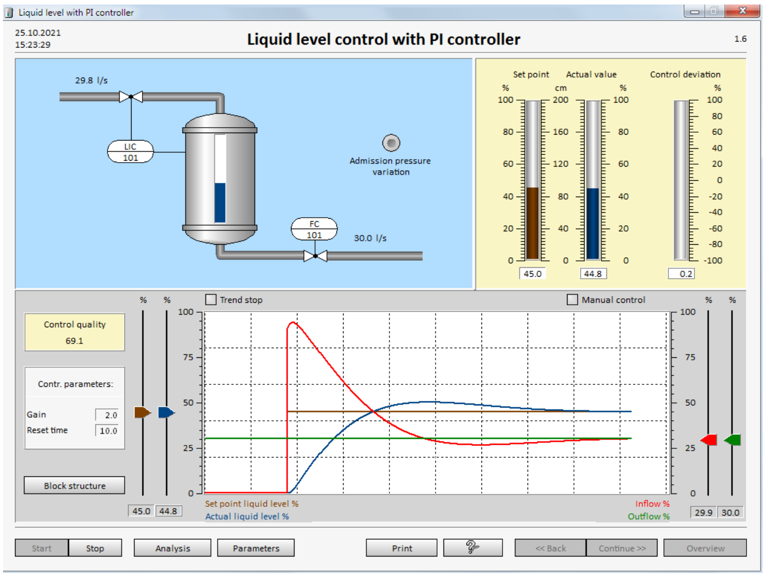
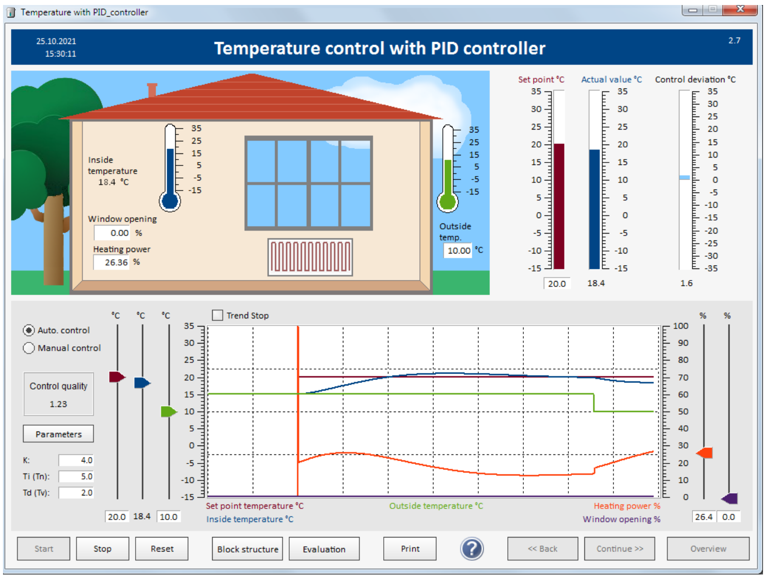
Ingenieurbüro
Dr.-Ing. Schoop

Tasks and Solutions
ControlTraining I / II





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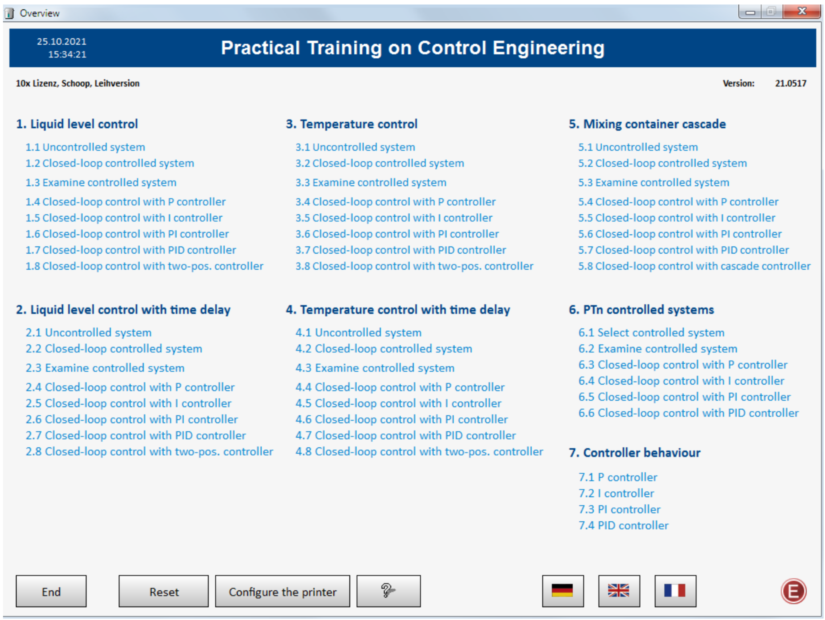
Version: 2022-01

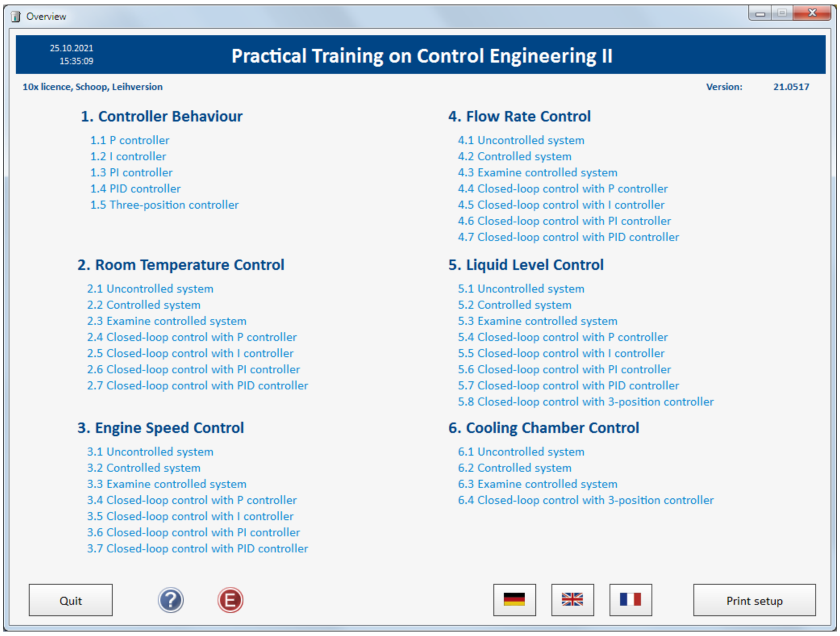
1 Introduction Control Training I / II

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

Here 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 also offers the option of examining the behavior of the three-position controller.

2.1 P Controller

Select in Control Training I or II under controller behavior the P controller (item 1.1 or item 7.1)

The P controller works like an amplifier.

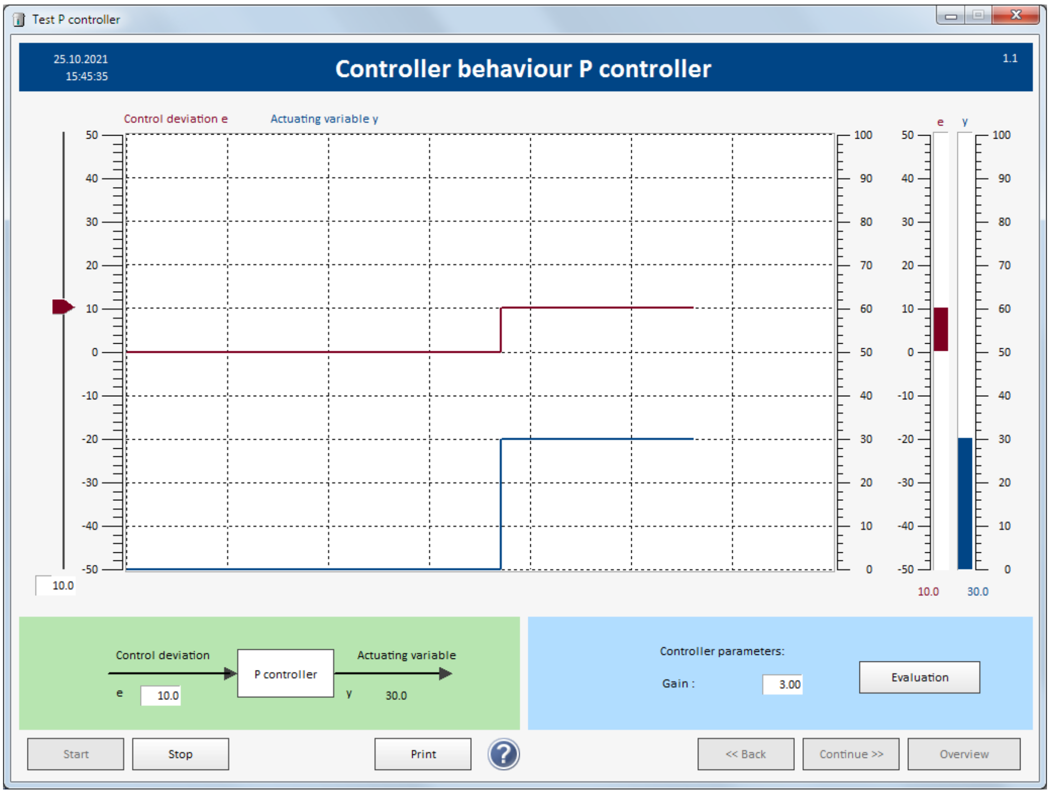
Task 1.

Press “Start”.

Set the controller parameter "Gain" to 3.

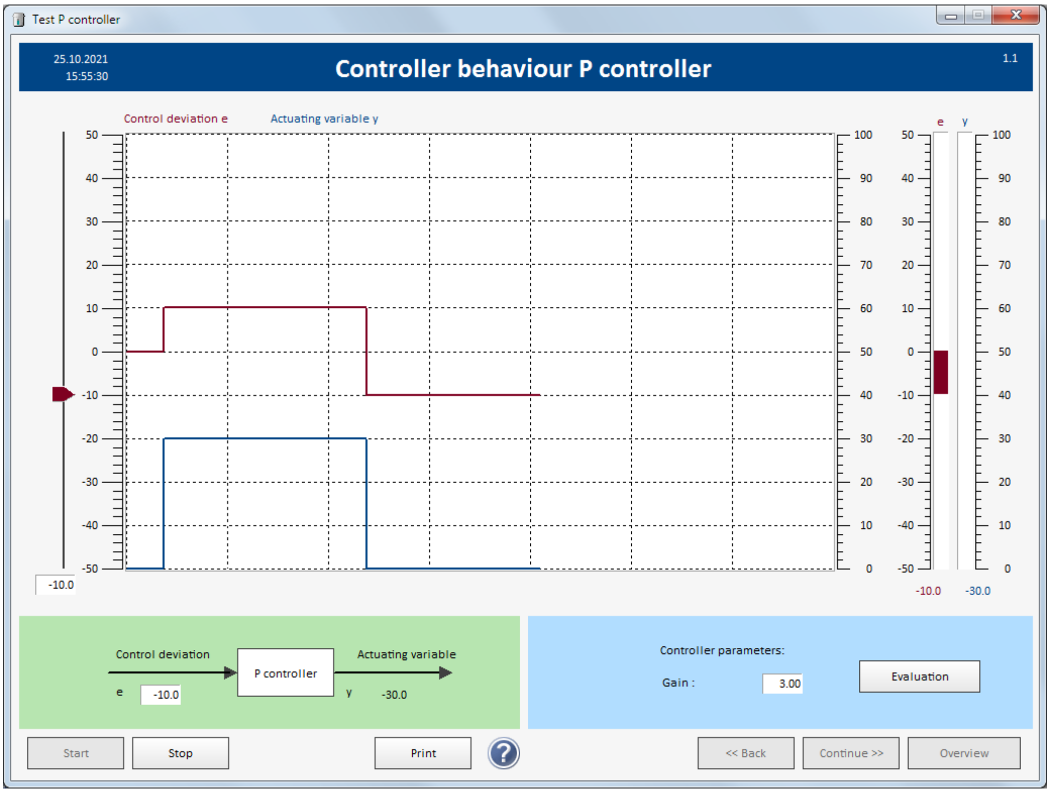
Enter the value 10 for the control deviation e.

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 cannot output negative values. Therefore, only the value 0 is displayed for y in the trend display.



2.2 I Controller

For controller behavior, select the I controller (item 1.2 or 7.2)

The I controller works like an integrator.

An integrator has the following behavior:

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

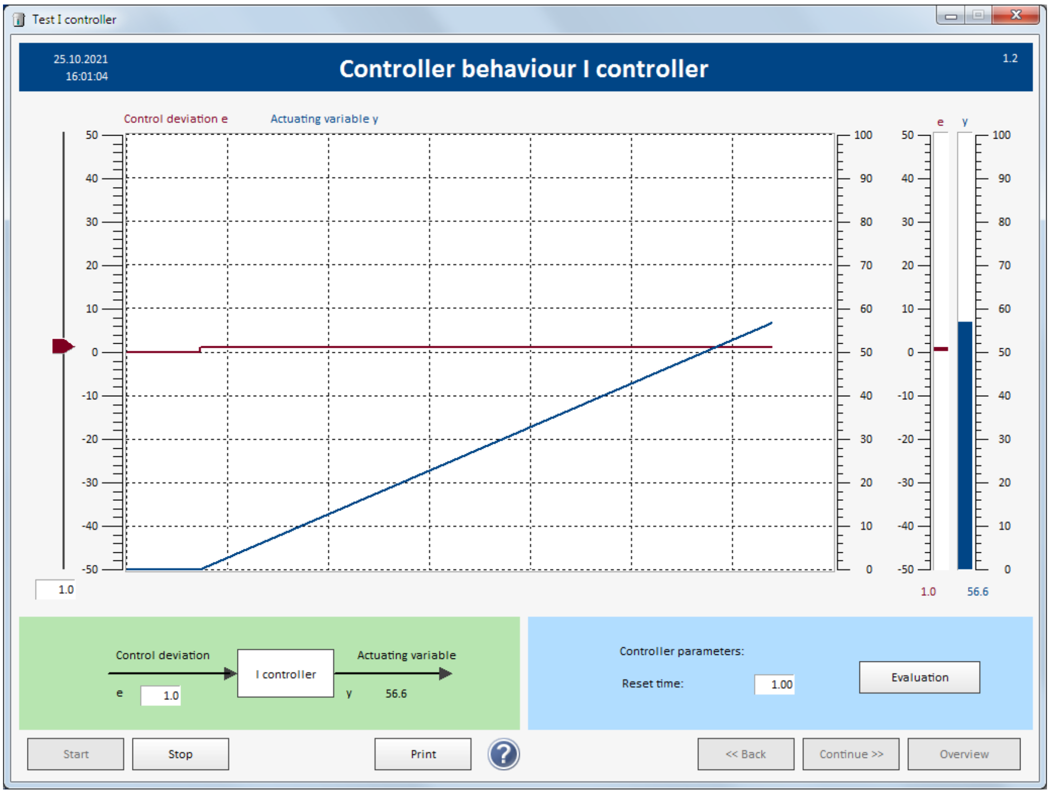
Task 2.

.Press “Start”.

Set the controller parameter "Integral time" (Reset time) to 1.

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

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.

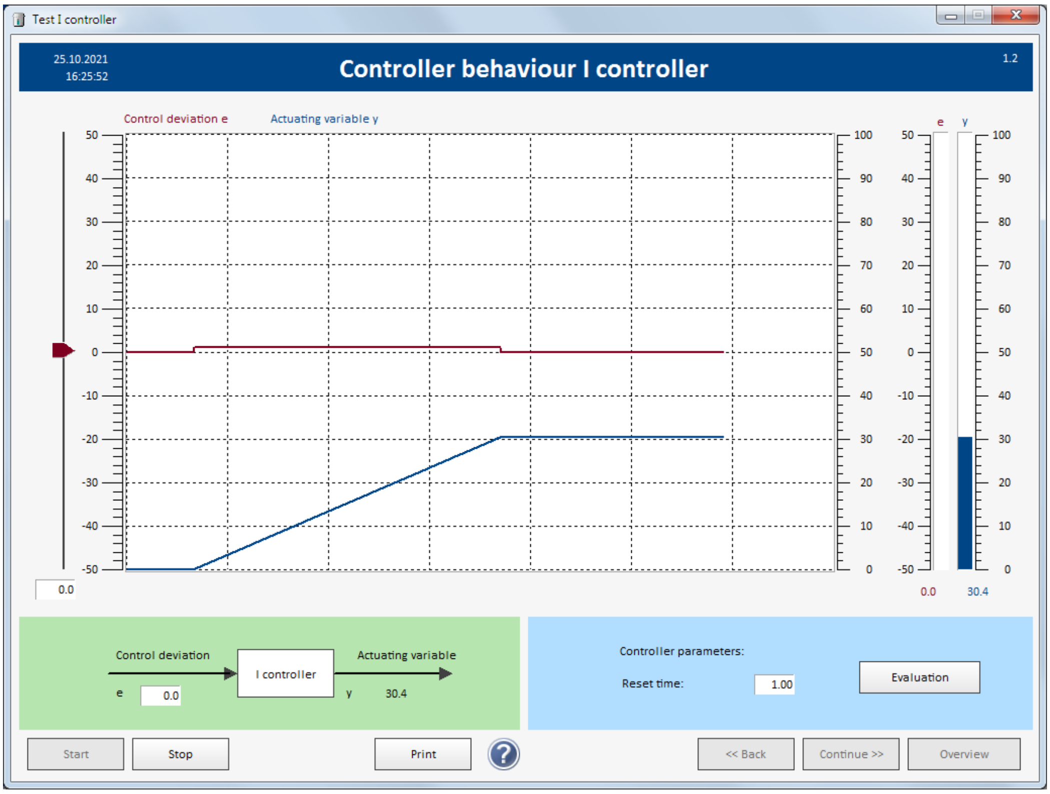
Press “Start”.

Set the controller parameter "Integral time" to 1 (Reset time).

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

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

Observe the behavior.

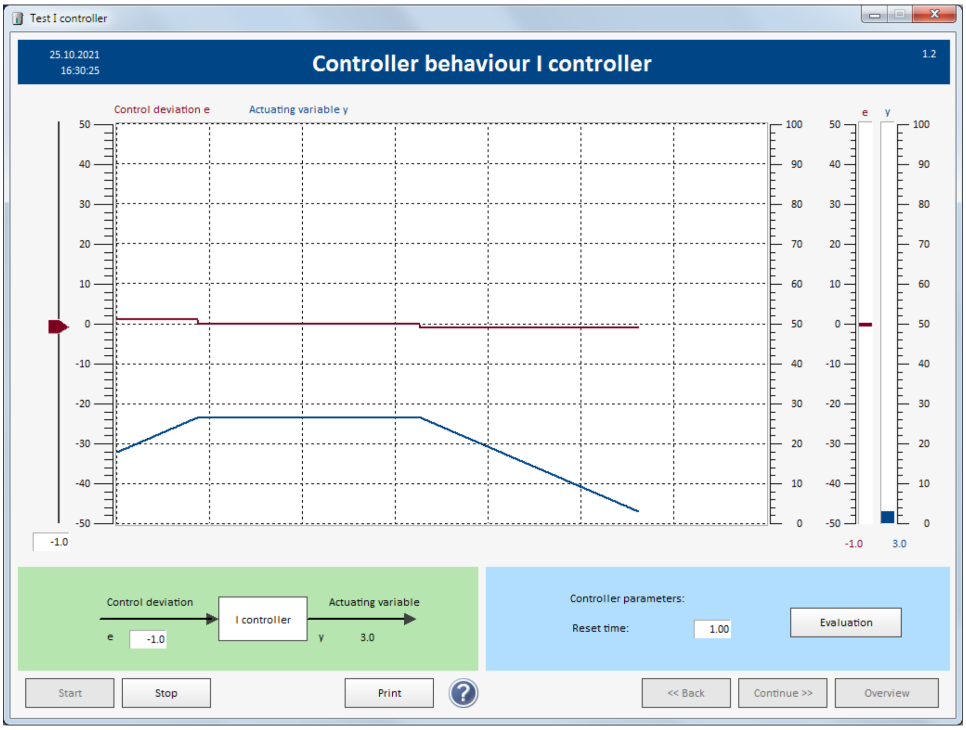


If the input e of the I controller (integrator) is 0, the output of the I controller retains its value (y remains constant).

Task 4.

Now change the input e to -1.

Observe the behavior.

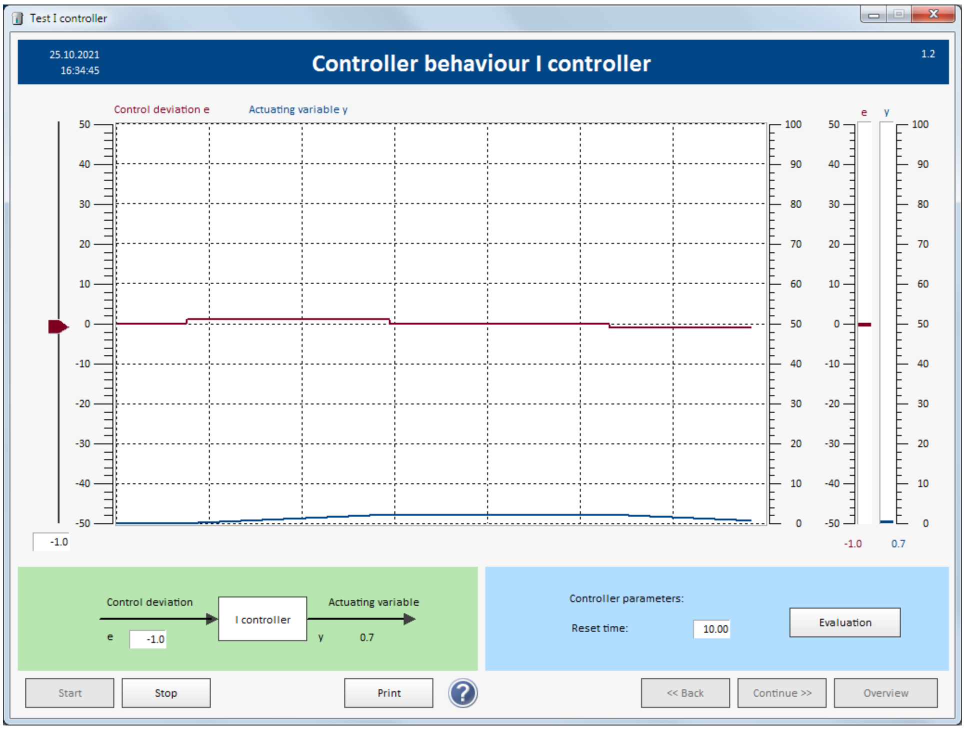


Since input e of the controller previously had the value 0, output y was constant. After input e was set to -1, output y began to decrease. It falls constantly with the slope -1, i.e. the output y decreases by 1 in one second.

Task 5.

Carry out the above experiments with the reset time 10.

Observe the behavior.



With input e = 1, output y begins to increase more slowly by a factor of 10 than in the previous tasks. If e = 0 the output remains constant. If the input is negative, the output falls with a 10x slower factor.

The slope of the output y depends on the reset time. The slope of 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 begins to increase the enlargement factor more quickly. The same applies if the input is negative.

As can be seen from these tasks, the I controller behaves like an integrator. If its input is positive, the output begins to rise continuously. If the input is zero, the output retains its value. If the input is negative, the output begins to decrease continuously.

Conclusion:

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

This follows from the fact that the I controller only outputs a constant value when its input e is equal to 0. The input of the controller is the difference between the setpoint and the actual value, i.e. only if the actual value is equal to the setpoint, the input e is equal to 0.

2.3 PI Controller

For controller behavior, select the PI controller (item 1.3 or 7.3)

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

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

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.

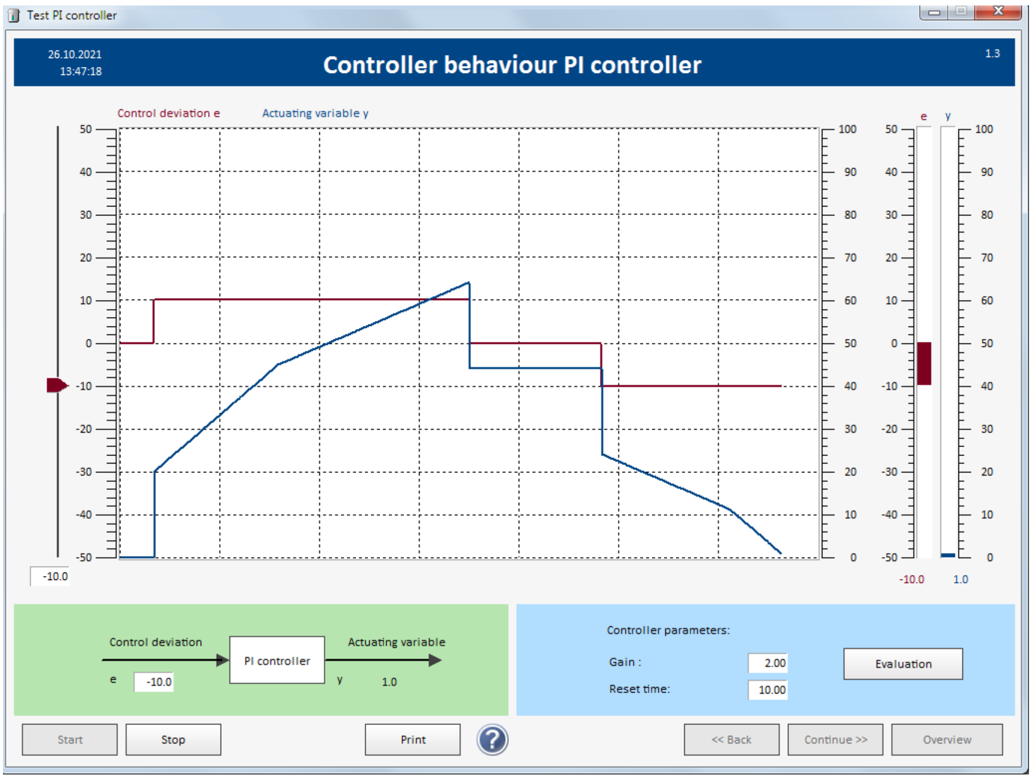
Press “Start”.

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

Enter 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 following trend display for e and y.

The investigation of the time behavior of the PI controller is shown in the figure above. First, a jump from 0 to 10 was given to input e of the PI controller. The input signal e (brown signal, control difference) went from 0 to 10. Since the gain of the PI controller was set to 2, the output signal y immediately assumed the value 20.

The reset time Ti (Tn) of the I component initially had the value 10. The gain 2 results in a total time constant of 10/2 = 5. The output signal y (blue signal, manipulated variable, control signal) rises evenly and continuously and therefore reaches after 10s a value increased by 20 (jump e to 10).

The reset time Ti was adjusted from 10 to 20. The rise of the output signal y now takes place more slowly because the time constant is now 20/2 = 10. With the time constant 10, the output reaches the value 1 after 10 seconds with an input jump of 1. Since we have specified an input jump of e = 10, output y increases by 10 after 10 seconds.

Then the input signal e was switched to 0. The P component then immediately goes to 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 a constant value is output that is 20 less than the value of the output signal at the switching point.

This was followed by a jump from e to -10. By gain 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

Under controller behavior select the PID controller (item 1.4 or 7.4)

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, the integrator and the D component.

Task 7.

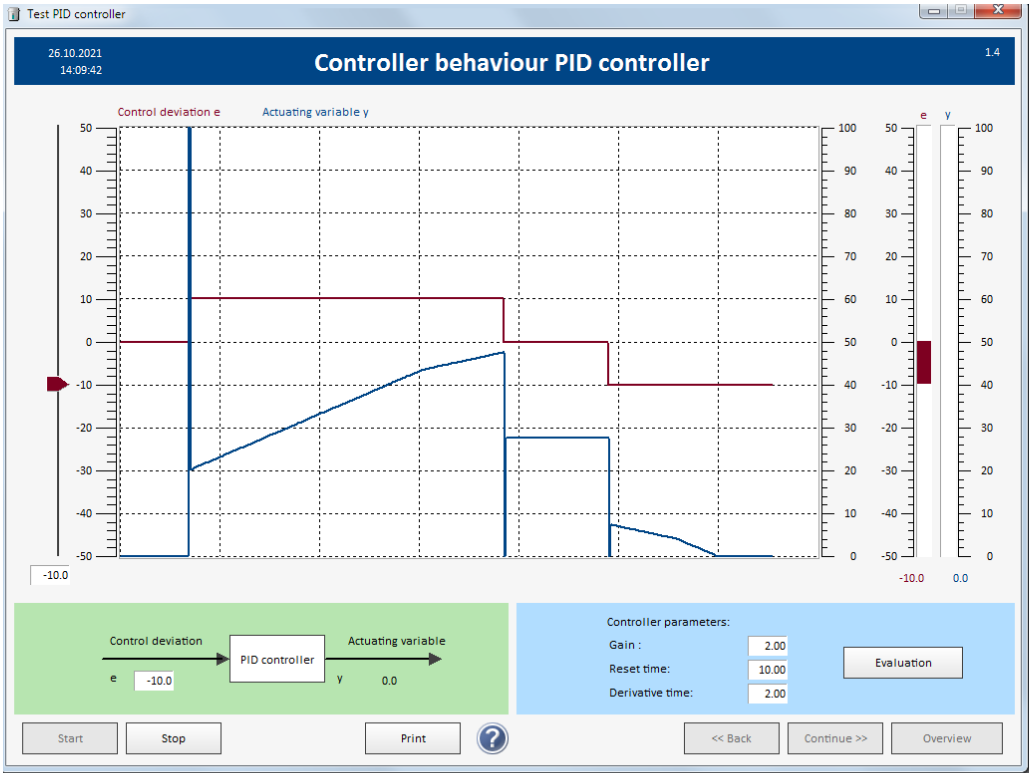
Press “Start”.

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 jump was given to the input of the PID controller. The input signal e (brown signal, control difference) went from 0 to 10. The D component of the PID controller immediately switches a peak to the output signal y, since the derivative of a sudden change in the input signal approaches infinity.

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

The D component is no longer effective because there is no change in the input signal e.

The reset time Ti of the PID controller was set to 10s. Since the gain of 2 also affects the I component of the PID controller, the overall time constant is 10/2 = 5. The output signal y (blue signal, manipulated variable, control signal) increases steadily and continuously and after 10s it reaches a level 20 higher value (input jump e = 10).

After a few seconds the reset time was changed from 10 to 20. The rise of the output signal y now takes place more slowly because the time constant is now 20/2 = 10. This means that with an input jump of 1, the output reaches the value 1 after 10 seconds. Since we entered an input jump of e = 10, output y increases by 10 after 10 seconds.

Then the input signal e was switched to 0. Due to the sudden change in the input signal, the D component of the PID controller acts again immediately and the output signal y received a peak downwards. The P component immediately went to 0, which made the output signal y 20 smaller.

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

Then there was a jump from e to -10. The D component caused a negative peak and the output signal suddenly decreased by 20 after the peak. The I component then decreases continuously with the reset time Ti.

By adjusting the reset time to 10s, the speed of decreasing was doubled.

The D component of the PID controller reacted three times in this example, namely always when the input signal e 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 between the setpoint and the actual value.

2.5 Three-Posion Controller

In Control Trainin II under controller behavior, select the three-point controller (item.1.5).

The three-point controller is a discontinuous controller that can output three states as a control signal. Depending on the difference between the setpoint and the actual value, one signal, the other signal or no signal is switched to the output.

An example of the use of a three-point 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 setpoint, neither heating nor cooling takes place.

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

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

Task 8.

Press “Start”.

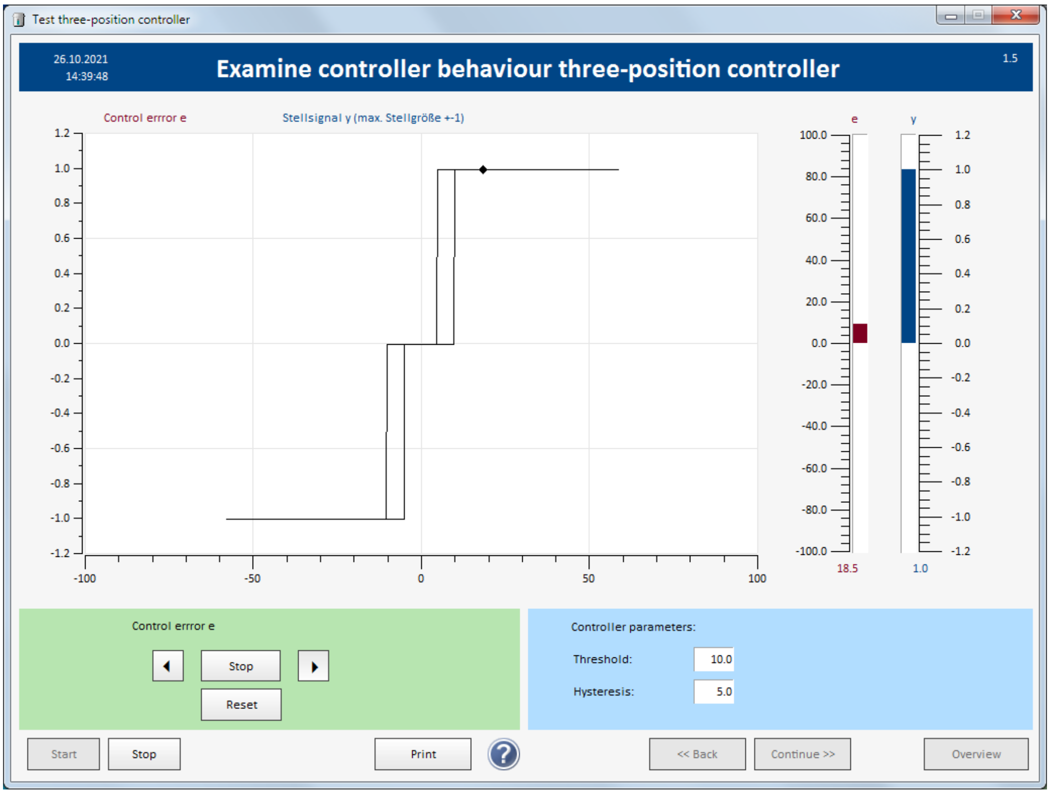
Set the controller parameters "Threshold" to 10 and "Hysteresis" to 5.

Press the arrow to the right of the “Stop” button. Wait until the control error has reached approximately 50. Then press the arrow to the left of “Stop”.

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

Watch 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 pressing the arrow next to the "Stop" button, the control error e slowly begins to increase continuously.

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

If the arrow to the left of the “Stop” button is pressed, the control error e slowly and continuously decreases.

Only when the control error e is smaller than the set hysteresis of 5 does the control signal y jump to 0.

If the control error e falls below the value -10 (threshold), the control signal y jumps to its minimum value -1.

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

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

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 setpoint. The heating output is the input variable (manipulated 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.

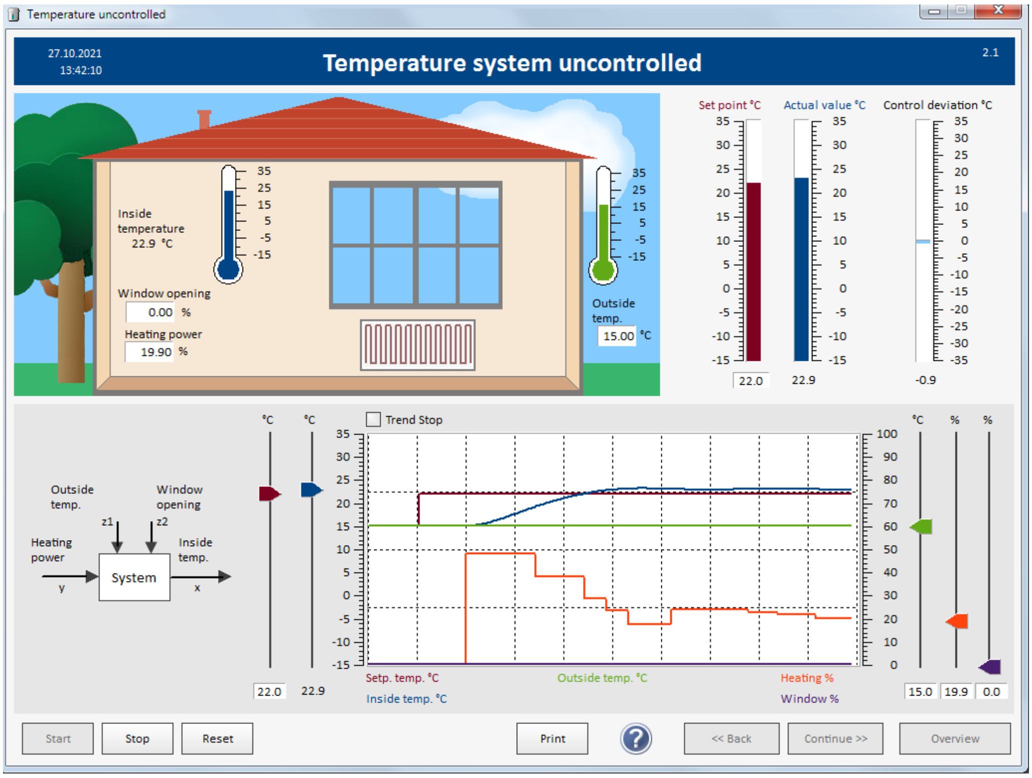
3.1 Uncontrolled System (Manual Control)

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

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

Task 1.

Set the setpoint (reference variable) to 22°C and try to bring the actual value (controlled variable, Inside temp.) to the setpoint (Setp. Temp.) by adjusting the heating output (control signal, Heating).

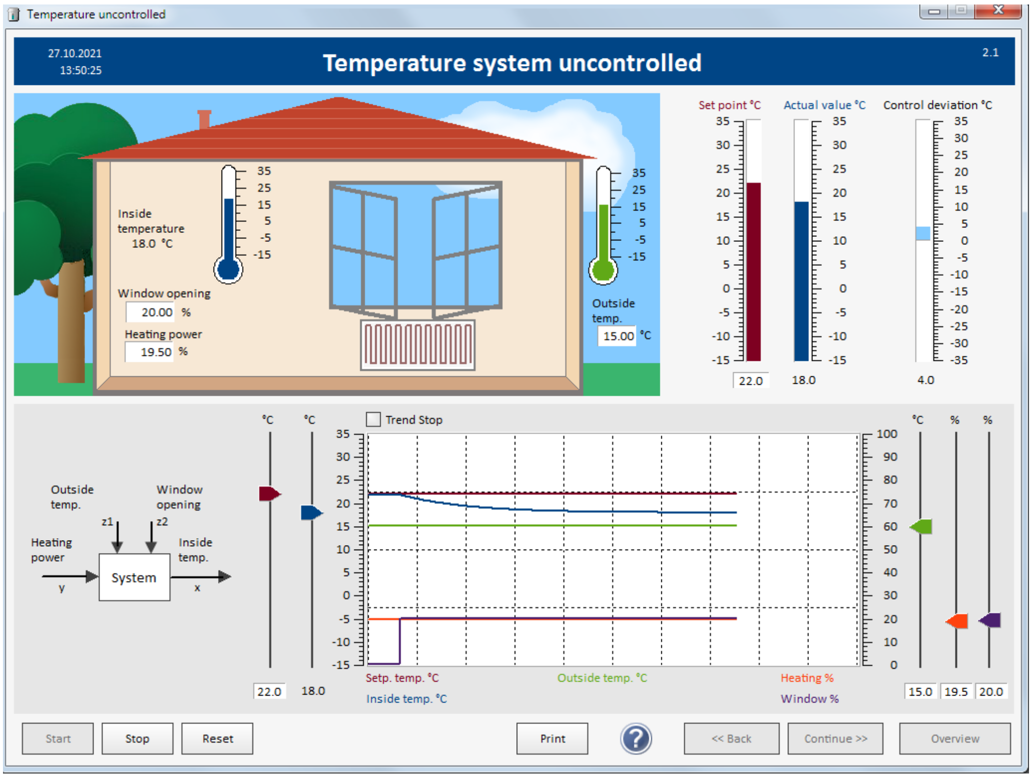


If the setpoint is adjusted and an attempt is made to bring the actual value (controlled variable) back to the new setpoint (reference variable), we speak of the command response.

Task 2.

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

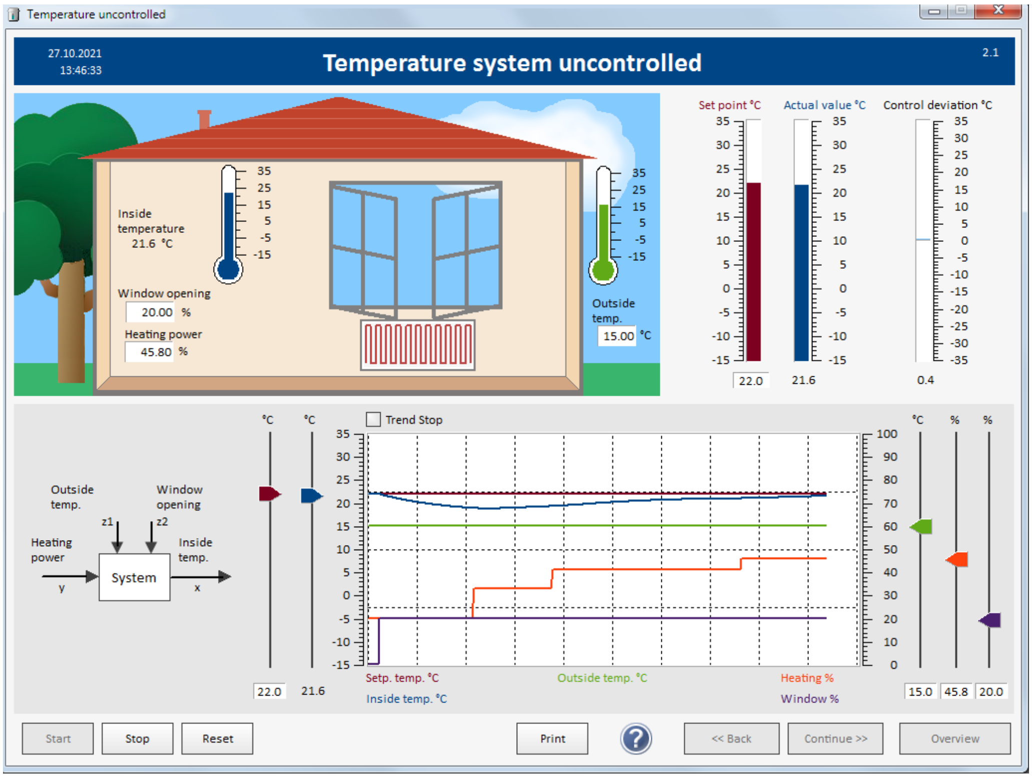
What will happen ?



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 bring the internal temperature back to the setpoint of 22°C by adjusting the heating power.



Due to the external disturbance, an attempt must be made to bring the actual value (controlled variable) back to the setpoint (reference variable) by adjusting the heating output (increasing the heating output).

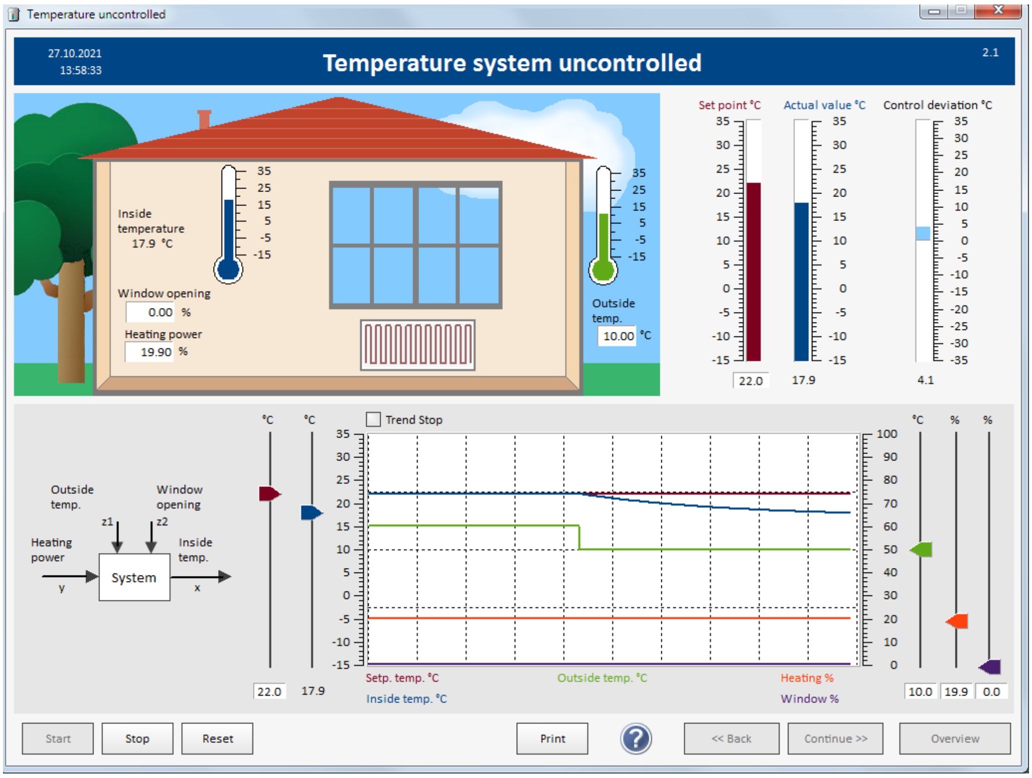
When responding to a disturbance in the system, one speaks of the disturbance response of the control loop.

Task 4.

Close the window and try to bring the internal temperature back to the setpoint value of 22°C by adjusting the heating power.

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

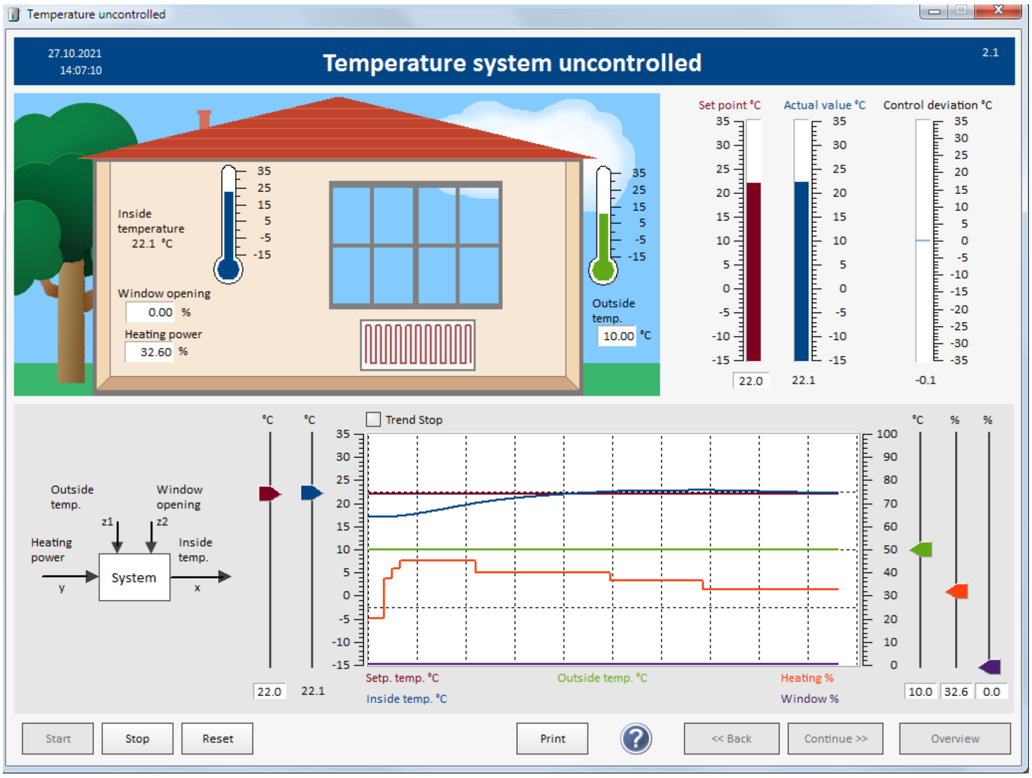
What will happen?



As the outside temperature decreases, the inside temperature in the room will get smaller.

Task 5.

Try to correct the disturbance caused by the changed outside temperature by adjusting the heating output.



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

In order to compensate for this disturbance, the heating output must be turned up. This is again about the disturbance response in the control loop.

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

3.2 Closed-loop Control System

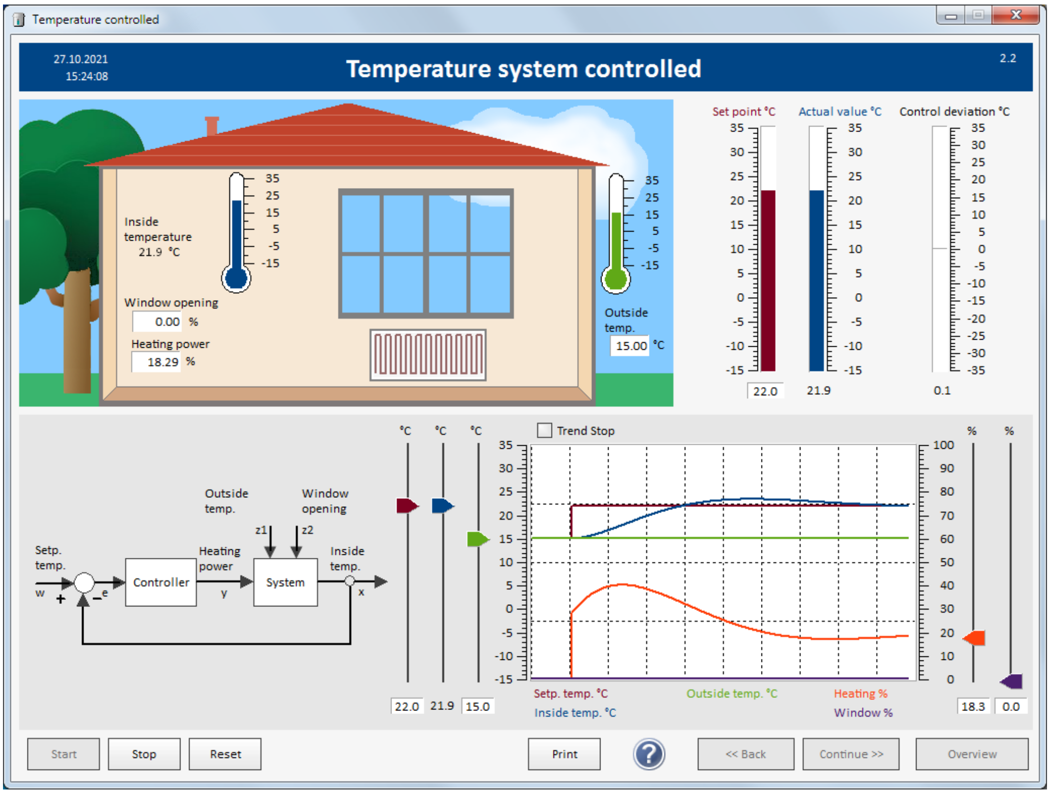
3.2.1 Closed-loop Control System

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 bringing the actual value to the setpoint.

Task 6.

Press “Start” and set the setpoint to 22°C.



With overshoot, the actual value goes to the setpoint after a certain time.

Even if you specify a fault by changing the outside temperature, the controller tries to bring the actual value back to the setpoint.

3.2.2 Closed Loop Control with P Controller

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

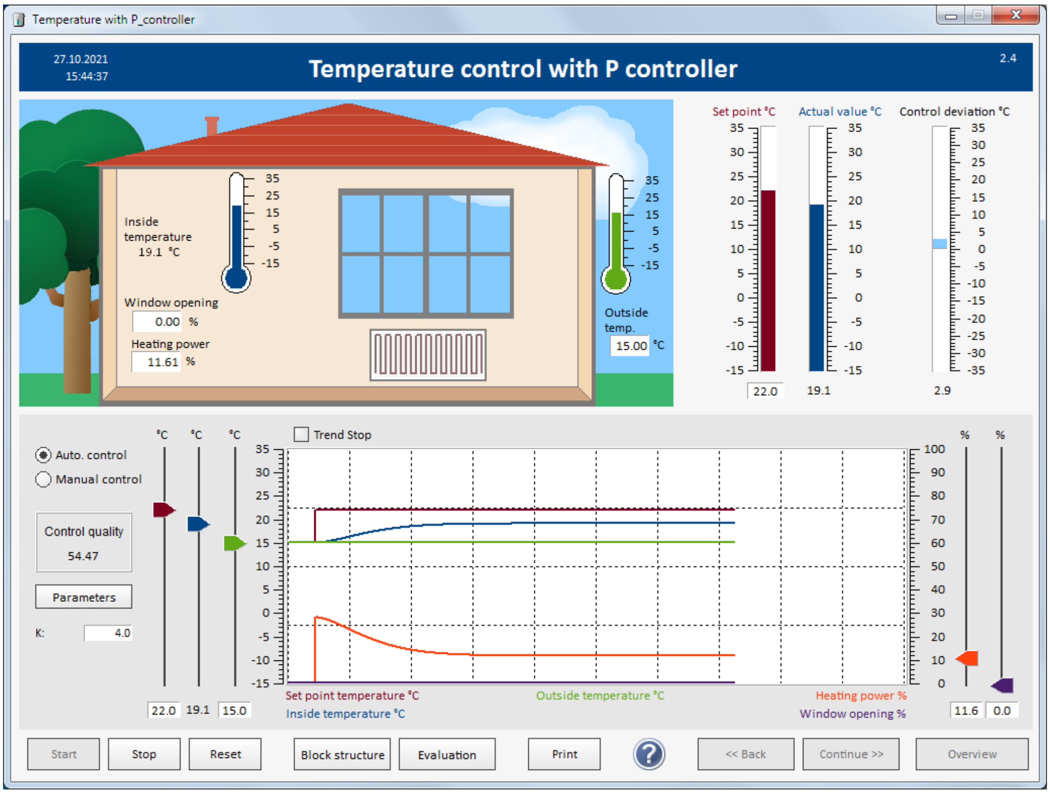
Press “Start”.

