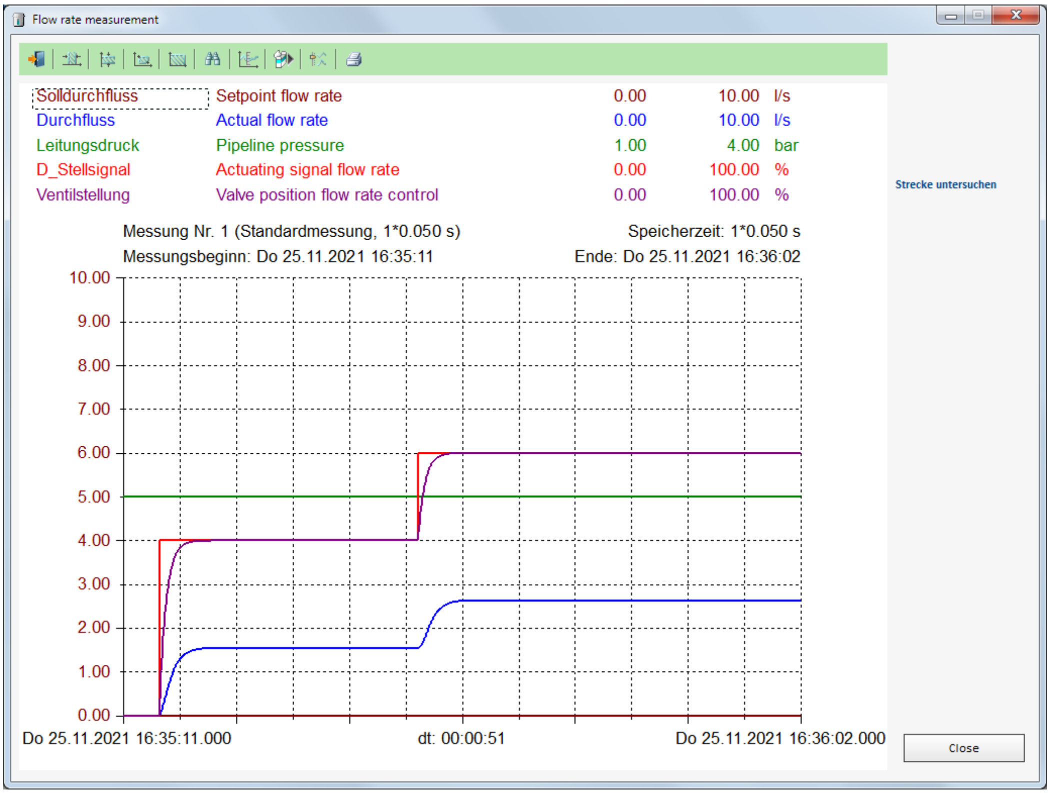
Under item flow control, select point 4.3 "Examine controlled system".

Task 15.

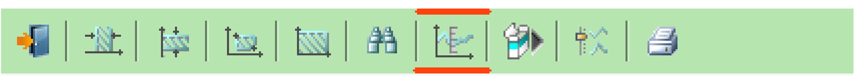
Click „Start“. Increase the control signal to 40%. Wait until the controlled variable (flow rate) has settled.

Then increase the control signal to 60% and wait again until the flow rate has settled.

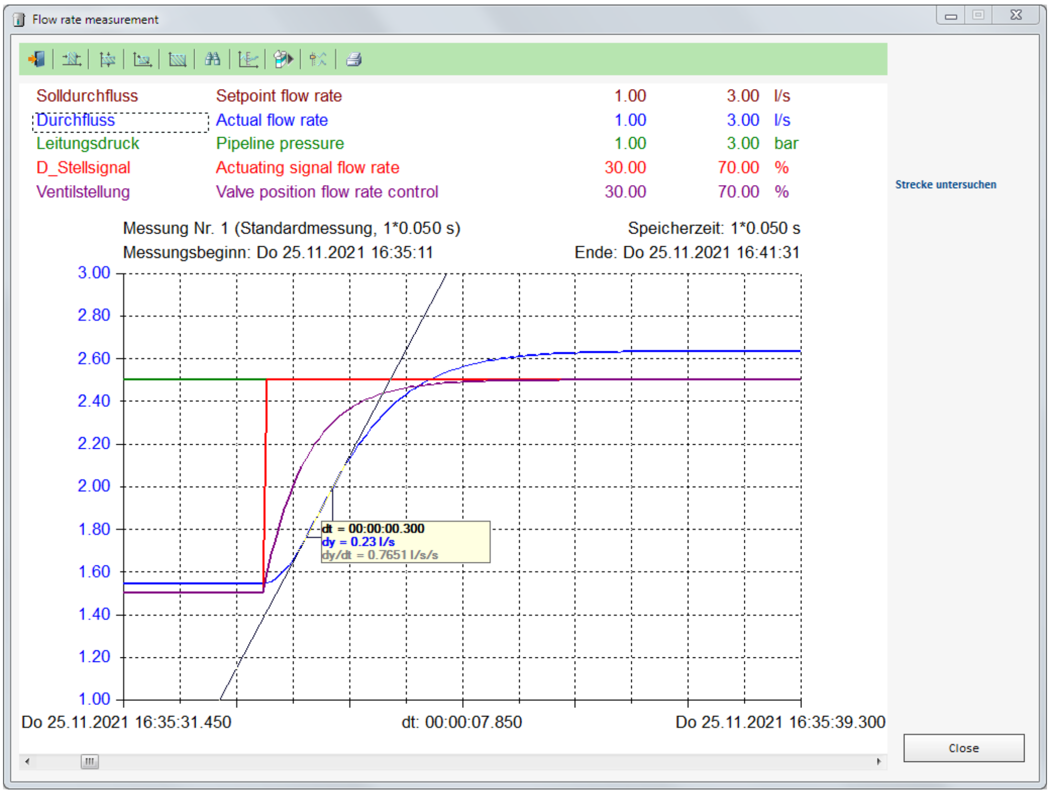
Click "Evaluation" and try to measure the recorded system behavior for the step to 60%.



With the help of the button bar at the top of the window you can change time and display sections (zoom).



Click on the blue signal (controlled variable, actual flow rate) and try to determine the gradient of the flow curve by drag and drop.



The gradient of the tangent at the turning point can be read approximately from the two curves shown above: dx/dt = 0.75l/s/s.

After the sudden change in the control signal from 40% to 60%, the flow rate goes from 1.5l/s after the settling phase to 2.6l/s.

This enables the compensation time Tg to be calculated:

dx/dt = (End value – Start value) / Tg , so

Tg = (2,6l/s – 1,5l/s) / 0,75l/s/s = 1,466s

Since we have entered a step height of 20% for the control signal, we have to take this into account when calculating Ks.

Ks = (End value – Start value) / Step height

= (2,6l/s – 1,5l/s) / 20 = 0,055

The delay time Tu can be measured and is approximately 0,2s.

Hence: Te = Tu = 0,2s Tb = Tg = 1,466s Ks = 0,055

This results in the following controller parameters from the table for the PI controller:

PI controller

Command response with 20% overshoot

K = 0,6*Tb / (Ks*Te)	79,96
Tn = Tb	1,47

Command response aperiodic

K = 0,35*Tb / (Ks*Te)	46,65
Tn = 1,2 * Tb	1,76

Disturbance response with 20% overshoot

K = 0,7*Tb / (Ks*Te)	93,29
Tn = 2,3 * Te	0,46

Disturbance response aperiodic

K = 0,6*Tb / (Ks*Te)	79,96
Tn = 4 * Te	0,80

Since the investigation of the system was carried out for an operating point with a flow rate of 2l/s, a set point step from 0l/s to 2l/s should be used.

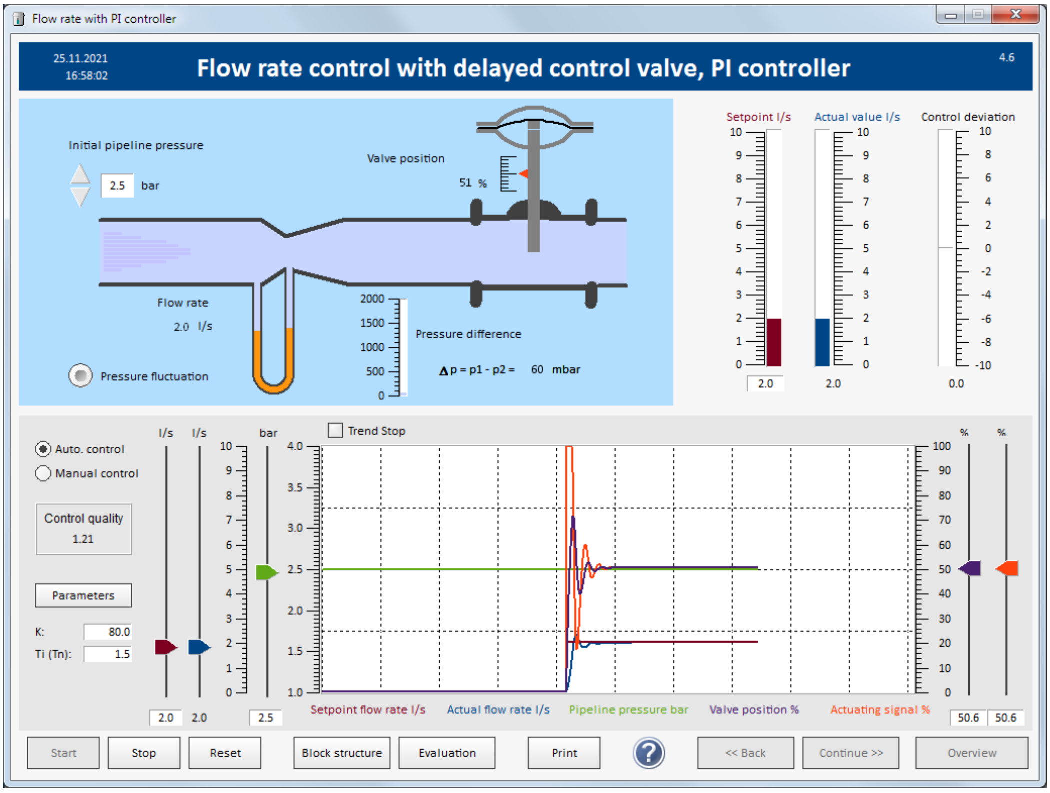


Figure 19: Command response with 20% overshoot

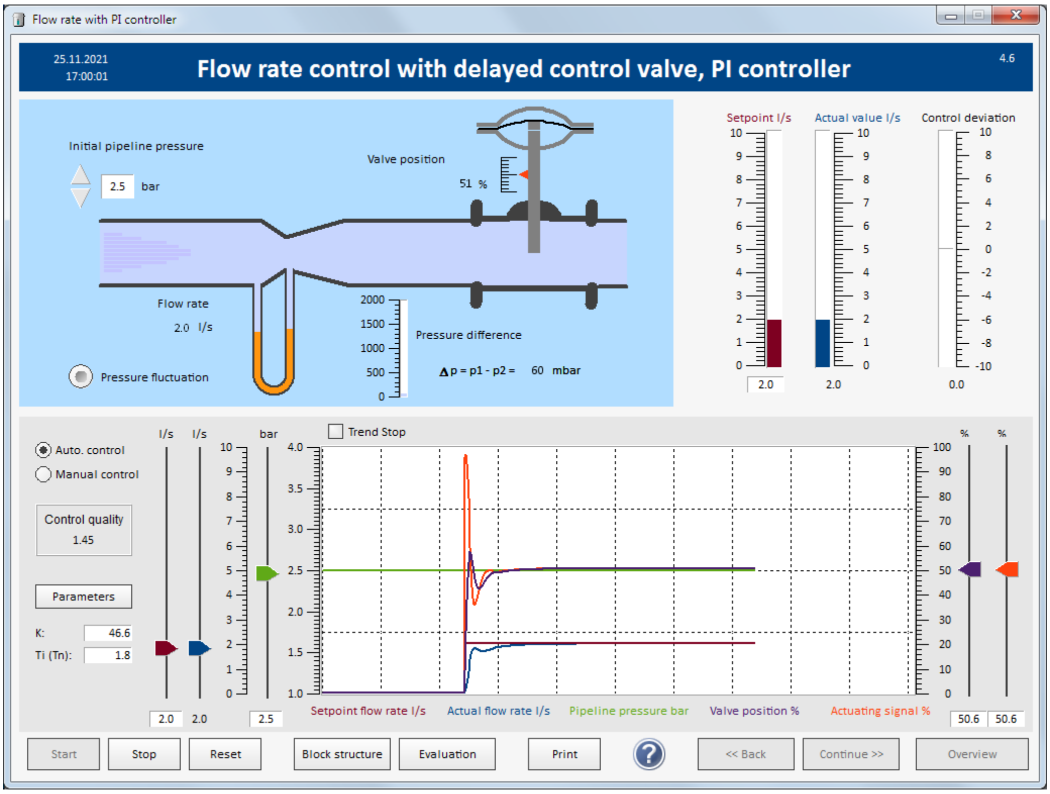


Figure 20: Command response aperiodic

Disturbance response: Pipe line pressure from 2,5bar to 3,5bar:

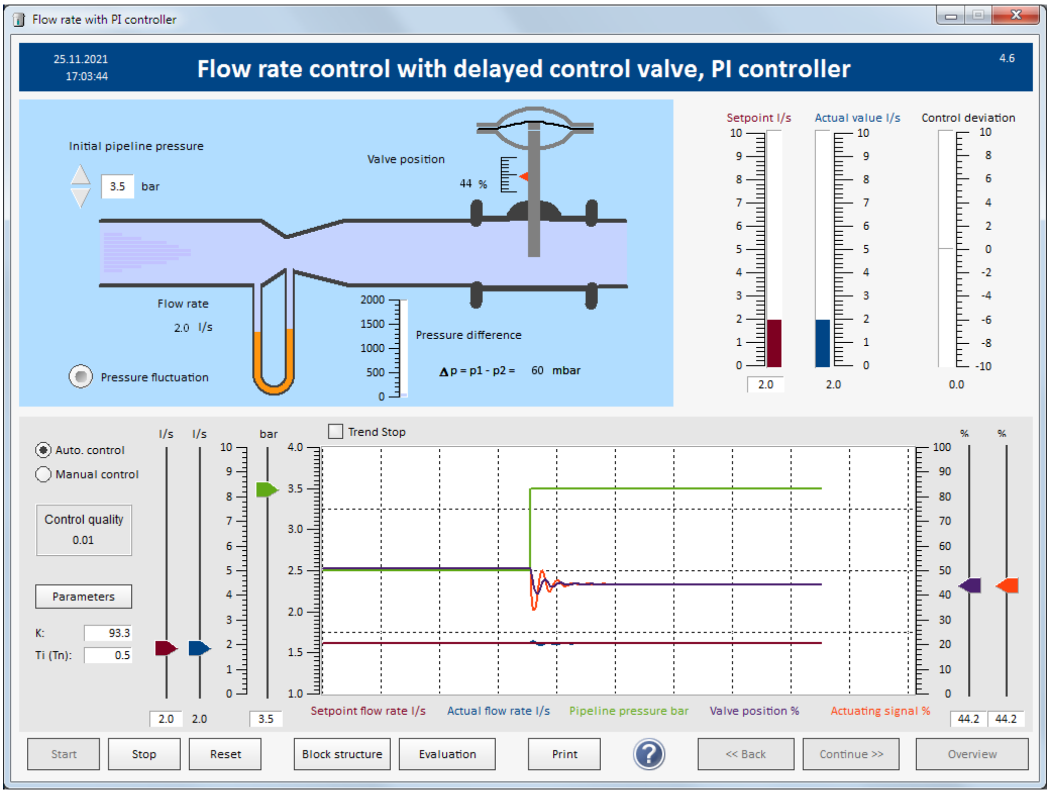


Figure 21:Disturbance response with 20% overshoot

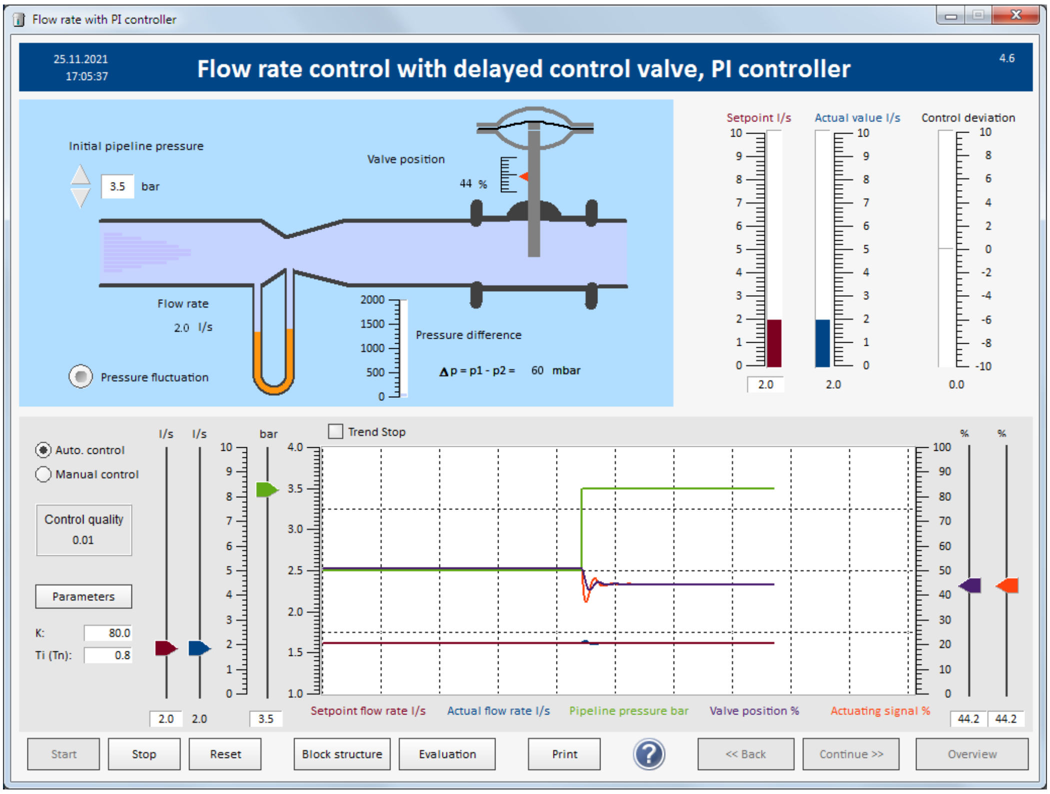


Figure 22:Disturbance response aperiodic

For the PID controller, inserting the values in the table gives us the following parameters:

PID controller

Command response with 20% overshoot

K = 0,95*Tb / (Ks*Te)	126,61
Tn = 1,35 * Tb	1,98
Td = 0,47 * Te	0,09

Command response aperiodic

K = 0,6*Tb / (Ks*Te)	79,96
Tn = Tb	1,47
Td = 0,5 * Te	0,10

Disturbance response with 20% overshoot

K = 1,2*Tb / (Ks*Te)	159,93
Tn = 2 * Te	0,40
Td = 0,42 * Te	0,08

Disturbance response aperiodic

K = 0,95*Tb / (Ks*Te)	126,61
Tn = 2,4 * Te	0,48
Td = 0,42 * Te	0,08

Set point step from 0l/s to 2l/s:
0.2s was taken as derivative time, since the entry is limited to 0.2s

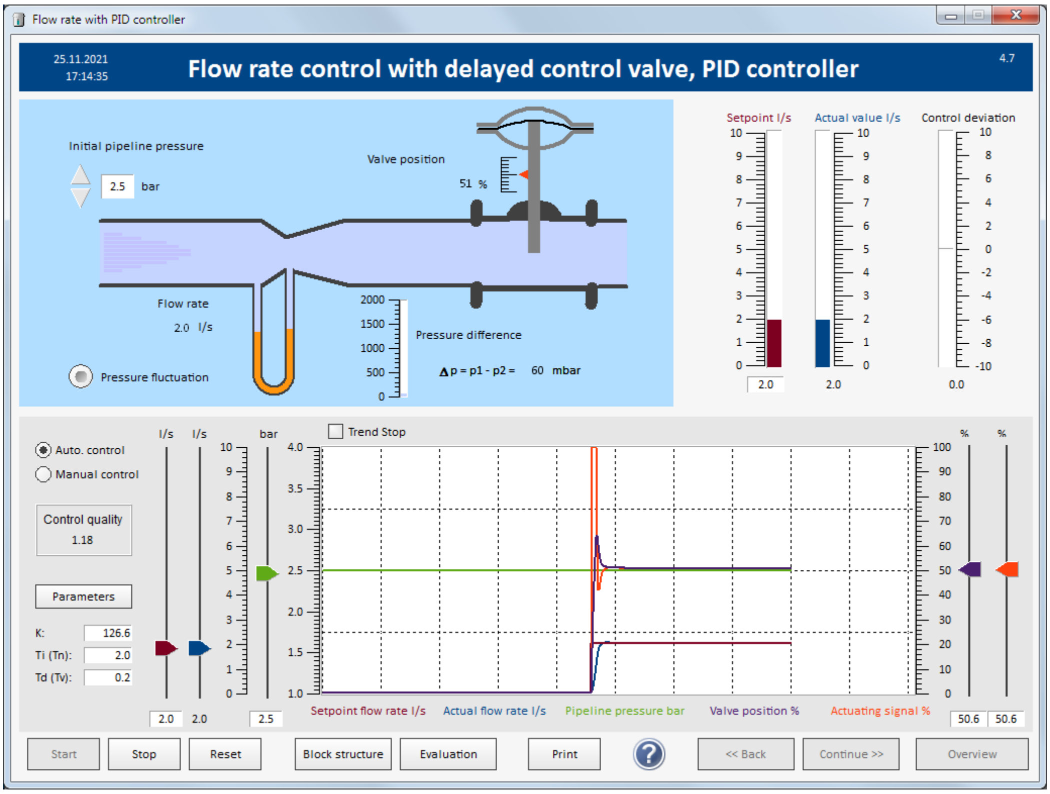


Figure 23: Command response with 20% overshoot

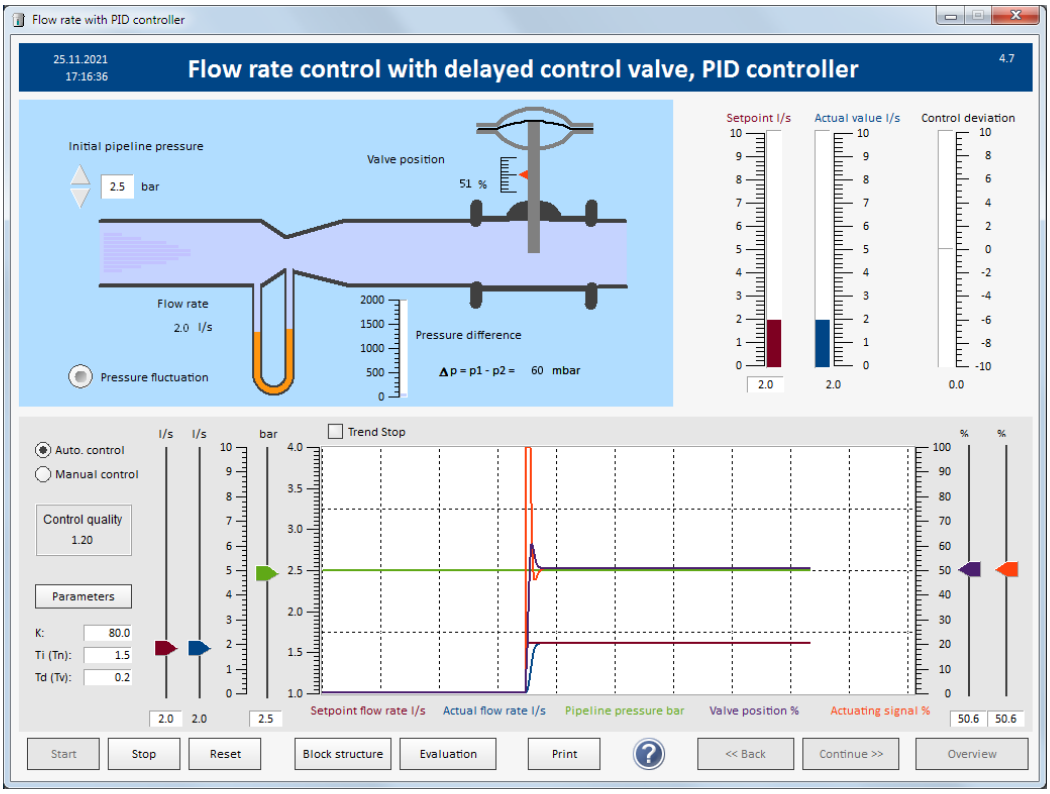


Figure 24: Command response aperiodic

Disturbance response: Pipe line pressure from 2.5bar to 3.5bar.

0.2s was taken as derivative time, since the entry is limited to 0.2s

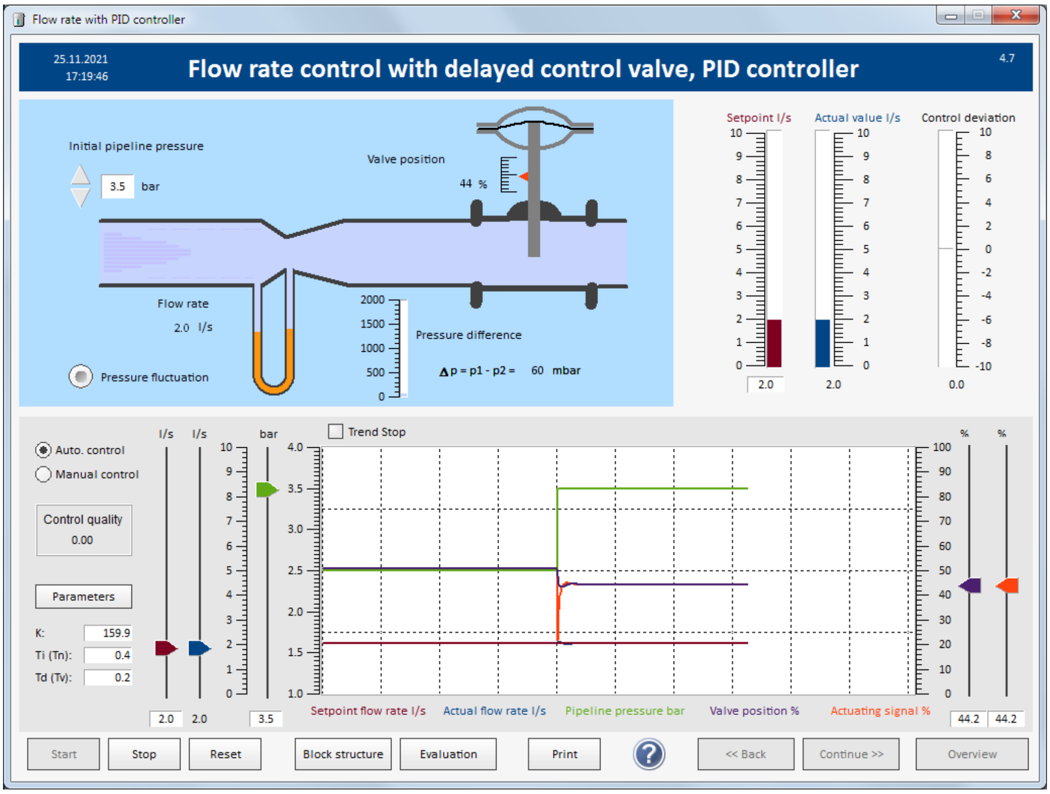


Figure 25:Disturbance response with 20% overshoot

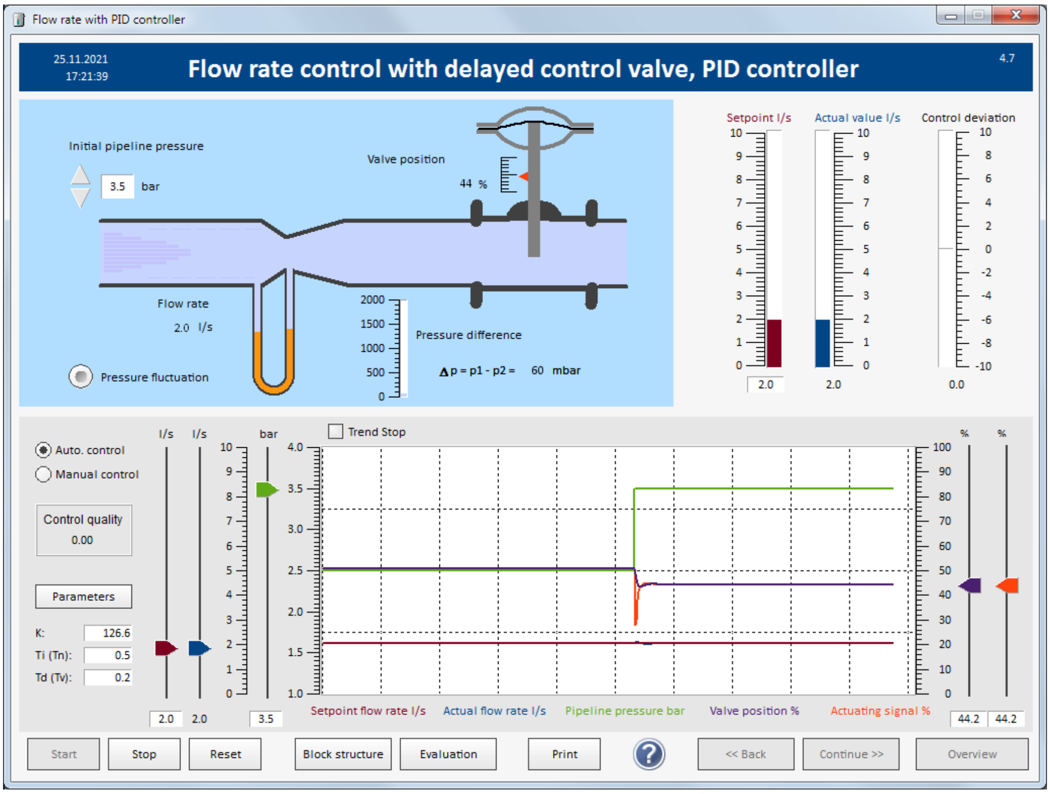


Figure 26: Disturbance response aperiodic

5.5 Assessment of the Controller Tuning Rules

Controller tuning rules are empirically determined methods that are often suitable for calculating good controller parameters by rule of thumb.

The settings for calculating controller parameters distinguish between disturbance and command response. Different controller parameters are calculated.

If you need controller parameters for both cases (disturbance and control behavior), you have to make a compromise between the calculated parameters of the disturbance behavior and the control behavior.

The above examples show that a reasonable control loop behavior can be obtained with the calculated controller parameters. However, the behavior does not exactly correspond to the expected behavior as selected in the table.

The fact that the system has not settled exactly aperiodically or with 20% overshoot is also due to the fact that the control signal has partially reached its limit and the time constants could not be determined exactly.

But in the examples and tasks shown, the controller parameters proposed by Chien / Hrones / Reswick were well suited for this control system.

6 Temperature Control (without/with Time Delay) (Control Training I)

This process involves a container through which water flows continuously. A level change does not take place. With the help of an electric heater, the temperature of the water in the container can be influenced. The technical control task is to control the temperature of the water in the tank by changing the heating power so that it corresponds to a specified set point. The heating power is the input variable (actuating variable, control signal), the temperature of the outflowing water is the output variable (controlled variable) of the system. Fluctuations in the temperature in the input represent a disturbance variable.

In this chapter the items "3. Temperature control " and "4. Temperature control with time delay " are treated together, since the processes are the same systems. The difference is that under 3. the temperature (controlled variable) is measured in the container while in the other case the temperature is measured in the pipeline. This (chapter 4.) results in a delayed measurement of the controlled variable (actual temperature). The temperature in the container is only measured with a time delay in the pipeline.

Although the two systems are the same apart from the temperature measurement, the systems behave differently.

6.1 Uncontrolled System (Manual Control)

Select item 3.1 „Uncontrolled system".

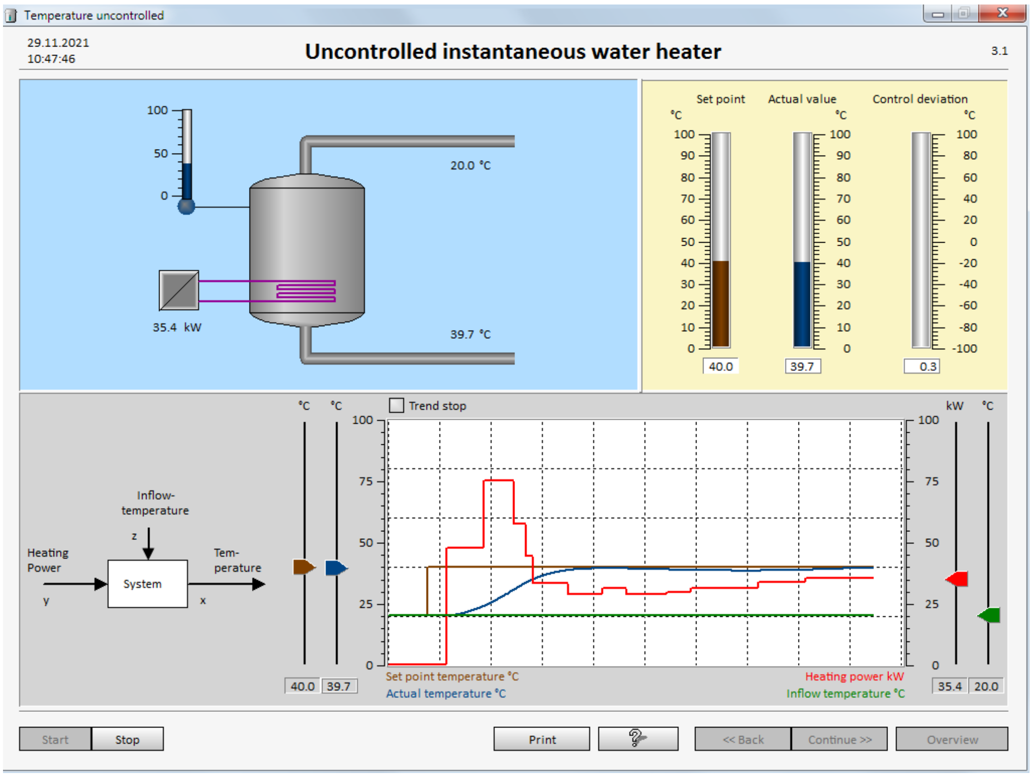
Click „Start".

You can change the values for the set point (Set point temperature °C), the control value (Heating power kW) and the disturbance (Inflow temperature °C) using the slider or by entering values below the slider.

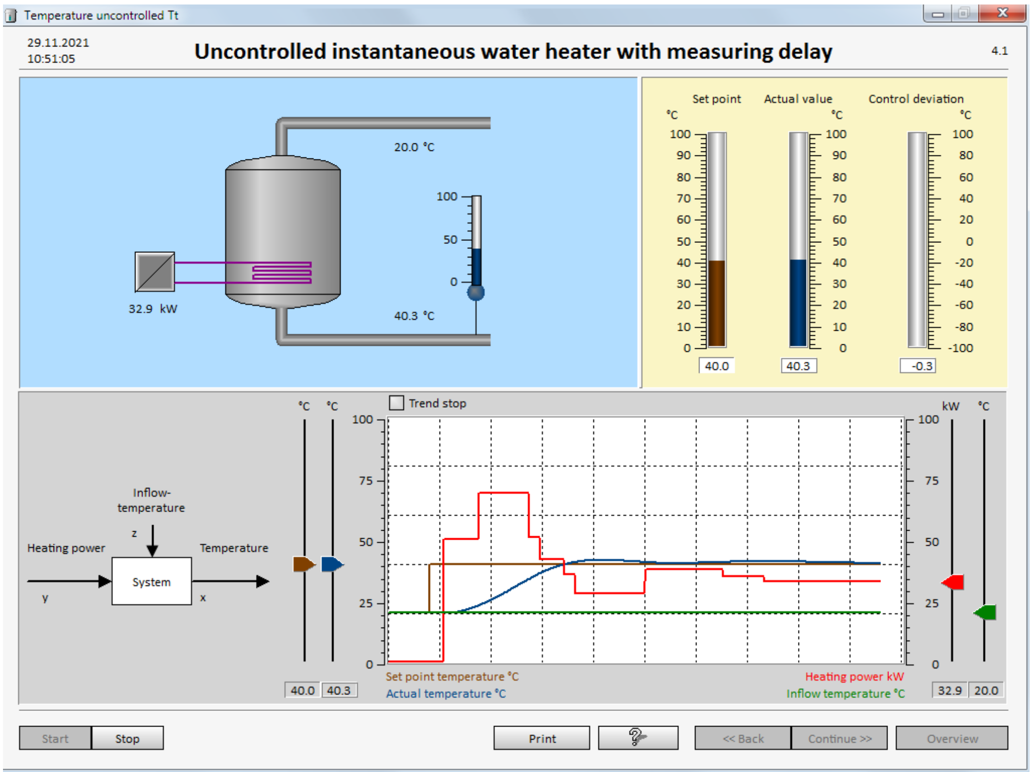
Task 1.

Set the set point temperature to 40°C and then try to adjust the actual temperature (controlled variable) in the container to the set point temperature by adjusting the heating power (control variable).

In this case one speaks of command response. The set point is adjusted and an attempt is made to adjust the actual value (controlled variable) to the new set point (reference variable).



Select item 4.1 (Temperature control with time delay, Uncontrolled system) and repeat the experiment.

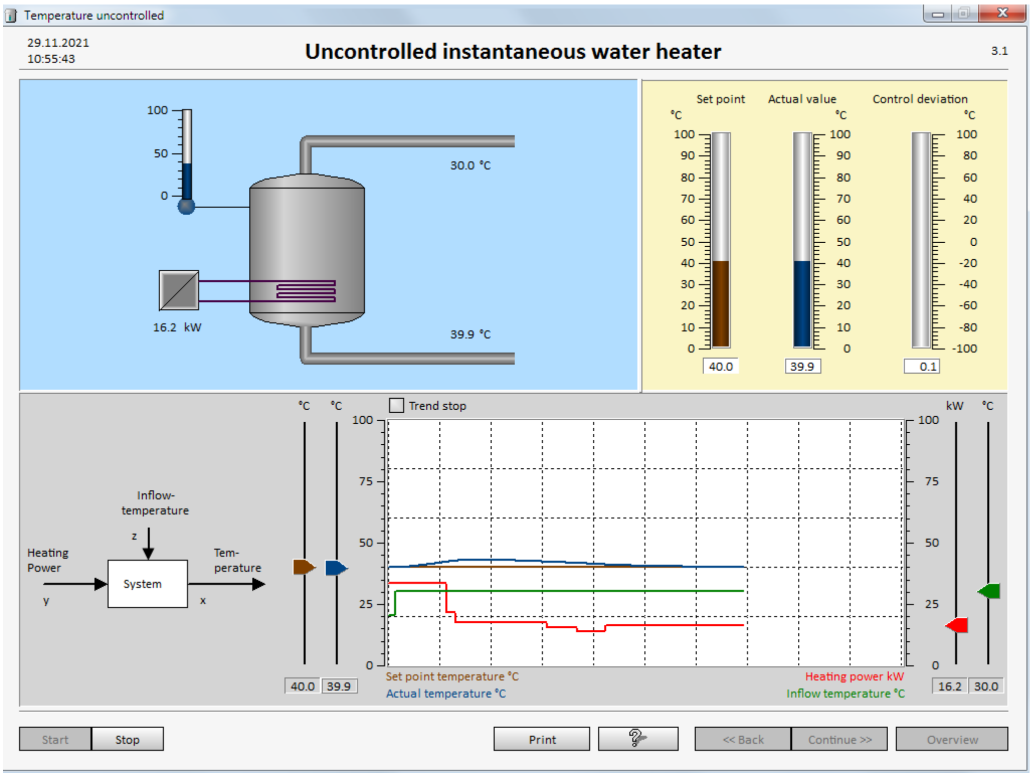


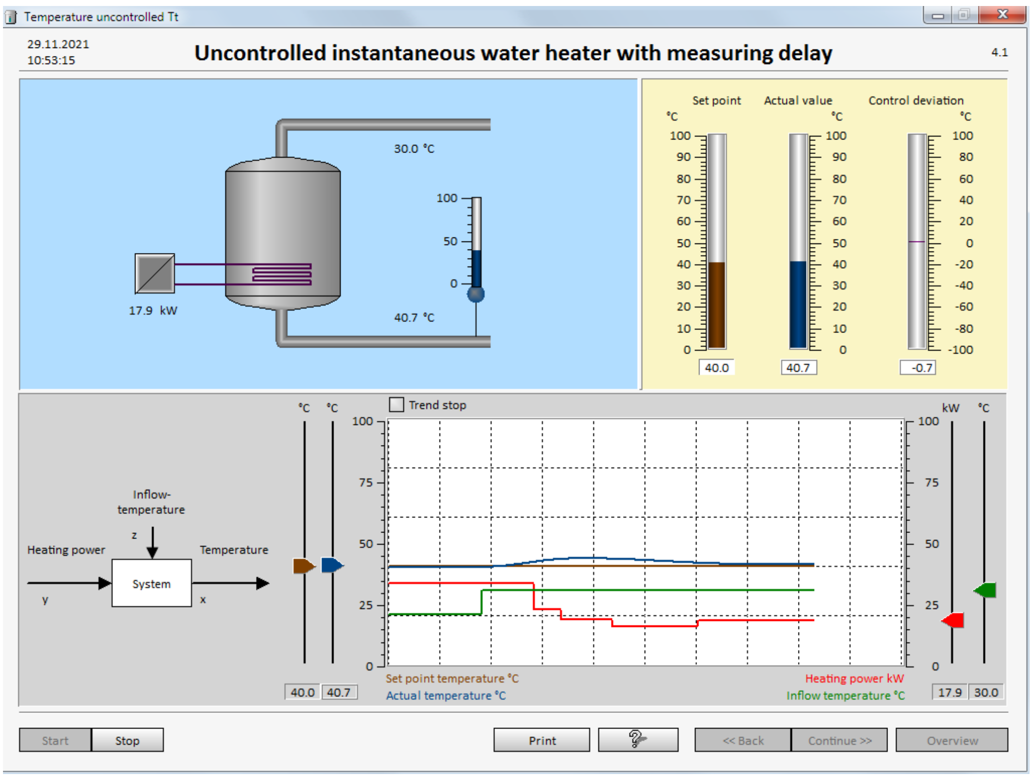
In the picture below you can see that after the change in heating power, the actual temperature starts to rise later.

Task 2.

Enter a disturbance. Change inflow temperature to 30°C.

Describe the behavior and try to control the disturbance.





Due to the increasing inflow temperature, the internal temperature increases and the heating power must be reduced. If an attempt is made to regulate a disturbance, this is referred to as the investigation of the disturbance response.

6.2 Controlled System

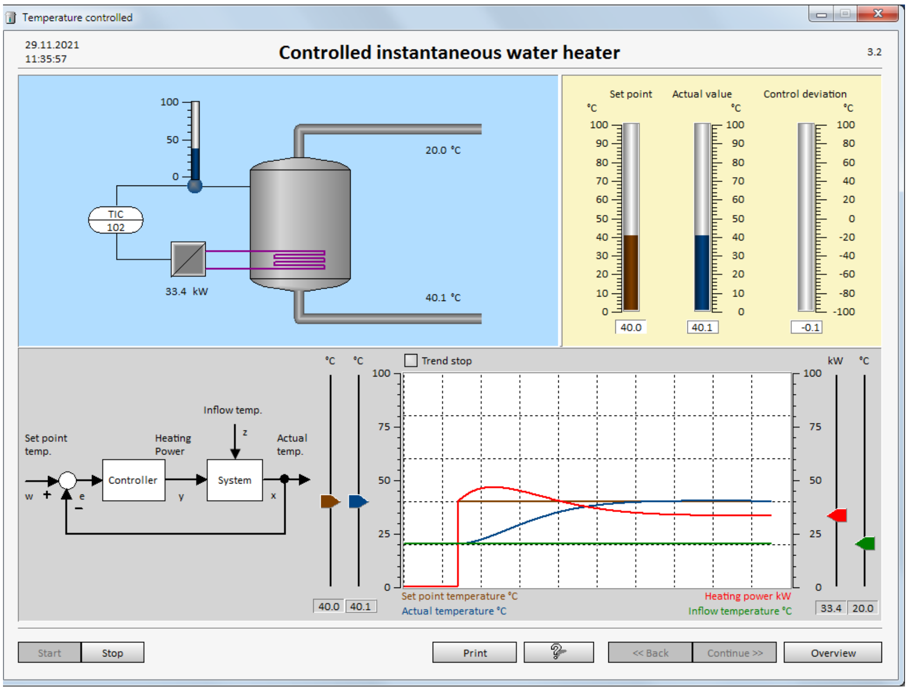
6.2.1 Closed-loop Controlled System

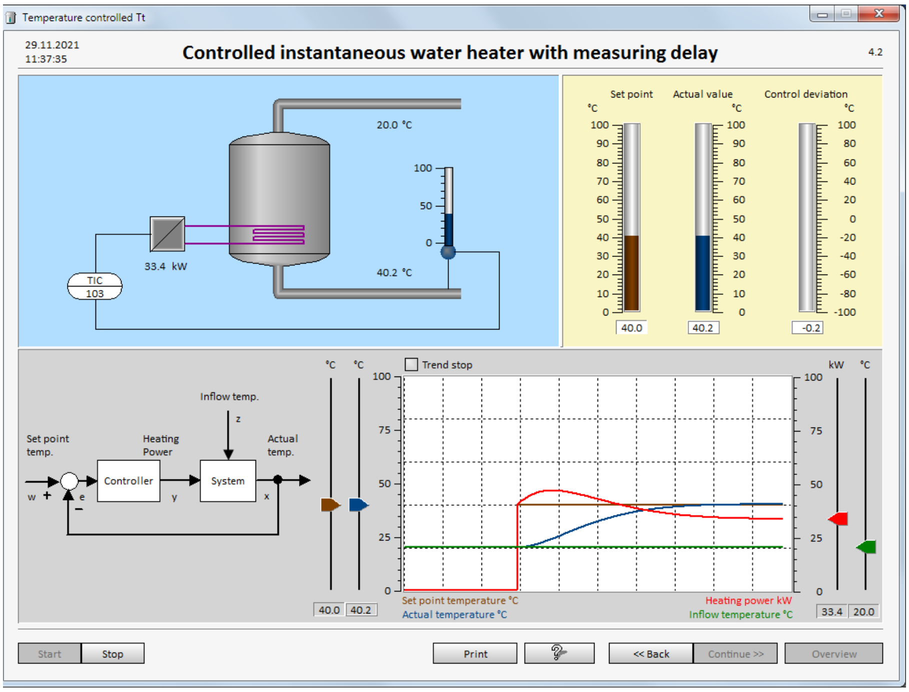
Go to „Overview“ and select item 3.2 respectively 4.2 „Closed-loop control system“.

Here you can see how the system behaves in principle if, instead of manual control by user, a controller takes over the task of adjusting the actual value to the set point.

Task 3.

Click „Start“ and change set point to 40°C.





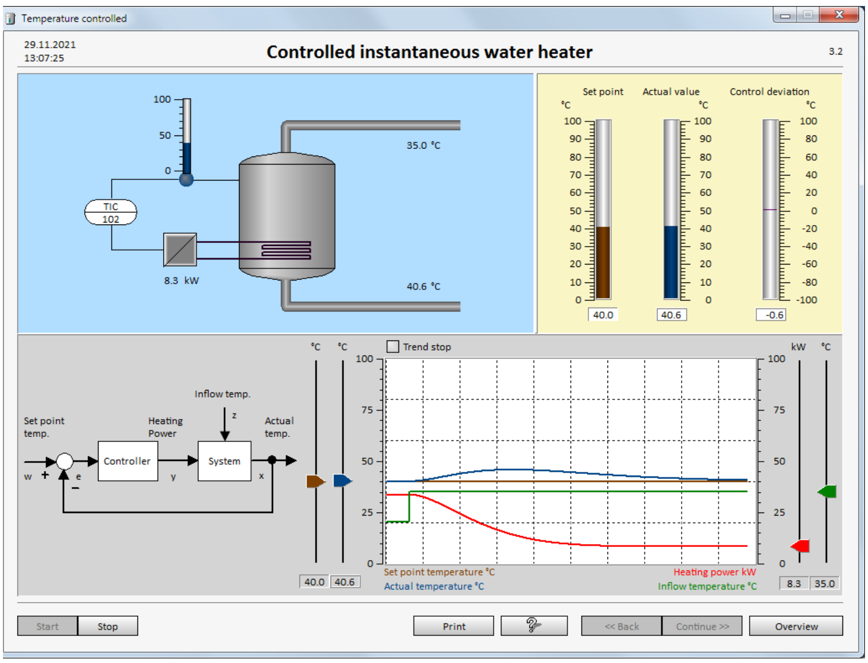
With a small overshoot, the actual value reaches the set point after a certain time in both cases. The examination of the system for a change in the set point (reference variable) is called command response.

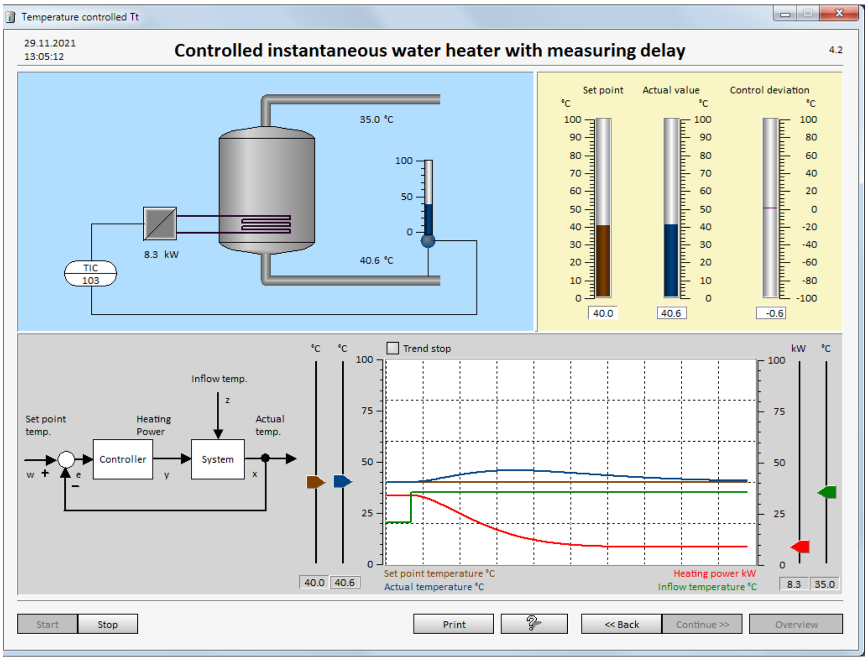
Task 4.

Investigate the disturbance response.

Set the set point to 40°C and wait until the system has settled (the actual temperature has reached 40°C and it no longer changes).

Increase the inflow temperature to 35°C. Observe the system behavior.





The internal temperature begins to rise. The controller therefore reduces the heating power.

6.2.2 Closed-loop Control with P Controller

Go to „Overview".

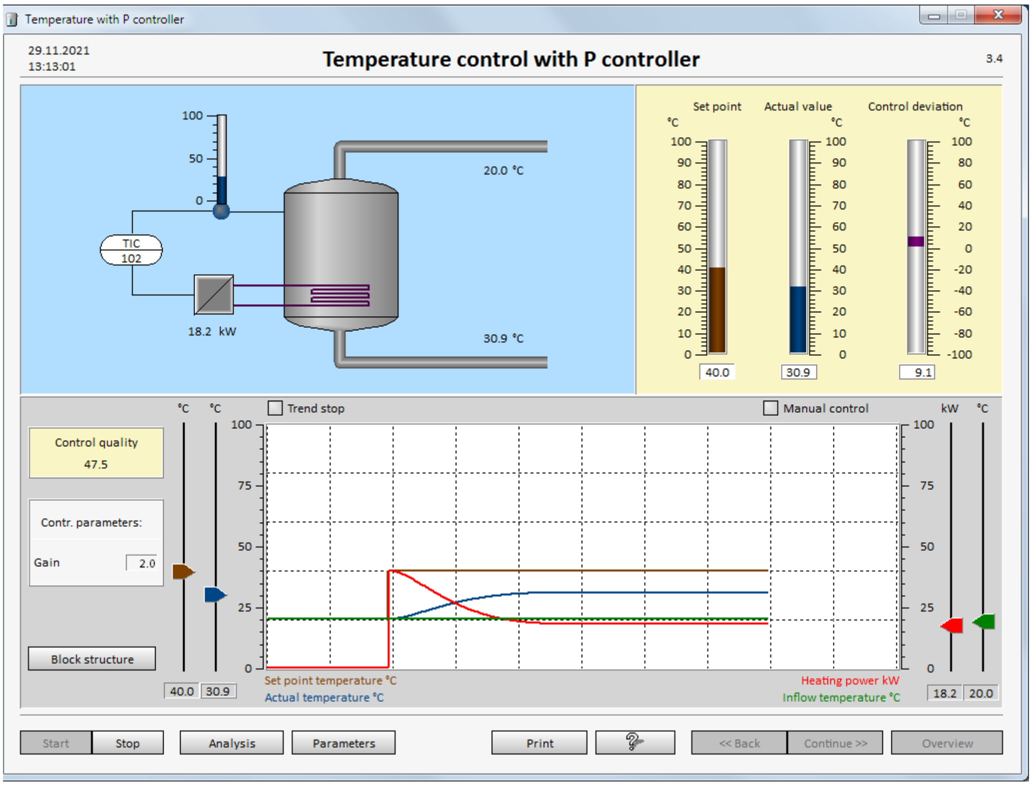
Select item 3.4 respectively 4.4 „Closed-loop control with P controller"

Click „Start".

Task 5.

Change the set point temperature (reference variable) to 40°C and wait until the control loop has settled, i.e. until the actual value no longer changes.

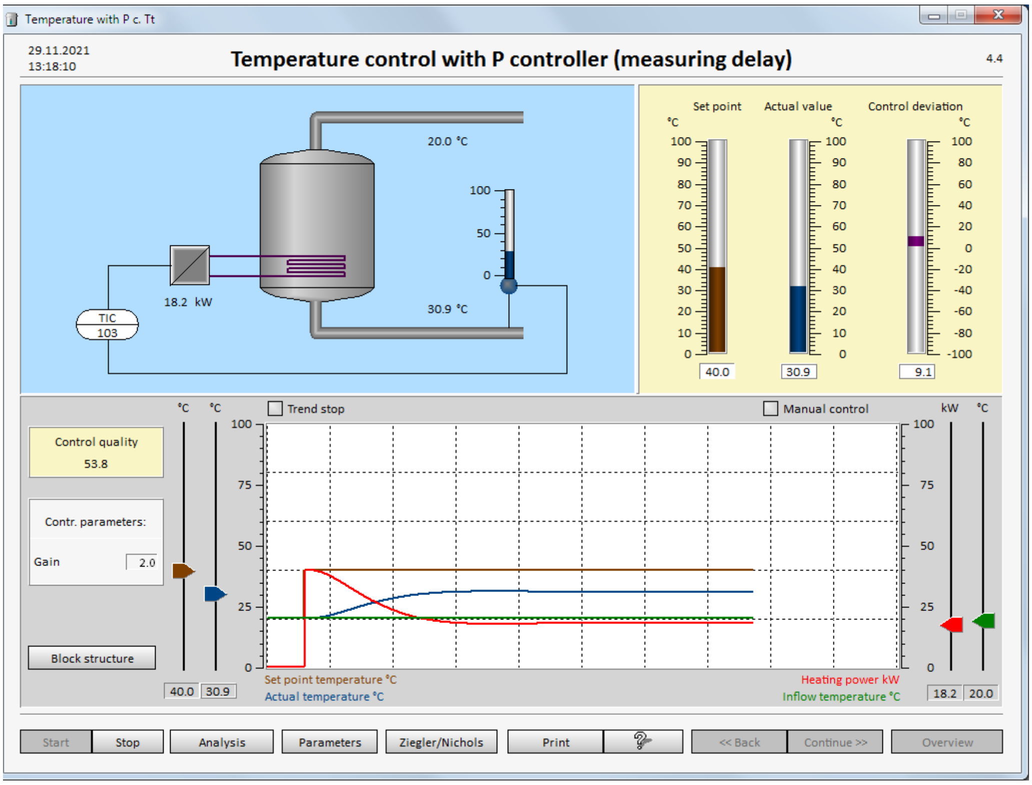
Observe the behavior.



After the settling phase, it can be clearly seen that the actual value (controlled variable) does not reach the set point (reference variable). We get a steady-state control error.

The control error e is defined as e = w – x, with

w = reference variable (set point) and x = controlled variable (actual value).



The P controller works like an amplifier. The input signal to the controller w - x (set point - actual value) is amplified with the specified amplification factor (here K = 2). In order for the P-controller to output a control signal (heating power) that is not equal to zero, the set point and actual value must be different, i.e. steady-state error.

If the P controller outputs 0, the heating power is switched off.

In the steady-state case, the value of the control signal y can be calculated using the control difference and the gain.

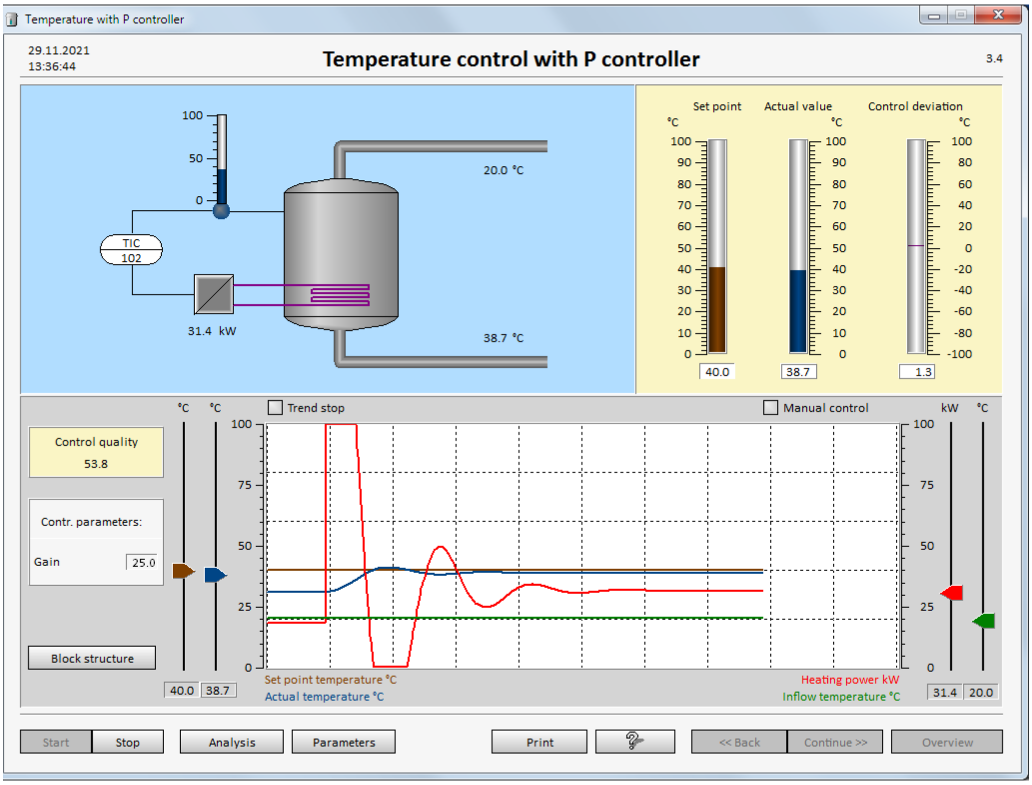
In the steady-state case, the actual value x (actual temperature) reaches the value 30.9°C at the set point value w = 40°C.

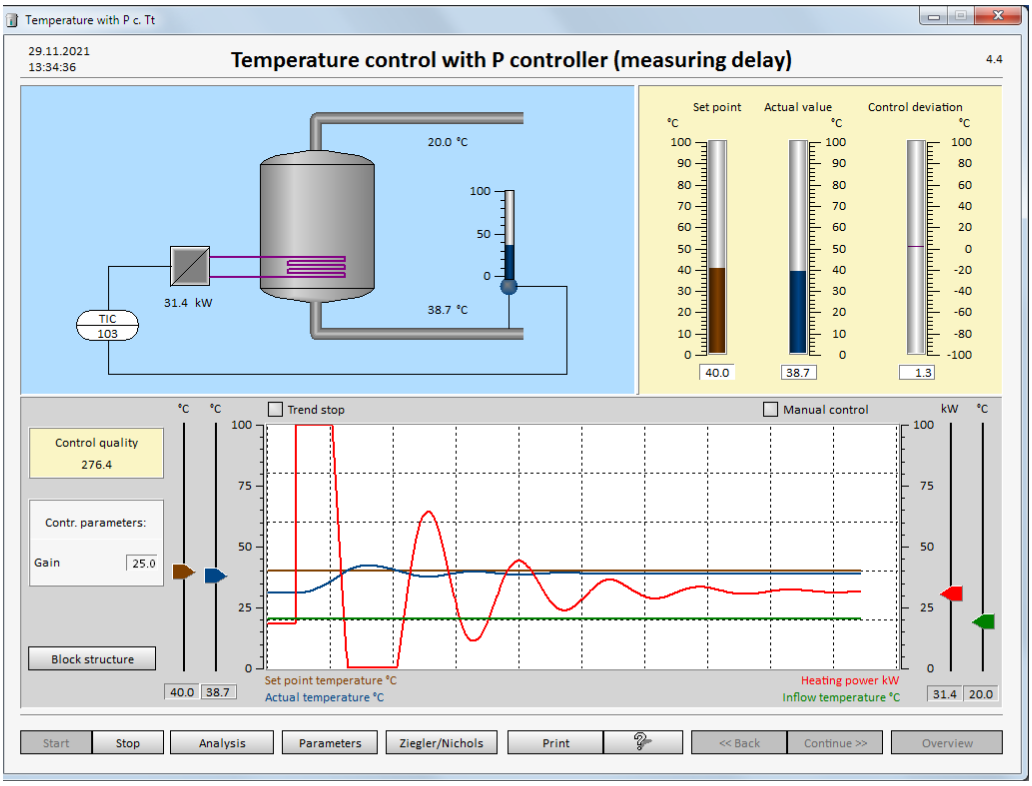
This results in:

Control signal y = K * (w – x) = 2 * (40 – 30,9) = 18,2

Task 6.

Change the gain of the P controller from 2 to 25 and wait until the control loop has settled again.





The control difference between the set point and the actual value becomes significantly smaller when the gain K is increased from 2 to 25. However, the P controller does not manage to adjust the actual value to the set point here either. For the reason described above, we also get a permanent, albeit significantly smaller, control error (e = w - x).

A difference in the system behavior with the gain 25 between the temperature control with and without time delay can be clearly seen.

The control loop with time delay (point 4.4) oscillates more. It is also possible to generate a continuous oscillation with an even higher gain. This can be used to determine controller parameters using the Ziegler/Nichols controller setting method. For further information you can click the button “Ziegler/Nichols” under point 4.4 “Temperature control with P controller (measurement delay)”.

The P controller also reacts to a disturbance (change in the inflow temperature). A steady-state control error is also obtained for this.

As can be seen from the settling response, the P controller reacts immediately and quickly to changes in the set point and disturbance values. However, with the P-controller you get a steady-state control error or the control loop can become unstable.

6.2.3 Closed-loop Control with I Controller

Go to „Overview“

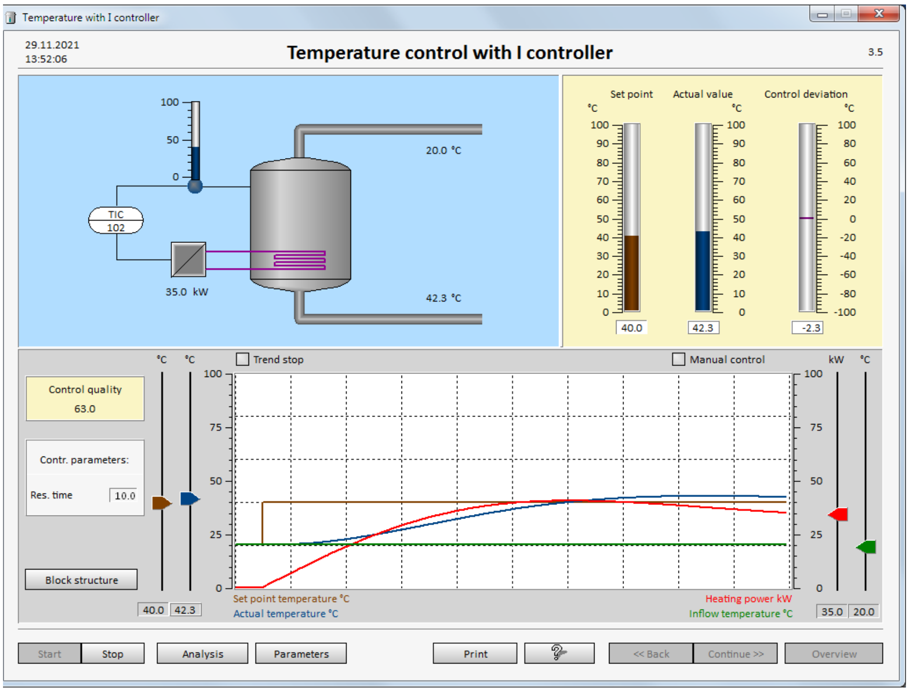
Select item 3.5 and respectively 4.5 „Closed-loop control with I controller“.

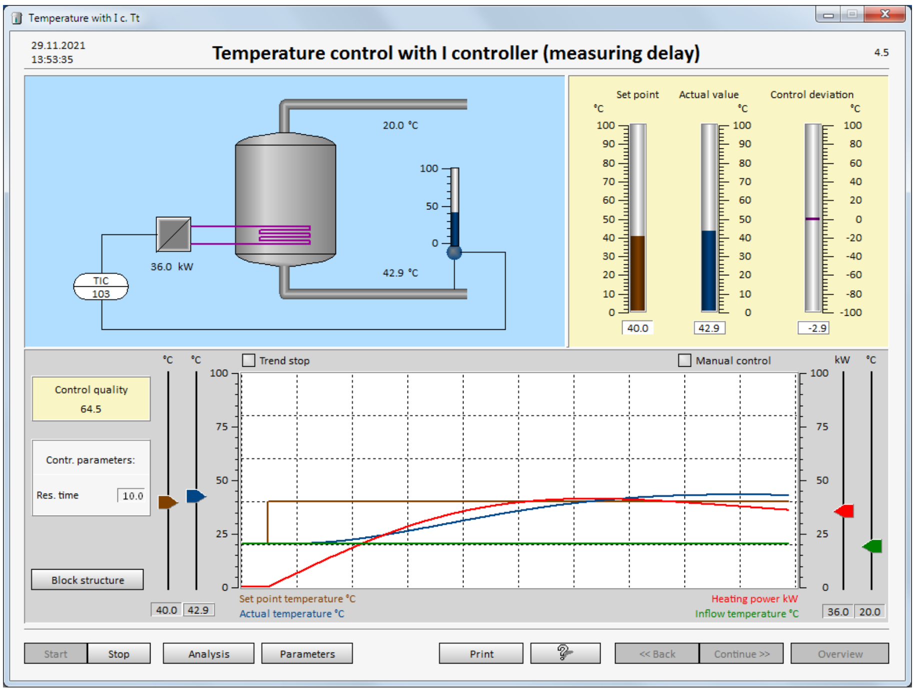
Click „Start“.

Task 7.

Keep the preset integration time Ti at 10. Examine command response.

Change the set point temperature (reference variable) to 40°C and wait until the control loop has settled, i.e. until the actual value no longer changes.



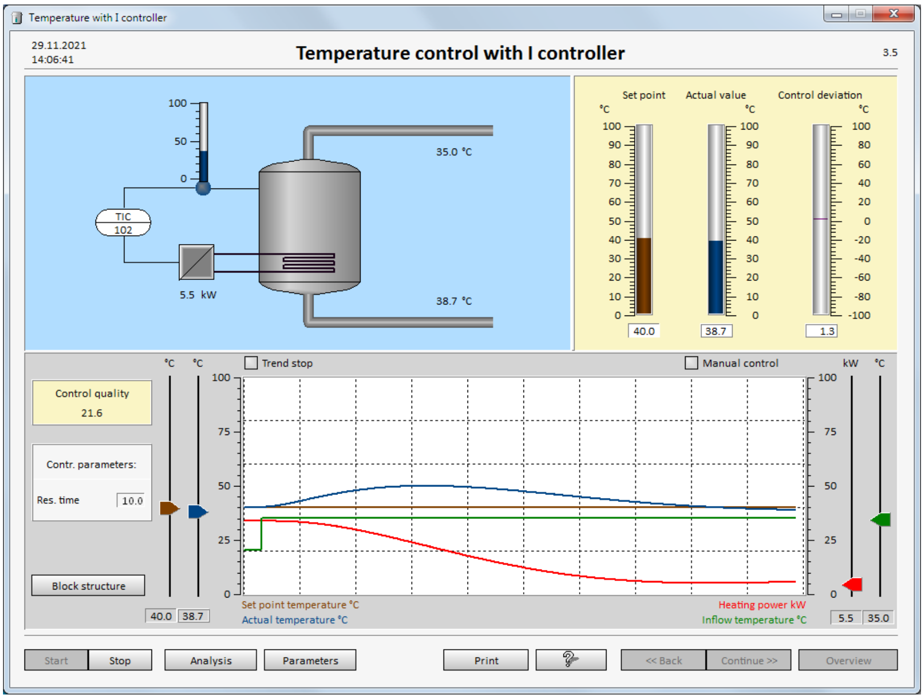


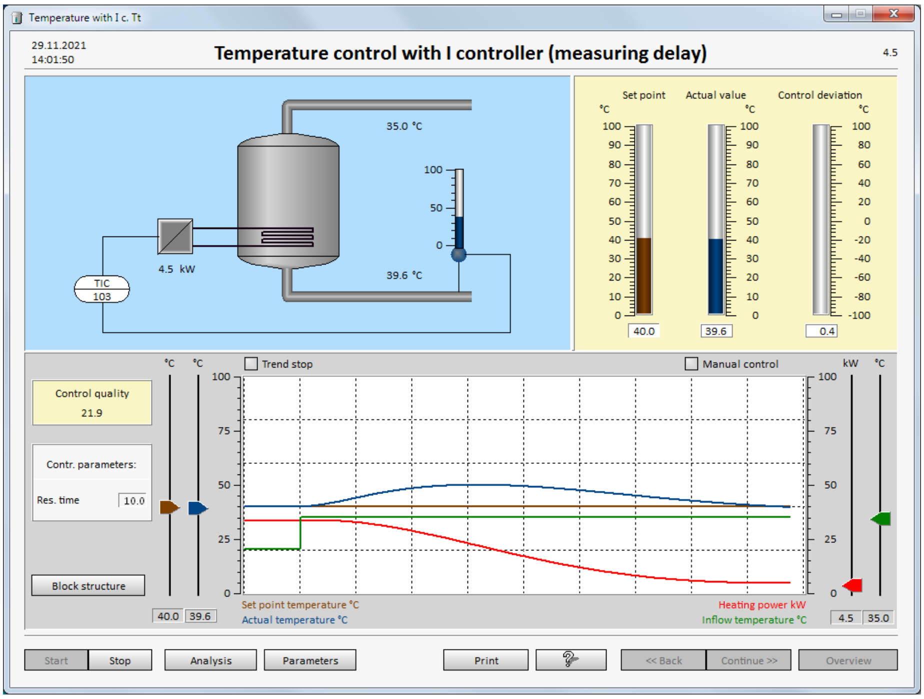
After a long settling phase, the actual value reaches the set point with an overshoot (using the integration time Ti of 10). You will not receive a steady-state control error.

Task 8.

Investigate the disturbance behavior. Enter a disturbance, change the inflow temperature to 35°C.

How does the control loop behave.

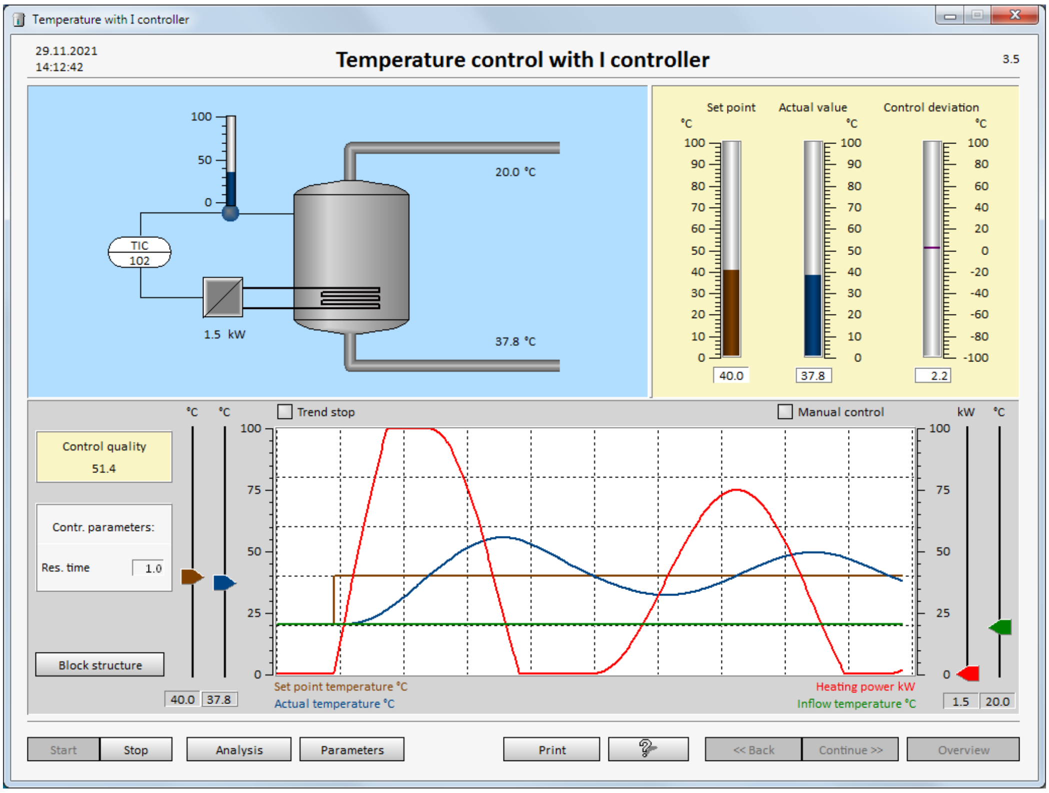




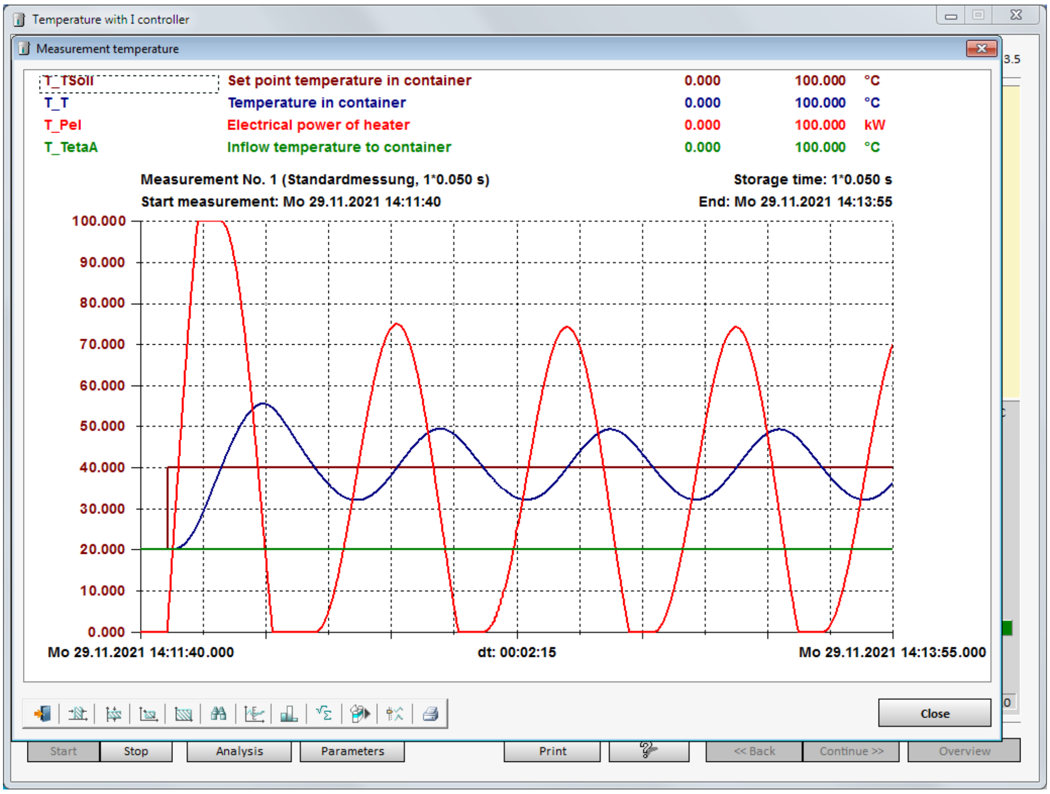
After a long settling phase, the actual value returns to the set point. There is also no steady-state control error for the disturbance behavior.

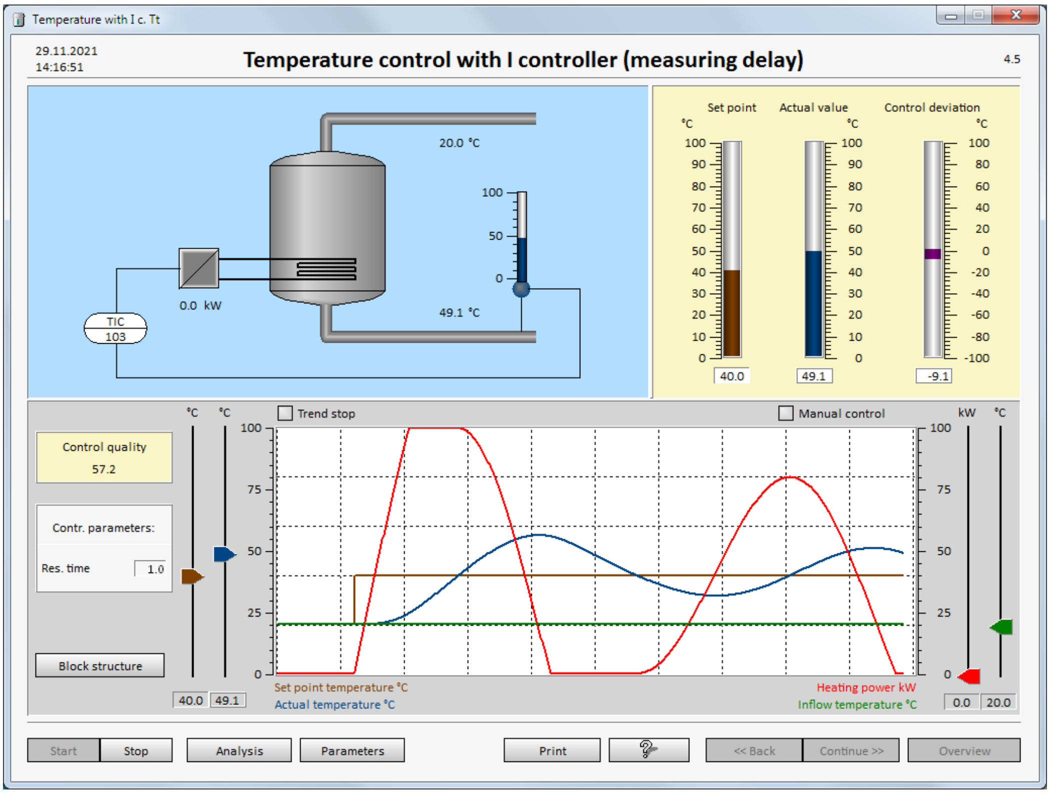
Task 9.

Restart the temperature control with the I-controller.

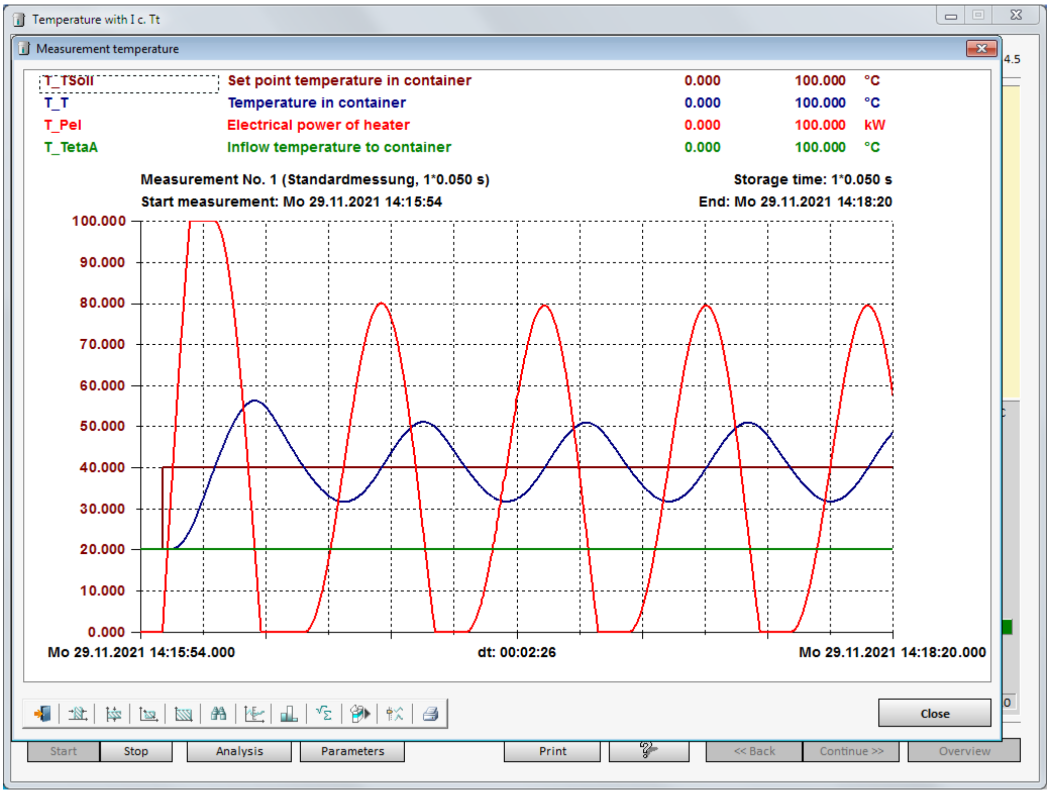


By clicking on "Analysis" you will get the recorded signal curves.





By clicking on "Analysis" you will get the recorded signal curves.



The control loop for temperature control with/without measurement delay becomes unstable. The actual value oscillates continuously around the set point.

In general:

Info:

If there is an I component (integrator) in the controller, the controller either manages to adjust the actual value to the set point after a settling phase or the control loop becomes unstable.

This is explained by the behavior of the integrator:

If the value of the input signal to an integrator is positive, the value of the output signal (control signal) increases. If the input signal is equal to zero, the integrator retains its output value (the value remains constant). If the input value is negative, the output value of the integrator decreases continuously.

In order for a control loop to settle to a value, the control signal (output of the controller) must be constant. The output value of an integrator is only constant when the input value of the integrator is equal to zero, i.e. when the set point and actual value are the same.

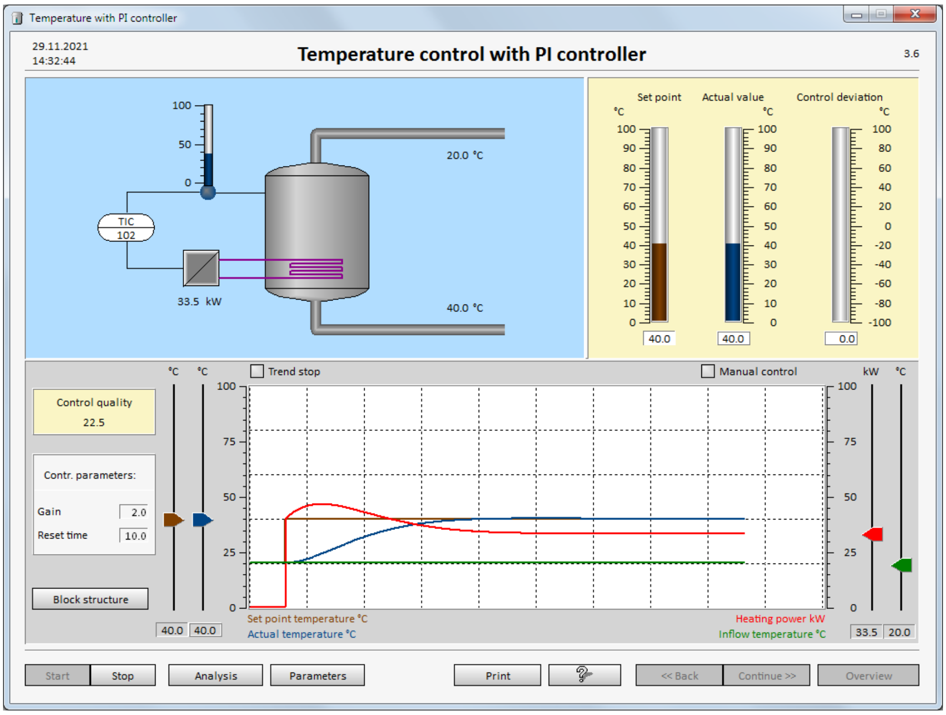
6.2.4 Closed-loop Control with PI Controller

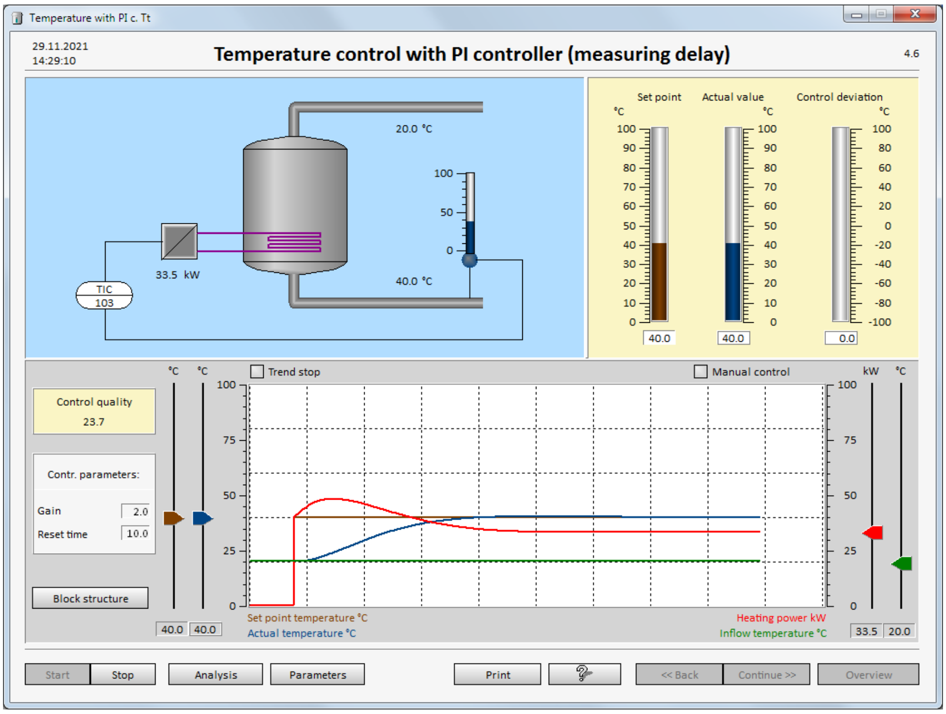
Go to „Overview“ and select item 3.6 respectively 4.6 „Closed-loop control with PI controller“. Click „Start“.

Task 10.

Set the parameters to K = 2, Ti = 10. Examine the command response

Change the set point from 20°C to 40°C.





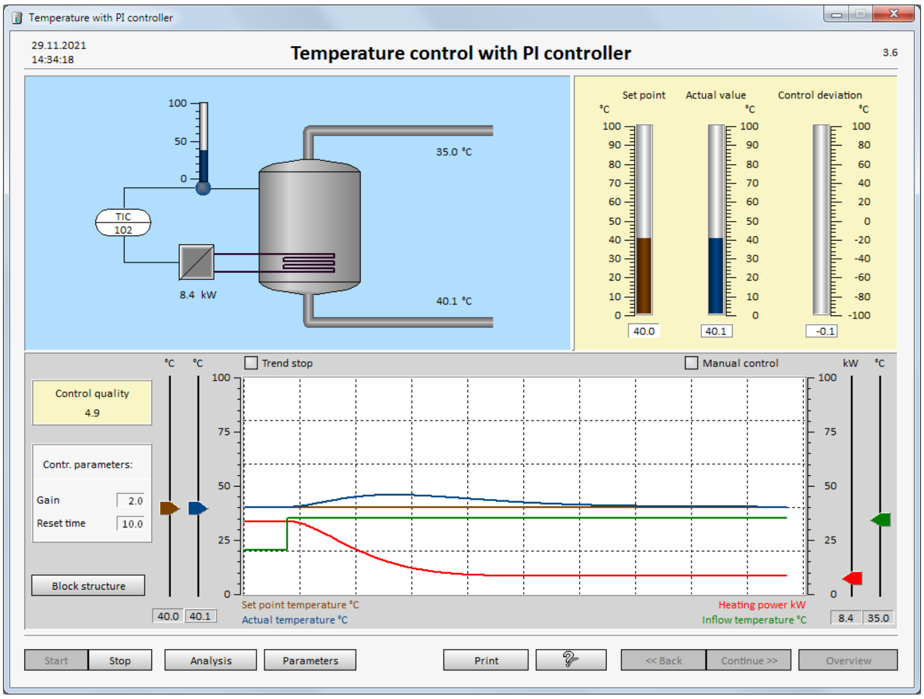
The control loop with the PI controller and the set parameters oscillates to the set point with a small overshoot. The actual value (controlled variable) reaches the set point (reference variable).

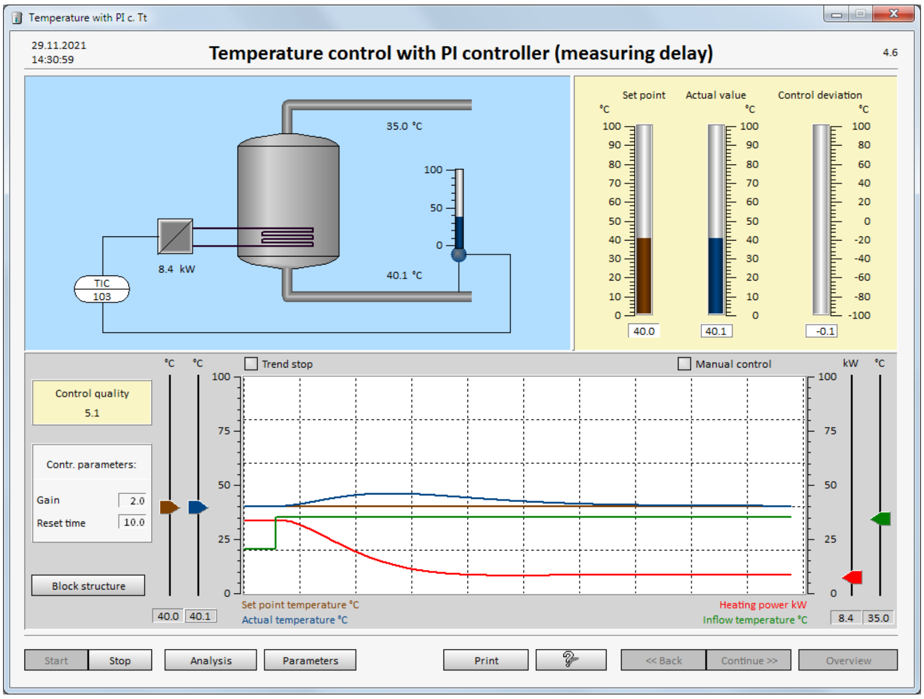
Task 11.

Investigate the disturbance response.

Let the control loop settle to the set point 40°C with the parameters K = 2 and Ti = 10.

When the control loop has settled, change the inflow temperature to 35°C and observe the behavior.





The higher inflow temperature causes the actual temperature in the container to rise. The controller tries to counteract this and reduces the heating power. After a settling phase, the actual value reaches the set point again.

Task 12.

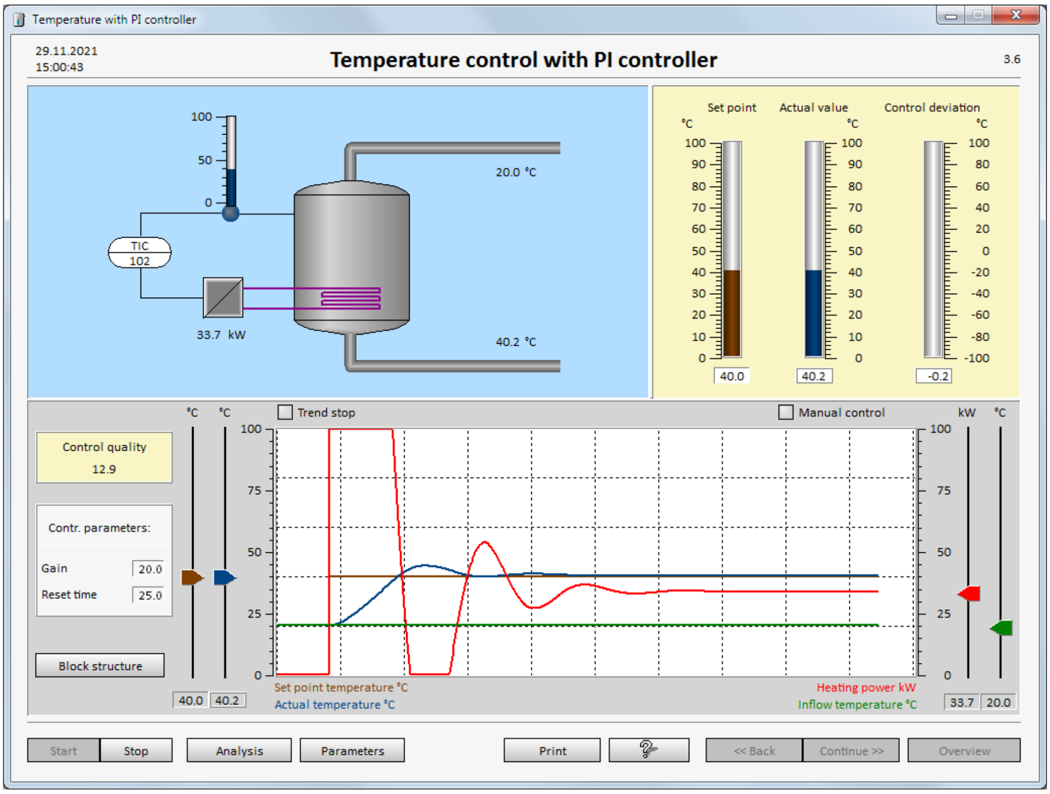
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled, when the actual value has reached the set point.

Try to reduce the value for the control quality by adjusting the controller parameters.

With the controller parameters K = 2 and Ti = 10, a control quality of 22.5 respectively 23.7 (temperature control with time delay) was achieved with a set point step from 20°C to 40°C.

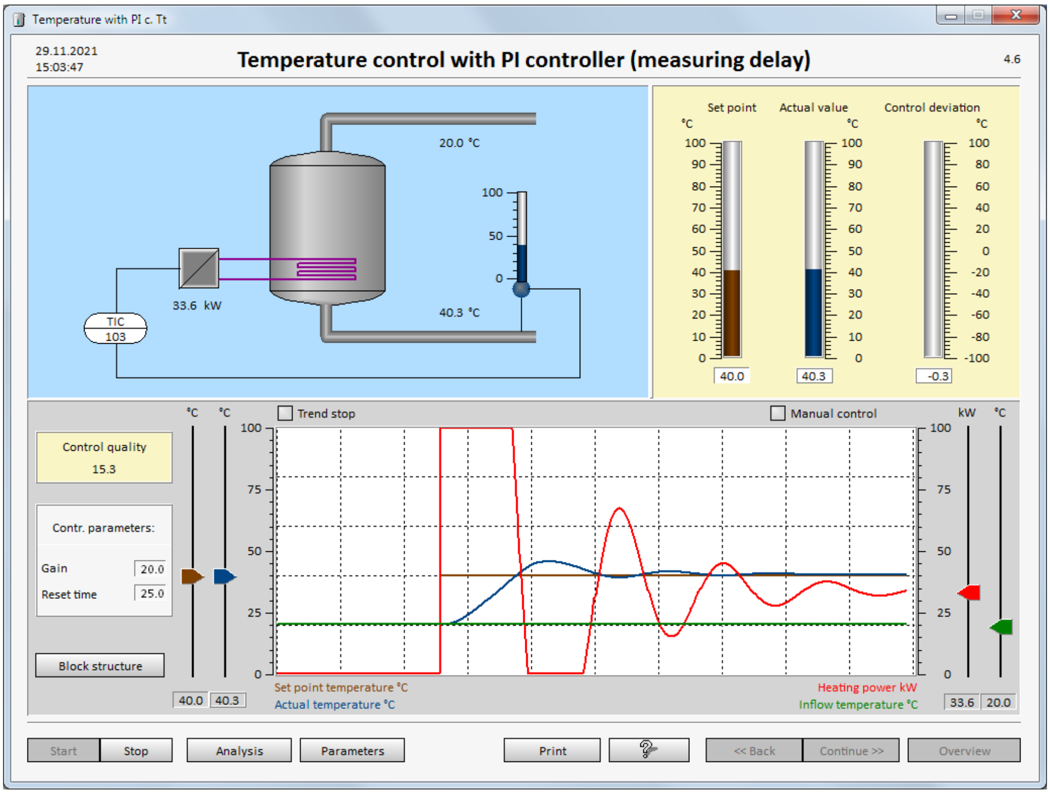
In order for the control quality to be comparable, all tests must be started with the same initial states. The best way to do this is to click “Stop” and then “Start” again. This means that the set point temperature (reference variable), inflow temperature (disturbance variable) and actual temperature (controlled variable) are restored to their initial values.

Now change the controller parameters and then adjust the set point to 40°C. Wait until the control loop has settled.



With the parameters gain K = 20 and reset time Ti = 25, a control quality of 12.9 is obtained, for example.

With these parameters you get a control quality of over 15 for the temperature control with measuring delay and a very restless settling with many overshoots.



Carry out the experiments with further controller parameters:

- Click „Stop“ and „Start“
- Set controller parameters
- Set the set point to 40°C
- Wait until the control loop has settled

> *Info:*
>
> Since the PI controller has an I component (integrator), it also applies here that the controller adjusts the actual value to the set point after a settling phase or that the control loop becomes unstable.

This is explained by the behavior of the integrator:

If the input value to an integrator is positive, the value of the output signal (control signal) increases. If the input signal is zero, the integrator retains its output value (the value remains constant). If the input value is negative, the output value of the integrator decreases.

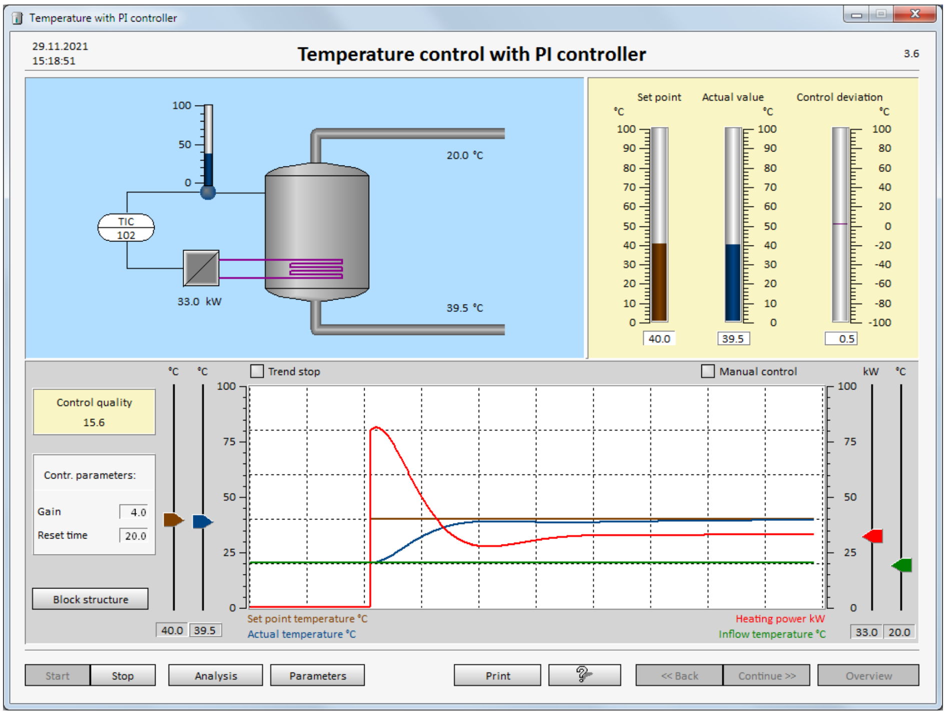
In order for a control loop to settle to a value, the control signal must be constant (output of the controller). The output value of an integrator is only constant when the input value of the integrator is equal to zero, i.e. when the set point and actual value are the same.

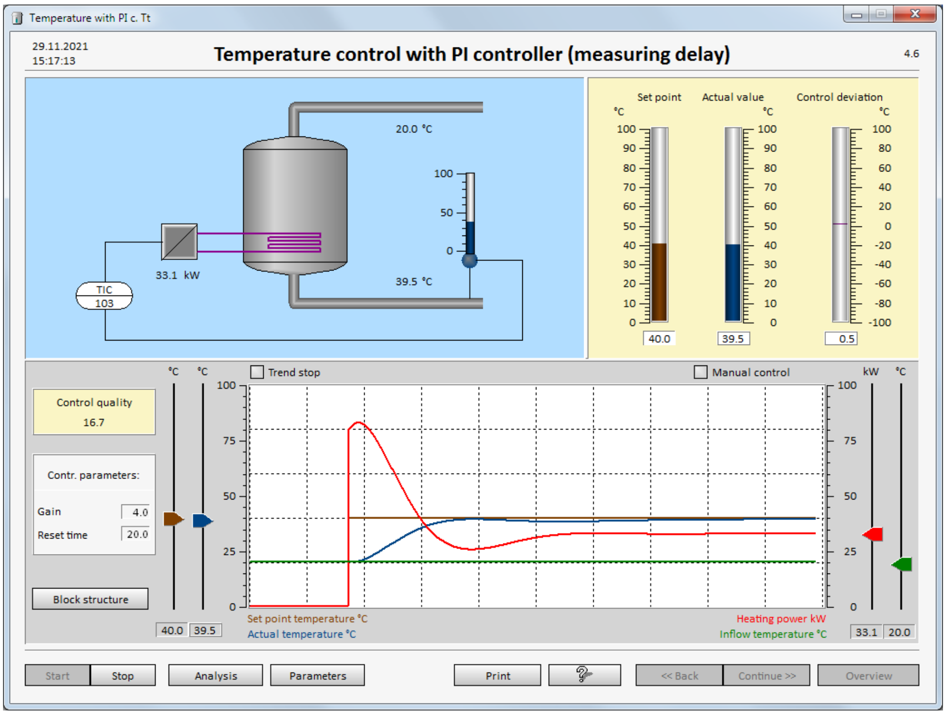
Task 13.

Restart the temperature control with the PI controller.

Try to find controller parameters with which the actual value reaches the set point without overshooting. In this case one speaks of an aperiodic case (without overshoot).

Go back to the initial state, adjust the parameters and then change set point to 40°C.





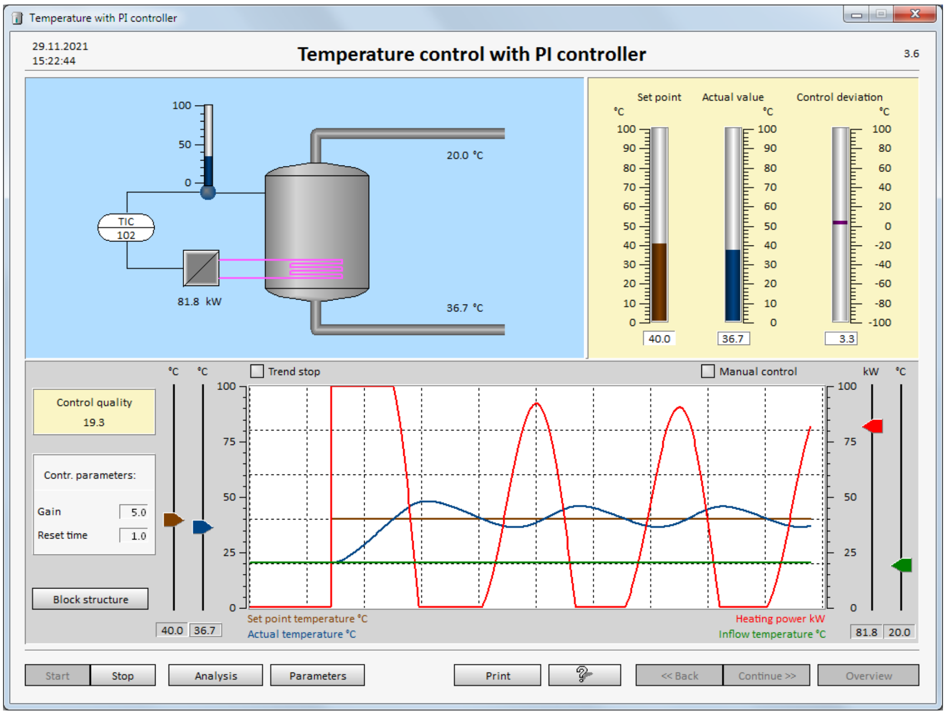
With the parameters K = 4 and Ti = 20, for example, an aperiodic behavior is obtained for both temperature controls.

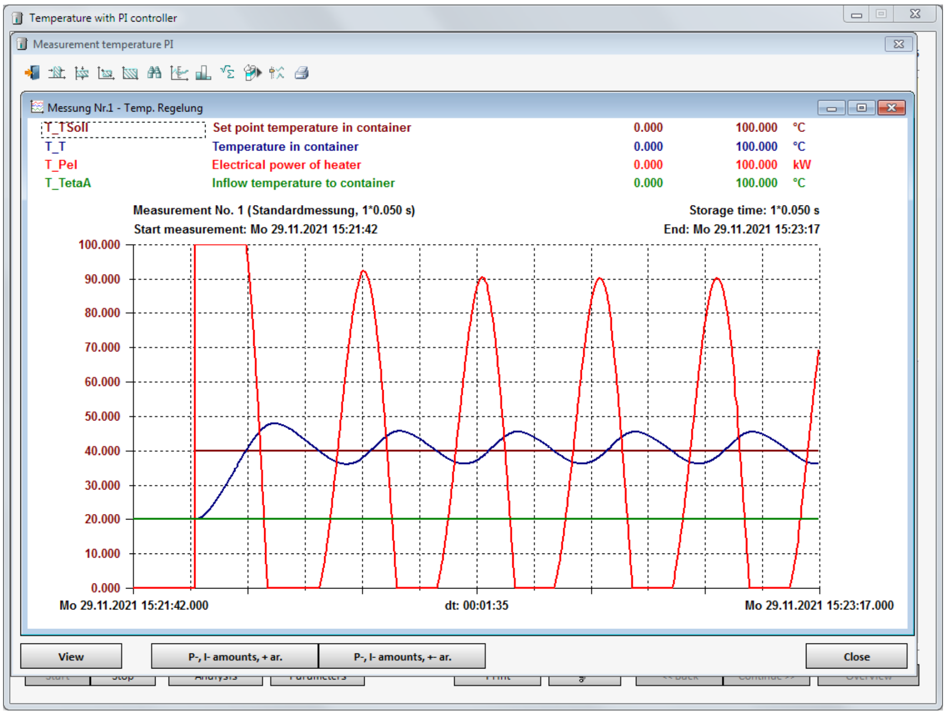
Task 14.

Restart the temperature control with the PI controller.

Try to set the controller parameters so that the control loop becomes unstable.

Enter a set point step from 20°C to 40°C in each case.