Task 7.

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

Change the setpoint 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 setpoint (reference variable). We get a steady-state control error.

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

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

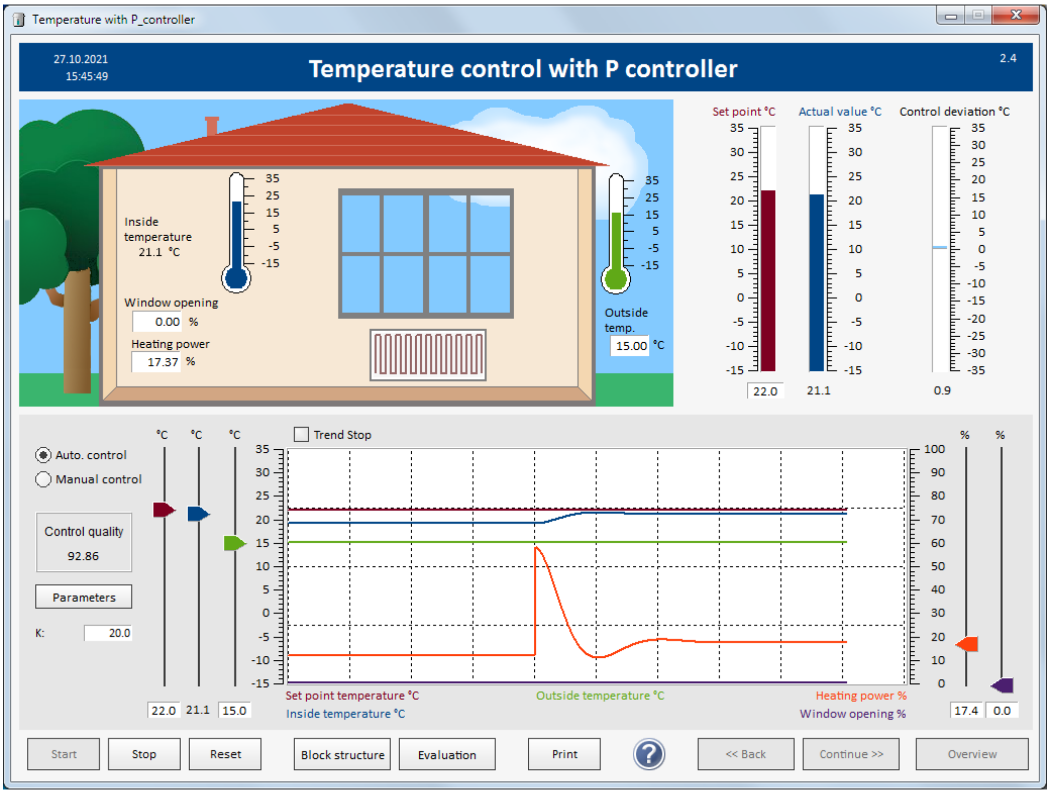
The P controller works like an amplifier. The input signal to the controller w - x (setpoint - actual value) is amplified with the gain K (in our case 4).

In our case, the setpoint w was set to 22°C. An actual value x of 19.1 ° C was achieved. The control difference 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 a value for the control signal of (22-19.1) * 4 = 11.6. This control signal can also be read in the process picture.

In general, the following applies: In order for the P-controller to output a control signal (a heating output) that is not equal to zero, the setpoint and actual value must be different, i.e. steady state control error.

Task 8.

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



The control difference between the setpoint and the actual value becomes significantly smaller as the gain K is increased from 4 to 20. However, the P controller does not manage to bring the actual value to the setpoint 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 here how large the control signal will be.

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

As can be seen from the settling time, the P controller reacts immediately and quickly to changes in the setpoint and disturbance input. 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".

Press “Start”.

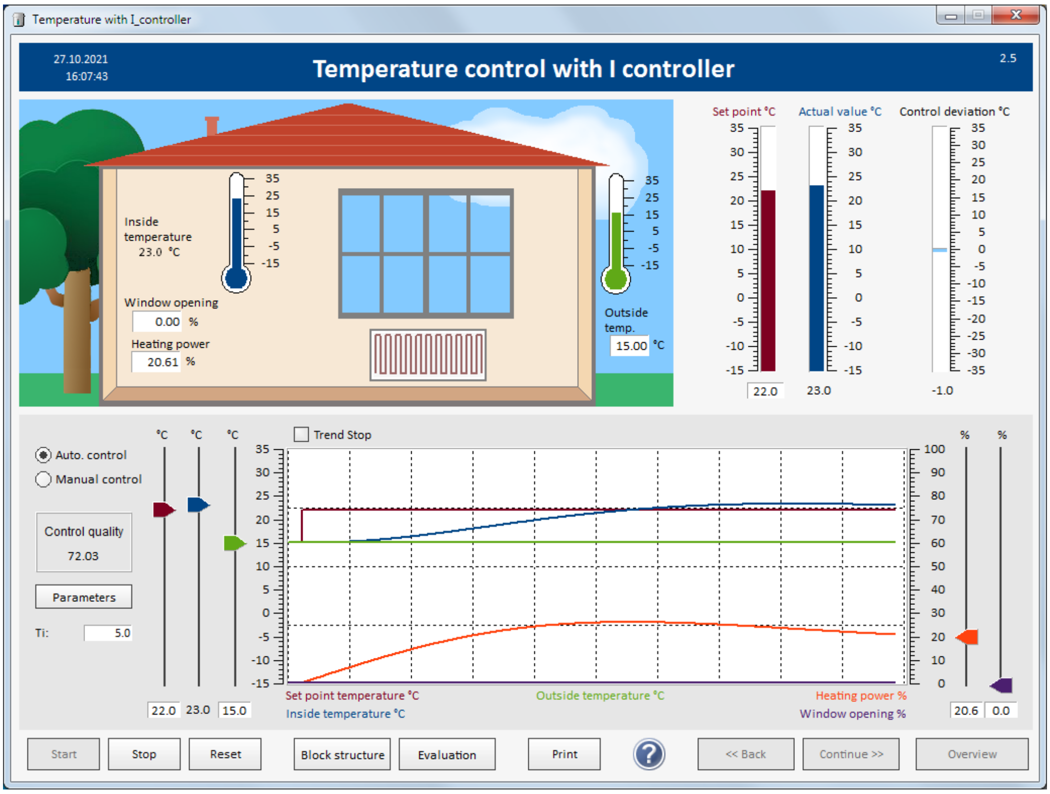
Task 9.

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

Leave the set reset time Ti at 5.

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

Describe the behavior.



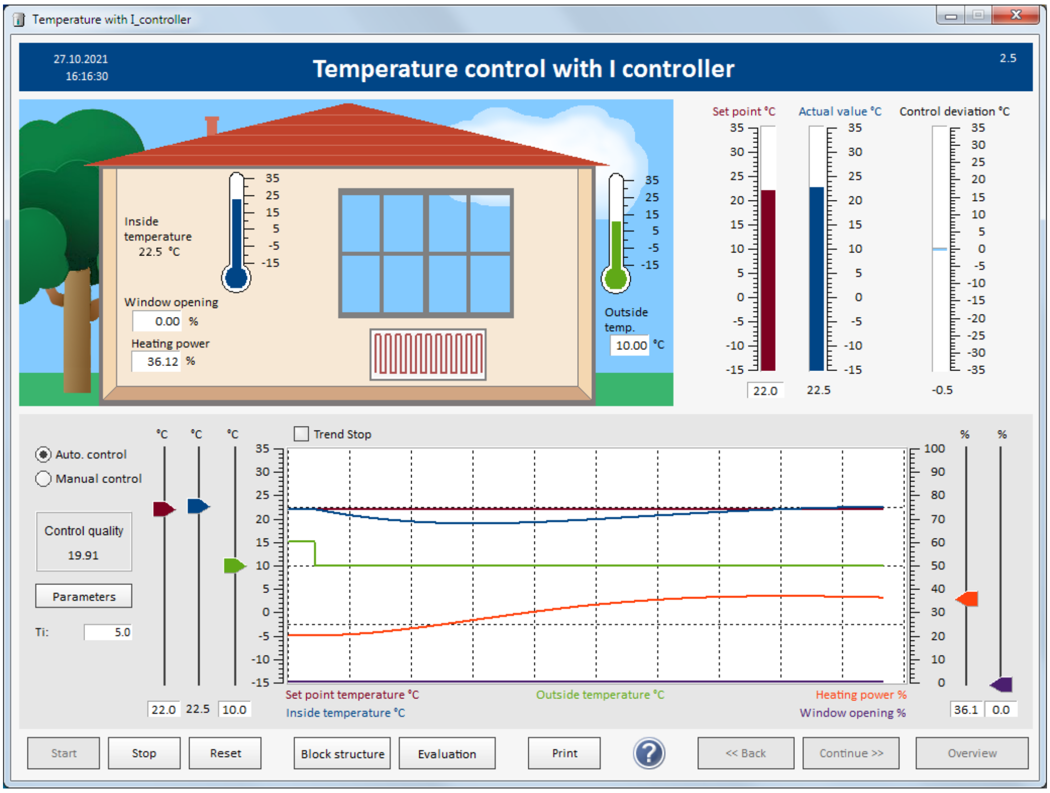
After a significantly longer settling phase than with the P controller, the actual value reaches the setpoint with a small overshoot at the set integration time Ti = 5. There is no steady-state control error.

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

Task 10.

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

How does the control loop behave?



After a longer settling phase, the actual value returns to the setpoint.

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

However, settling takes a long time.

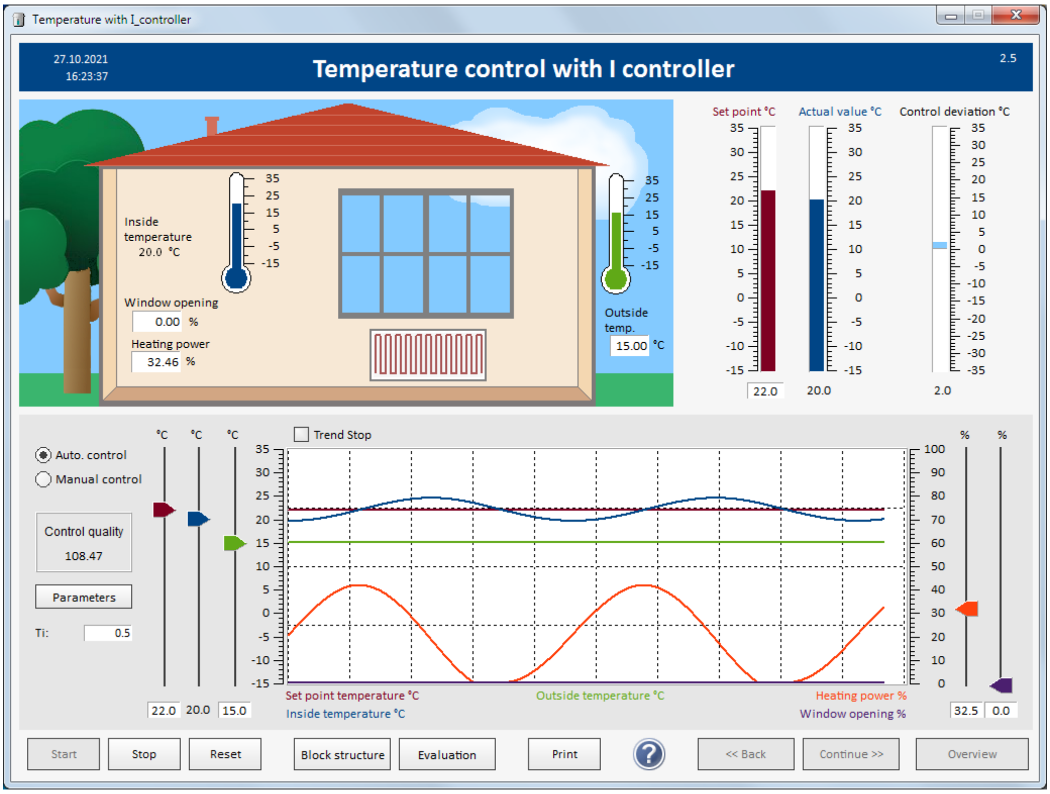
Task 11.

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

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

Change the set reset time Ti to 0.5.

Set the setpoint to 22°C and observe the control loop.



The control loop becomes unstable. The actual value swings continuously around the setpoint.

In general:

If there is an I component (integrator) in the controller, the controller either manages to bring the actual value to the setpoint 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 setpoint 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".

Press “Start”.

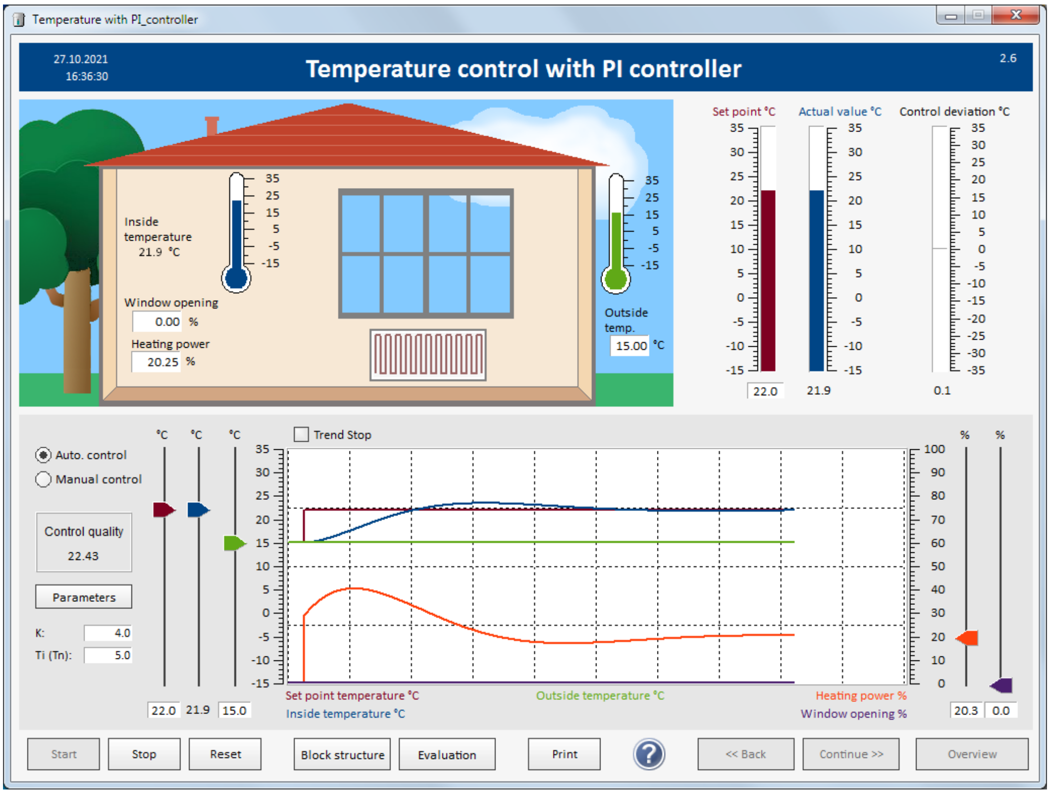
Task 12.

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

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

Change the setpoint from 15°C to 22°C.

Observe the settling behavior.



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

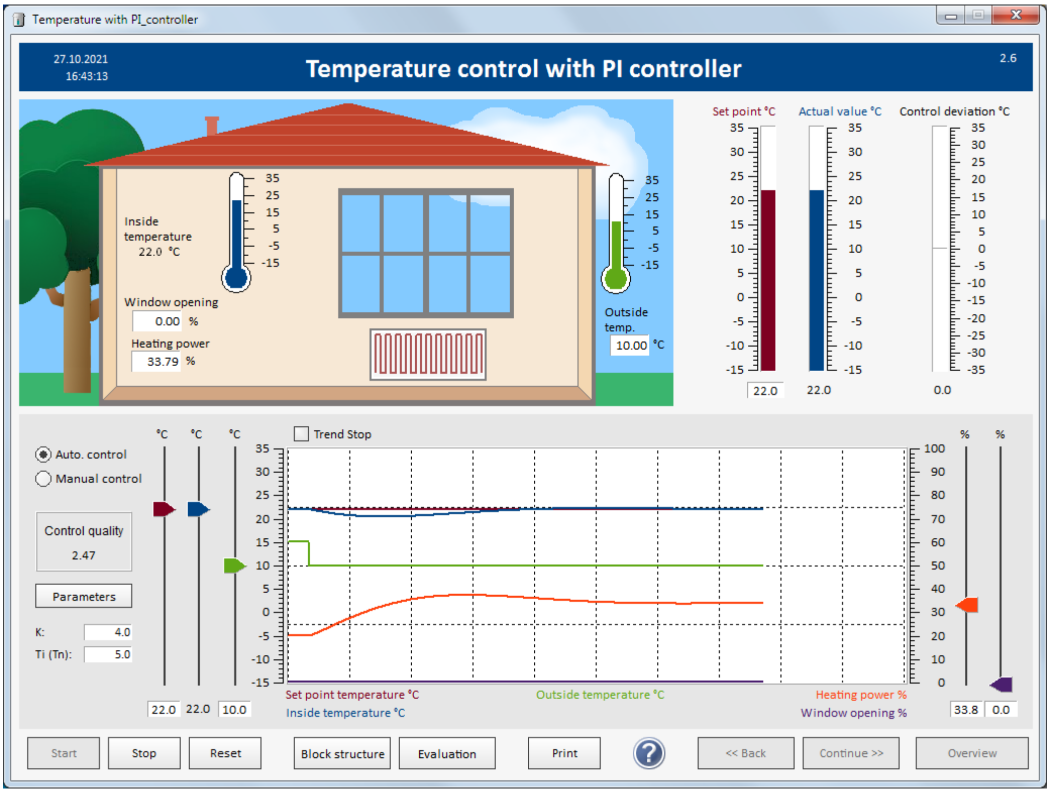
The settling of the control loop by changing the setpoint is referred to as the command response.

Task 13.

Examine the disturbance response.

Let the control loop settle to the setpoint 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 output. After a settling phase, the actual value reaches the setpoint again.

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

Task 14.

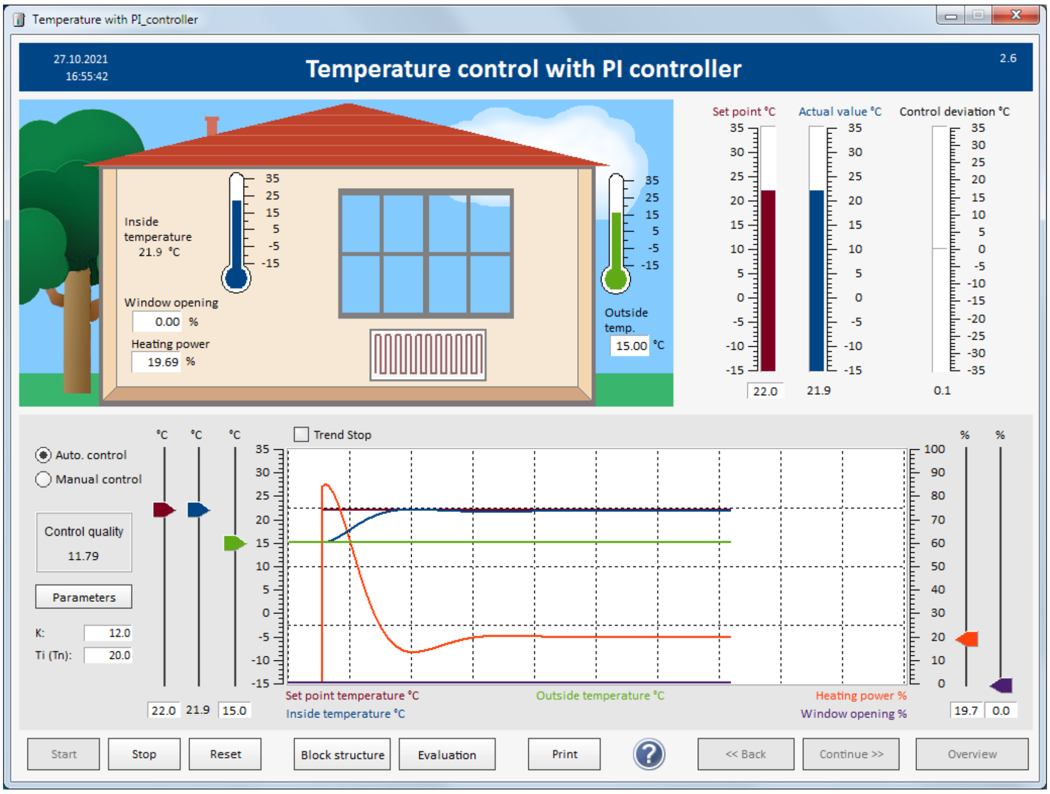
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the setpoint.

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 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 press "Reset". This means that the setpoint, outside temperature and inside temperature are again given the value 15°C and the window is closed.

Now change the controller parameters and then adjust the setpoint 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:

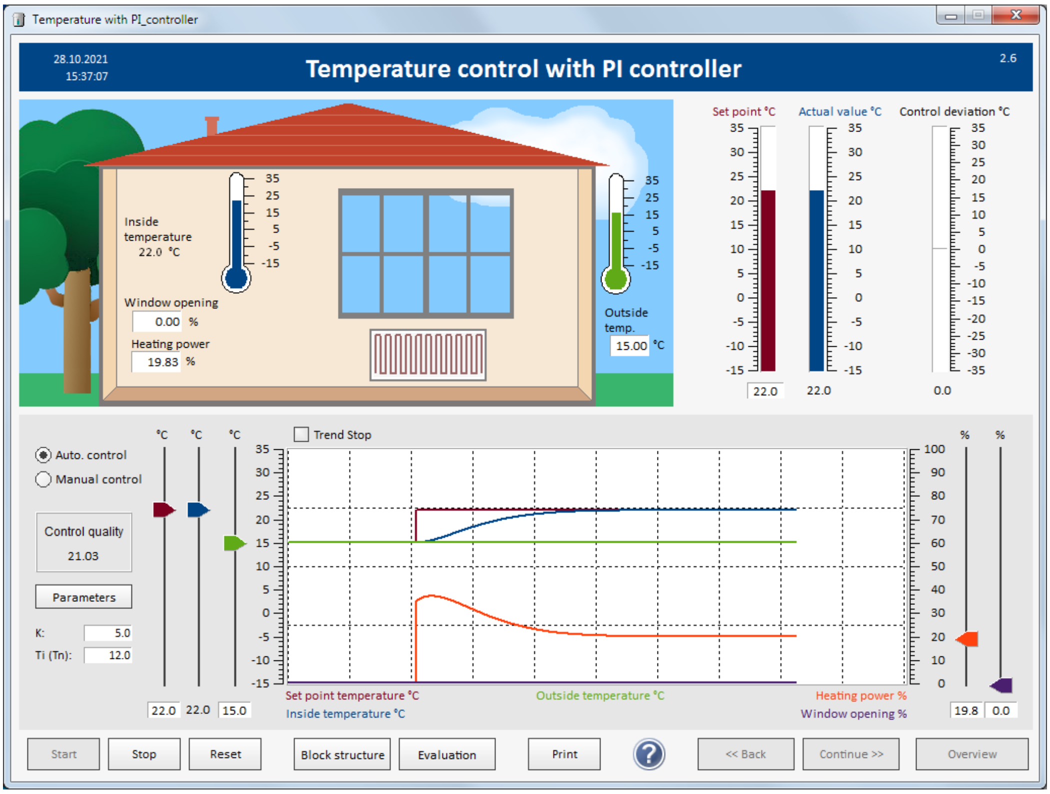
- Press reset,
- Set controller parameters,
- Set the setpoint to 22 ° C,
- Wait until the control loop has settled.

Task 15.

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

Try to adjust the controller parameters to ensure that the actual value reaches the setpoint 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 setpoint 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 setpoint without overshooting.

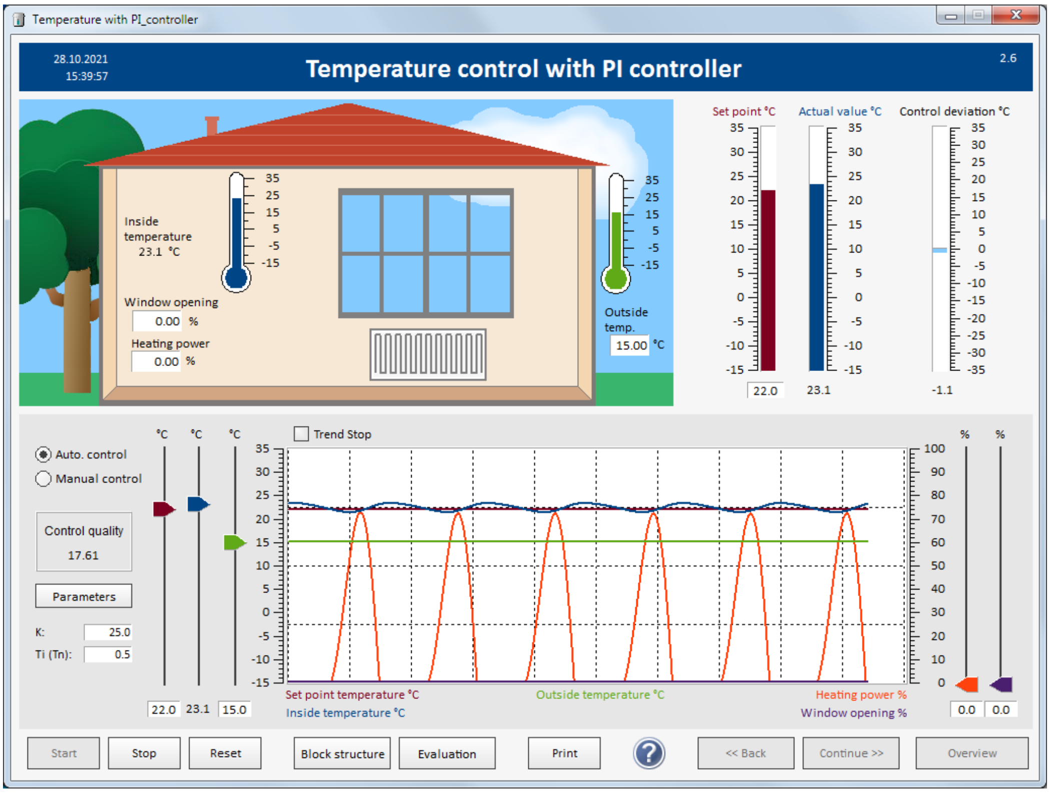
For example, it may be necessary for a bioreactor that a certain temperature is not exceeded, because otherwise the cells in the reactor can die.

Task 16.

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

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

Watch the control loop.



The system becomes unstable. The actual value swings around the setpoint.

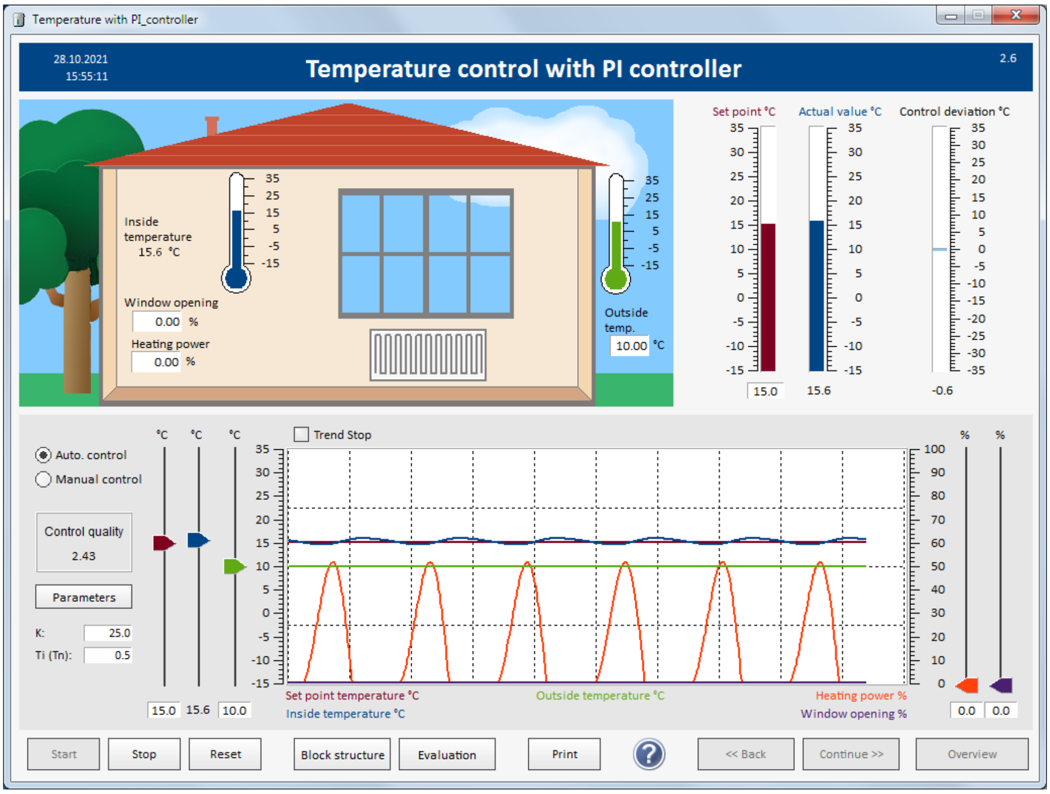
By pressing "Evaluation" you have the option of evaluating the stored signal curves and examining the settling behavior.

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 press "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.

In conclusion, it can be said:

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

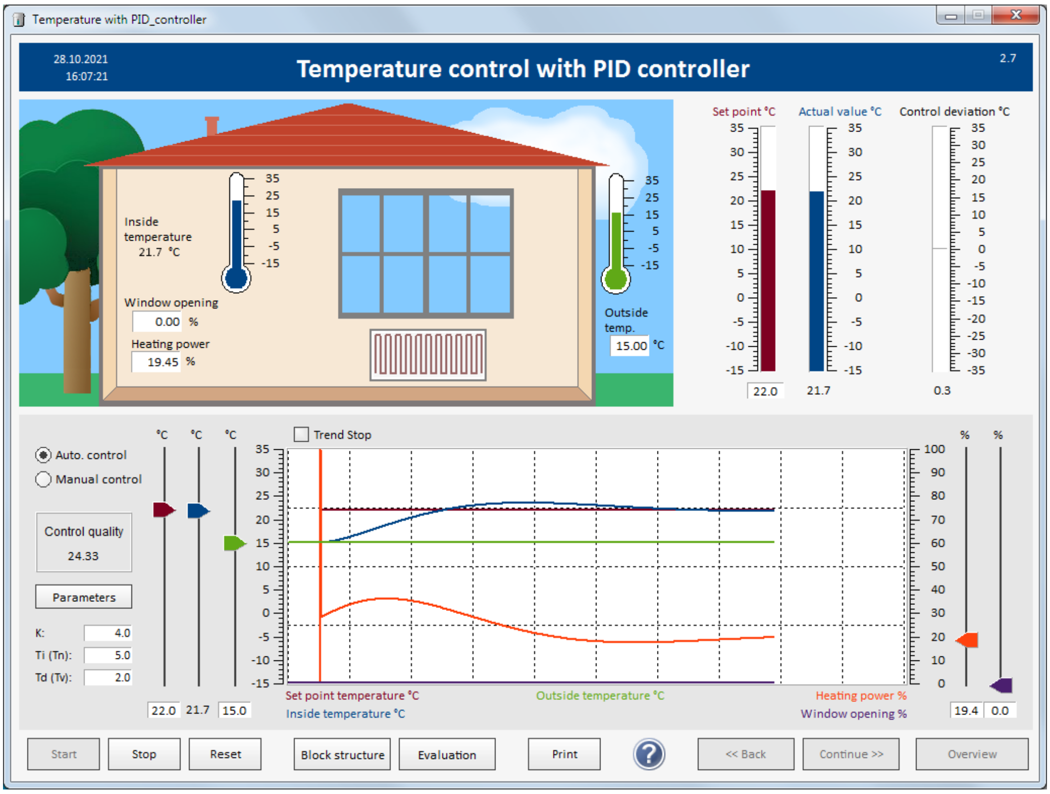
Press “Start”.

Task 18.

Examine the command response with the preset parameters.

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

Press “Reset” and change the setpoint to 22°C.



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

As can be seen in the trend diagram, the sudden change in the setpoint causes a peak in the control signal (heating output). 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:

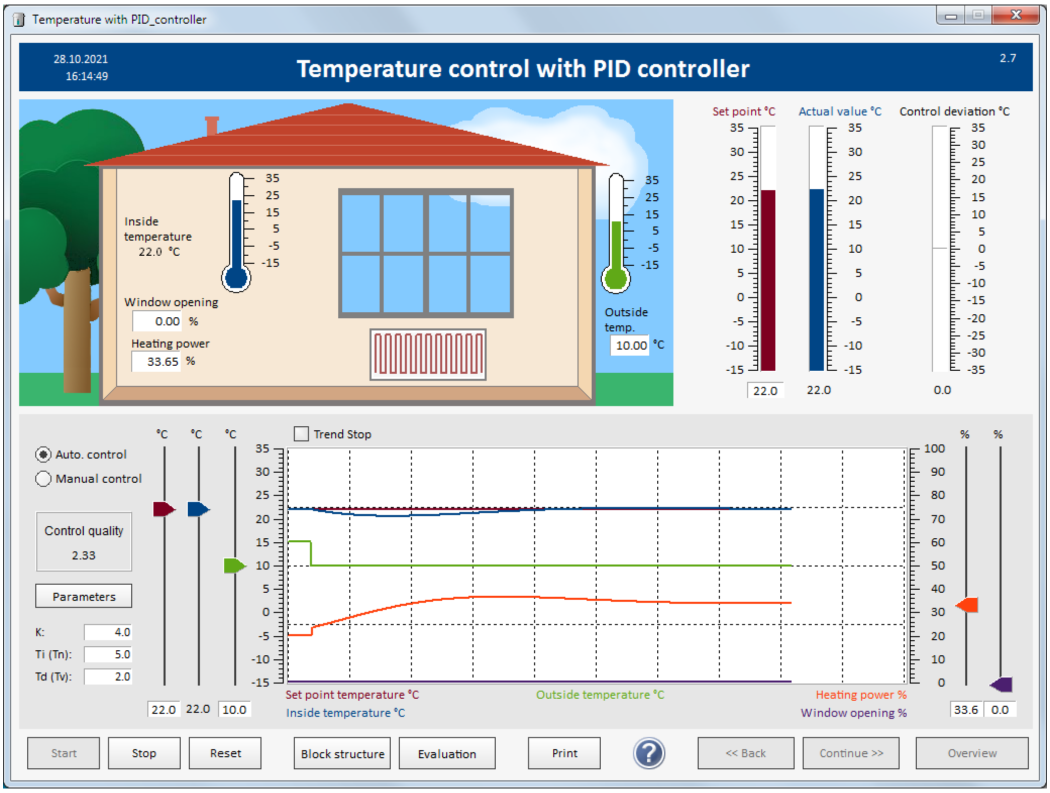
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Evaluation" (display of the stored signal values) and selection of a corresponding time range.

Task 19.

Examine the disturbance behavior with the preset parameters:

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

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

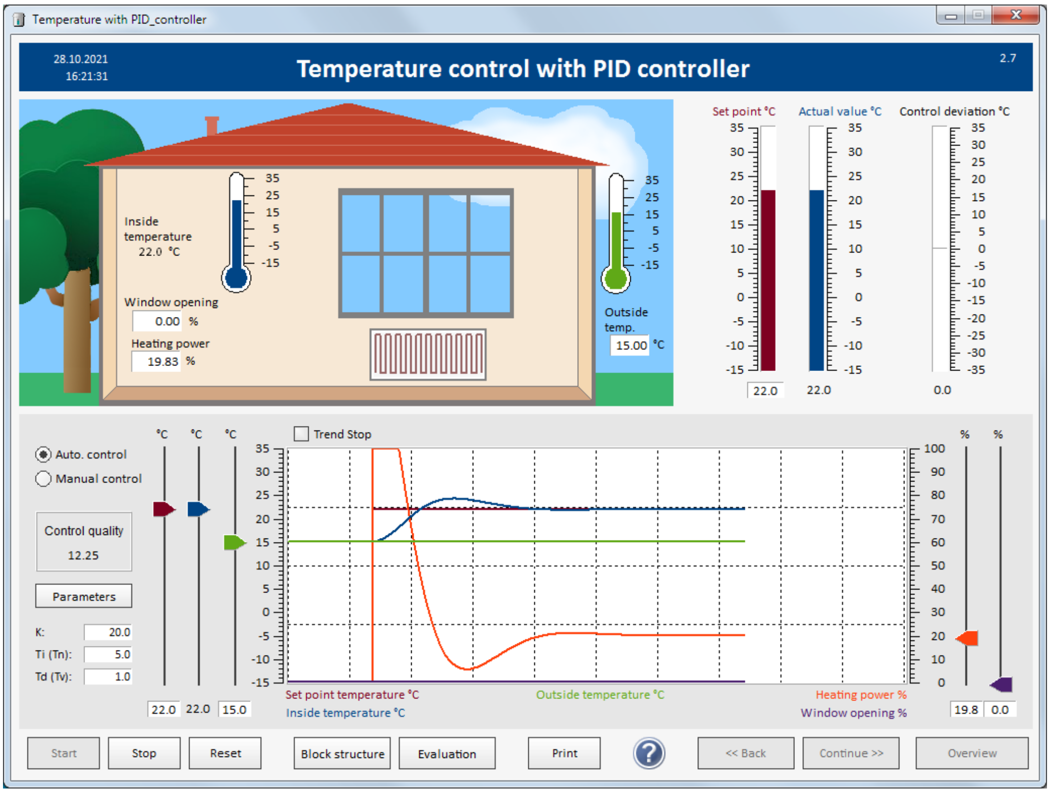


In the event of a disturbance, the control loop is controlled with the specified controller parameters and the actual value (controlled variable) reaches the setpoint (reference variable) again after a period of time.

Task 20.

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 press “Reset”, change the controller parameters and then adjust the setpoint 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.).

Note:

In practice, the PI controller is mainly used as a controller. If a PID controller is used, the D component is often turned away 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 setpoint and the actual value. If the change increases, i.e. the difference between the setpoint and actual value increases, the D component adds a calculated value to the control signal. If the change between the setpoint and the actual value becomes smaller, i.e. the difference between setpoint and actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend as to whether the difference between the setpoint and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the setpoint and actual value is smaller, the control signal is reduced.

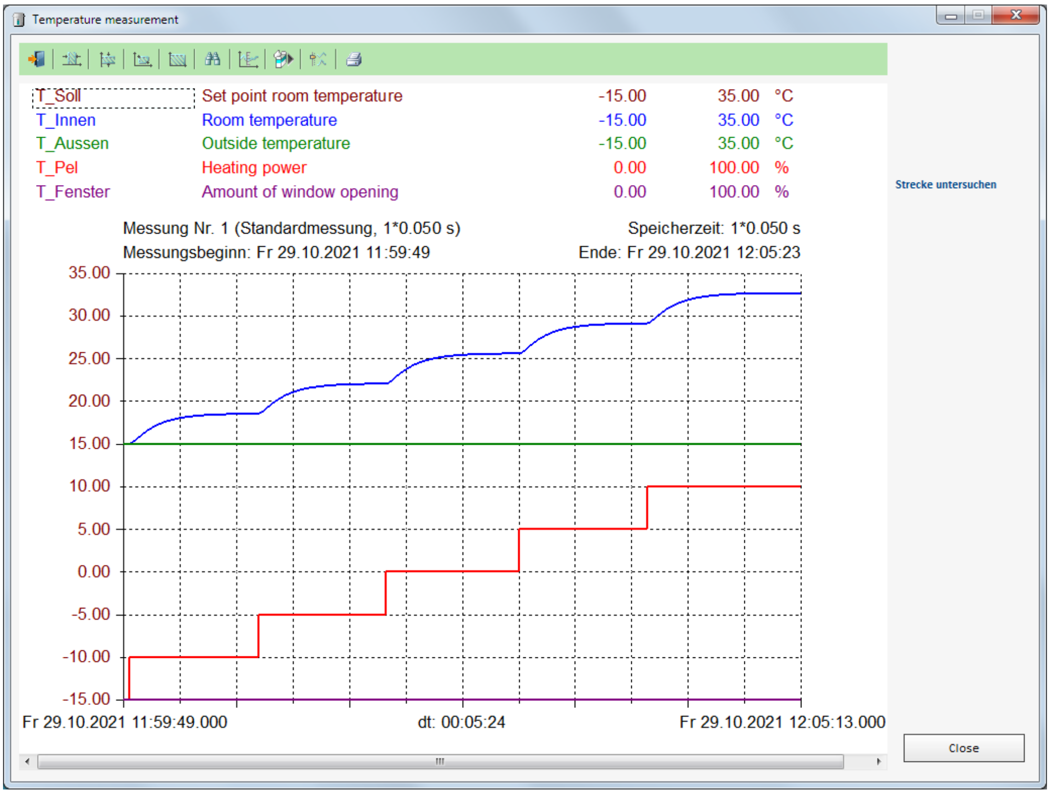
3.3 Examine Controlled System

For room temperature control, select item 2.3 "Examine controlled system".

Task 21.

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

Observe the temperature behavior.



As can be seen from the recorded data (press “evaluation”), the System behavior is similar for the jumps. The actual temperature always rises by approx. 3.5°C when the heating output jumps 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.

3.4 Controller Tuning Rules

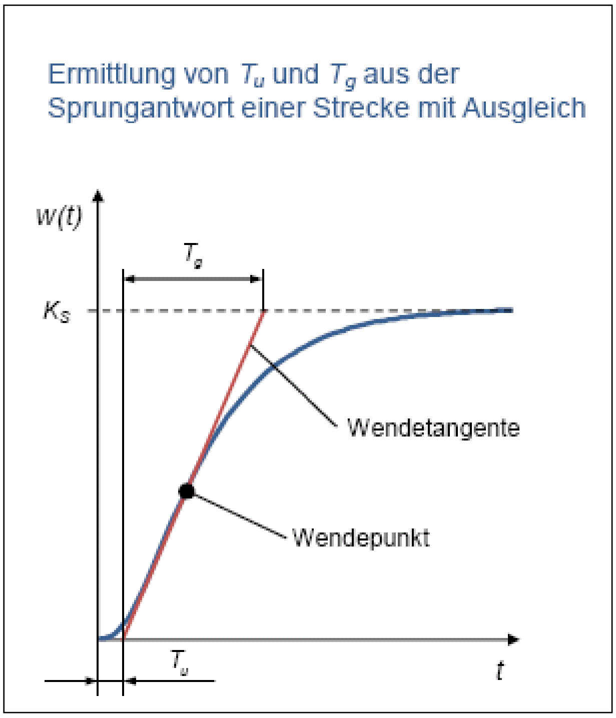
The room temperature system is a controlled system with self-regulation.

In the event of a sudden change in the control signal, a controlled system with self-regulation swings 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 output is suddenly adjusted, the temperature returns 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 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 jump in the control signal (sudden change in the control signal by 1):



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

Regler-verhalten	Gütekriterium: Überschwingung nach Gegenseite mit 20% von x_m, kürzeste Schwingungsdauer		Gütekriterium: aperiodischer Regelvorgang mit kürzester Dauer	
	Störung	Führung	Störung	Führung
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	$K_P \approx \frac{1{,}2}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2 \cdot Tu$ $T_v \approx 0{,}42 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1{,}35 \cdot T_g$ $T_v \approx 0{,}47 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2{,}4 \cdot T_u$ $T_v \approx 0{,}42\, T_u$	$K_P \approx \frac{0{,}6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$ $T_v \approx 0{,}5 \cdot T_u$

Für Regelstrecken *ohne Ausgleich* ist statt $\frac{T_g}{K_S \cdot T_u}$ der Ausdruck $\frac{1}{K_{IS} \cdot T_u}$ einzusetzen.

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

Task 22.

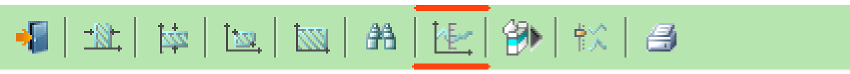
For room temperature control, select item 2.3 "Examine controlled system“.

Press “Start”. Enter a jump in the heating output from 0% to 10%.

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

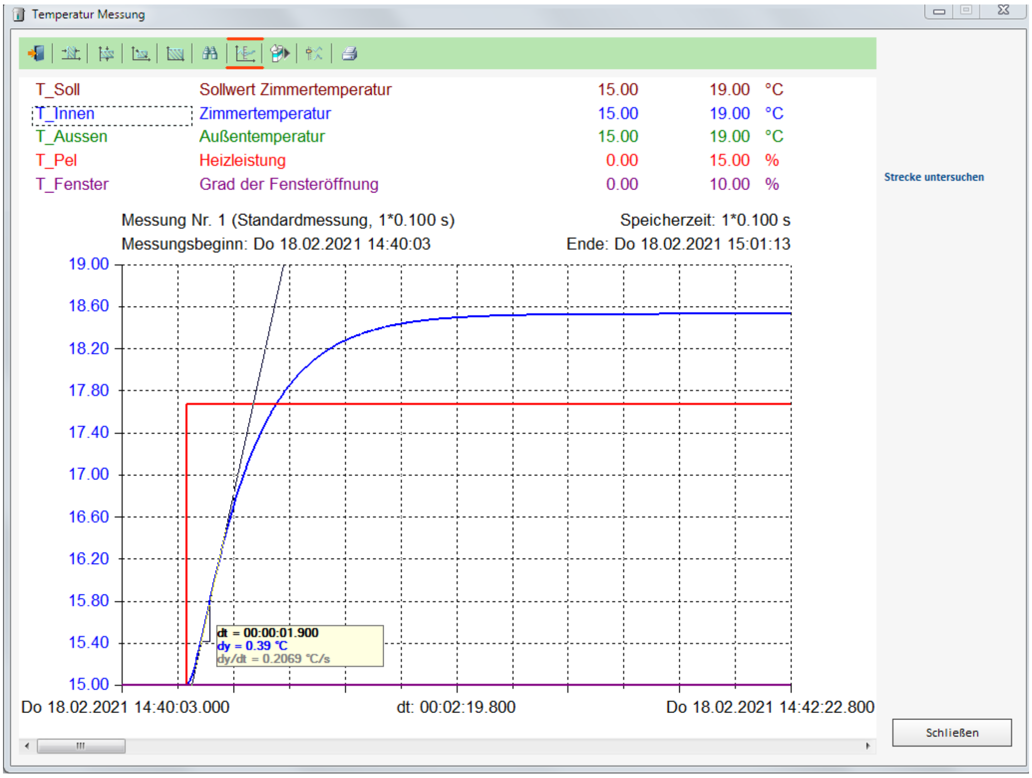
Determine the parameters Ks, Te (Tu) and Tb (Tg) from the stored signal curves.

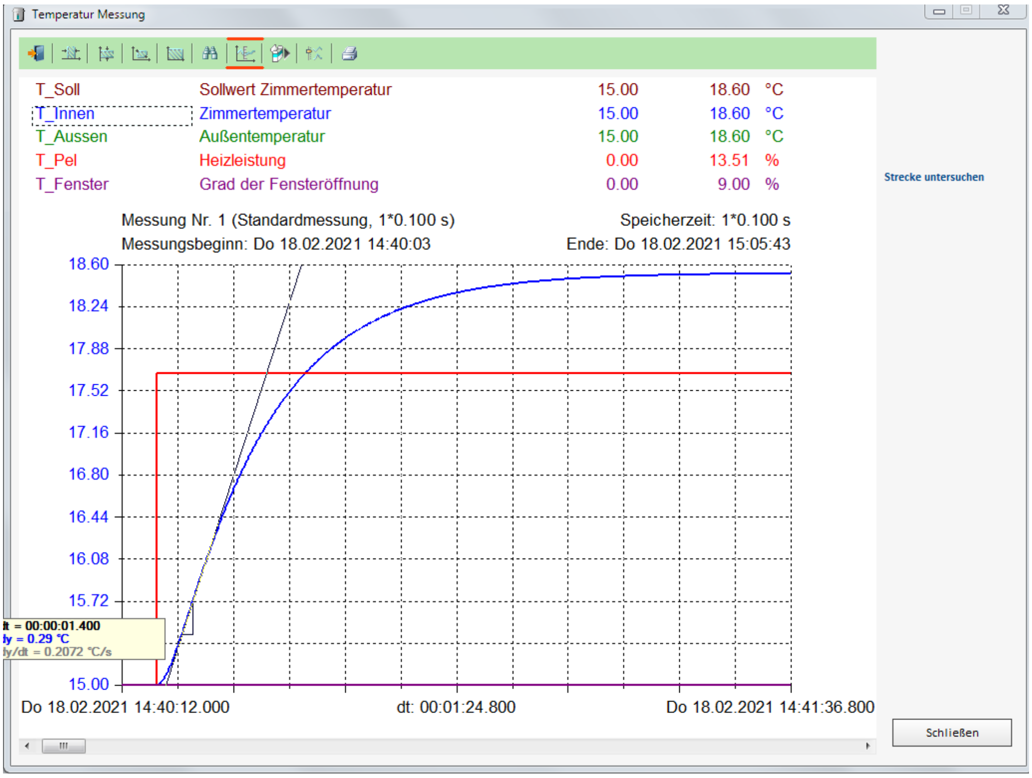
By clicking on the "Evaluation" button, you will get the measurement curves. With the help of the button bar in the windows, time and value segments can be selected.



Try to set the area of interest for the evaluation with the jump 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.





It is also possible to measure the values in the diagram. To do this, click on the blue signal "T_innen". Click on the blue curve to get the associated measured value and time. By holding and pulling, the time 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 output 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)) / Jump height(Heating output)

= (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:

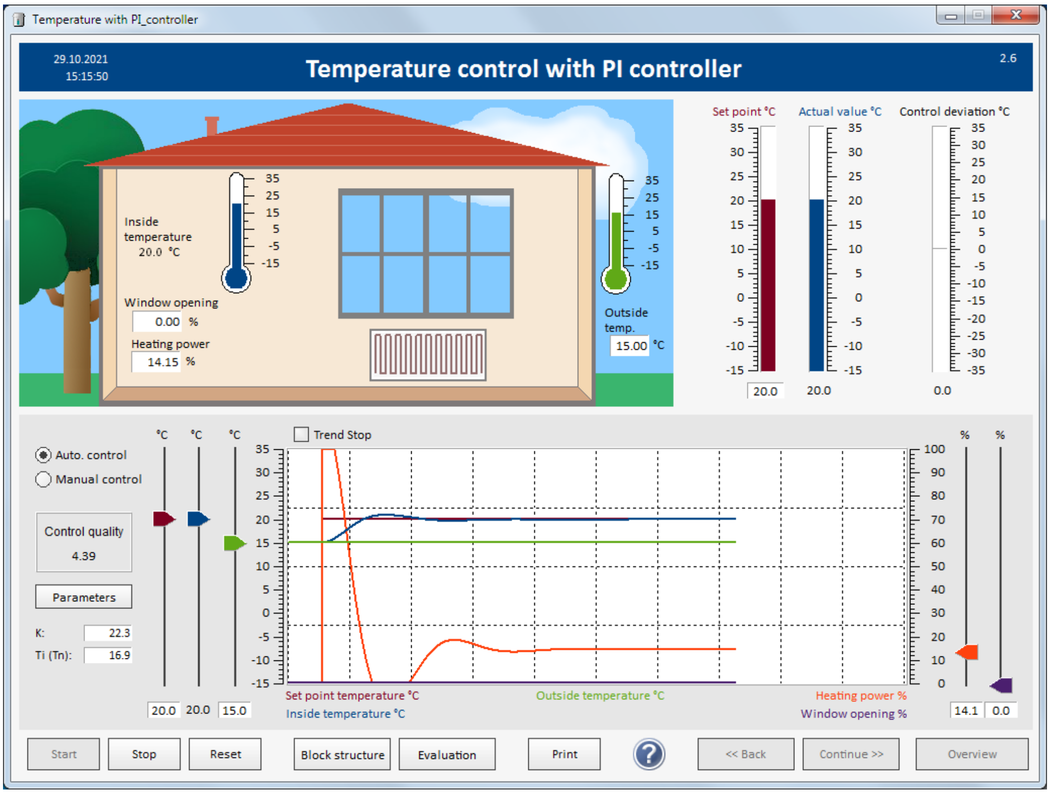
PI controller

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

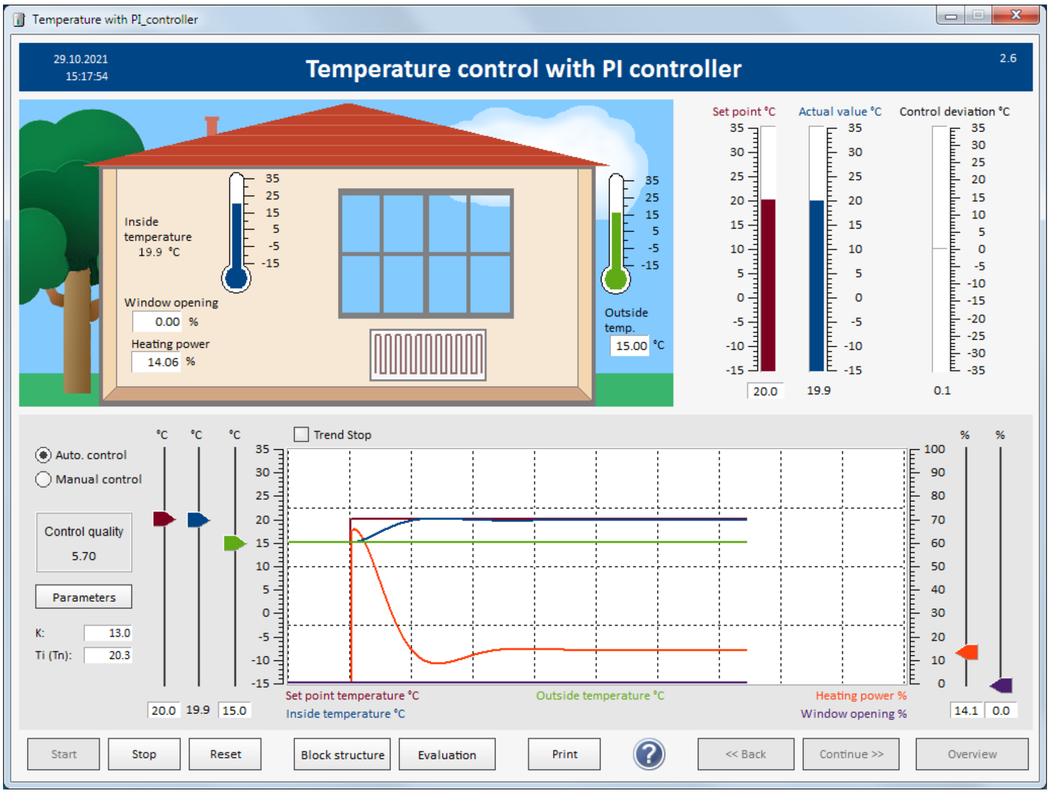
Since the parameters differ significantly depending on the application, the user must decide which type of control is important for his control loop (disturbance or control behavior, with or without overshoot).