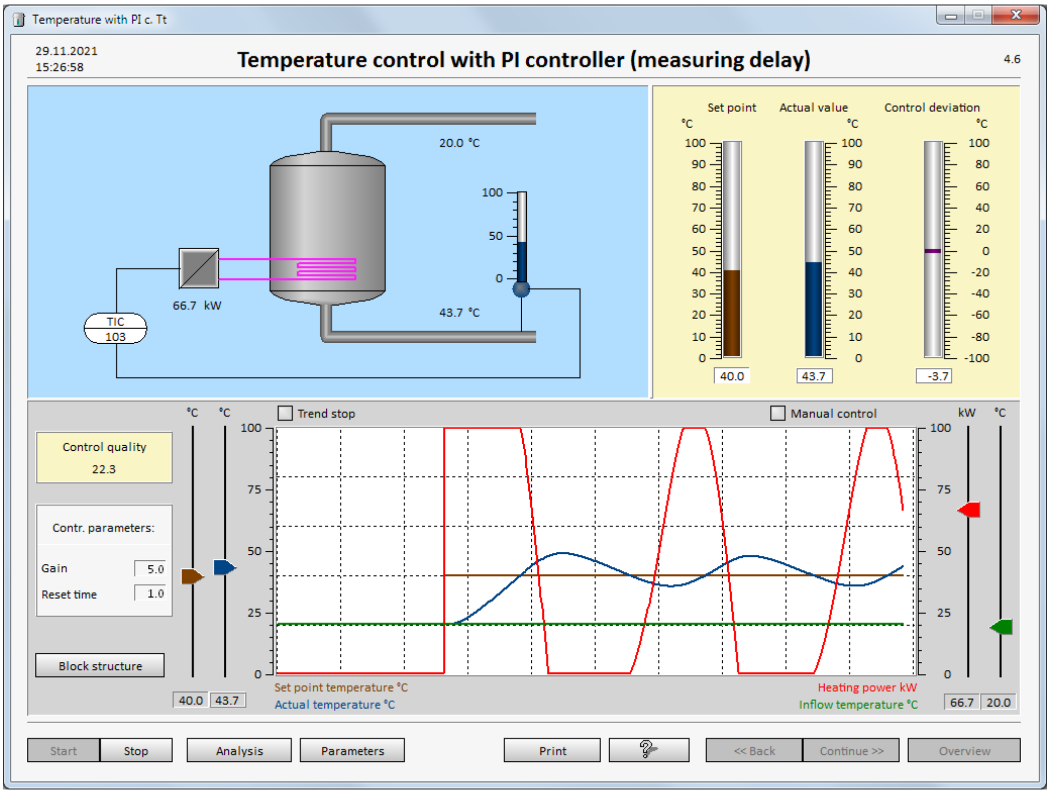


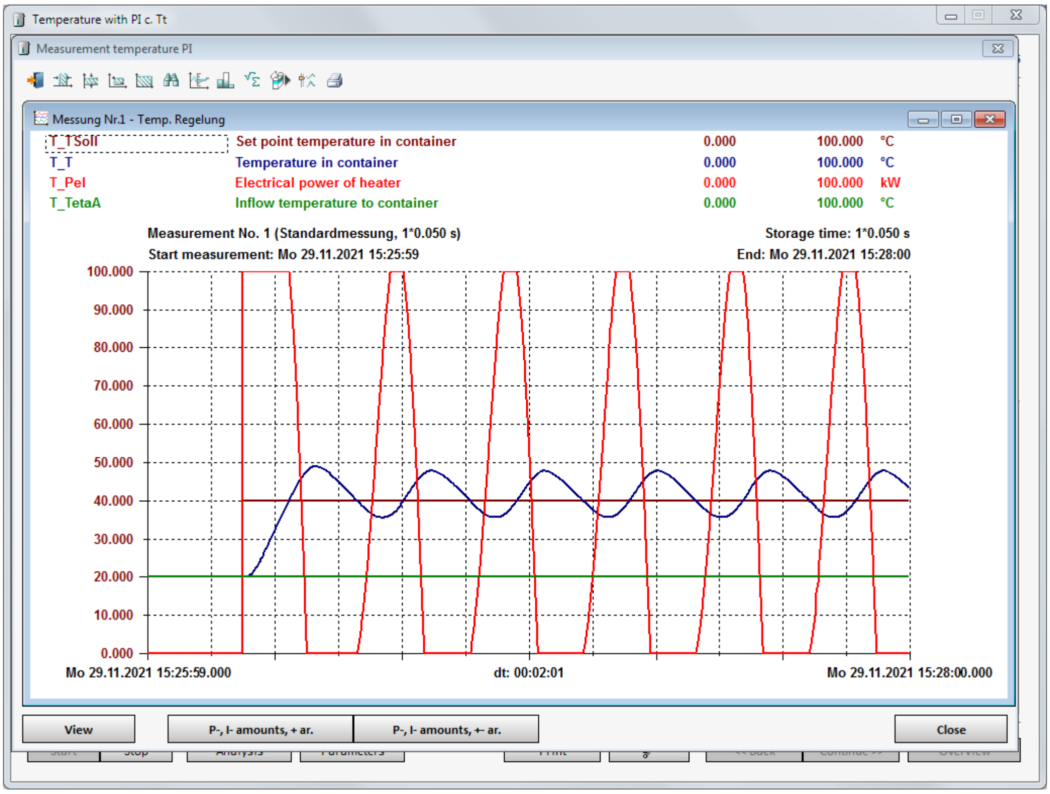


You can achieve this with the controller parameters:

Gain K = 5 and reset time Ti = 1s.

Even with temperature control with time delay, you will get an unstable behavior with these parameters.





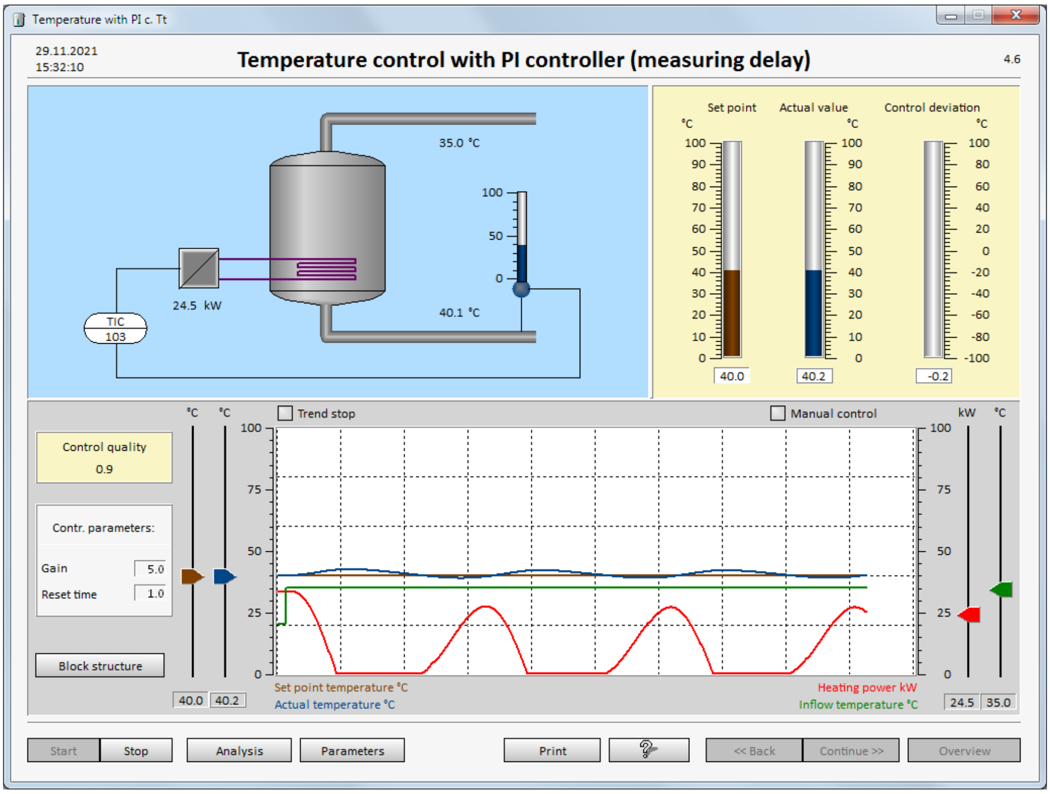
By clicking "Analysis" you have the option of looking at the stored signal curves and examining the settling behavior.

Task 15.

In the above task, the control behavior was investigated with the parameters gain K = 5 and the reset time Ti = 1s.

Now examine the disturbance behavior with these parameters.

Let the control loop settle stably to the set point of 40°C. Then change the parameters to gain K = 5 and reset time Ti = 1. Enter a fault step from 20°C to 35°C.



The control loop with these parameters also becomes unstable for the disturbance response.

As a conclusion it can be said:

- With the PI controller and appropriately well set controller parameters, the control loop can be regulated quickly and easily. The actual value reaches the set point and remains at the set point.
- This applies to the command response as well as to the disturbance response.
- If the parameters are set incorrectly, the control loop can also become unstable.

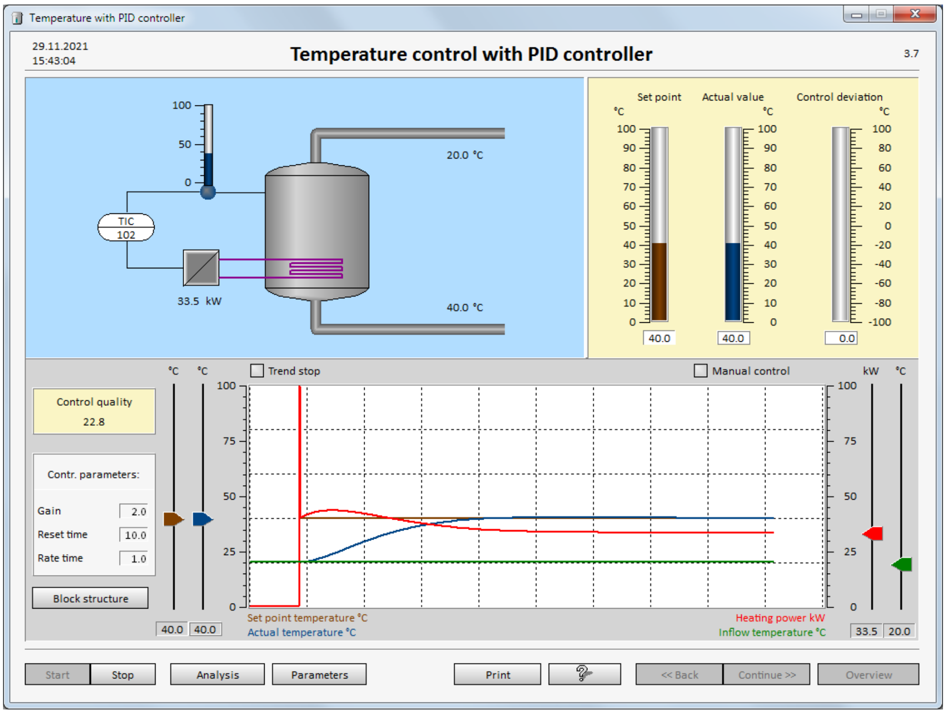
6.2.5 Closed-loop Control with PID Controller:

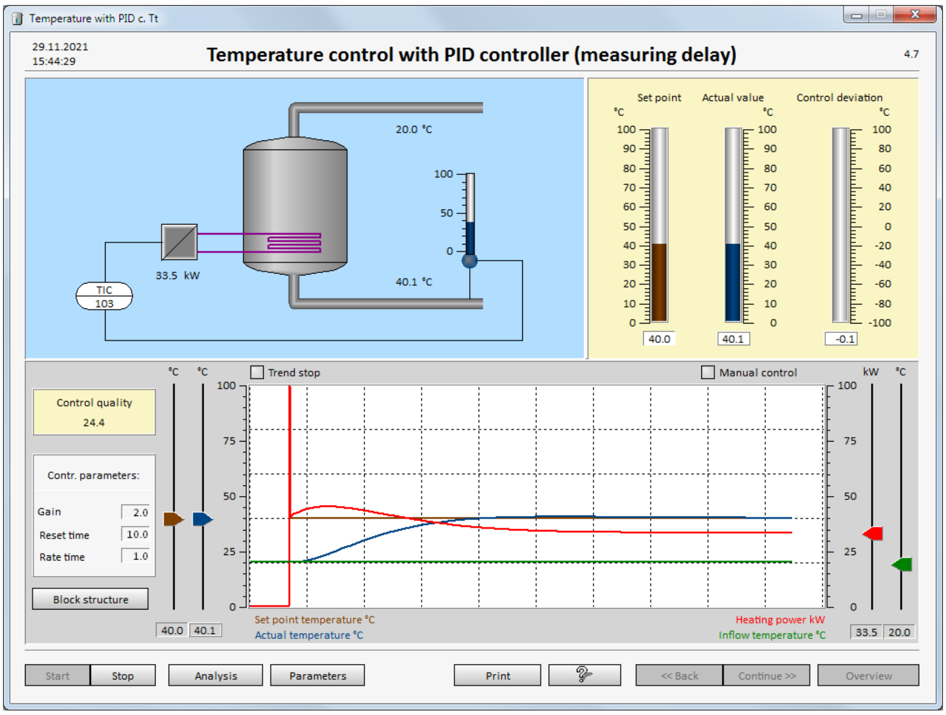
Go to „Overview“ and select item 3.7 respectively 4.7 „Closed-loop control with PID controller“. Click „Start“.

Task 16.

Investigate the control behavior with the preset parameters: Gain K = 2, reset time Ti = 10, derivative time (rate time) Td = 1

Change the set point to 40°C.





The control loop goes into a stable state with a small overshoot. The actual value reaches the set point.

As can be seen in the trend diagram, the sudden change in the set point causes a peak in the control signal (heating power). This peak is triggered by the D component of the controller. The derivation of a sudden change causes an (infinitely) large value.

The control quality reaches 22.8 respectively 24.4 and is therefore similar to the PI controller with the parameters K = 2 and Ti = 10.

Note on the trend display with the PID controller:

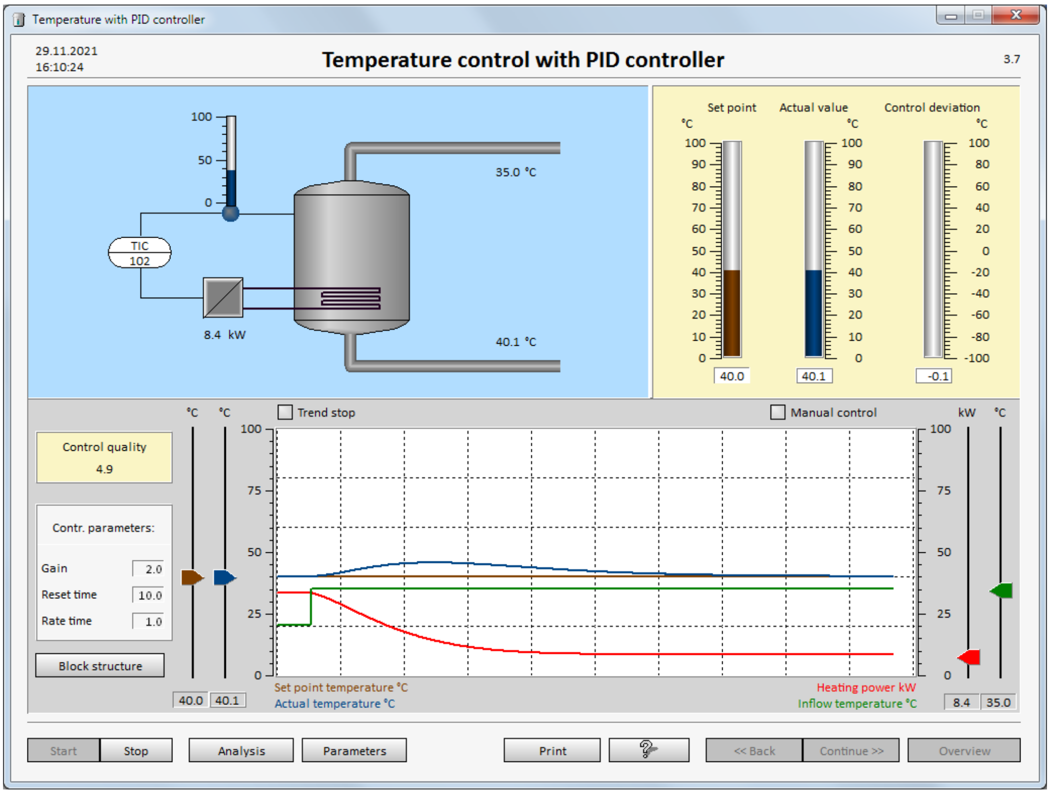
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Analysis" (display of the stored signal values) and selection of a corresponding time range.

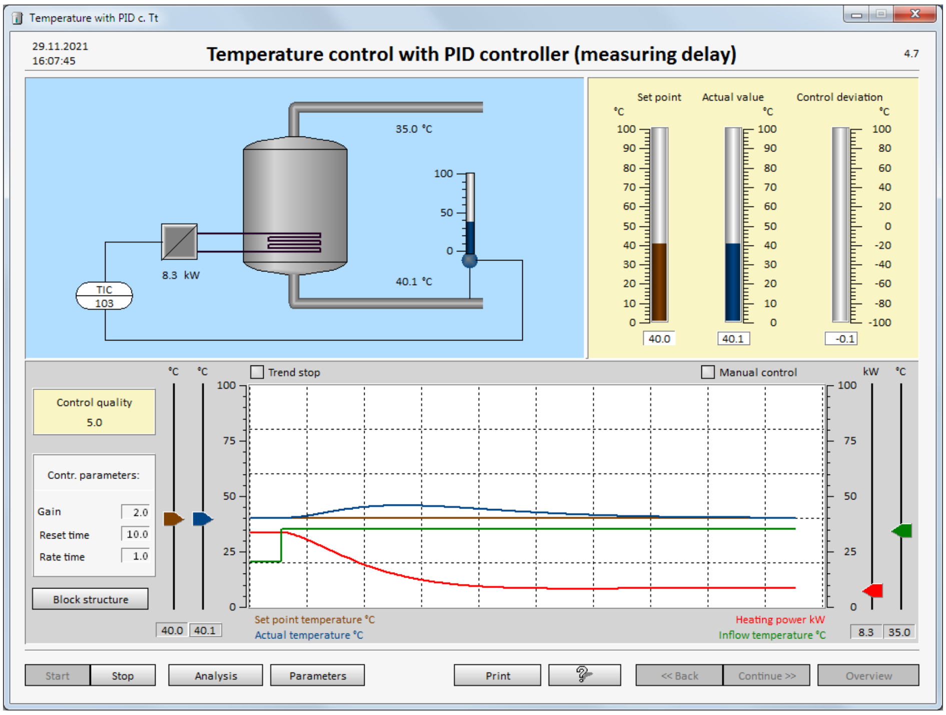
Task 17.

Investigate the disturbance behavior with the preset parameters:

Gain K = 2, reset time Ti = 10, derivative time (rate time) Td = 1

Let the system settle to the set point temperature of 40°C (the actual temperature reaches 40°C and does not change any more) and change the inflow temperature from 20°C to 35°C



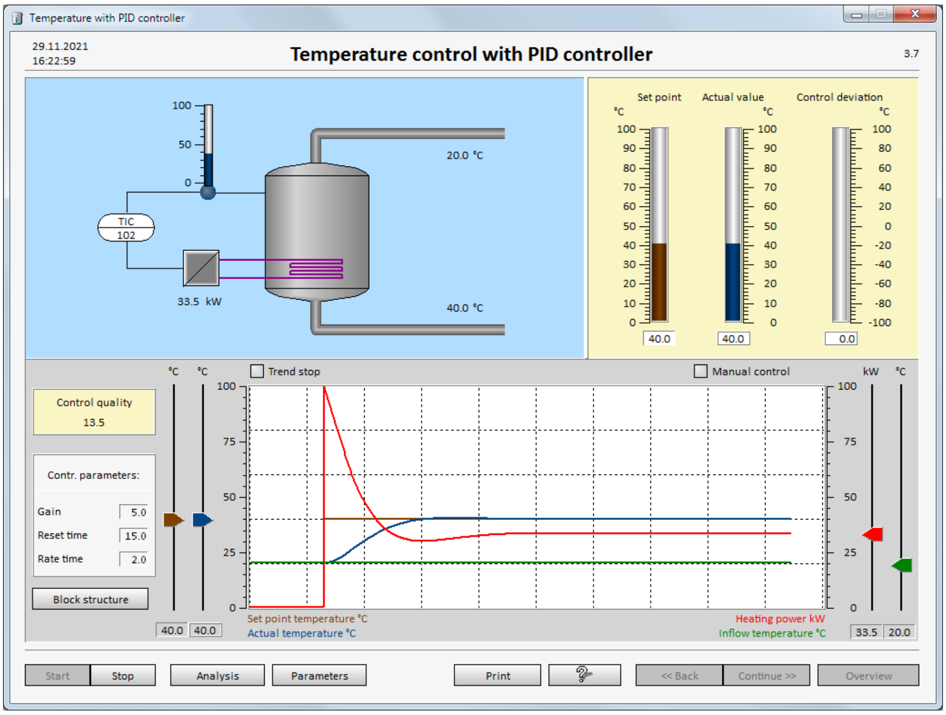


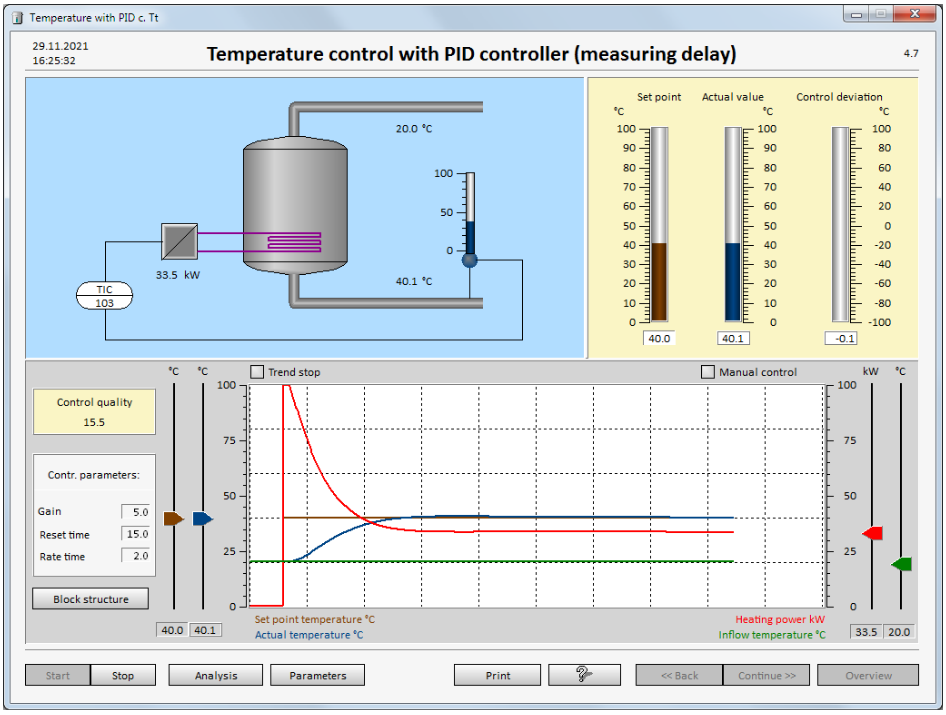
In the event of a disturbance response, too, the control loop is controlled with the specified controller parameters and the actual temperature (controlled variable) reaches the set point temperature (reference variable) again after a period of time.

Task 18.

Try to improve the control quality by adjusting the controller parameters.

So that you can compare the experiments, you must always start from the same initial states. Therefore click “Stop” and “Start” again, change the controller parameters and then adjust the set point to 40°C.





With the controller parameters K = 5, Ti = 15 and Td = 2 you get e.g. a control quality of 13.5 respectively 15.5.

The experiments that were carried out with the PI controller can also be carried out with the PID controller (unstable behavior, aperiodic behavior, etc.).

Info:

In practice, the PI controller is most common. If a PID controller is used, the D component is often turned off so that the controller only works as a PI controller.

One of the reasons for this is that the D behavior in a control loop is difficult to assess. In principle, the D component gives you the option of making the control faster (which is often very difficult, however).

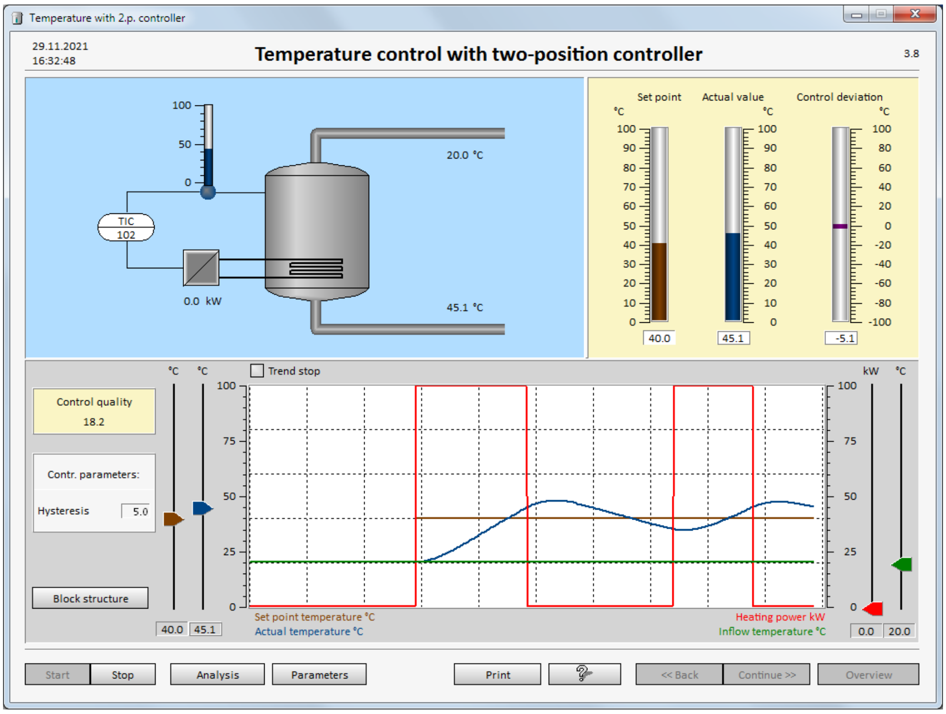
The D component considers the change between the set point and the actual value. If the change increases, i.e. the difference between the set point and actual value increases, the D component adds a calculated value to the control signal. If the difference between the set point and the actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend, whether the difference between the set point and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the set point and actual value decreases, the control signal is reduced.

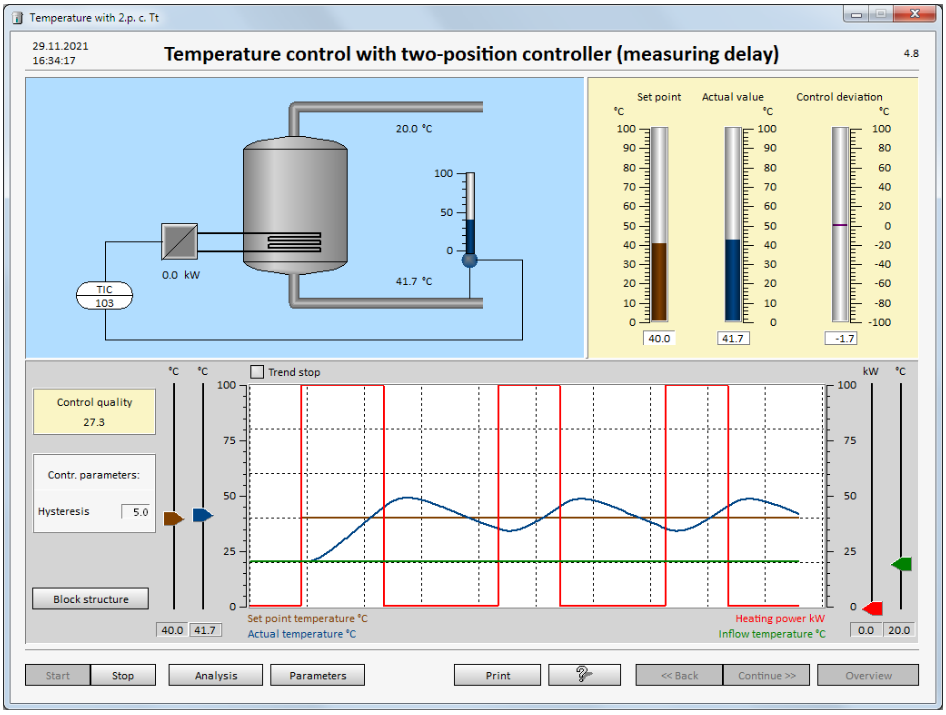
6.2.6 Closed-loop Control with two-pos. Controller

Go to „Overview“ and select item 3.8 respectively 4.8 „Closed-loop control with two-pos. controller“. Click „Start“.

Task 19.

Set the hysteresis to 5. Change the set point to 40°C and observe the behavior.





The actual temperature (controlled variable) fluctuates around the set point. The amplitude of the oscillation depends on the parameter (hysteresis).

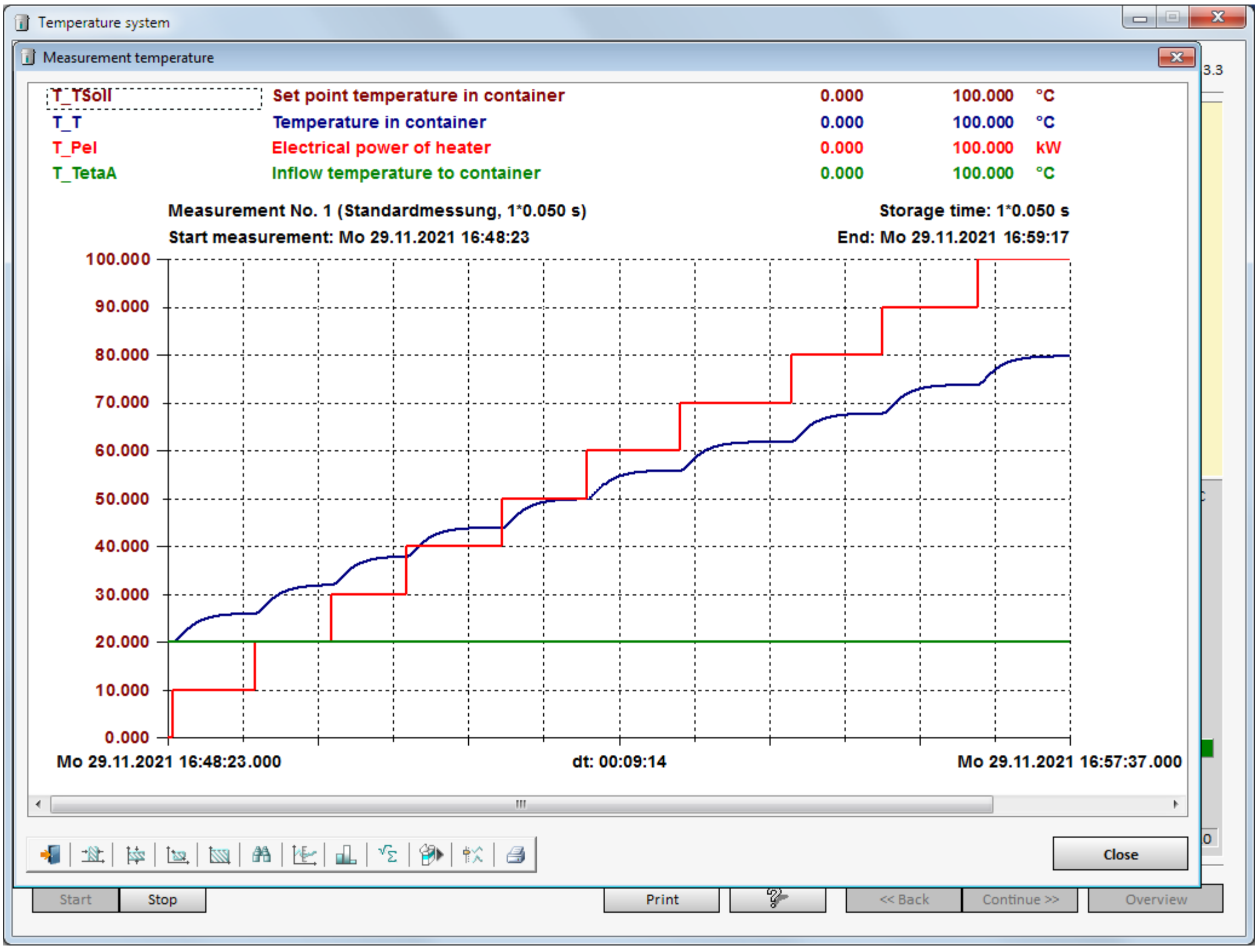
6.3 Examine Controlled System

Select point 3.3 respectively 4.3 "Examine controlled system".

Task 20.

Increase the heating power by 10% each time and wait each time until the actual temperature no longer changes.

Observe the temperature behavior.



As can be seen from the recorded data, the behavior of the system during the steps is similar. The actual temperature always changes by approx. 6°C when the heating power changes by 10%. This does not always have to be the case with a controlled system.

With many controlled systems, the behavior depends on the operating point. This means that the controls will behave differently in different operating points with the same controller and the same controller parameters.

6.4 Controller Tuning Rules

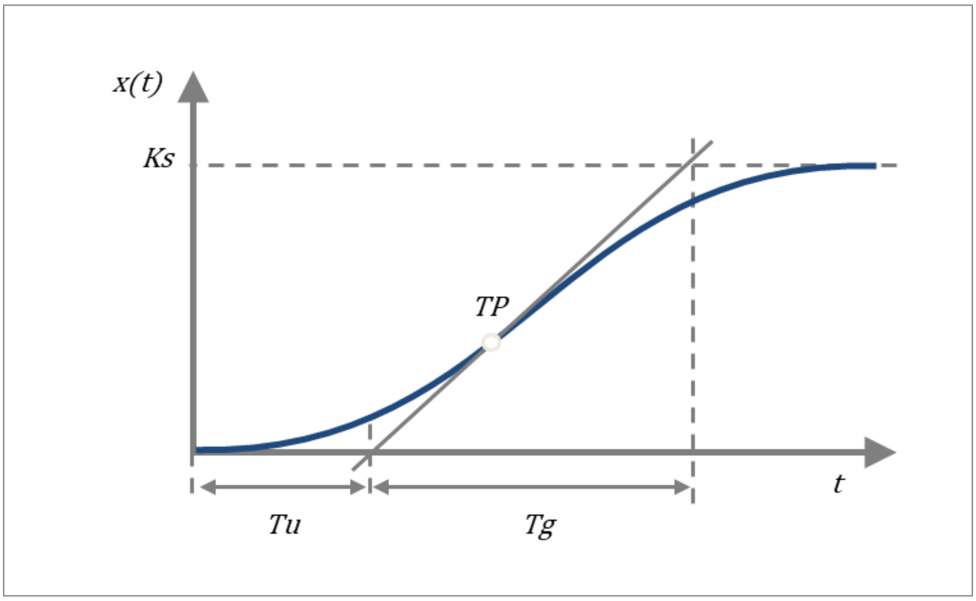
The temperature system with and without time delay is a controlled system with self-regulation.

In the event of a sudden change in the actuating variable (control signal), a controlled system with self-regulation oscillates to a constant value after a finite time, while with a controlled system without self-regulation, the controlled variable (actual value) continues to rise.

The behavior of the temperature in the container is a controlled system with self-regulation, since when the heating power is suddenly adjusted, the temperature returns to a fixed value after a certain time (inflow temperature remain constant), as was shown under point 6.3.

The method according to Chien/Hrones/Reswick is to be used as a controller tuning procedure for controlled system with self-regulation.

A controlled system with self-regulation has roughly the following behavior in response to a step in the control signal (sudden change in the control signal by 1):



In the new standard, the delay time is designated with Te, the compensation time with Tb and the turning point with P.

Since the terms Tu and Tg are still used in most of the literature, we keep the old terms here, or use both.

The parameters Ks, Tg and Tu can be determined from this step response, as shown in the figure above. The controlled system´s gain Ks (final value of the actual variable) results from the abrupt change in the control signal by 1. If the amount of change is greater, you have to divide the resulting system´s gain value by the amount the control step value in order to obtain Ks.

It means:

Te = Tu = Delay time

Tb = Tg = Compensation time

Ks = Gain

With the help of these three parameters, the controller parameters can then be determined from the setting table according to Chien / Hrones / Reswick:

Table 4: Equations to calculate controller parameters according to Chien/Hrones/Reswick

Controller	Quality criteria			
	With 20 % Overshoot		Aperiodic case	
	Disturbance	Command	Disturbance	Command
P	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$
PI	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.3 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 4 \cdot T_U$	$K_P \approx \frac{0.35}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.2 \cdot T_g$
PID	$K_P \approx \frac{1.2}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2 \cdot T_U$ $T_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.35 \cdot T_U$ $T_V \approx 0.47 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.4 \cdot T_U$ $T\_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$ $T_V \approx 0.5 \cdot T_U$

For systems without self-regulation use $\frac{T_g}{(K_S \cdot T_U\ )}$ instead of $\frac{1}{(K_{IS} \cdot T_U\ )}$.

The table was taken from: E. Samal, Grundriss der praktischen Regelungstechnik, Oldenbourg

Task 21.

For temperature control select item 3.3 respectively 4.3 „Examine controlled system“.

Click „Start“. Enter a step of the heating power from 0% to 10%.

All signal curves are saved and can be measured and evaluated using "Analysis".

Determine the parameters Ks, Te (Tu) and Tb (Tg) from the stored signal curves.

By clicking on the "Analysis" button, you will get the measurement curves. With the help of the button bar in the window, time and value segments can be selected (Zooming).

Try to find the area of interest for the evaluation with the step in heating power and the settling of the actual temperature.

For example, you can then print out the diagram and measure the curves using a ruler to determine Te and Tb.

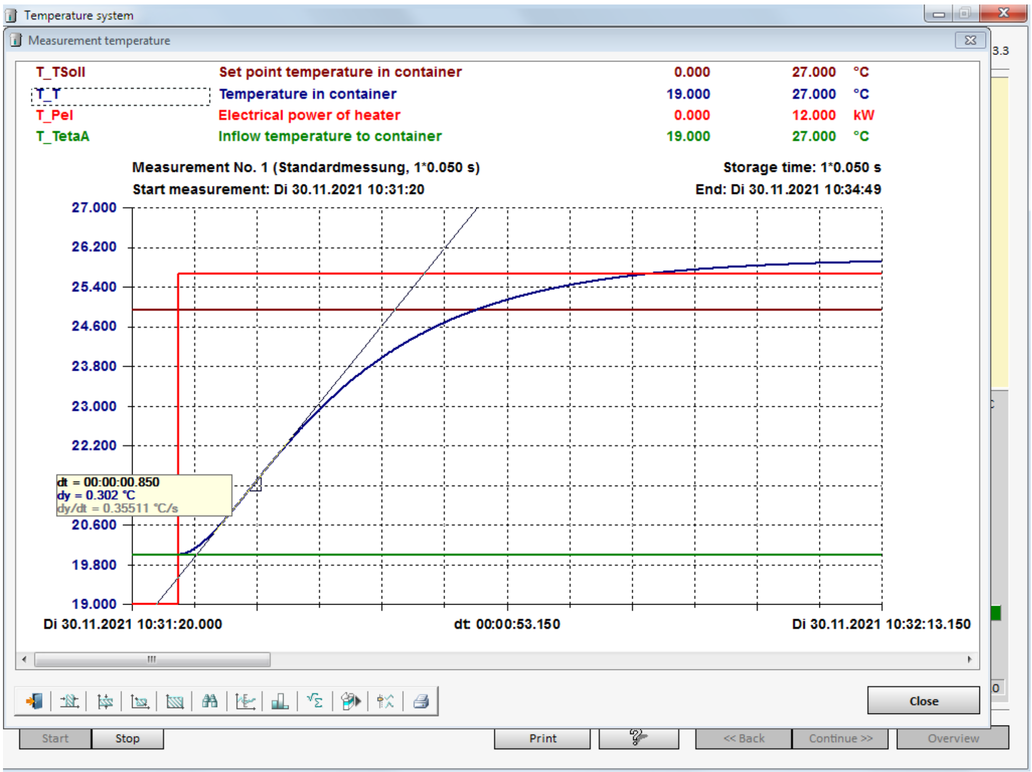


Figure 27: Signal curve for temperature system without time delay

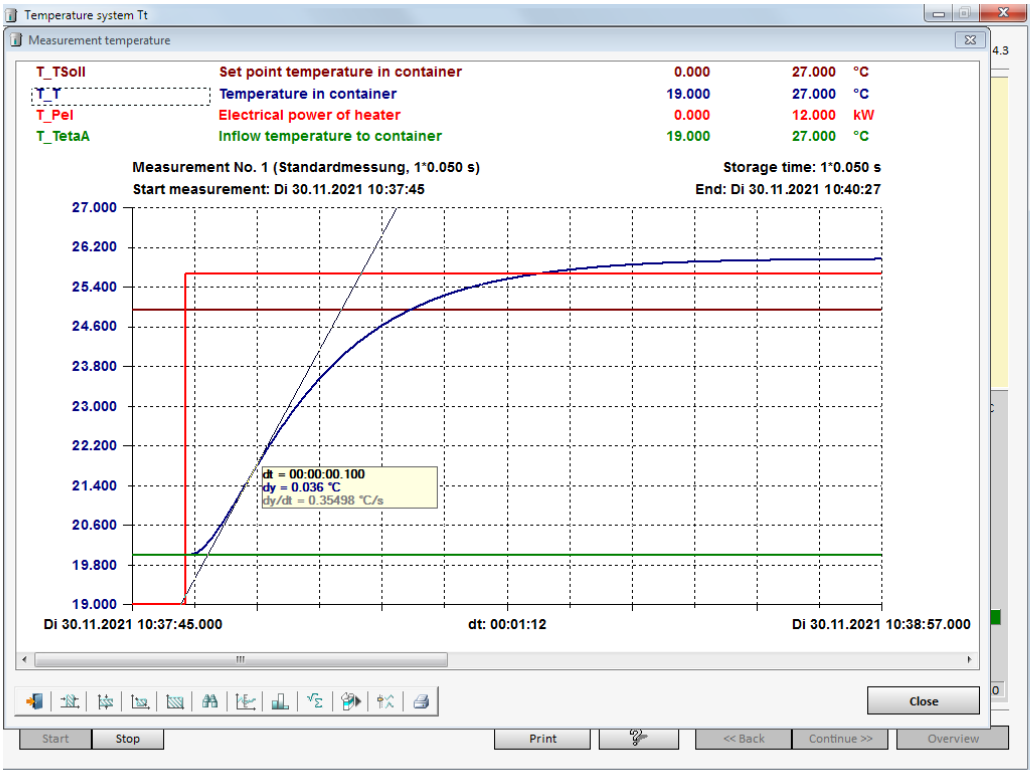


Figure 28: Signal curve for temperature system with time delay

It is also possible to measure the values in the diagram. To do this, click on the blue signal "T_T" in the header (Temperature in container). Click on the blue curve to get the associated measured value and time. By drag and drop, the time and value difference as well as the slope are indicated. With this you can try to determine the derivation of the blue curve at the turning point.

For both temperature sections (with and without time delay), the gradient of the tangents at the turning point can be read from the curves shown above. Both have approximately the derivation dx/dt = 0.355°C/s.

After the sudden change in the heating power from 0% to 10%, the temperature in the container goes from 20°C to 26°C after the settling phase.

This enables the compensation time Tg to be calculated:

dx/dt = (End value – Start value) / Tg , i.e.

Tg = (End value – Start value) / (dx/dt)

Tg = (26°C – 20°C) / 0,35°C/s = 17,14s

Ks results from:

Ks = (End value – Start value) / Step height(Heating power)

= (26°C – 20°C) / 10% = 0,6°C/%

The delay time Tu for the system without time delay can be measured and is approximately 1,3s.

So: Te = Tu = 1,3s Tb = Tg = 17,14s Ks = 0,6

The delay time Tu for the system with time delay can be measured and is approximately 2,3s.

So: Te = Tu = 2,3s Tb = Tg = 17,14s Ks = 0,6

In the diagram below, a step in heating power from 0% to 40% was specified for the temperature system with time delay. The temperature in the container then reached approximately the end value of 44°C.

The tangent at the turning point is approximately 1.4°C/s. If you put these values in the calculation above, you get similar values for Tg and Ks. Tu can be measured to Tu = 2.3s

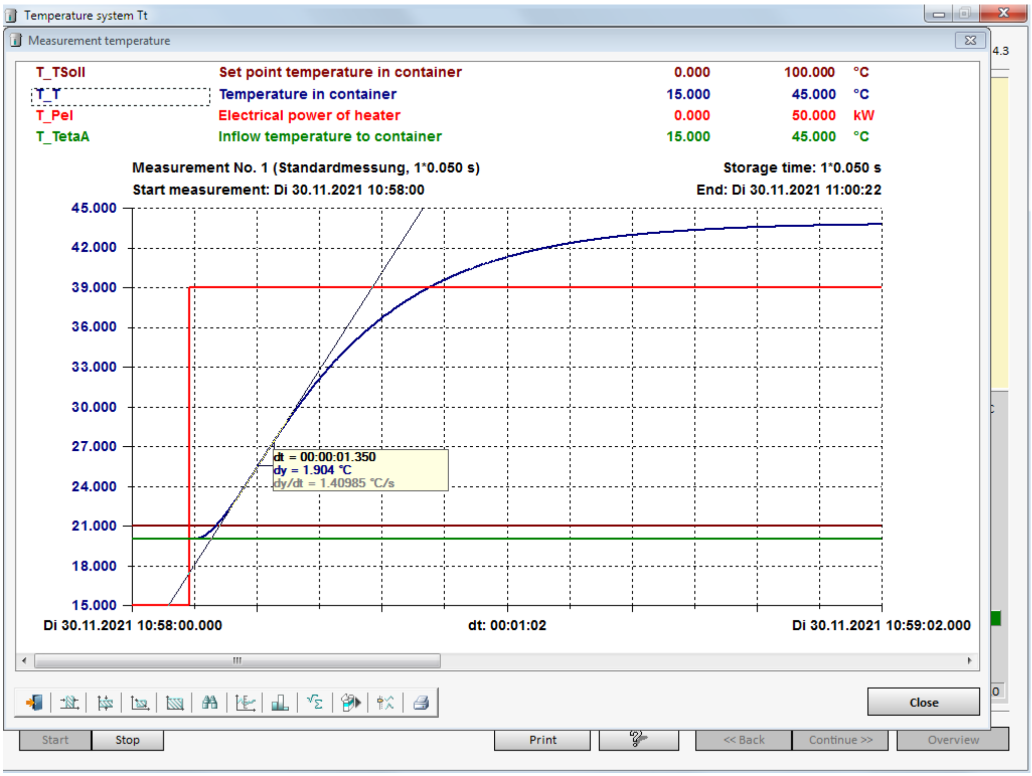


Figure 29: Temperature system with time delay and step in heating power from 0% to 40%

For the path without time delay, the following controller parameters for the PI controller result from the table:

PI controller

Command response with 20% overshoot

K = 0,6*Tb / (Ks*Te)	13,18
Tn = Tb	17,14

Command response aperiodic

K = 0,35*Tb / (Ks*Te)	7,69
Tn = 1,2 * Tb	20,57

Disturbance response with 20% overshoot

K = 0,7*Tb / (Ks*Te)	15,38
Tn = 2,3 * Te	2,99

Disturbance response aperiodic

K = 0,6*Tb / (Ks*Te)	13,18
Tn = 4 * Te	5,20

In order not to reach the limit, a step from 25°C to 30°C was specified, after which the controlled variable had settled to 25°C.

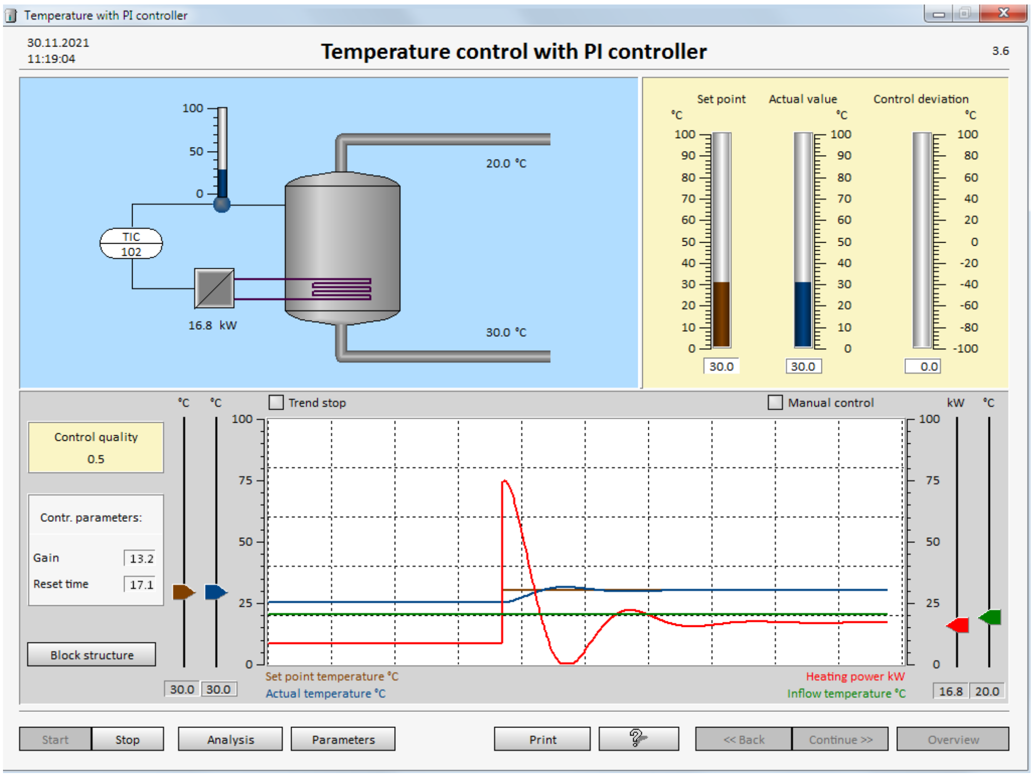


Figure 30: Command response with 20% overshoot

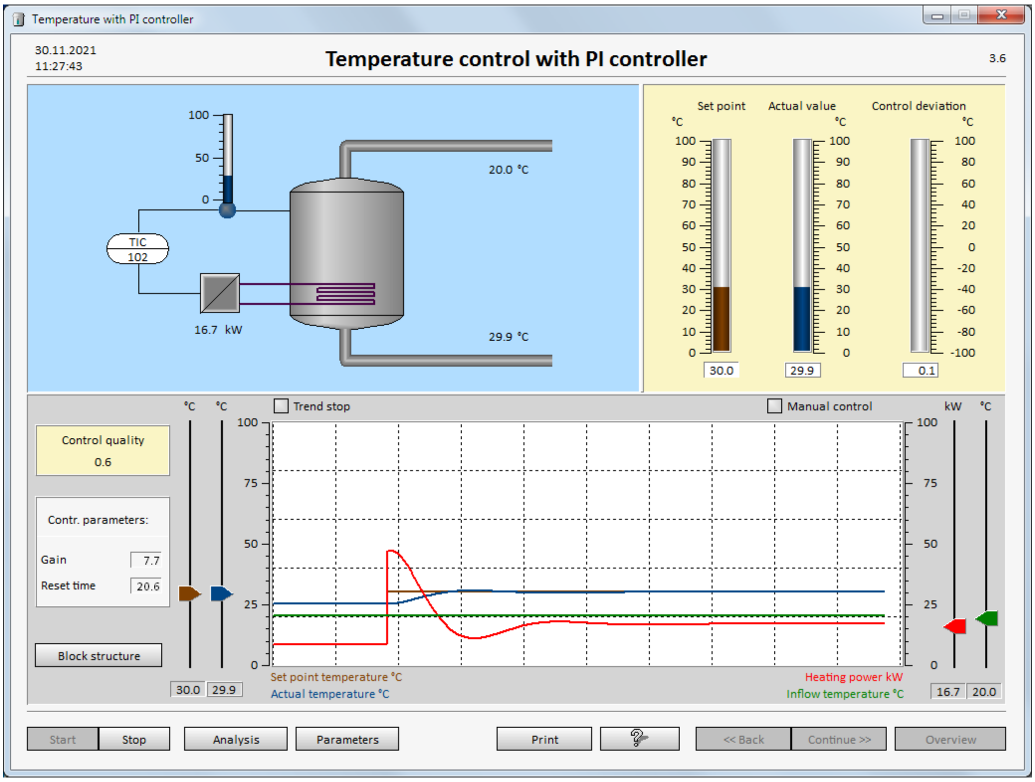


Figure 31: Command response aperiodic

In the following, the system had settled to 30°C and a disturbance was specified by the inflow temperature from 20°C to 25°C.

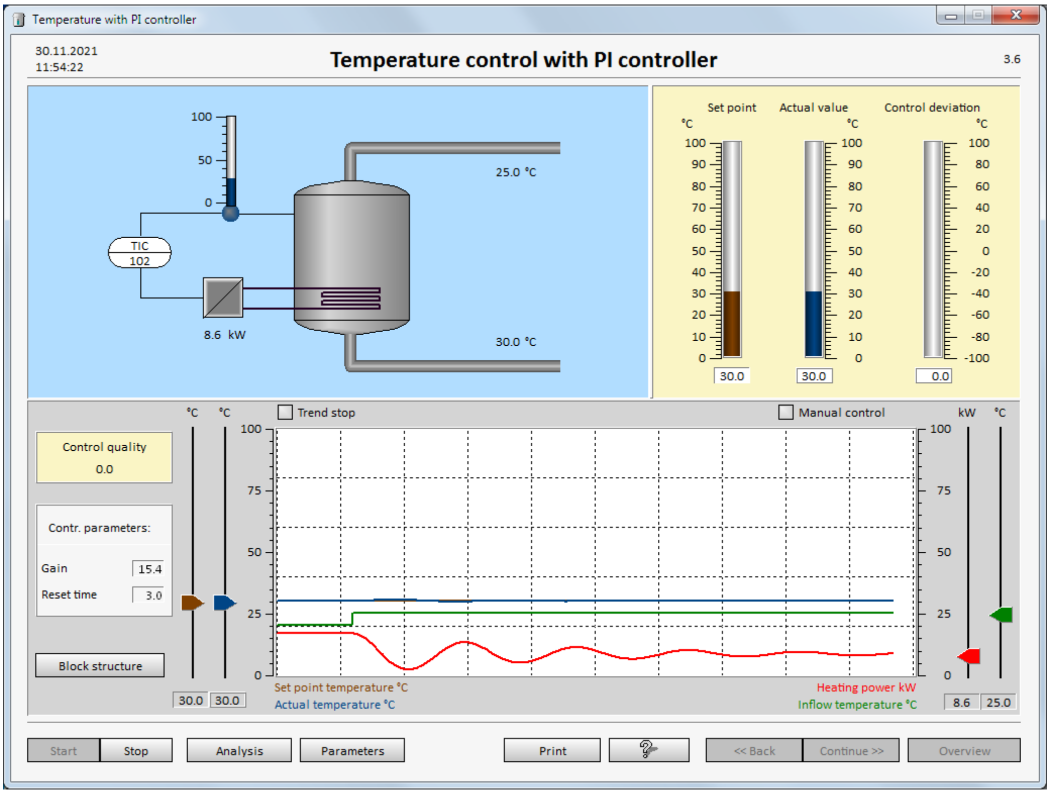


Figure 32: Disturbance response with 20% overshoot

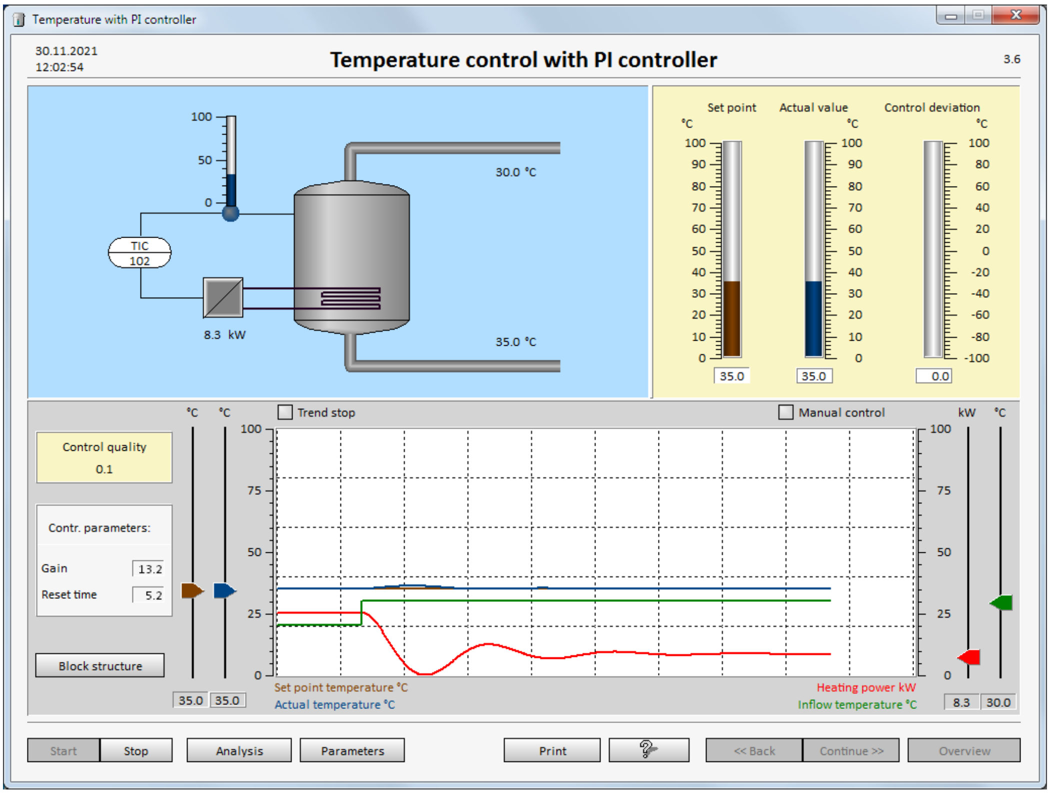


Figure 33: Disturbance response aperiodic

In the following, the system had settled to 35°C and a disturbance was specified by the inflow temperature from 20°C to 30°C.

For the system with time delay, the following controller parameters for the PI controller result from the table:

PI controller

Command response with 20% overshoot

K = 0,6*Tb / (Ks*Te)	7,45
Tn = Tb	17,14

Command response aperiodic

K = 0,35*Tb / (Ks*Te)	4,35
Tn = 1,2 * Tb	20,57

Disturbance response with 20% overshoot

K = 0,7*Tb / (Ks*Te)	8,69
Tn = 2,3 * Te	5,29

Disturbance response aperiodic

K = 0,6*Tb / (Ks*Te)	7,45
Tn = 4 * Te	9,20

In order not to reach the limit, a step from 25°C to 30°C was specified after the controlled variable had settled to 25°C.

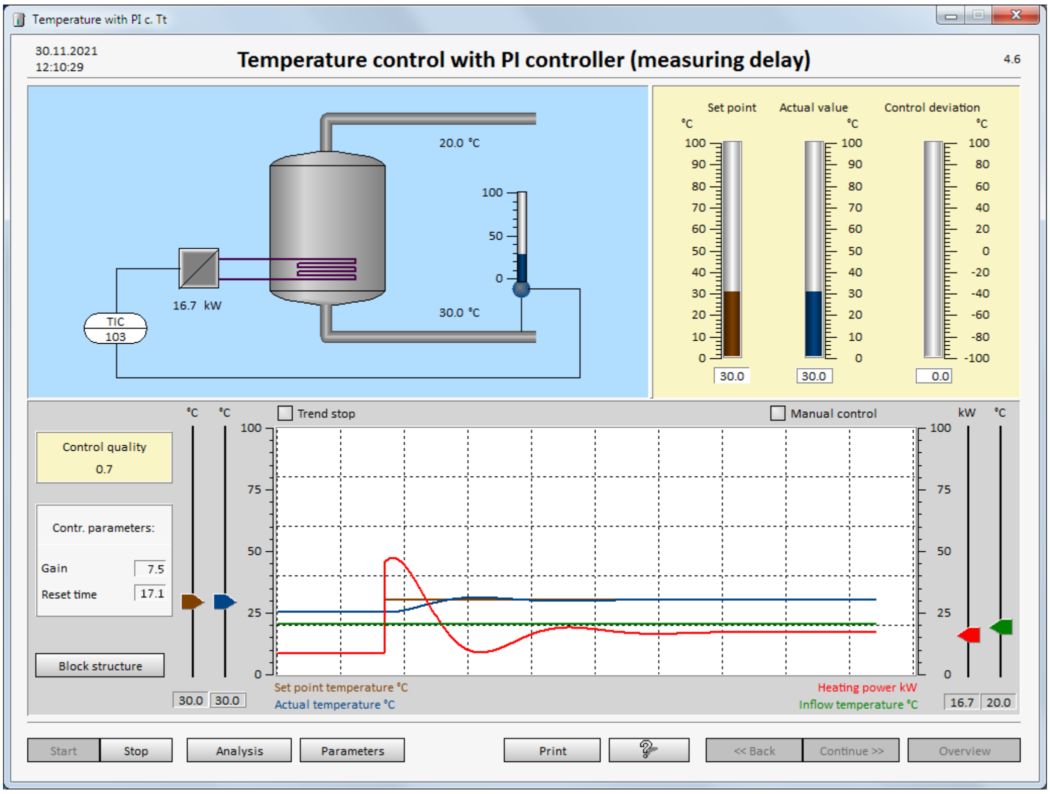


Figure 34: Command response with 20% overshoot

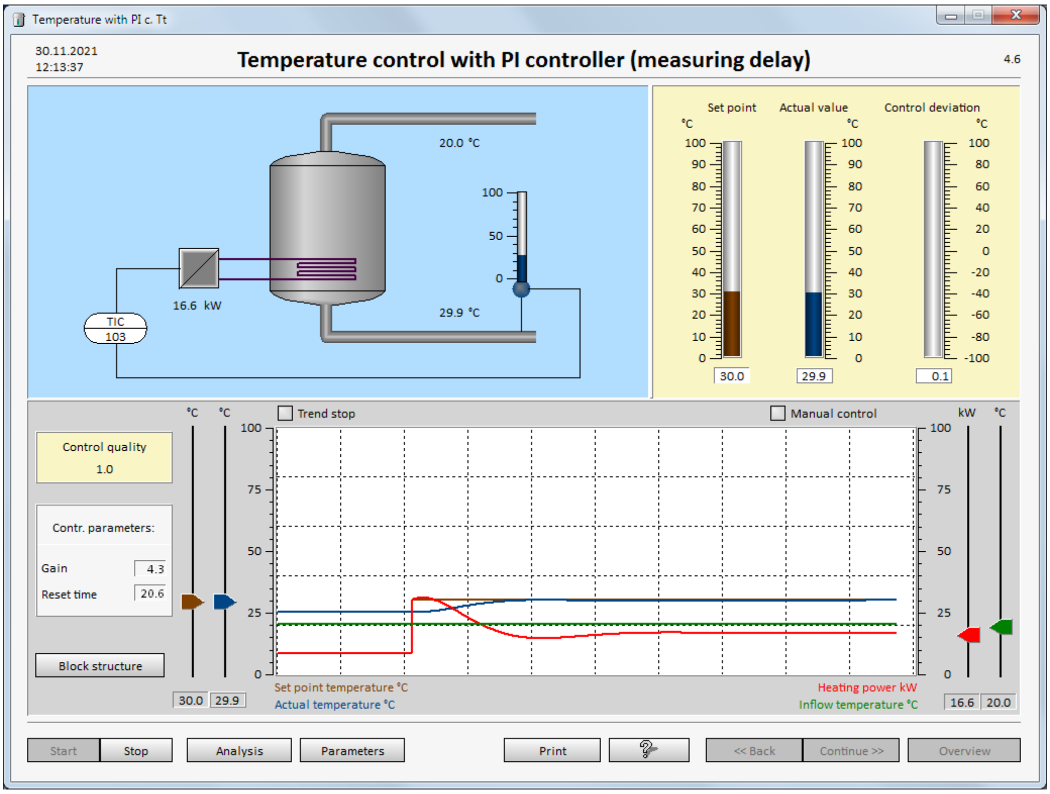


Figure 35: Command response aperiodic

In order not to reach the limitation, a disturbance from 20°C to 25°C was specified for the inflow temperature.

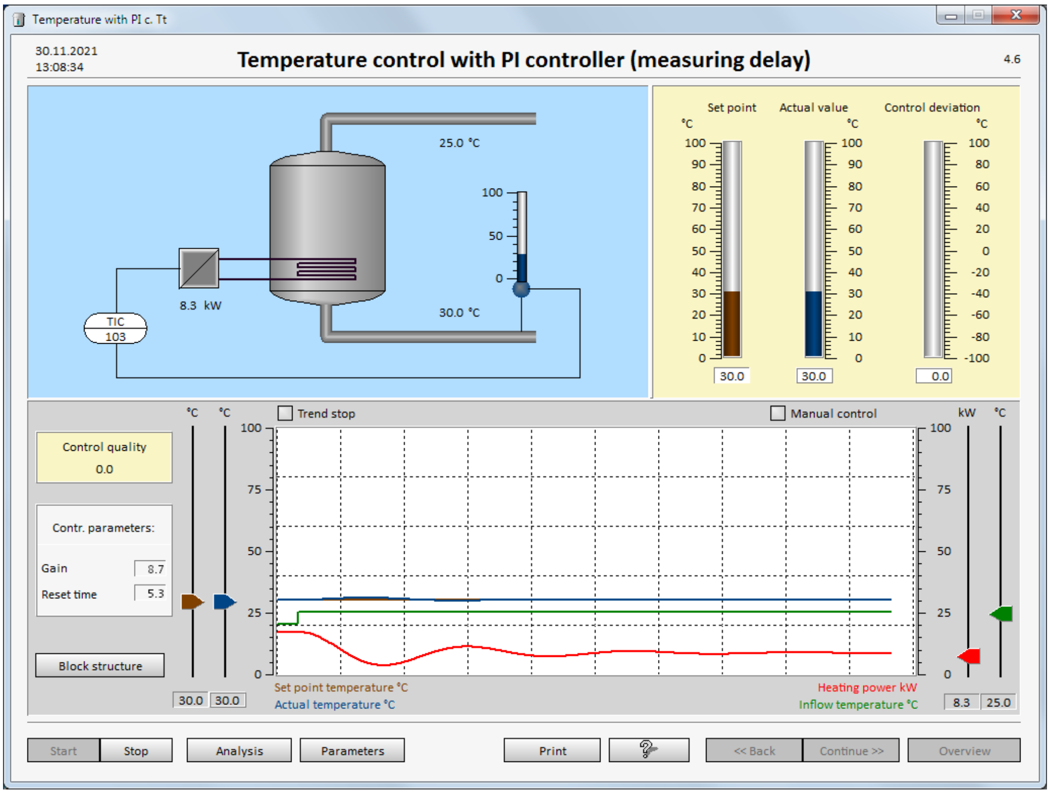


Figure 36: Disturbance response with 20% overshoot

In the following, the system had settled at 35°C. and a step in the inflow temperature from 25°C. to 30°C. was entered.

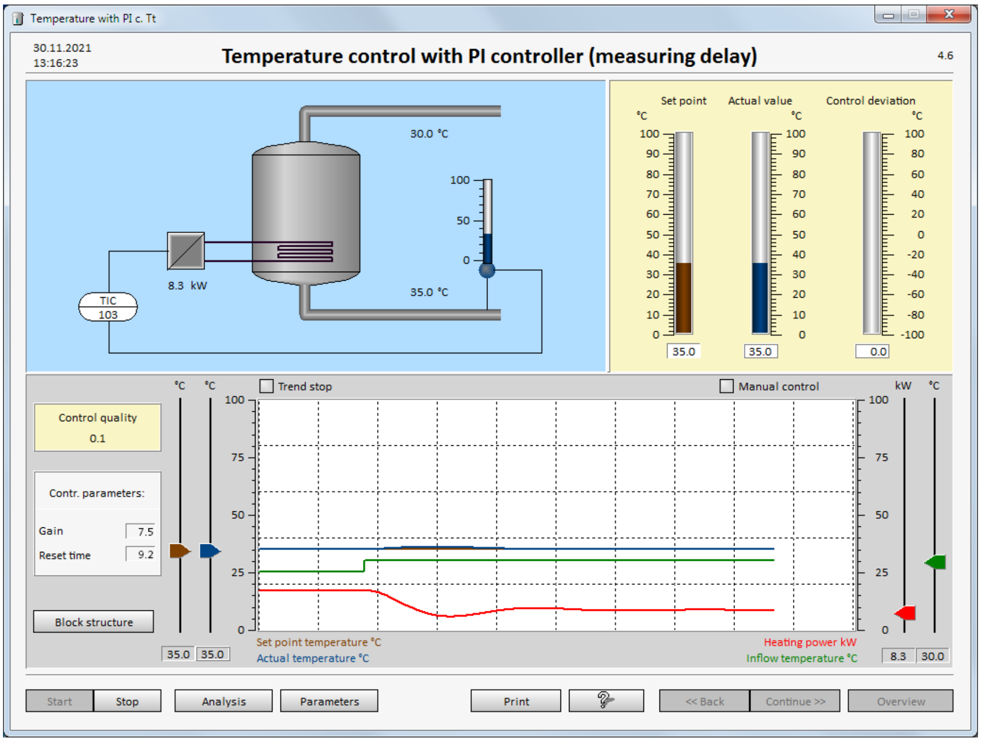


Figure 37: Disturbance response aperiodic

For the system with time delay, the following parameters result for the PID controller according to the table:

PID controller

Command response with 20% overshoot

K = 0,95*Tb / (Ks*Te)	11,80
Tn = 1,35 * Tb	23,14
Td = 0,47 * Te	1,08

Command response aperiodic

K = 0,6*Tb / (Ks*Te)	7,45
Tn = Tb	17,14
Td = 0,5 * Te	1,15

Disturbance response with 20% overshoot

K = 1,2*Tb / (Ks*Te)	14,90
Tn = 2 * Te	4,60
Td = 0,42 * Te	0,97

Disturbance response aperiodic

K = 0,95*Tb / (Ks*Te)	11,80
Tn = 2,4 * Te	5,52
Td = 0,42 * Te	0,97

In order not to reach the limit, a step from 25°C to 30°C was carried out after the controlled variable had settled to 25°C.

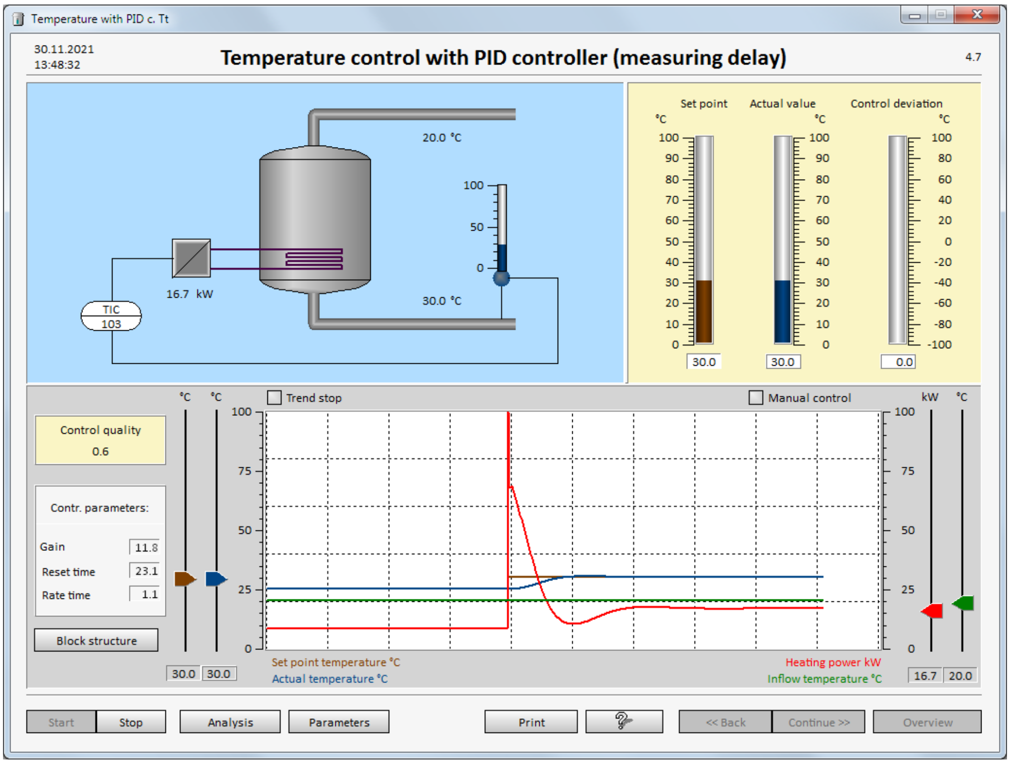


Figure 38: Command response with 20% overshoot

In order not to reach the limit, a step from 30°C to 35°C was carried out after the controlled variable had settled to 30°C.

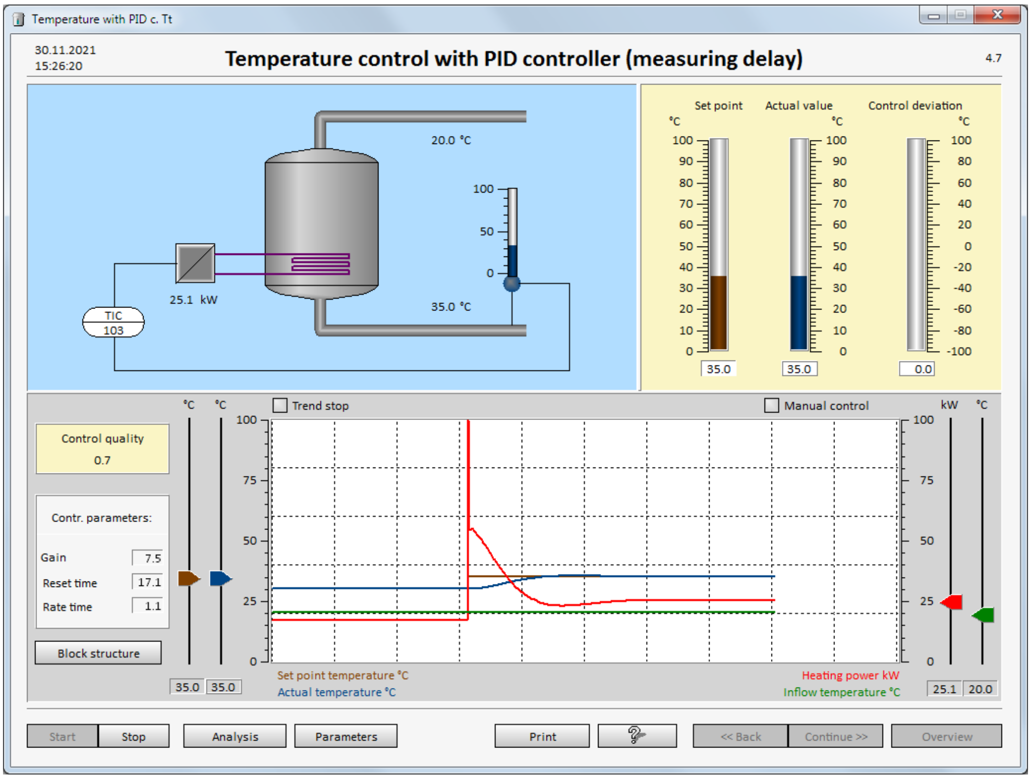


Figure 39: Command response aperiodic

The system then settled at 35°C. A disturbance was specified by changing the inflow temperature from 20°C to 30°C.

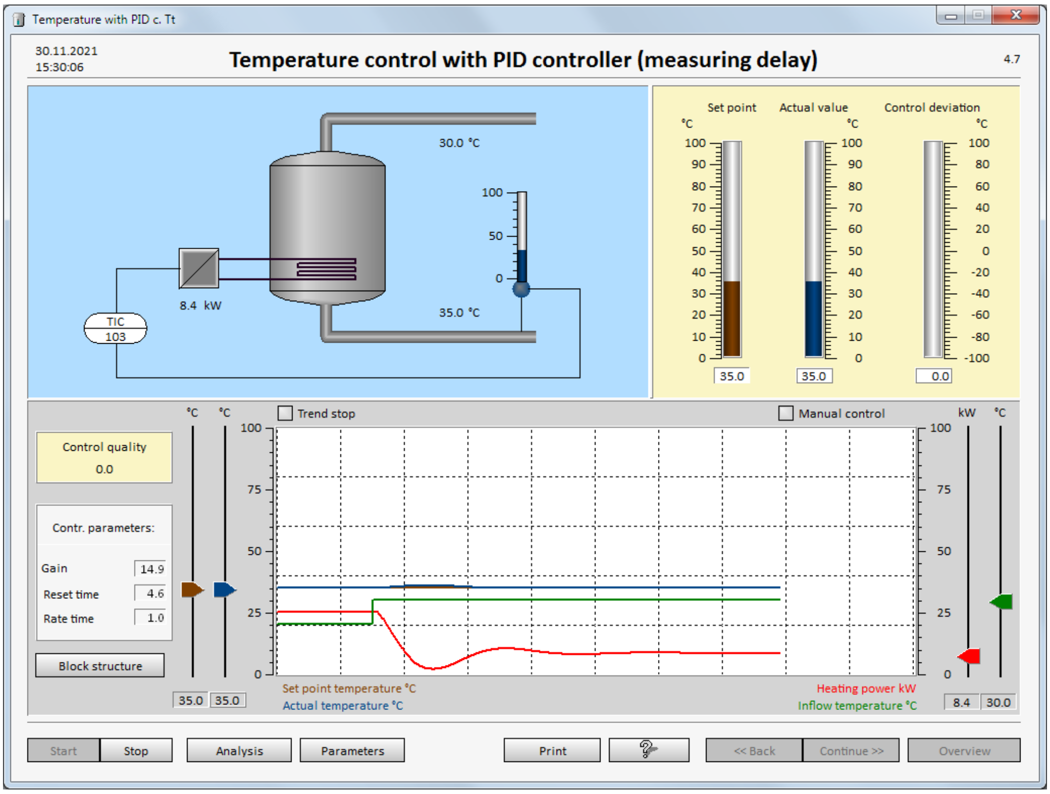


Figure 40: Disturbance response with 20% overshoot

In the following picture the system had settled at 35°C. A disturbance was specified by changing the inflow temperature from 20°C to 30°C.

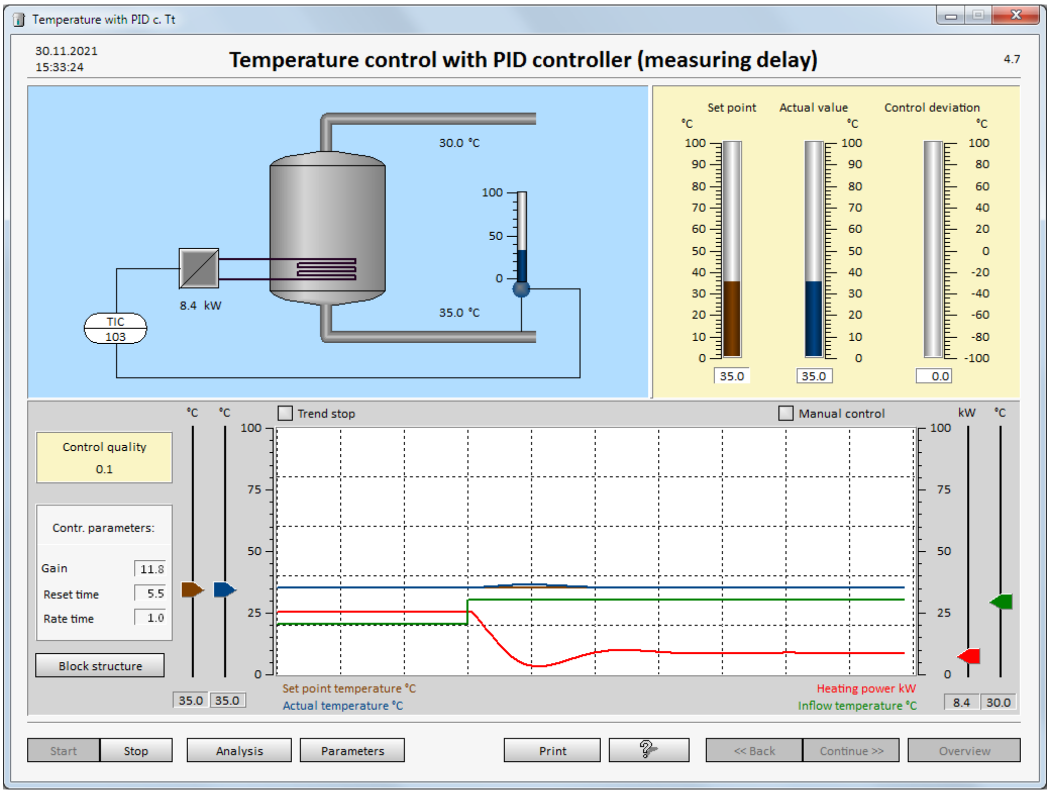


Figure 41: Disturbance response aperiodic

Since the parameters differ significantly depending on the application, the user must decide which type of control is important for his control loop (disturbance or command control behavior, with or without overshoot).

The user may have to compromise between the controller parameters.

6.5 Assessment of the Controller Tuning Rules

Controller tuning rules are empirically determined methods that are often suitable for calculating good controller parameters by rule of thumb.

The settings for calculating controller parameters distinguish between disturbance and command response. Different controller parameters are calculated.

If you need controller parameters for both cases (disturbance and control behavior), you have to make a compromise between the calculated parameters of the disturbance behavior and the control behavior.

The above examples show that a reasonable control loop behavior can be obtained with the calculated controller parameters. However, the behavior does not exactly correspond to the expected behavior as selected in the table.

The fact that the system has not settled exactly aperiodically or with 20% overshoot is also due to the fact that the control signal has partially reached its limit and the time constants could not be determined exactly.

But the examples and tasks shown for this control system show that the controller parameters proposed by Chien/Hrones/Reswick are suitable for sensible control.

7 Mixing Container Cascade (Control Training I)

The system structure essentially consists of three stirred tanks, each with an inlet and an outlet. The outflow of the first boiler is connected to the inflow of the second, the outflow of the second boiler to the inflow of the third. In this simulation example, a salt solution is mixed with water. A mixture of a stream of water and a stream of salt solution flows to the first tank. The flow rates of these streams can be varied separately from one another via valves.

The control task is to control the salt concentration of the third tank so that it corresponds to a specified set point (reference value). The flow rate of the salt solution is regarded as the input variable (actuating variable, control signal), the salt concentration of the liquid flowing out of the third tank is the output variable (controlled variable) of the system.

Fluctuations in the flow rate of the incoming water flow as well as changes in the salt concentration of the salt solution represent disturbance variables.

7.1 Uncontrolled System (Manual Control)

In control Training I select item 5.1 „Uncontrolled system“.

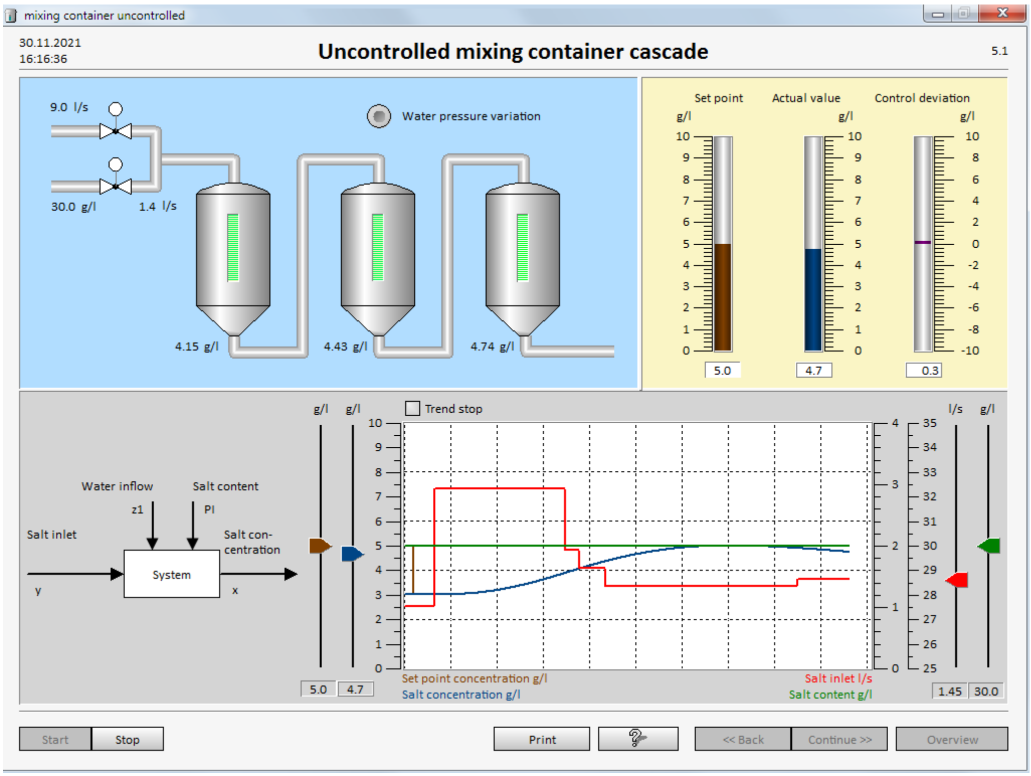
Click „Start“.

You can change the values for the set point (set point concentration g/l), the control value (salt inlet l/s) and the disturbance (salt content g/l) using the slider or by entering values below the slider.

Task 1.

Adjust the set point concentration (reference variable) to 5g/l and then try to adjust the salt concentration (controlled variable) in the third container to the set point concentration by adjusting the salt inlet (actuating variable).

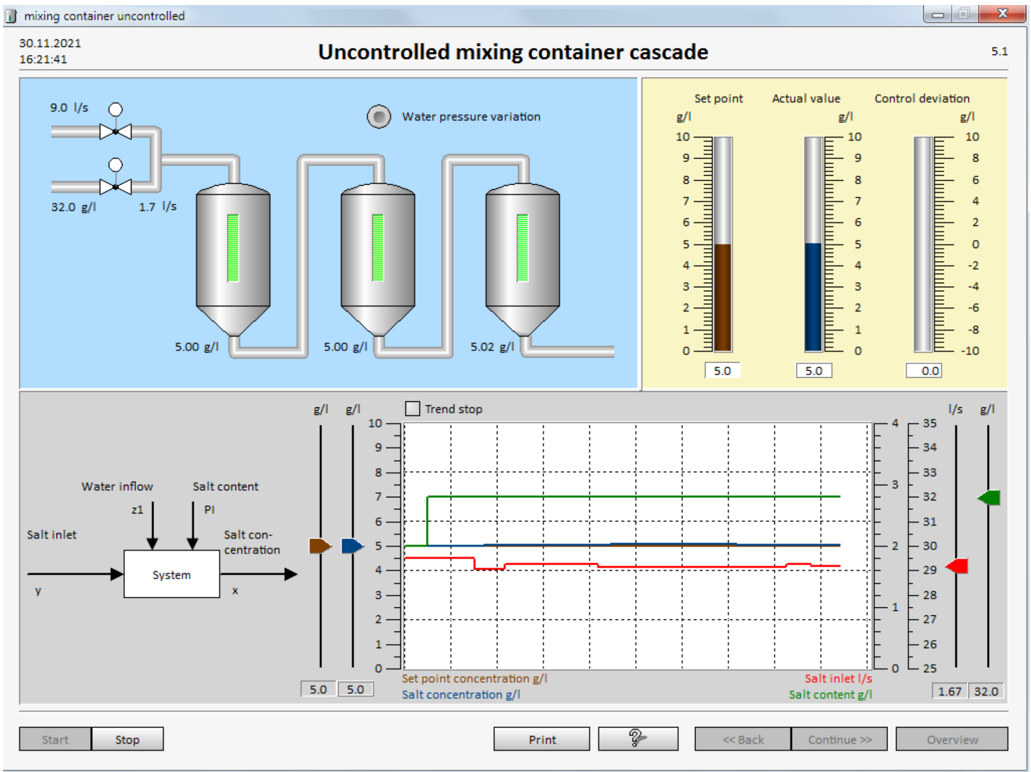
In this case one speaks of command response. The set point is adjusted and an attempt is made to adjust the actual value (controlled variable, salt concentration) to the new set point (set point concentration).



Since the system is a very slow process, it is very difficult to adjust the control loop to the new set point.

Task 2.

Specify a disturbance. Change the salt content to 32g/l. Describe the behavior and try to correct the disturbance.



The increased salt content increases the salt concentration. The inflow of salt must therefore be reduced. In this case one speaks of disturbance response, since an attempt is made to correct a disturbance.

7.2 Controlled System

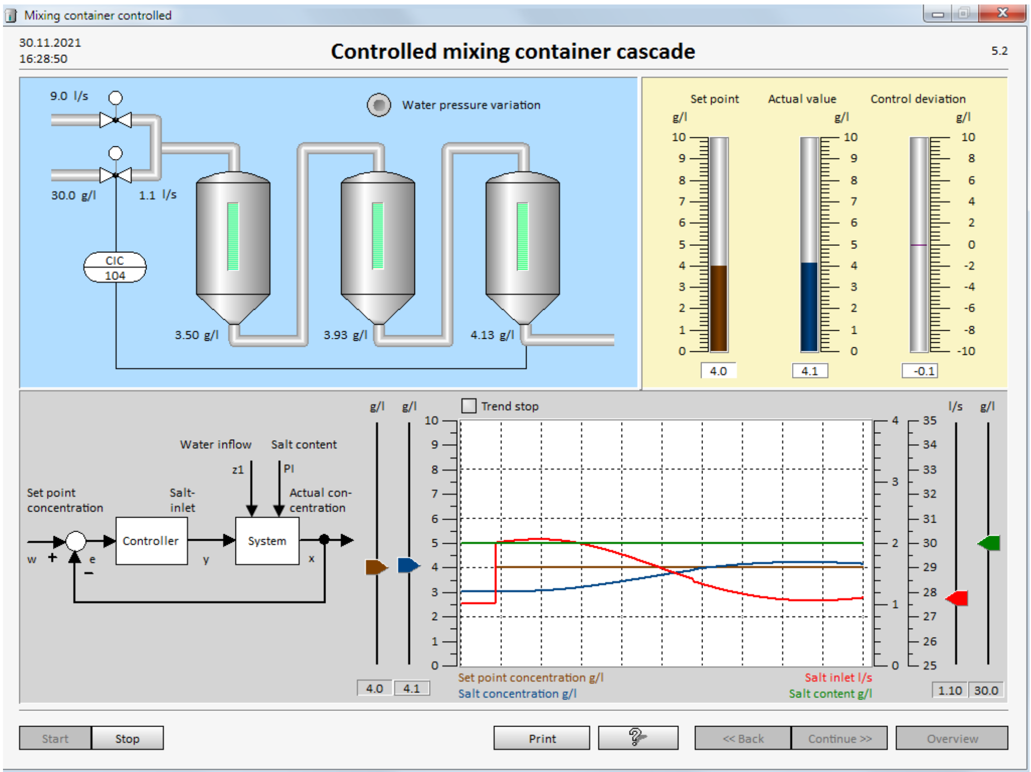
7.2.1 Closed-loop Controlled System

Go to „Overview“ and select item 5.2 „Closed-loop control system“.

Here you can see how the system behaves in principle if, instead of manual control, a controller takes on the task of adjusting the actual value to the set point.

Task 3.

Click „Start“ and set the set point to 4g/l.



With a small overshoot, the actual value reaches the set point after a long period of time.

This is referred to as the command response, since the control reacts to a change in the set point (reference variable).

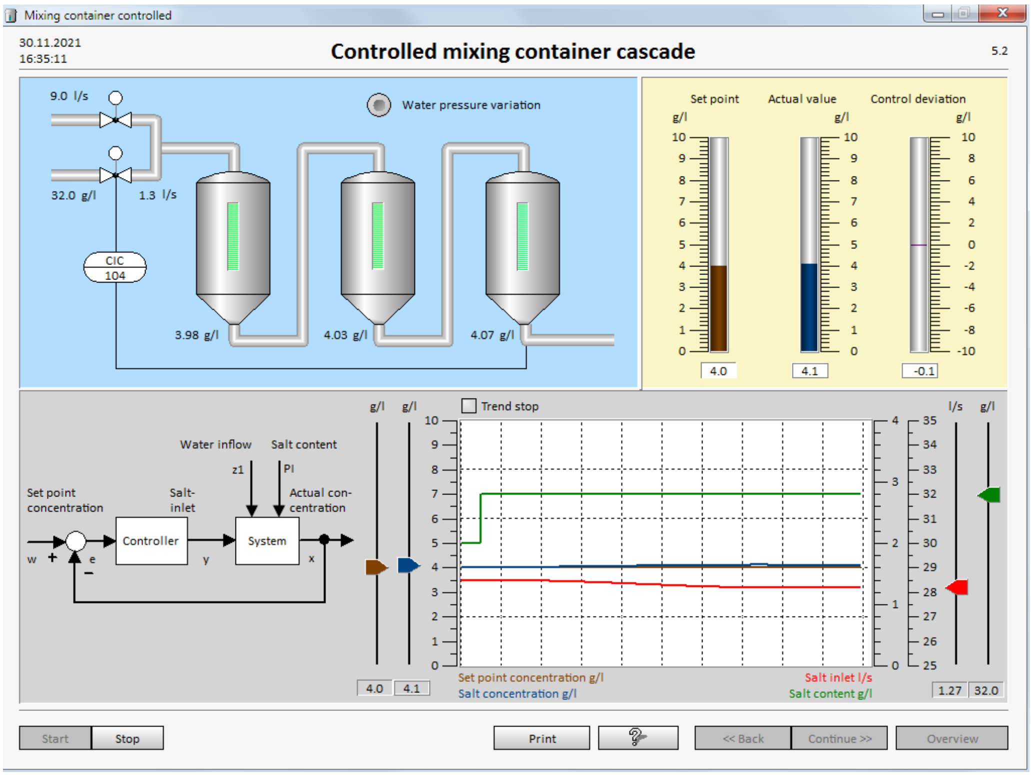
Task 4.

Investigate the disturbance behavior.

Set the set point to 4g/l and wait until the system has settled (the salt concentration has reached 4g/l and it no longer changes).

Change the salt content in the inflow to 32g/l.

Observe the system behavior.



The salt concentration begins to increase.

Therefore the controller reduces the salt inlet.

Here, too, it can be seen that the process reacts very slowly and the change in salt concentration occurs very slowly.

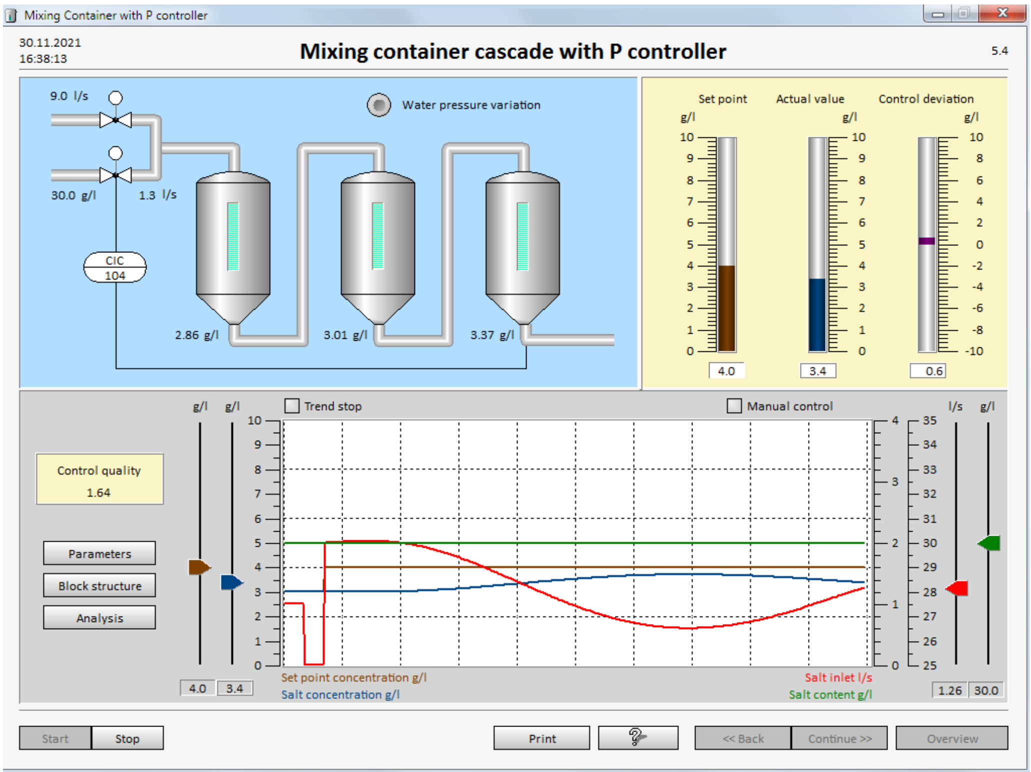
7.2.2 Closed-loop Control with P Controller

Go to „Overview“ and select item 5.4 „Closed-loop control with P controller“.

Click „Start“.

Task 5.

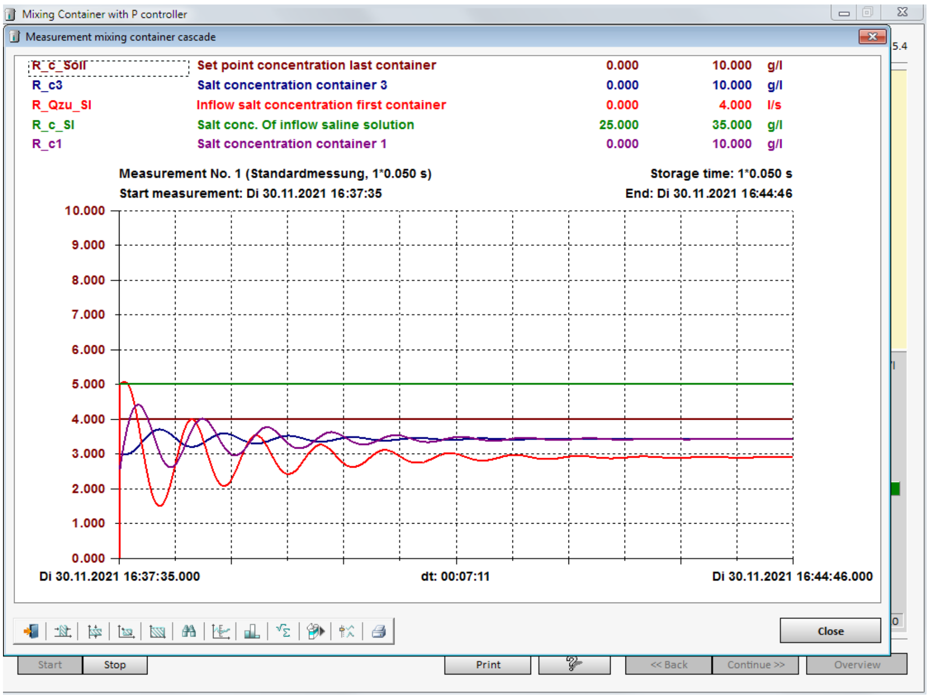
Change the set point concentration (reference variable) to 4g/l and wait until the control loop has settled, i.e. until the actual value no longer changes.



The control loop begins to oscillate. After a long settling phase, it has settled and the actual value (controlled variable, salt concentration) no longer changes. The actual value (controlled variable) does not reach the set point (reference variable). We get a steady-state control error.

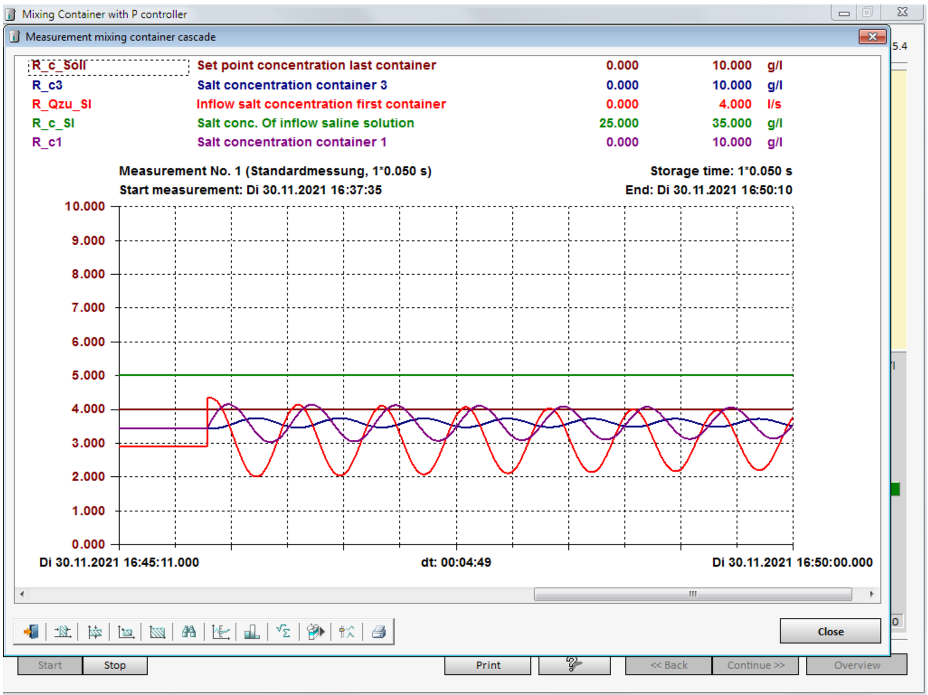
The control error e is defined as e = w – x, with

w = reference variable (set point) and x = controlled variable (actual value).



If the gain of the P-controller is set to 1, the control loop begins to oscillate less when the set point changes, but it also retains a steady-state control error.

If you change the gain to 3, the control loop becomes unstable and begins to oscillate.



The P controller works like an amplifier. The input signal to the controller w - x (set point - actual value) is amplified with the specified amplification factor (in our case 2). In order for the P-controller to output a control signal that is not equal to zero, the set point and actual value must be different, i.e. steady-state control error.

7.2.3 Closed-loop Control with I Controller:

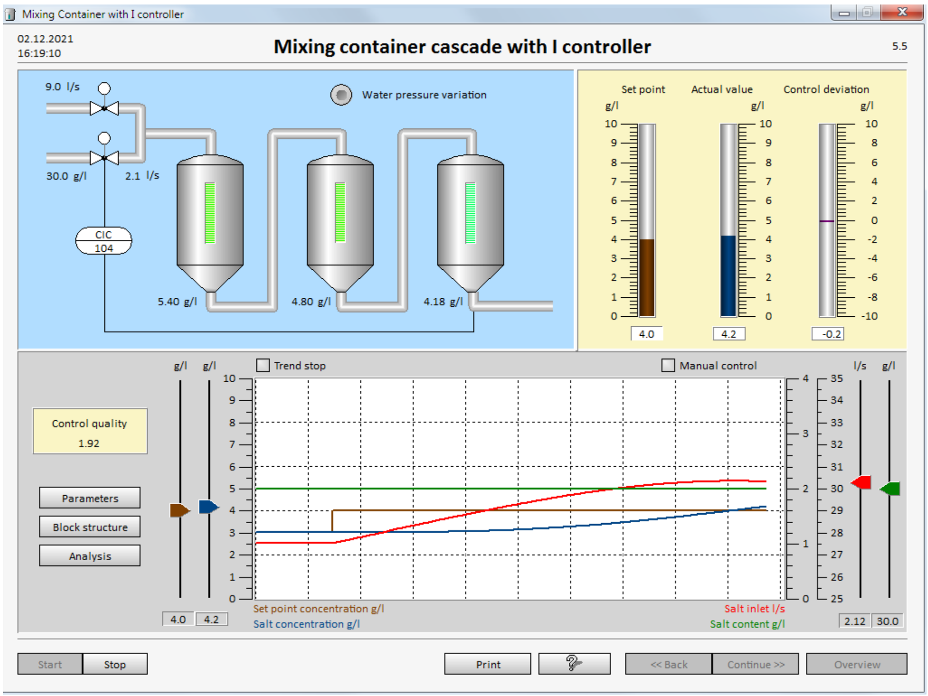
Go to „Overview“ and select item 5.5 „Closed-loop control with I controller“.

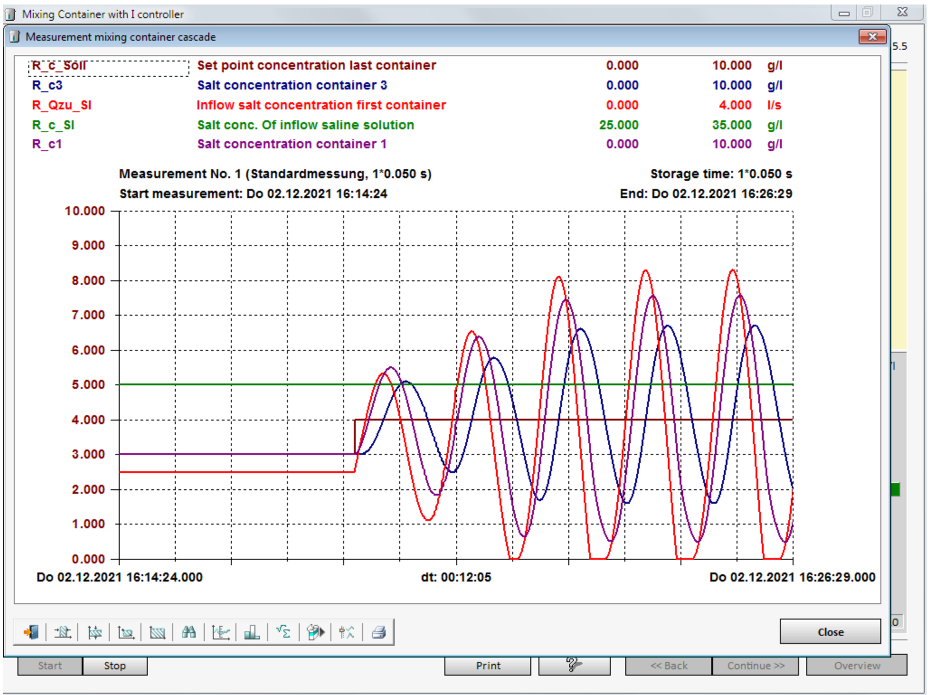
Click „Start“.

Task 6.

Keep the set reset time Ti at 20. Investigate the command response.

Change the set point concentration (reference variable) to 4g/l and wait until the control loop has settled, i.e. until the actual value no longer changes.





The control loop reacts very slowly and begins to oscillate. It becomes unstable and oscillates continuously.

By clicking on "Analysis" you will get the recorded signal curves. The upswing can be clearly seen here.

The I-controller cannot be used for disturbance behavior either.

7.2.4 Closed-loop Control with PI Controller

Go to „Overview“ and select item 5.6 „Closed-loop control with PI controller“.

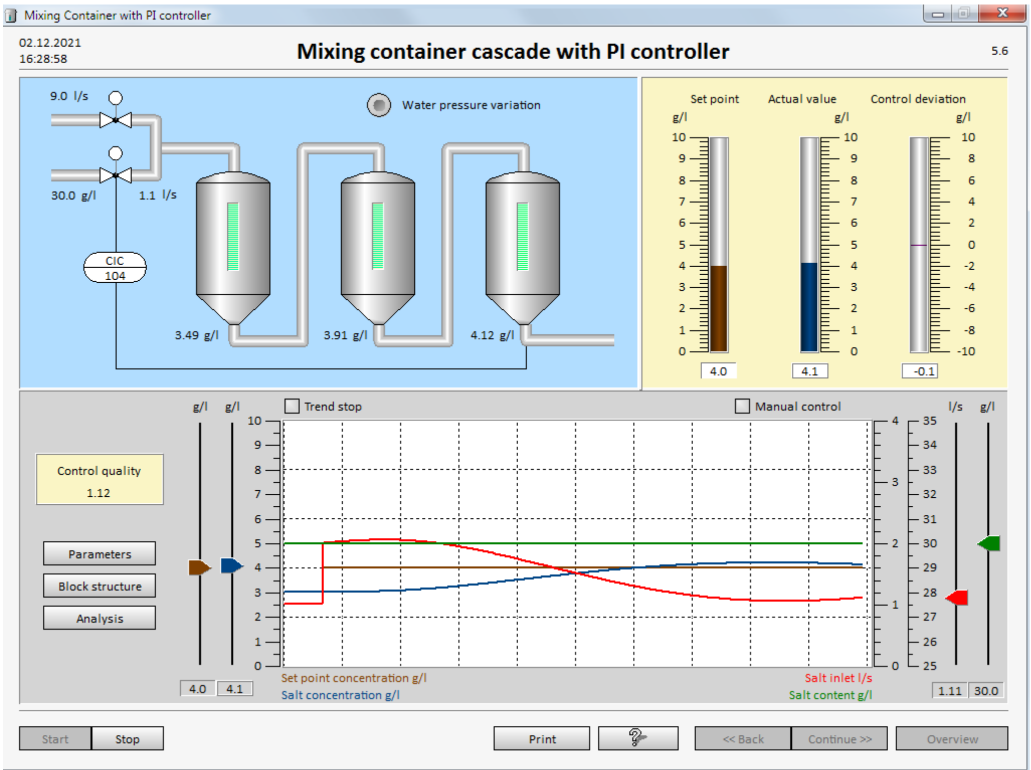
Click „Start“.

Task 7.

Keep the set parameters: K = 1, Ti = 50

Examine command response.

Change the set point concentration (reference variable, target concentration) from 3g/l to 4g/l.



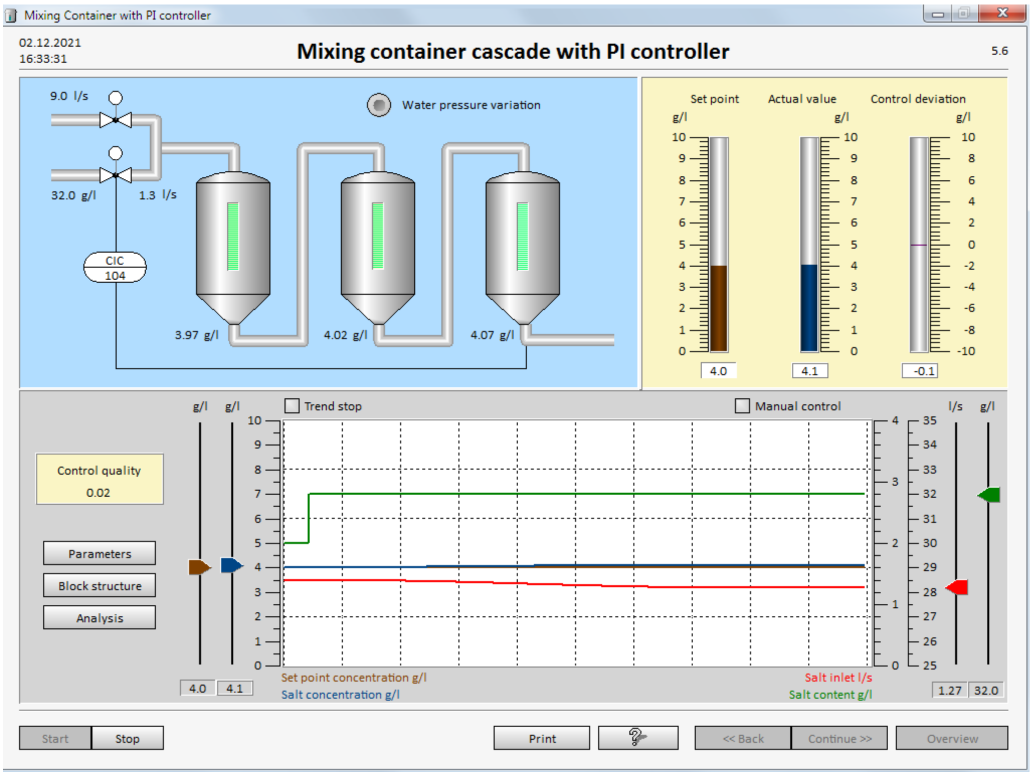
The control loop with the PI controller and the set parameters oscillates to the set point with a small overshoot. The actual value (controlled variable, salt concentration) reaches the set point (reference variable).