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 setpoint jump from 15°C to 20°C:

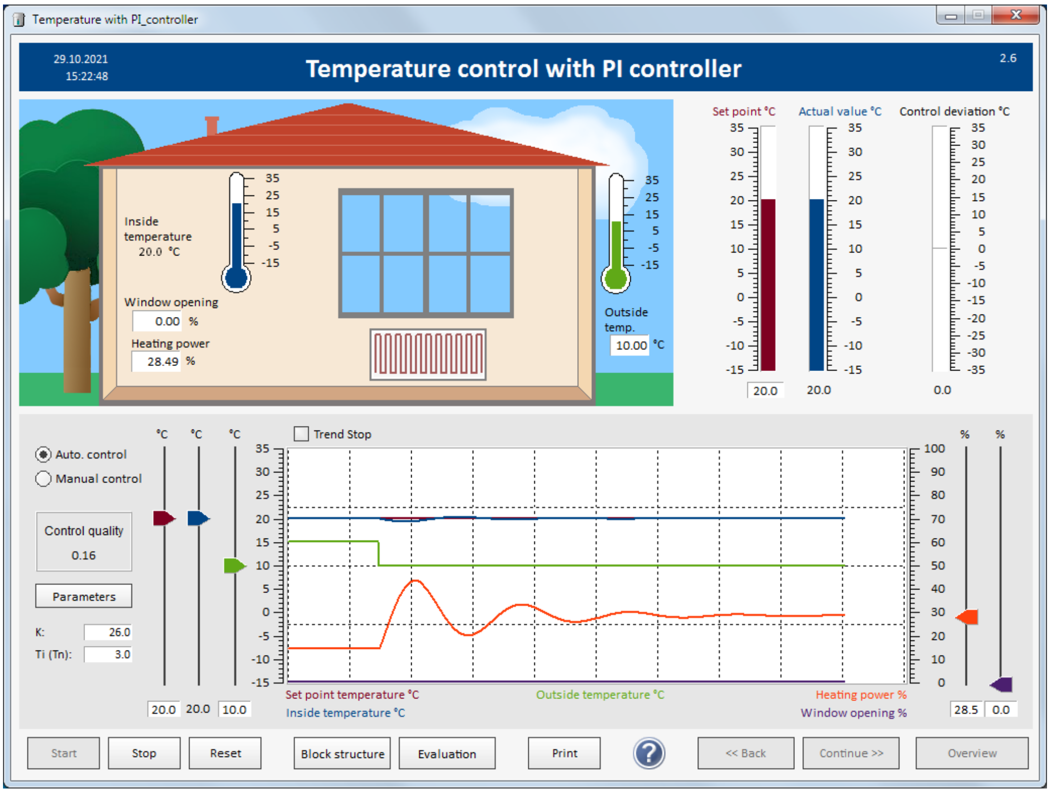


Command response 20% overshoot

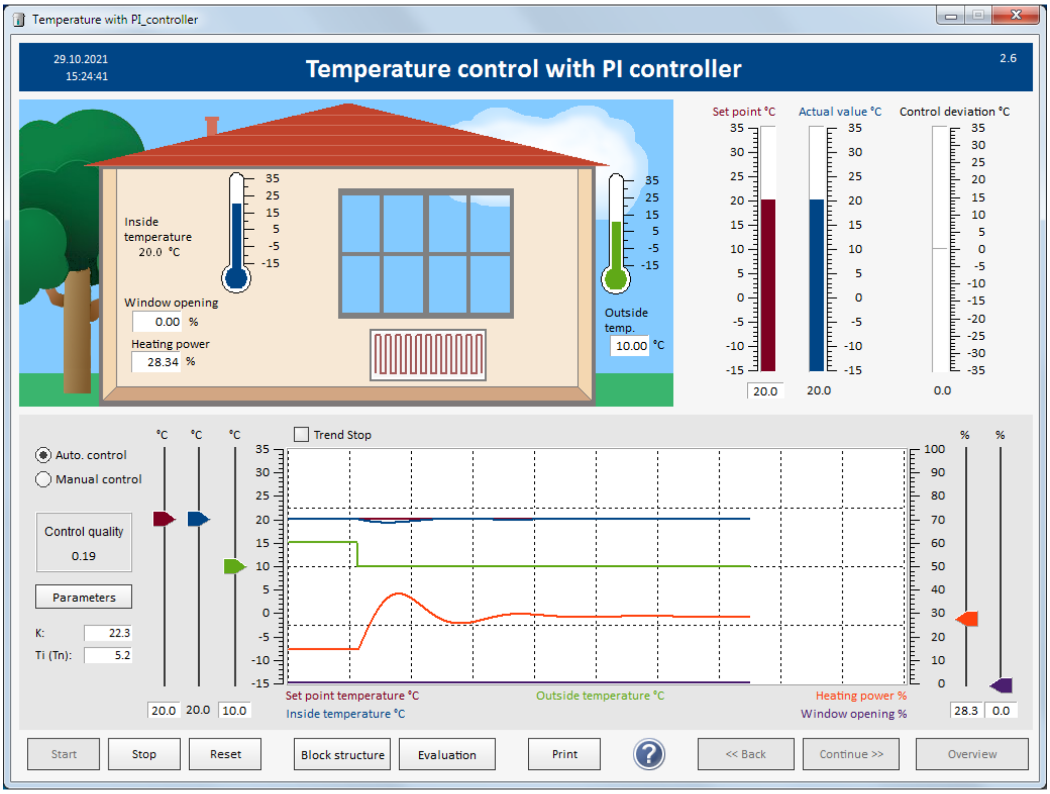


Command response aperiodic

A steady control loop with setpoint 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:



Disturbance response 20% overshoot



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

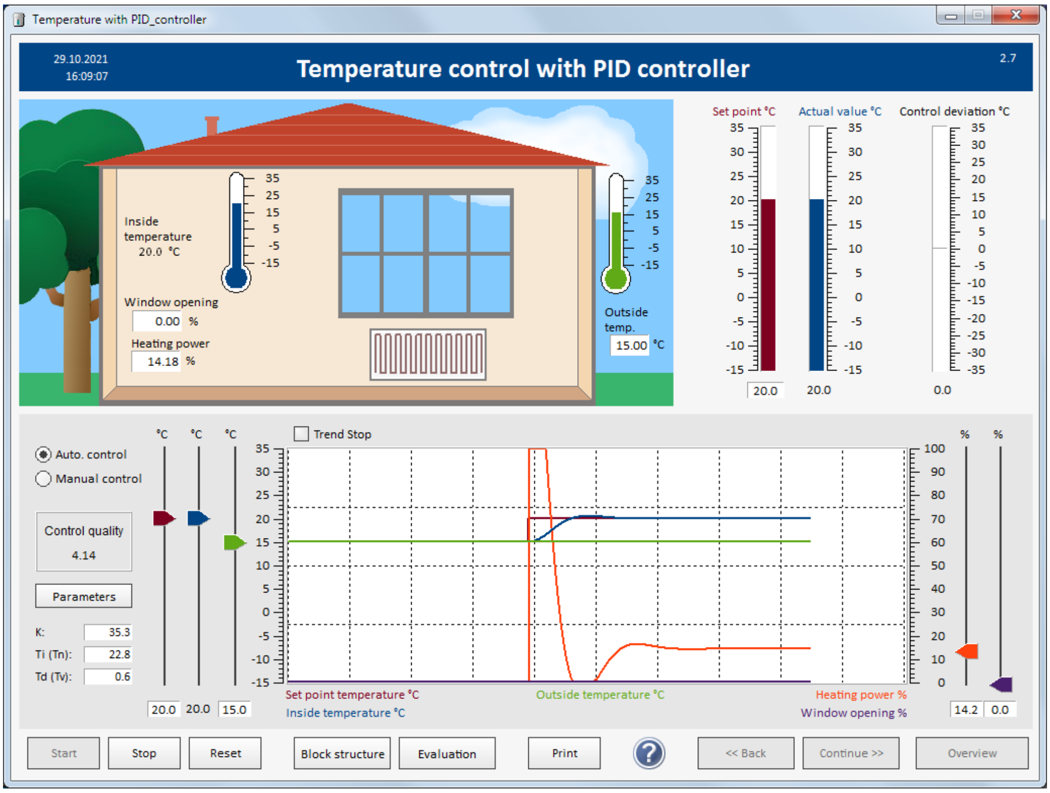
Disturbance response aperiodic

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

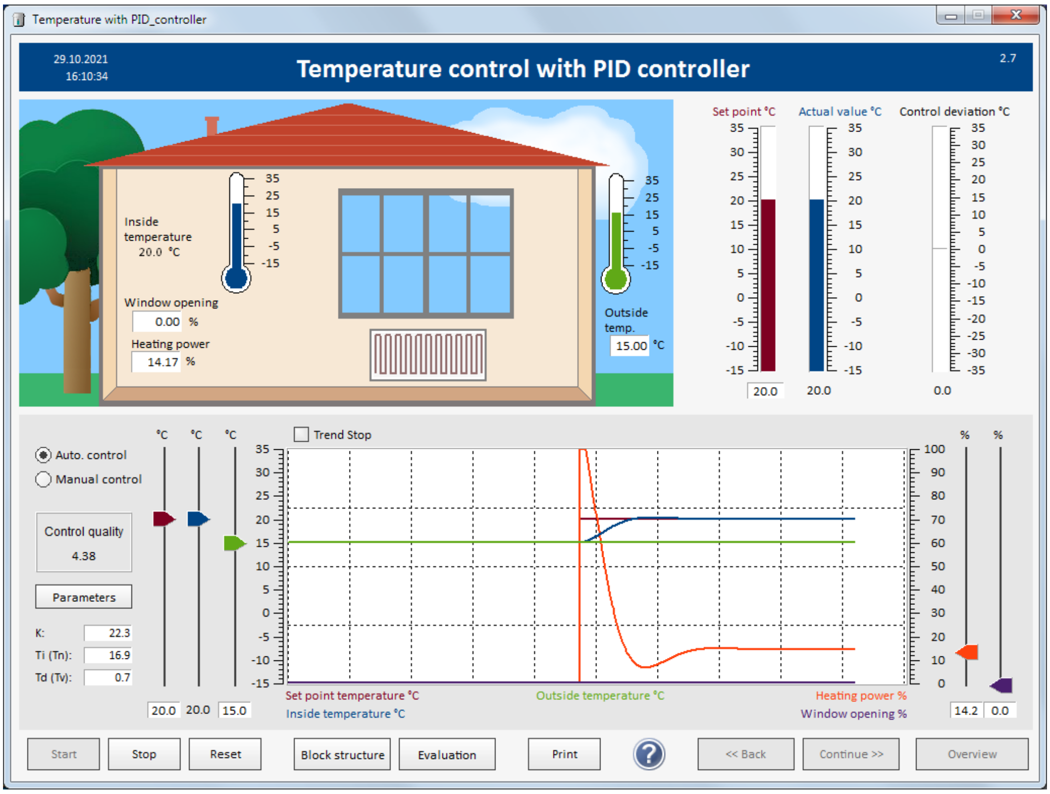
Here, too, the parameters differ significantly depending on the application (disturbance or control behavior).

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.

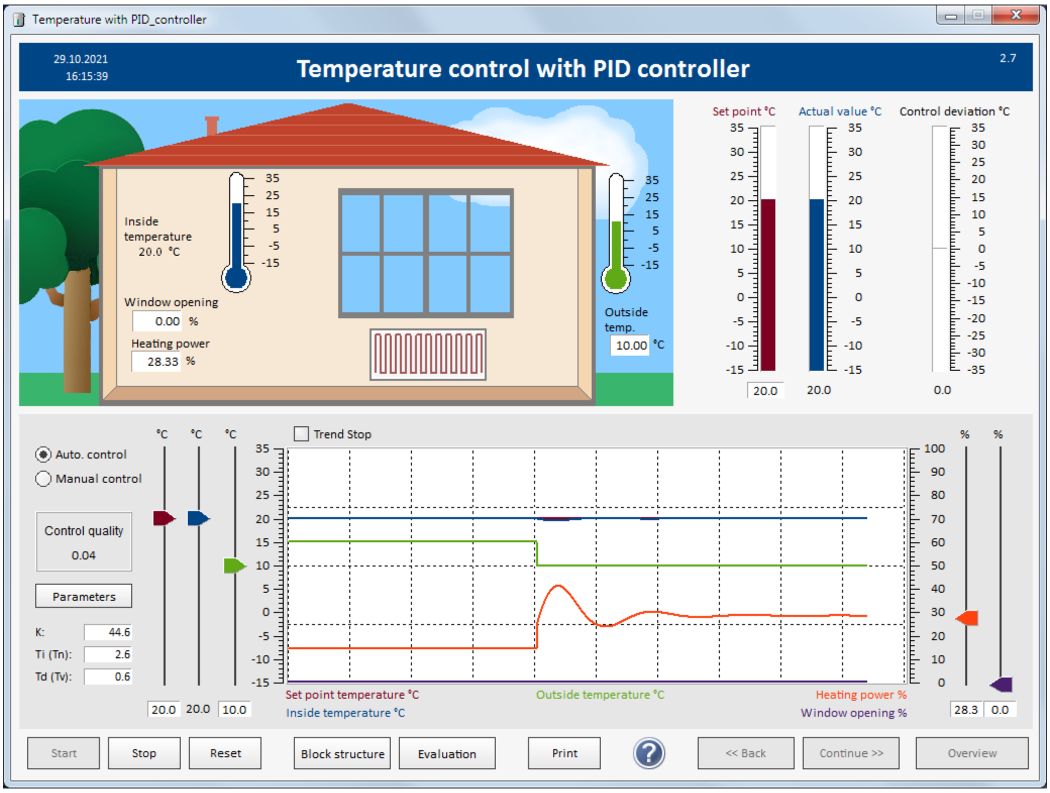


Command response 20% overshoot

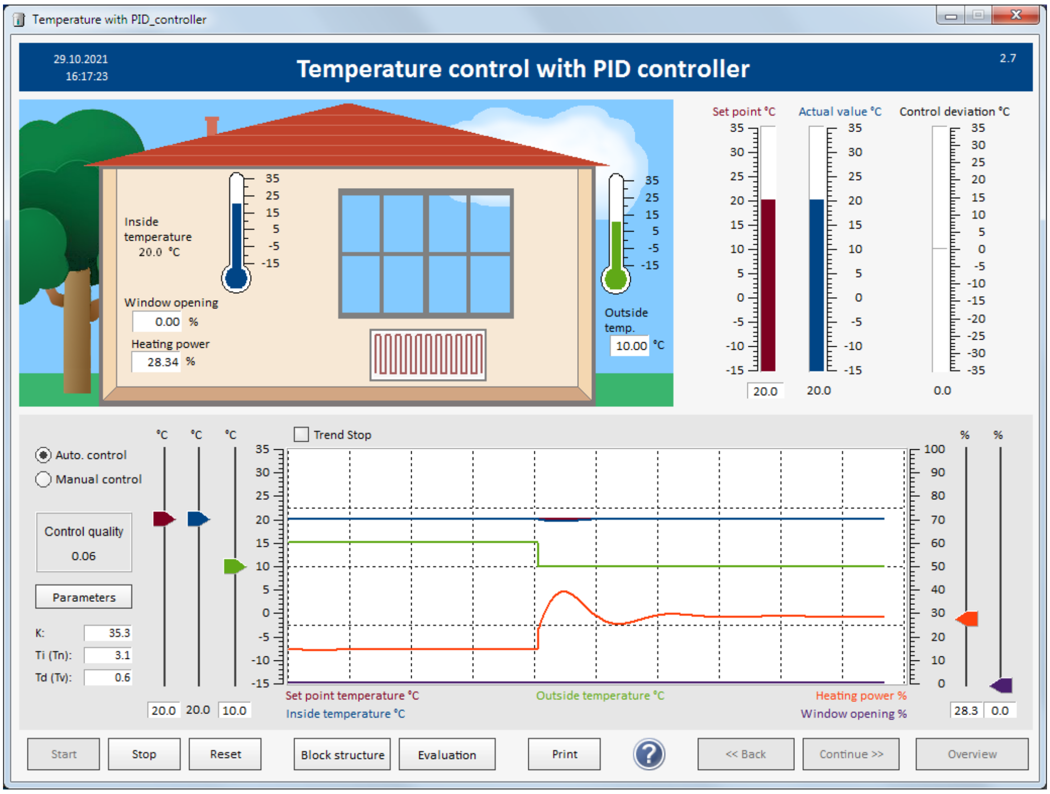


Command response aperiodic

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.



Disturbance response 20% overshoot



Disturbance response aperiodic

3.5 Assessment of the Controller Tuning Rules

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

The settings for the controller parameters differentiate 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 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.

4 Liquid Level Control (Control Training I)

At this control system you can give water into a container via inflow. 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 fill 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.

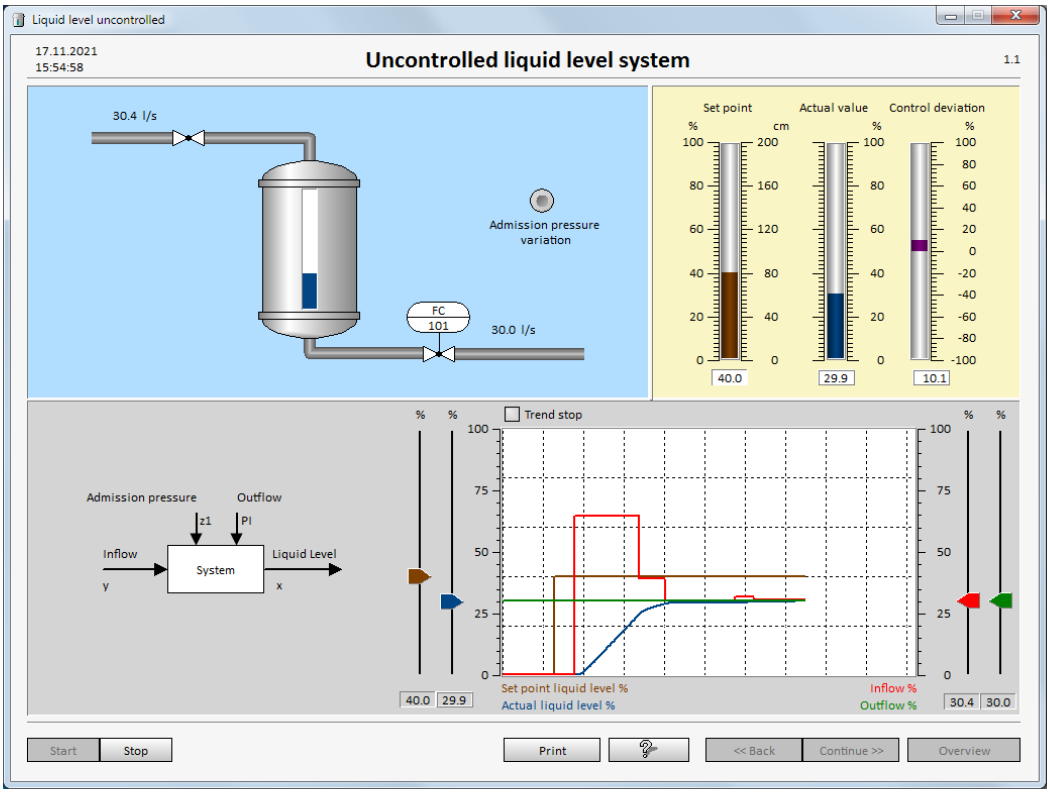
4.1 Uncontrolled System (Manual Control)

In Control Training I, select item 1.1 "Uncontrolled system".

Press “Start”. You can now change the values for the setpoint value (Setpoint 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 setpoint (reference variable) to 40% and try to bring the actual value (controlled variable, actual liquid level) to the setpoint (Setpoint liquid level) by adjusting the control signal (inflow).



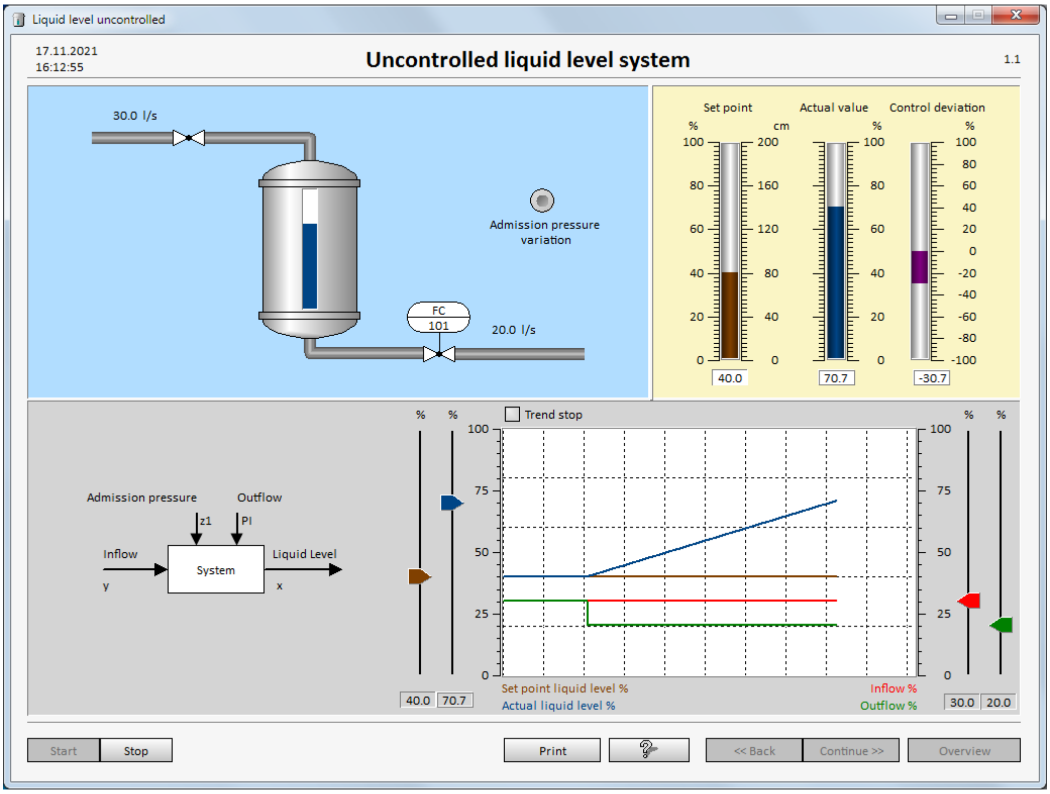
Only when the inflow is the same as the outflow (30l/s) the level remains constant. You must therefore try to set the inflow to 30l/s (30%) when the actual value has reached the setpoint.

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

Task 2.

Change outflow to 20%.

What will happen?

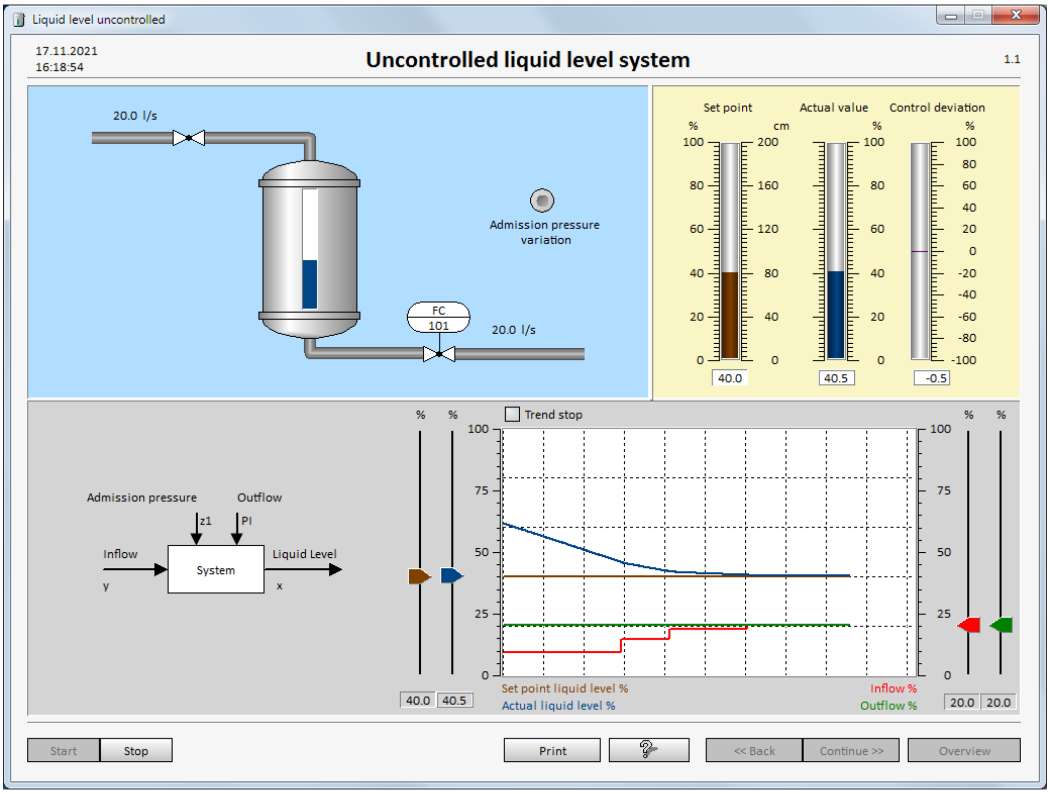


The level begins to rise continuously, as 10l/s (10%) more flows in than out.

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

Task 3.

Try to bring the level back to the setpoint of 40% by adjusting the inflow.



In this case, an attempt is made to react to a disturbance (change of outflow). Here, too, the inflow must become exactly as large as the outflow so that the fill level no longer changes.

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

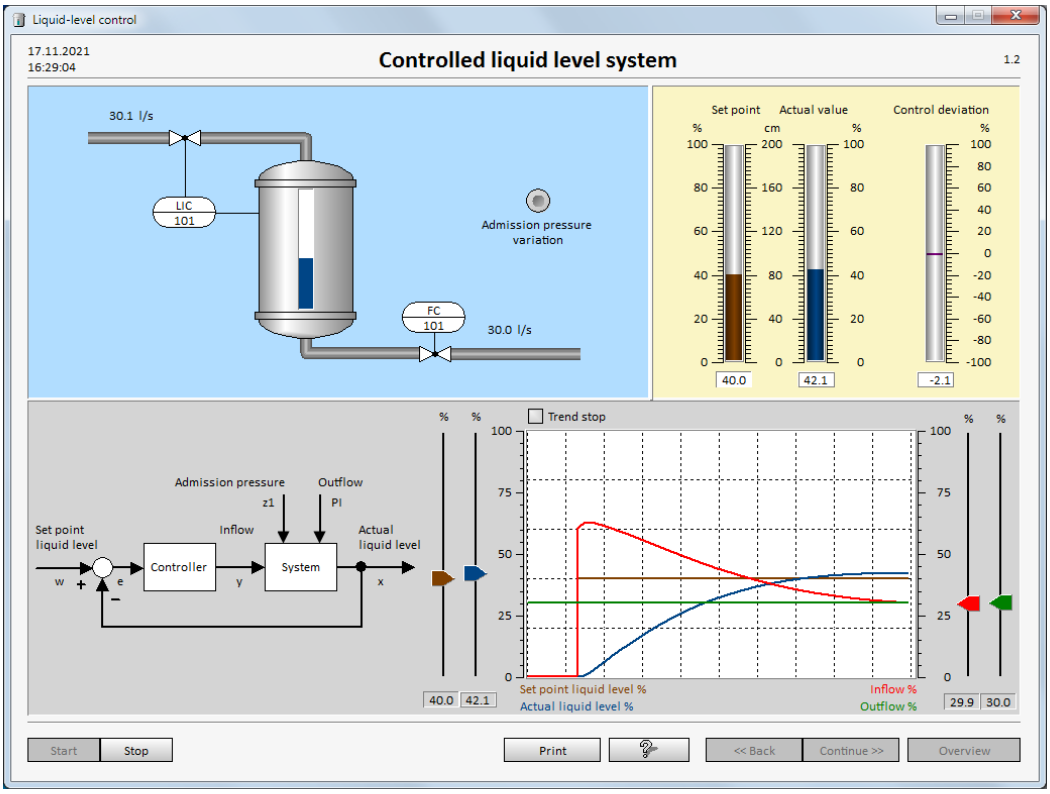
4.2.1 Closed-loop Controlled System

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 bringing the actual value to the setpoint.

Task 4.

Press „Start“ and set the setpoint to 40%.



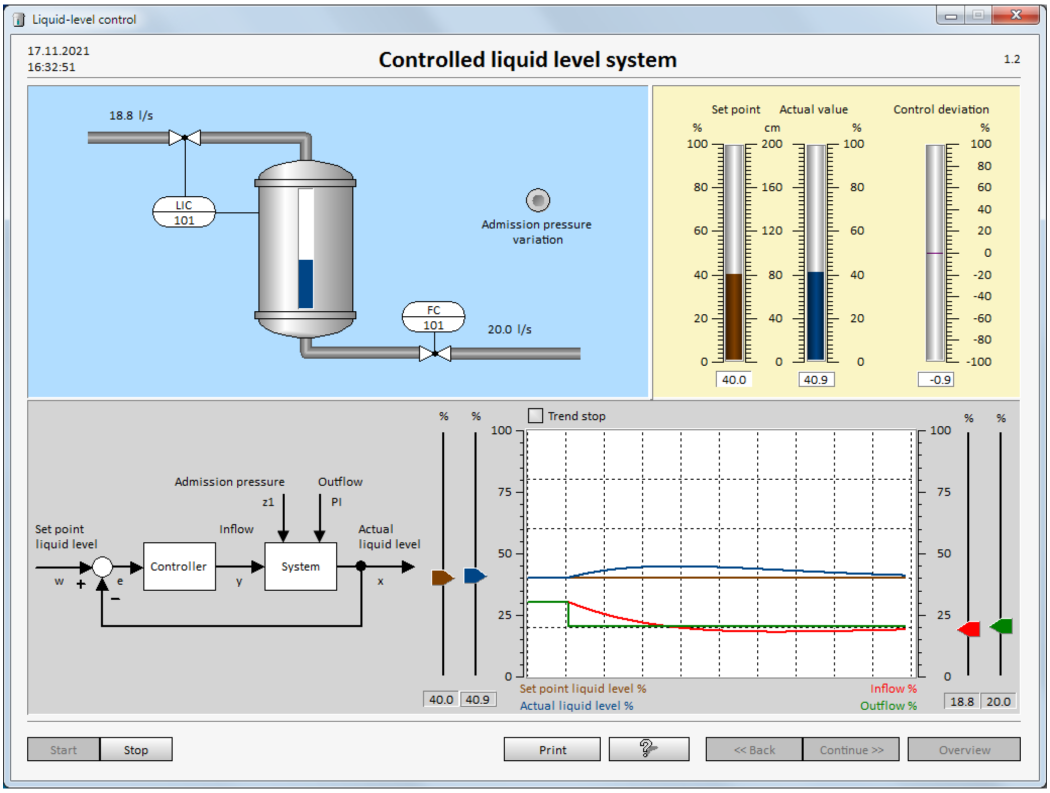
With overshoot, the actual value goes to the setpoint after a certain time.

Even if you specify a disturbance by changing the outflow, the controller tries to bring the actual value back to the setpoint.

Task 5.

Change outflow to 20%.

What will happen?



The level begins to rise.

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

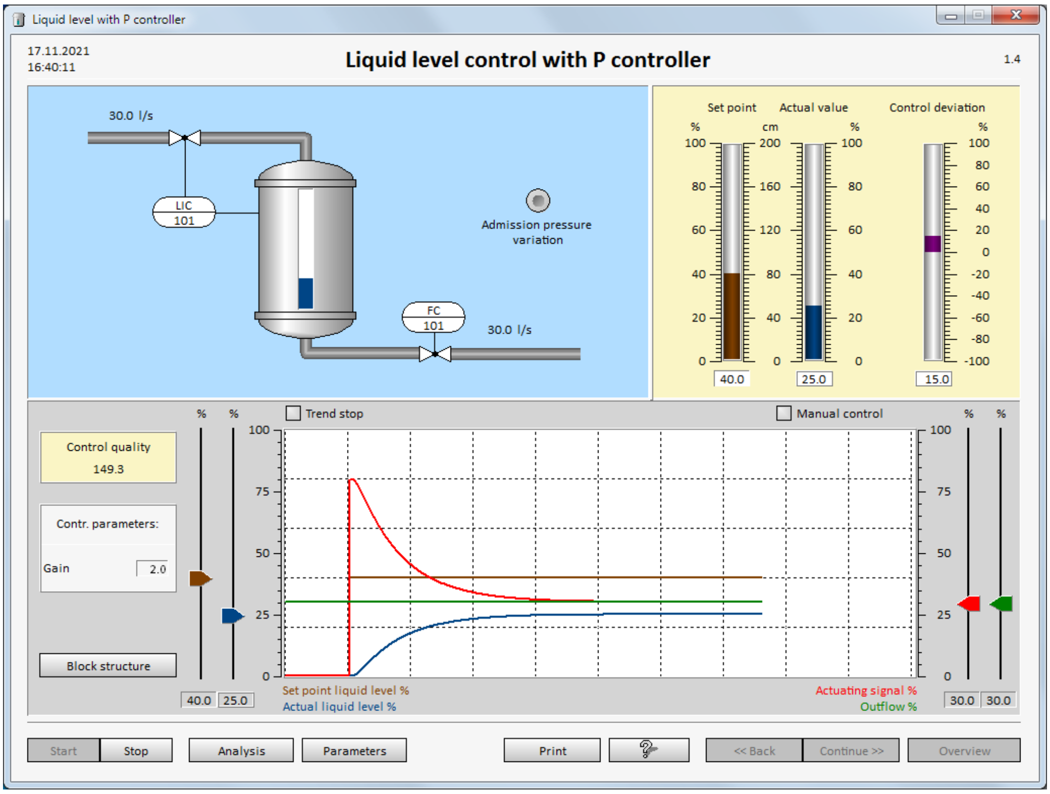
4.2.2 Closed-loop Control with P Controller

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

Press „Start“.

Task 6.

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



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

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

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

Reason:

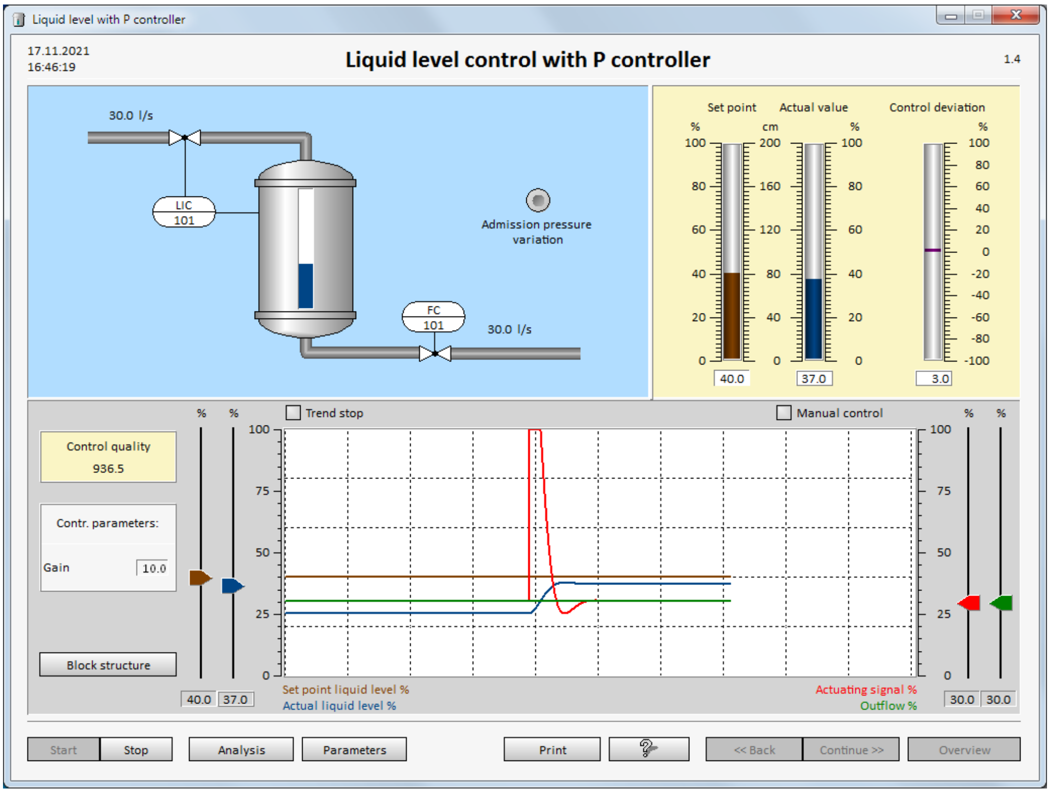
The P controller works like an amplifier. The input signal to the controller w - x (setpoint - actual value) is amplified with the gain K (in our case 2).

In order for the P-controller to output a control signal (an inflow) that is not equal to zero, the setpoint 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 is settled.



The control difference between the setpoint 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 bring the actual value to the setpoint here either. For the reason described above, we also get a albeit significantly smaller, steady state control error (e = w – x).

In our case the setpoint w was set to 40% and the 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. So that the system has settled (the level remains constant), the inflow must be the same as the 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 signal will be calculated to:

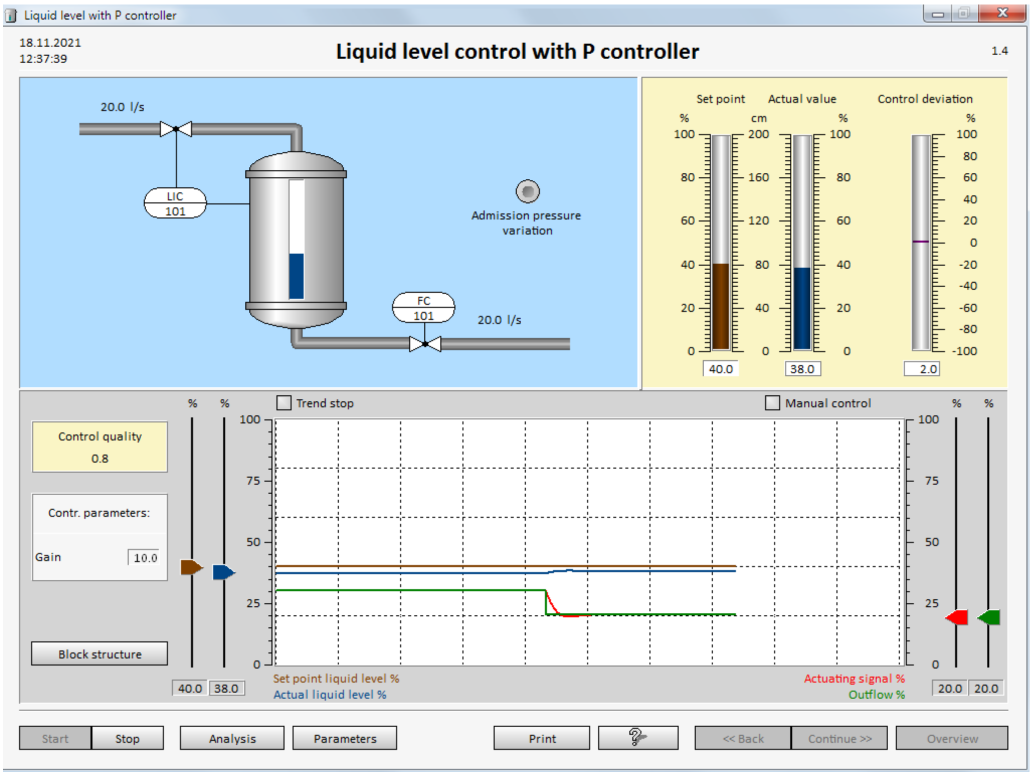
Controlled variable x = 40 – y/2 = 40 – 15 = 25.

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 setpoint 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

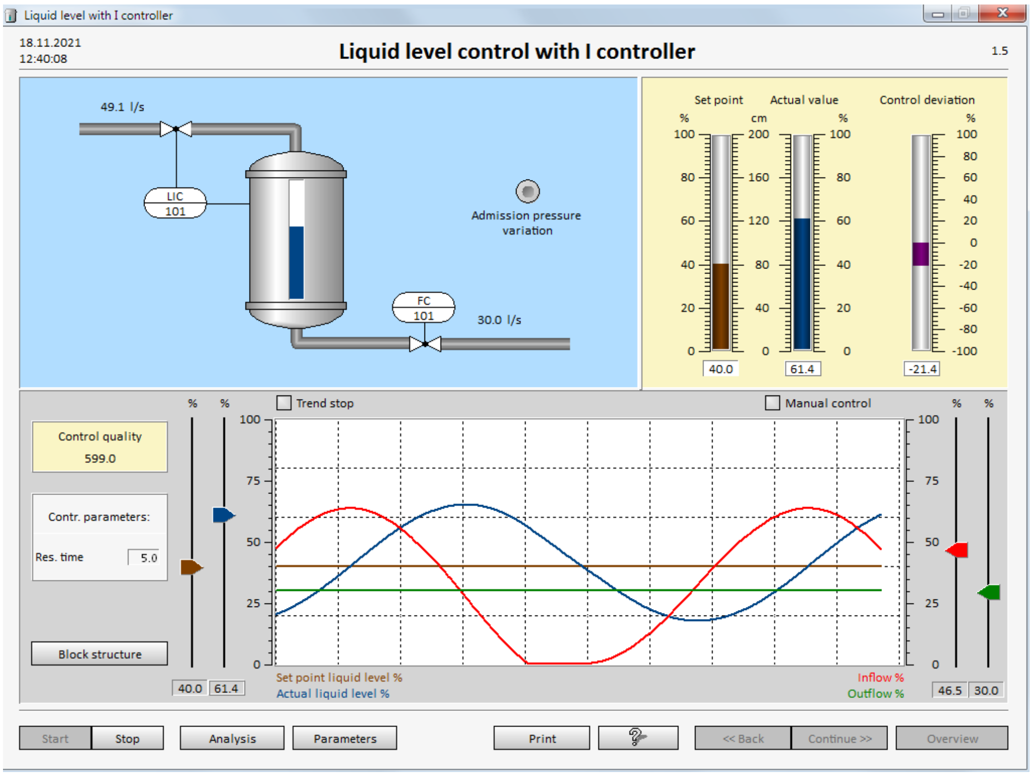
Go to „Overview“ and select item 1.5 „Closed-loop control with I controller“.

Press „Start“.

Task 9.

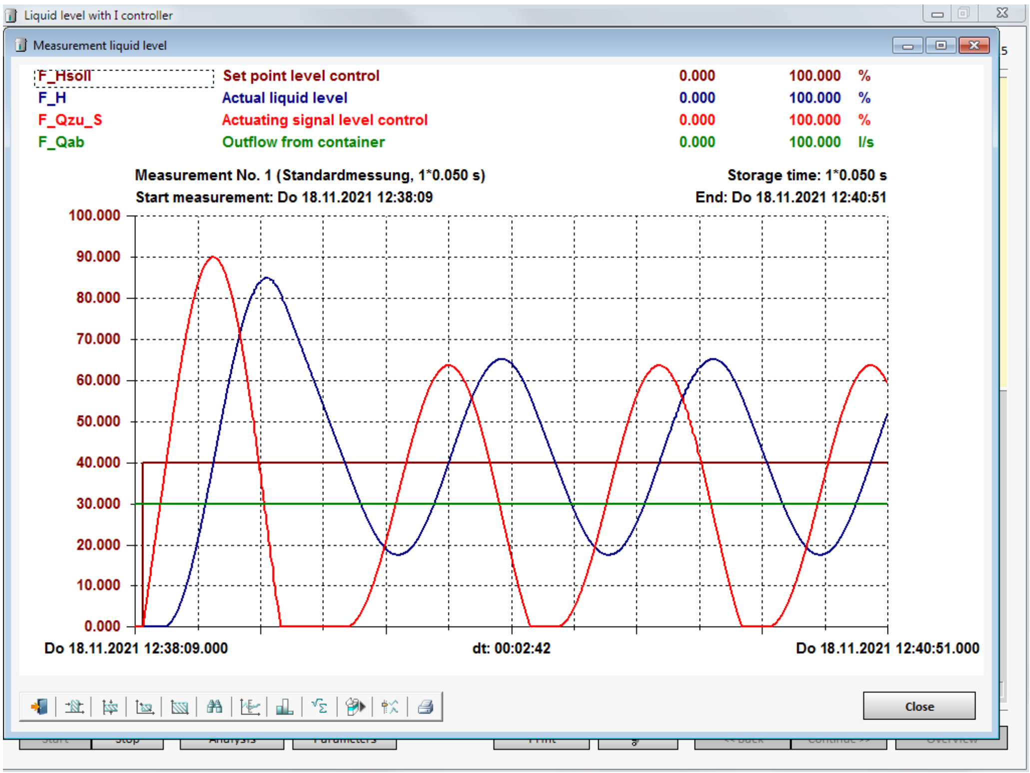
Change setpoint to 40%.

What will happen?



The control loop system begins to carry out a continuous oscillation. The actual value oscillates around the setpoint.

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 the 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“.

Press „Start“.

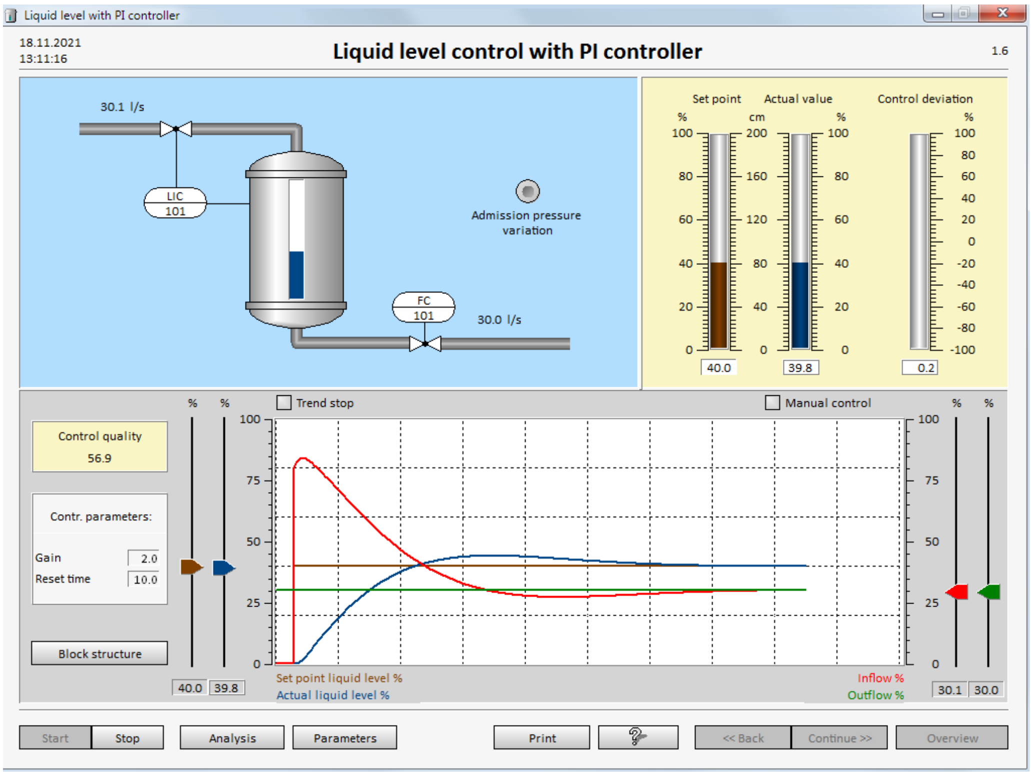
Task 10.

Keep the set parameters:

Gain K = 2, Reset time Ti = 10.

Change the setpoint to 40%.

Observe the settling behavior.



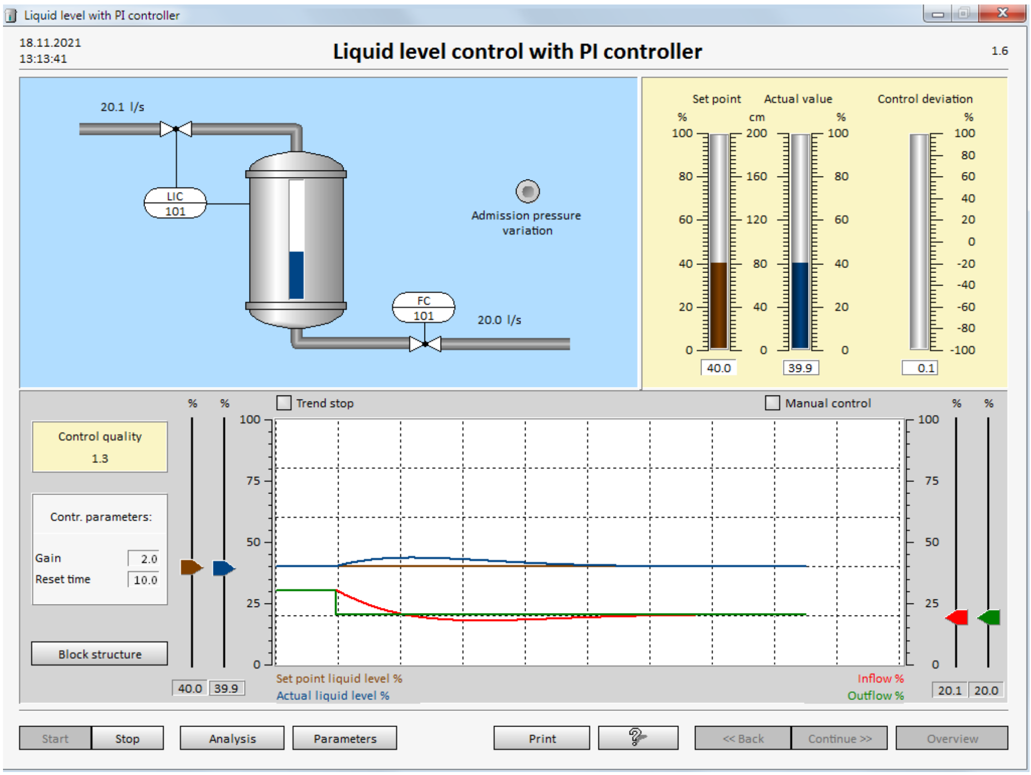
The control loop with the PI controller and the set parameters swings to the setpoint with a small overshoot. The actual value (controlled variable) reaches the setpoint (reference variable).

The settling of the control loop by changing the setpoint 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 setpoint again.

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

Task 12.

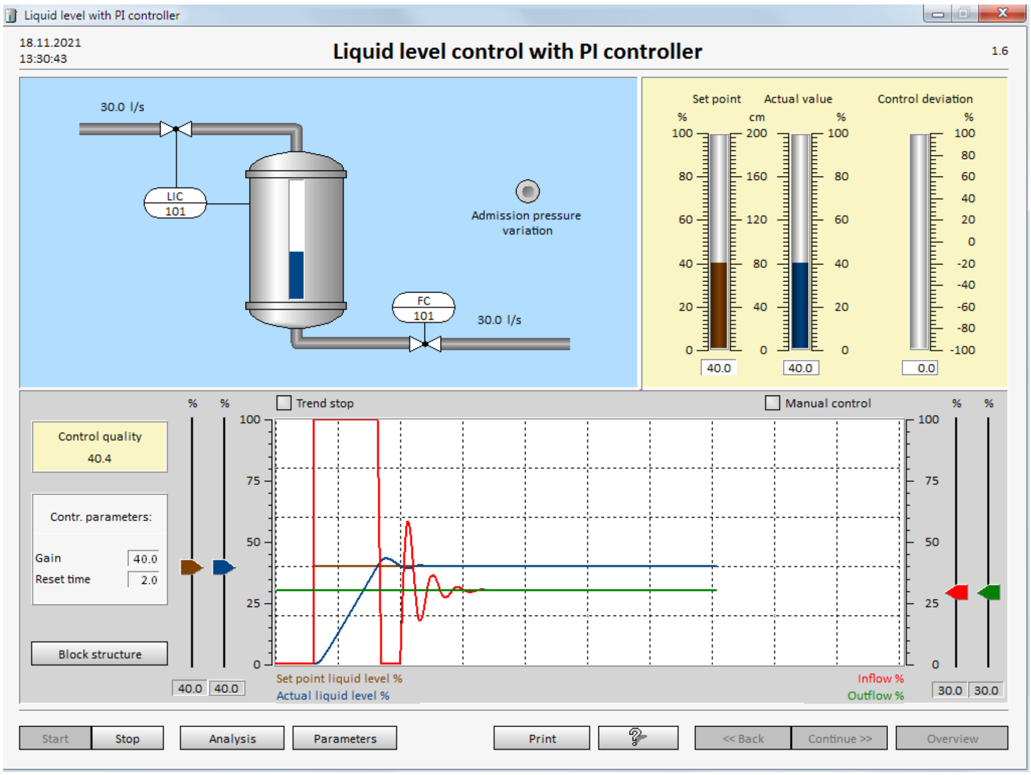
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the setpoint.

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.

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 press "Stop" and then “Start”. This means that the setpoint, the level and the outflow are again given the initial values.

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

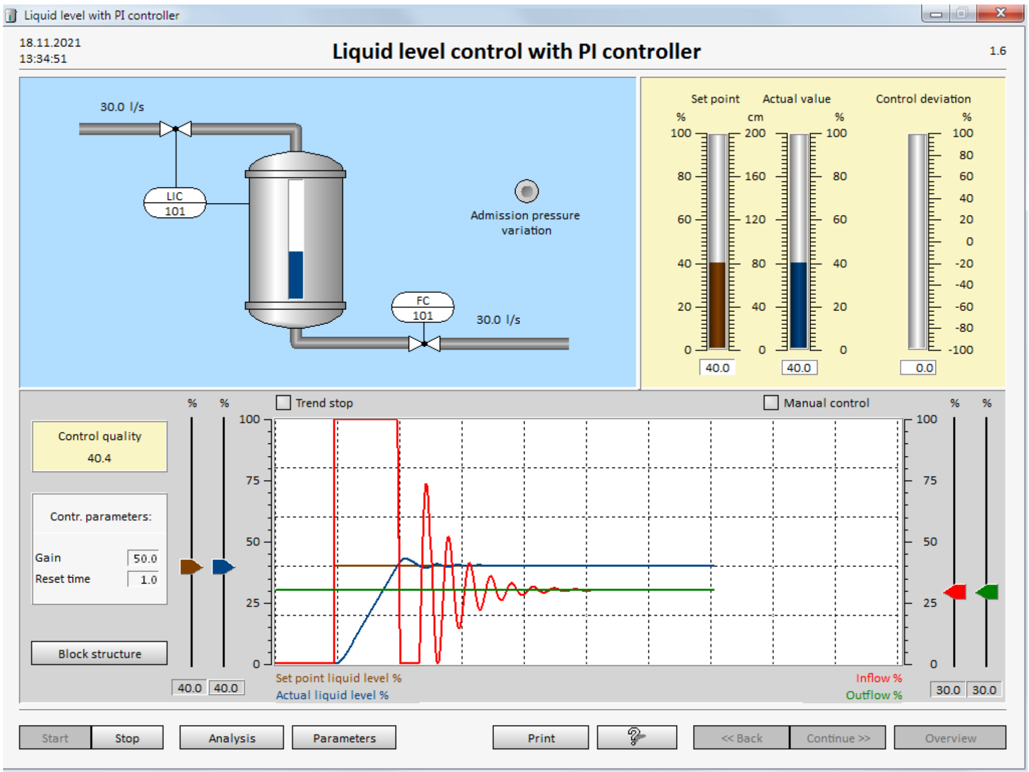


With the parameters K = 40 und Ti = 2 a control quality of 40,4 was obtained.

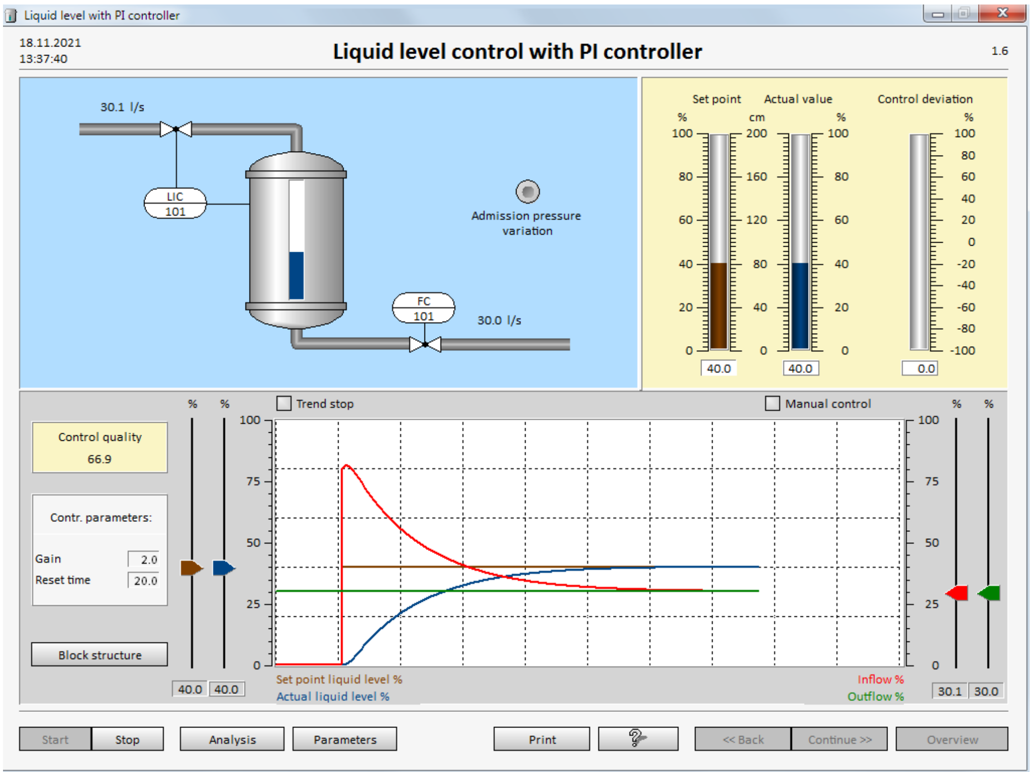
Carry out the experiments with further controller parameters:

- Press „Stop“ and „Start“ again,
- Set controller parameters,
- Set the setpoint 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 Punkt 1.7 „Closed-loop control with PID-controller“.

Press „Start“.

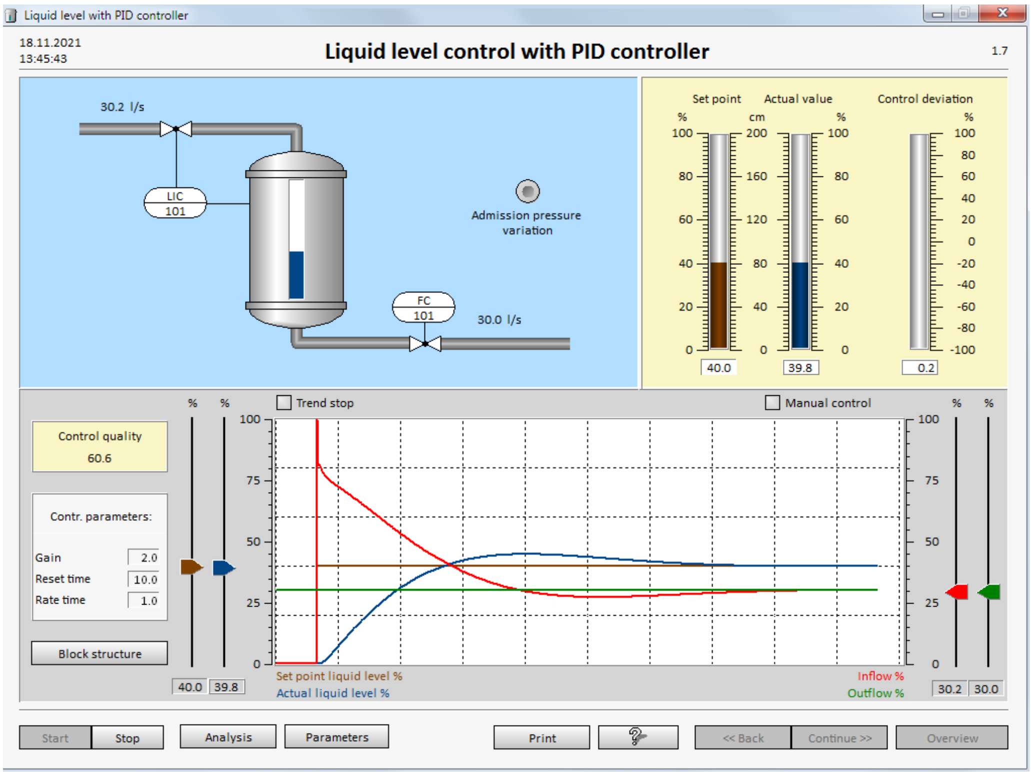
Task 13.

Examine the command response with the preset parameters.

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

Change setpoint to 40%.

Observe the behavior.



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

As can be seen in the trend diagram, the sudden change in the setpoint causes a peak in the control signal (heating output). 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:

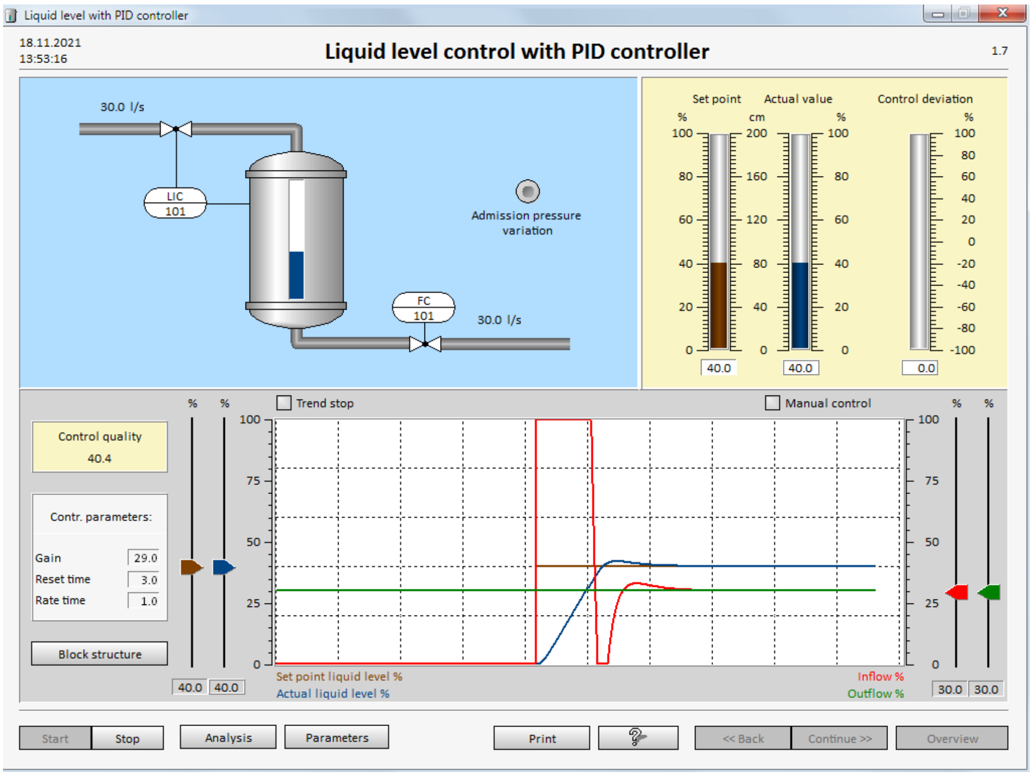
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Analysis" (display of the stored signal values) and selection of a corresponding time range.

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:

- Press “Stop” and “Start” again
- Change the controller parameters
- Adjust the setpoint 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

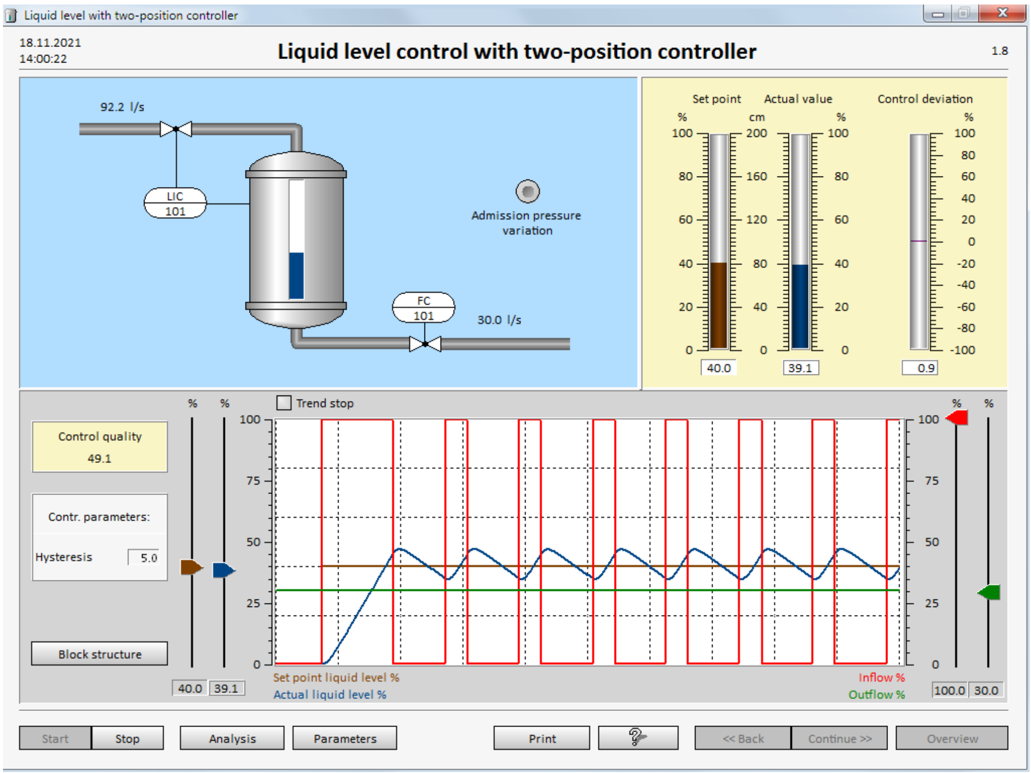
Go to „Overview“ and select item 1.8 „Closed-loop control with two-pos. controller“.

Press „Start“.

Task 15.

Investigate the command response with the preset parameter:

Hysteresis = 5



The level (actual value) oscillates around the setpoint. The size 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.

Note:

In practice, the PI controller is mainly used as a controller. If a PID controller is used, the D component is often turned away 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 setpoint and the actual value. If the change increases, i.e. the difference between the setpoint and actual value increases, the D component adds a calculated value to the control signal. If the change between the setpoint and actual value becomes smaller, i.e. the difference between setpoint and actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend as to whether the difference between the setpoint and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the setpoint and actual value gets smaller, the control signal is reduced.

4.3 Examine Controlled System

Select item 1.3 „Examine controlled system“.

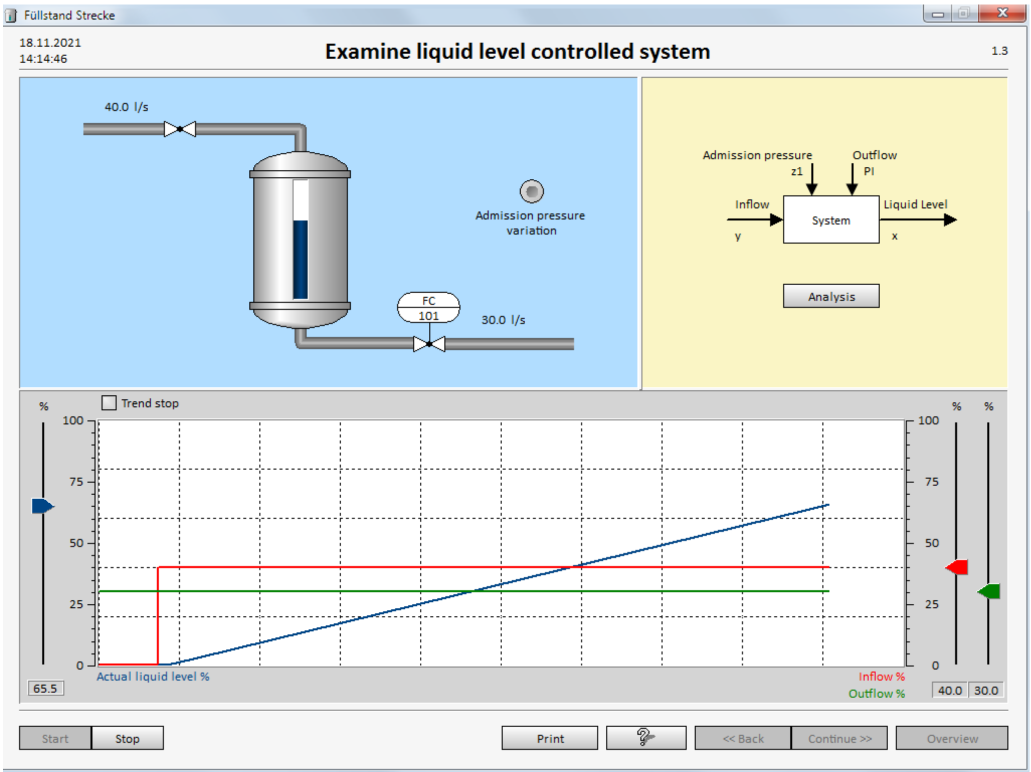
The level system is a controlled system without self-regulation. In the event of a sudden change in the control signal (inflow> outflow), the controlled variable (actual level) begins to increase. The output variable of the system (controlled variable) does not assume a permanent final state.

Aufgabe 1:

Press „Start“ and set inflow to 40%.

The inflow must be selected 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 unit jump is given to the input signal of the controlled system (control signal). The behavior of the output signal of the system (controlled variable) can then be measured.

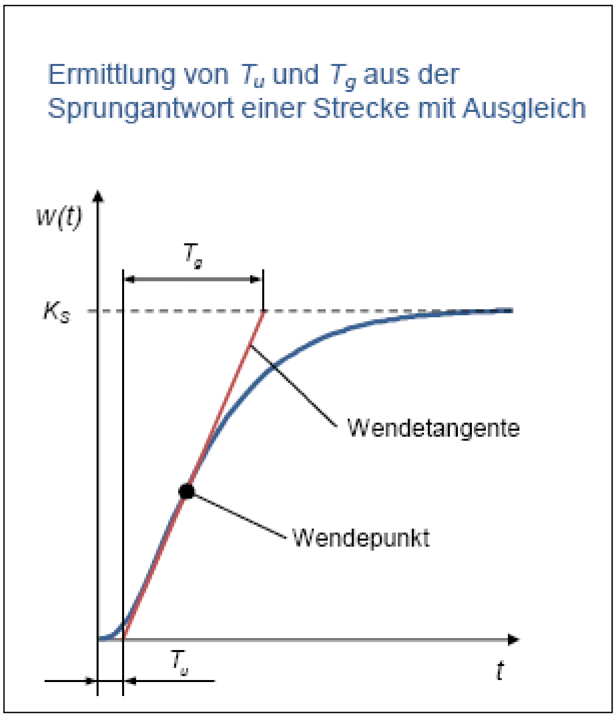
The parameters Tu, Tg and Ks are determined for the controller tuning rules for the controlled systems with self-regulation, as shown in the figure below.

It means:

Te = Tu = Delay time

Tb = Tg = Compensation time

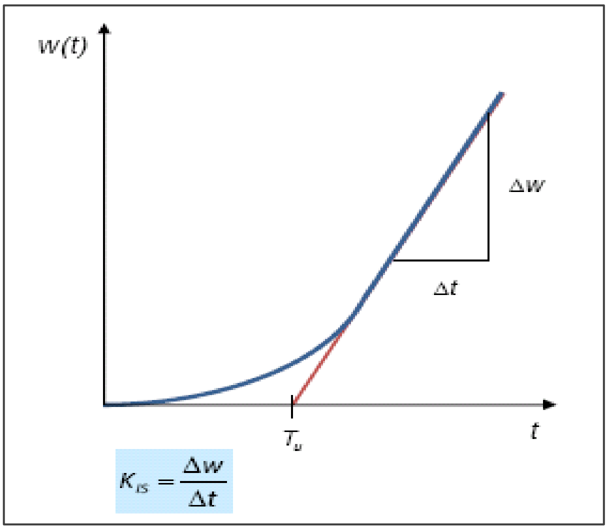
Ks = Gain



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 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 timet
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:

Regler-verhalten	Gütekriterium			
	Überschwingung nach Gegenseite mit 20% von x_m, kürzeste Schwindungsdauer		aperiodischer Regelvorgang mit kürzester Dauer	
	Störung	Führung	Störung	Führung
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	$K_P \approx \frac{1{,}2}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2 \cdot Tu$ $T_v \approx 0{,}42 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1{,}35 \cdot T_g$ $T_v \approx 0{,}47 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2{,}4 \cdot T_u$ $T_v \approx 0{,}42\, T_u$	$K_P \approx \frac{0{,}6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$ $T_v \approx 0{,}5 \cdot T_u$

Für Regelstrecken *ohne Ausgleich* ist statt $\frac{T_g}{K_S \cdot T_u}$ der Ausdruck $\frac{1}{K_{IS} \cdot T_u}$ einzusetzen.

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 controlled systems without self-regulation you have to use the expression 1/(Kis*Tu) in the table instead of the expression Tg/(Ks*Tu) and replace the time constant Tg with Ti = 1/Kis.

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 jump of 1%, a jump of 10% is used here.

In the case of the liquid level system, the jump 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.

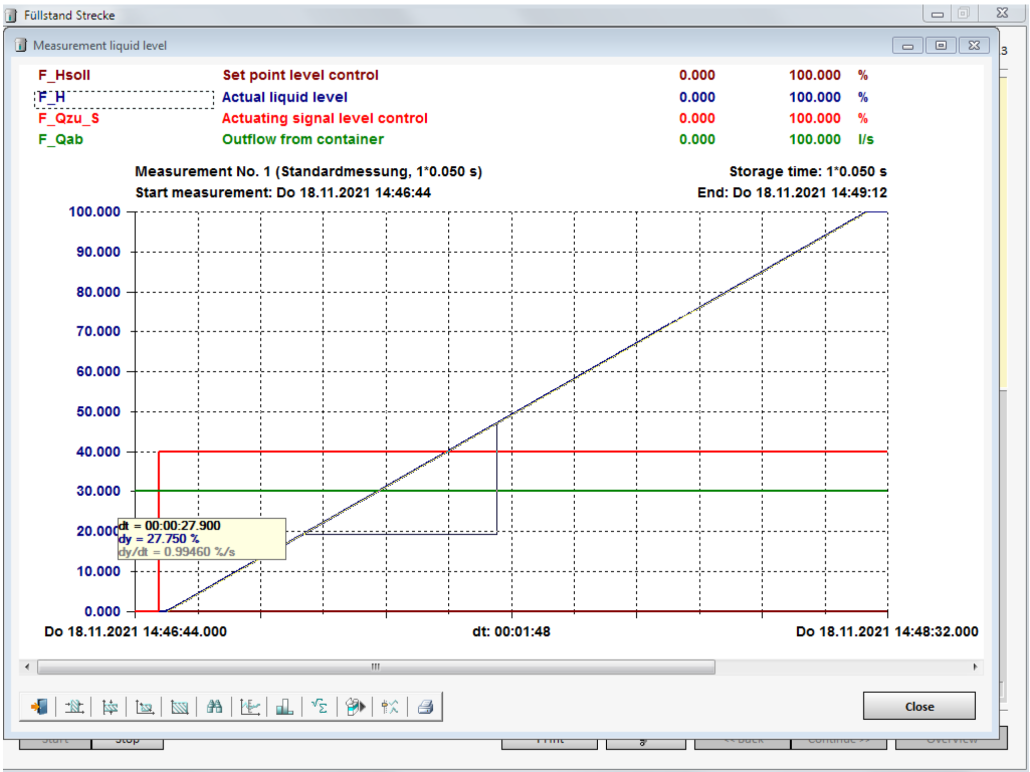
Select item 1.3 „Examine controlled system“.

Task 16.

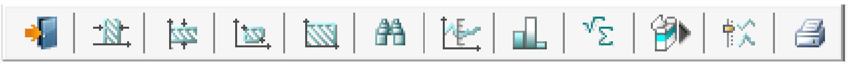
Press „Start“ and set inflow to 40%.

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

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



With the help of the button bar in the windows, time and value segments can be selected.



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

The gradient of the straight line is approximately 1%/s. Since the jump difference was 10% (40% - 30%), Kis as the gradient of the tangent on a unit jump 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

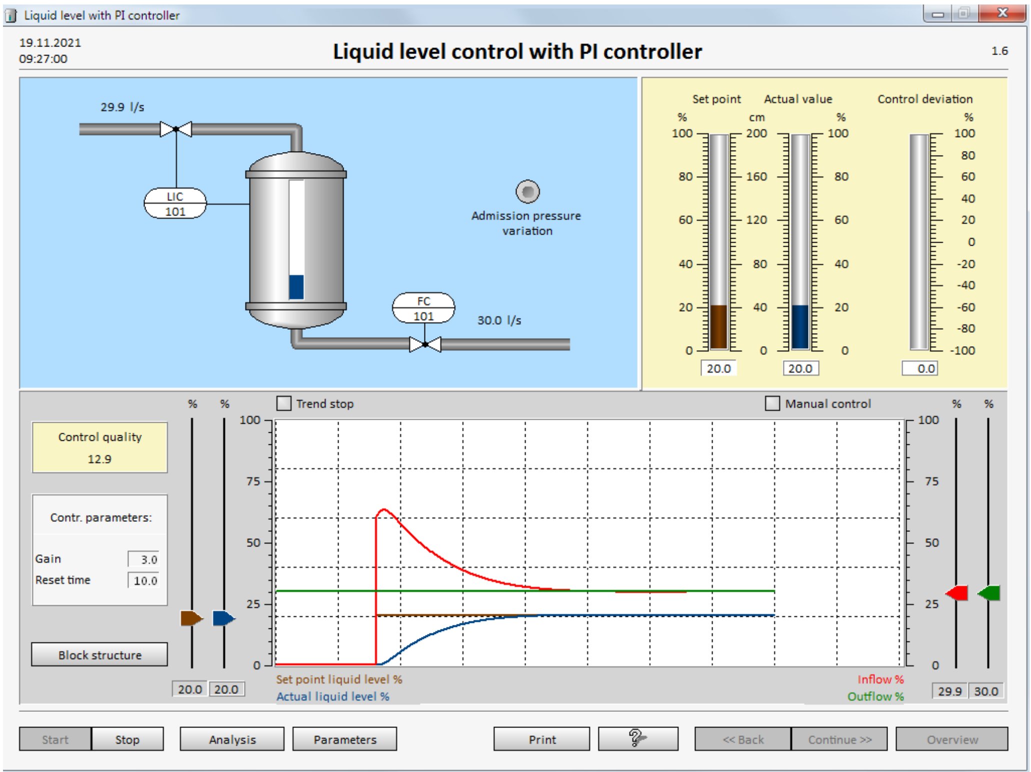
Disturbance response with 20% overschoot

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

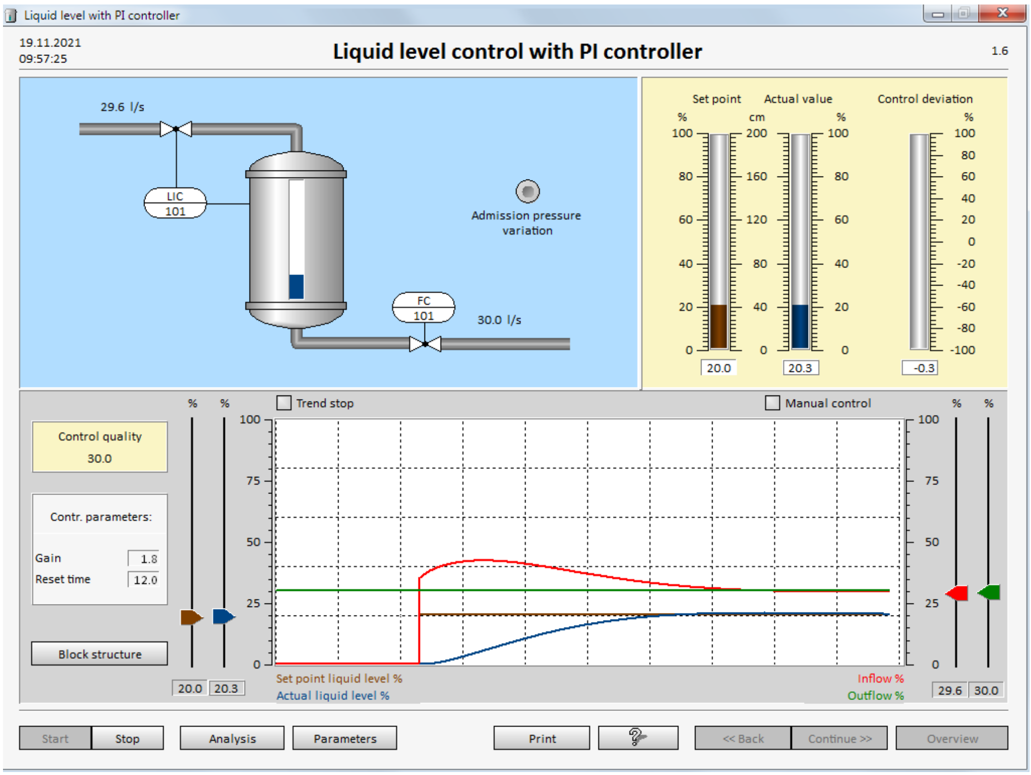
Disturbance response aperiodic

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

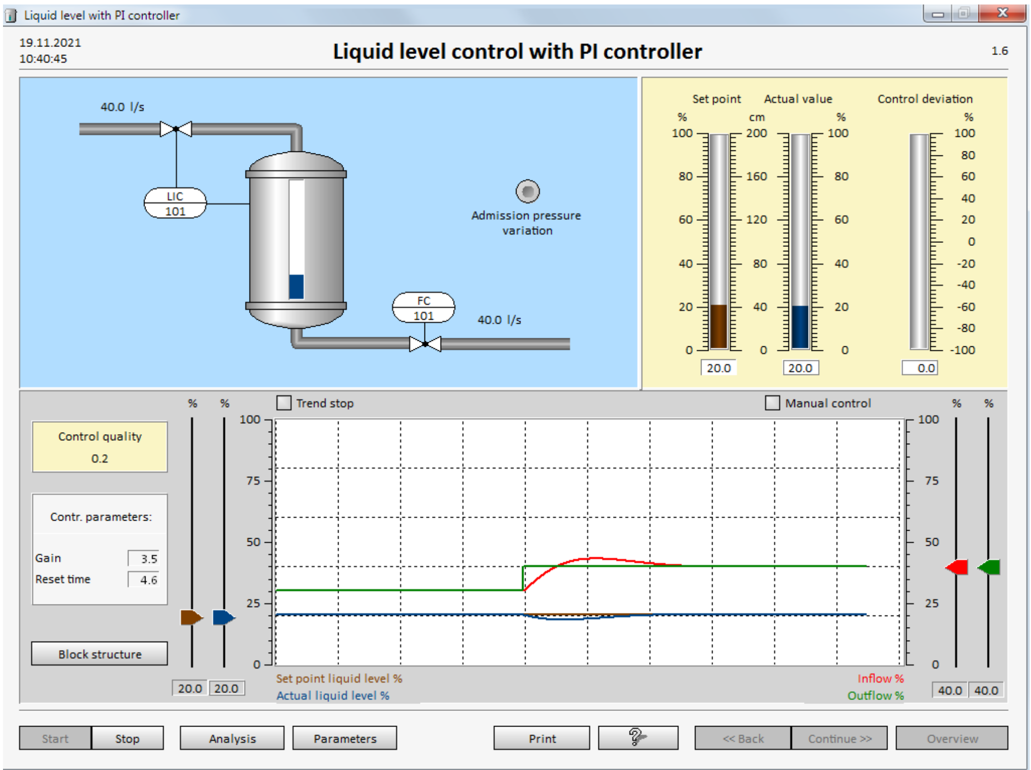
Since with a jump in the setpoint from 0% to 40% the control signal goes into the upper limit and thus falsifies the settling, only a jump from 0% to 20% is specified.



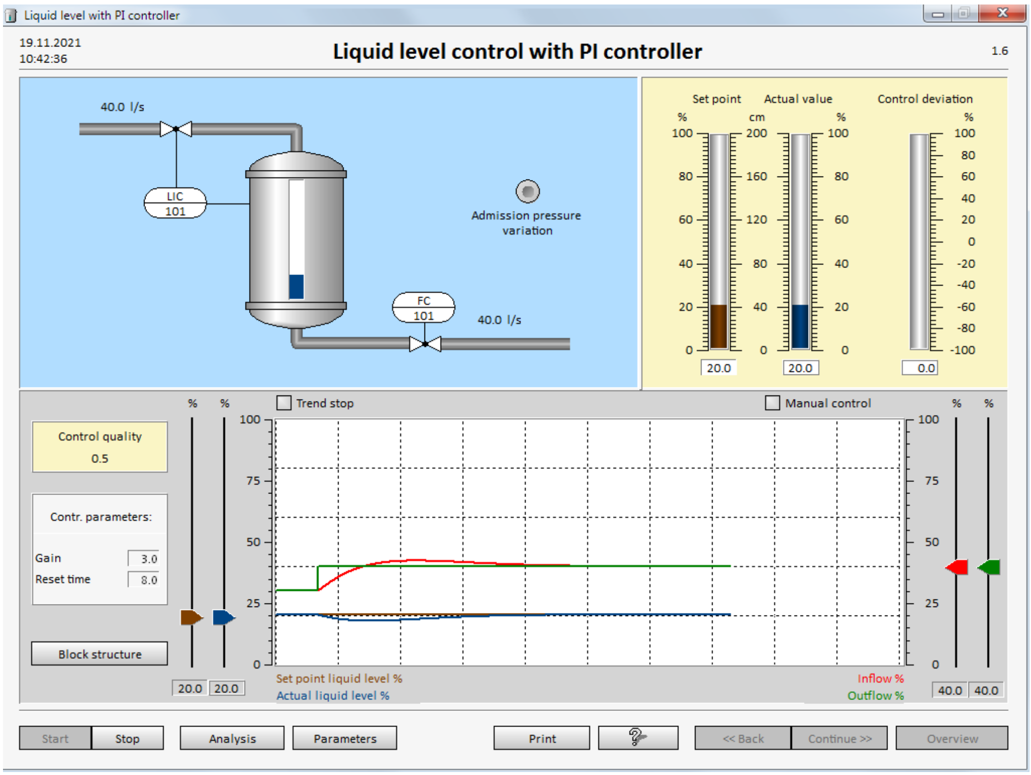
Command response 20% overshoot



Command response aperiodic



Disturbance response with 20% overshoot



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

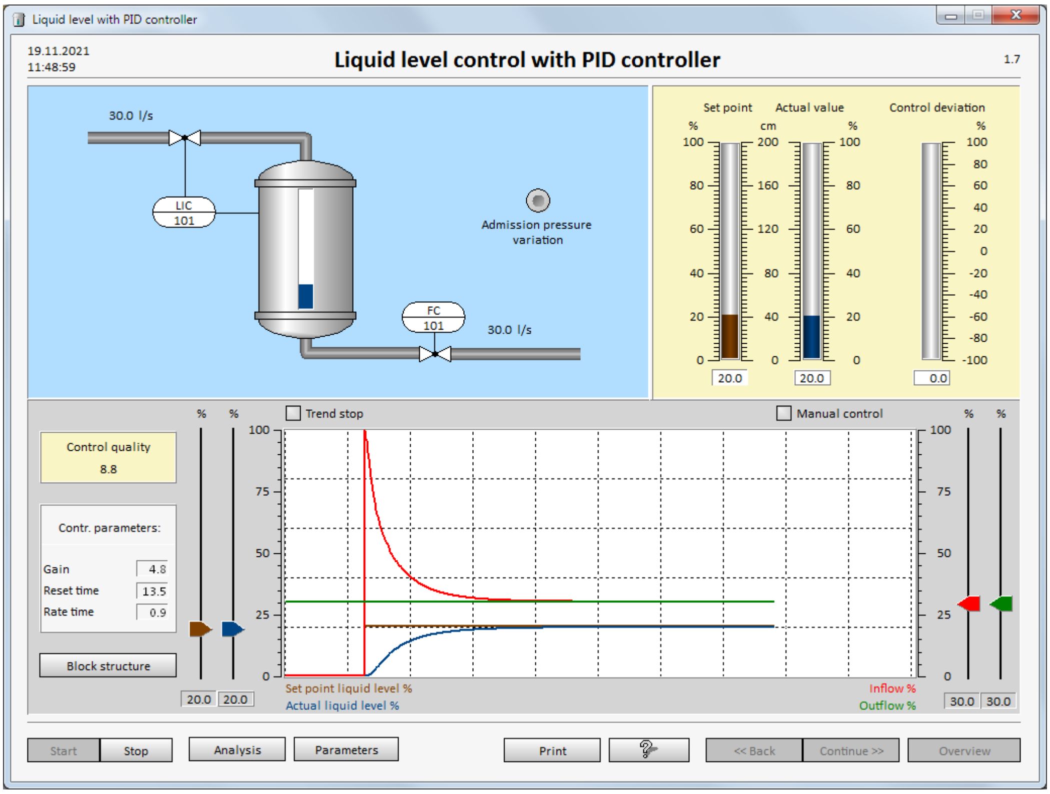
Disturbance response with 20% overshoot

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

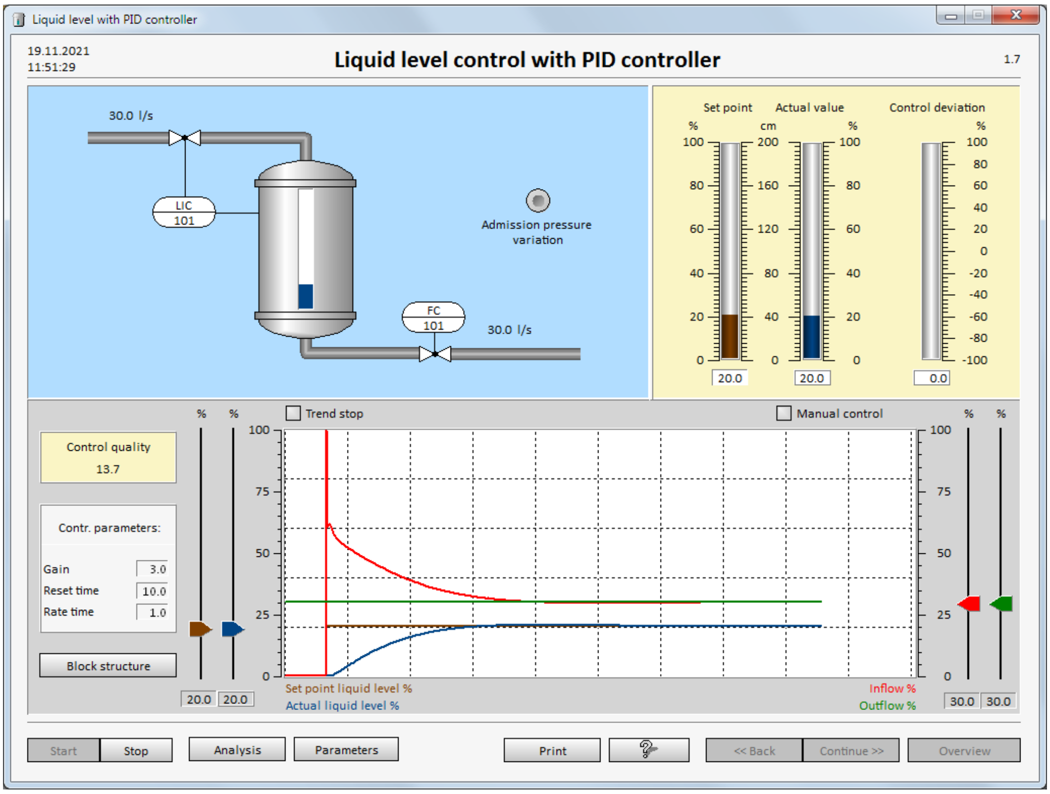
Disturbance response aperiodic

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%:

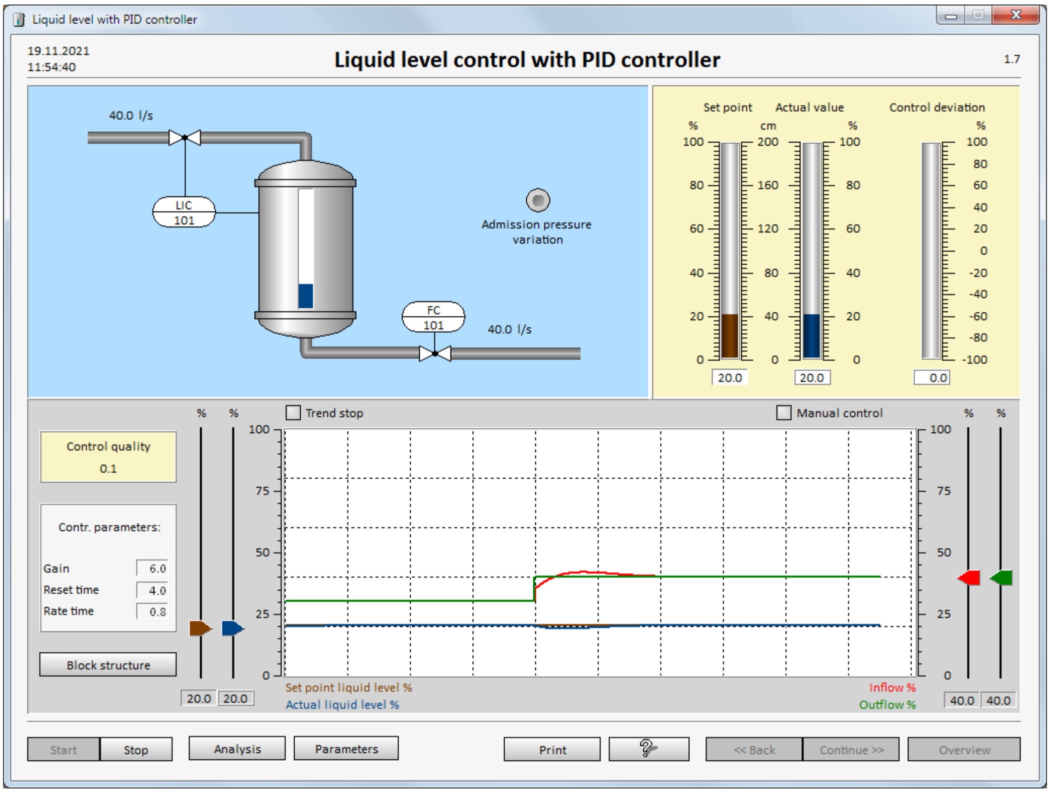


Command response with 20% overshoot

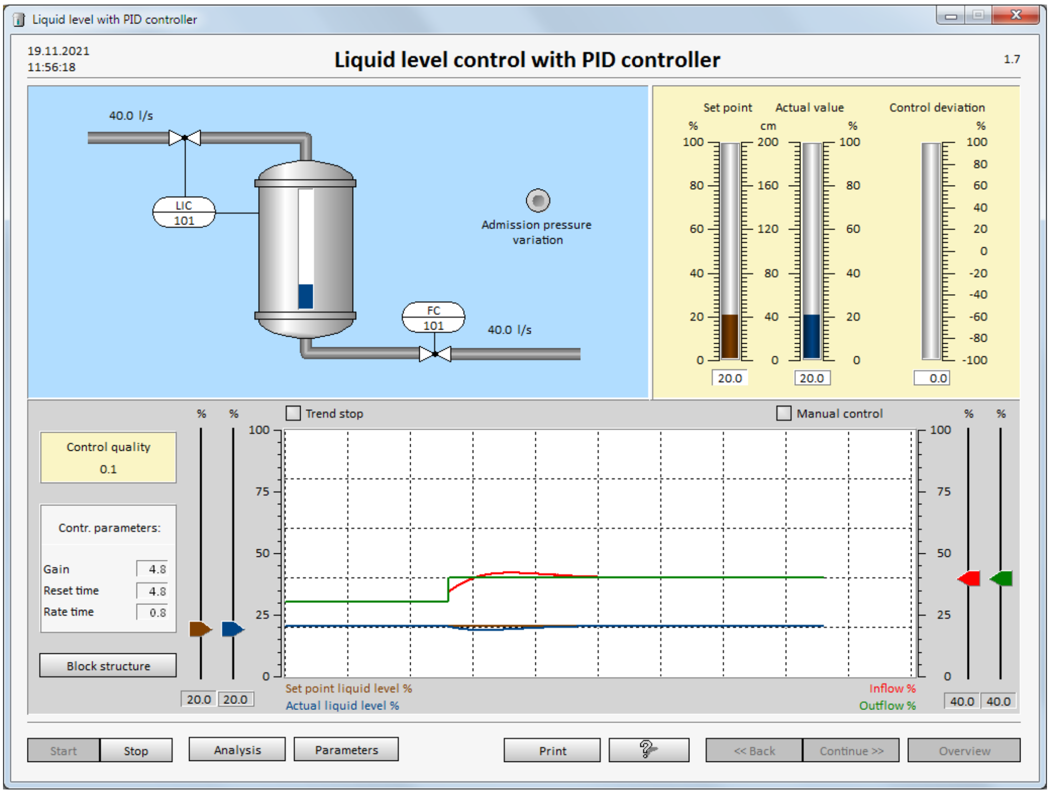


Command response aperiodic

Disturbance response from 30% to 40%:



Disturbance response woth 20% response



Disturbance response aperiodic

4.5 Assessment of the Controller Tuning Rules

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

The settings for the controller parameters differentiate between disturbance and command behavior. Different controller parameters are calculated.

If you want to cover both cases (disturbance and control behavior) with your controller parameters, 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 settling 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 pipe with a valve through which water flows at a set pipeline pressure. The technical control task is to control the flow through the pipeline by changing the valve position so that the actual flow corresponds reaches the specified setpoint. The 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 system of the flow control 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)

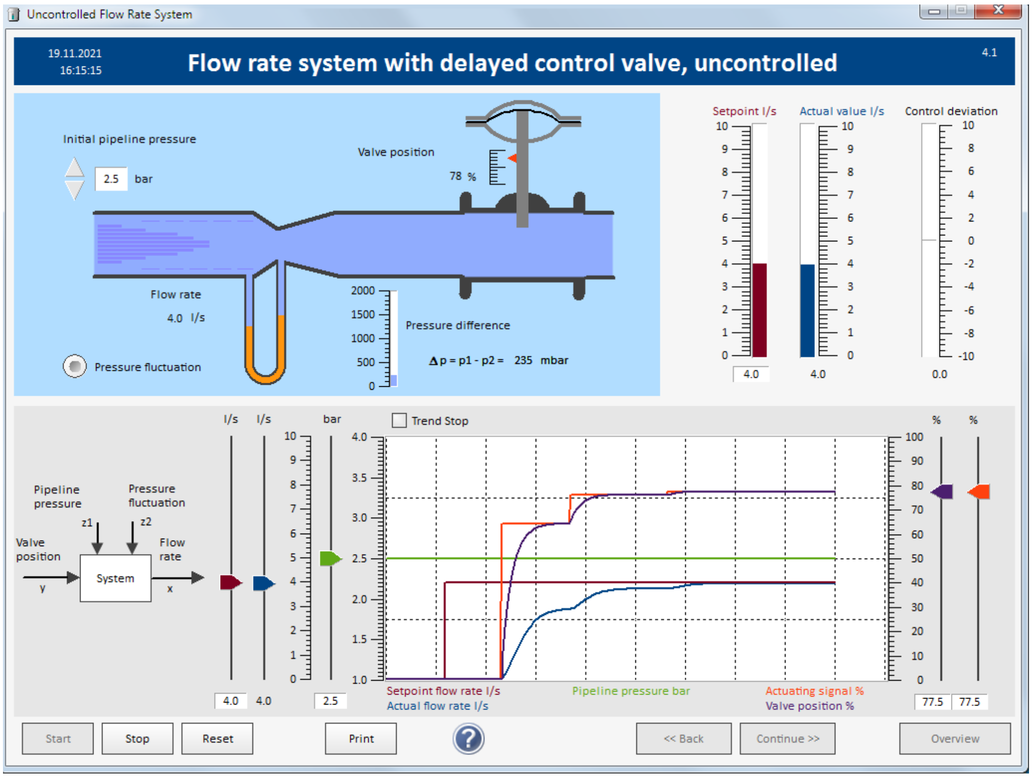
In control training II select item 4.1 „Uncontrolled system“.

Press „Start“.

You can now change the values for the setpoint (Setpoint flow rate l/s), the control signal (Actuating signal %) and the disturbance signal (Pipeline pressure bar) using the slider or by entering values below the slider

Task 1.

Set the setpoint (reference variable, Setpoint flow rate l/s) to 4 l/s and try to adjust the control signal (Actuating signal %) to bring the actual value (controlled variable, Actual flow rate l/s) to the setpoint (Setpoint flow rate l/s).

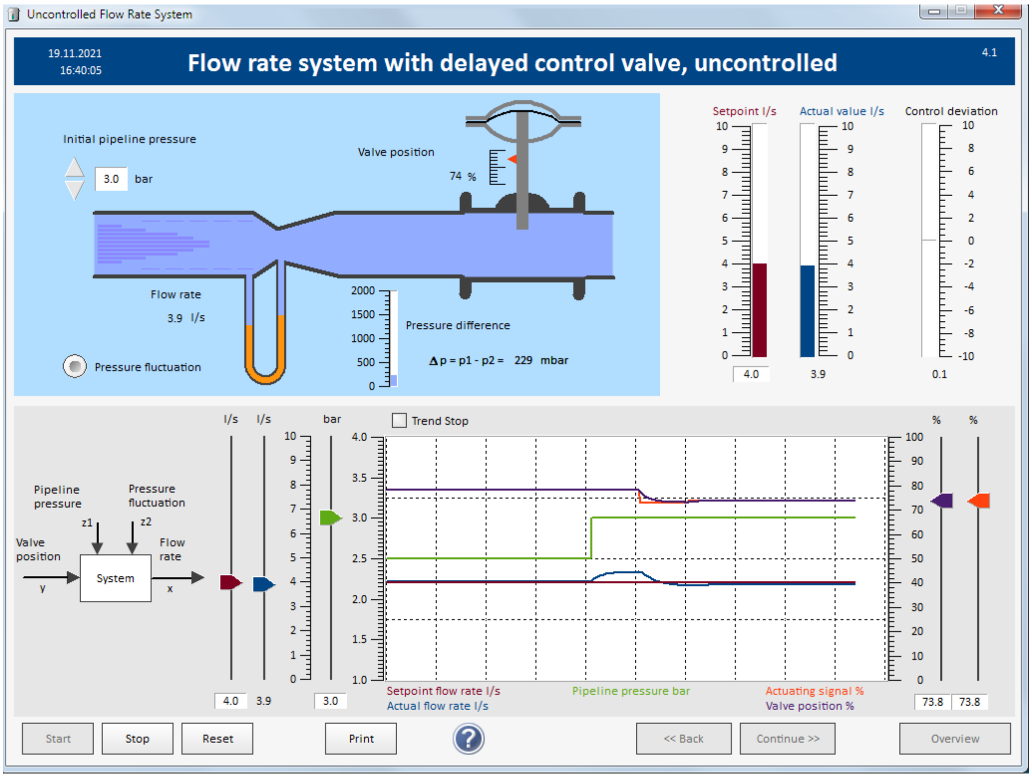


This type of control is known as command input response. The setpoint (reference variable) is adjusted and an attempt is made to bring the actual value (controlled variable) back to the new setpoint (reference variable).

With this system it can be observed that the actual valve position lags behind 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 pipeline pressure to 3 bar and try to correct the disturbance by adjusting the control signal.