Task 8.

Investigate the disturbance response.

Let the control loop settle to the set point 4g/l with the parameters K = 1 and Ti = 50.

When the control loop has settled, change the salt content from 30g/l to 32g/l and observe the behavior.



The higher salt content causes the salt concentration to rise. The closed-loop controller tries to counteract this and reduces the inflow of salt. After a settling phase, the PI controller also manages to control the disturbance and adjust the actual value to the set point.

Task 9.

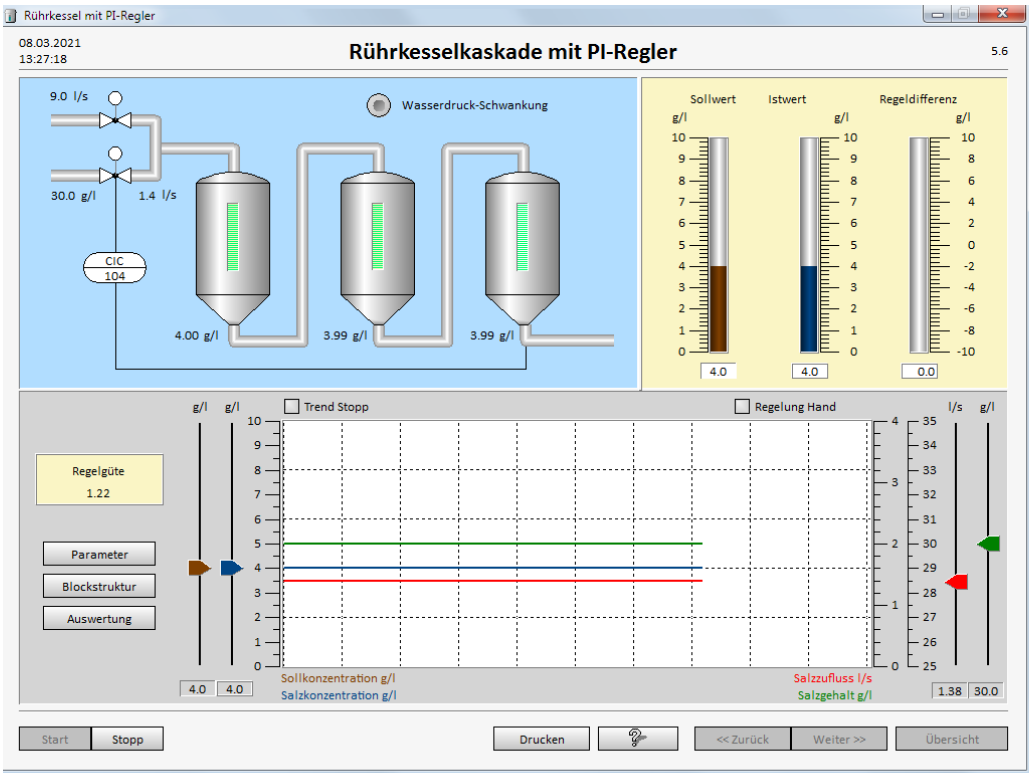
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the set point.

Try to reduce the value for the control quality by adjusting the controller parameters.

In order for the control quality to be comparable, all tests must be started with the same initial states. The best way to do this is to click “Stop” and then “Start” again. The set point concentration (reference variable), salt content (disturbance variable) and salt concentration (controlled variable) are restored to their initial values.

Now change the controller parameters and then adjust the set point to 4g/l. Wait until the control loop has settled.

With the preset controller parameters K = 1 and Ti = 50, a control quality of 1.23 was achieved.



With the parameters gain K = 1.1 and reset time Ti = 60, a control quality of 1.22 is obtained, for example

Carry out the experiments with further controller parameters:

- Click „Stop“ and „Start“
- Set controller parameters
- Set set point to 4g/l
- Wait until control loop has settled

In general:

Info:

Since the PI controller has an I component (integrator), it also applies here that the controller adjusts the actual value to the set point after a settling phase or that the control loop becomes unstable.

This is explained by the behavior of the integrator:

If the value of the input signal to an integrator is positive, the value of the output signal (control signal) increases. If the input signal is zero, the integrator retains its output value (the value remains constant). If the input value is negative, the output value of the integrator decreases.

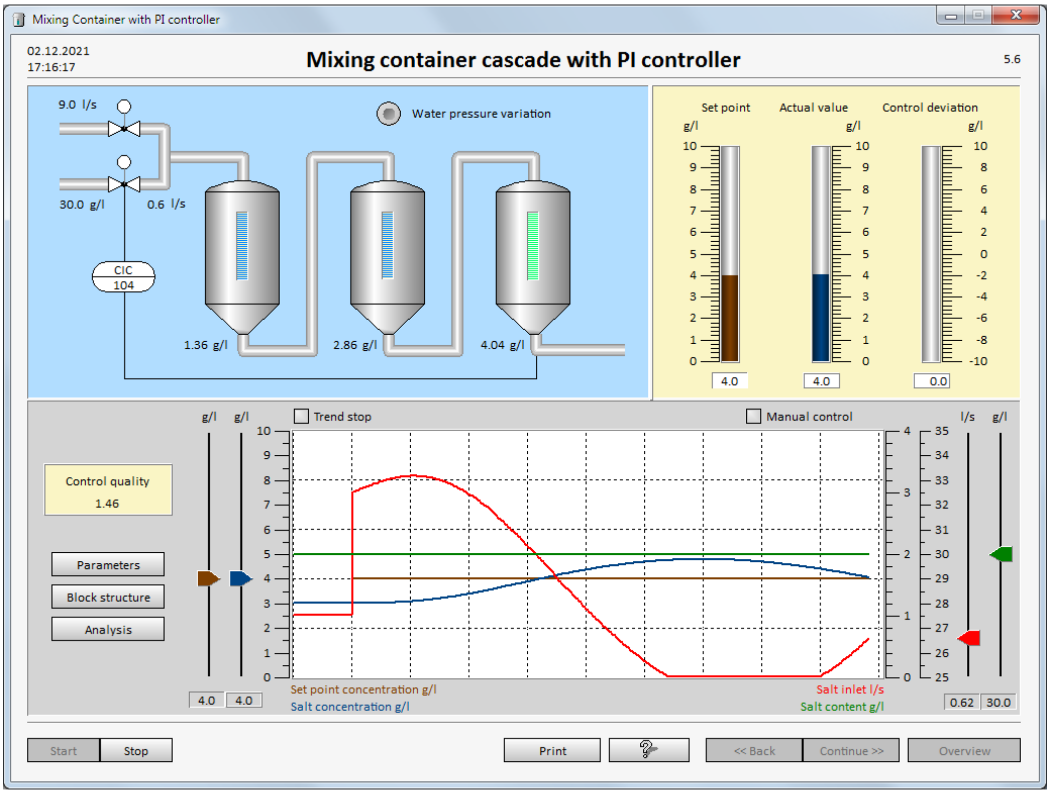
In order for a control loop to settle to a value, the control signal must be constant (output of the controller). The output value of an integrator is only constant when the input value of the integrator is equal to zero, i.e. when the set point and actual value are the same.

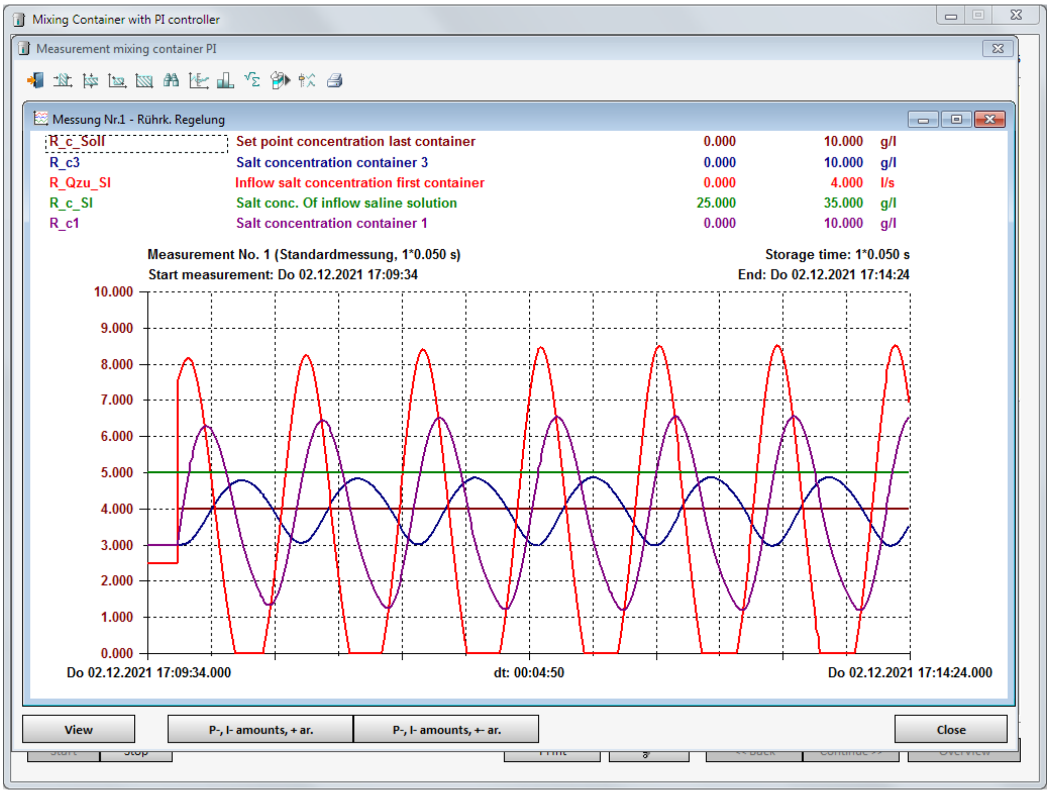
Task 10.

Restart the mixing container cascade with PI controller.

Try to set the controller parameters so that the control loop becomes unstable.

Enter a set point step from 3g/l to 4g/l.





You can achieve this with the controller parameters K = 2 and Ti = 20, for example:

The control loop with these parameters also becomes unstable for the disturbance behavior.

As a conclusion it can be said:

- With the PI controller and appropriately well set controller parameters, the control loop can be controlled, the actual value reaches the set point and remains at the set point.
- This applies to the command response as well as to the disturbance response.
- If the parameters are poorly set, the control loop becomes unstable.

7.2.5 Closed-loop Control with PID Controller

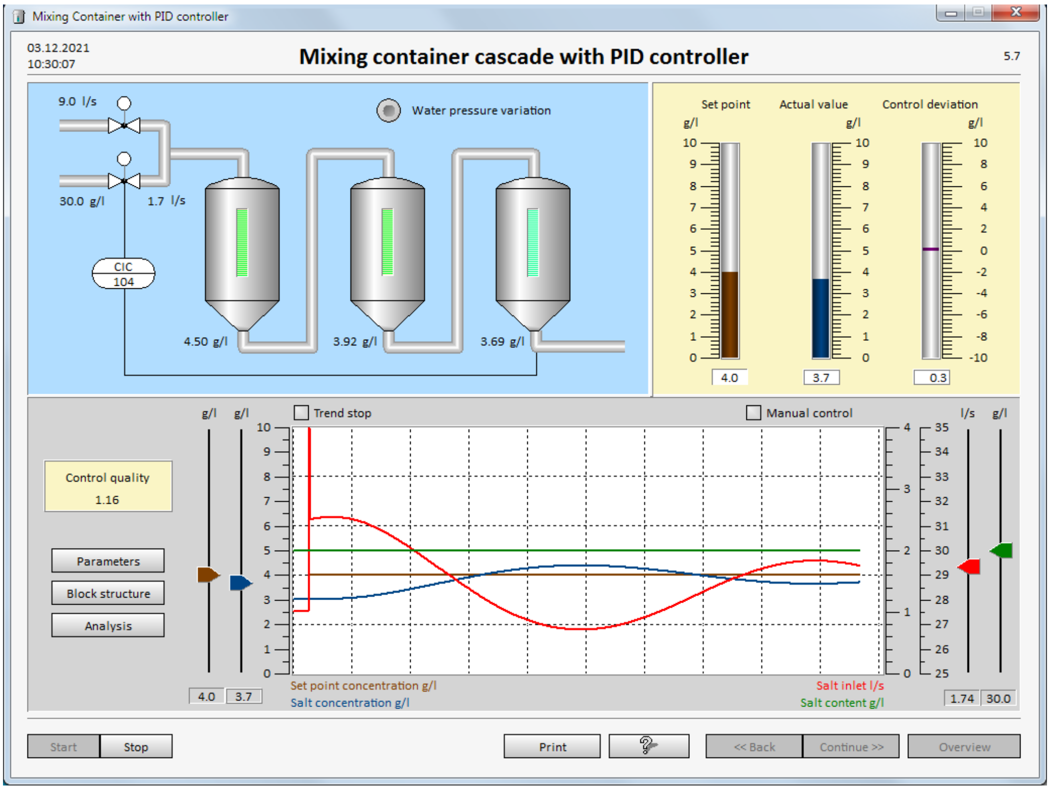
Go to „Overview“ and select item 5.7 „Closed-loop control with PID controller“.

Click „Start“.

Task 11.

Investigate the command response with the preset parameters: Gain K = 1.5, reset time Ti = 50, derivative time (rate time) Td = 1

Change the set point to 4g/l.



The control loop begins to oscillate slightly and goes into a stable state after a long period of time. The actual value reaches the set point.

As you can see in the trend diagram, the sudden change in the set point causes a peak in the control signal (salt inlet). This peak is triggered by the D component of the controller. The derivation of a sudden change causes an (infinitely) large value.

The control quality reaches 1.27 and is therefore greater than with the PI controller with the parameters K = 1 and Ti = 50.

Note on the trend display with the PID controller:

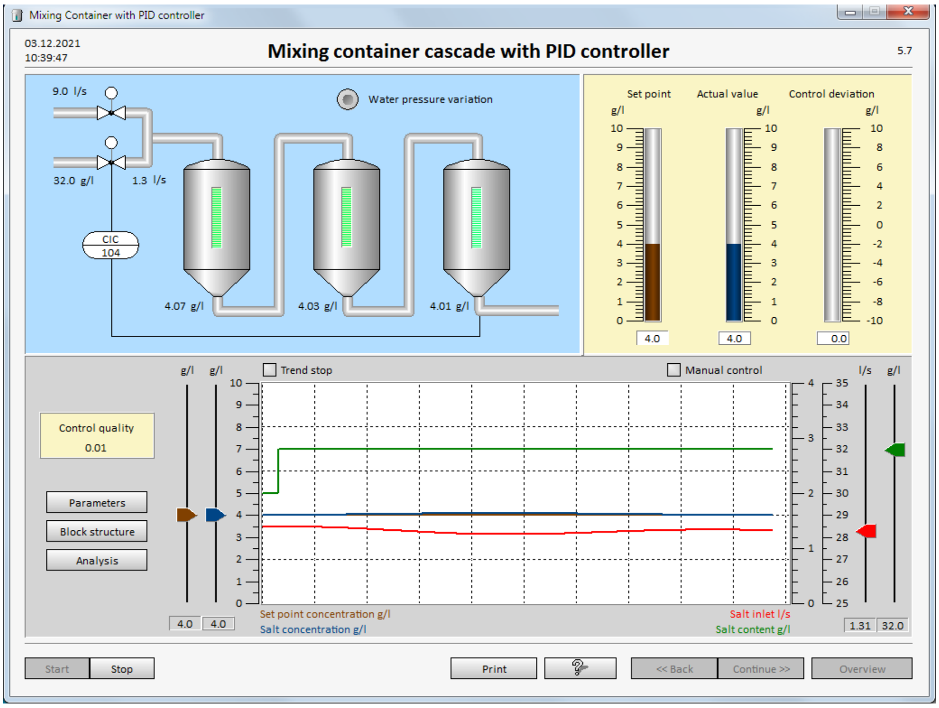
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Analysis" (display of the stored signal values) and selection of a corresponding time range.

Task 12.

Investigate the disturbance behavior with the preset parameters:

Gain K = 1,5, reset time Ti = 50, rate time Td = 1

Let the system settle to the set point concentration of 4g/l (the salt concentration reaches 4g/l and does not change any more). Change the salt content in the inflow from 30g/l to 32g/l. Observe the behavior.



The disturbance response is well controlled with the specified controller parameters. The salt concentration (controlled variable) reaches the set point concentration (reference variable) again after a period of time.

Info:

In practice, the PI controller is most common. If a PID controller is used, the D component is often turned off so that the controller only works as a PI controller.

One of the reasons for this is that the D behavior in a control loop is difficult to assess. In principle, the D component gives you the option of making the control faster (which is often very difficult, however).

The D component considers the change between the set point and the actual value. If the change increases, i.e. the difference between the set point and actual value increases, the D component adds a calculated value to the control signal. If the difference between the set point and the actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend, whether the difference between the set point and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the set point and actual value decreases, the control signal is reduced.

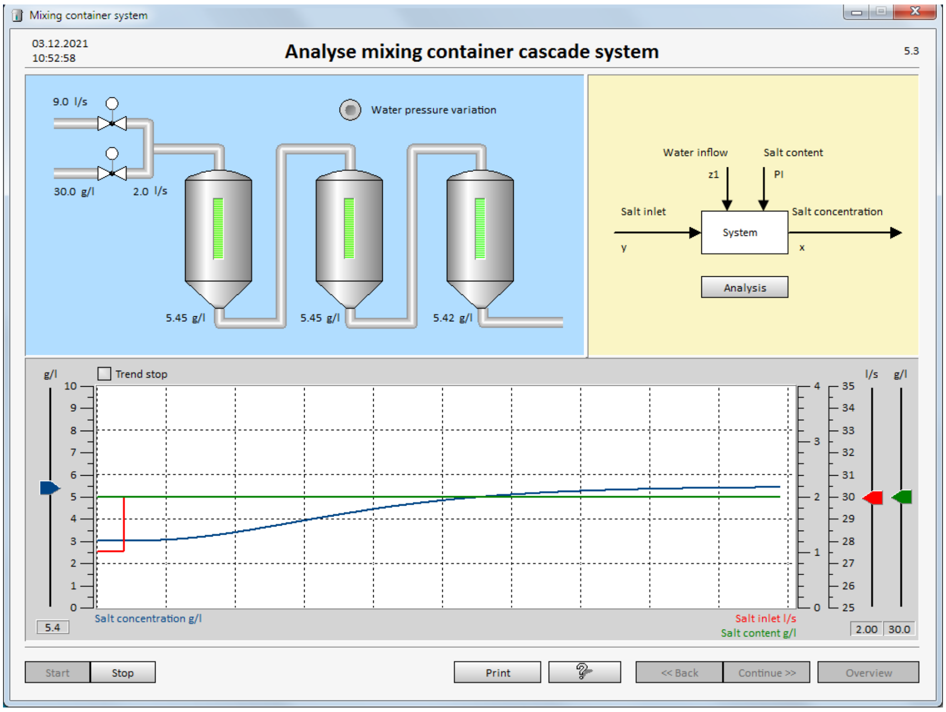
7.3 Examine Controlled System

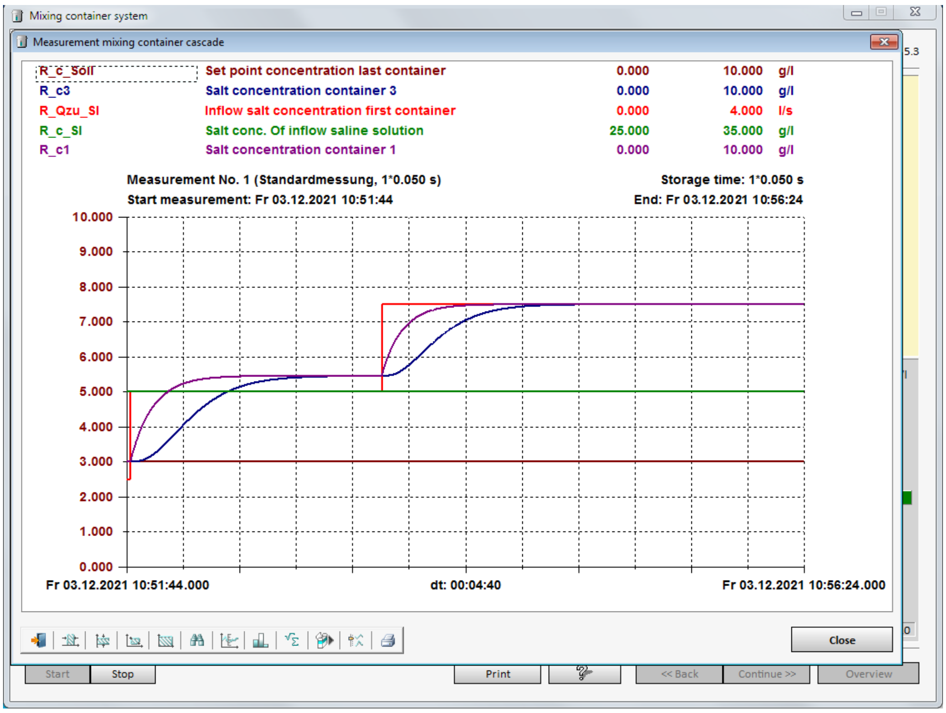
Select item 5.3 „Examine controlled system“. Click „Start“.

Task 13.

Increase the salt inlet from 1l/s to 2l/s and wait until the salt concentration no longer changes. Then change the salt flow to 3l/s.

Observe the behavior of the concentration.





As can be seen from the recorded data, the behavior of the controlled system is different for the steps. The salt concentration changes when the salt inflow changes from 1l/s to 2l/s from 3g/l to 5.5g/l (difference is 2.5g/l). When the salt inflow steps from 2l/s to 3l/s, the salt concentration changes from 5.5g/l to 7.5g/l (difference is 2g/l).

The behavior of this controlled system depends on the operating point. This means that the controls will behave differently with the same controller and the same controller parameters at different operating points (e.g. salt inlet = 2l/s or 3l/s).

7.4 Controller Tuning Rules

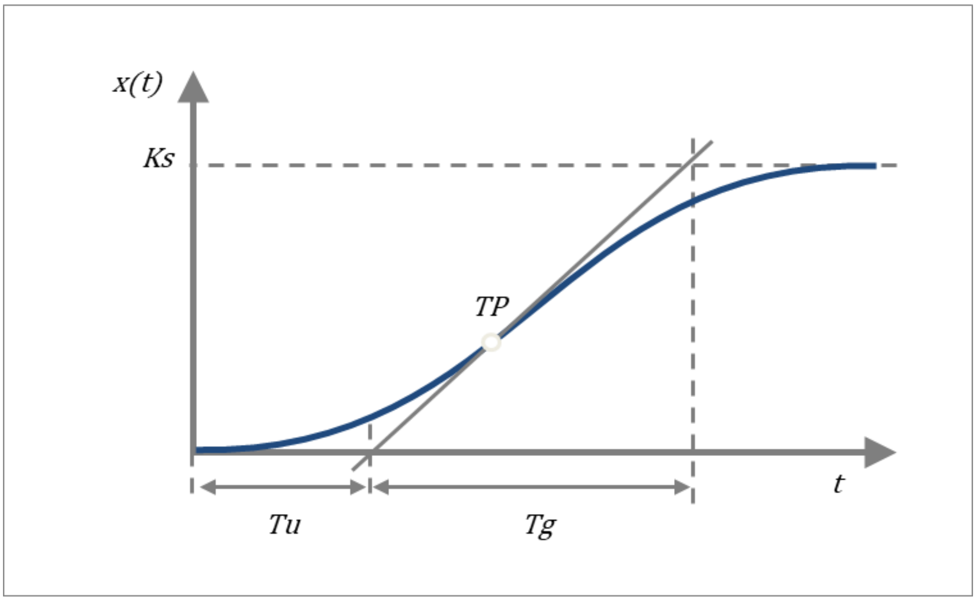
The mixing container cascade is a system with self-regulation.

After a finite time, a system with self-regulation oscillates to a constant output value (controlled variable) after a sudden change in the input value of the system (control signal), while with a system without self-regulation the controlled variable (actual value) continues to increase.

The behavior of the salt concentration in the third container is a system with self-regulation, since in the event of a sudden change in the salt inlet, the salt concentration assumes a fixed value again after a period of time (constant salt concentration), as can be seen under item 7.3.

The method according to Chien/Hrones/Reswick is to be used as a controller tuning rules for system with self-regulation.

A system with self-regulation has roughly the following behavior in response to a unit step in the control signal (sudden change in the control signal by 1):



In the new standard, the delay time is designated with Te, the compensation time with Tb and the turning point with P.

Since the terms Tu and Tg are still used in most of the literature, we keep the old terms here, or use both.

The parameters Ks, Tg and Tu can be determined from this step response, as shown in the figure above. The controlled system´s gain Ks (final value of the actual variable) results from the abrupt change in the control signal by 1. If the amount of change is greater, you have to divide the resulting system´s gain value by the amount the control step value in order to obtain Ks.

It means:

Te = Tu = Delay time

Tb = Tg = Compensation time

Ks = Gain

With the help of these three parameters, the controller parameters can then be determined from the setting table according to Chien / Hrones / Reswick:

Table 5: Equations to calculate controller parameters according to Chien/Hrones/Reswick

Controller	Quality criteria			
	With 20 % Overshoot		Aperiodic case	
	Disturbance	Command	Disturbance	Command
P	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$
PI	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.3 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 4 \cdot T_U$	$K_P \approx \frac{0.35}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.2 \cdot T_g$
PID	$K_P \approx \frac{1.2}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2 \cdot T_U$ $T_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.35 \cdot T_U$ $T_V \approx 0.47 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.4 \cdot T_U$ $T\_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$ $T_V \approx 0.5 \cdot T_U$

For systems without self-regulation use $\frac{T_g}{(K_S \cdot T_U\ )}$ instead of $\frac{1}{(K_{IS} \cdot T_U\ )}$.

The table was taken from: E. Samal, Grundriss der praktischen Regelungstechnik, Oldenbourg

Task 14.

For the mixing container cascade select item 5.3 „Examine controlled system“.

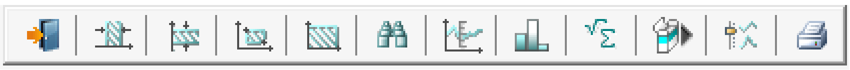
Click „Start“. Enter a step in the salt inlet from 1g/l to 2g/l.

All signal curves are saved and can be measured and evaluated using "Analysis".

Determine the parameters Ks, Te (Tu) and Tb (Tg) from the stored signal curves.

By clicking on the "Analysis" button, you will get the measurement curves.

With the help of the button bar in the window, time and value segments (zooming) can be selected.



Try to find the area of interest for the evaluation with the step in the salt inlet and the swing in the salt concentration.

To determine Te and Tb, you can, for example, print out the diagram and measure the curves with the aid of a ruler

It is also possible to measure the values in the diagram.

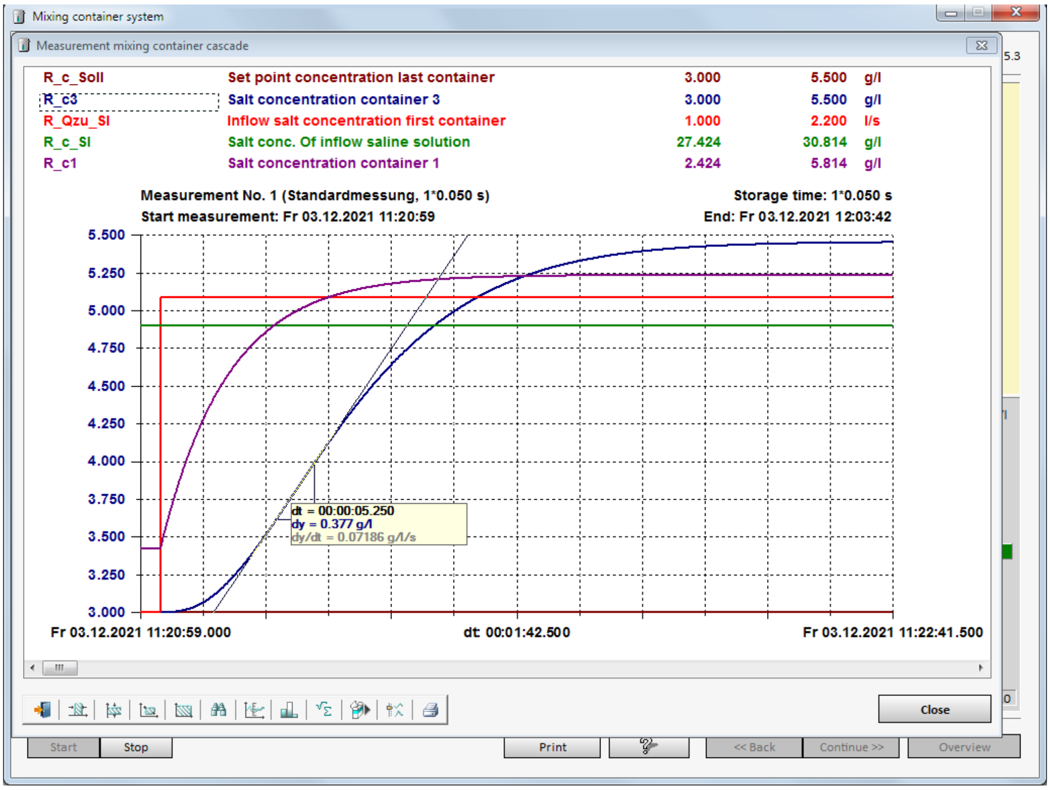


Figure 42:Signal curve for the salt concentration

To do this, click on the blue signal „R_c3" (salt concentration in container 3) in the header.

By clicking on the blue curve, the associated measured value and the time are displayed. By drag and drop you will get the time and value difference as well as the derivation. Try to determine the derivation of the blue curve at the turning point.

The gradient of the tangent at the turning point can be read approximately from the curve shown above, dx/dt = 0.072g/l/s.

After the sudden change in the salt inflow from 1g/l to 2g/l, the salt concentration goes from 3g/l to 5.5g/l after the settling phase.

This enables the compensation time Tg to be calculated:

dx/dt = (end value – start value) / Tg, so

Tg = (end value – start value) / (dx/dt) = (5,5g/l – 3g/l)/0,072g/l/s = 34,7s

Ks results from:

Ks = (end value – start value) / Step height = (5,5 – 3) / 1 = 2,5

The delay time Tu can be measured and is approximately 7,3s.

Hence: Te = Tu = 7,3s Tb = Tg = 34,7s Ks = 2,5

This results in the following controller parameters from the table for the PI controller:

PI controller

Command response with 20% overshoot

K = 0,6*Tb / (Ks*Te)	1,14
Tn = Tb	34,70

Command response aperiodic

K = 0,35*Tb / (Ks*Te)	0,67
Tn = 1,2 * Tb	41,64

Disturbance response with 20% overshoot

K = 0,7*Tb / (Ks*Te)	1,33
Tn = 2,3 * Te	16,79

Disturbance response aperiodic

K = 0,6*Tb / (Ks*Te)	1,14
Tn = 4 * Te	29,20

According to the table, the following parameters result for the PID controller:

PID controller

Command response with 20% overshoot

K = 0,95*Tb / (Ks*Te)	1,81
Tn = 1,35 * Tb	46,85
Td = 0,47 * Te	3,43

Command response aperiodic

K = 0,6*Tb / (Ks*Te)	1,14
Tn = Tb	34,70
Td = 0,5 * Te	3,65

Disturbance response with 20% overshoot

K = 1,2*Tb / (Ks*Te)	2,28
Tn = 2 * Te	14,60
Td = 0,42 * Te	3,07

Disturbance response aperiodic

K = 0,95*Tb / (Ks*Te)	1,81
Tn = 2,4 * Te	17,52
Td = 0,42 * Te	3,07

Task 15.

Investigate the control behavior and the disturbance behavior for the mixed container cascade with the parameters determined according to Chien/Hrones/Reswick for the PI controller and the PID controller.

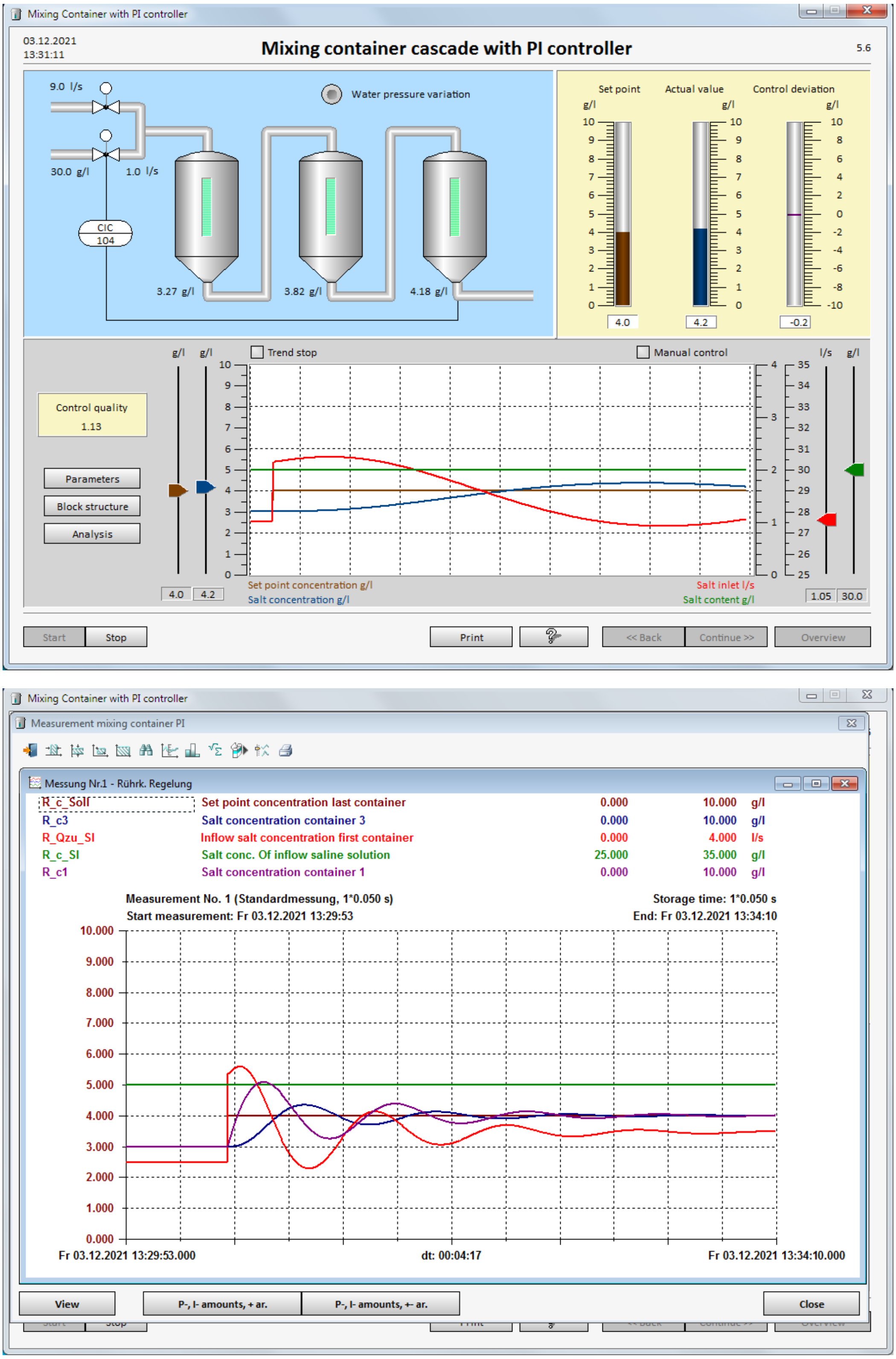
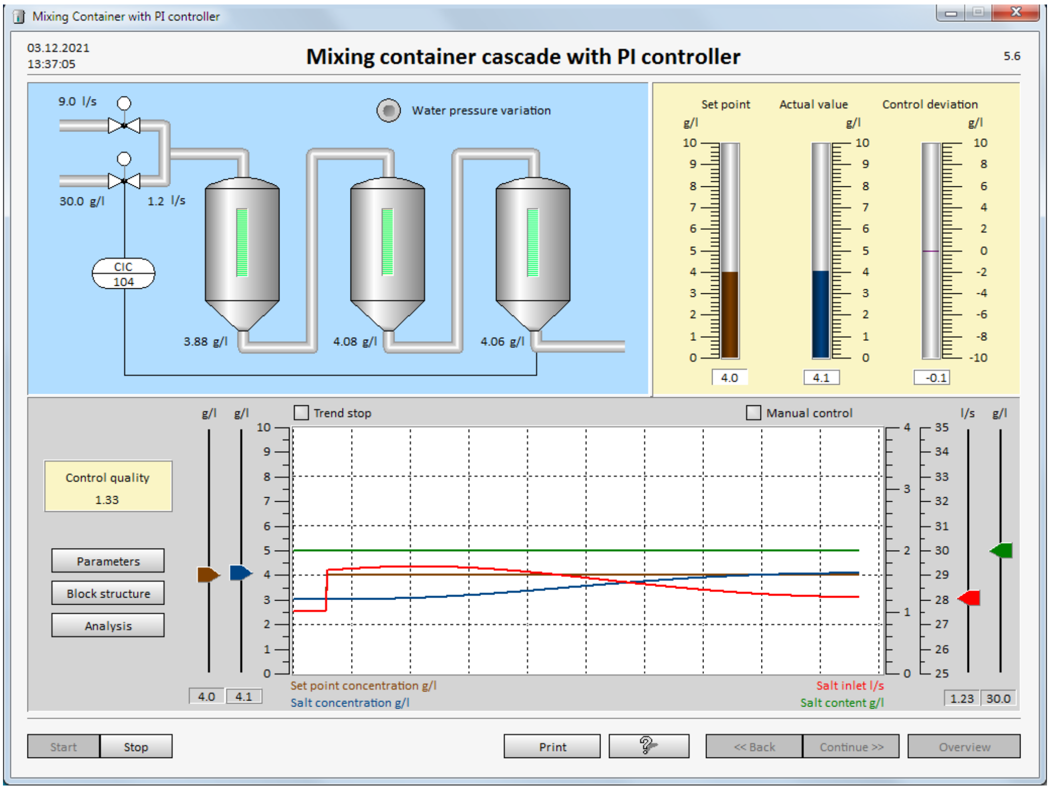


Figure 43: Command response with 20% overshoot / Change of the set point from 3g/l to 4g/l.



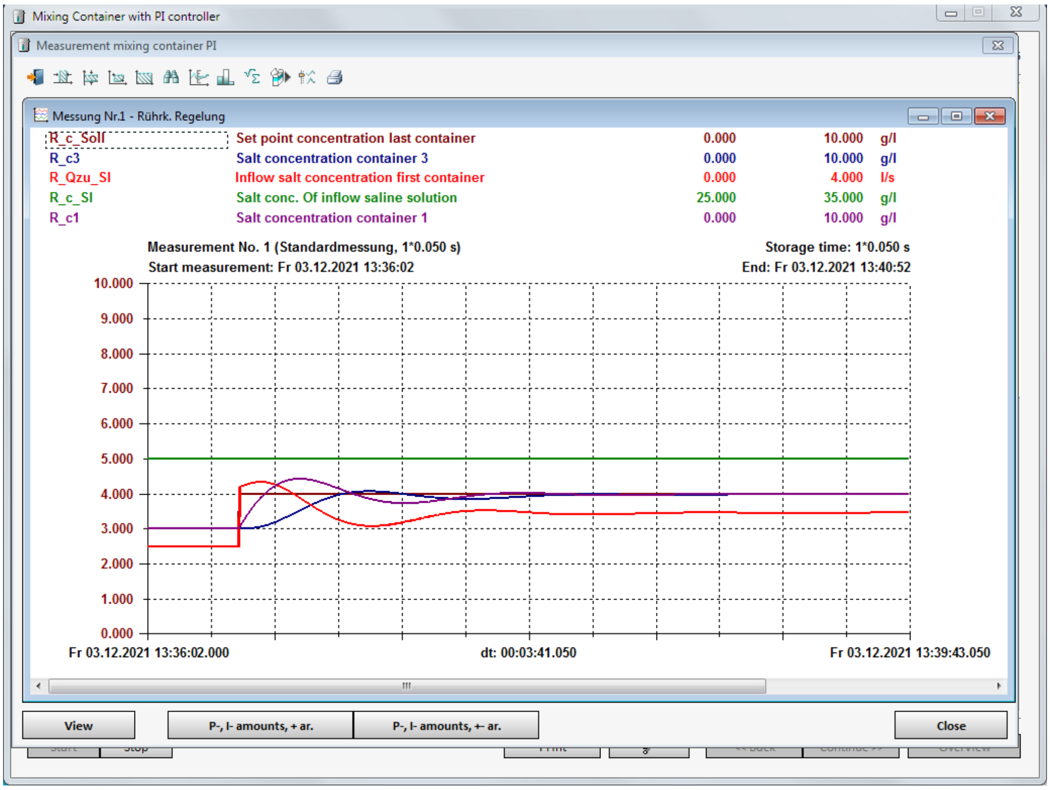


Figure 44: Command response aperiodic / Change of the set point from 3g/l to 4g/l.

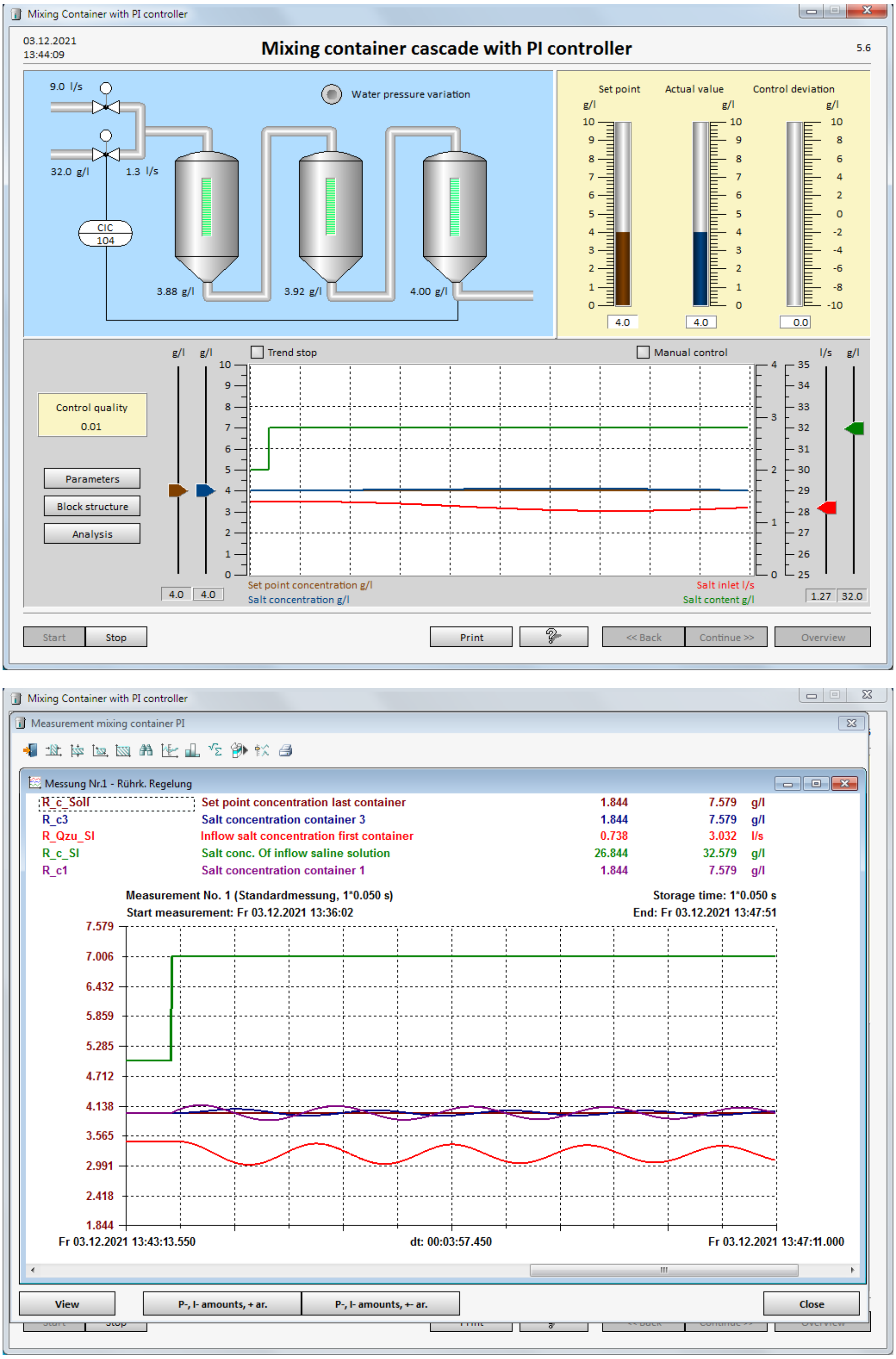
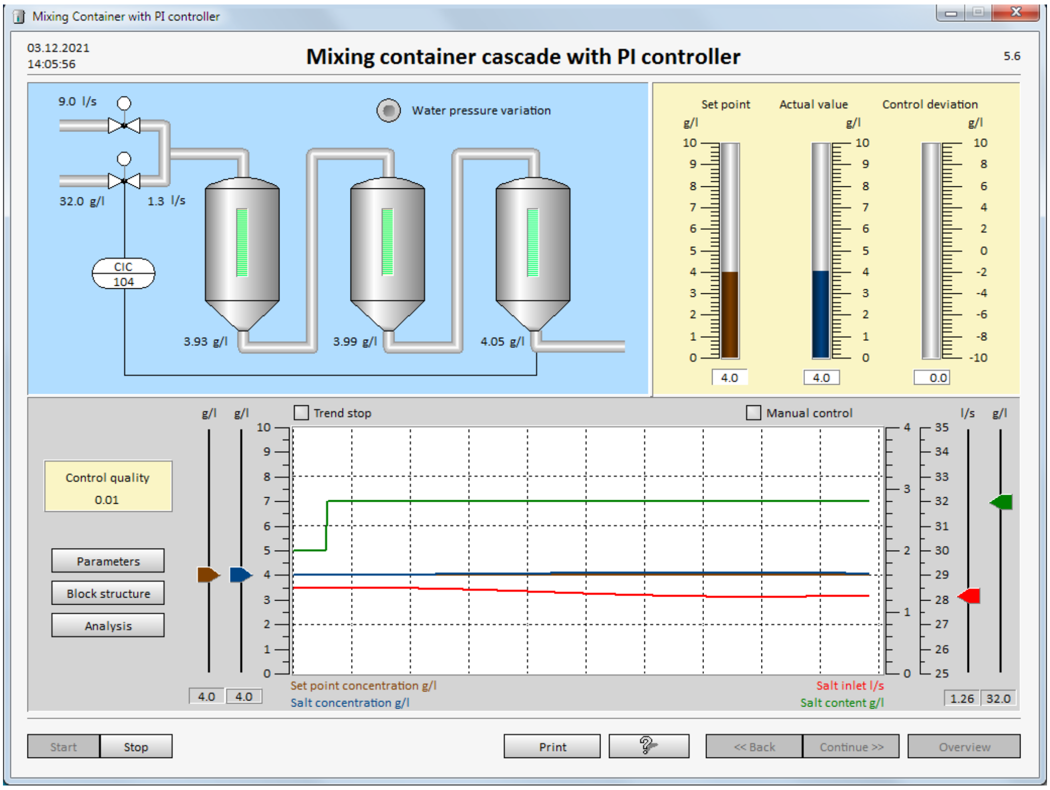


Figure 45: Disturbance response with 20% overshoot / Change of the disturbance input (salt content) from 30l/s to 32l/s.

The disturbance is not controlled with these parameters



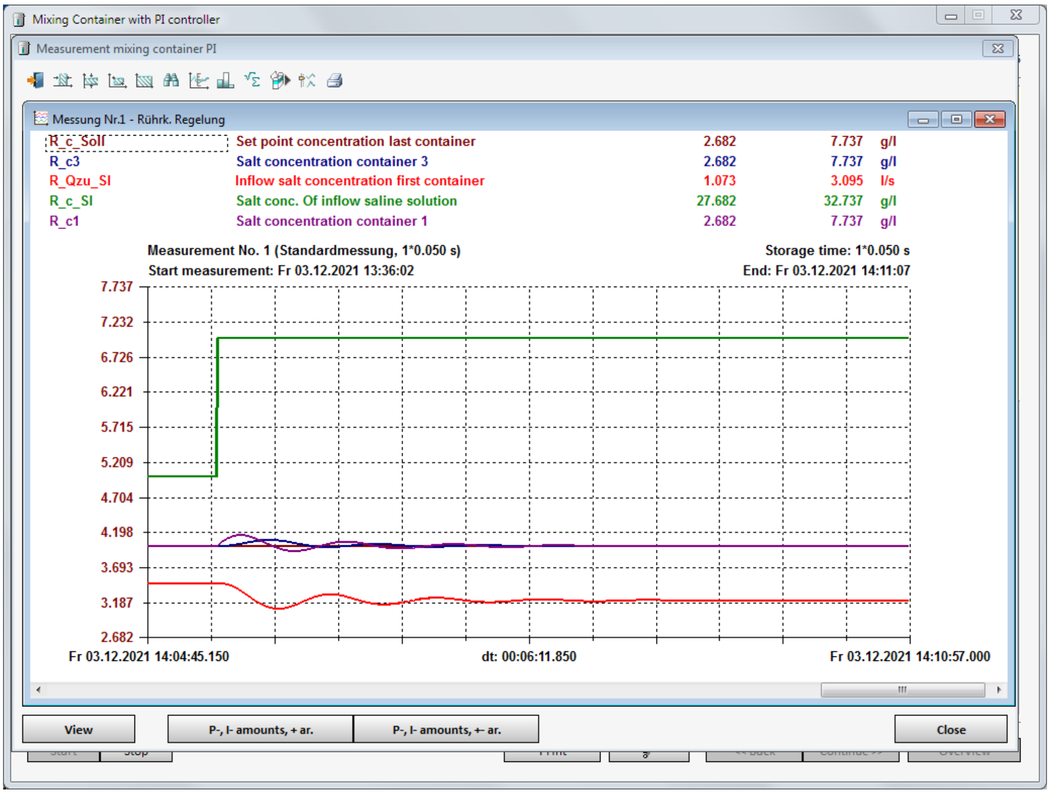


Figure 46: Disturbance response aperiodic / Change of salt content from 30l/s to 32l/s.

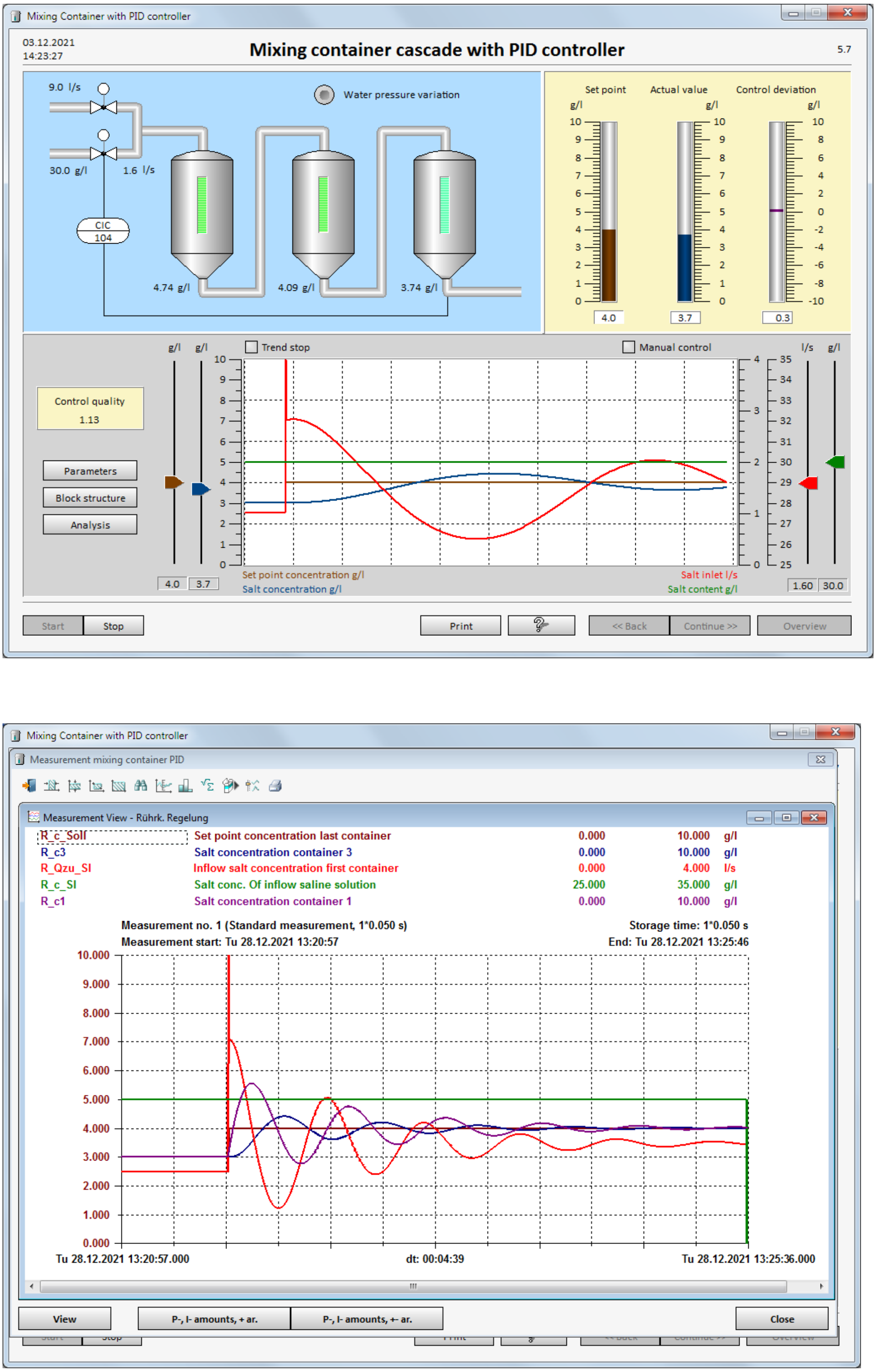


Figure 47: Command response with 20% overshoot / Change of the set point from 3g/l to 4g/l.