As the pipeline pressure increases, the flow 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 lags behind 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

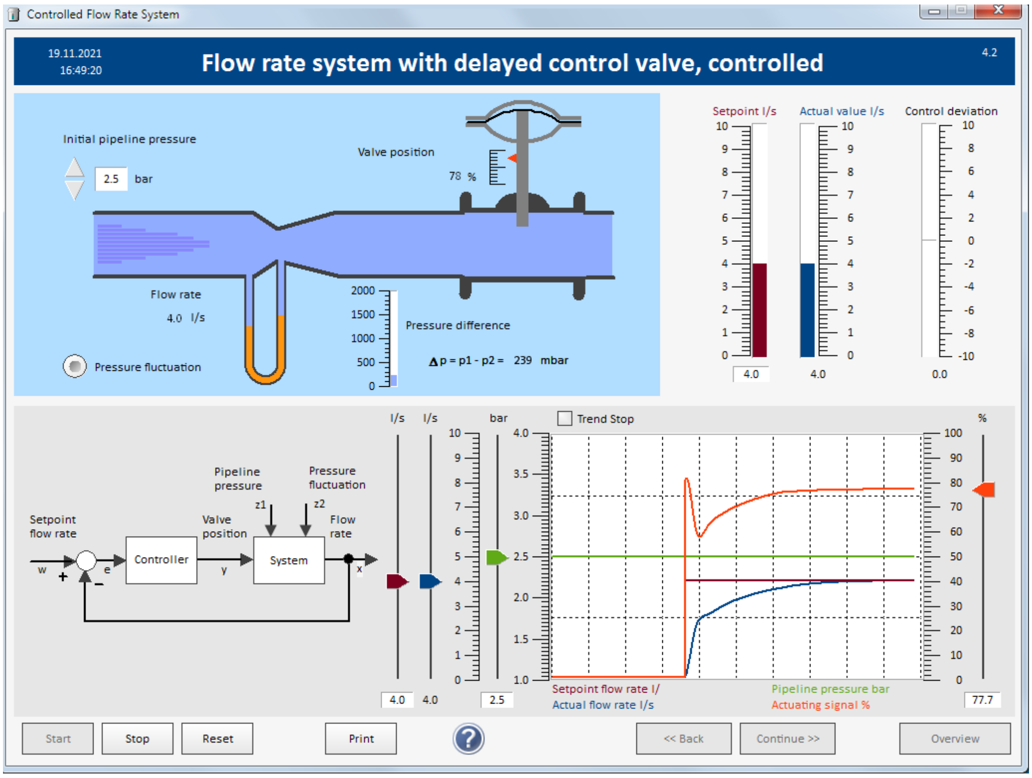
Go to „Overview“ and select item 4.2 „Closed-loop controlled system“.

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 bringing the actual value to the setpoint.

Task 3.

Press „Start“ and set the setpoint to 4l/s.

What will happen?

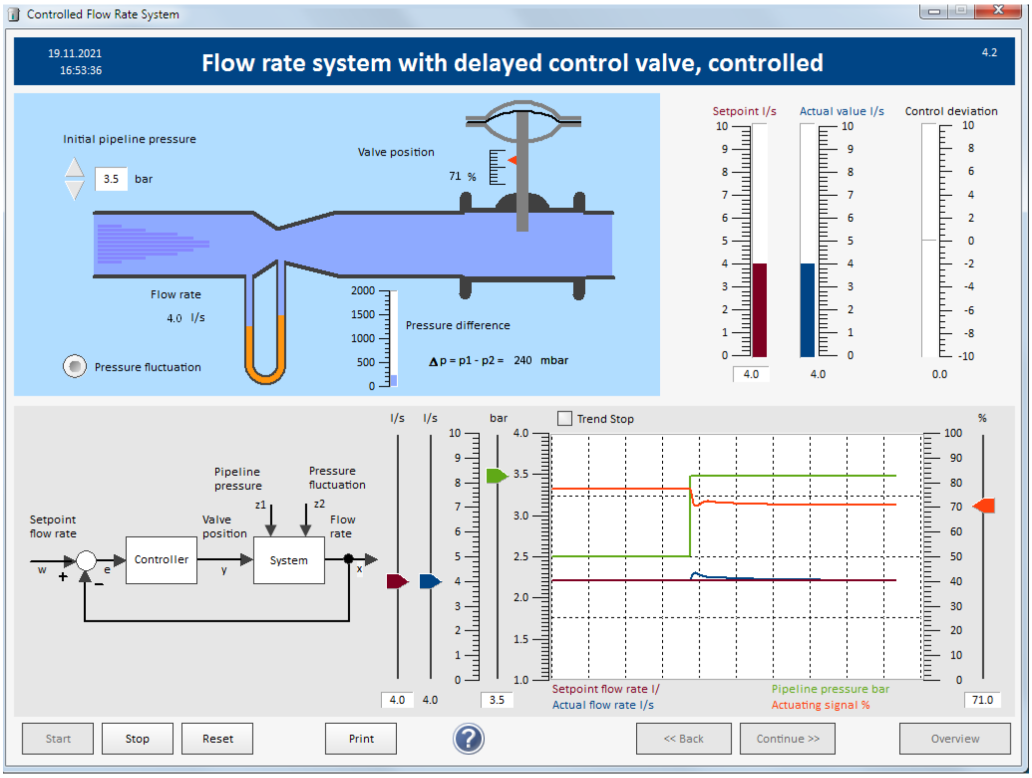


The actual value (flow rate) goes to the new setpoint (reference variable) after a certain time without overshooting. This is again a matter of examining the command response, since the setpoint (reference variable) has been adjusted.

Task 4.

Change the pipeline pressure to 3.5 bar.

What will happen?



The flow begins to increase.

The controller tries to bring the actual value (actual flow rate) back to the setpoint 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.

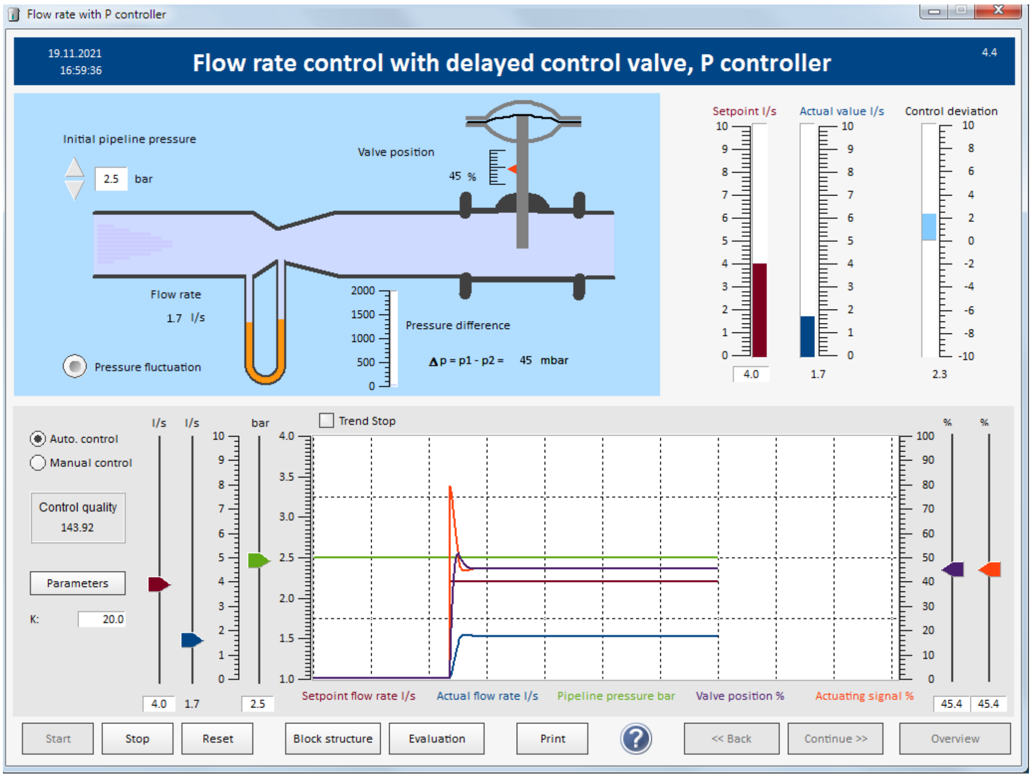
5.2.2 Closed-loop Control with P Controller

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

Press „Start“.

Task 5.

Change the setpoint 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 setpoint (reference variable, setpoint flow rate). We get a steady-state control error.

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

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

Reason:

The P controller works like an amplifier. The input signal to the controller w - x (setpoint - 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 setpoint 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 setpoint 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:

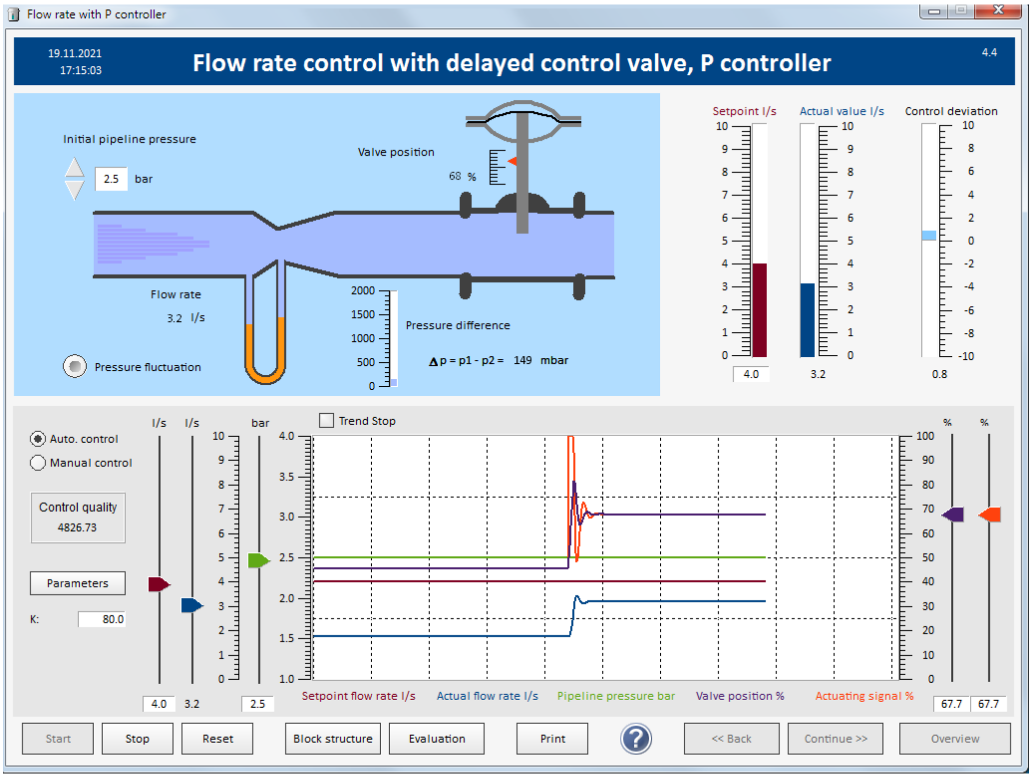
Control signal y = K * (w – x) = 20 * (4 – 1,7) = 46.

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 setpoint 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 bring the actual value to the setpoint 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.

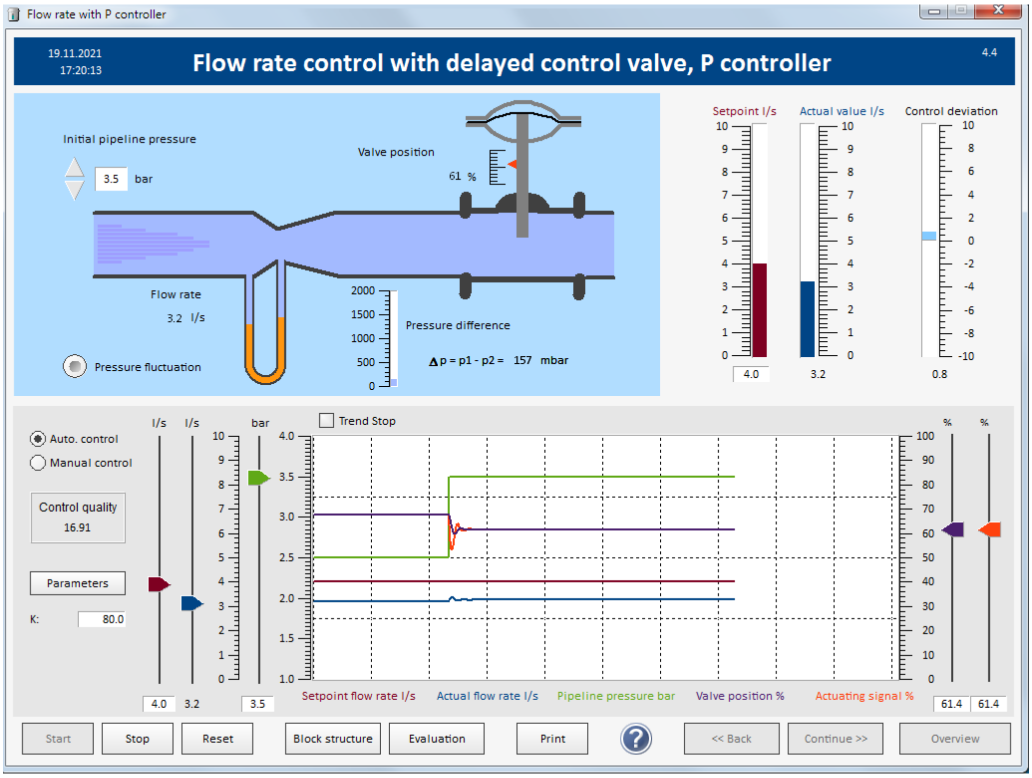
The value corresponds approximately to the displayed value of the control signal.

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

Task 7.

Change the pipeline 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 setpoint and disturbance value changes (command response and disturbance response).

5.2.3 Closed-loop Control with I Controller:

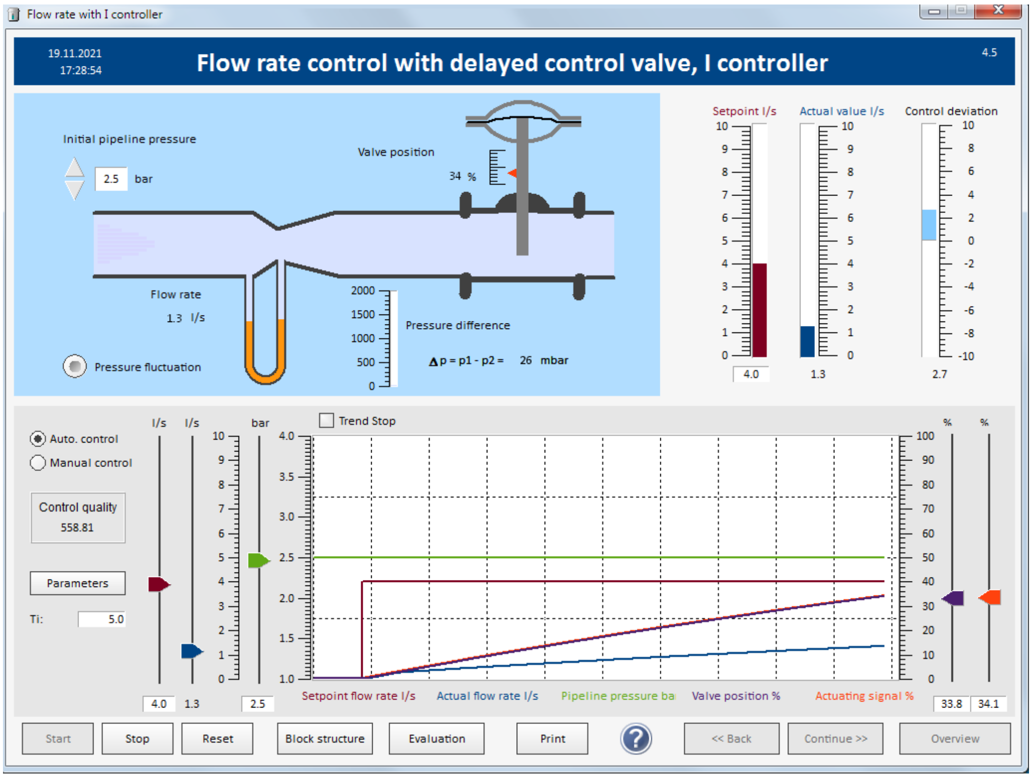
Go to „Overview“ and select item 4.5 „Closed-loop control with I controller“.

Press „Start“.

Task 8.

Change setpoint to 4l/s.

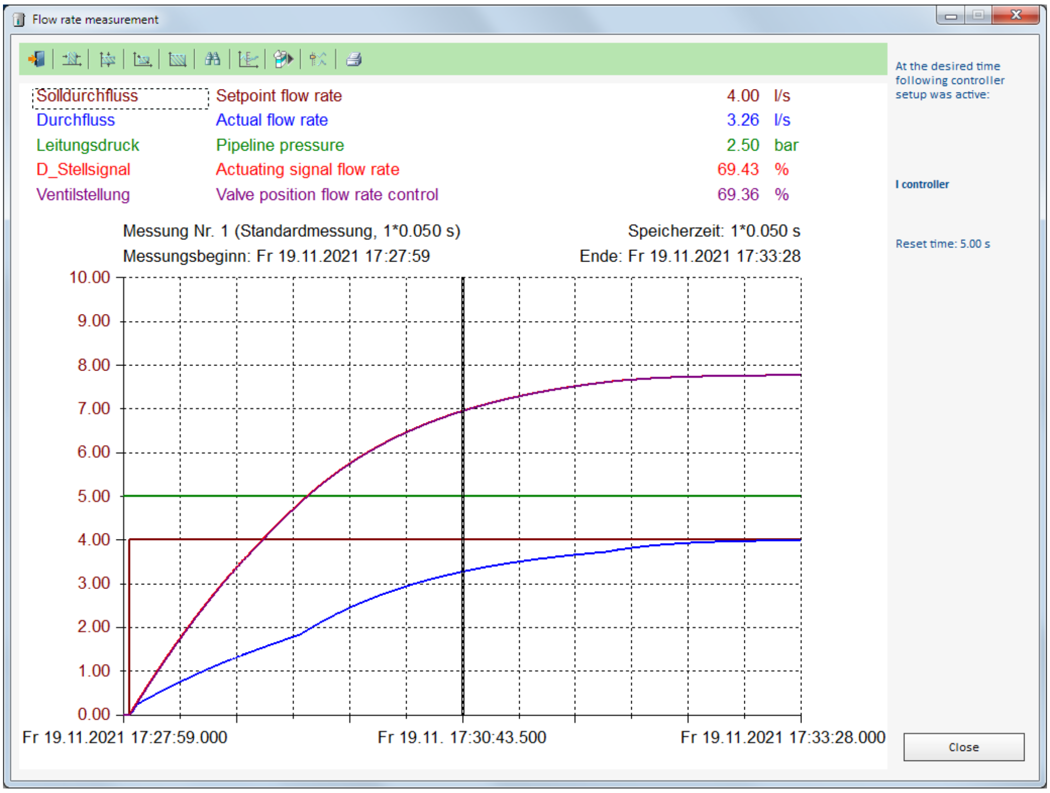
What will happen?



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

By reducing the integration time (e.g. to 1), the actual value reaches the setpoint 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“.

Press „Start“.

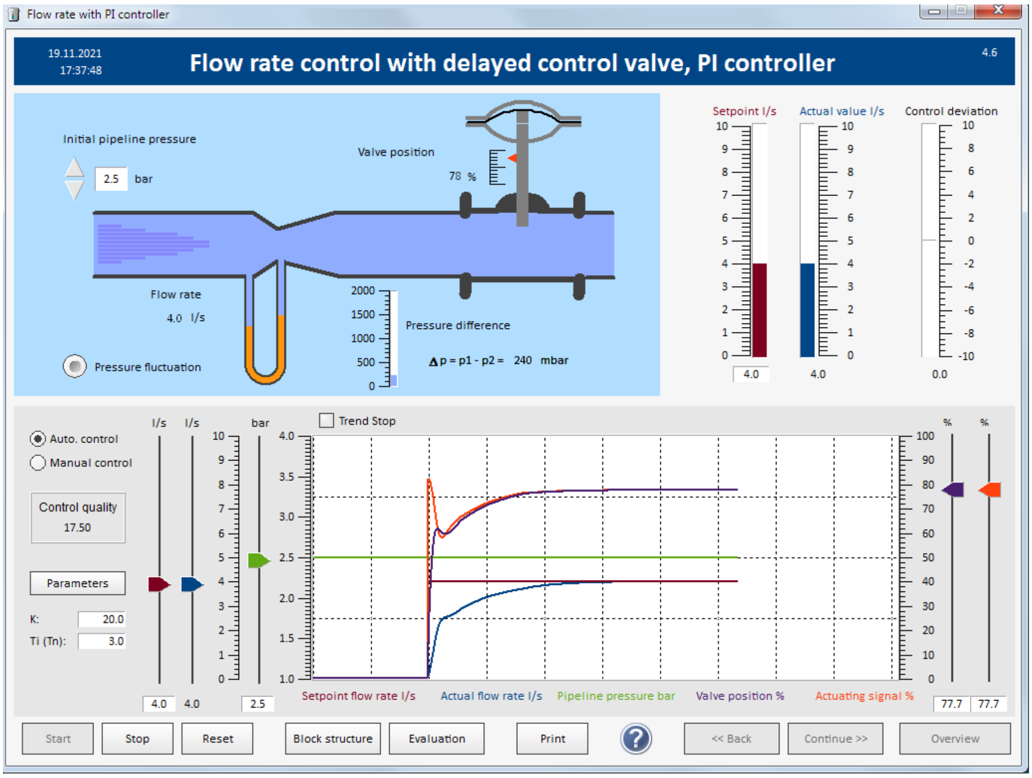
Task 9.

Keep the set parameters:

Gain K = 20, Reset time Ti = 3.

Change the setpoint to 4l/s.

Observe the settling behavior.



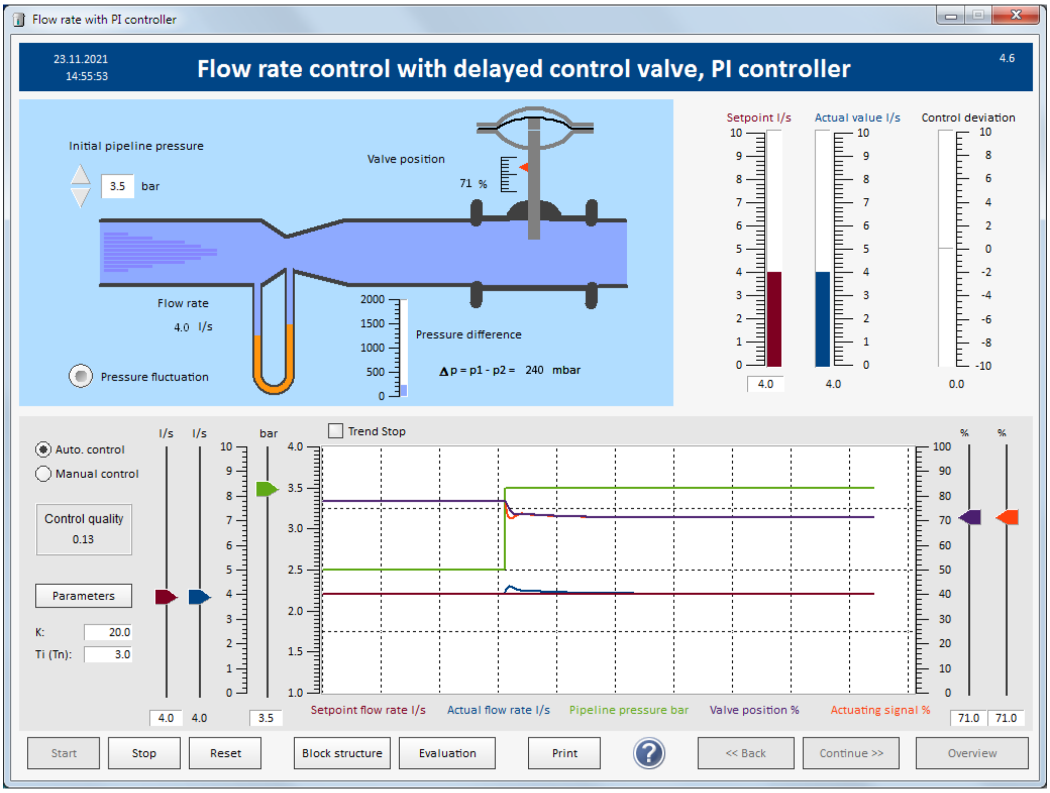
The actual value (controlled variable, actual flow rate l/s) of the control loop with the PI controller and the set parameters reaches the new setpoint (reference variable, setpoint flow rate l/s) after a short time without overshooting.

Since the setpoint 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 pipeline pressure to 3.5 bar and observe the behavior.



The higher pipeline 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 setpoint again.

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

Task 11.

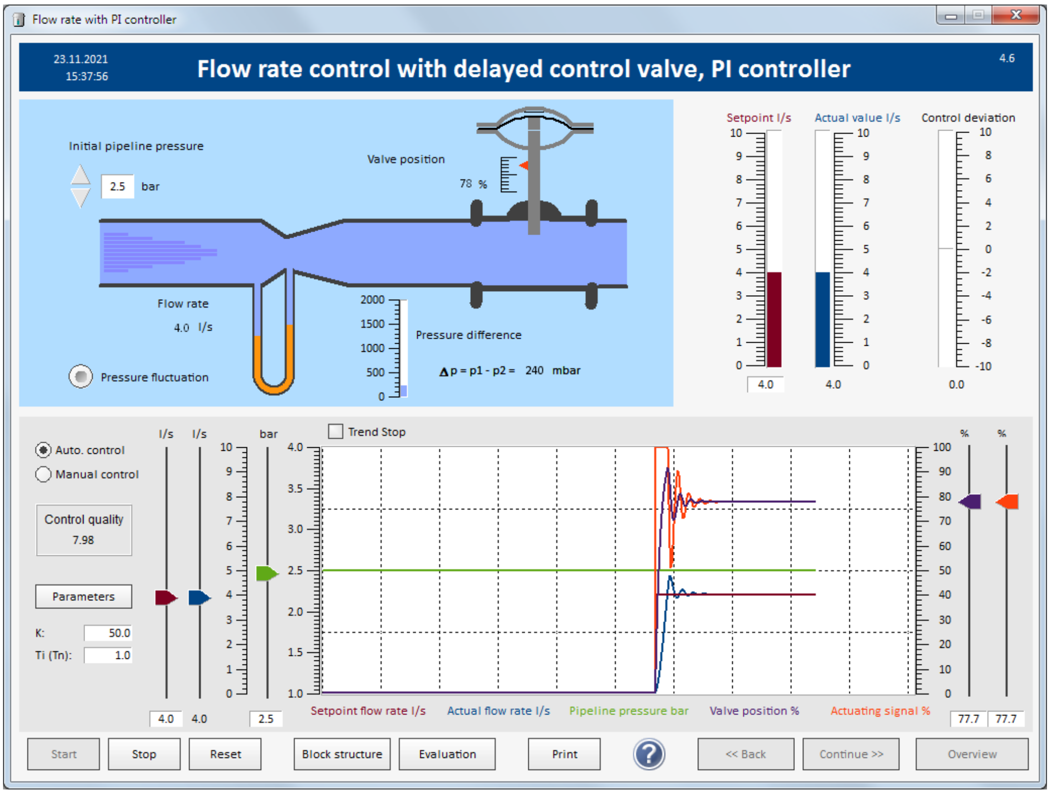
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the setpoint.

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 press "Reset". This means that the setpoint flow rate, pipeline pressure and actual flow rate are again given the initial values.

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



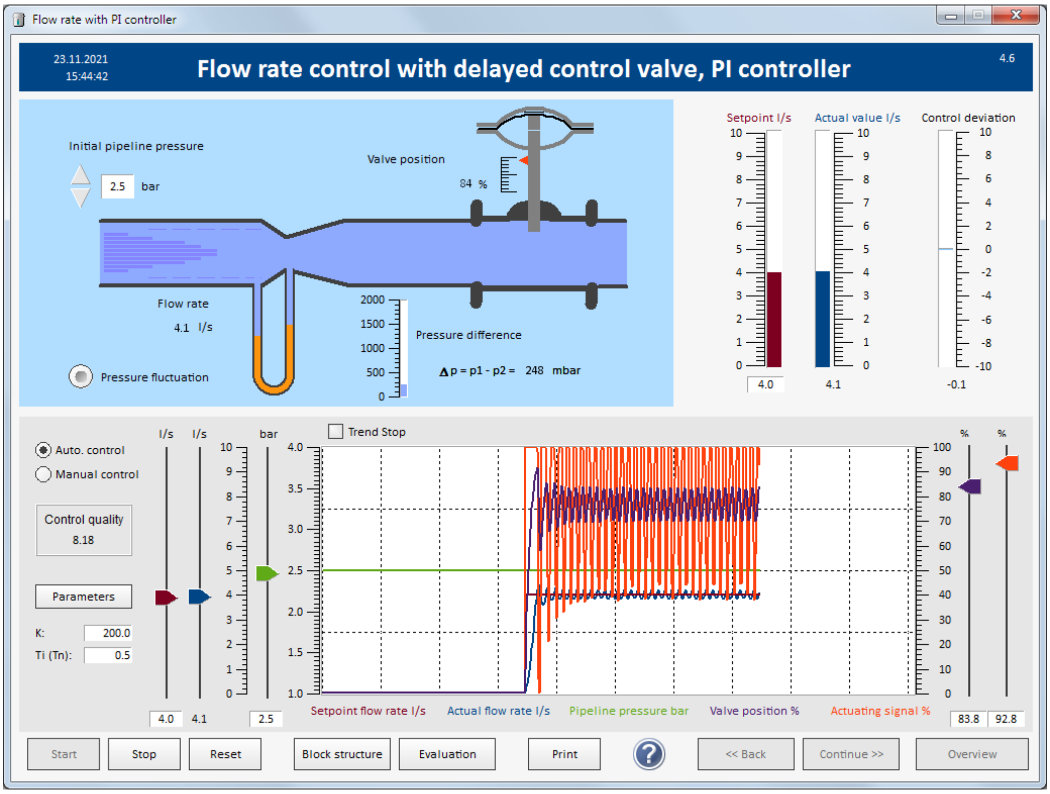
With the parameters K = 50 und Ti = 1, a control quality of 7,98 is obtained.

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:

- Press reset
- Set controller parameters
- Set the setpoint 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“.

Press „Start“.

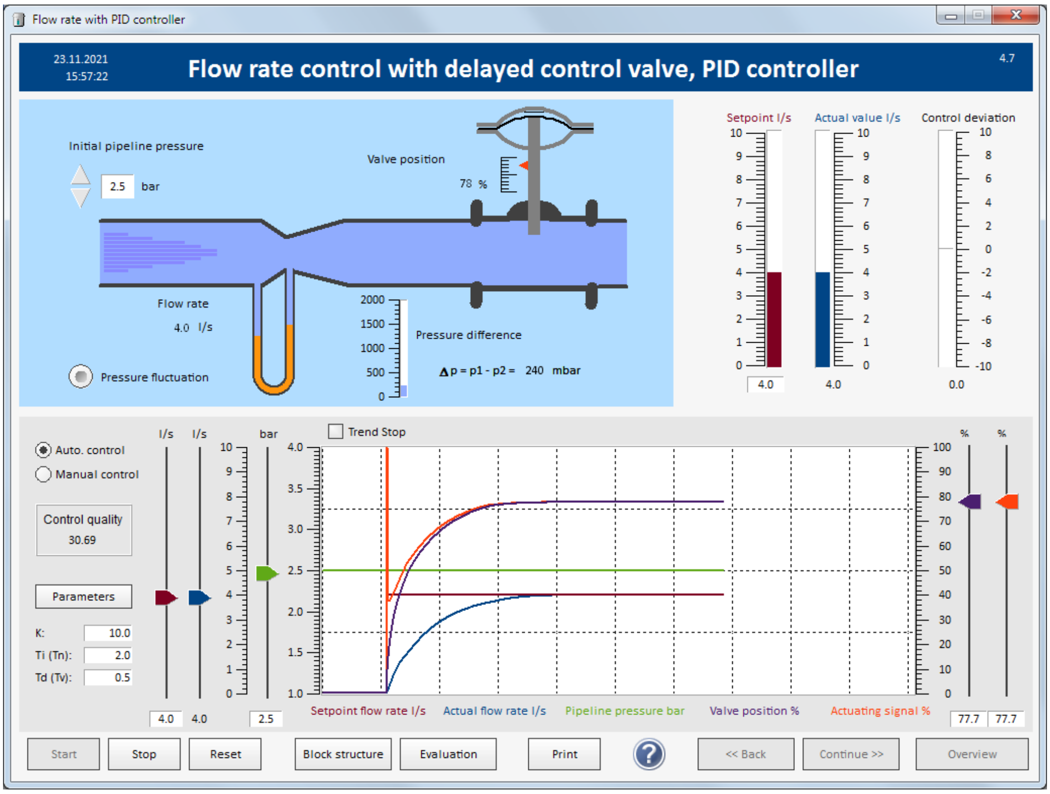
Task 12.

Investigate the command response with the preset parameters:

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

Change setpoint to 4l/s.

What will happen?



The control loop goes aperiodically (without overshoot) into a stable state. The actual value reaches the setpoint.

As can be seen in the trend diagram, the sudden change in the setpoint 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:

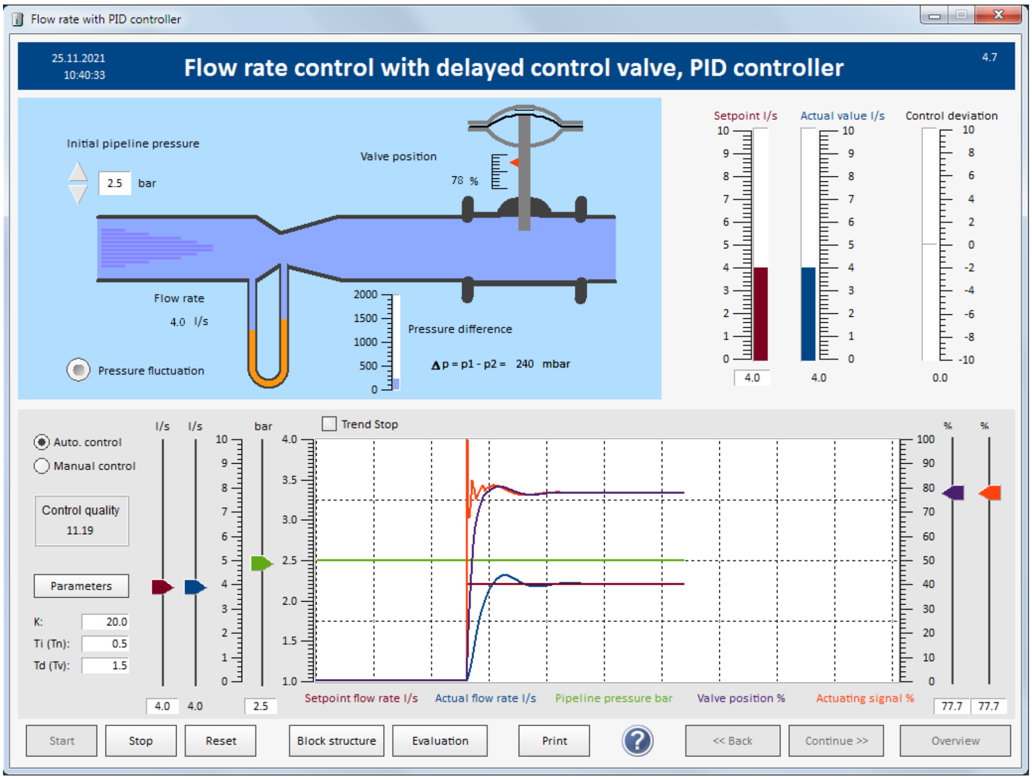
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Evaluation" (display of the stored signal values) and selection of a corresponding time range.

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

- Press “Reset”
- Change the controller parameters
- Adjust the setpoint 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.

Note:

In practice, the PI controller is mainly used as a controller. If a PID controller is used, the D component is often turned away 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 setpoint and the actual value. If the change increases, i.e. the difference between the setpoint and actual value increases, the D component adds a calculated value to the control signal. If the change between the setpoint and actual value becomes smaller, i.e. the difference between setpoint and actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend as to whether the difference between the setpoint and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between the setpoint and actual value becomes smaller, the control signal is reduced.

5.3 Examine Controlled System

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

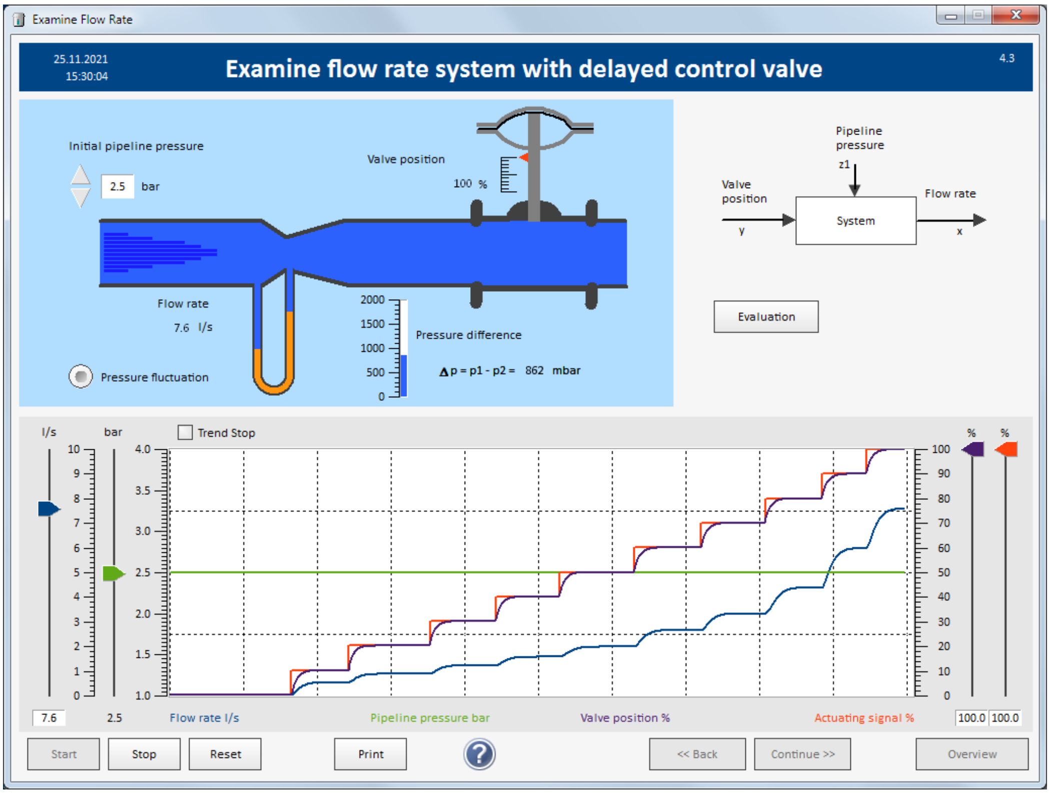
The flow rate control is a system with self-regulation. In the event of a sudden change in the control signal, the actual value (controlled variable, actual flow rate) settles to a constant value after a finite time.

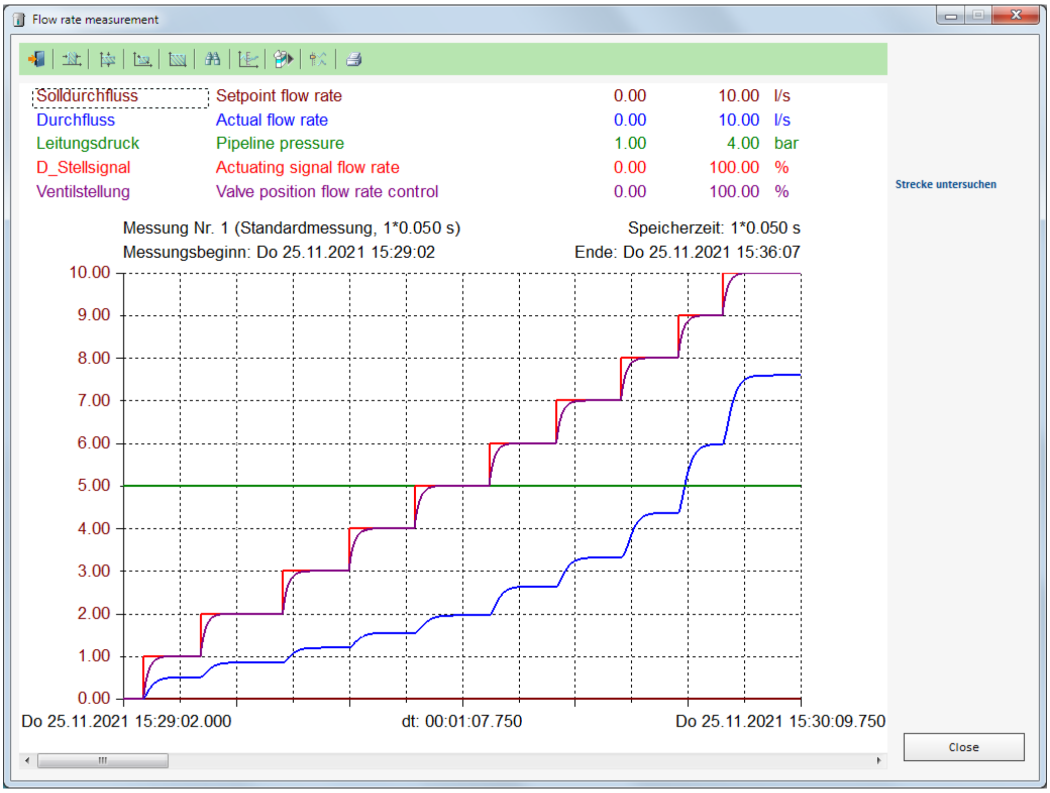
Task 14.

Press „Start“.

Increase the actuating signal by 10% each time after the settling phase.

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 jump 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 around 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 swings to a constant value after a finite time, while with a controlled system without self-regulation, the controlled variable (actual value) continues to rise.

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

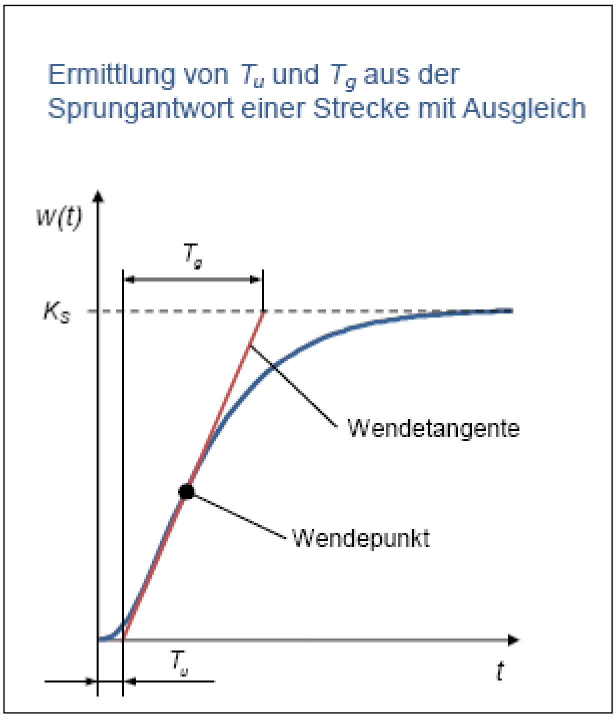
A unit jump is given to the input signal of the system (control signal of the system). The behavior of the output signal of the system (controlled variable) can then be measured.

For the controller setting procedures for systems with self-redulation, 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 point of inflection with P. Since the designations Tu and Tg are still used in most of the literature, we use both terms.

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

Regler-verhalten	Gütekriterium			
	Überschwingung nach Gegenseite mit 20% von x_m, kürzeste Schwindungsdauer		aperiodischer Regelvorgang mit kürzester Dauer	
	Störung	Führung	Störung	Führung
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	$K_P \approx \frac{1{,}2}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2 \cdot Tu$ $T_v \approx 0{,}42 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1{,}35 \cdot T_g$ $T_v \approx 0{,}47 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2{,}4 \cdot T_u$ $T_v \approx 0{,}42\, T_u$	$K_P \approx \frac{0{,}6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$ $T_v \approx 0{,}5 \cdot T_u$

Für Regelstrecken *ohne Ausgleich* ist statt $\frac{T_g}{K_S \cdot T_u}$ der Ausdruck $\frac{1}{K_{IS} \cdot T_u}$ einzusetzen.

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

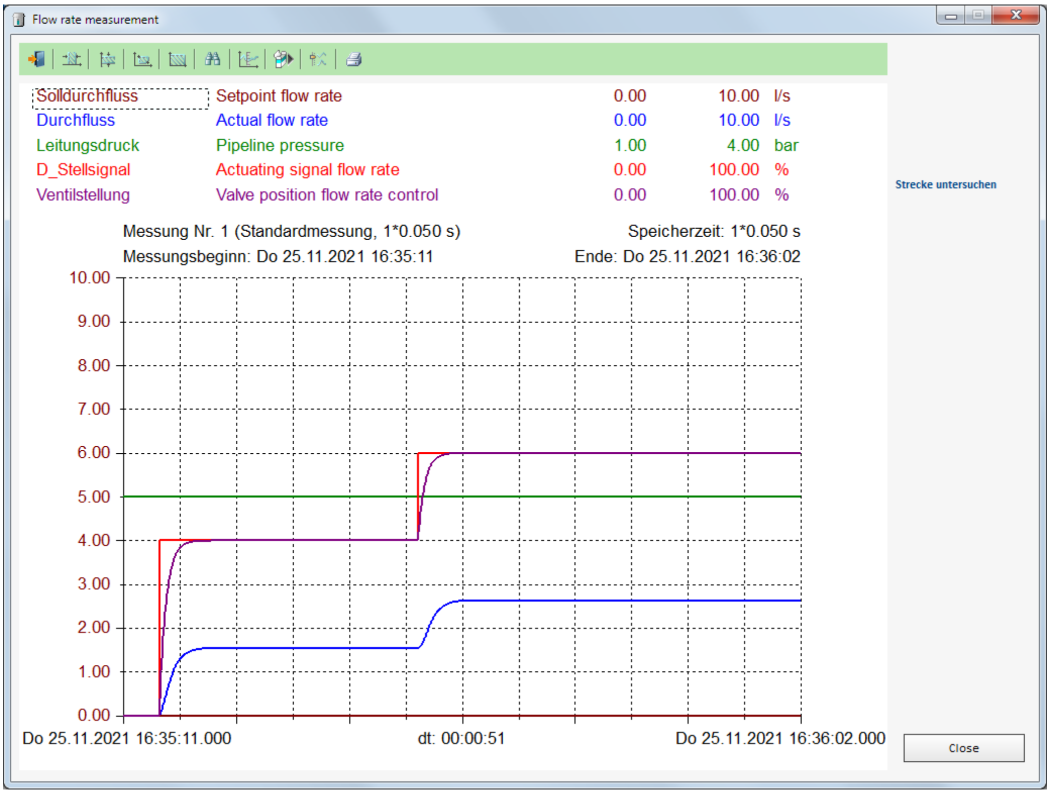
For flow control, select point 4.3 "Examine controlled system".

Task 15.

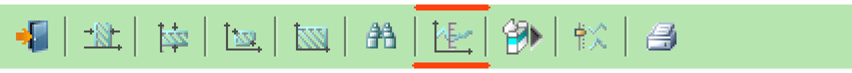
Press „Start“. Increase the control signal to 40%. Wait until the controlled variable (flow rate) has settled.

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

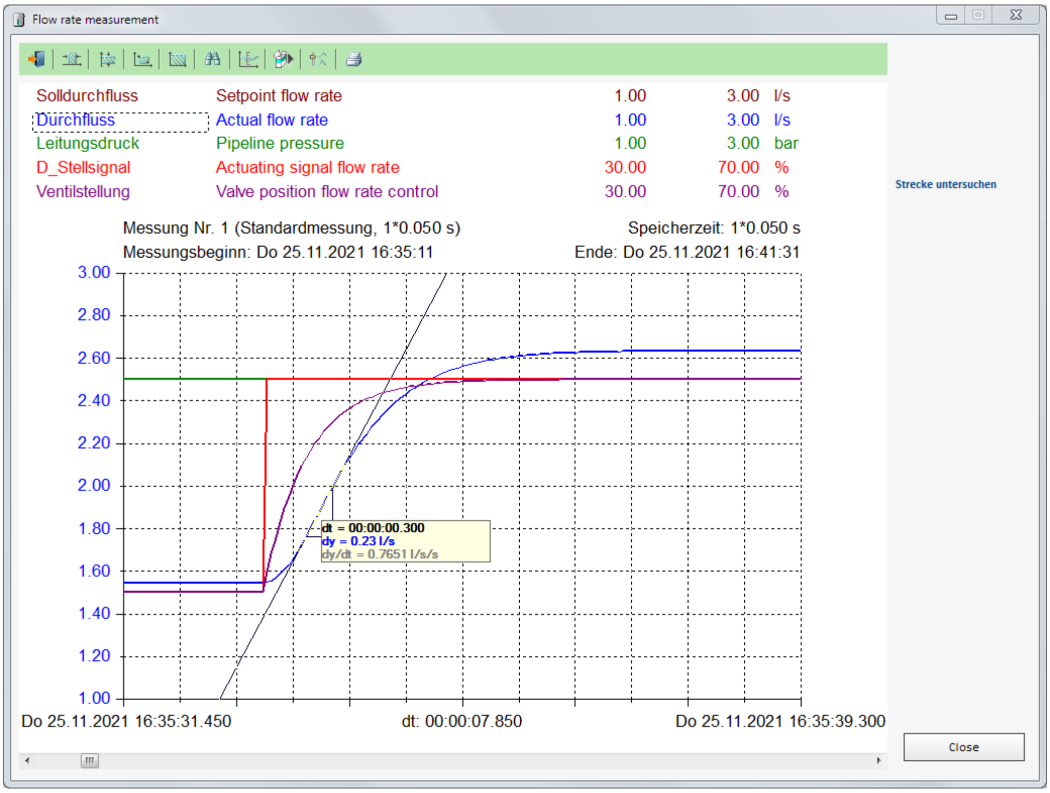
Press "Evaluation" and try to measure the recorded system behavior for the jump to 60%.



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 holding and dragging.



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.

So: 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

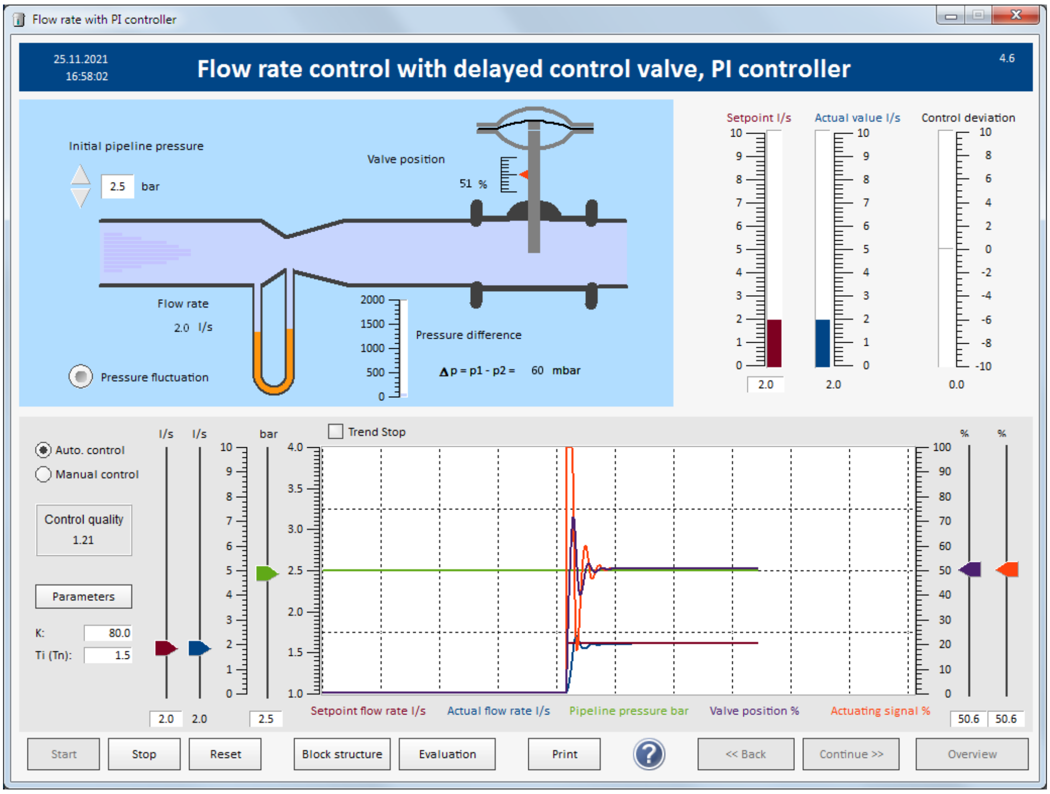
Disturbance response with 20% overshoot

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

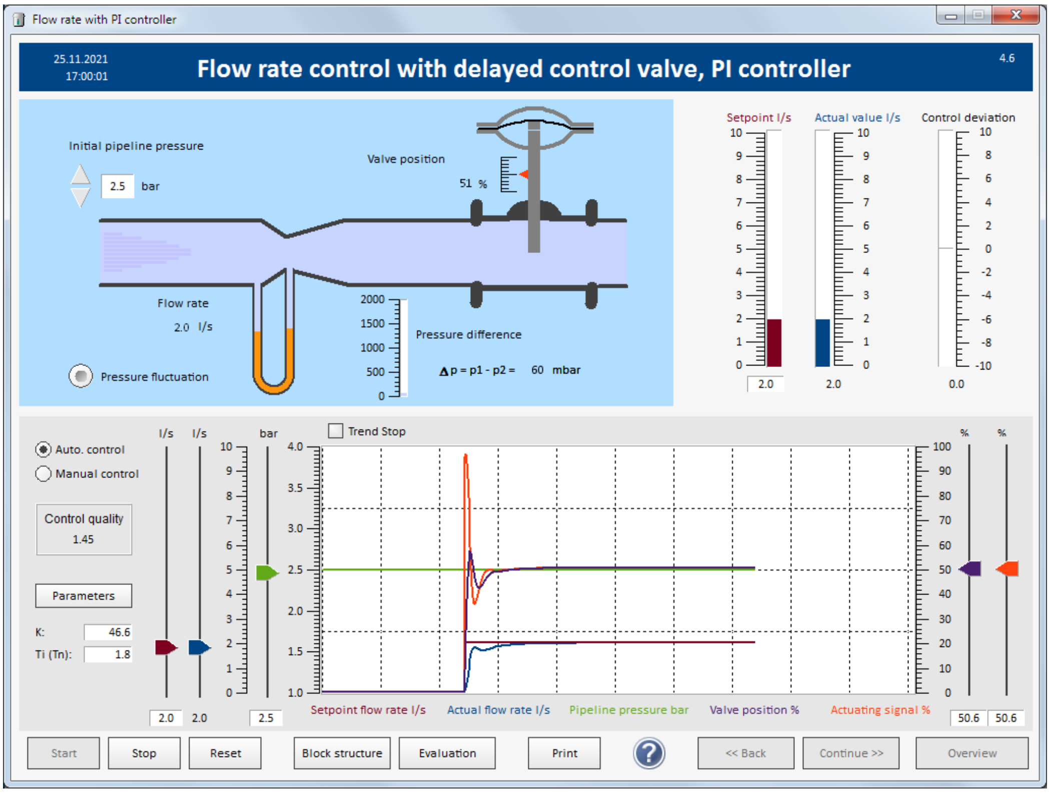
Distrurbance response aperiodic

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 setpoint jump from 0l/s to 2l/s should be used.