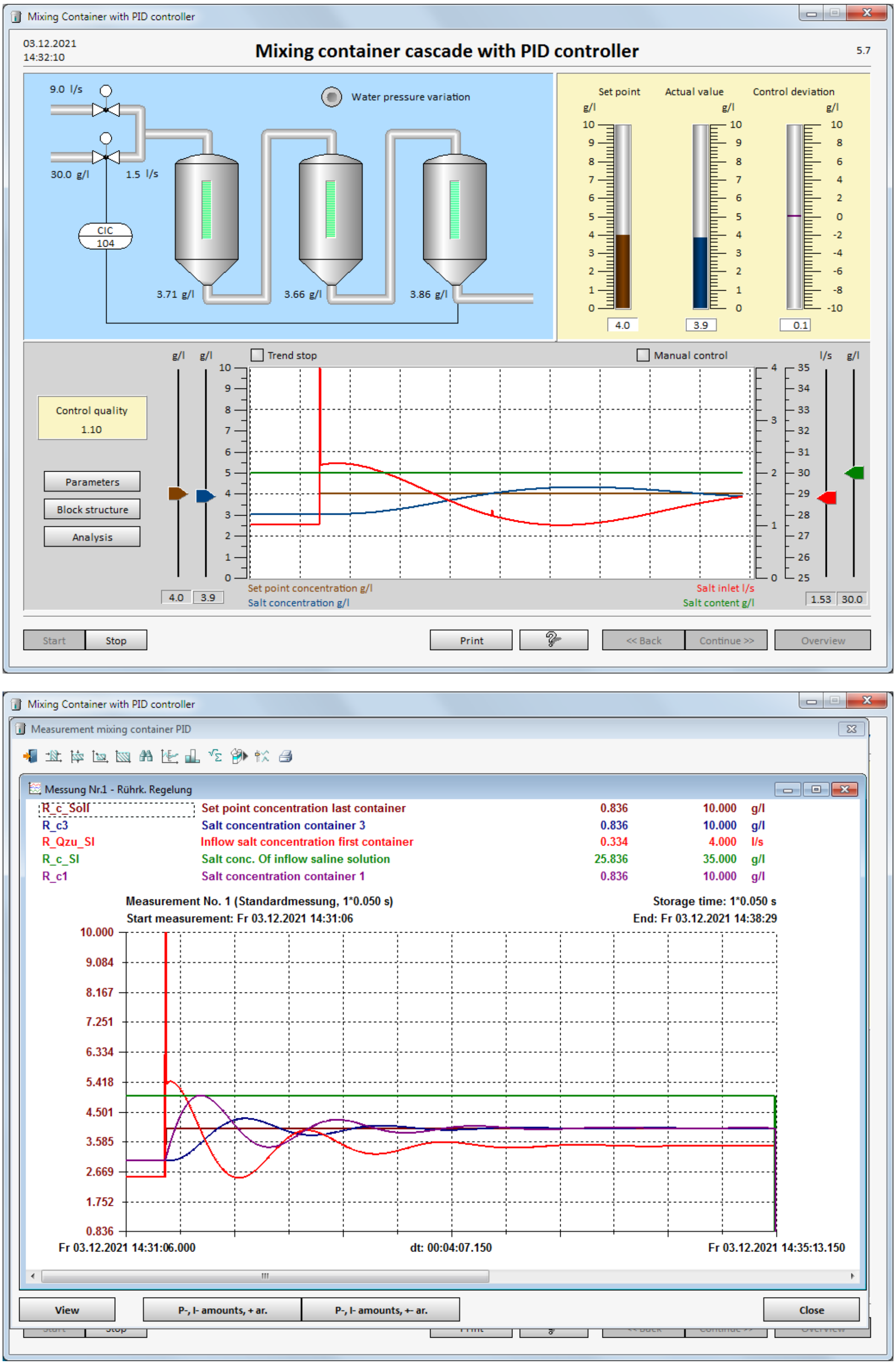


Figure 48: Command response aperiodic

The controller tuning rule from Chien/Hrones/Reswick is not well suited here, as the calculated parameters do not cause an aperiodic settling.

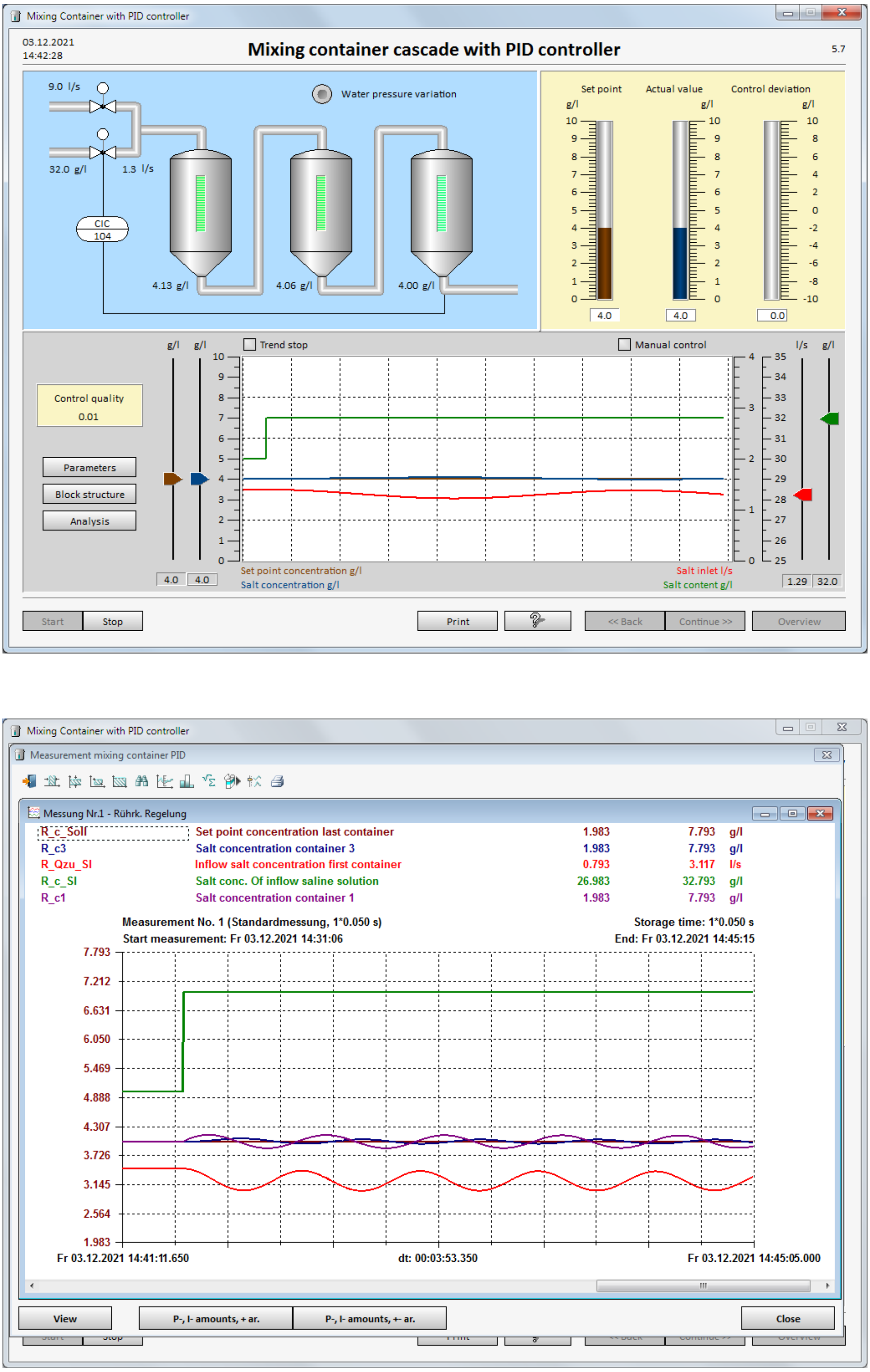


Figure 49: Disturbance response aperiodic

The controller tuning rule from Chien/Hrones/Reswick is not suitable here, as the calculated parameters make the control loop unstable

7.5 Evaluation of the Controller Tuning Rules

The controller tuning rule from Chien/Hrones/Reswick was not well suited for this system, especially the disturbance behavior.

Since the controller tuning rules are empirical and not based on mathematical principles, it cannot be assumed that they will provide reasonable results for every system.

7.6 Closed-loop Control with Cascade Controller

With cascade control, attempts are made to improve and accelerate the control with the help of further measured variables.

The cascade control consists of two control loops. The outer main control loop with a PID controller is subordinated to an inner loop with a PI controller. Since the system has a relatively large time constant, it takes a long time for changes in the input variable to become noticeable at the output. In the case of a single-loop control, this has a disadvantageous effect on the speed of the control.

With the cascade control of the mixed container cascade, the salt concentration (output variable) of the first tank is accessed. Changes (disturbances) in the salted inlet are measured in the first tank sooner than in the third tank. The inner control loop is therefore quicker to control disturbance, so that the total control is accelerated. Another advantage is that large control deviations, which occur in a single-loop control, are avoided in the first container due to the inner circle.

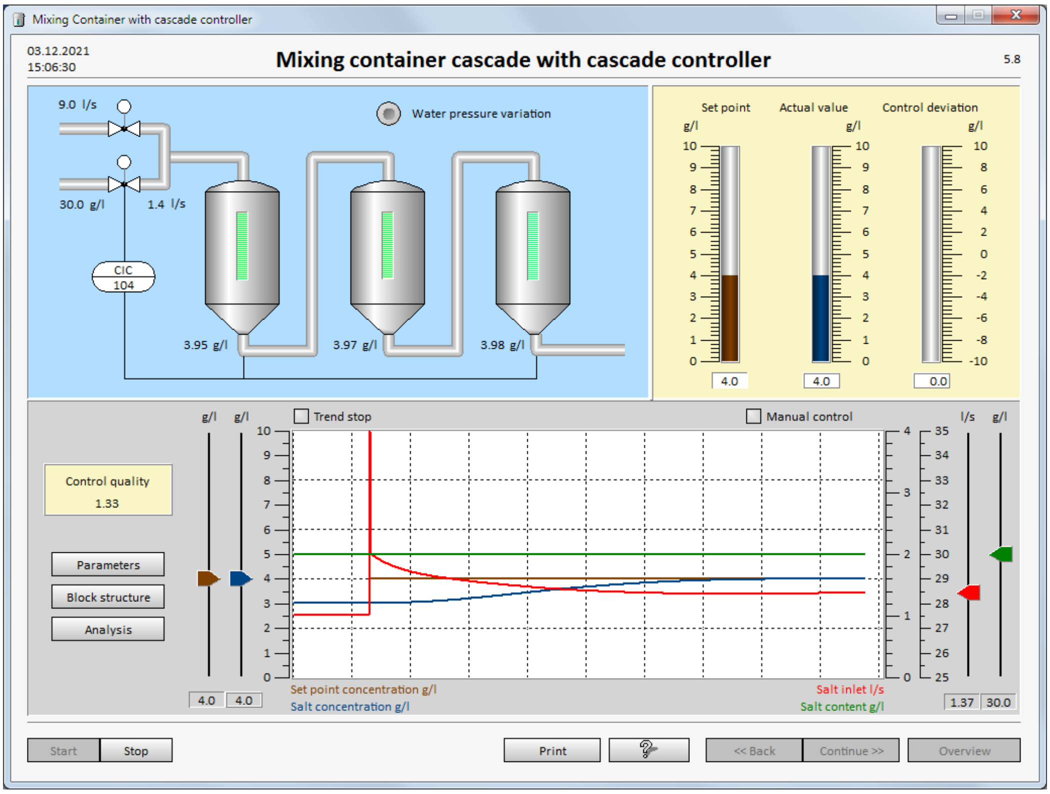
Task 16.

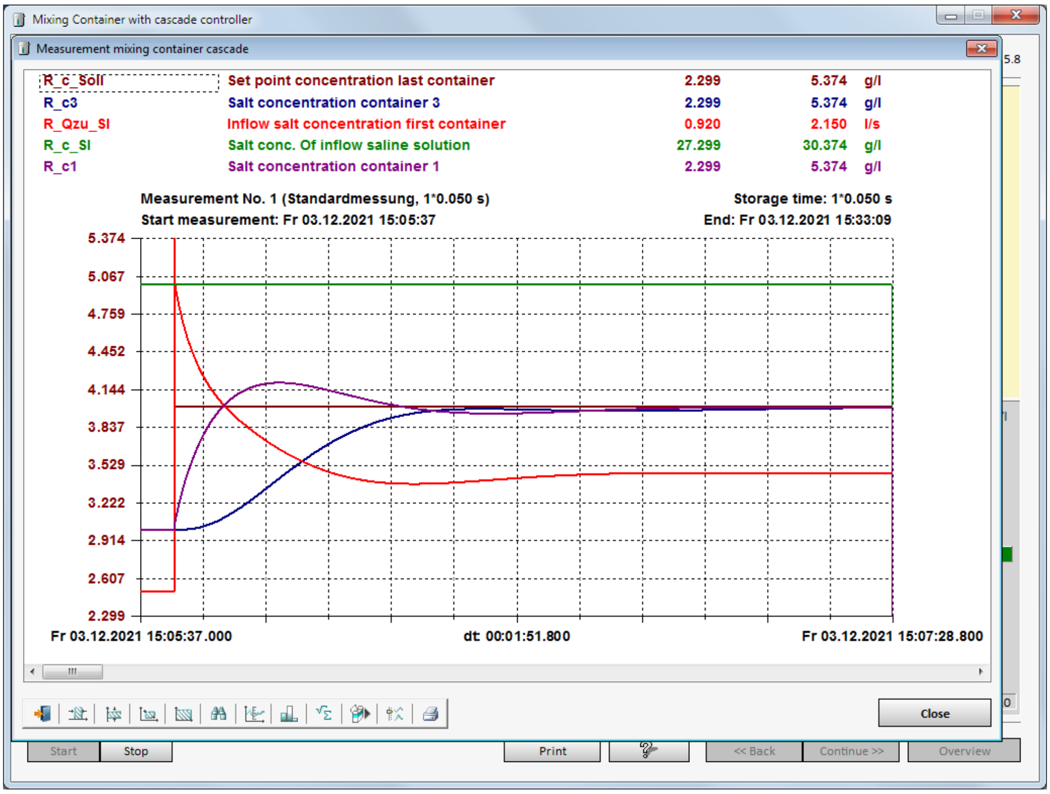
Select the item 5.8 „Closed-loop control with cascade controller“ for the mixed container cascade and click „Start“.

Enter a step in the set point concentration from 3g/l to 4g/l.

Observe the control behavior.

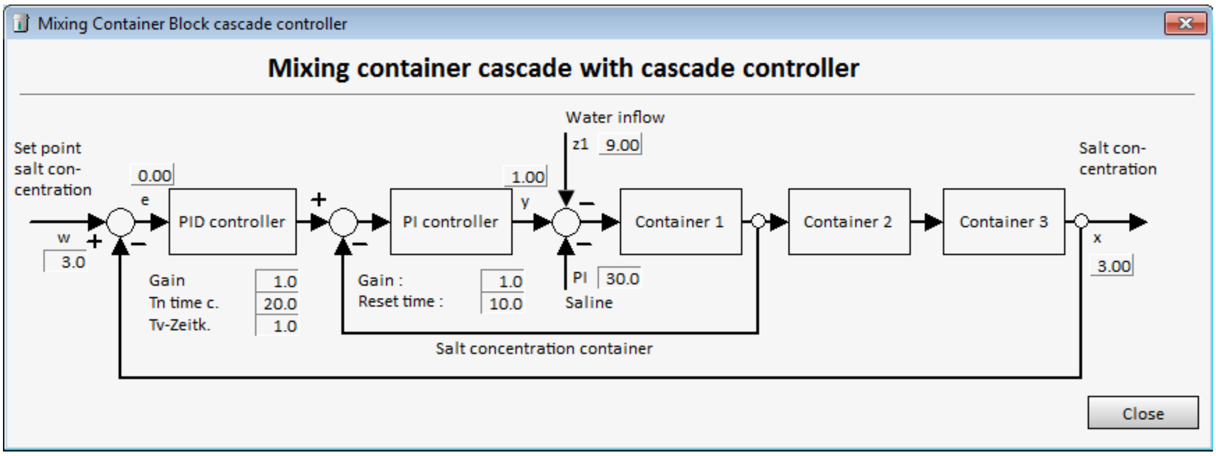
With the preset values of the two controllers, the behavior of the control is very good. The actual value (salt concentration in the 3rd container) goes quickly and without overshooting to the set point (set point concentration).


Mixing Container with cascade controller
03.12.2021
15:06:30
Mixing container cascade with cascade controller
5.8
Water pressure variation
Set point
Actual value
Control deviation
Control quality
1.33
Parameters
Block structure
Analysis
Trend stop
Manual control
Set point concentration g/l
Salt concentration g/l
Salt inlet l/s
Salt content g/l
Start
Stop
Print
<< Back
Continue >>
Overview


Mixing Container with cascade controller
Measurement mixing container cascade
R_c_Soll Set point concentration last container 2.299 5.374 g/l
R_c3 Salt concentration container 3 2.299 5.374 g/l
R_Qzu_Sl Inflow salt concentration first container 0.920 2.150 l/s
R_c_Sl Salt conc. Of inflow saline solution 27.299 30.374 g/l
R_c1 Salt concentration container 1 2.299 5.374 g/l
Measurement No. 1 (Standardmessung, 1*0.050 s)
Start measurement: Fr 03.12.2021 15:05:37
Storage time: 1*0.050 s
End: Fr 03.12.2021 15:33:09
Fr 03.12.2021 15:05:37.000
dt: 00:01:51.800
Fr 03.12.2021 15:07:28.800
Close

The inner control loop (with PI controller) tries to adjust the salt concentration of the 1st container to the actuating variable of the outer controller (PID controller). The salt inflow is the resulting actuating variable (output) of this inner control loop. The output of the PID controller is the reference variable (input) for the inner control loop. Since the salt concentration is transmitted from the 1st to the 3rd container, the salt concentrations from the 1st to the 3rd container must be the same when the target concentration is reached. In the steady-state case, the output of the external controller is the set point of salt concentration. The outer control-loop has the reference value for the inner control loop as a result, that in the steady-state case approaches the set target concentration. This reference value is compared with the measured concentration in the 1st container and the inner controller tries to achieve this concentration by adjusting the salt inlet.

The fact that the adjustment of the salt inlet depends on the measured concentration in the 1st container and that the control signal of the external controller is the reference variable for the inner controller makes it possible to achieve good and fast control loop behavior.



8 Liquid Level Control (Control Training II)

The next controlled system is a container with inflow and outflow. The amount of outflow is influenced by the valve position. The technical control task is to control the level by opening or closing the valve so that it corresponds to a specific set point. The valve position represents the input variable of the system, the level in the container is the output variable of the system. The inflow acts as a disturbance variable.

The valve is controlled by a motor that is driven by a three-position controller. By activating the motor, the valve can open, close or remain in the current position. The three-position controller issues the "open" and "close" commands. The desired valve position is the set point for the three-position controller. The actual value of the valve position is time delayed, because the motor opens or closes the valve to the desired position.

The reference variable is the set point of level, the controlled variable is the actual level, the disturbance variable is the inflow and the control signal is the "set point of valve position". Since the valve is opened and closed by a motor, it can take some time before the valve reaches the valve position "set point of valve position. For this reason, a distinction is made between the signals "set point of valve position" and "actual valve position".

In the initial state of the simulation, the valve is closed and the inflow is zero. In order for the level to change, the inflow must be set to values greater than zero.

It should also be noted for this control, that the controller output has been multiplied by 0.4 so that the control signal y is normalized to 0 to 100%, because the difference between the set point and actual value can have a maximum value of 250l/s.

8.1 Uncontrolled System (Manual Control)

Select „Overview“ and go to item 5.1 „Uncontrolled system“.

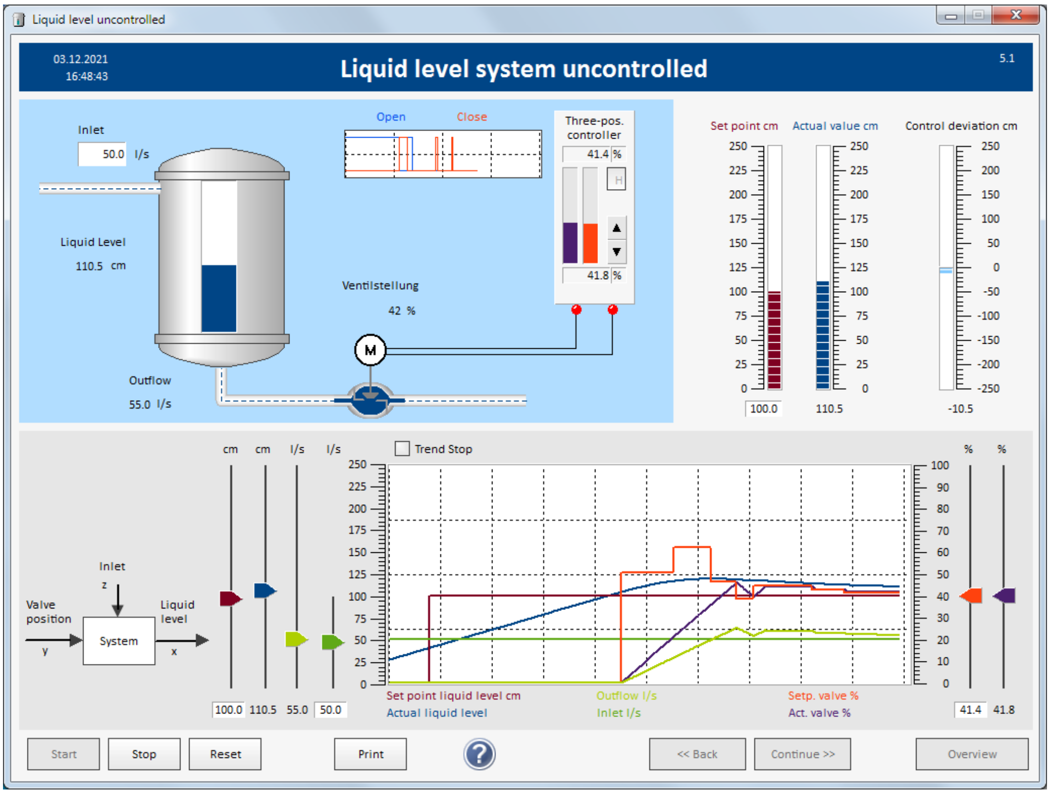
Click “Start”. You can now change the values for the set point (reference variable, actual liquid level cm), the control signal (set point of valve position) and the disturbance signal (inflow l/s) using the slider or by entering values below the slider.

Task 1.

Set the inflow to 50l/s and fill the container. Set the set point (reference variable, set point liquid level) to 100cm. By adjusting the control signal (setp. valve %) you can now try to adjust the actual value (controlled variable, actual liquid level) to the set point (reference variable, set point liquid level).

The actual valve position is delayed to the desired valve position (compare red and purple signal in the trend display).

The control can of course only be implemented if an inflow > 0 is set.

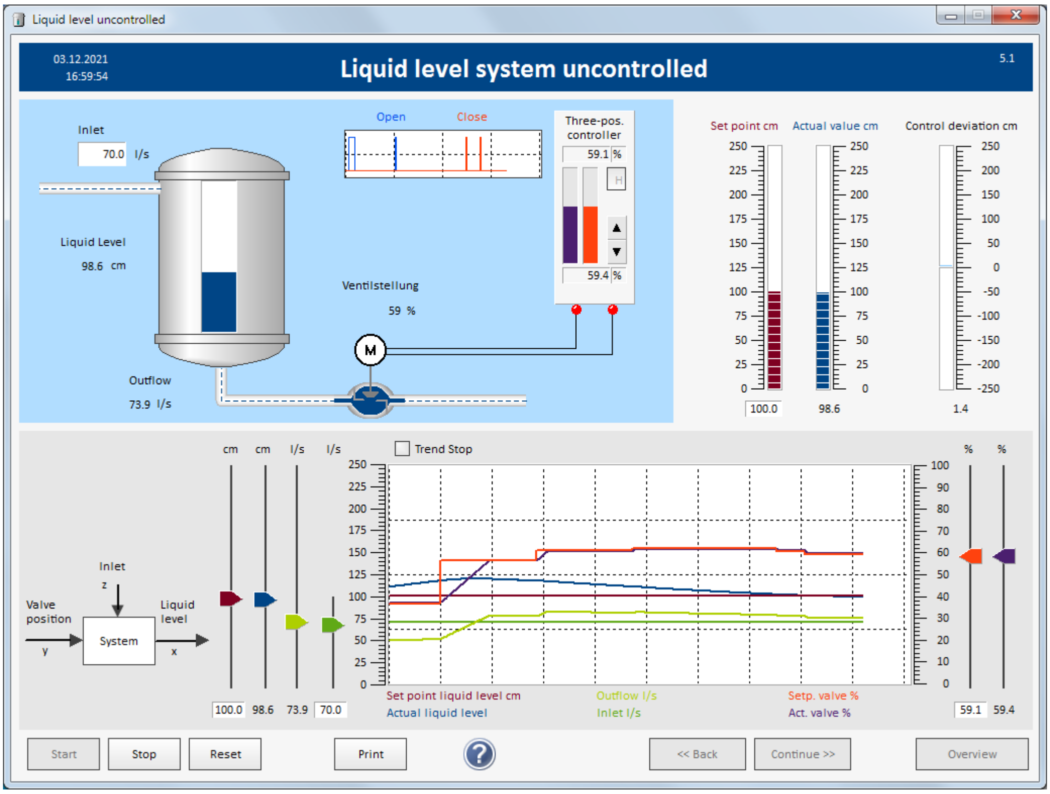


This type of control is known to as command response. The set point is adjusted and an attempt is made to adjust the actual value (controlled variable) to the new set point (reference variable) by adjusting the control signal.

It can be observed with this system that the actual valve position is delayed after the control signal. If the control signal is changed (red signal) it takes until the valve position adopts the value specified by the control signal. When the motor is activated, the valve needs a certain amount of time to move to the desired valve position.

Task 2.

Change the inflow to 70l/s and try to correct the disturbance by adjusting the control signal.



The level begins to rise. The control valve must be opened further so that the outflow increases and the level decreases.

Changing the inflow is a disturbance to the system. That is why one speaks here of the investigation of the disturbance response.

8.2 Controlled System

8.2.1 Closed-loop Controlled System

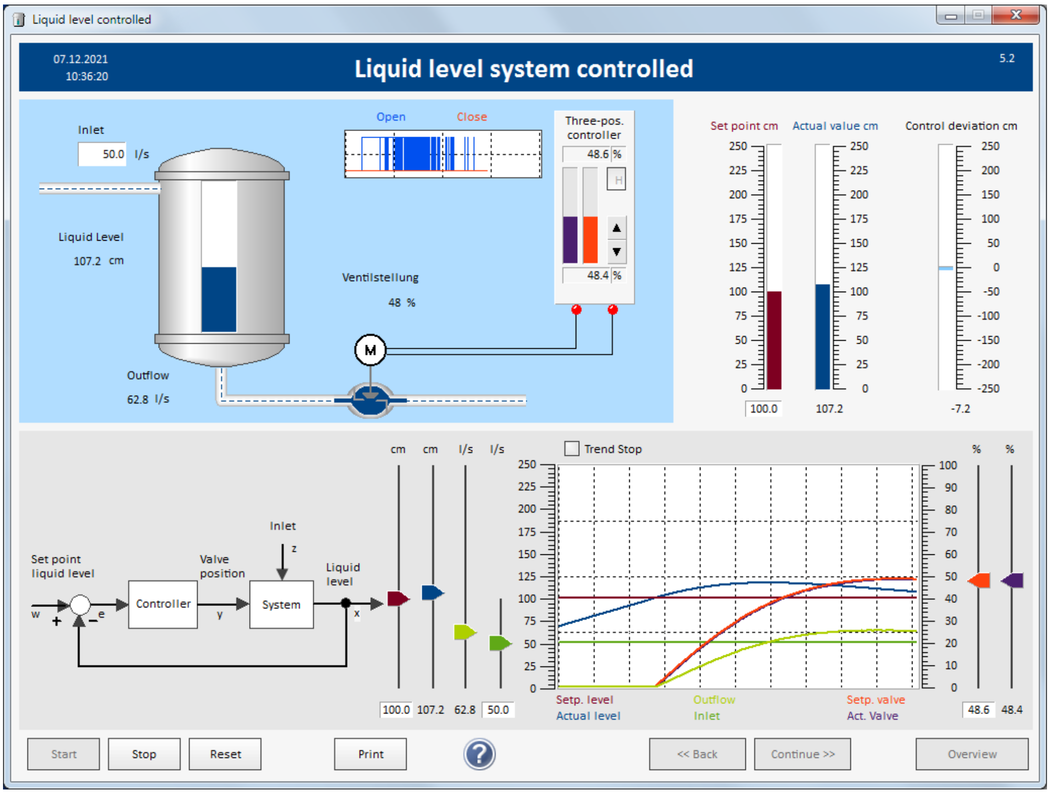
Go to „Overview“ and select item 5.2 „Controlled system“.

Here you can see how the system behaves in principle if, instead of manually control by the user, a controller takes on the task of adjusting the actual value to the set point.

Task 3.

Click „Start“. First set the target level (reference variable) to 100cm and then the inflow to 50l/s.

What will happen?



Only when the level of 100cm is reached the controller outputs a control signal greater than 0. As long as the level was below the set point level, the valve remained closed.

If the actual level exceeds the set point level, the valve is opened so that the outflow increases and the level drops again.

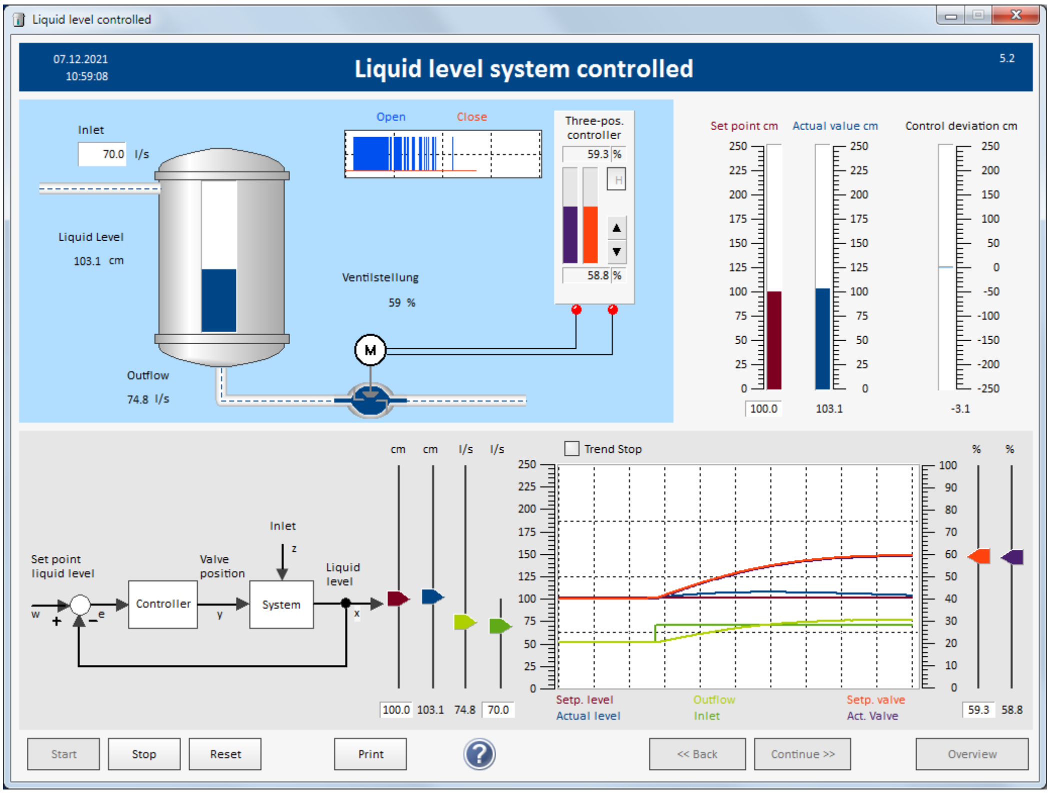
With an overshoot, the controller manages to adjust the actual level to the set point.

Since the control loop reacts to a change in the set point, this is referred to as the command response.

Task 4.

Change the inflow to 70l/ s.

What will happen?



The level begins to rise.

The controller tries to open the valve further so that outflow increases.

After a certain time, the controller has corrected the disturbance (disturbance response).

The valve is controlled by the motor, which opens or closes the valve or maintains the position.

8.2.2 Closed-loop Control with P Controller

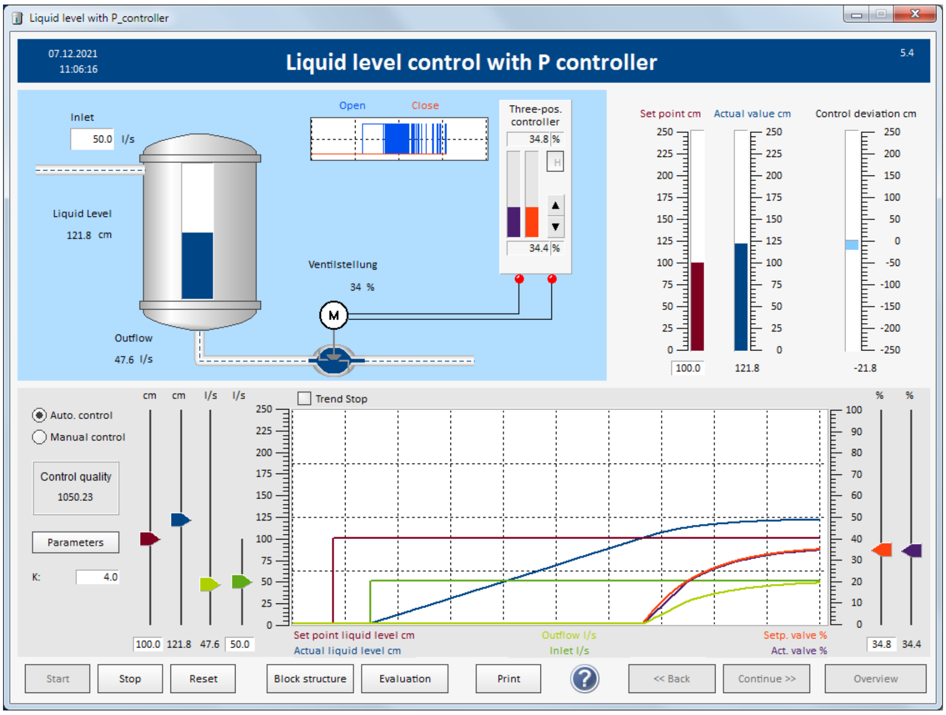
Go to „Overview“ and select item 5.4 „Closed-loop control with P controller“.

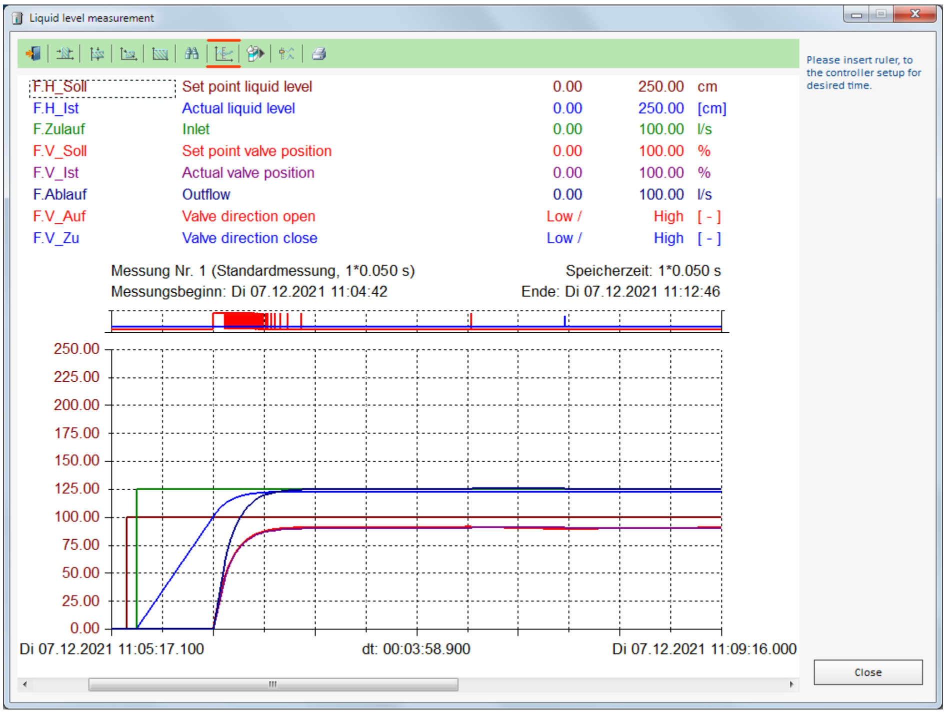
Click „Start“.

Task 5.

Set K to 4, the set point to 100cm and the inflow to 50l/s. Wait until the control loop has settled, i.e. until the actual value no longer changes.

Observe the behavior.





The level begins to rise after the inflow has been set to 50l/s. When the actual level exceeds the set point level, the controller issues a control signal and the valve is opened.

After the settling phase, it can be clearly seen that the actual value (controlled variable) does not reach the set point (reference variable). We get a steady-state control error.

The control error is defined as e = w - x, with

w = reference variable (set point) and x = controlled variable (actual value).

Reason:

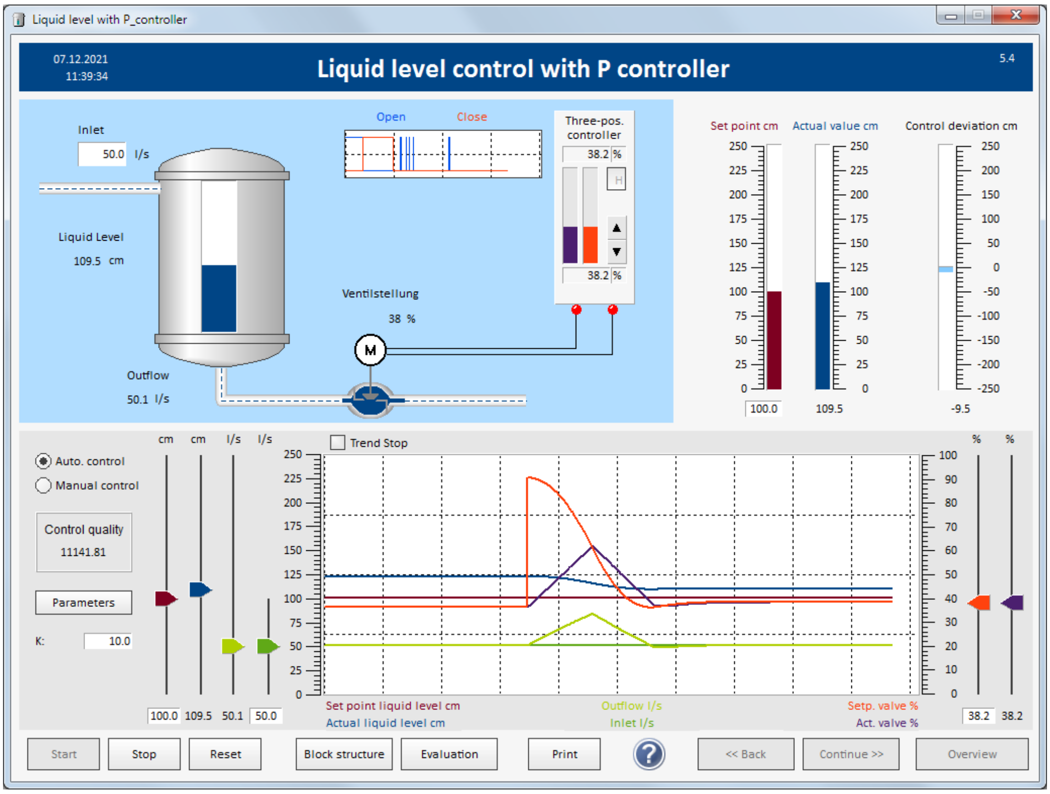
The P controller works like an amplifier. The input signal to the controller x-w (set point - actual value) is multiplied by the specified gain factor (in our case 4). In order for the P controller to output a control signal (valve position) not equal to zero, the set point and actual value must be different, i.e. steady-state control error.

If the controller outputs 0, the valve closes and the outflow goes to 0.

Task 6.

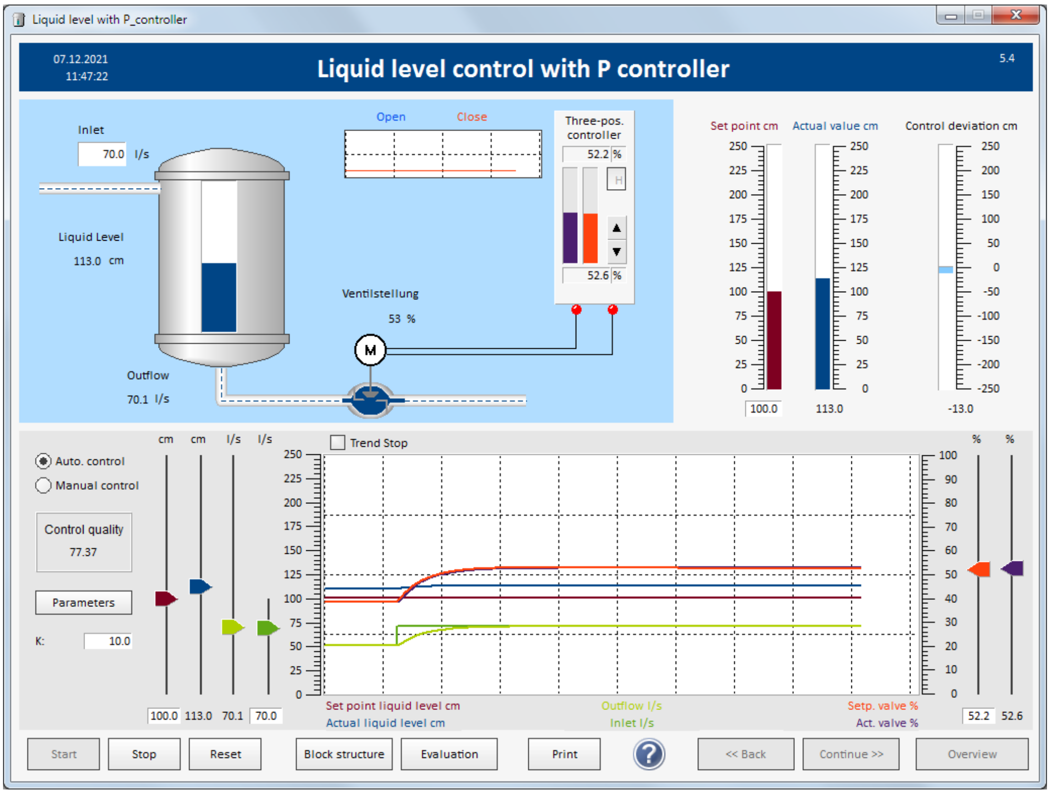
Change the gain of the P controller from 4 to 10 and wait until the control loop has settled again.

What will happen?



The control error between the set point and the actual value becomes significantly smaller as the gain K is increased from 4 to 10. However, the P controller does not manage to adjust the actual value to the set point here either. For the reason described above, we also get a steady-state, albeit smaller, control error x - w.

The P-controller also reacts to a disturbance (change in the inflow). A permanent control deviation is also obtained for this.



As can be seen from the settling response, the P controller reacts immediately and quickly to changes in the set point and disturbance values (control and disturbance response).

8.2.3 Closed-loop Control with I Controller

Go to „Overview“ and select item 4.5 „Closed-loop control with I controller“.

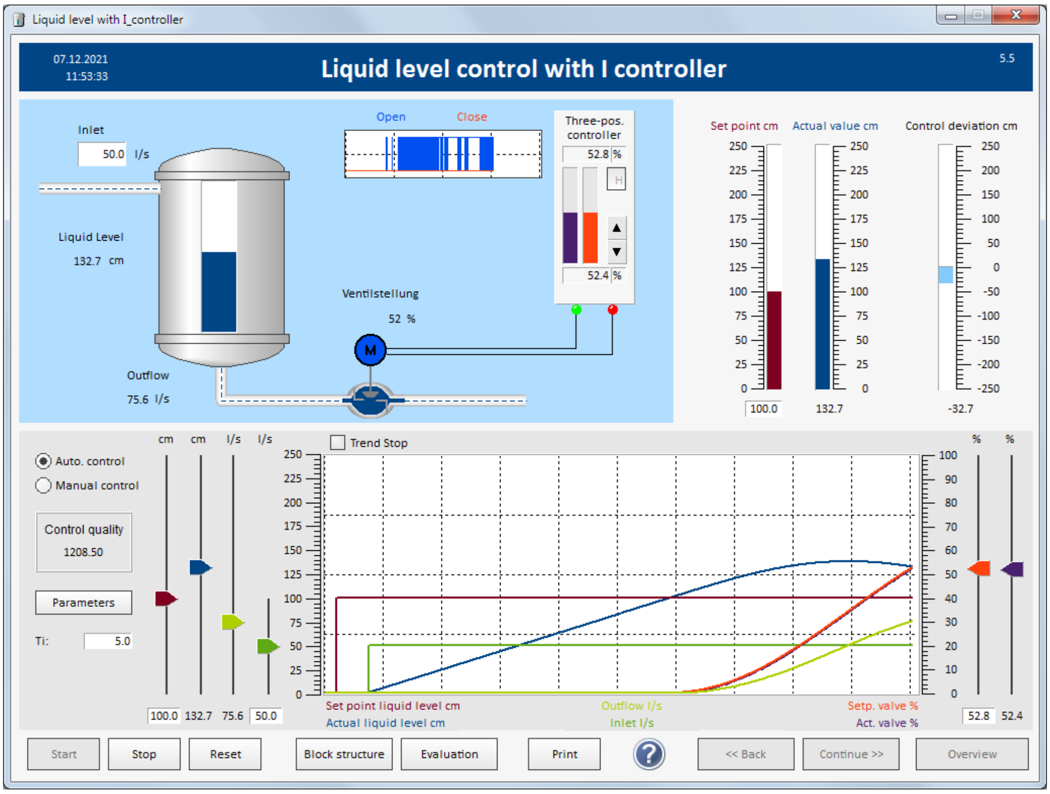
Click „Start“.

Task 7.

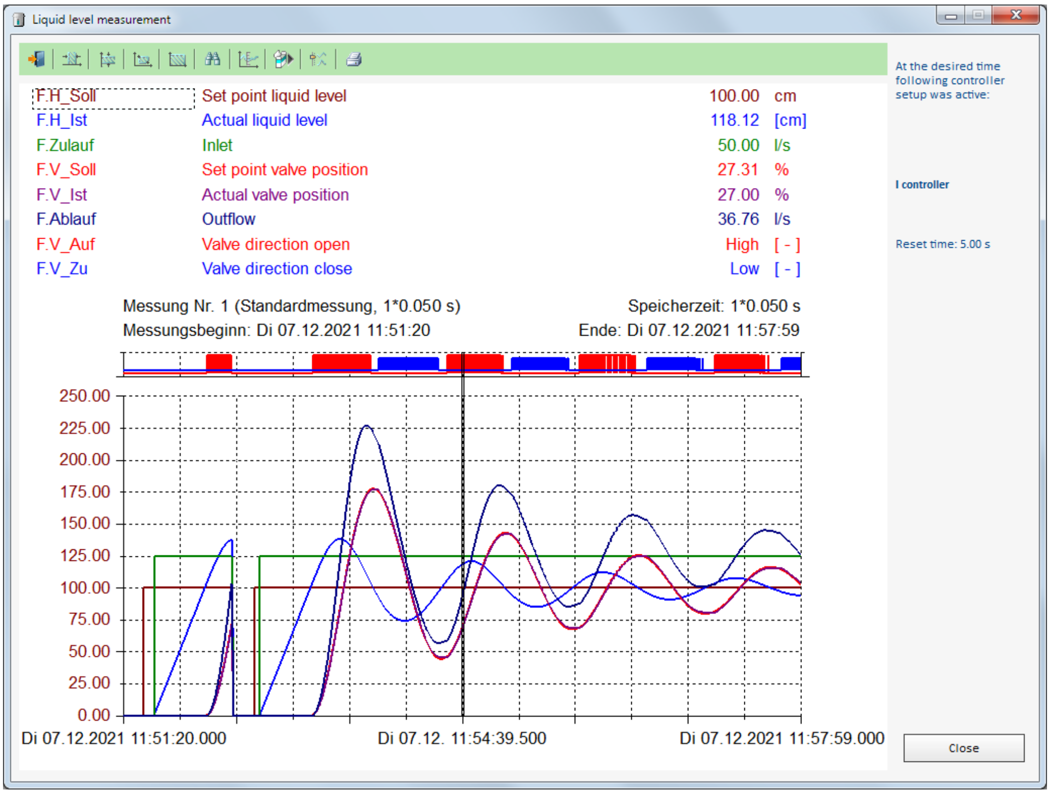
Set the controller parameter Ti to 5.

Change the set point to 100cm and the inflow to 50l/s.

Observe the behavior.



The valve is slowly opened by the I controller. After a long period of time with many overshoots, the actual value reaches the set point.



The I controller is not suitable for this level control because the settling takes too long.

Adjusting the controller parameter Ti also does not improve the settling behavior.

8.2.4 Closed-loop Control with PI Controller

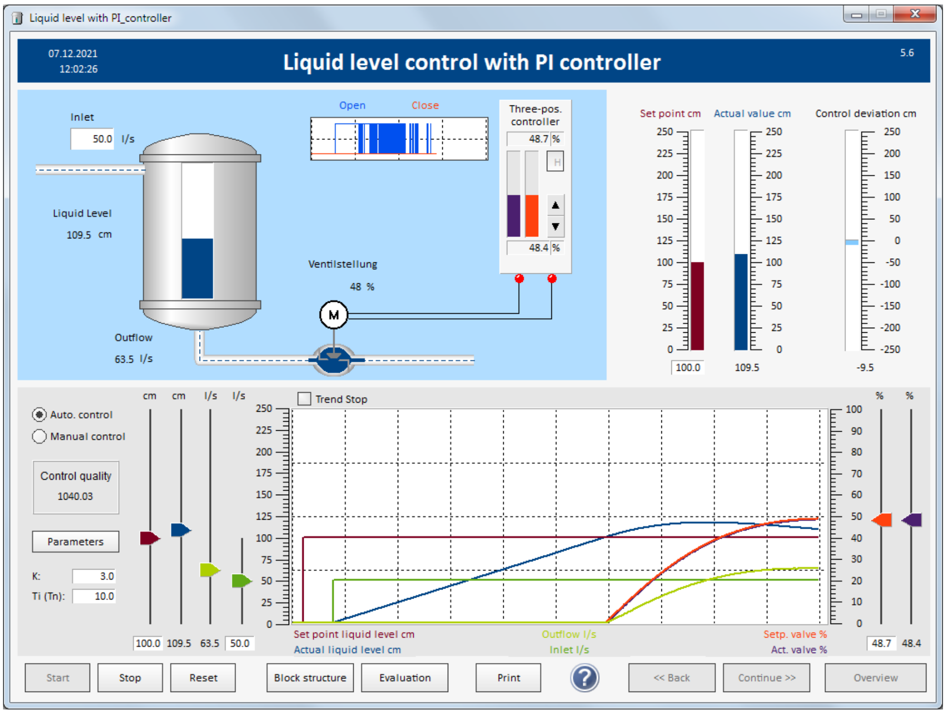
Go to „Overview“ and select item 5.6 „Closed-loop control with PI controller“.

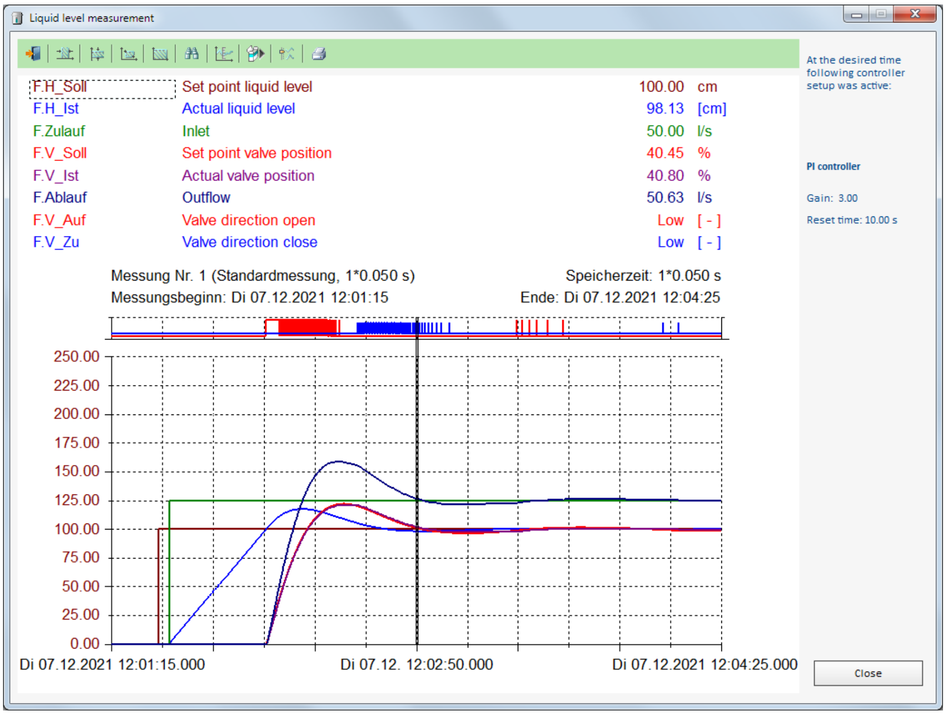
Click „Start“.

Task 8.

Keep the controller parameters on: Gain K = 3, Reset time Ti = 10.

Change the set point to 100cm and the inflow to 50l/s. Observe the settling behavior.





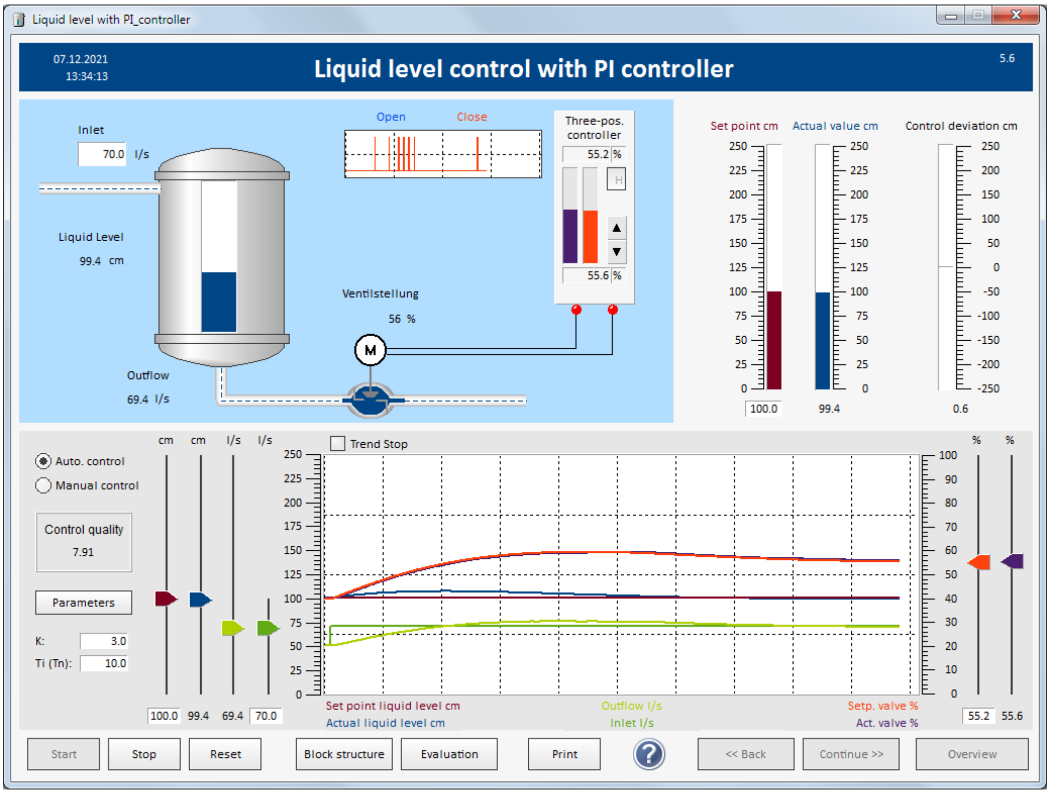
The actual value (controlled variable, actual level) reaches the new set point (reference variable, set point level) with the PI controller and the set parameters with overshoot.

Since the set point has been changed, this is about the investigation of the command response.

Task 9.

Investigate the disturbance response.

When the control loop has settled, change the inflow to 70l/s and observe the behavior.



The larger inflow causes an increase in the level. The controller tries to counteract this and increases the valve opening. After a short settling phase, the actual value reaches the set point again.

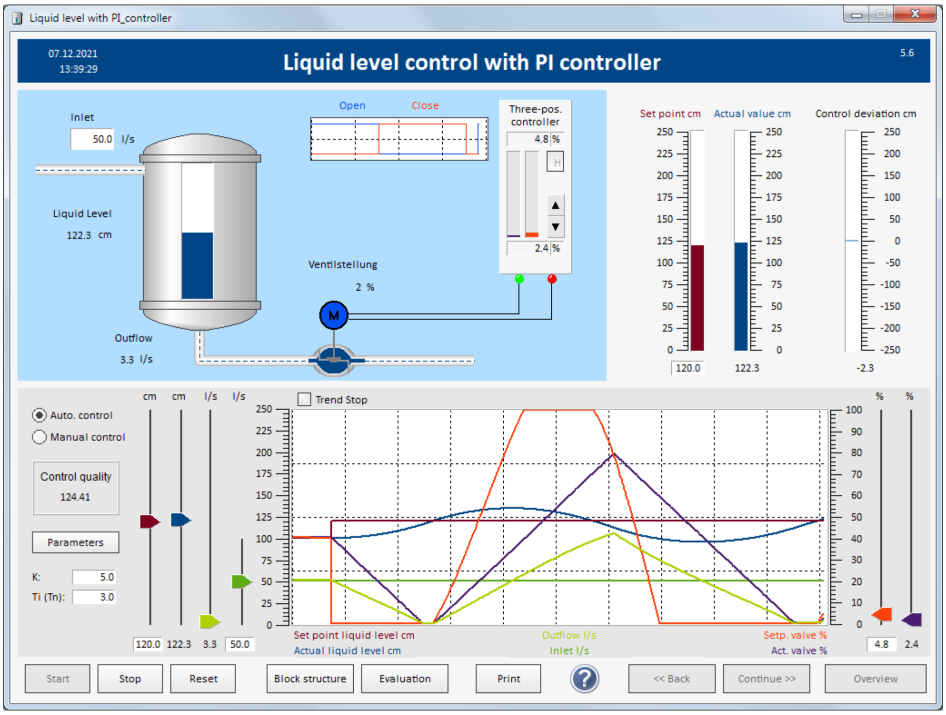
Since the control loop reacts to a change in the disturbance value, one speaks of disturbance response in this case.

Task 10.

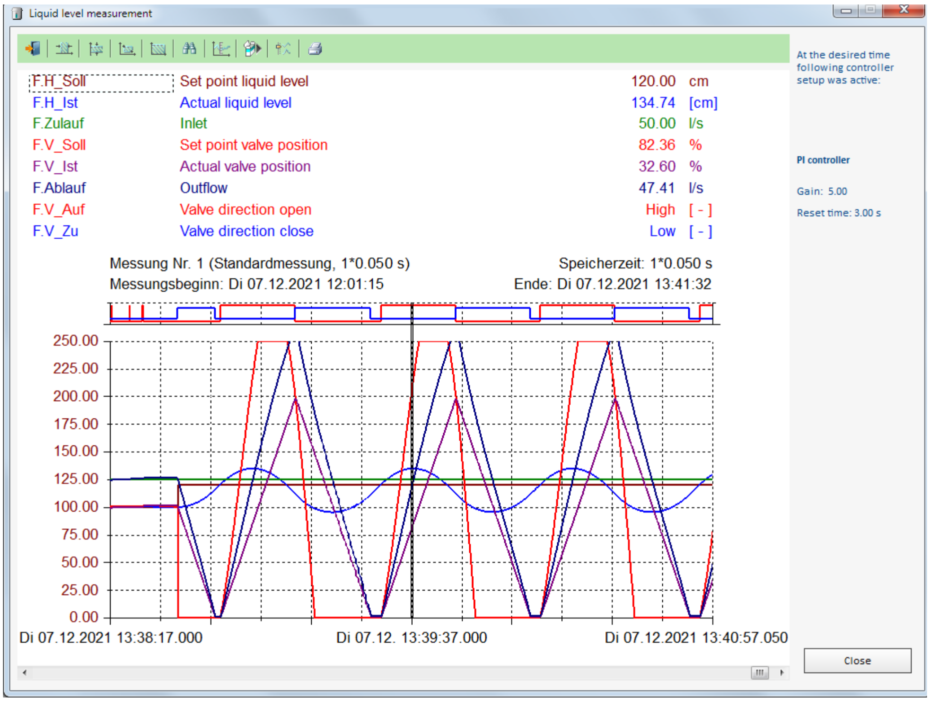
Let the system settle with the specified parameters of the PI controller to the set point 100cm with an inflow of 50l/s.

Change the controller parameters to K = 5 and Ti = 3.

Enter a step in the set point level from 100cm to 120cm. What will happen?



With these controller parameters, the control loop becomes unstable and the actual level oscillates around the set point level.

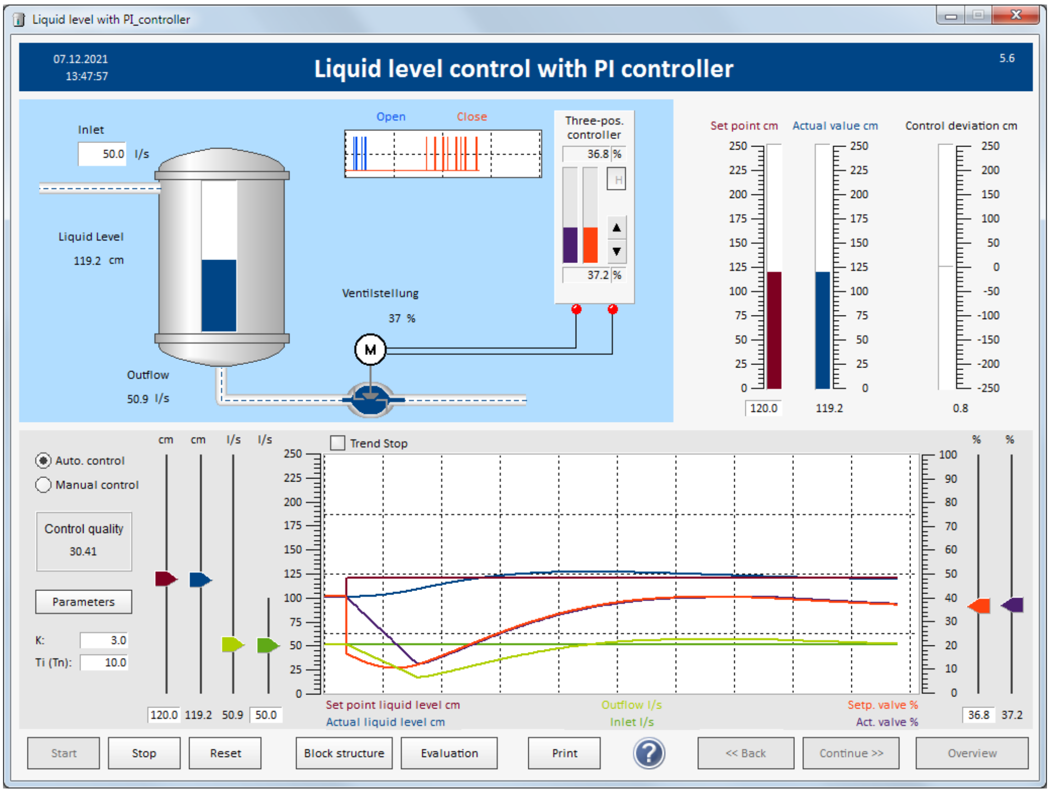


Task 11.

Let the system settle with the specified parameters K = 3 and Ti = 10 of the PI controller to the set point 100cm with the inflow 50l/s.

Enter a step in the set point level from 100cm to 120cm.

Determine the control quality for this step.



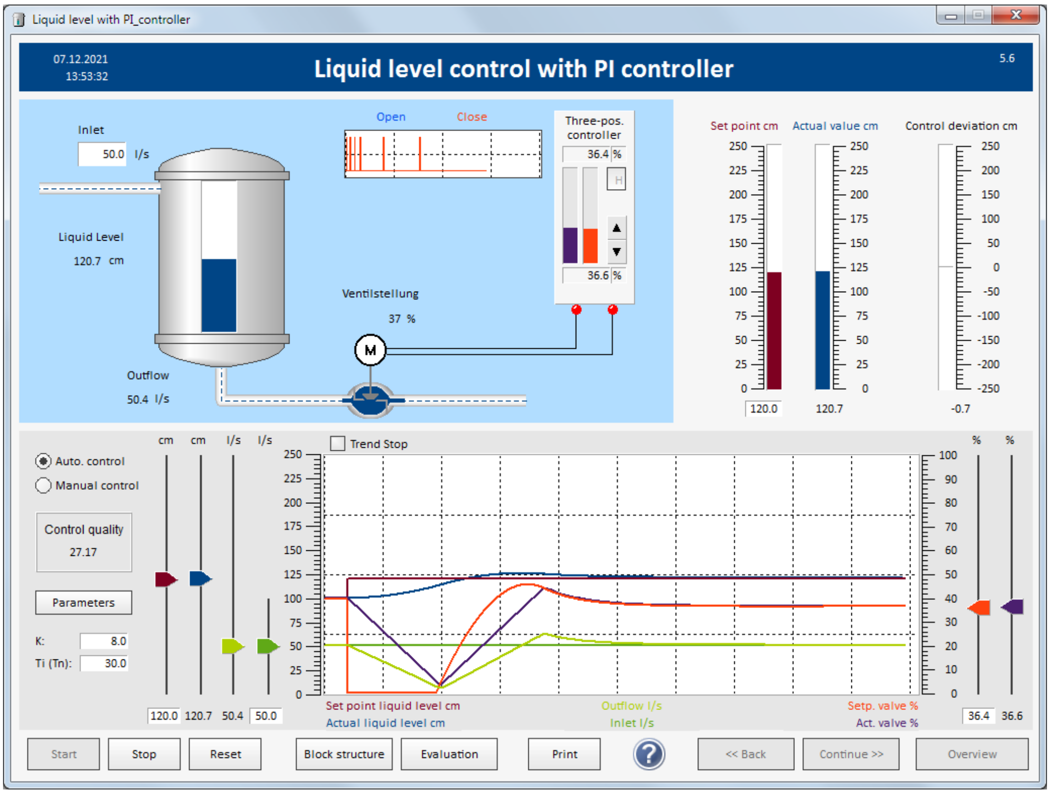
The control quality after settling is approx. 31.71.

Task 12.

The number in the box labeled "Control quality" indicates a value about the quality of the steady-state control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the set point.

Try to reduce the value for the control quality by adjusting the controller parameters.

In order to be able to compare the control quality with one another, the same initial conditions must be set for all tests.



With the controller parameters K = 8 and Ti = 30, a control quality of 27.2 was achieved.

The following are set as initial conditions:

With an inflow of 50 l/s, the system had settled to the set point level of 100 cm.

The set point was increased to 120l/s and it was waited until the control loop was settled again.

Carry out the experiments with further controller parameters:

- Let it settle with an inflow = 50l/s to the target level = 100cm
- Set controller parameters
- Set the set point to 120cm
- Wait until the control loop has settled.

Since the valve is controlled by pulses (opening, closing), the actual value fluctuates slightly around the set point.

8.2.5 Closed-loop Control with PID Controller

Go to „Overview“ and select item 5.7 „Closed-loop control with PID controller“.

Click „Start“.

Keep the set parameters K = 3, Ti = 10 and Td = 2. Enter 100cm as the set point level and set the inflow to 50l/s.

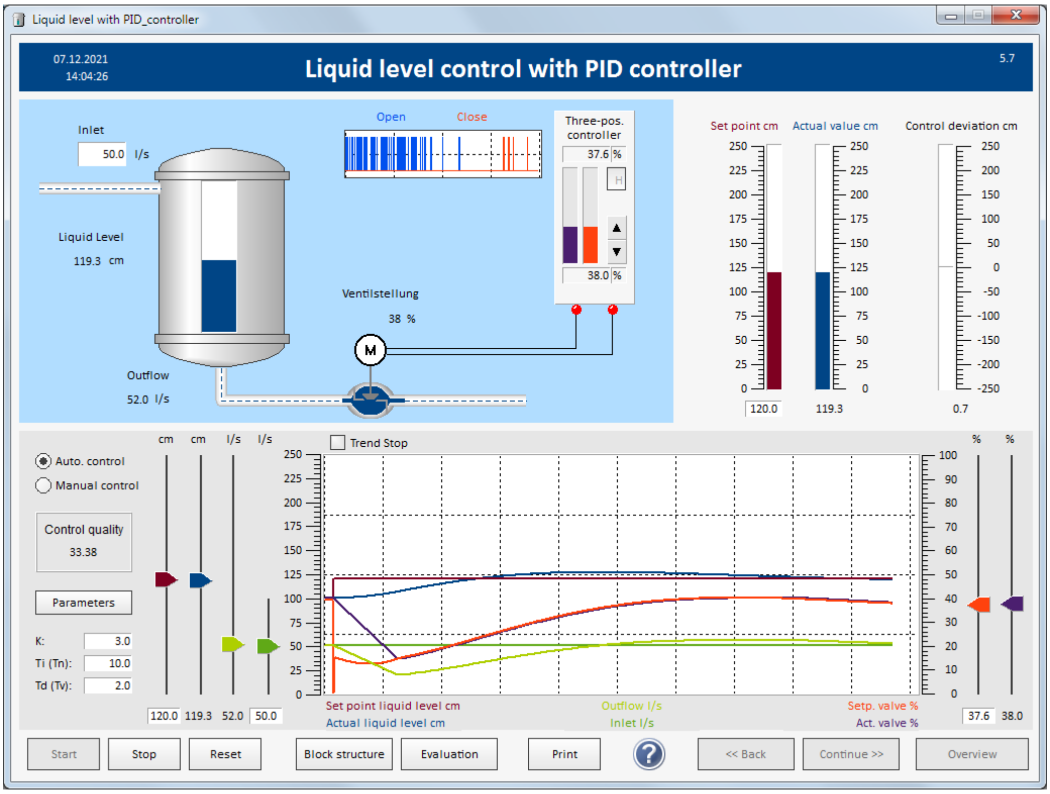
Wait until the control loop has settled.

Task 13.

Investigate the command response with the preset parameters:

Gain K = 3, Reset time Ti = 10, Derivative time Td = 2

Change the set point to 120cm.



The control loop goes into a stable state with overshoot. The actual value reaches the set point.

As can be seen in the trend diagram, the sudden change in the set point causes a peak in the control signal. This peak is triggered by the D component of the controller. The derivation of a sudden change causes an (infinitely) large value.

The peak goes down because the control signal has to decrease (valve closes) so that the level rises.

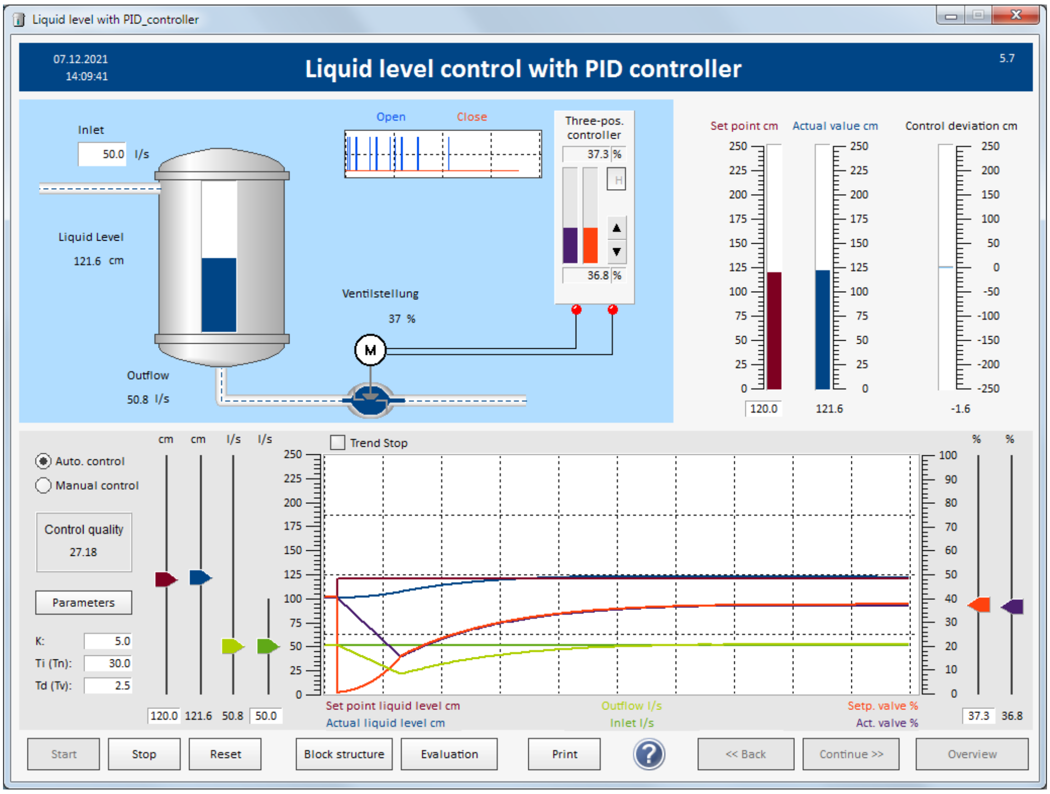
The control quality is over 33.5.

Since the valve is controlled by pulses (opening, closing), the actual value fluctuates slightly around the set point.

Task 14.

Carry out the tests with further controller parameters in order to improve the control quality:

- Let the system settle with an inflow = 50l/s to the set point level = 100cm
- Set controller parameters
- Set the set point to 120cm
- Wait until the control loop has settled.



With the parameters gain K = 5, reset time Ti = 30 and derivative time = 2.5 you get, for example, a control quality of 27.7.

Note to the trend display with the PID controller:

In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Evaluation" (display of the stored signal values) and selection of a corresponding time range.

Info:

In practice, the PI controller is most common. If a PID controller is used, the D component is often turned off so that the controller only works as a PI controller.

One of the reasons for this is that the D behavior in a control loop is difficult to assess. In principle, the D component gives you the option of making the control faster (which is often very difficult, however).

The D component considers the change between the set point and the actual value. If the change increases, i.e. the difference between the set point and actual value increases, the D component adds a calculated value to the control signal. If the difference between the set point and the actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend, whether the difference between the set point and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the set point and actual value decreases, the control signal is reduced.

9 Engine Speed Control (Control Training II)

This process is the simulation of an engine, of which the rotational speed is to be controlled by changing the input voltage of the motor. The voltage is the input variable (control signal) and the rotational speed is the output variable (controlled signal) of the system. The signal „Load“ acts as disturbance variable.

The engine speed process is a controlled system with self-regulation.

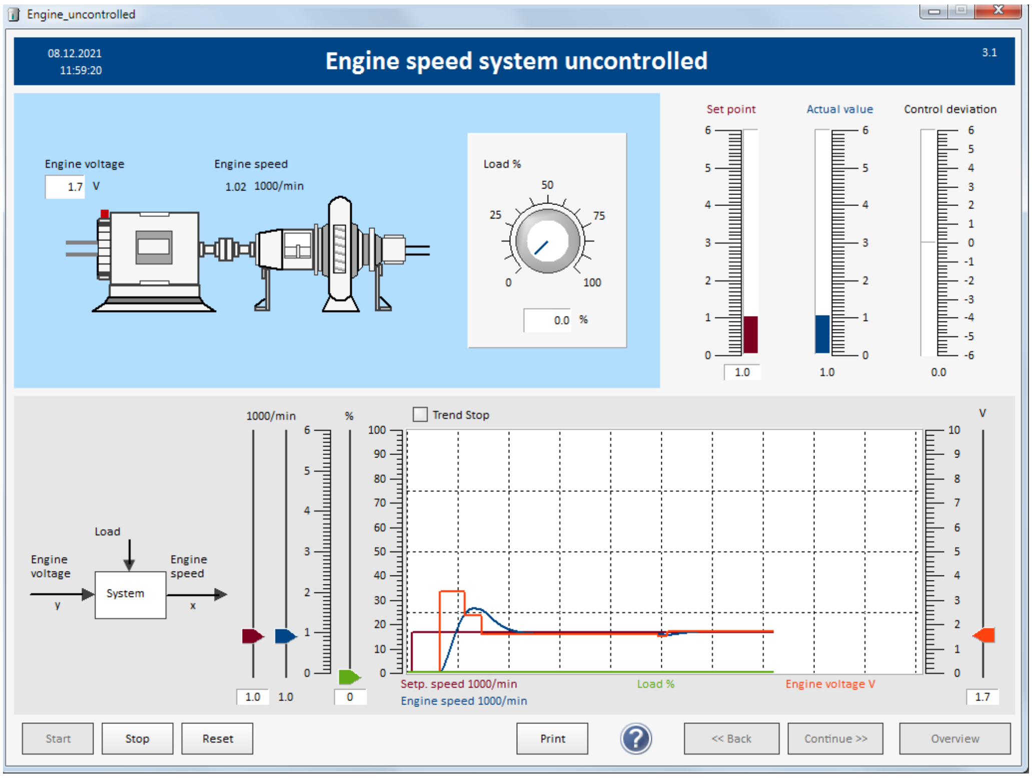
9.1 Uncontrolled System (Manual Control)

Select item 3.1 „Uncontrolled system“. Click „Start“.

You can now change the values for the set point (reference variable, set point speed 1000/min), the control signal (engine voltage V) and the disturbance signal (load%) using the slider or by entering values below the slider.

Task 1.

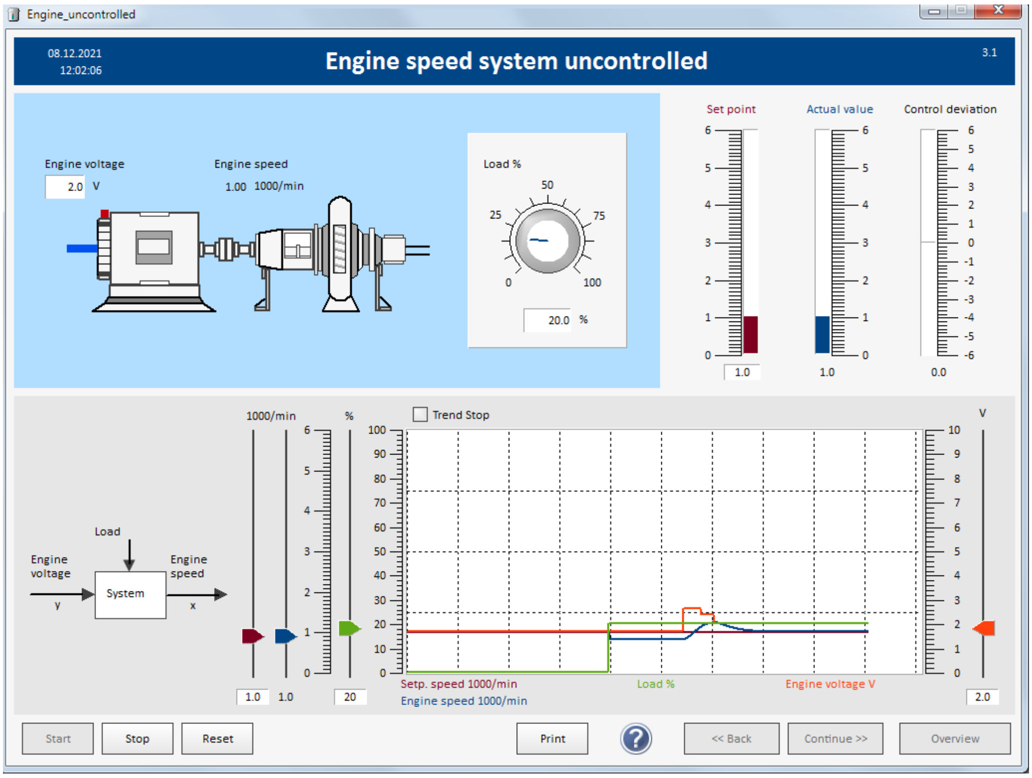
Set the set point (set point speed, reference variable) to 1 (corresponds to 1000/min) and try to adjust the actual value (Engine speed) to the set point speed (reference variable) by adjusting the engine voltage (control signal).



This type of control is known as command response. The set point is adjusted and an attempt is made to adjust the actual value (controlled variable) to the new set point (reference variable).

Task 2.

Change the load from 0% to 20% and try to correct the disturbance by adjusting the control signal.



As the load increases, the speed decreases.

To compensate for this, the control signal (engine voltage) must be increased.

Changing the load is a disturbance to the system. That is why one speaks here of the investigation of the disturbance response.

9.2 Controlled System

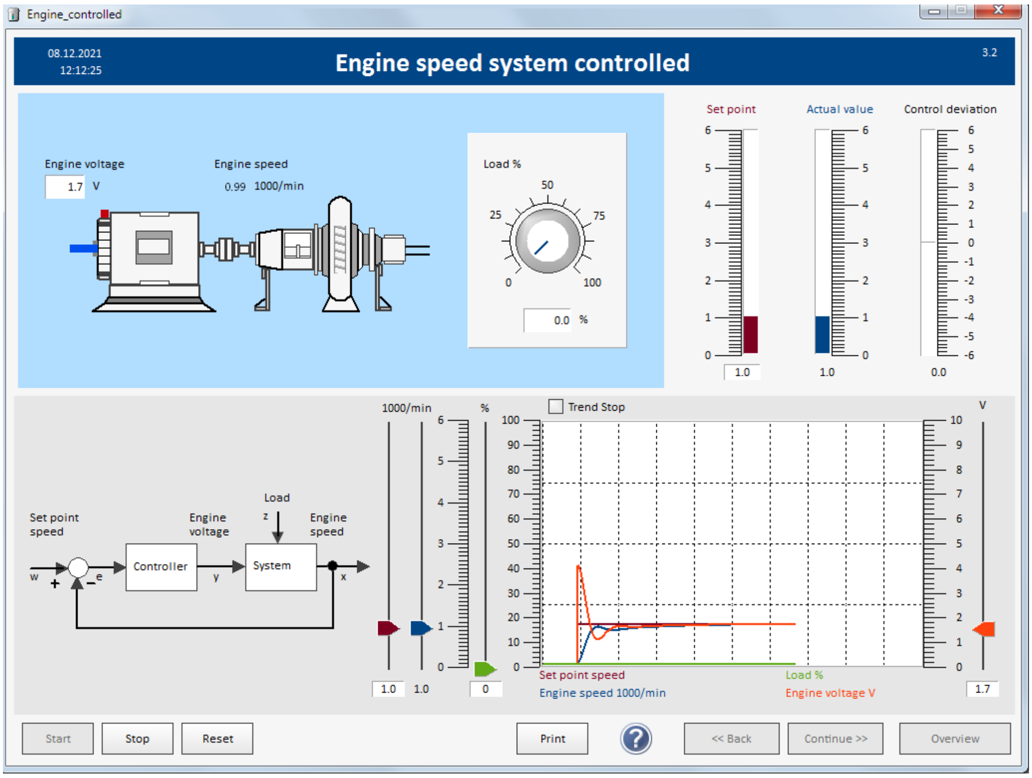
9.2.1 Closed-loop Controlled System

Go to „Overview“ and select item 3.2 „Closed-loop controlled system“.

Here you can see how the system behaves in principle if, instead of manual control by the user, a controller takes on the task of adjusting the actual value to the set point.

Task 3.

Click „Start“ and set the set point to 1 (1000/min). What will happen?

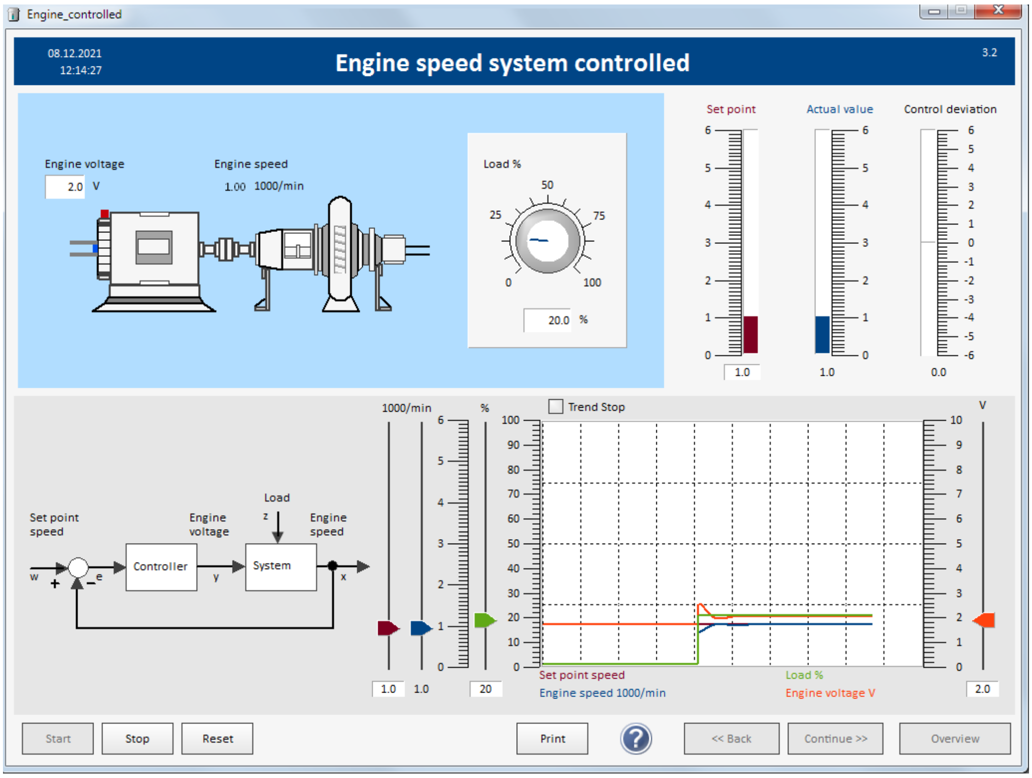


The actual value (engine speed) reaches the set point after a short time (command response).

Task 4.

Change the load from 0% to 20%.

What will happen?



The speed decreases.

The controller tries to adjust the actual value (engine speed) to the set point by increasing the engine voltage (control signal).

After a short time, the controller has corrected the disturbance (disturbance response).

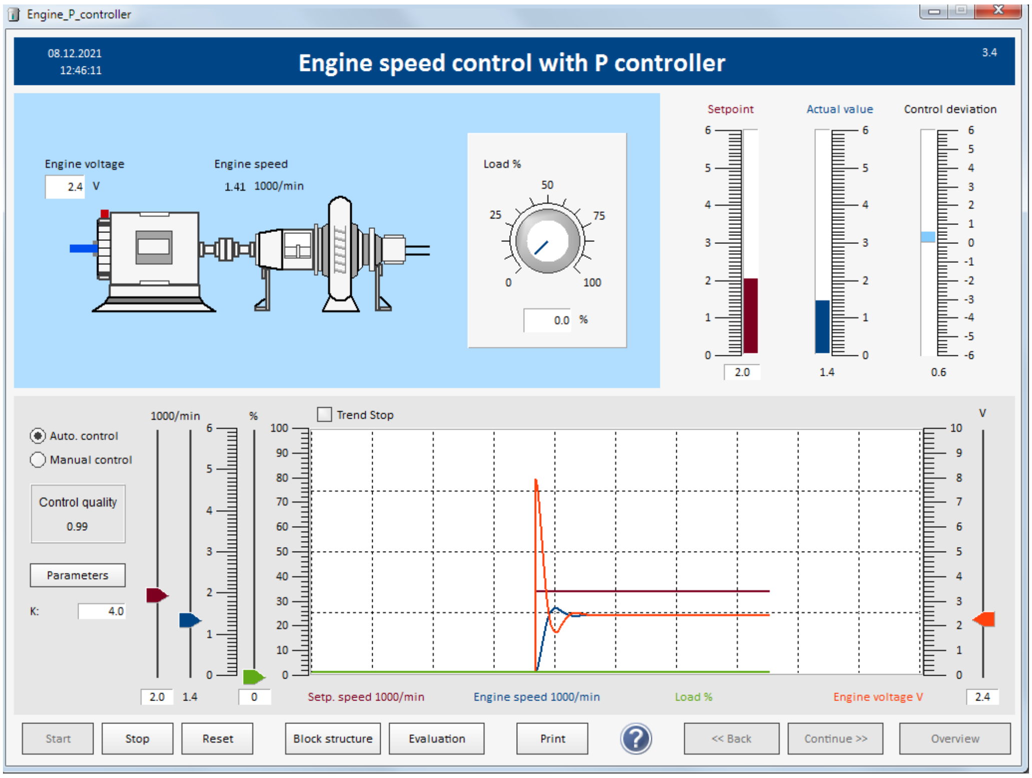
9.2.2 Closed-loop Control with P Controller

Go to „Overview“ and select item 3.4 „Closed-loop control with P controller“.

Click „Start“.

Task 5.

Change the set point to 2 (1000/min) and wait until the control loop has settled, i.e. until the actual value no longer changes.



After the settling phase, it can be clearly seen that the actual value (controlled variable, engine speed) does not reach the set point (reference variable, set point speed). We get a steady-state control error.

The control error e is defined as e = w - x, with

w = reference variable (set point) and x = controlled variable (actual signal).

Reason:

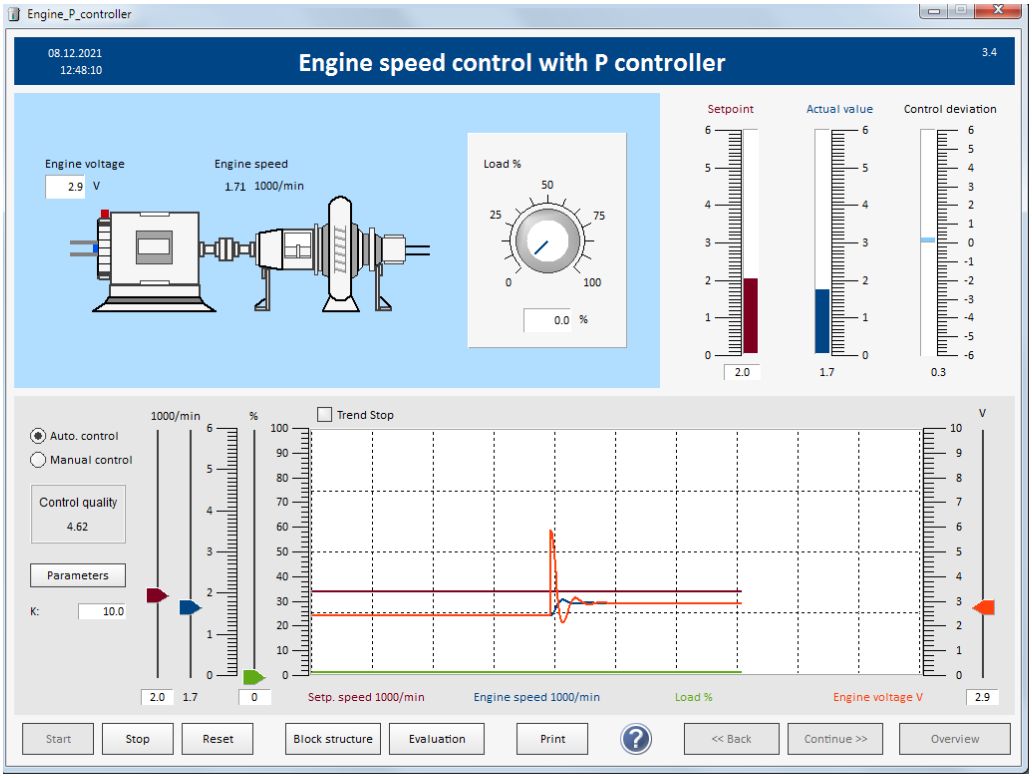
The P controller works like an amplifier. The input signal to the controller w - x (set point - actual value) is amplified with the specified amplification factor (in our case 4). In order for the P-controller to output a control signal (an engine voltage) that is not equal to zero, set point and actual value must be different, i.e. steady-state error.

If the controller outputs 0, the motor speed also goes to 0.

Task 6.

Change the gain of the P controller from 4 to 10 and wait until the control loop has settled again.

Observe the behavior.



The control error between the set point and the actual value becomes significantly smaller when the gain K is increased from 4 to 10. However, the P controller does not manage to adjust the actual value to the set point here either. For the reason described above, we also get a, albeit significantly smaller, steady-state control error (e = w - x).

The size of the control signal y in the steady state can be calculated from the steady-state error (w-x) and the gain factor K:

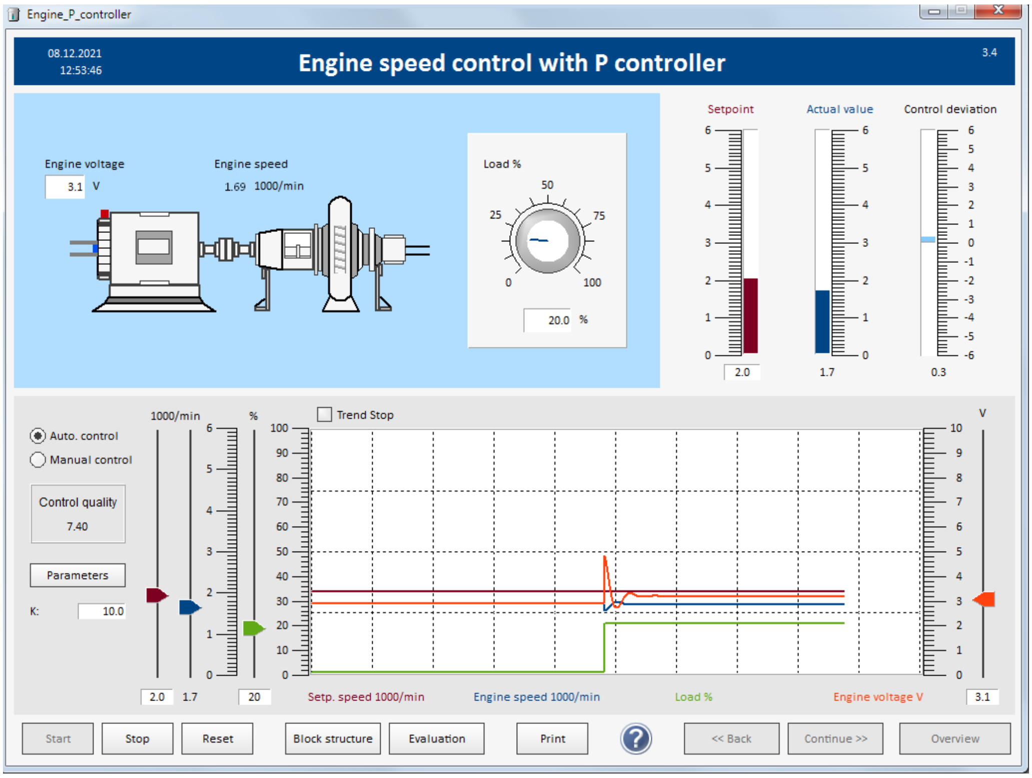
Control signal y = K * (w – x) = 10 * (2 – 1,71) = 2,9

(The actual value x can be read off more precisely via "Evaluation" than via the picture above)

The P controller also reacts to a disturbance (change in load). A steady-state control error is also obtained for this.

Task 7.

Change the load from 0% to 20%. What will happen?



The P controller reacts to the fault, the steady-state control error remains.

As can be seen from the settling behavior, the P controller reacts immediately and quickly to changes in set point and disturbance variable (command response and disturbance response).

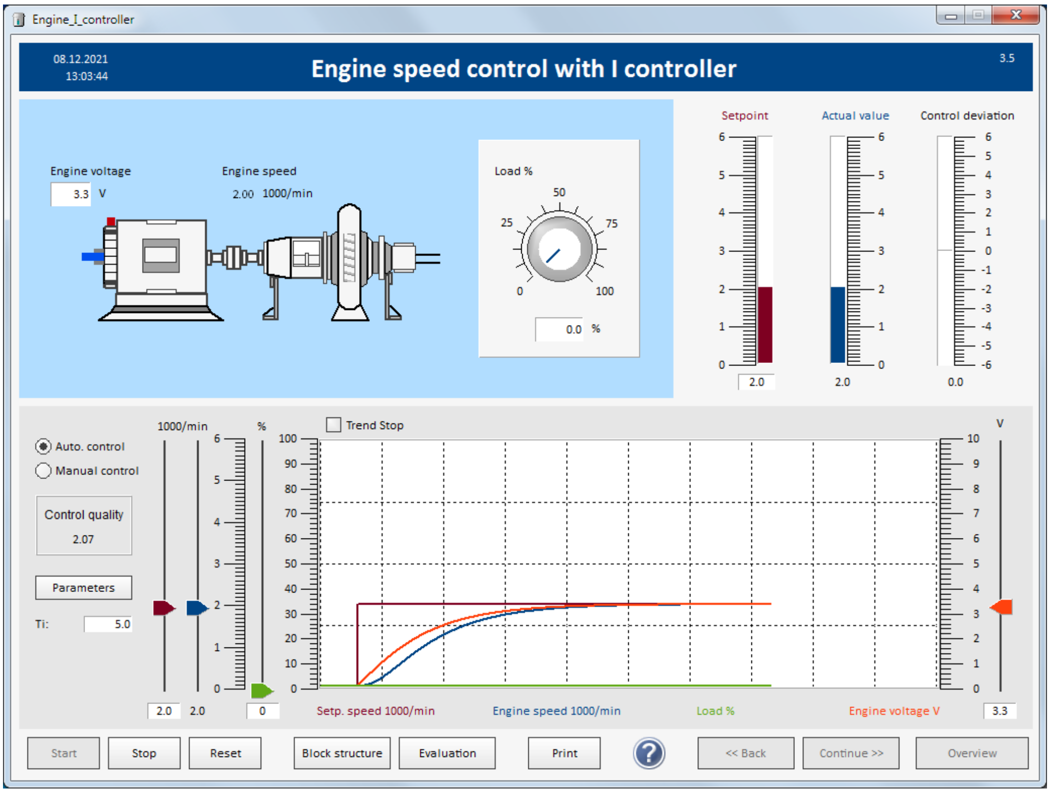
9.2.3 Closed-loop Control with I Controller:

Go to „Overview“ and select item 3.5 „Closed-loop control with I controller“.

Click „Start“.

Task 8.

Change the set point to 2 (1000/min). What will happen?



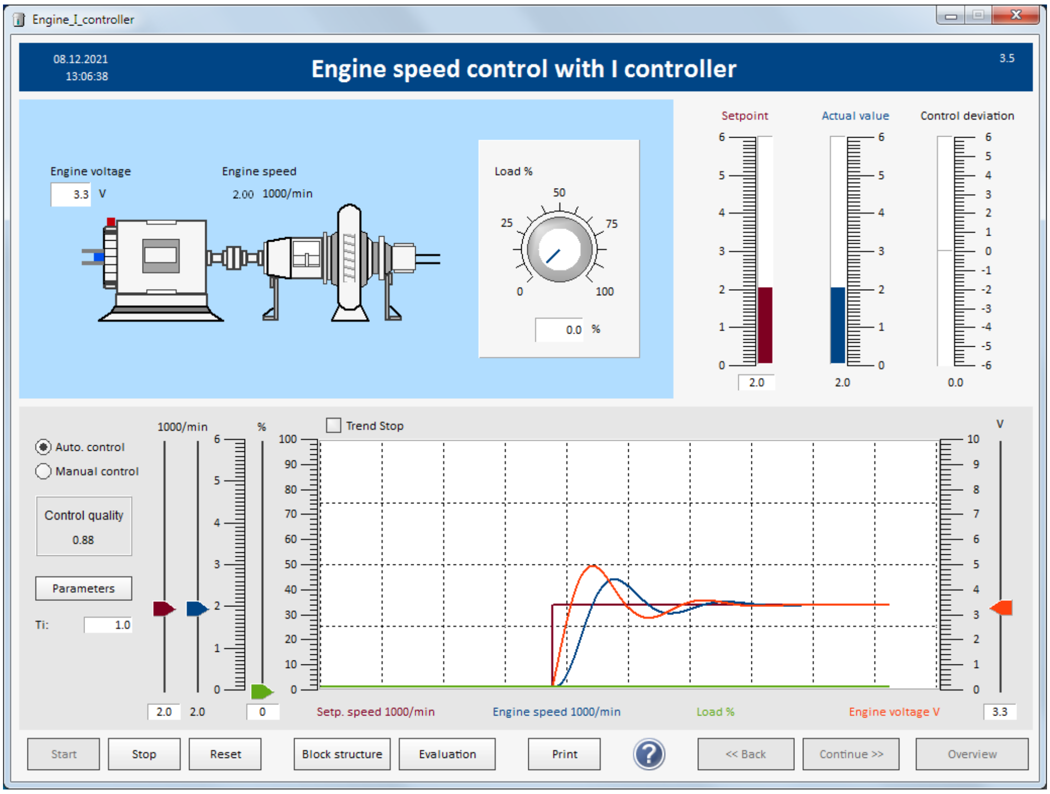
The engine speed is slowly increased by the I controller. The actual value reaches the set point after a long period of time.

Task 9.

Click „Reset“.

Change the time constant Ti to 1 and specify a set point step from 0 to 2 (1000/min).

What will happen?



By reducing the integration time to 1, the control loop begins to oscillate. However, the actual value reaches the set point after a period of time.

9.2.4 Closed-loop Control with PI Controller

Go to „Overview“ and select item 3.6 „Closed-loop control with PI controller“.

Click „Start“.

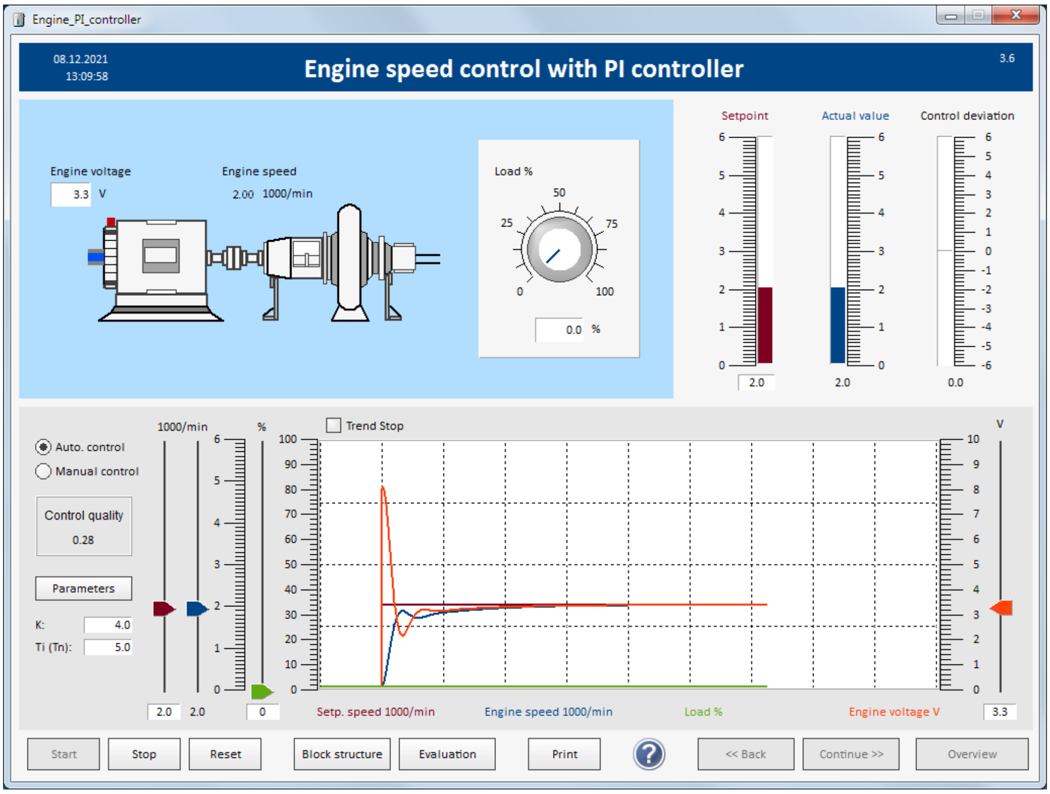
Task 10.

Keep the preset parameters:

Gain K = 4, Reset time Ti = 5.

Change the set point from 0 to 2 (1000/min).

Observe the settling behavior.



The actual value (controlled variable, engine speed) of the control loop with the PI controller and the set parameters reaches the new set point (reference variable, set point speed) without overshooting.

The value for the control quality reaches 0.28.

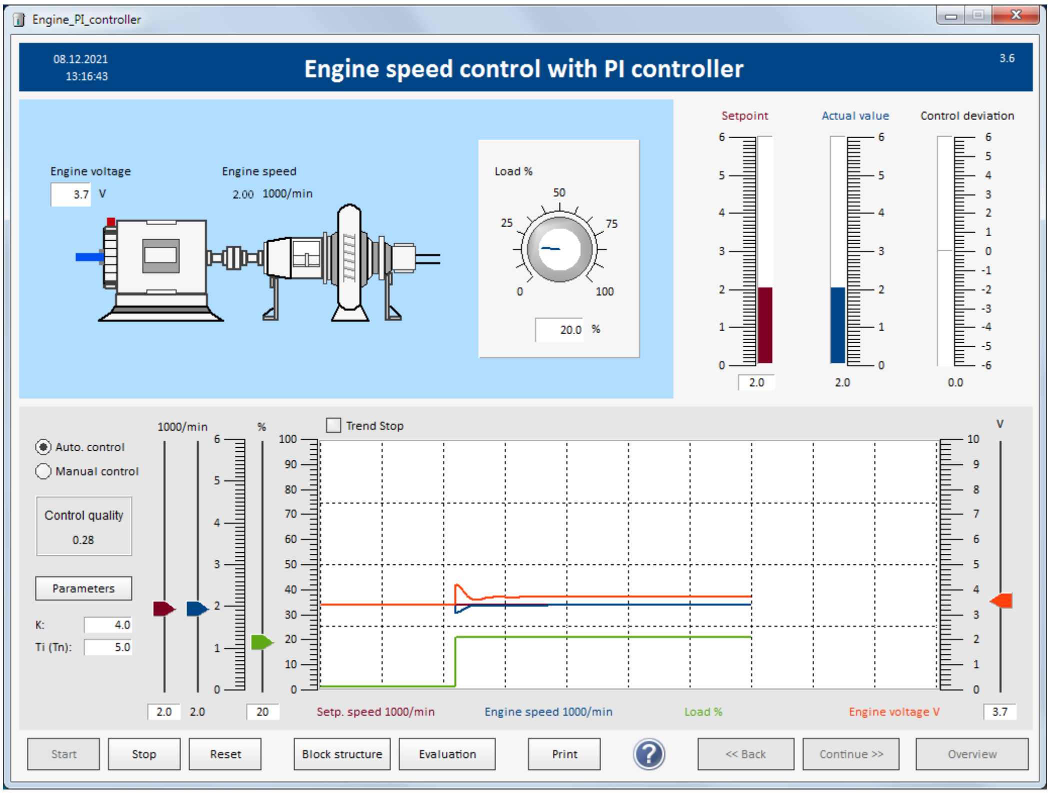
Since the set point has been changed, this is about the investigation of the command response.

Task 11.

Investigate the disturbance response.

When the control loop has settled, change the load from 0% to 20%.

Observe the behavior.



The greater load causes the engine speed to decrease. The controller tries to counteract this and increases the engine voltage. After a short settling phase, the actual value reaches the set point again.

Since the control loop reacts to a change in the disturbance value, one speaks of disturbance response in this case.