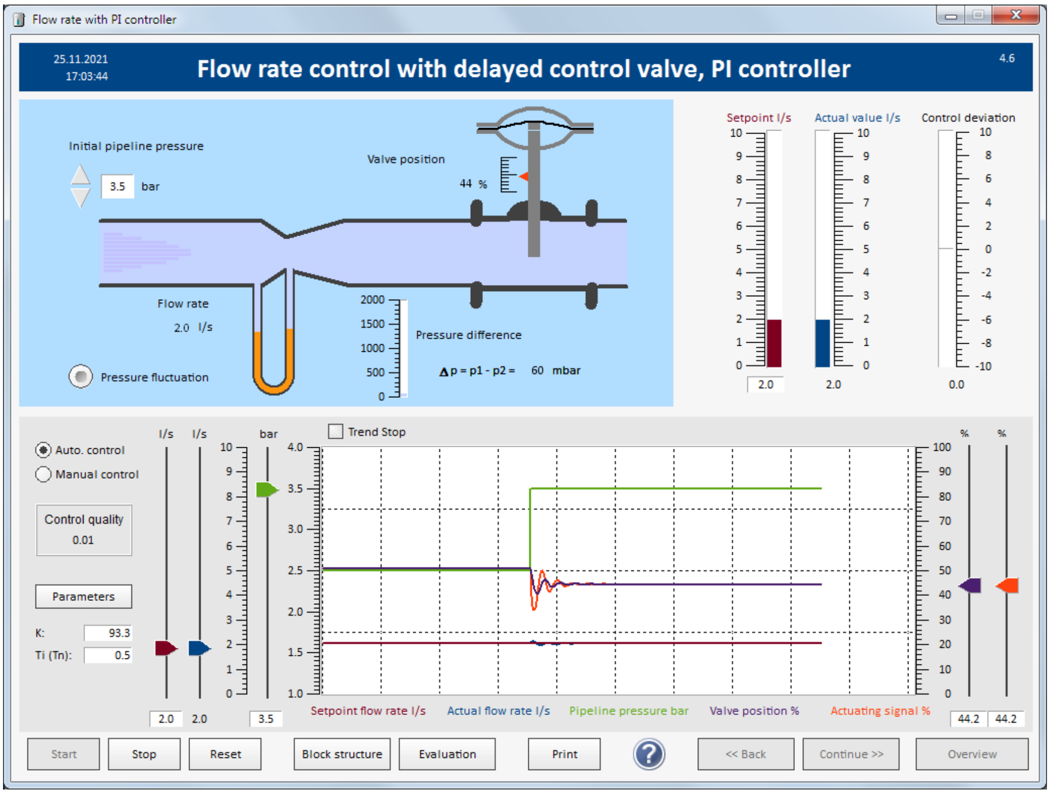


Command response with 20% overshoot

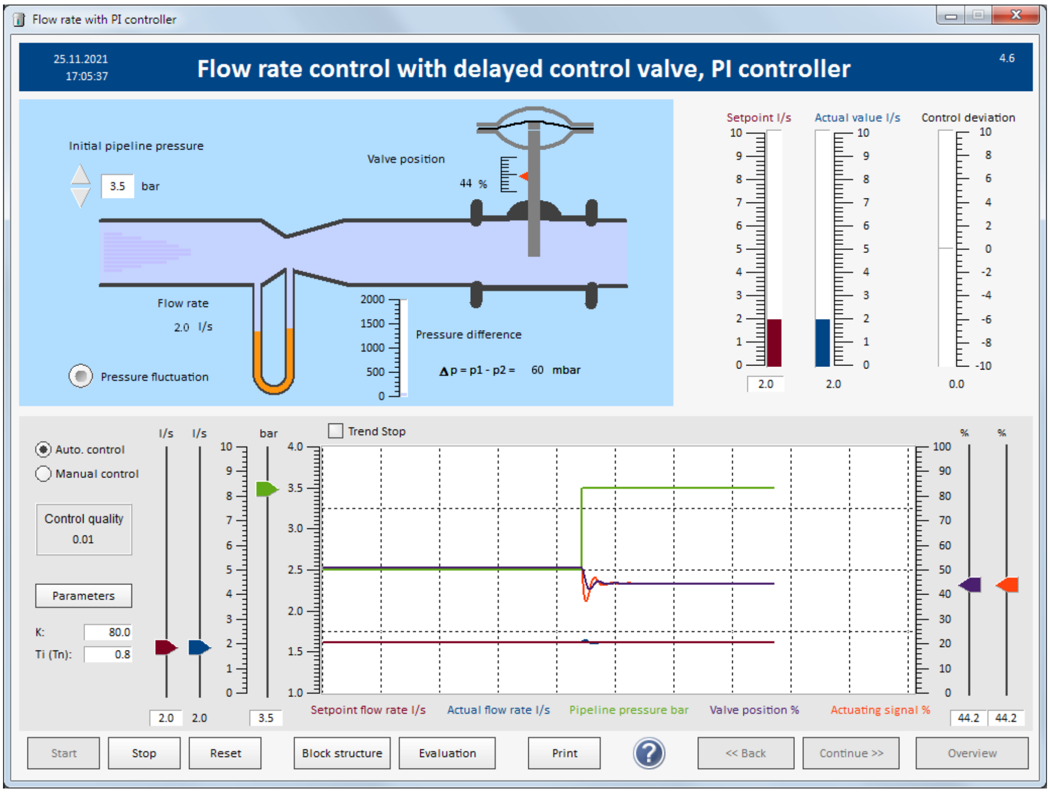


Command response aperiodic

Disturbance response: Pipeline pressure from 2,5bar to 3,5bar:



Disturbance response with 20% obershoot



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

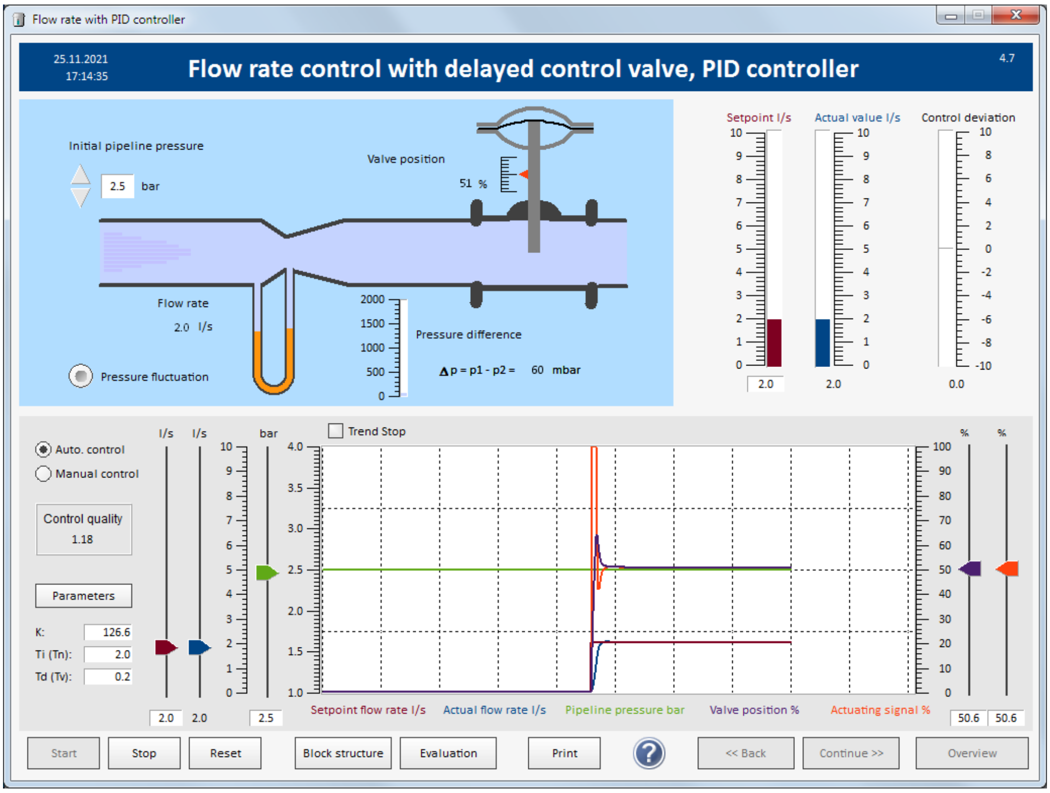
Distrubance response with 20% overshoot

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

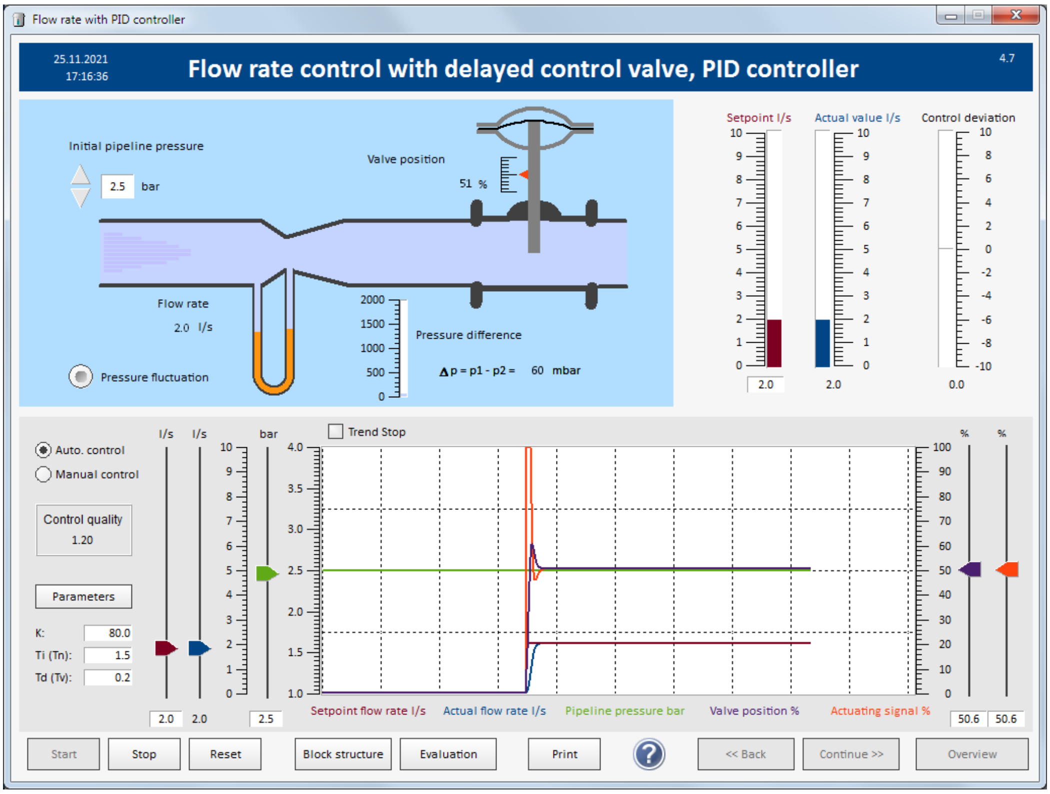
Distrubance response aperiodic

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

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



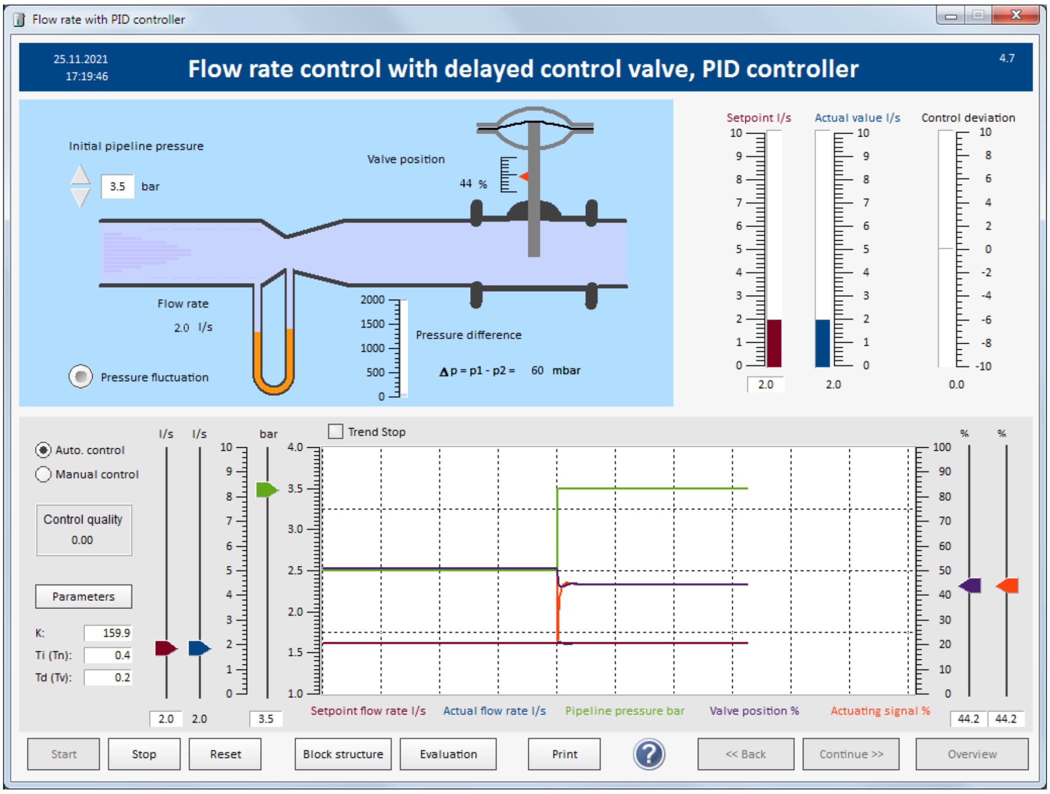
Command response with 20% overshoot



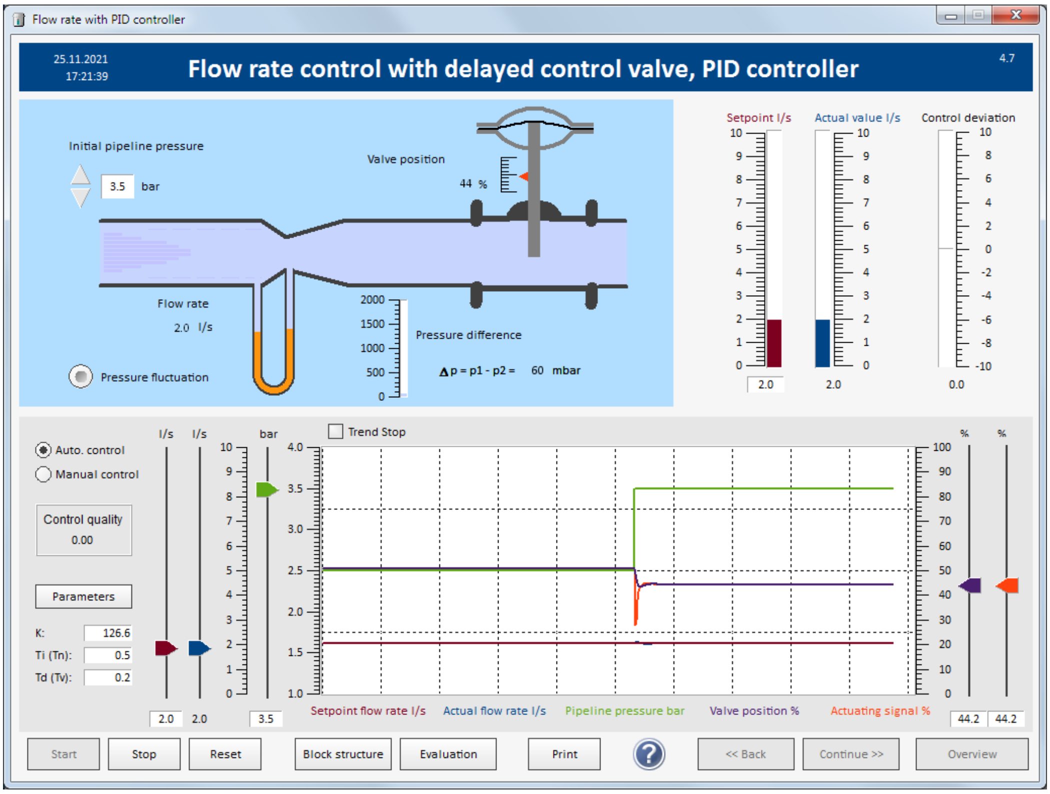
Command response aperiodic

Disturbance response: Pipeline pressure from 2.5bar to 3.5bar.

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



Disturbance response with 20% overshoot



Disturbance response aperiodic

5.5 Assessment of the Controller Tuning Rules

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

The settings for the controller parameters differentiate between disturbance and command behavior. Different controller parameters are calculated.

If you want to cover both cases (disturbance and control behavior) with your controller parameters, 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)

The 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 setpoint. The heating output is the input variable (manipulated 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 points “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“.

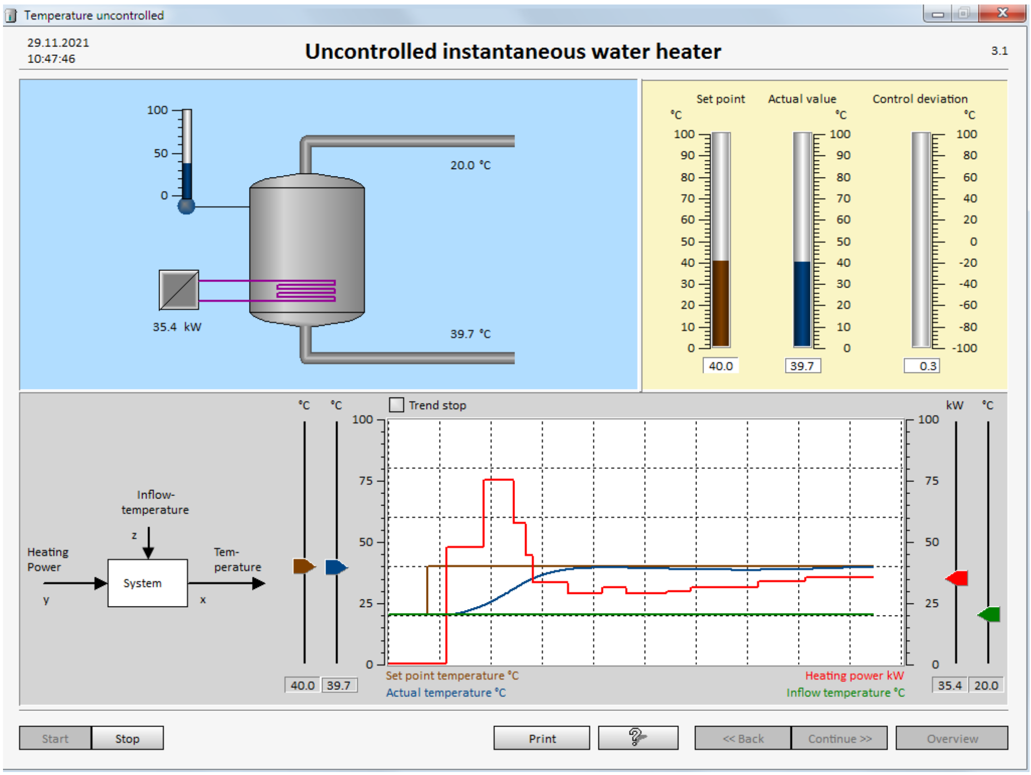
Press „Start“.

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

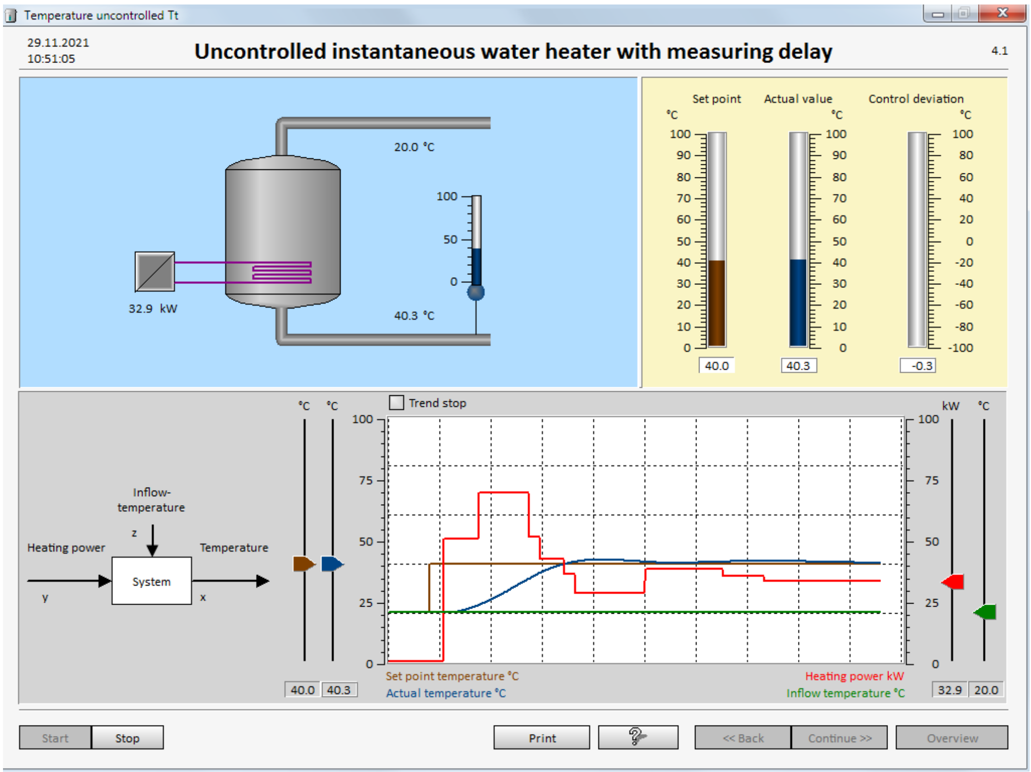
Task 1.

Set the setpoint temperature to 40°C and then try to bring the actual temperature (controlled variable) in the container to the setpoint temperature by adjusting the heating output (control variable).

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



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

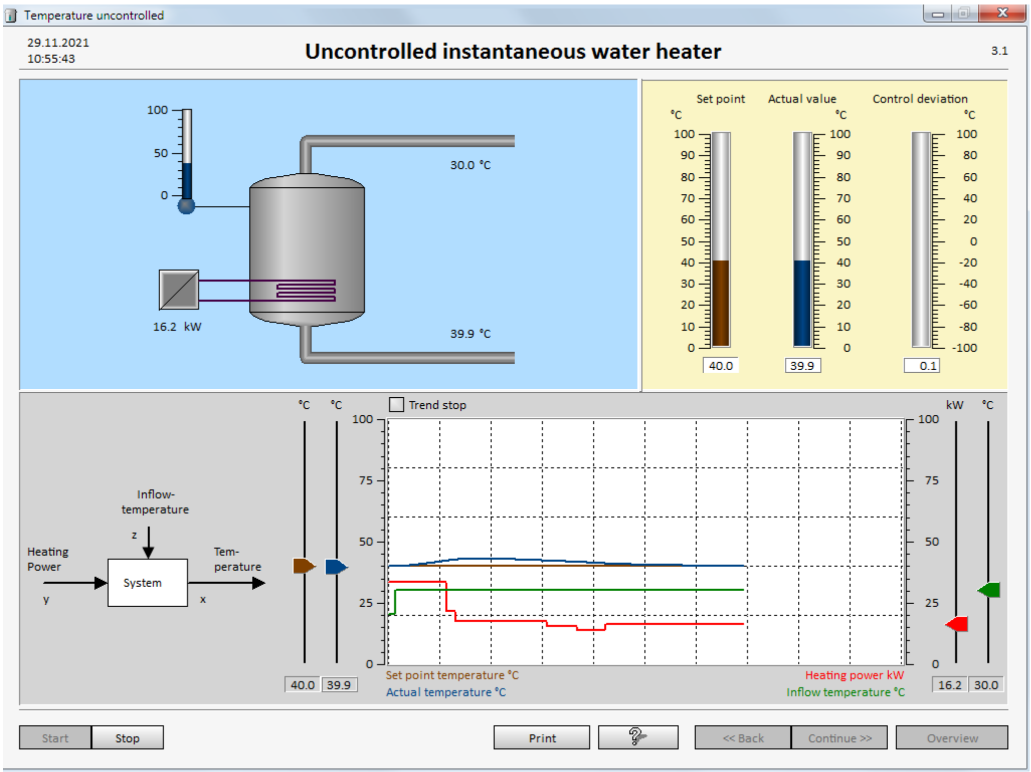


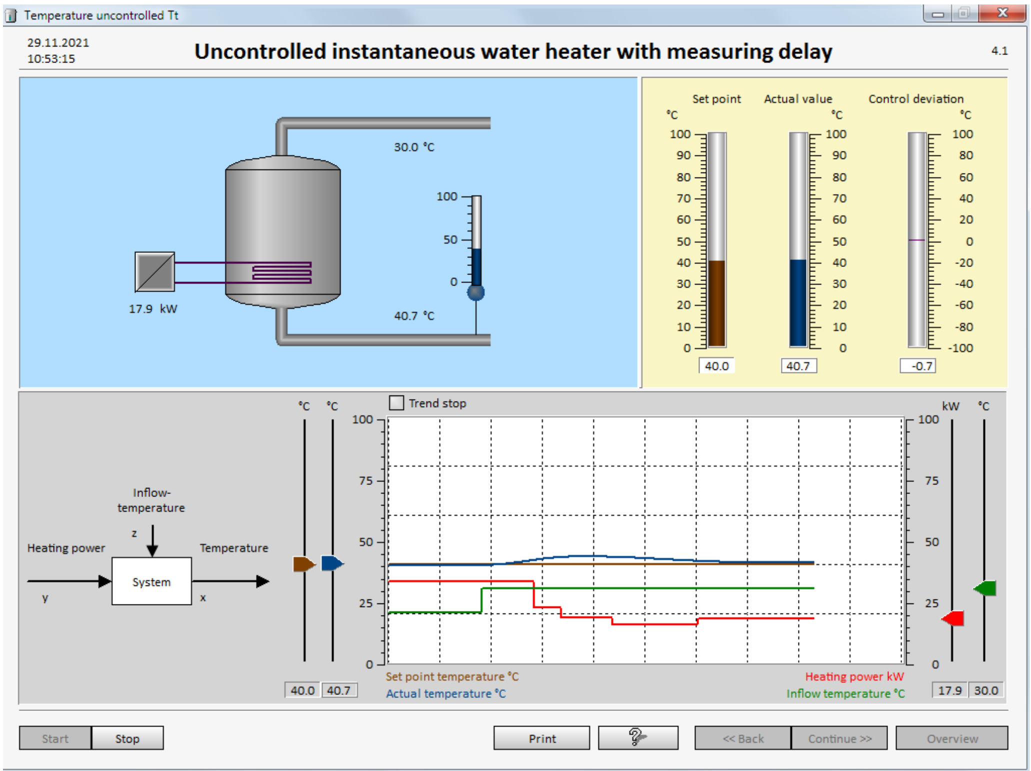
In the picture below you can see that after the change in heating power, the actual temperature starts to rise later.

Task 2.

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

Describe the behavior and try to control the disturbance.





Due to the rising inflow temperature, the internal temperature rises and the heating output 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

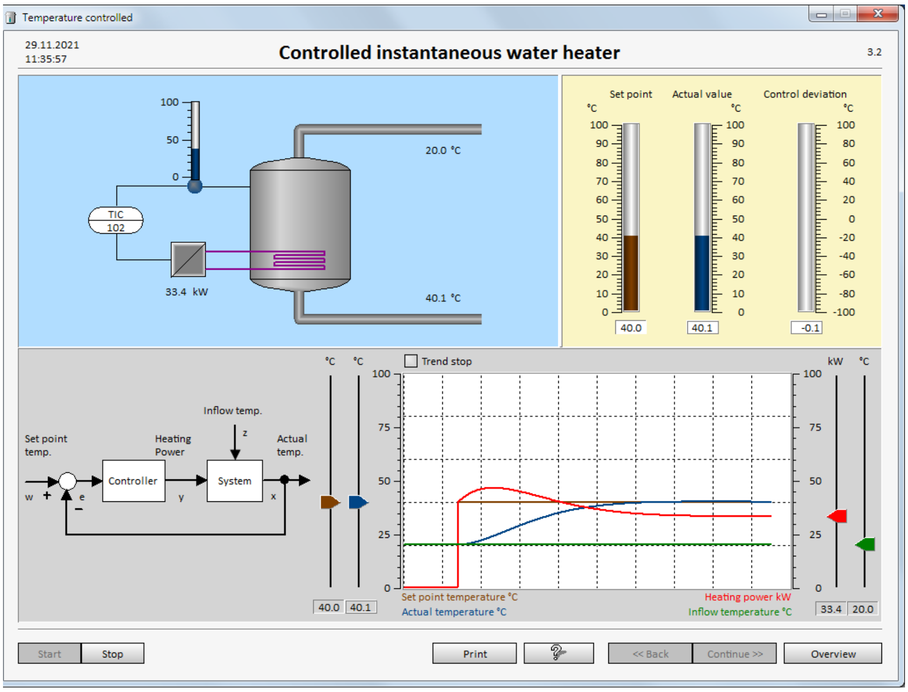
6.2.1 Closed-loop Controlled System

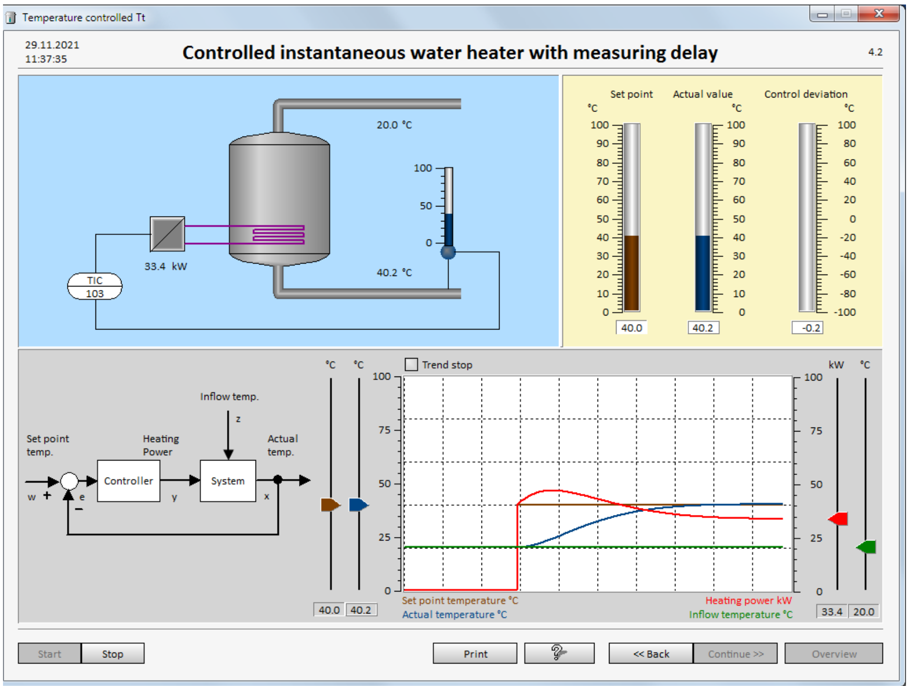
Go to „Overview“ and select item 3.2 respectively 4.2 „Closed-loop control system“.

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

Task 3.

Press „Start“ and change setpoint to 40°C.





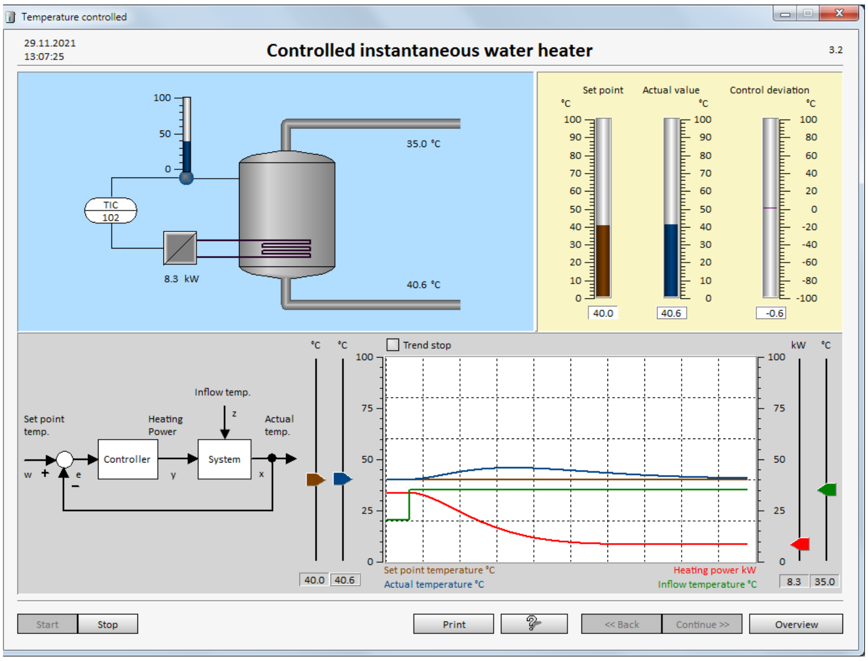
With a small overshoot, the actual value goes to the setpoint after a certain time in both cases. The examination of the system for a change in the setpoint (reference variable) is called command response.

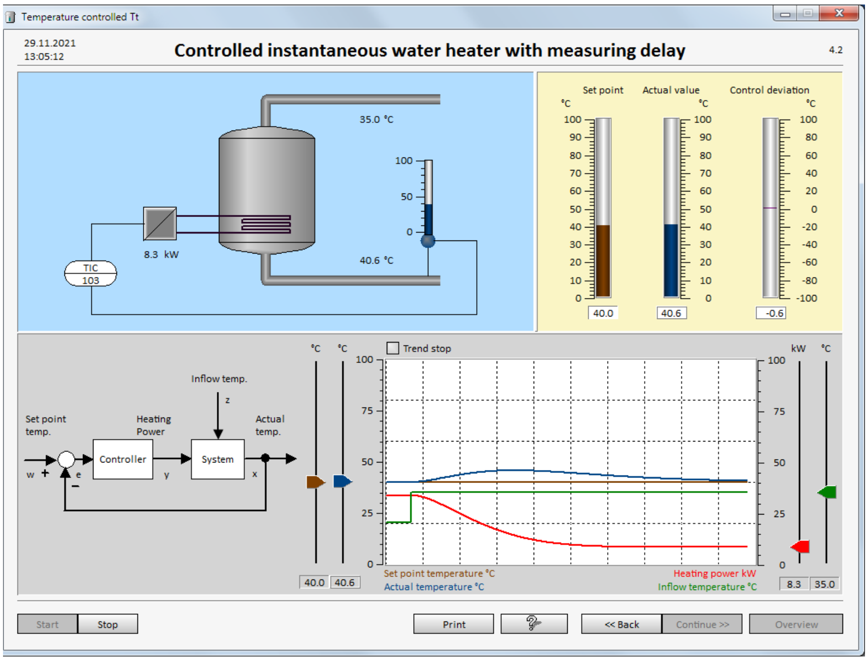
Task 4.

Investigate the disturbance response.

Set the setpoint 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 output.

6.2.2 Closed-loop Control with P Controller

Go to „Overview“.

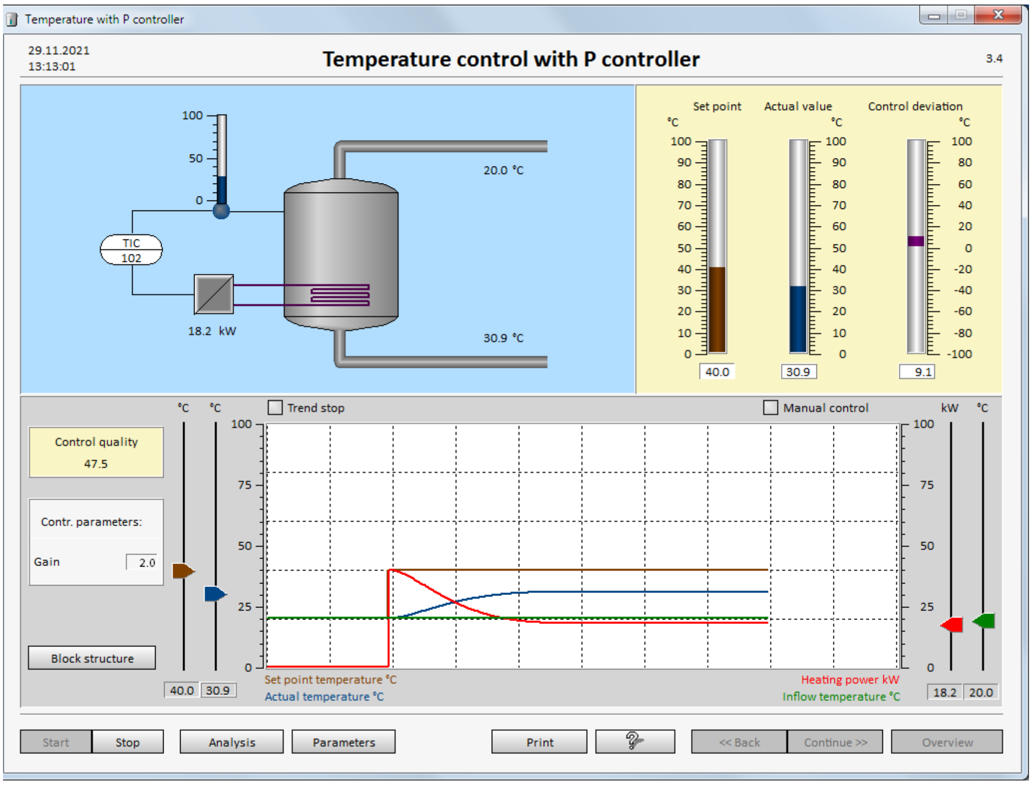
Select item 3.4 respectively 4.4 „Closed-loop control with P controller“

Press „Start“.

Task 5.

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

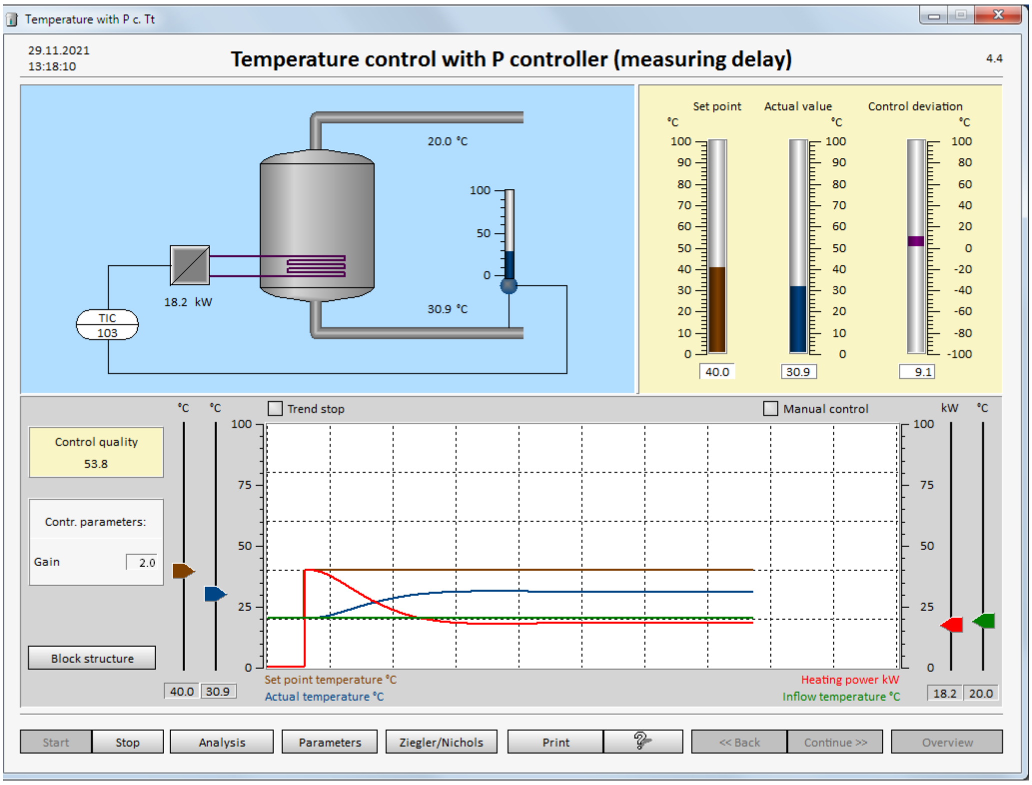
Observe the behavior.



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

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

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



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

If the P controller outputs 0, the heating output 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.

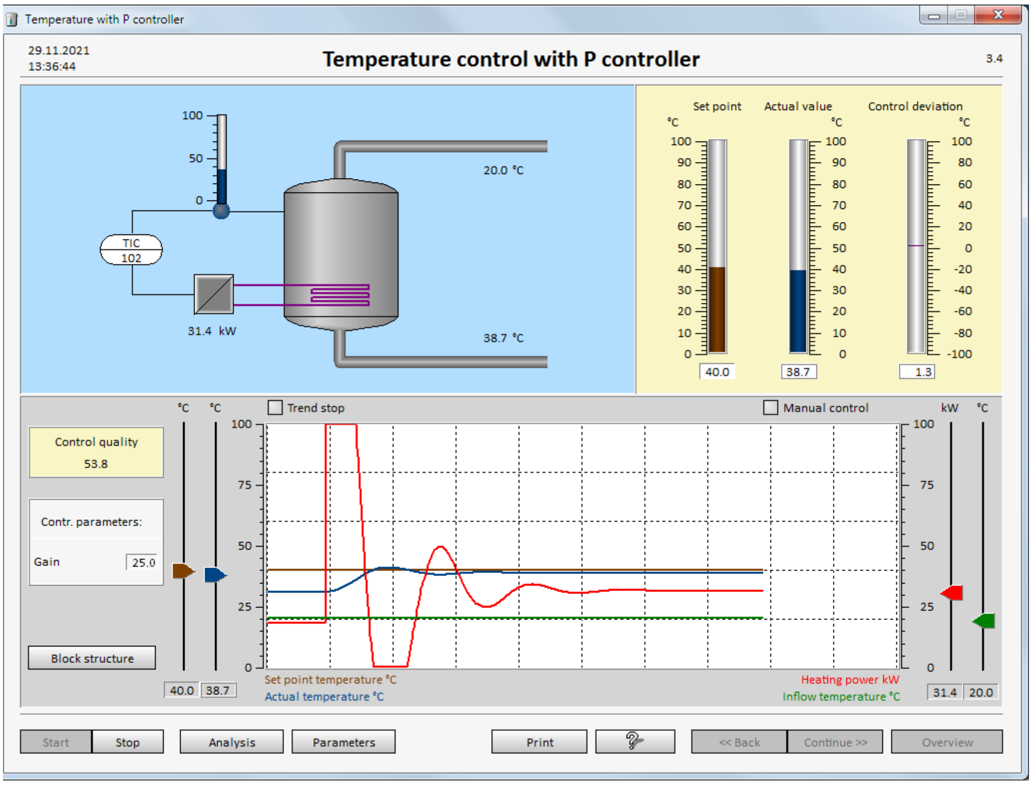
In the steady-state case, the actual value x (actual temperature) reaches the value 30.9°C at the setpoint value w = 40°C.

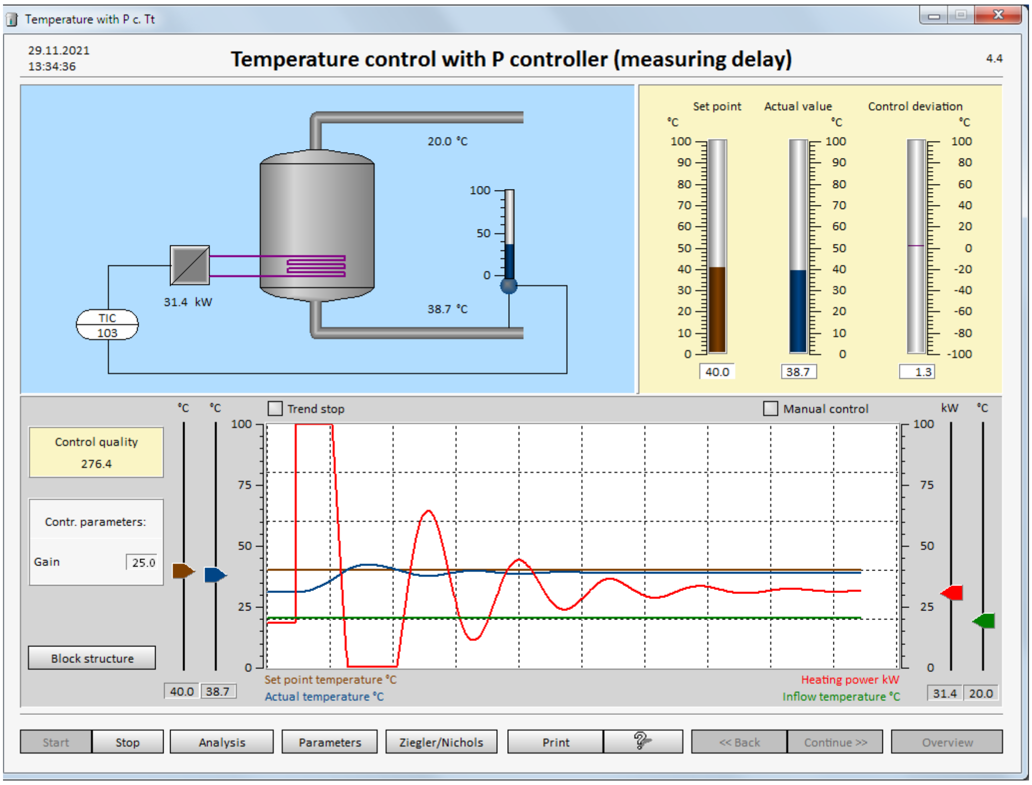
This results in:

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 setpoint 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 bring the actual value to the setpoint 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) begins to oscillate much 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 press 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 setpoint 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“

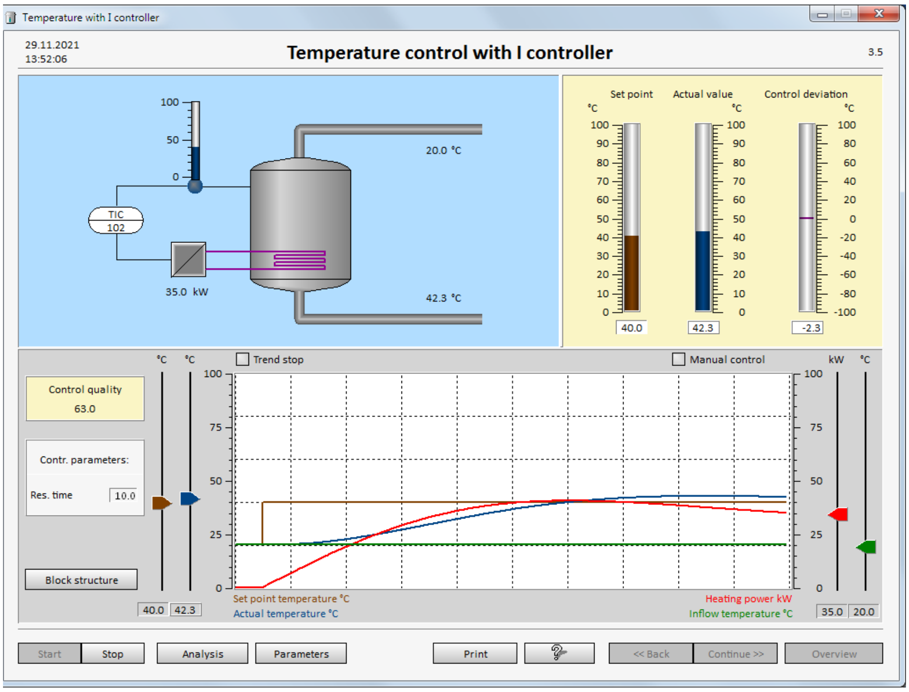
Select item 3.5 respectively 4.5 „Closed-loop control with I controller“.

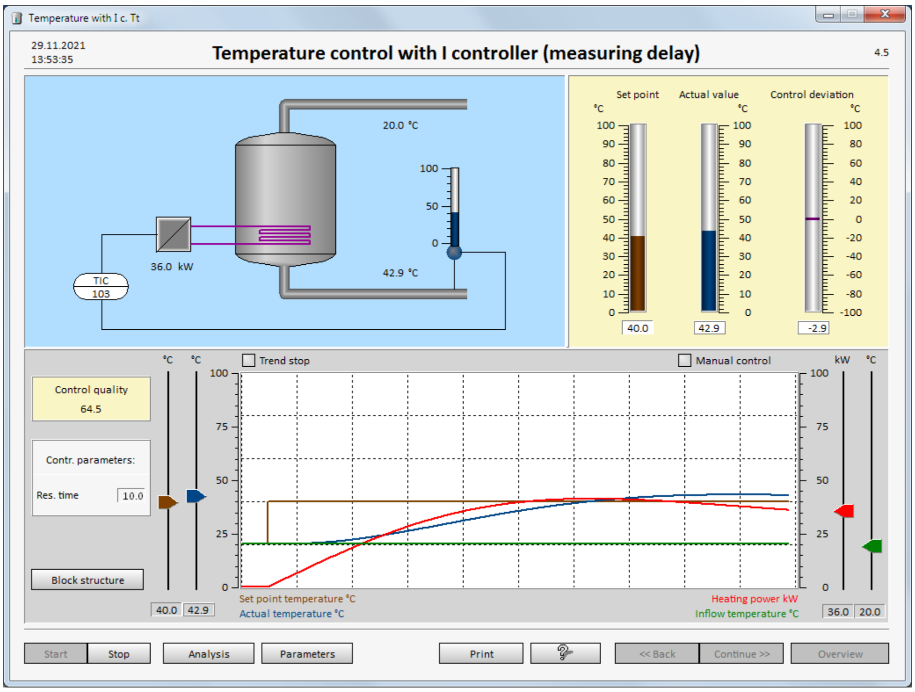
Press „Start“.

Task 7.

Leave the set integration time Ti at 10. Examine command response.

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



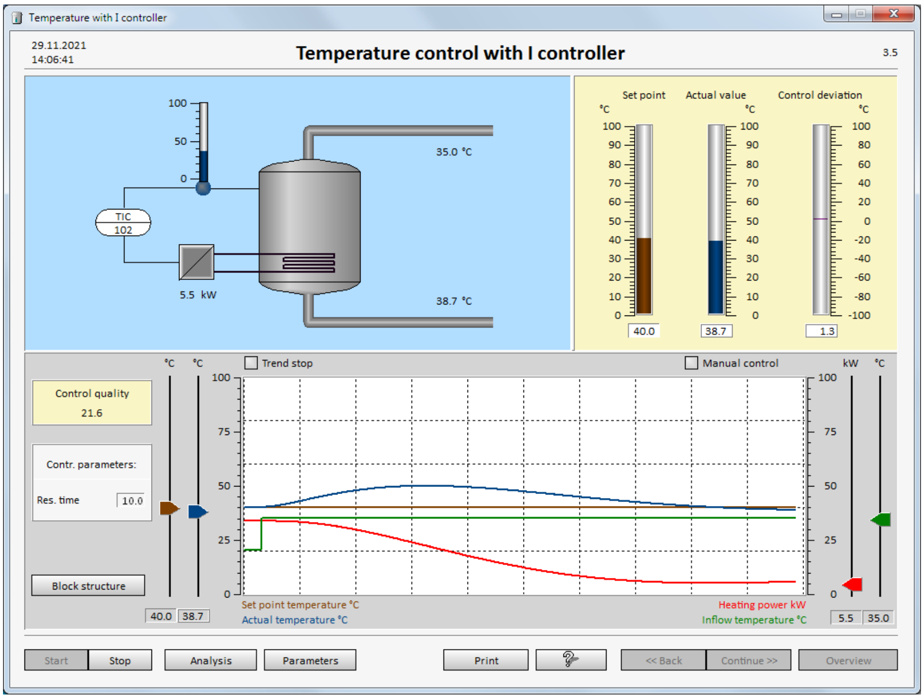


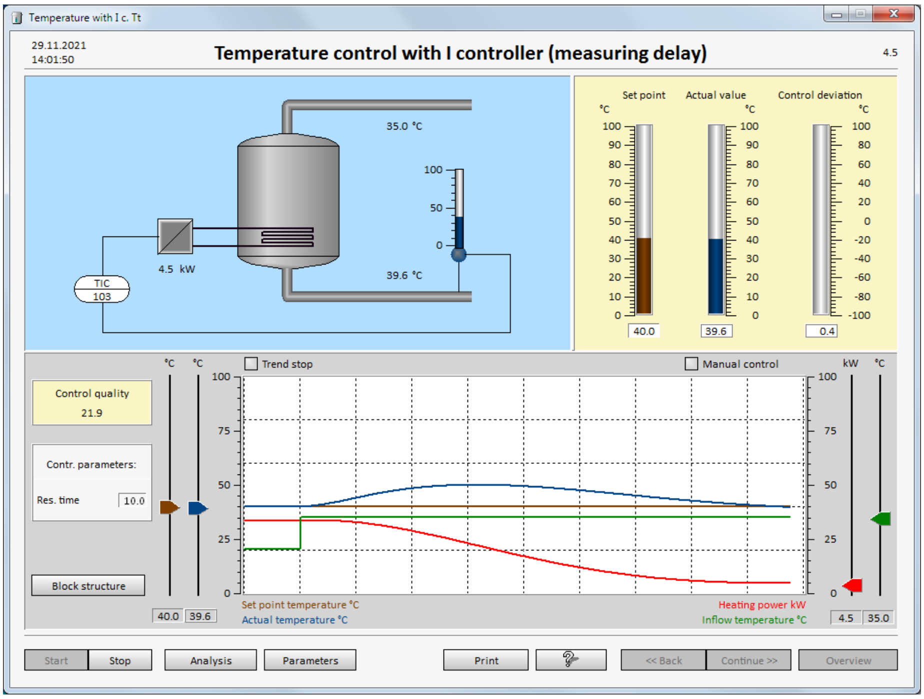
After a long settling phase, the actual value reaches the setpoint with an overshoot (using the integration time Ti of 10). You will not receive a steady-state control error.

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 setpoint.

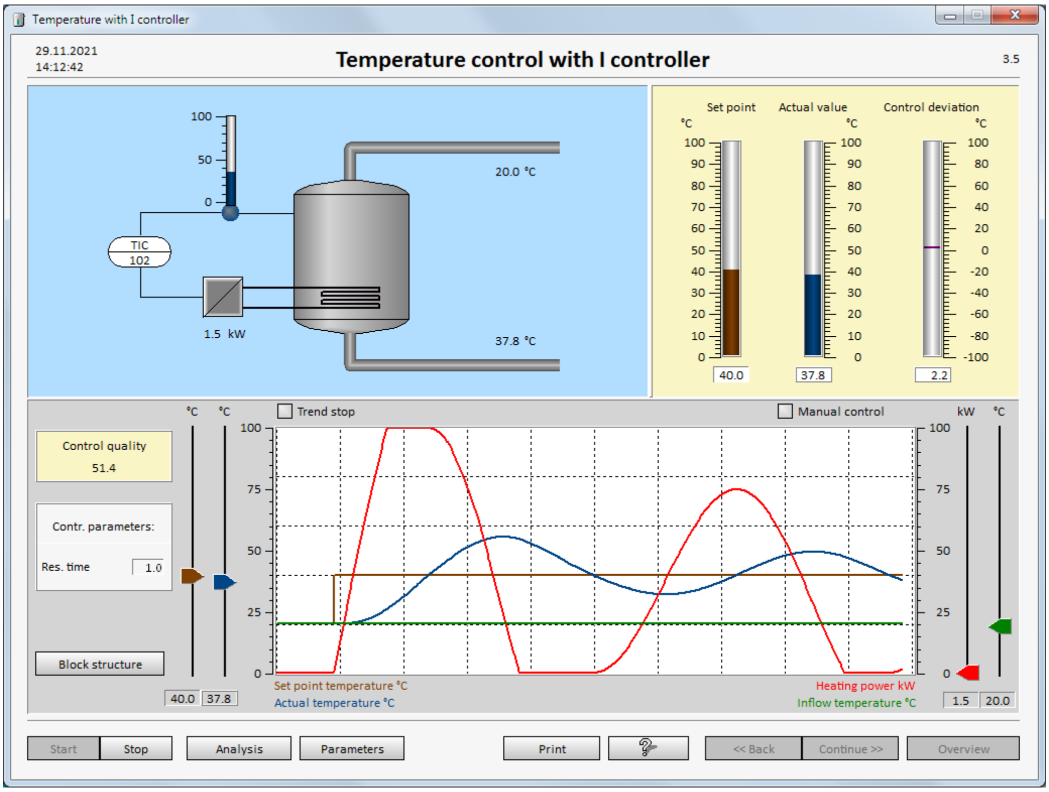
There is also no steady-state control error for the disturbance behavior.

Task 9.

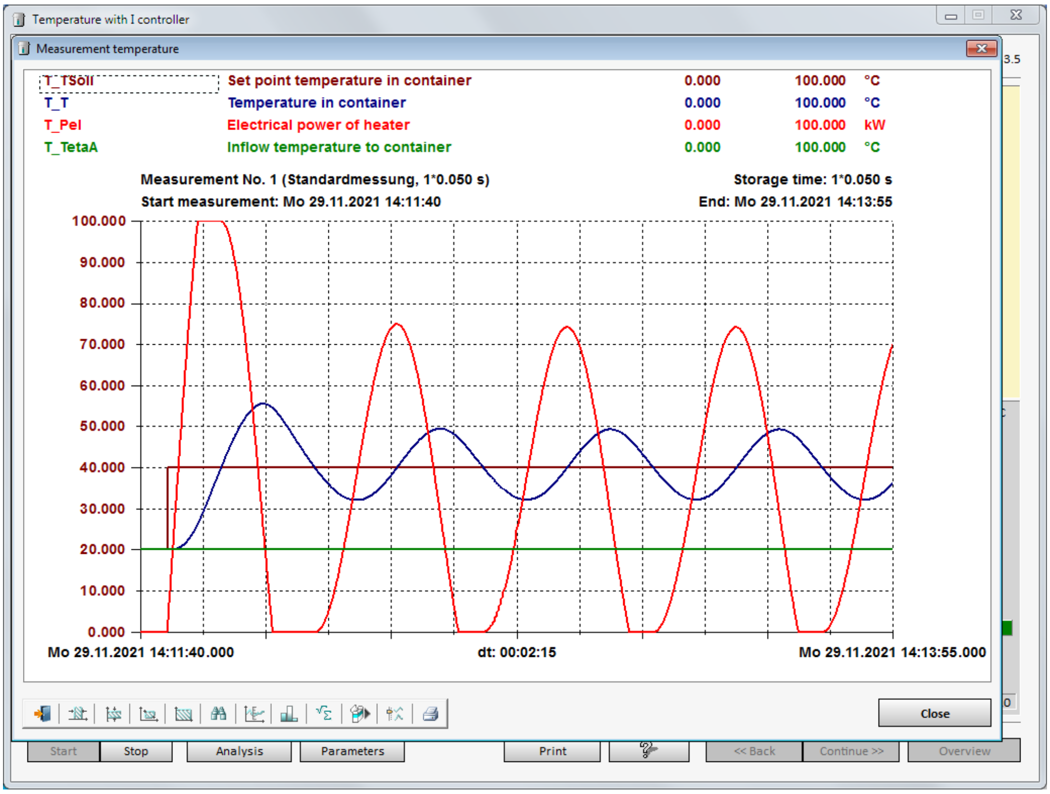
Restart the temperature control with the I-controller.

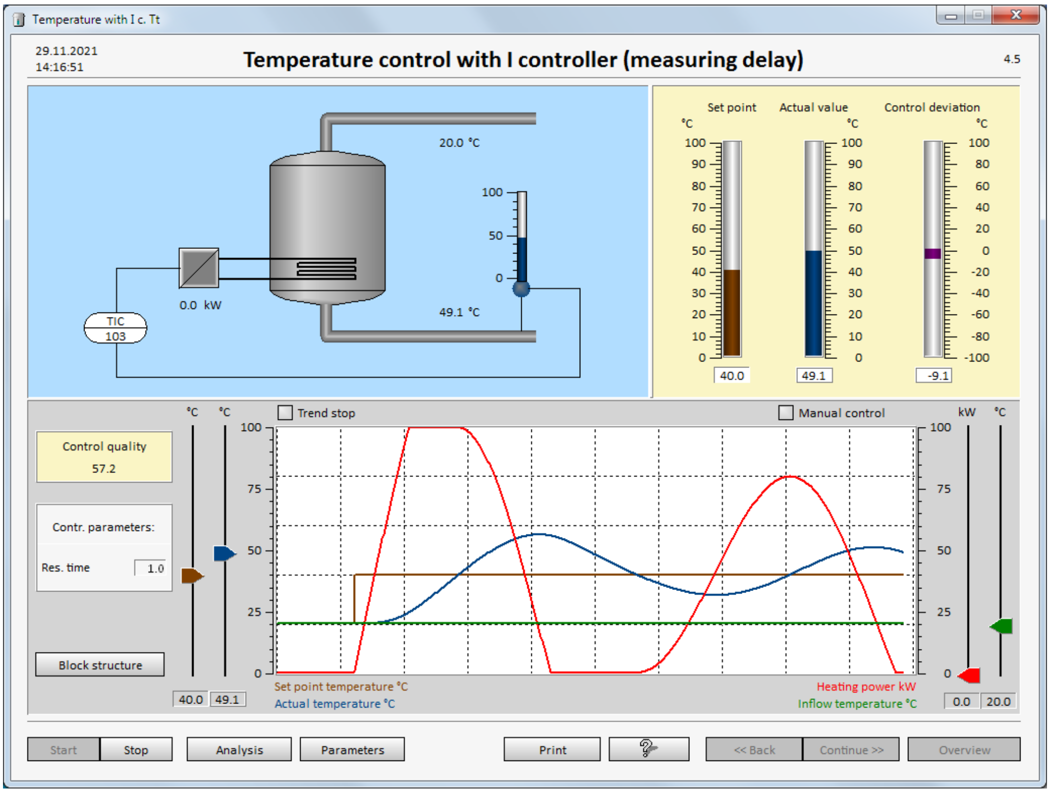
Change the set integration time (Res. Time) Ti to 1.

Examine the command response. Change the setpoint to 40°C.

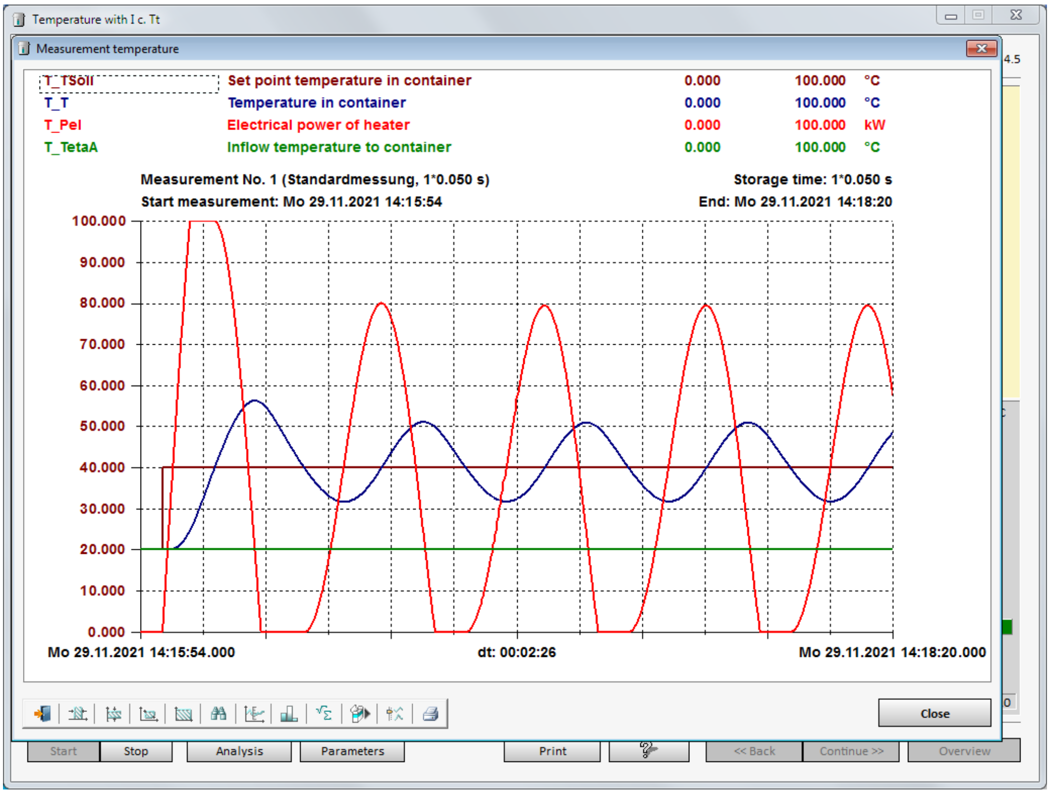


By clicking on "Analysis" you will get the recorded signal curves.





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 swings continuously around the setpoint.

In general:

If there is an I component (integrator) in the controller, the controller either manages to bring the actual value to the setpoint 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 setpoint and actual value are the same.

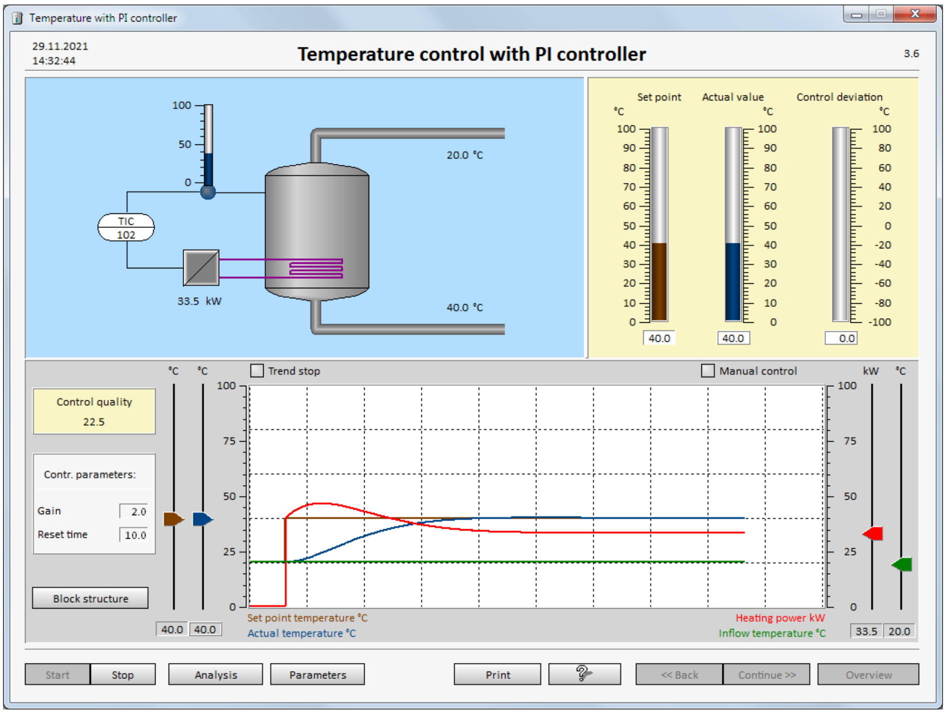
6.2.4 Closed-loop Control with PI Controller

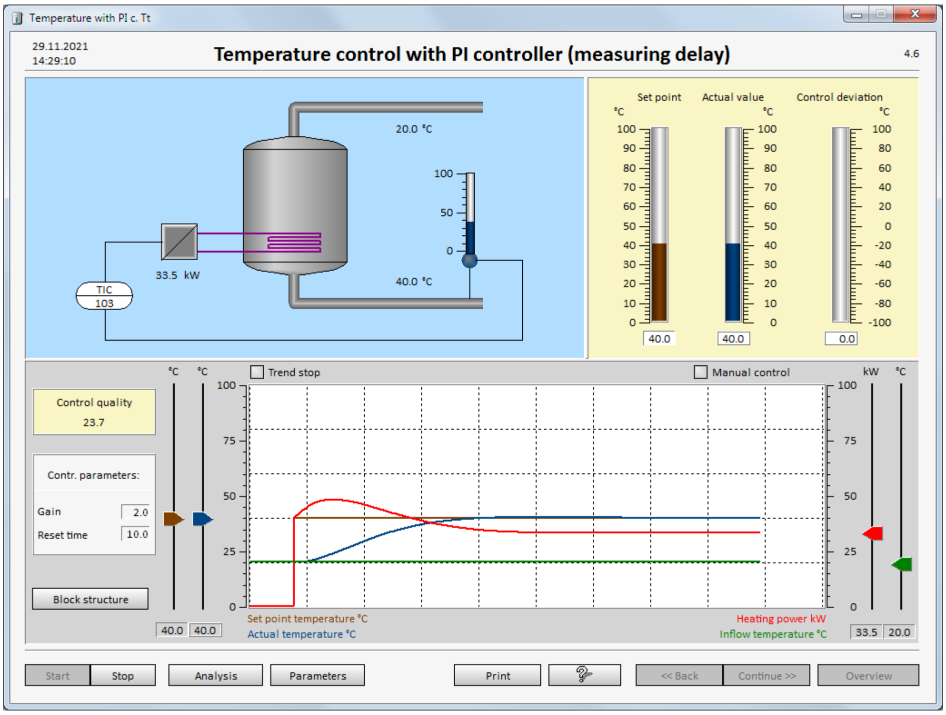
Go to „Overview“ and select item 3.6 respectively 4.6 „Closed-loop control with PI controller“. Press „Start“.

Task 10.

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

Change the setpoint from 20°C to 40°C.





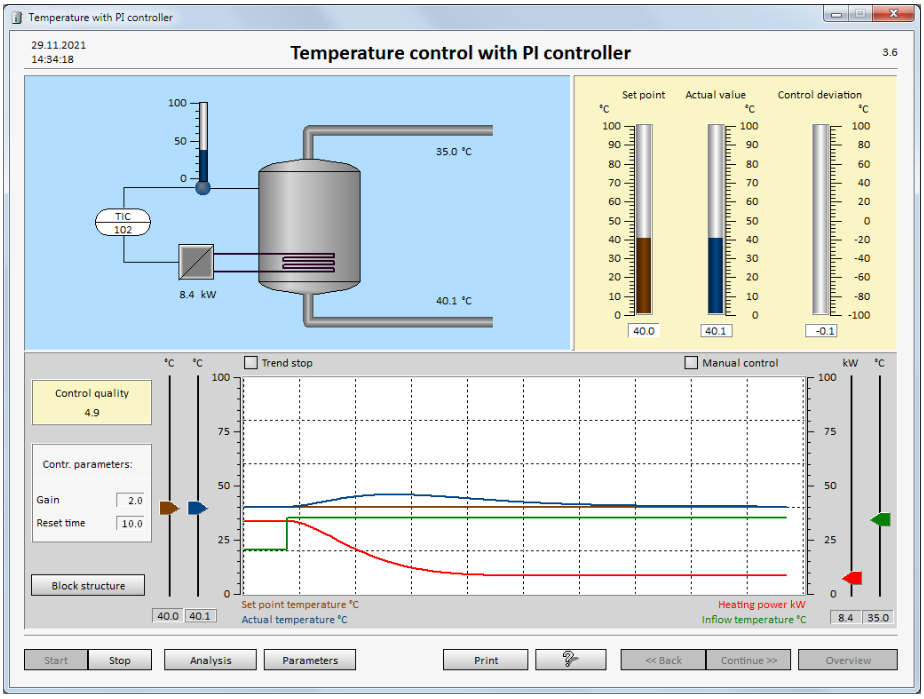
The control loop with the PI controller and the set parameters swings to the setpoint with a small overshoot. The actual value (controlled variable) reaches the setpoint (reference variable).

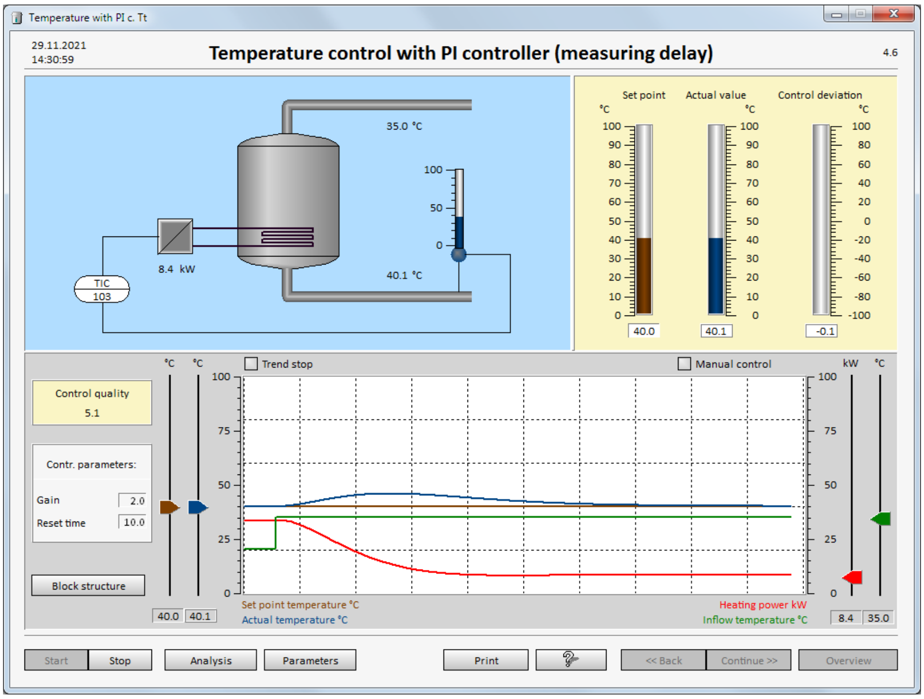
Task 11.

Investigate the disturbance response.

Let the control loop settle to the setpoint 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 output. After a settling phase, the actual value reaches the setpoint again.

Task 12.

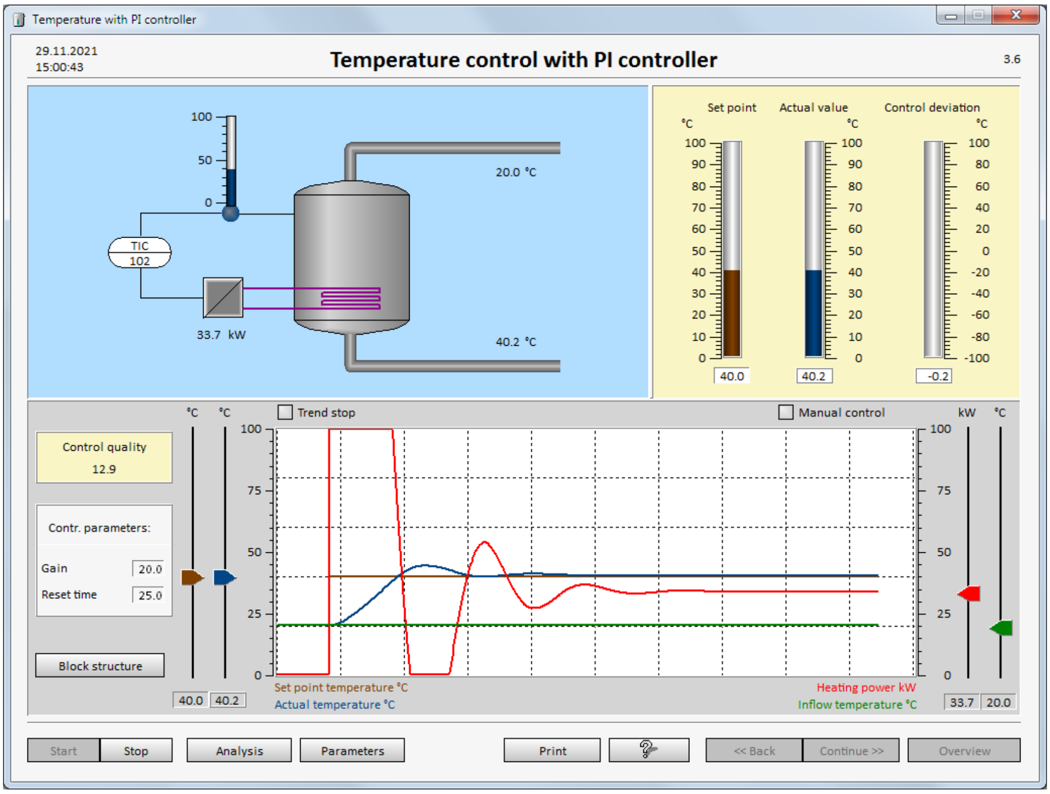
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled, when the actual value has reached the setpoint.

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 setpoint jump from 20°C to 40°C.

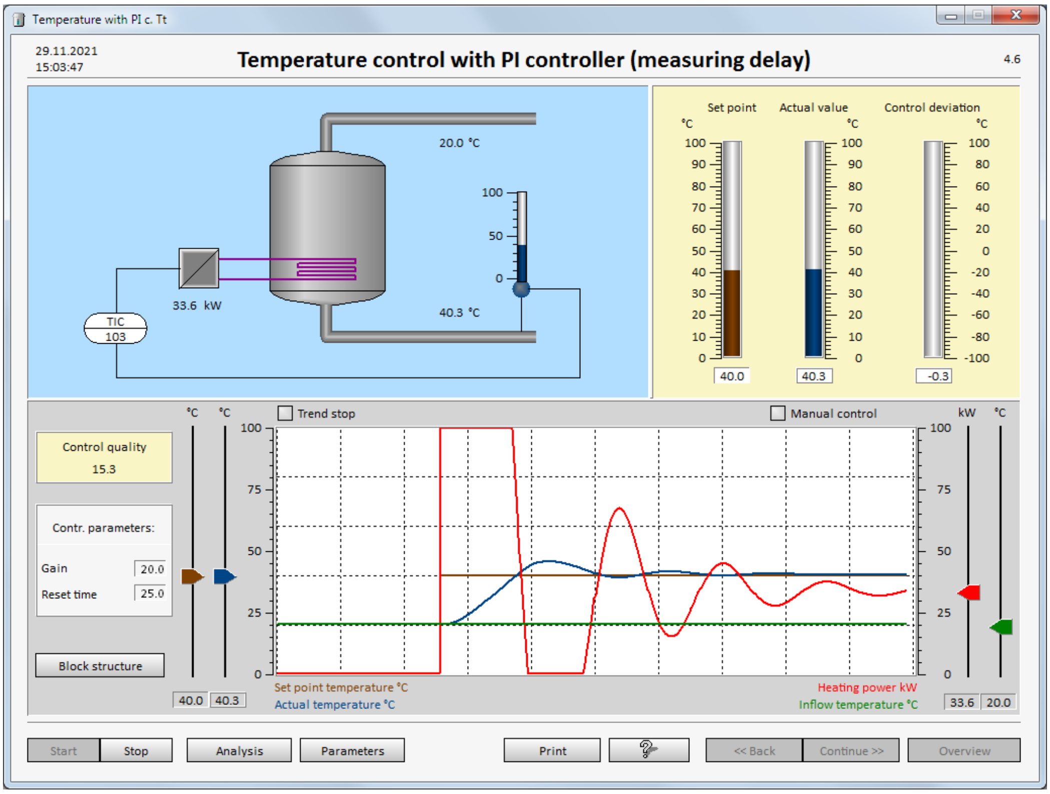
In order for the control quality to be comparable, all tests must be started with the same initial states. The best way to do this is to press “Stop” and then “Start” again. This means that the setpoint temperature (reference variable), inflow temperature (disturbance variable) and actual temperature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

Now change the controller parameters and then adjust the setpoint 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:

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

In general:

Since the PI controller has an I component (integrator), it also applies here that the controller brings the actual value to the setpoint 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.

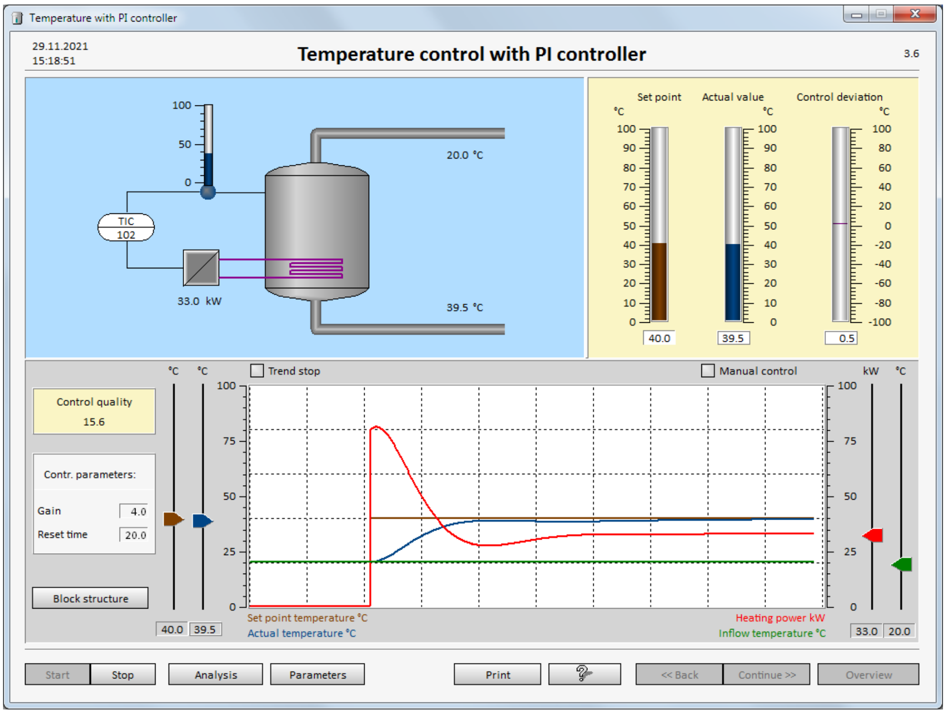
In order for a control loop to settle to a value, the control signal must be constant (output of the controller). The output value of an integrator is only constant when the input value of the integrator is equal to zero, i.e. when the setpoint and actual value are the same.

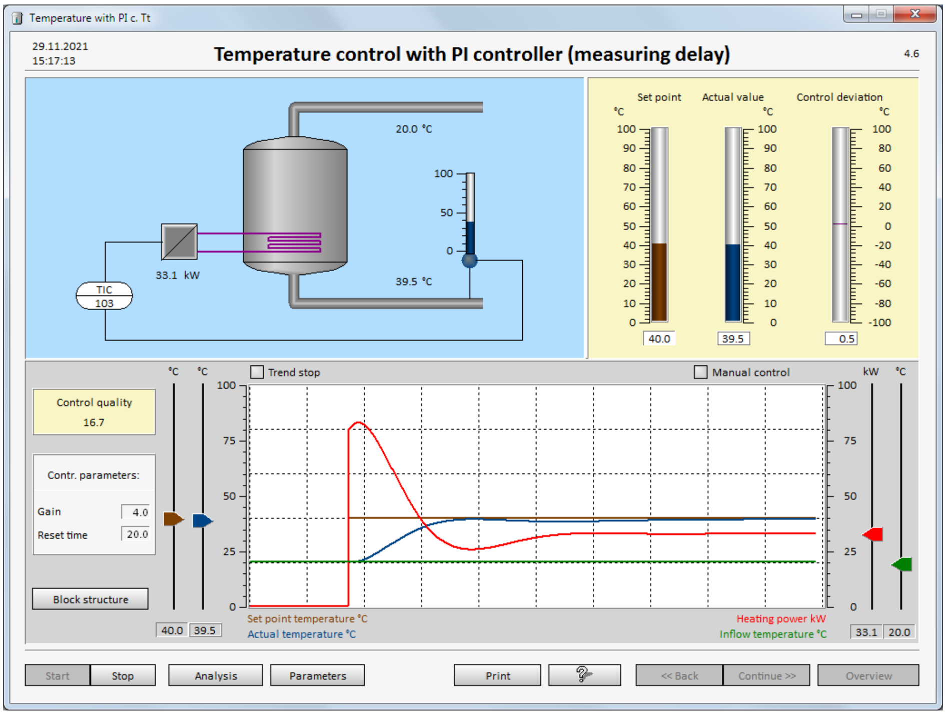
Task 13.

Restart the temperature control with the PI controller.

Try to find controller parameters with which the actual value reaches the setpoint 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 setpoint to 40°C.





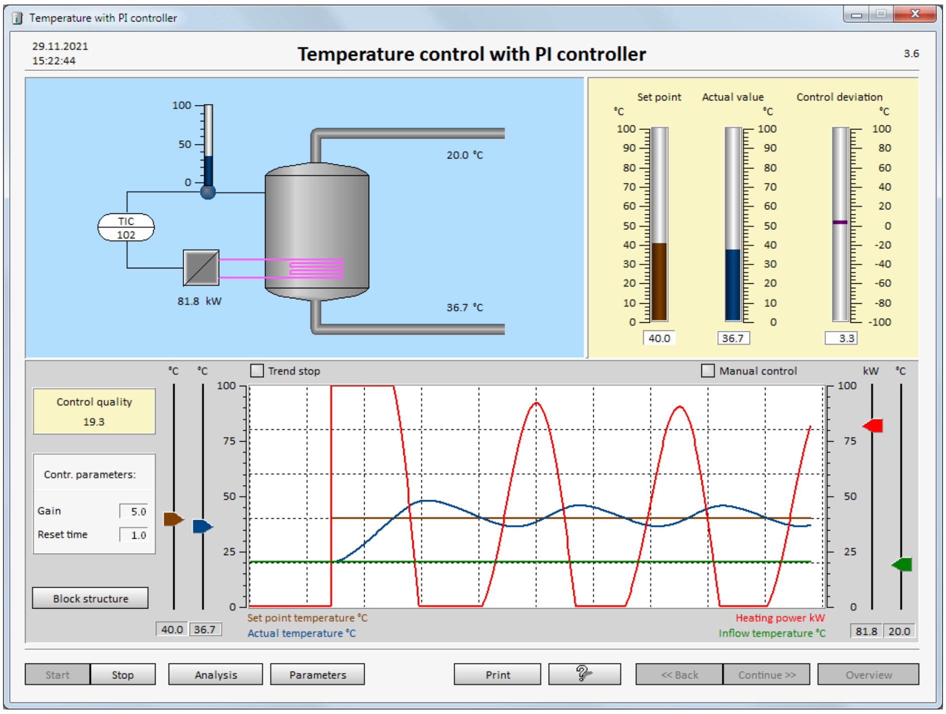
With the parameters K = 4 and Ti = 20, for example, an aperiodic behavior is obtained for both temperature controls.

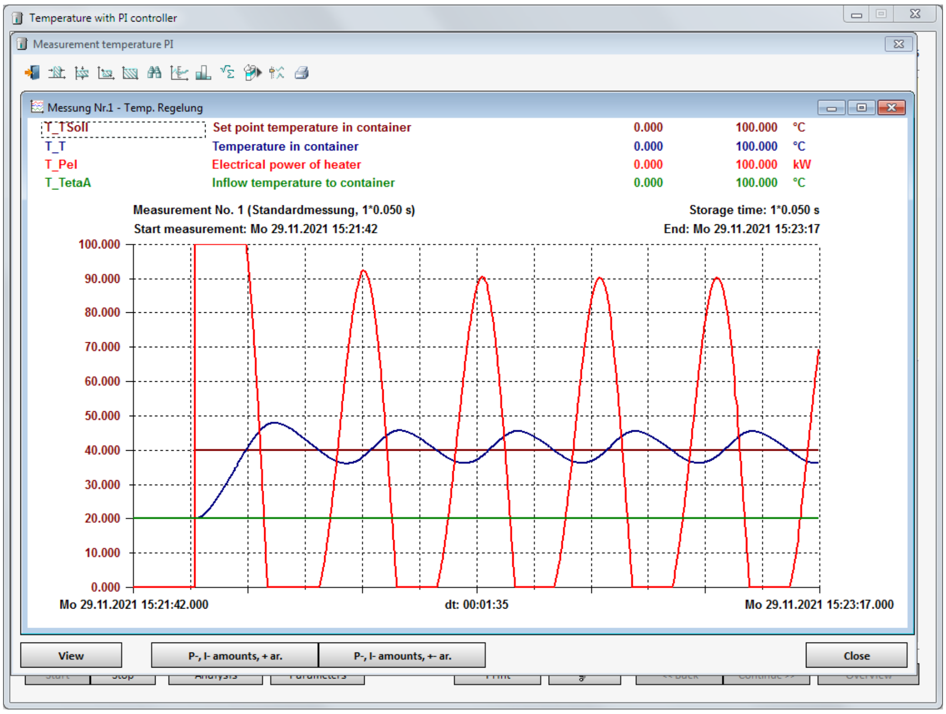
Task 14.

Restart the temperature control with the PI controller.

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

Enter a setpoint jump from 20°C to 40°C in each case.

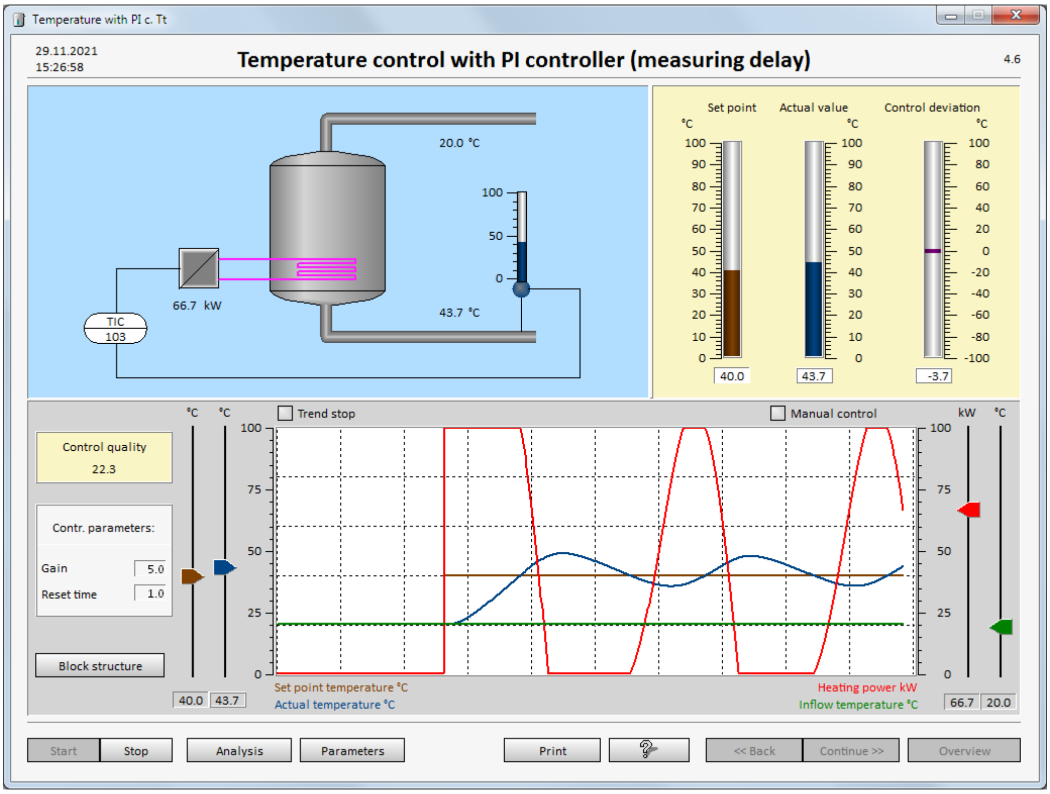


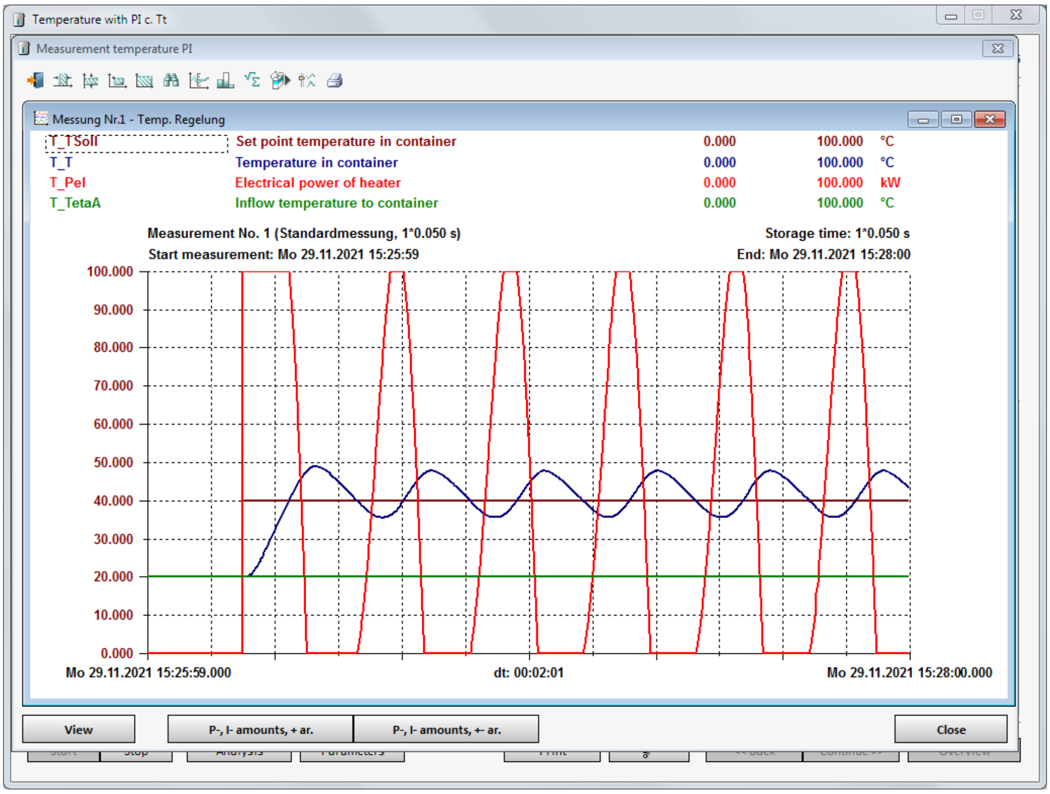


You can achieve this with the controller parameters:

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

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





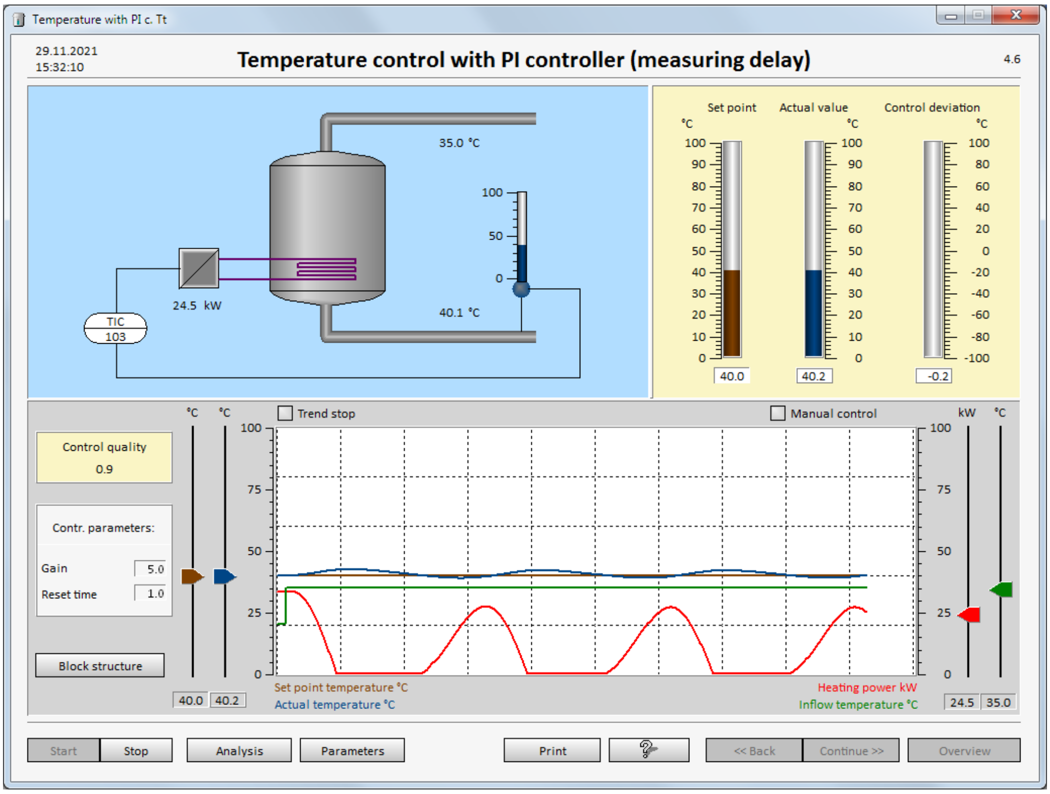
By pressing "Analysis" you have the option of looking at the stored signal curves and examining the settling behavior.

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 setpoint of 40°C. Then change the parameters to gain K = 5 and reset time Ti = 1. Enter a fault jump 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 setpoint and remains at the setpoint.
- 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.

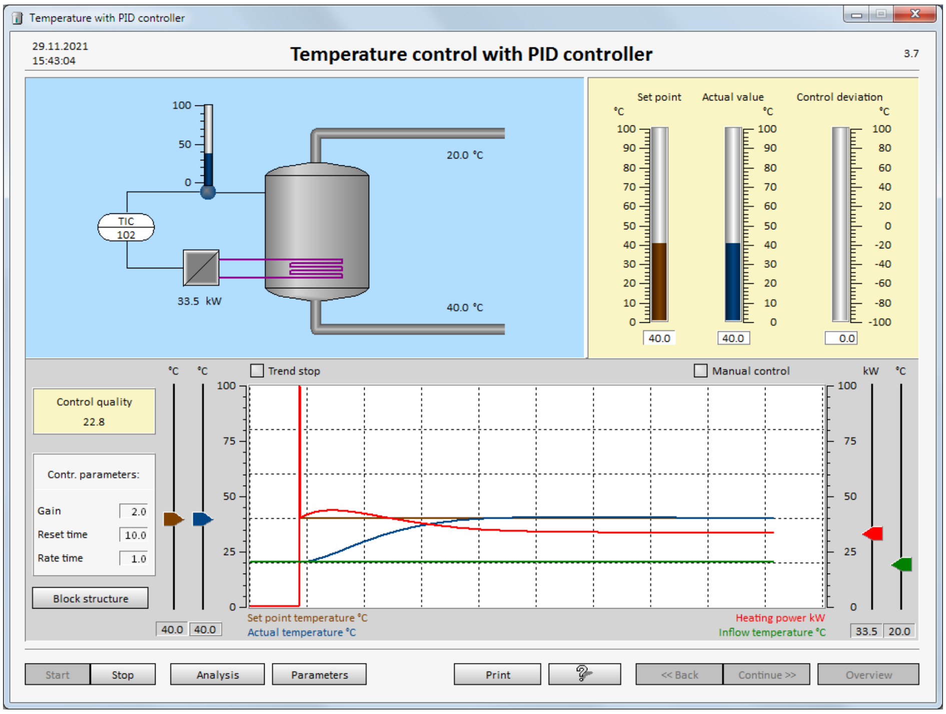
6.2.5 Closed-loop Control with PID Controller:

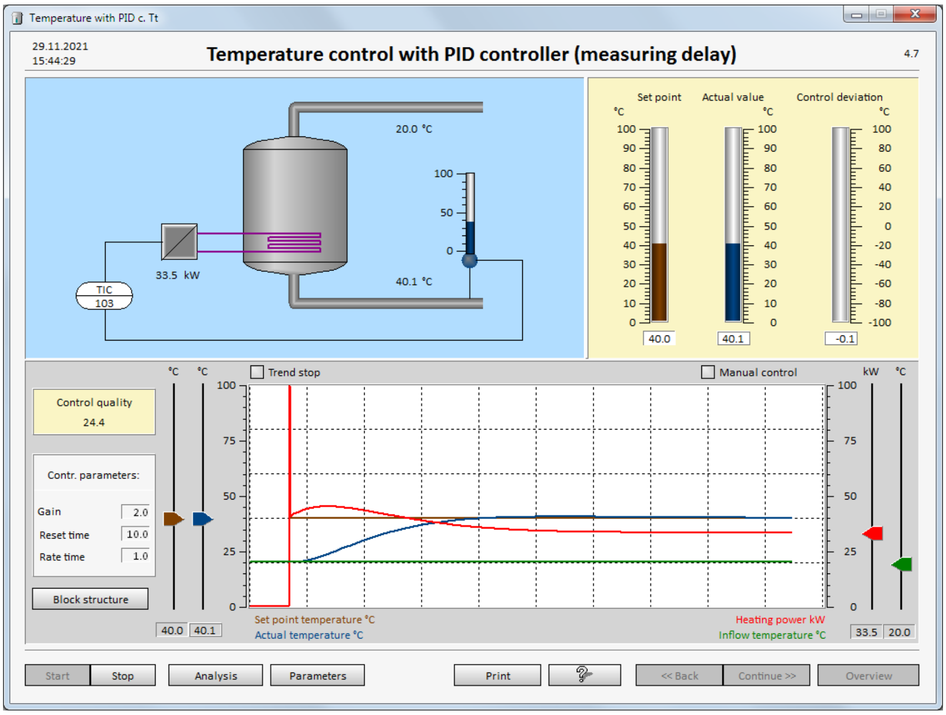
Go to „Overview“ and select item 3.7 respectively 4.7 „Closed-loop control with PID controller“. Press „Start“.

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 setpoint to 40°C.





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

As can be seen in the trend diagram, the sudden change in the setpoint causes a peak in the control signal (heating output). 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 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:

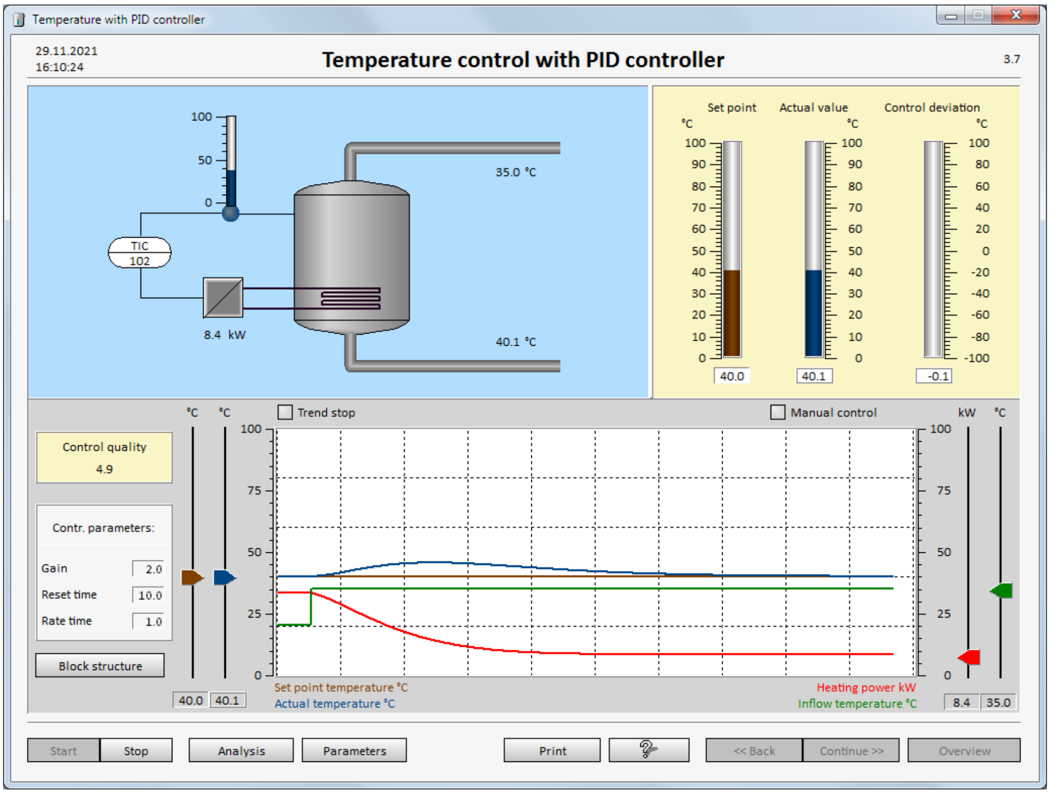
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Analysis" (display of the stored signal values) and selection of a corresponding time range.