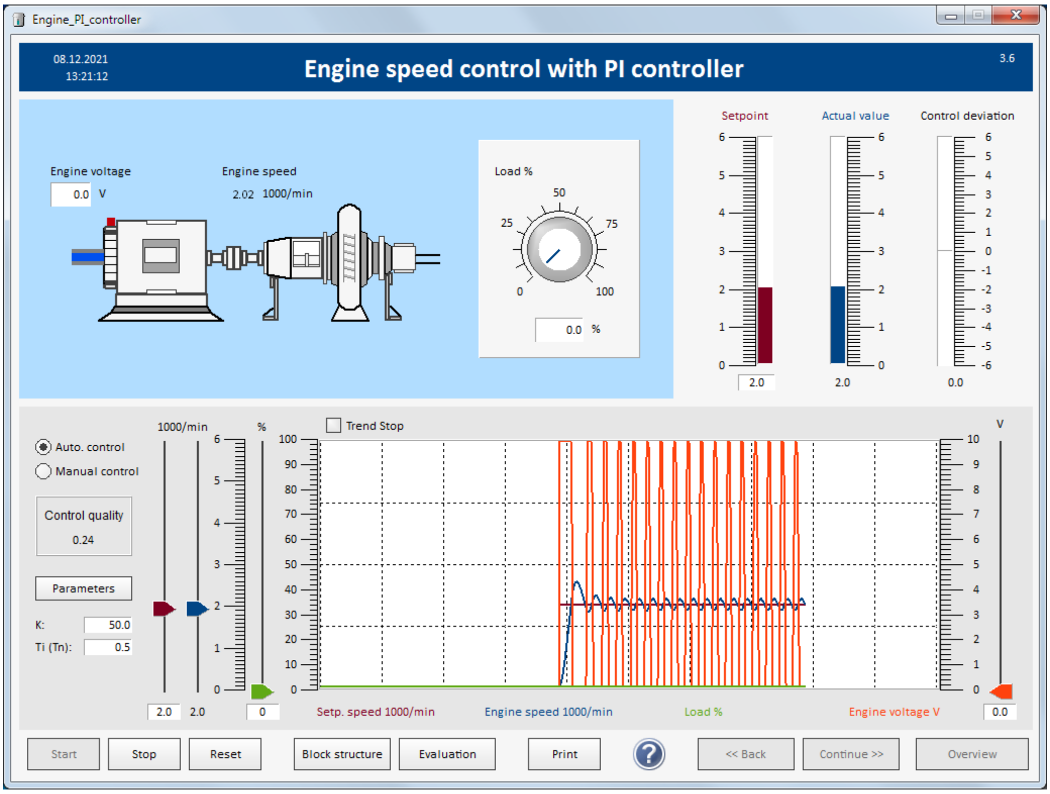
Task 12.

Click „Reset“.

Set the controller parameters to gain K = 50 and reset time Ti = 0.5.

Enter a set point step from 0 to 2 (1000 rpm).

Observe the behavior.



The control loop becomes unstable with these controller parameters. The actual value (controlled variable, engine speed) fluctuates around the set point (reference variable, set point speed)

With these controller parameters, the PI controller is not suitable for this control loop.

Task 13.

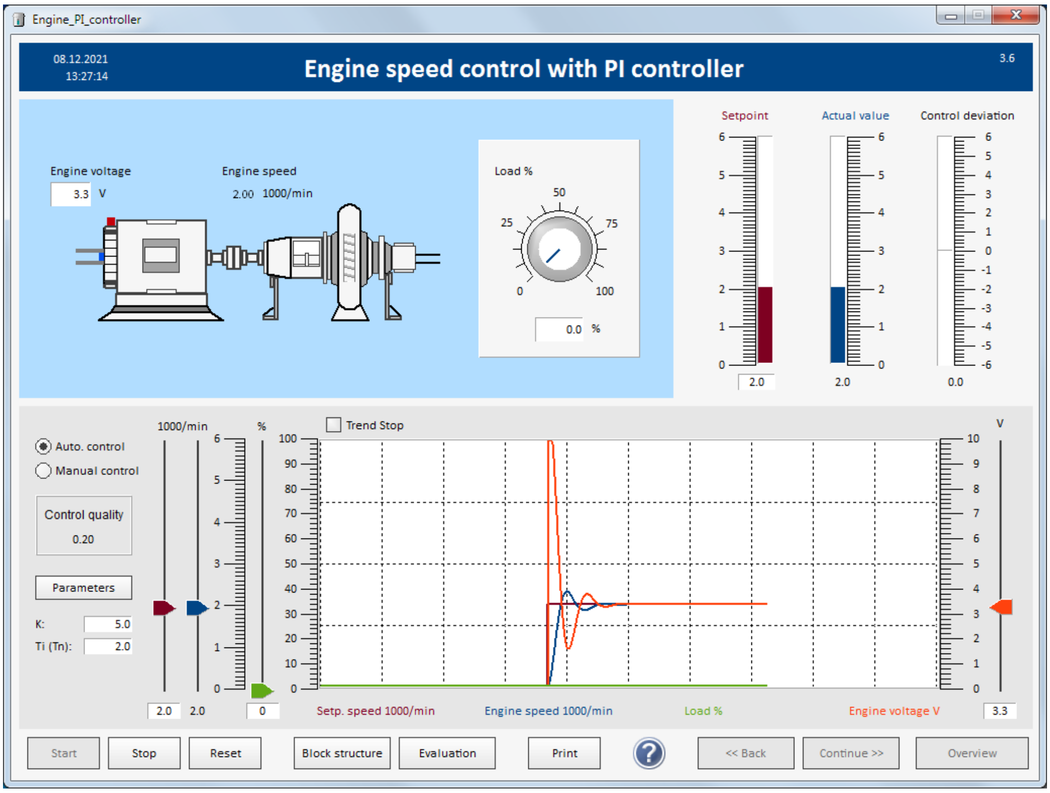
The number in the box labeled "Control quality" indicates a value about the quality of the steady-state control loop. The smaller the number, the faster the control loop has settled, i.e. the actual value has reached the set point and is no longer changing.

Try to reduce the value for the control quality by adjusting the controller parameters.

With the controller parameters K = 4 and Ti = 5, a control quality of 0.28 was achieved.

In order for the control quality to be comparable in all tests, the tests must be started with the same initial states. The best way to do this is to click "Reset". Set point speed (set point), engine speed (controlled variable), control signal (engine voltage) and disturbance (load) receive their initial values again.

Change the controller parameters and then set the set point to 2 (1000/min). Wait until the control loop has settled.



With the parameters K = 5 and Ti = 2, for example, a control quality of 0.2 is achieved.

Carry out the experiments with further controller parameters:

- Click Reset
- Set the controller parameters
- Set set point to 2
- Wait until the control loop has settled.

In order to achieve an aperiodic settling response (without overshoot), you can use the preset parameter values.

9.2.5 Closed-loop Control with PID Controller

Go to „Overview“ and select item 3.7 „Closed-loop control with PID controller“.

Click „Start“.

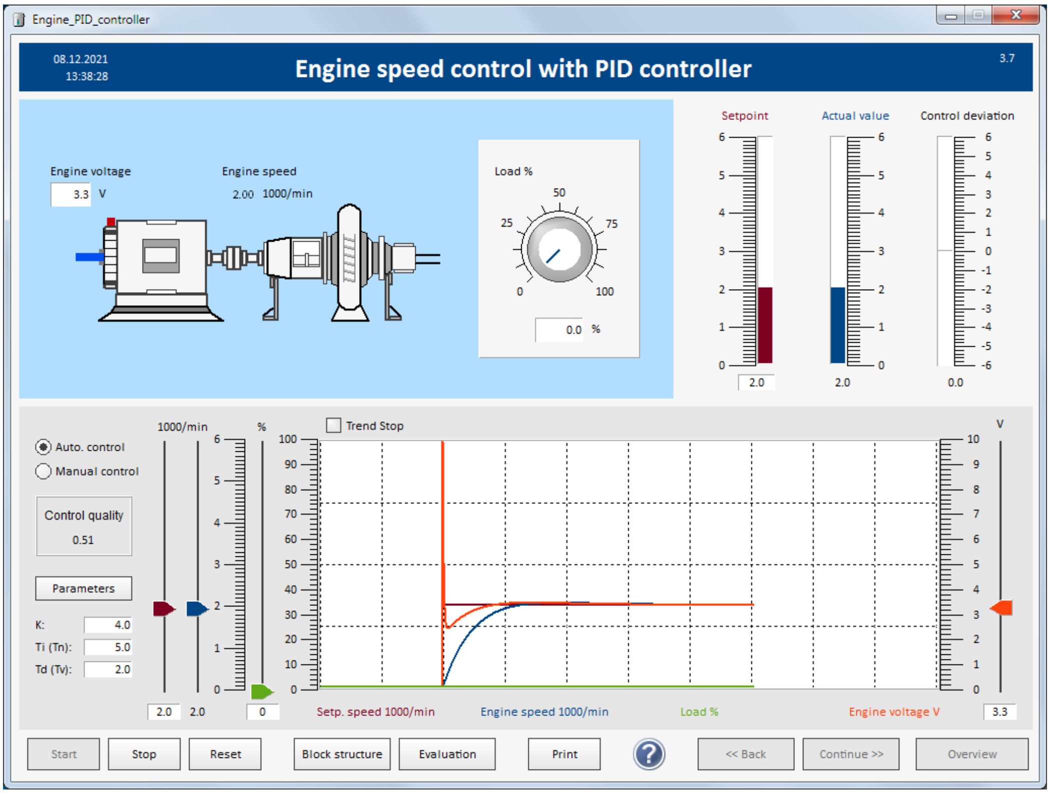
Task 14.

Investigate the command response with the preset parameters:

Gain K = 4, reset time Ti = 5, derivative time Td = 2.

Change the set point to 2 (1000/min).

Observe the behavior.



The control loop goes into a stable state with a small overshoot. The actual value reaches the set point.

As can be seen in the trend diagram, the sudden change in the set point causes a peak in the control signal. This peak is triggered by the D component of the controller. The derivation of a sudden change causes an (infinitely) large value.

The control quality reaches 0.51 and is therefore worse than with the PI controller with the parameters K = 4 and Ti = 5.

Note on the trend display with the PID controller:

In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Evaluation" (display of the stored signal values) and selection of a corresponding time range.

Task 15.

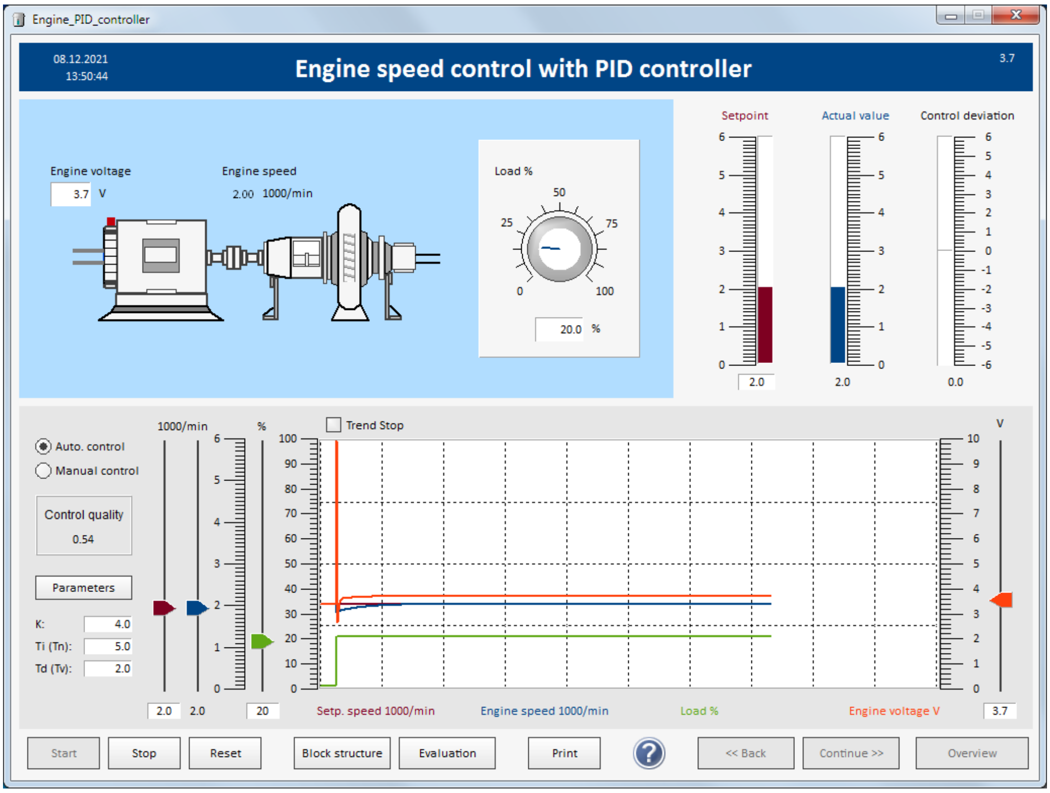
Investigate the disturbance response with the preset parameters:

Gain K = 4, reset time Ti = 5, derivative time Td = 2.

Set the target speed to 2 (1000/min) and wait until the control loop has settled.

Change the load from 0% to 20%.

Observe the behavior.

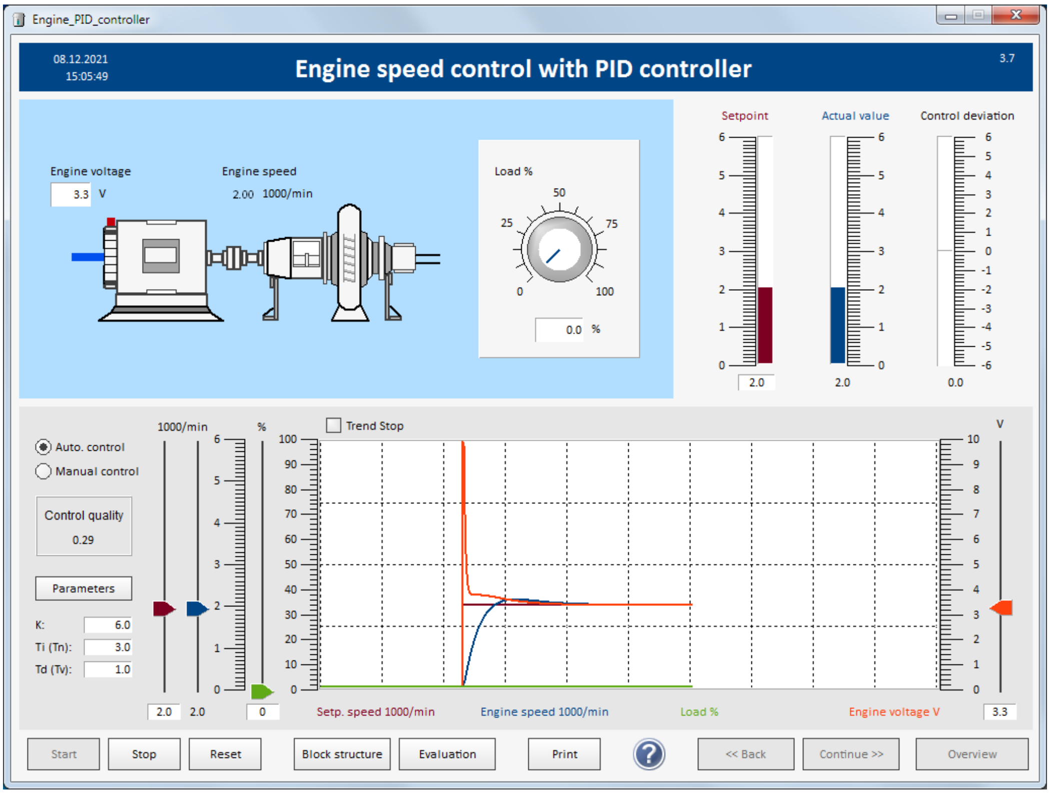


The controller controls the disturbance without overshooting.

Task 16.

Carry out tests for the command response with further controller parameters in order to improve the control quality:

- Click „Reset“
- Set the controller parameters
- Set the set point to 2 (1000/min)
- Wait until the control loop has settled.



With the parameters gain K = 6, reset time Ti = 3 and derivate time = 1, you get, for example, a control quality of 0.29.

Info:

In practice, the PI controller is most common. If a PID controller is used, the D component is often turned off so that the controller only works as a PI controller.

One of the reasons for this is that the D behavior in a control loop is difficult to assess. In principle, the D component gives you the option of making the control faster (which is often very difficult, however).

The D component considers the change between the set point and the actual value. If the change increases, i.e. the difference between the set point and actual value increases, the D component adds a calculated value to the control signal. If the difference between the set point and the actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend, whether the difference between the set point and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the set point and actual value decreases, the control signal is reduced.

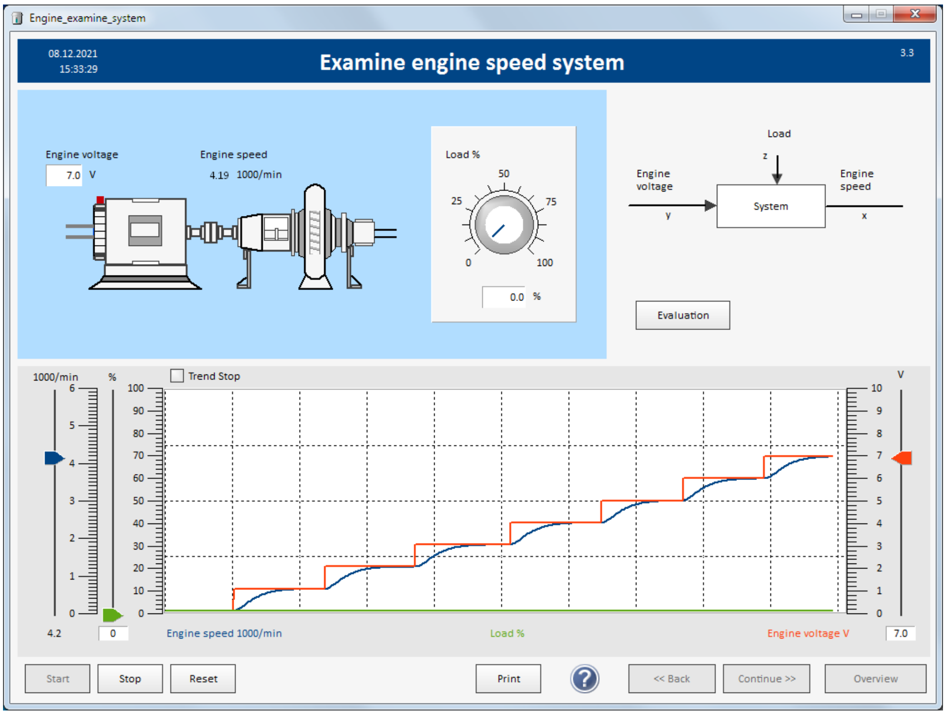
9.3 Controlled System

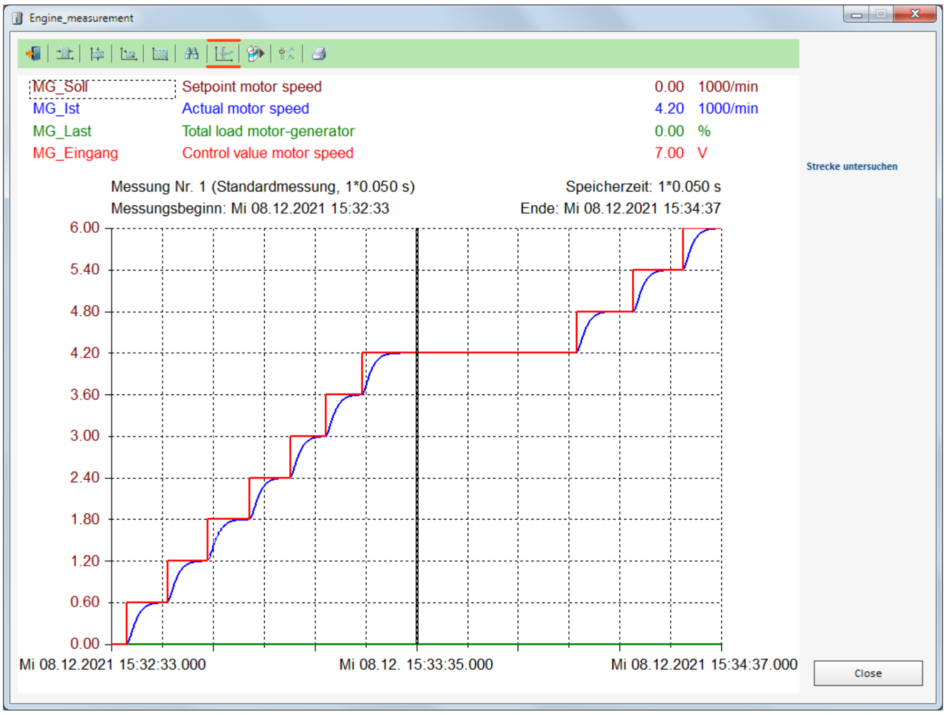
For engine speed control, select item 3.3 "Examine controlled system".

The engine speed system is a controlled system with self-regulation. In the event of a sudden change in the control signal, the actual value (controlled variable) settles to a constant value after a finite time.

Task 17.

Click “Start” and increase the control signal by 1V wait a moment and increase again. Observe the engine speed behavior (controlled variable).





The behavior of the engine speed is the same over the entire range from 0V to 10V.

The system is not dependent on the operating point. This is not the case for all systems.

If the system behavior is different, the control loop behavior will also be different depending on the operating point. For this reason, it must always be taken into account in these systems at which operating point the control is to be operated.

9.4 Controller Tuning Rules

In order to use the controller tuning rules, e.g. according to Chien/Hrones/Reswick, the controlled systems must be examined.

A unit step is given to the input signal of the system (control signal of the controlled system). The behavior of the output signal of the system (actual signal, controlled variable) must then be measured.

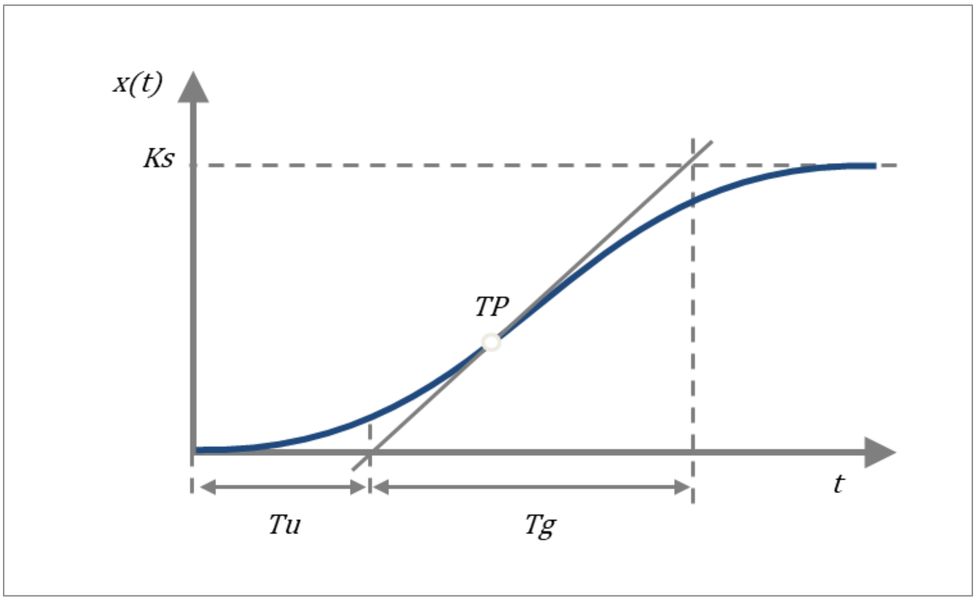
For the controller tuning rules for systems with self-regulation, the parameters Tu, Tg and Ks must be determined as shown in the figure below.

It means:

Te = Tu = Delay time

Tb = Tg = Compensation time

Ks = Gain



In the new standard, the delay time is designated with Te, the compensation time with Tb and the turning point with P.

Since the terms Tu and Tg are still used in most of the literature, we keep the old terms here, or use both.

The parameters Ks, Tg and Tu can be determined from this step response, as shown in the figure above. The controlled system´s gain Ks (final value of the actual variable) results from the abrupt change in the control signal by 1. If the amount of change is greater, you have to divide the resulting system´s gain value by the amount the control step value in order to obtain Ks.

It means:

Te = Tu = Delay time

Tb = Tg = Compensation time

Ks = Gain

With the help of these three parameters, the controller parameters can then be determined from the setting table according to Chien / Hrones / Reswick:

Table 6: Equations to calculate controller parameters according to Chien/Hrones/Reswick

Controller	Quality criteria			
	With 20 % Overshoot		Aperiodic case	
	Disturbance	Command	Disturbance	Command
P	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$	$K_P \approx \frac{0.3}{K_S} \cdot \frac{T_g}{T_U}$
PI	$K_P \approx \frac{0.7}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.3 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 4 \cdot T_U$	$K_P \approx \frac{0.35}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.2 \cdot T_g$
PID	$K_P \approx \frac{1.2}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2 \cdot T_U$ $T_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 1.35 \cdot T_U$ $T_V \approx 0.47 \cdot T_U$	$K_P \approx \frac{0.95}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx 2.4 \cdot T_U$ $T\_V \approx 0.42 \cdot T_U$	$K_P \approx \frac{0.6}{K_S} \cdot \frac{T_g}{T_U}$ $T_n \approx T_g$ $T_V \approx 0.5 \cdot T_U$

For systems without self-regulation use $\frac{T_g}{(K_S \cdot T_U)}$ instead of $\frac{1}{(K_{IS} \cdot T_U)}$.

The table was taken from: E. Samal, Grundriss der praktischen Regelungstechnik, Oldenbourg

Please note that according to the new standard, the following terms are used:

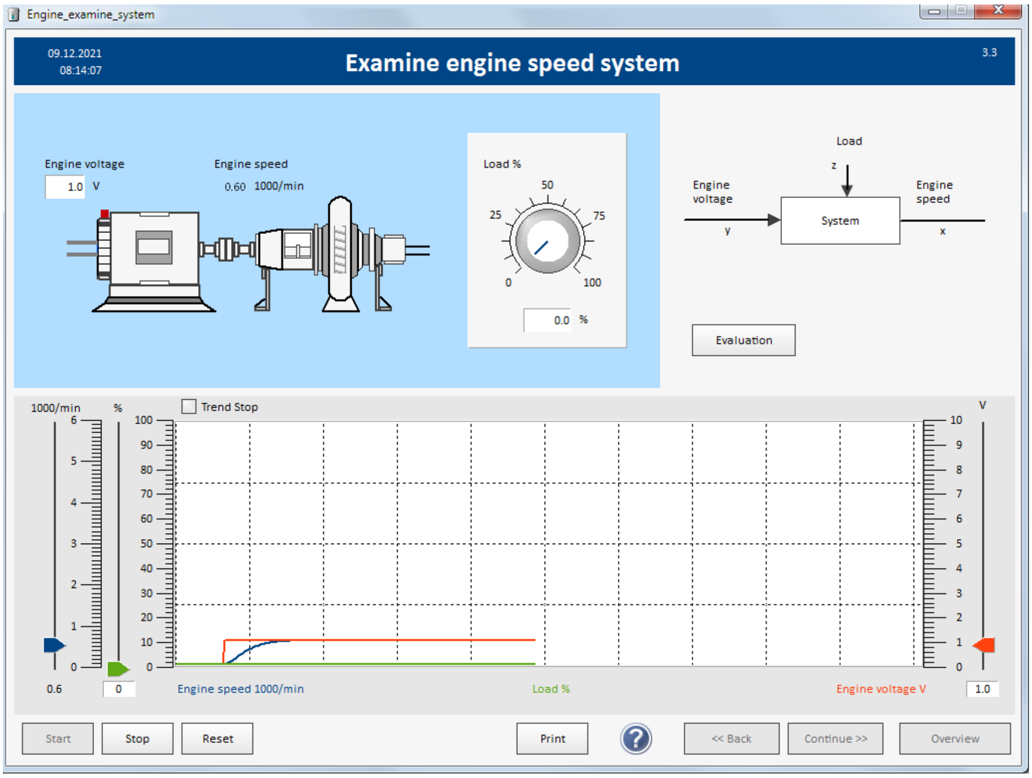
Tu = Te, Tg = Tb

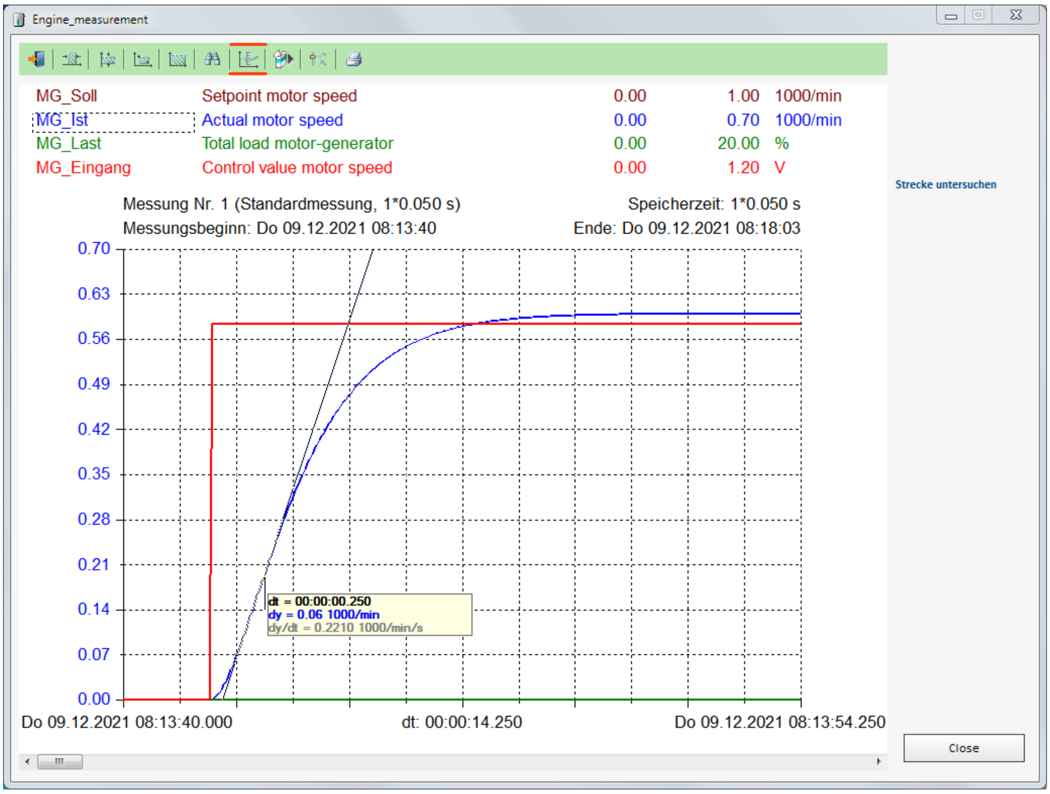
For the engine speed system, select point 3.3 "Examine controlled system”.

Task 18.

Click „Start“ and increase the control signal (engine voltage) to 1V.

Wait until the controlled variable (engine speed) has settled.





By clicking on "Evaluation" you will get the saved signal curves.

With the help of the button bar at the top, you can change time and display sections. Try to zoom in on the area of interest. Click on the signal name "MG_Ist" (actual motor speed) and examine the signal course of the blue signal. Try to determine the gradient of the engine speed curve at the turning point by drag and drop.

The gradient of the tangent at the turning point can be read approximately from the curve shown above: dx/dt = 0.22 1000/min/s.

After the sudden change in the control signal from 0V to 1V, the engine speed goes from 0 to 0.6 (1000/min).

This enables the compensation time Tg to be calculated:

dx/dt = (end value – start value) / Tg, so

Tg = (0,6 – 0) / 0,22 = 2,727s

Since we entered a step height of 1V for the control signal, the engine speed increased from 0 to 0.6, therefore Ks = 0.6.

Ks = 0,6

The delay time Tu can be measured and is approximately 0,3s.

Also: Te = Tu = 0,3s Tb = Tg = 2,727s Ks = 0,6

By inserting the values in the table, we get for the PI controller:

PI controller

Command response with 20% overshoot	
K = 0,6*Tb / (Ks*Te)	9,09
Tn = Tb	2,73
Command response aperiodic	
K = 0,35*Tb / (Ks*Te)	5,30
Tn = 1,2 * Tb	3,27
Disturbance response with 20% overshoot	
K = 0,7*Tb / (Ks*Te)	10,61
Tn = 2,3 * Te	0,69
Disturbance response aperiodic	
K = 0,6*Tb / (Ks*Te)	9,09
Tn = 4 * Te	1,20

With these controller parameters, the following control loop behavior results with a reference step of the set point speed from 0 to 2 (1000/min)

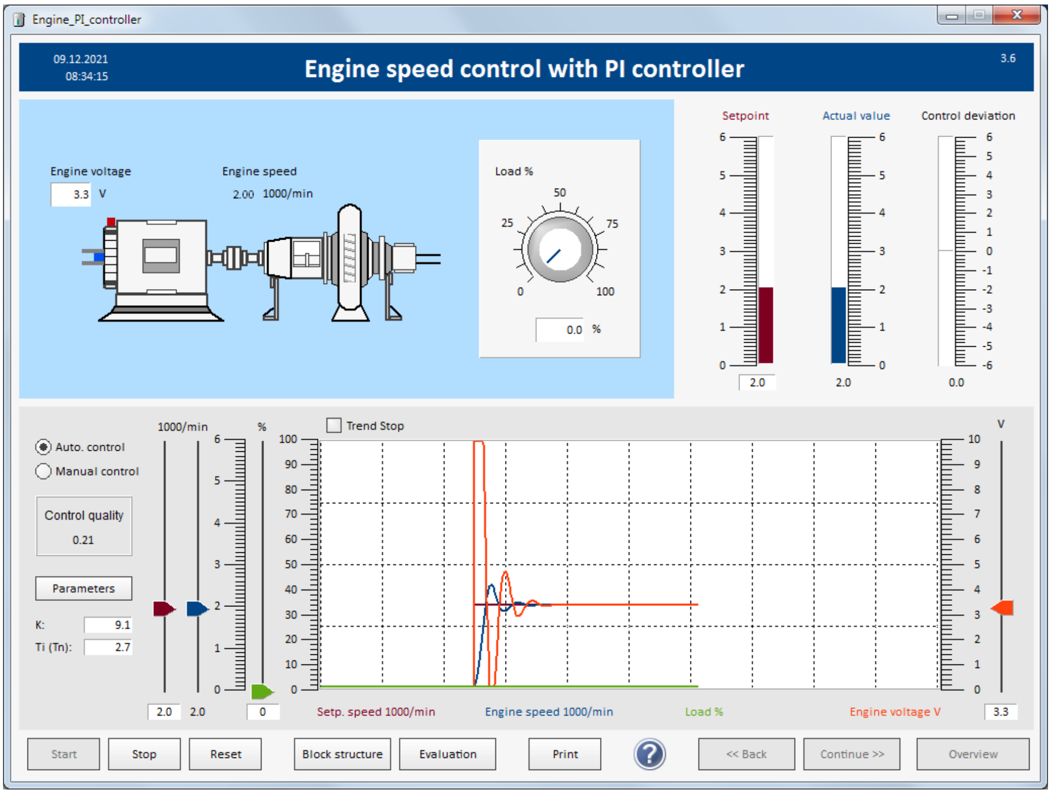


Figure 50: Command response with 20% overshoot

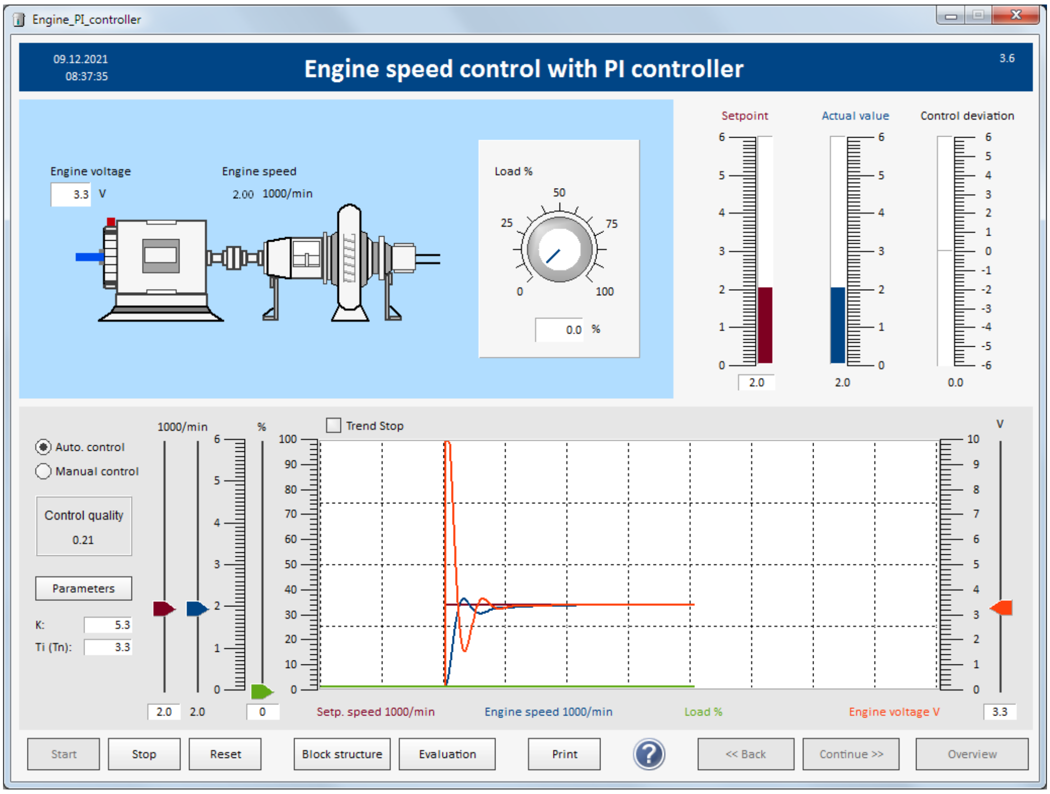


Figure 51: Command response aperiodic

For the disturbance the load was set from 0% to 20%.

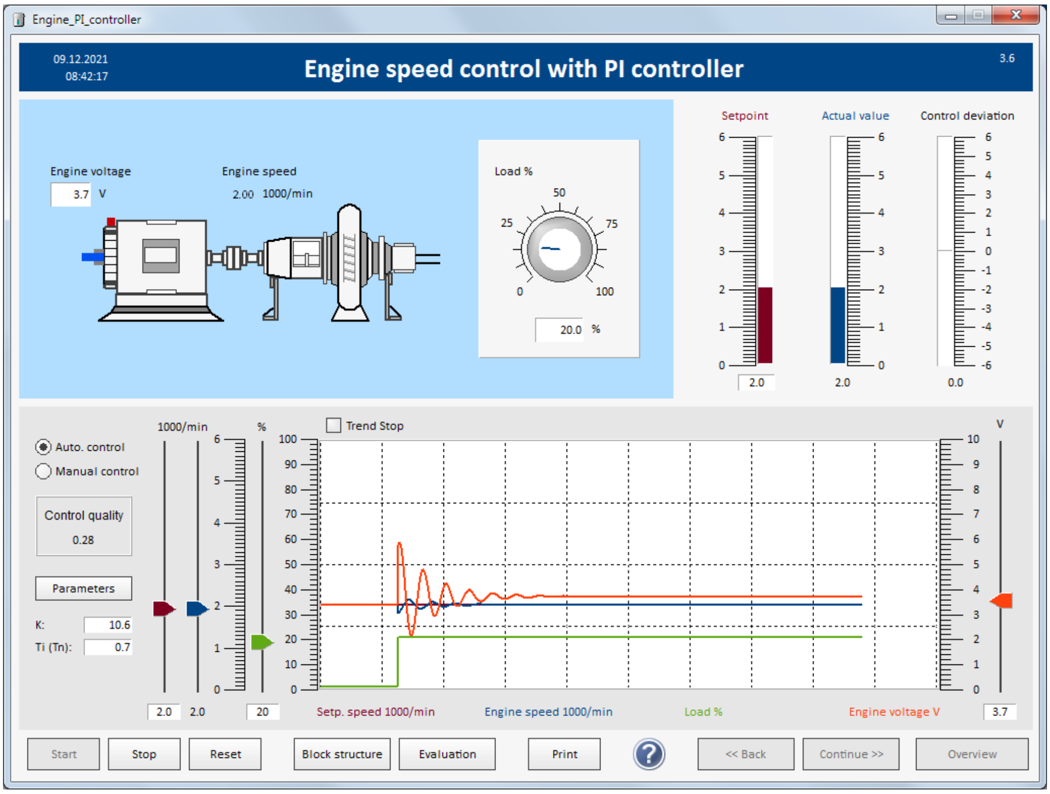


Figure 52: Disturbance response with 20% overshoot

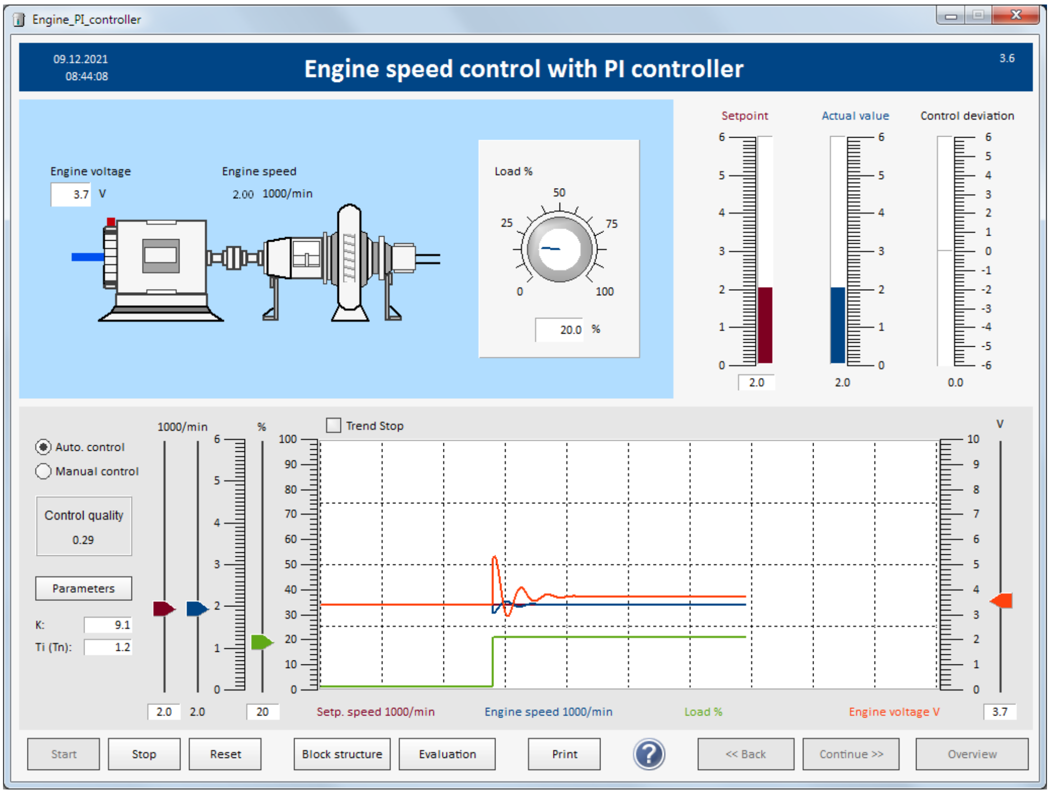


Figure 53: Disturbance response aperiodic

According to the table, the following parameters result for the PID controller:

PID controller

Command response with 20% overshoot

K = 0,95*Tb / (Ks*Te)	14,39
Tn = 1,35 * Tb	3,68
Td = 0,47 * Te	0,14

Command response aperiodic

K = 0,6*Tb / (Ks*Te)	9,09
Tn = Tb	2,73
Td = 0,5 * Te	0,15

Disturbance response with 20% overshoot

K = 1,2*Tb / (Ks*Te)	18,18
Tn = 2 * Te	0,60
Td = 0,42 * Te	0,13

Disturbance response aperiodic

K = 0,95*Tb / (Ks*Te)	14,39
Tn = 2,4 * Te	0,72
Td = 0,42 * Te	0,13

With these controller parameters, the following control loop behavior results with a reference step of the set point speed from 0 to 2 (1000/min).

The derivative time was taken as 0.5s, as the entry is limited to 0.5s

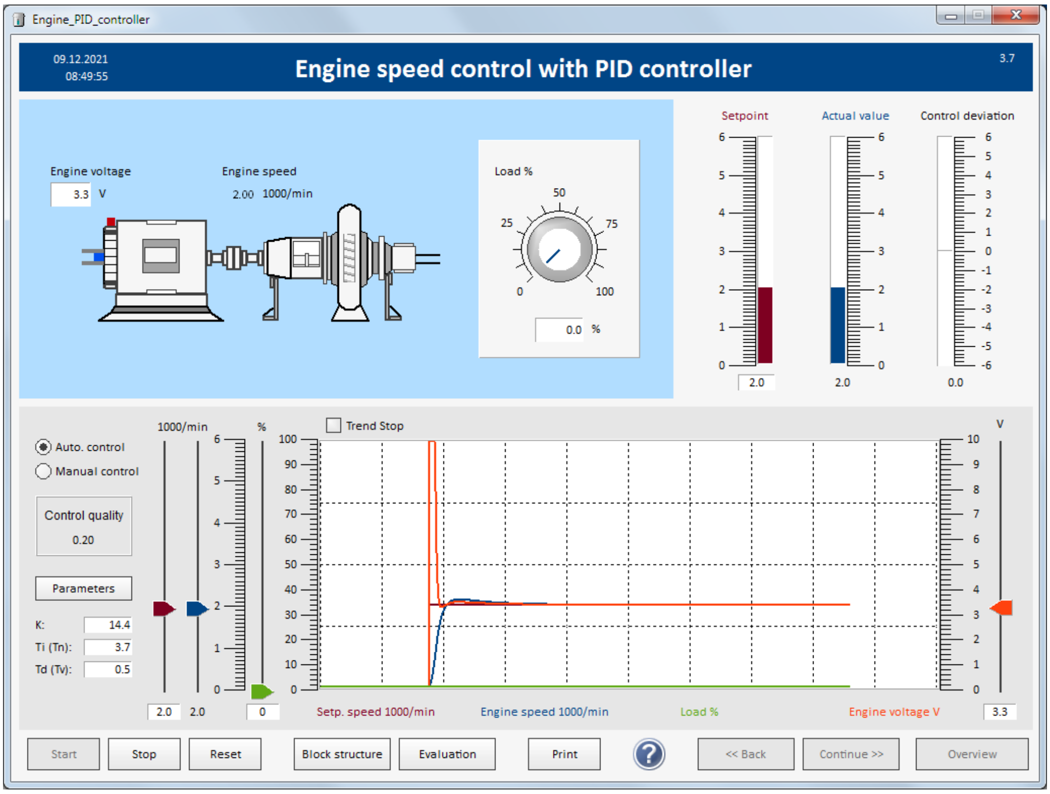


Figure 54: Command response with 20% overshoot

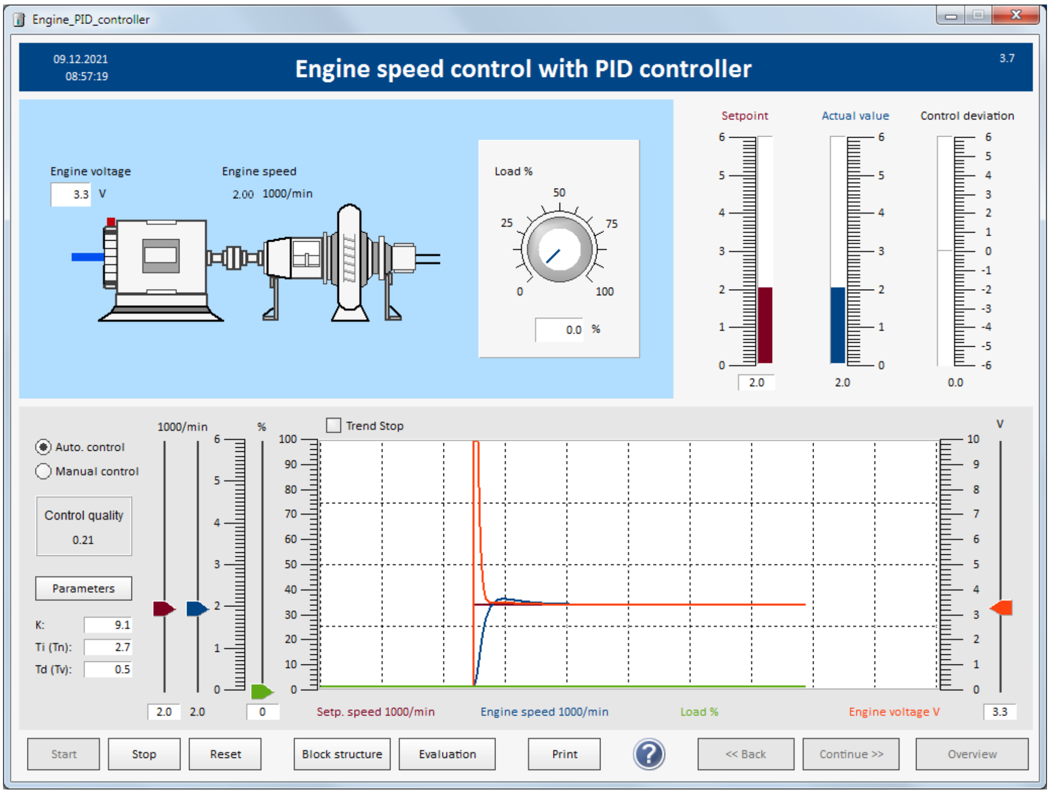


Figure 55: Command response aperiodic

For the disturbance the load was set from 0% to 20%.

The derivative time was taken as 0.5s, as the entry is limited to 0.5s

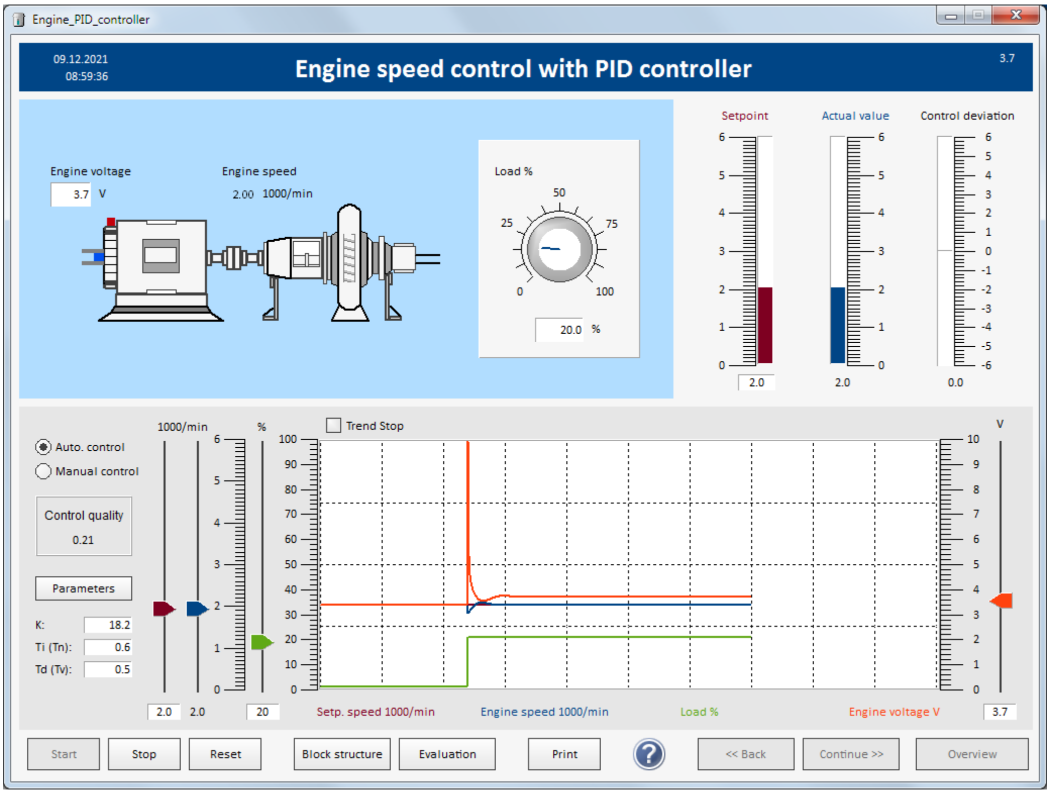


Figure 56: Disturbance response with 20% overshoot

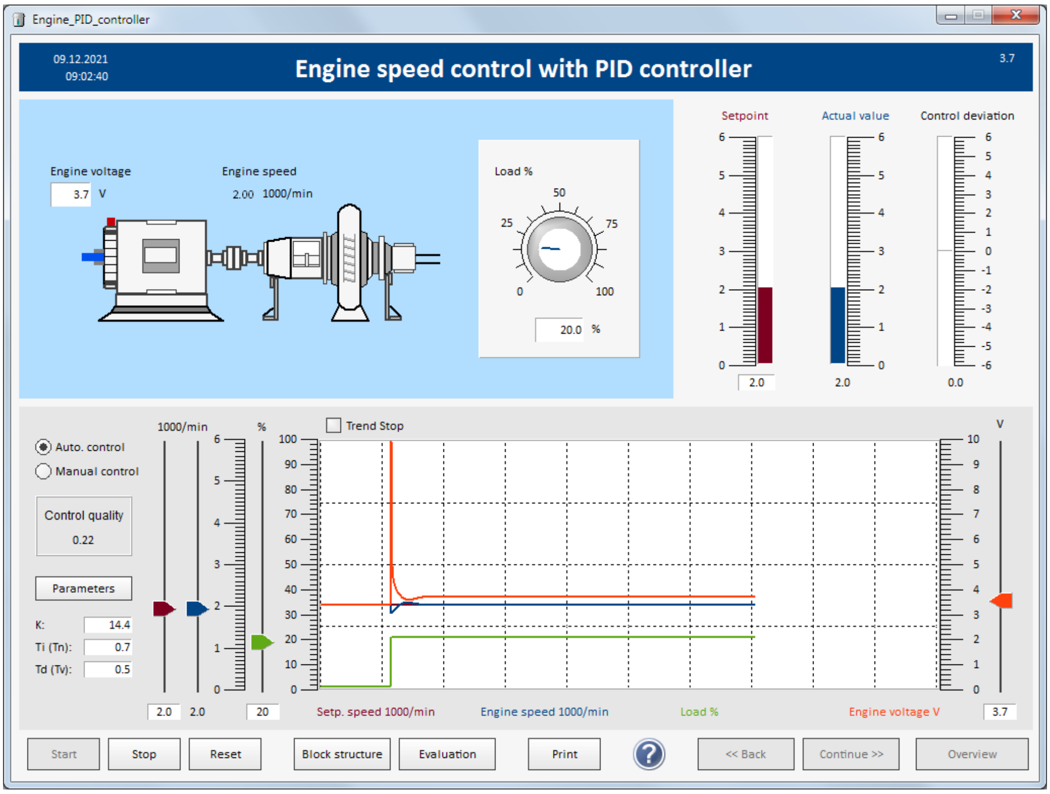


Figure 57: Disturbance response aperiodic

9.5 Assessment of the Controller Tuning Rules

Controller tuning rules are empirically determined methods that are often suitable for calculating good controller parameters by rule of thumb.

The settings for calculating controller parameters distinguish between disturbance and command response. Different controller parameters are calculated.

If you need controller parameters for both cases (disturbance and control behavior), you have to make a compromise between the calculated parameters of the disturbance behavior and the control behavior.

The above examples show that a reasonable control loop behavior can be obtained with the calculated controller parameters. However, the behavior does not exactly correspond to the expected behavior as selected in the table.

The fact that the system has not settled exactly aperiodically or with 20% overshoot is also due to the fact that the control signal has partially reached its limit and the time constants could not be determined exactly.

But in the examples and tasks of the engine speed system shown above, the controller parameters proposed by Chien/Hrones/Reswick were well suited for sensible control.

If you would like to have more information about our other practical courses or about the WinErs process control and simulation system (SCADA system), please contact:

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