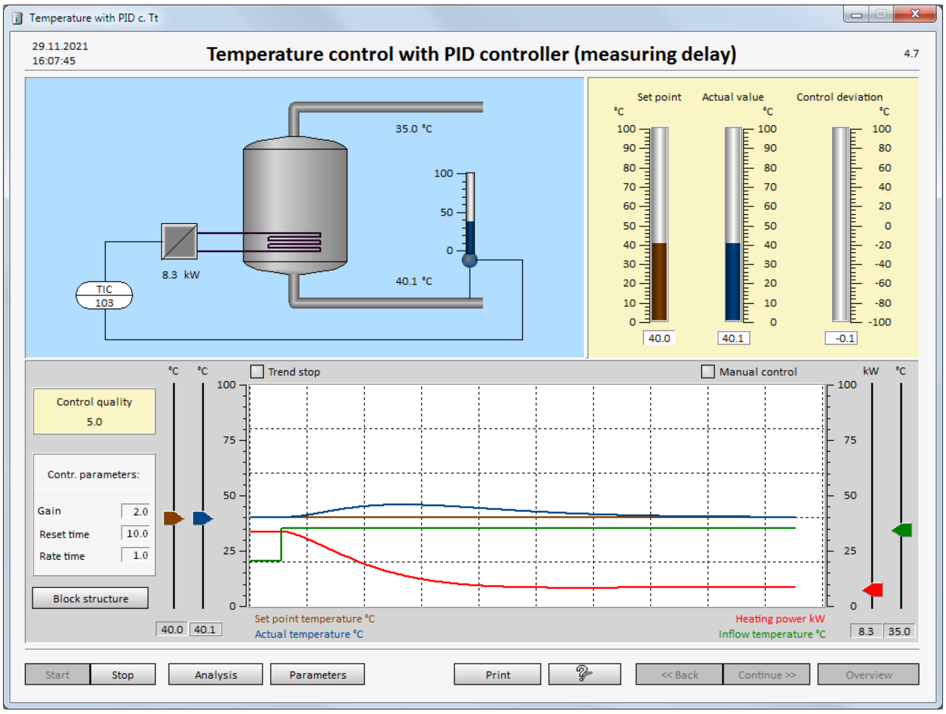
Task 17.

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 setpoint 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



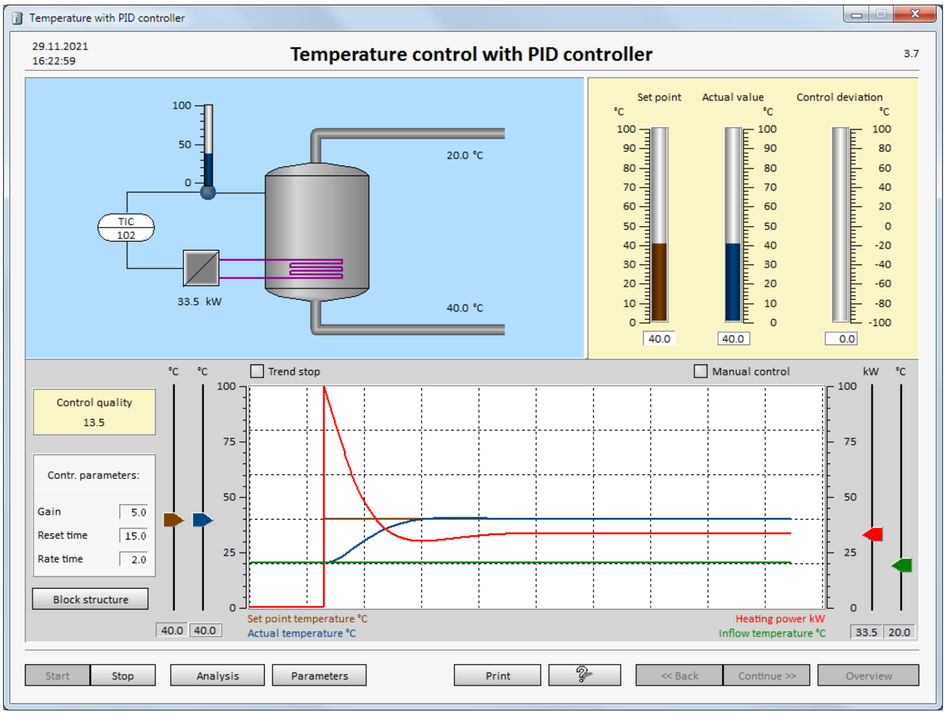


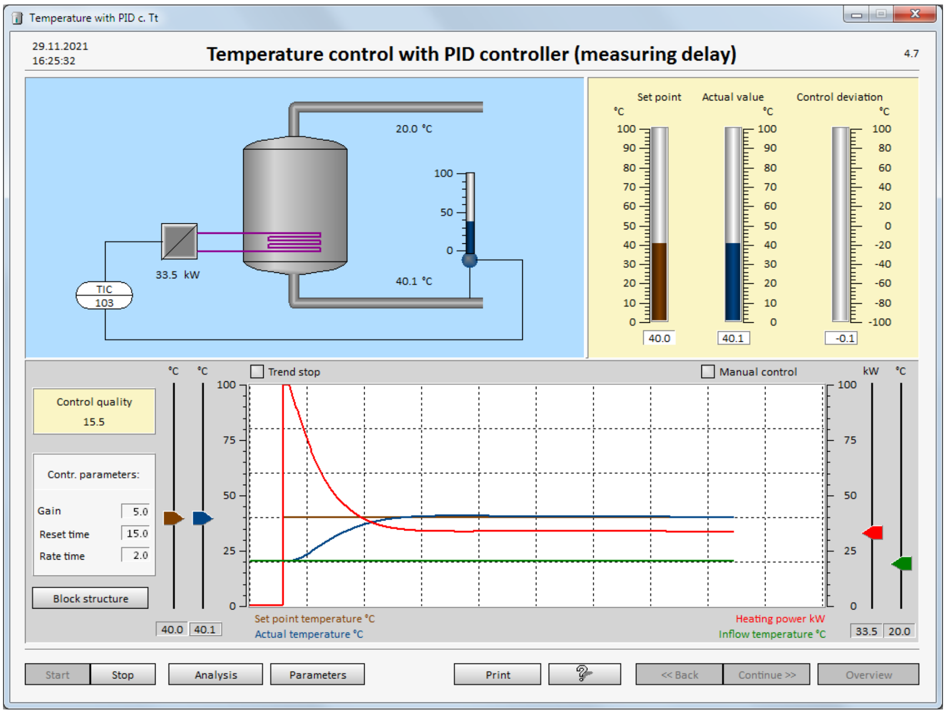
In the event of a disturbance response, too, the control loop is controlled with the specified controller parameters and the actual temperature (controlled variable) reaches the setpoint temperature (reference variable) again after a period of time.

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 press “Stop” and “Start” again, change the controller parameters and then adjust the setpoint 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.).

Note:

In practice, the PI controller is mainly used as a controller. If a PID controller is used, the D component is often turned away 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).

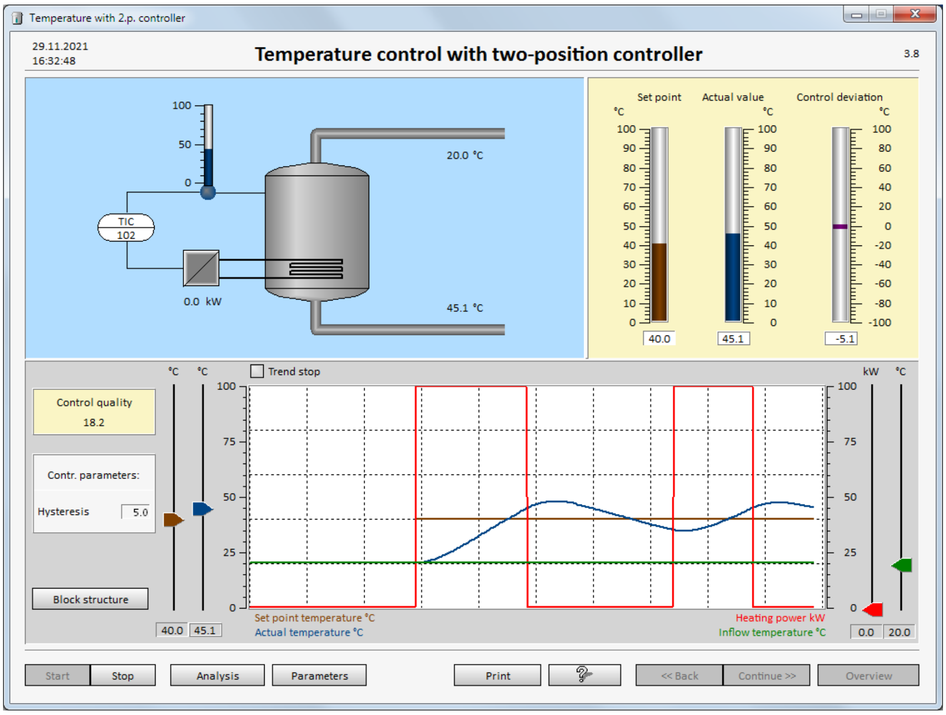
The D component considers the change between the setpoint and the actual value. If the change increases, i.e. the difference between the setpoint and actual value increases, the D component adds a calculated value to the control signal. If the change between the setpoint and actual value becomes smaller,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

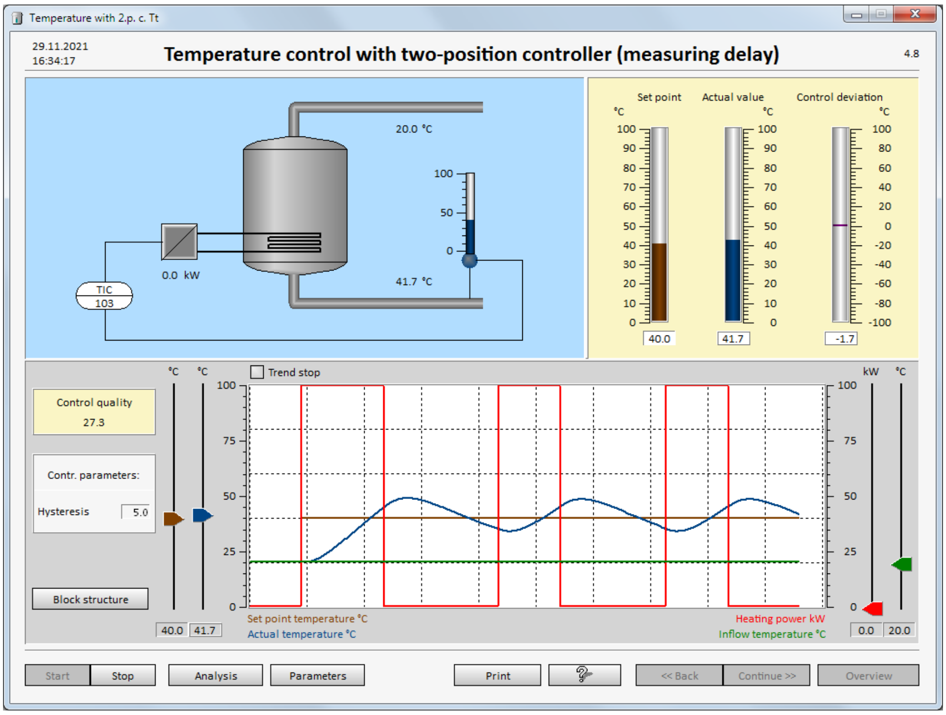
6.2.6 Closed-loop Control with two-pos. Controller

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

Task 19.

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





The actual temperature (controlled variable) fluctuates around the setpoint. The size of the oscillation depends on the parameter (hysteresis).

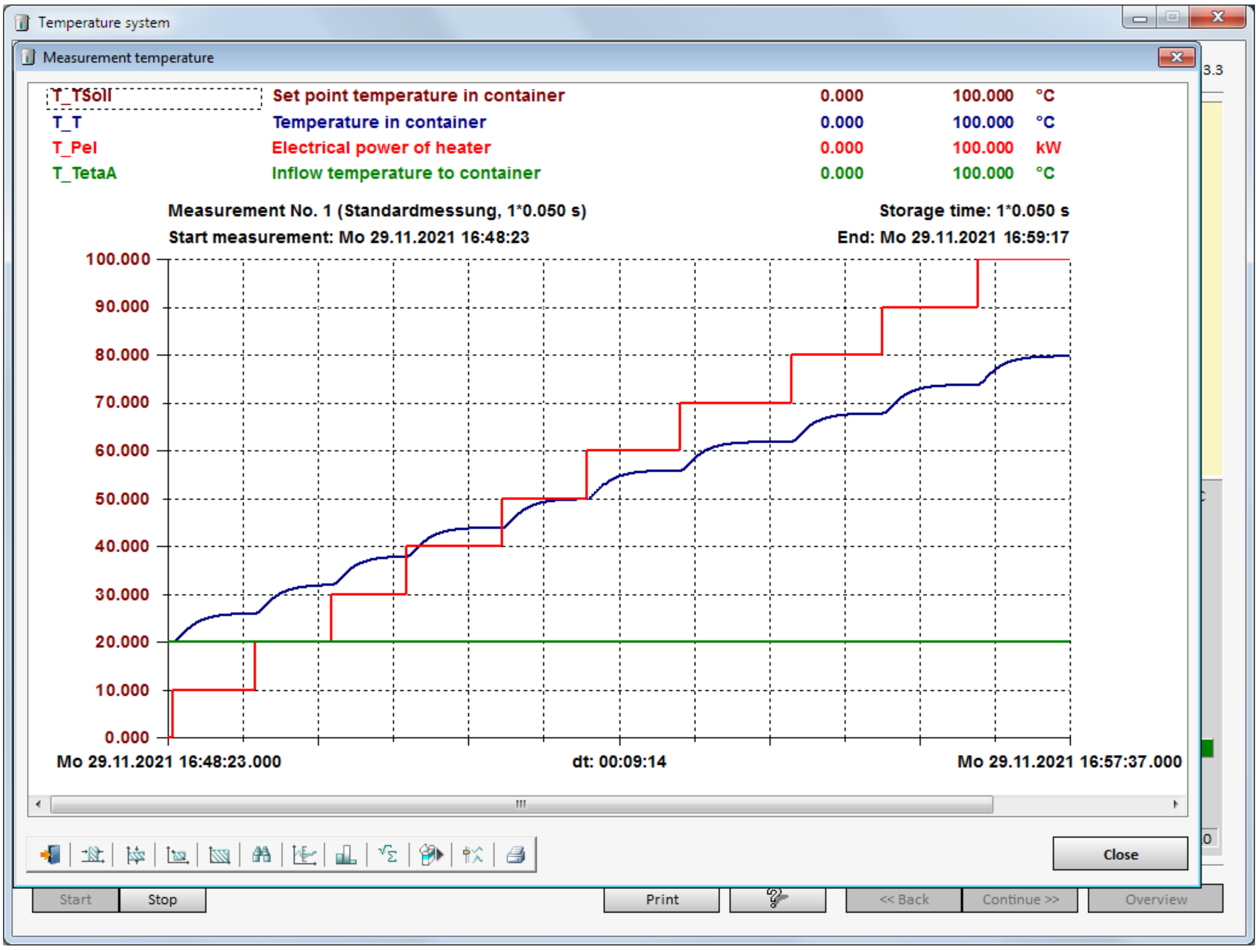
6.3 Examine Controlled System

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 route during the jumps is similar. The actual temperature always changes by approx. 6°C when the heating output 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

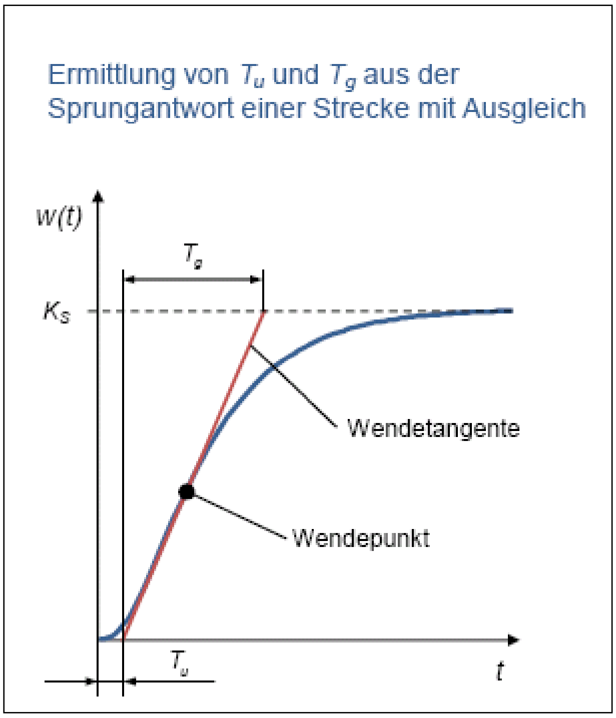
The temperature system with and without time delay is a controlled system with self-regulation.

In the event of a sudden change in the manipulated variable (control signal), a controlled system with self-regulation swings 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 output 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 jump in the control signal (sudden change in the control signal by 1):



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

It means:

Te = Tu = Delay time

Tb = Tg = Compensation tine

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:

Regler-verhalten	Gütekriterium: Überschwingung nach Gegenseite mit 20% von x_m, kürzeste Schwindungsdauer		Gütekriterium: aperiodischer Regelvorgang mit kürzester Dauer	
	Störung	Führung	Störung	Führung
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	$K_P \approx \frac{1{,}2}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2 \cdot Tu$ $T_v \approx 0{,}42 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1{,}35 \cdot T_g$ $T_v \approx 0{,}47 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2{,}4 \cdot T_u$ $T_v \approx 0{,}42\, T_u$	$K_P \approx \frac{0{,}6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$ $T_v \approx 0{,}5 \cdot T_u$

Für Regelstrecken *ohne Ausgleich* ist statt $\frac{T_g}{K_S \cdot T_u}$ der Ausdruck $\frac{1}{K_{IS} \cdot T_u}$ einzusetzen.

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“.

Press „Start“. Enter a jump of the heating power from 0% to 10%.

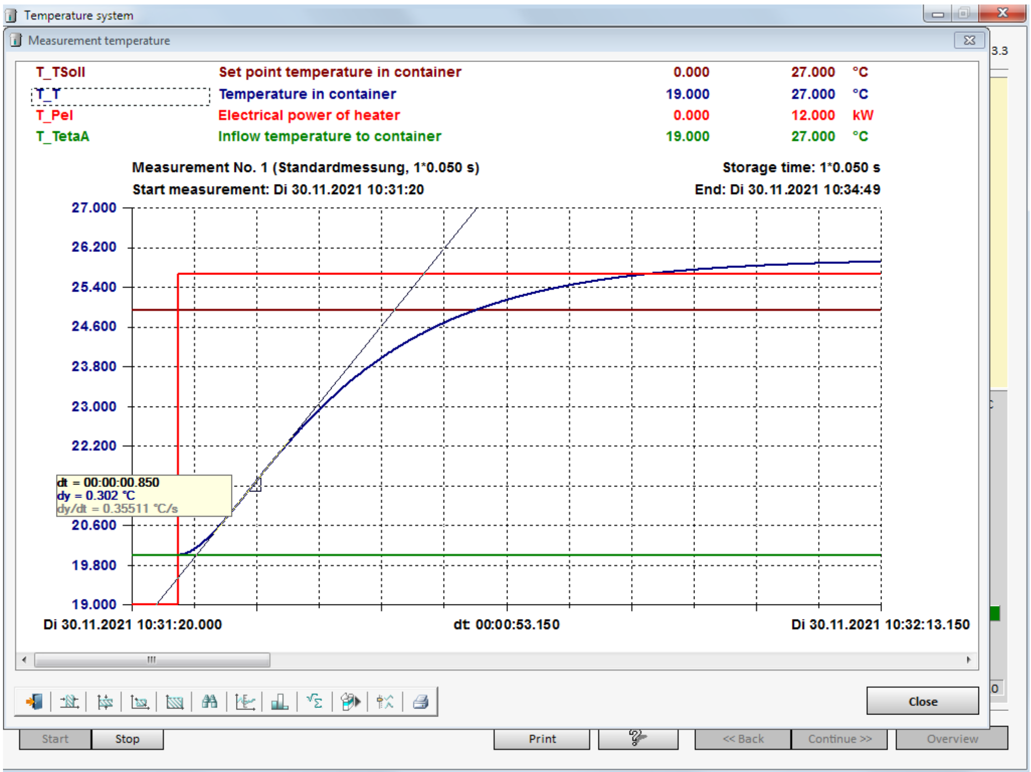
All signal curves are saved and can be measured and evaluated using "Analysis".

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

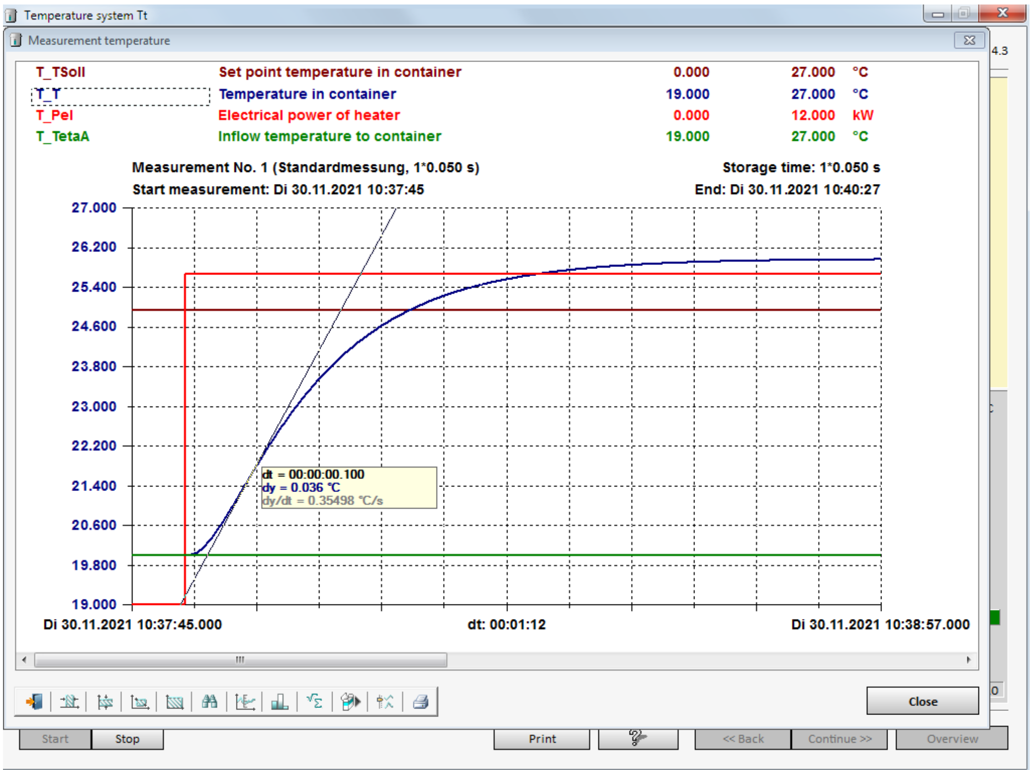
By clicking on the "Analysis" button, you will get the measurement curves. With the help of the button bar in the window, time and value segments can be selected (Zooming).

Try to find the area of interest for the evaluation with the jump 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.



Signal curve for temperature system without time delay



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" (Temperature in container). Click on the blue curve to get the associated measured value and time. By holding and pulling, 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) / Jump 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.

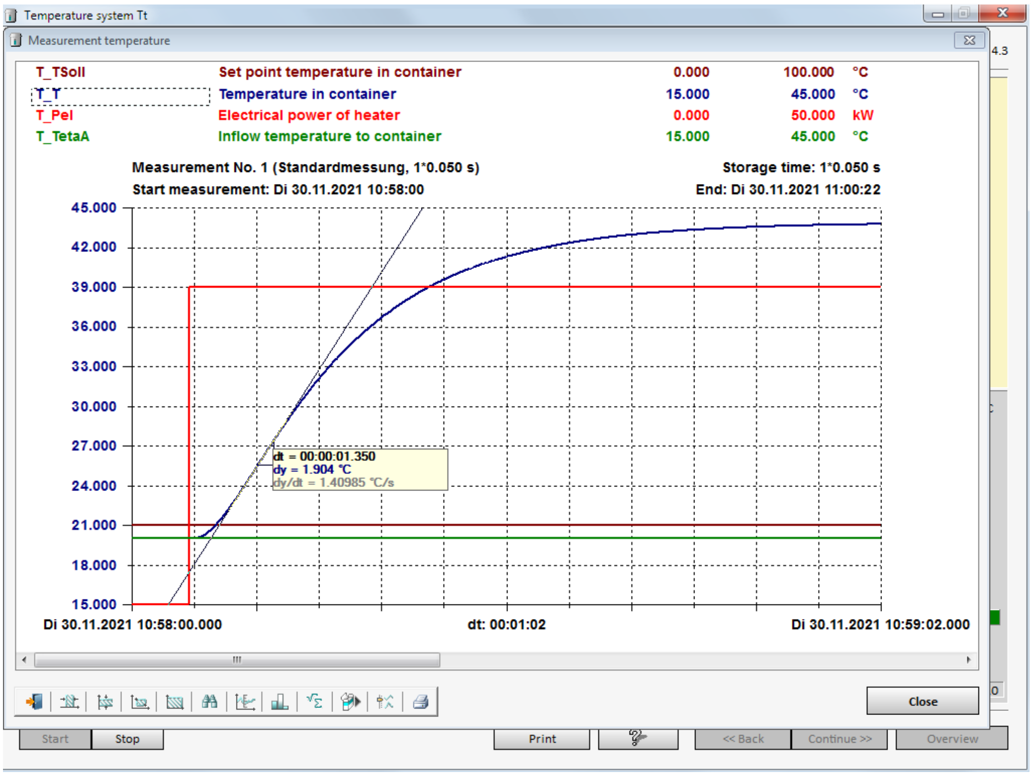
So: Te = Tu = 1,3s   Tb = Tg = 17,14s   Ks = 0,6

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 jump 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



Temperature system with time delay and jump 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

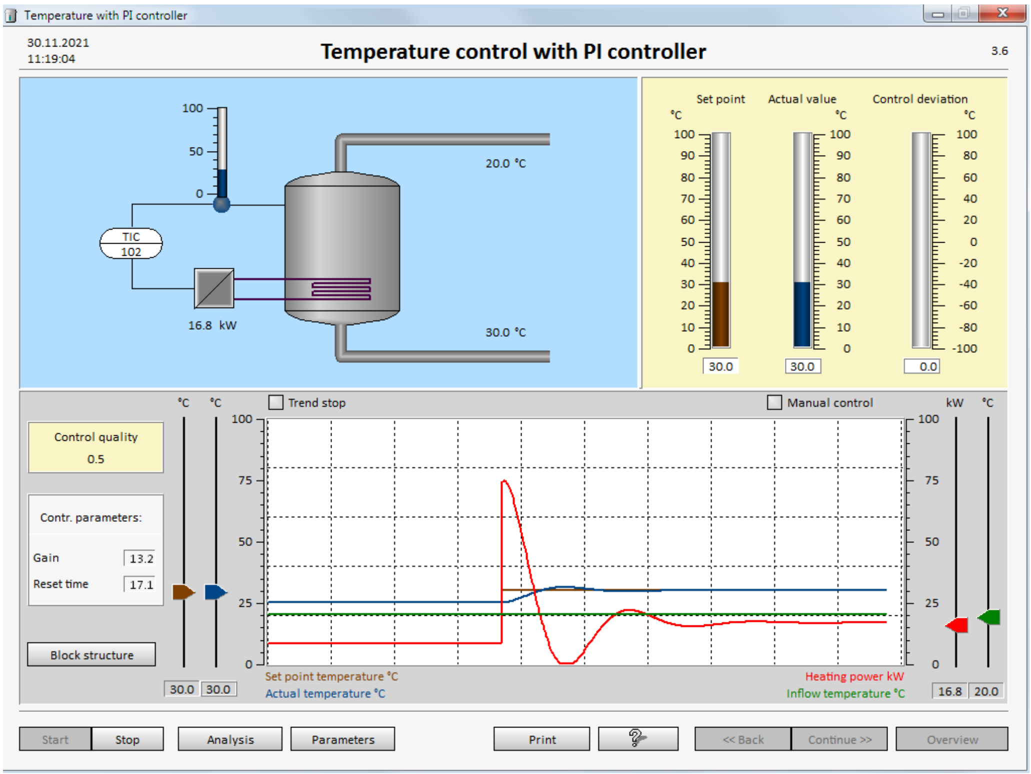
Disturbance response with 20% overshoot

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

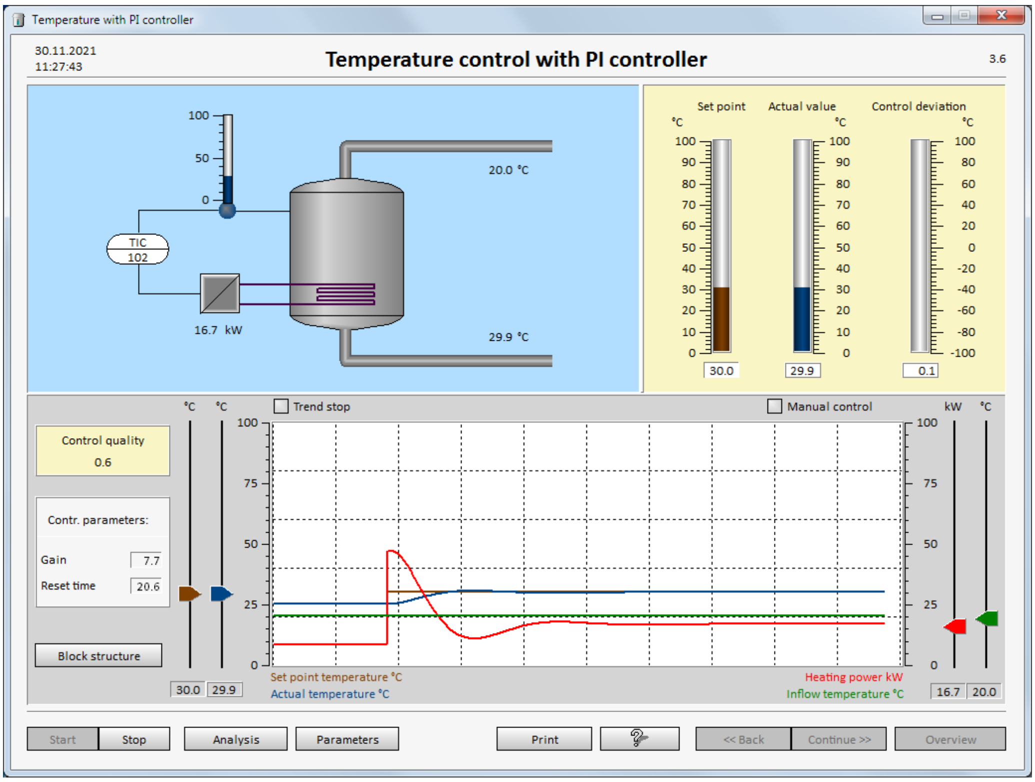
Disturbance response aperiodic

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

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

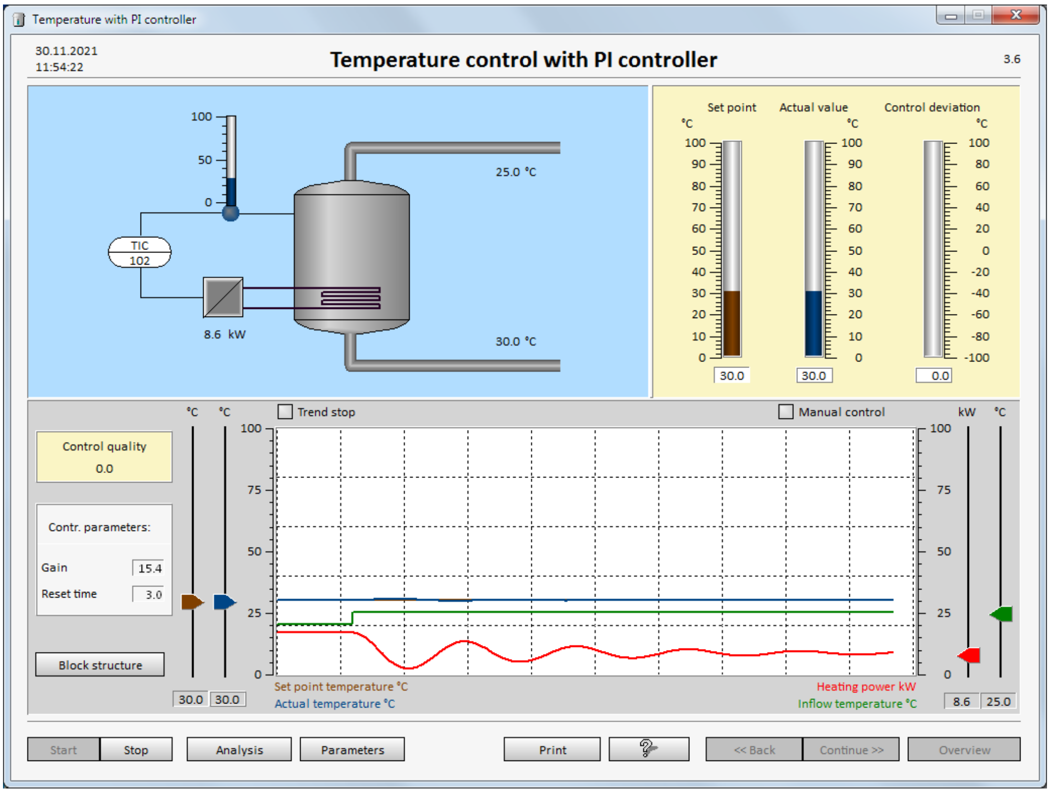


Command response with 20% overshoot



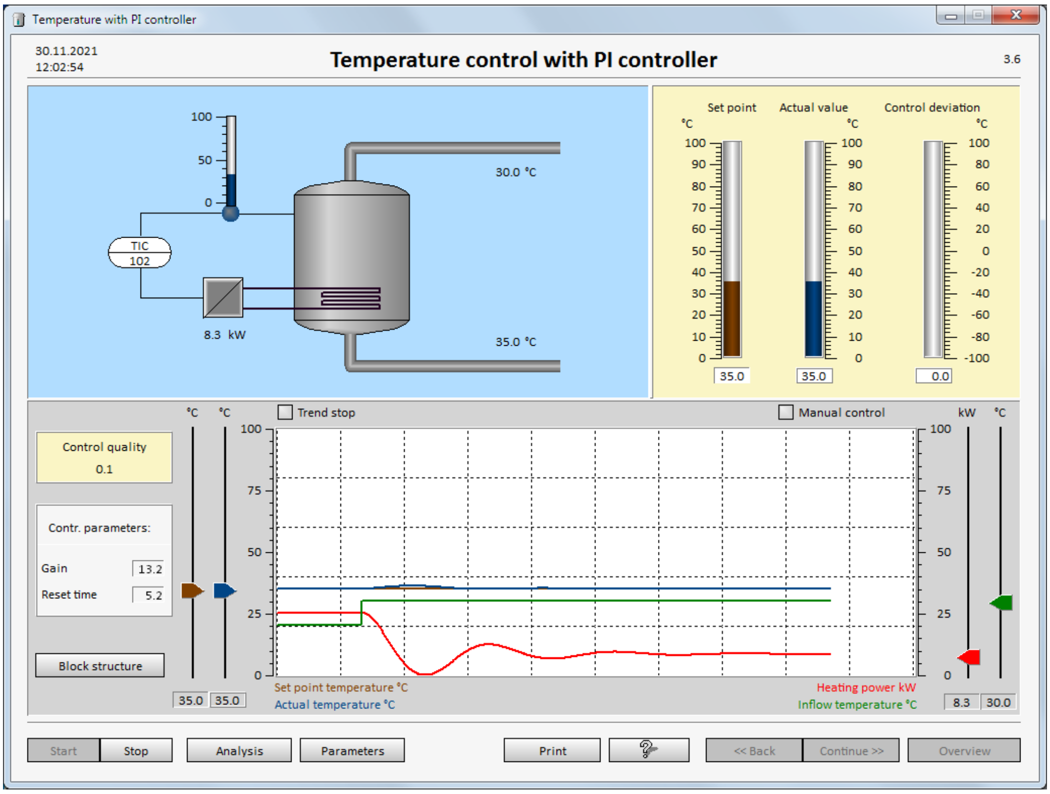
Command response aperiodic

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.



Disturbance response with 20% overshoot

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.



Disturbance response aperiodic

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

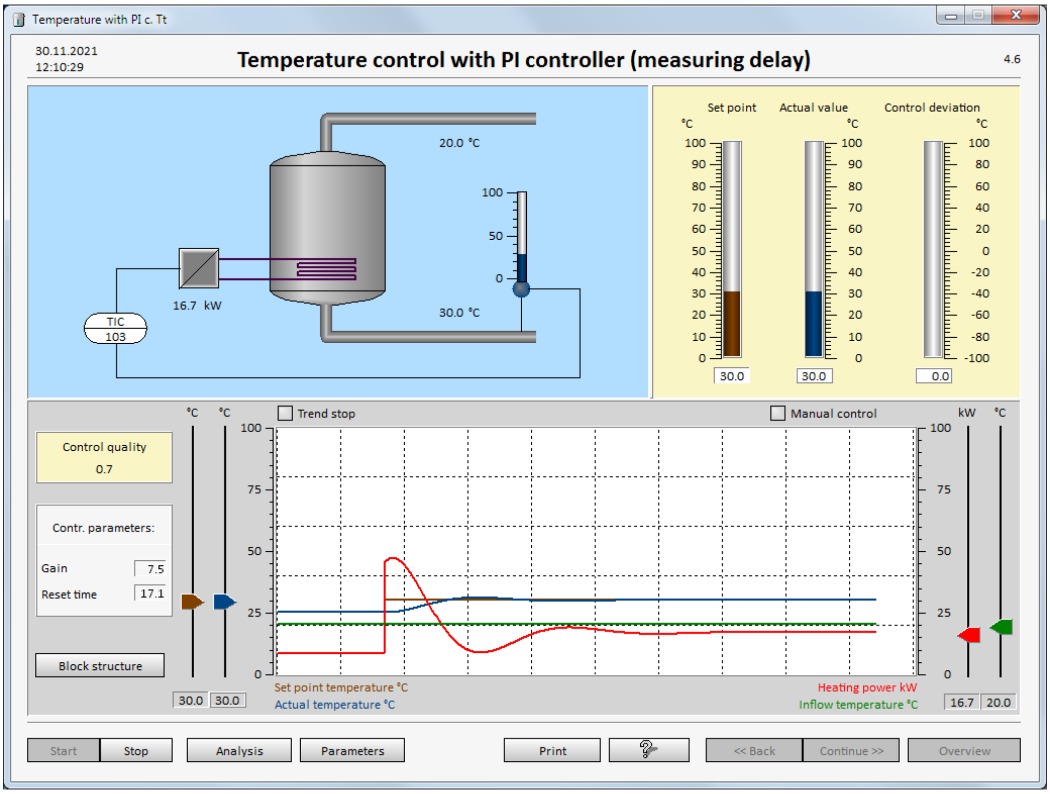
Disturbance response with 20% overshoot

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

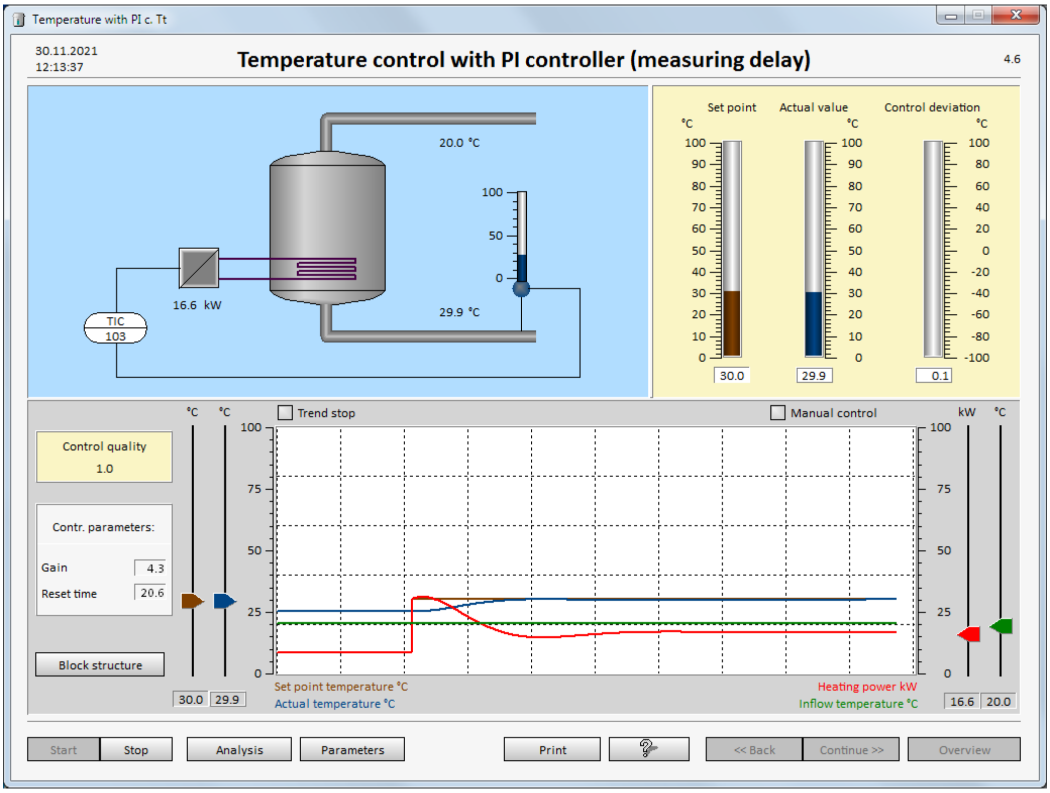
Disturbance response aperiodic

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

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

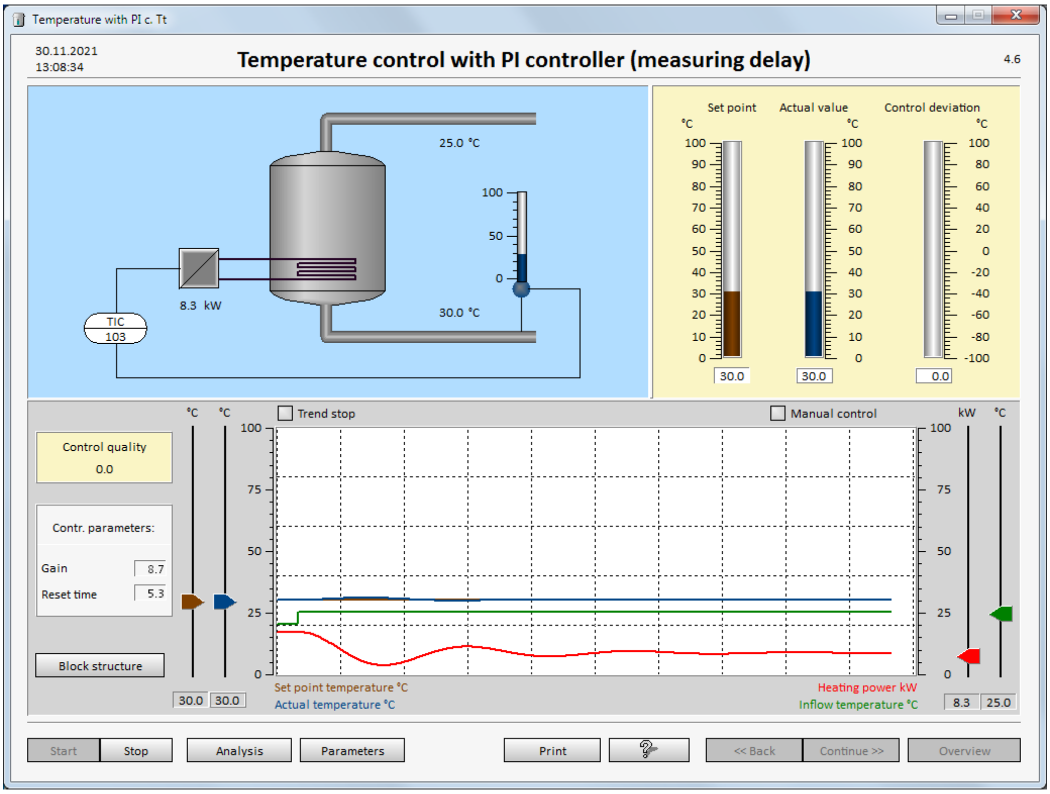


Command response with 20% overshoot



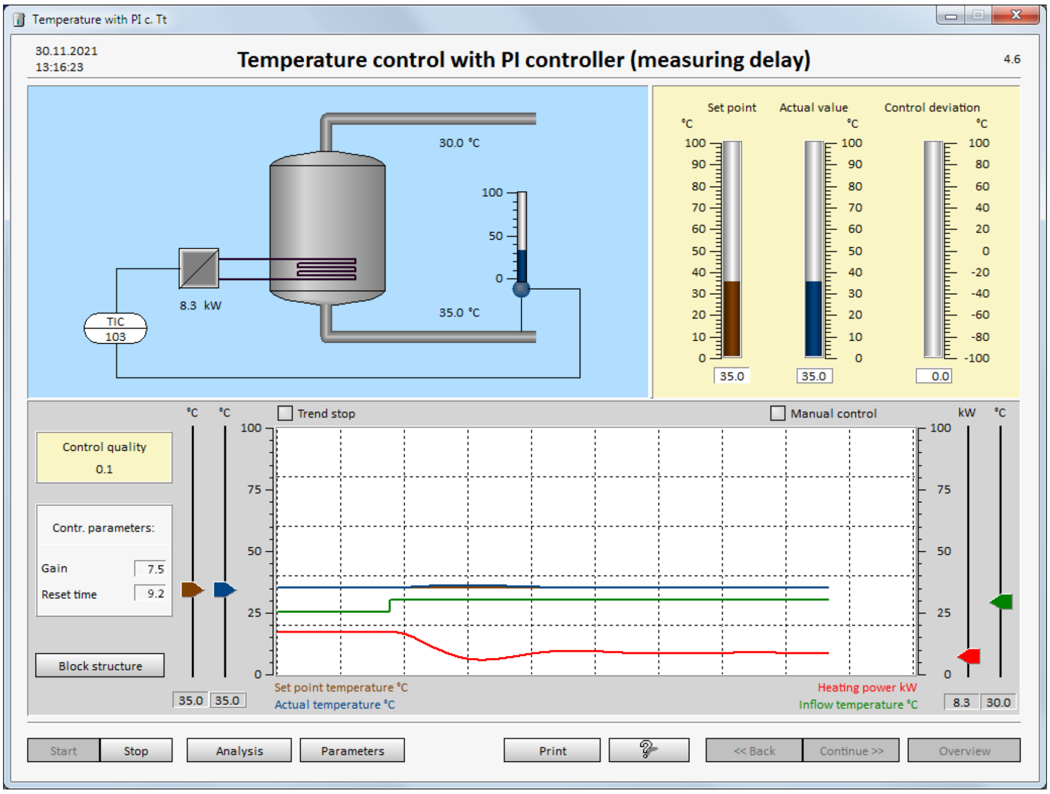
Command response aperiodic

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



Disturbance response with 20% overshoot

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



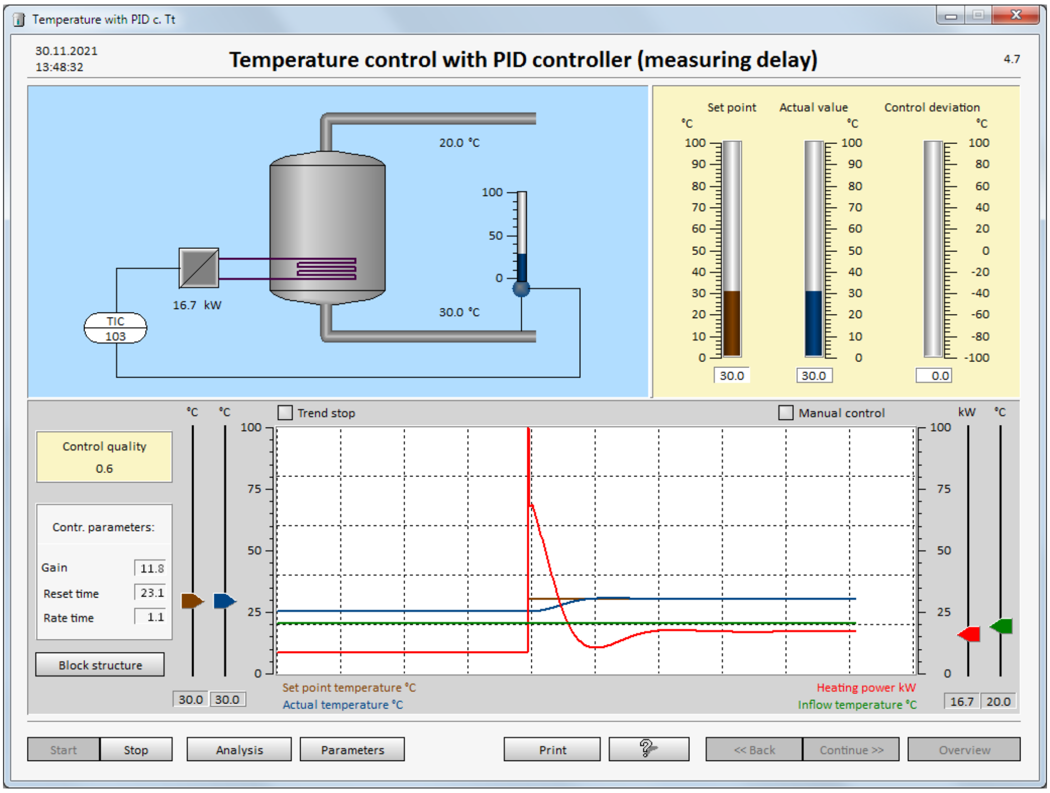
Disturbance response aperiodic

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

PID controller

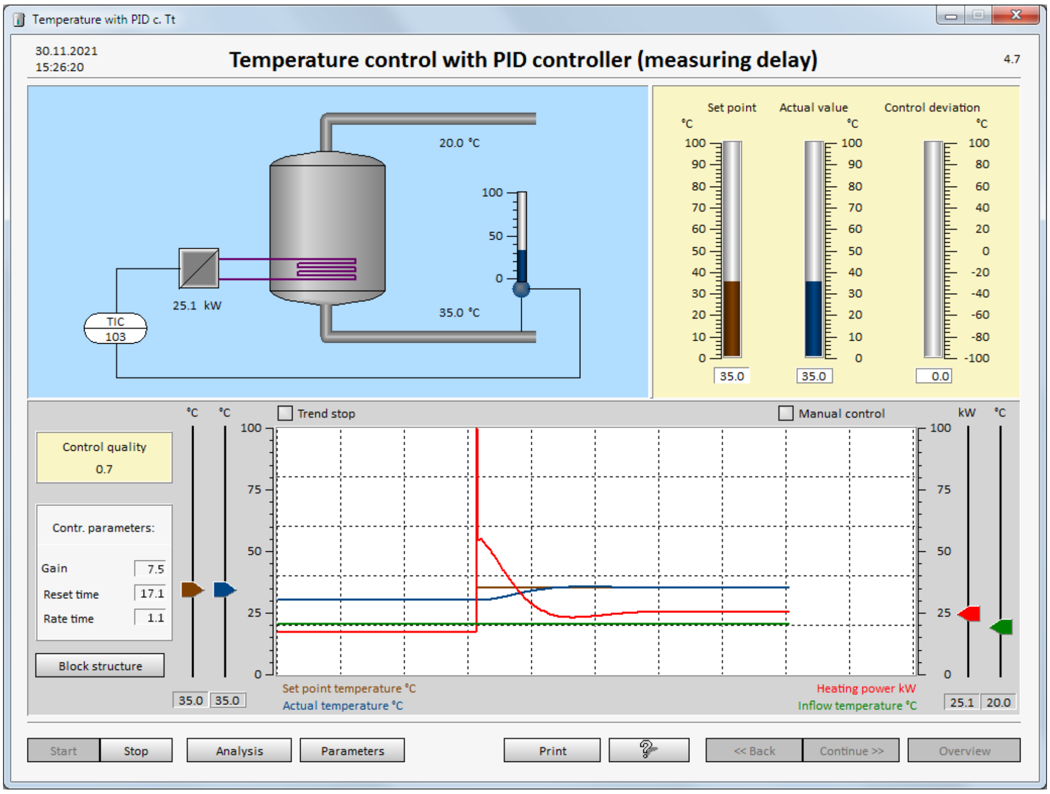
Command response with 20% overshoot	
K = 0,95*Tb / (Ks*Te)	11,80
Tn = 1,35 * Tb	23,14
Td = 0,47 * Te	1,08
Command response aperiodic	
K = 0,6*Tb / (Ks*Te)	7,45
Tn = Tb	17,14
Td = 0,5 * Te	1,15
Disturbance response with 20% overshoot	
K = 1,2*Tb / (Ks*Te)	14,90
Tn = 2 * Te	4,60
Td = 0,42 * Te	0,97
Disturbance 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 jump from 25°C to 30°C was carried out after the controlled variable had settled to 25°C.



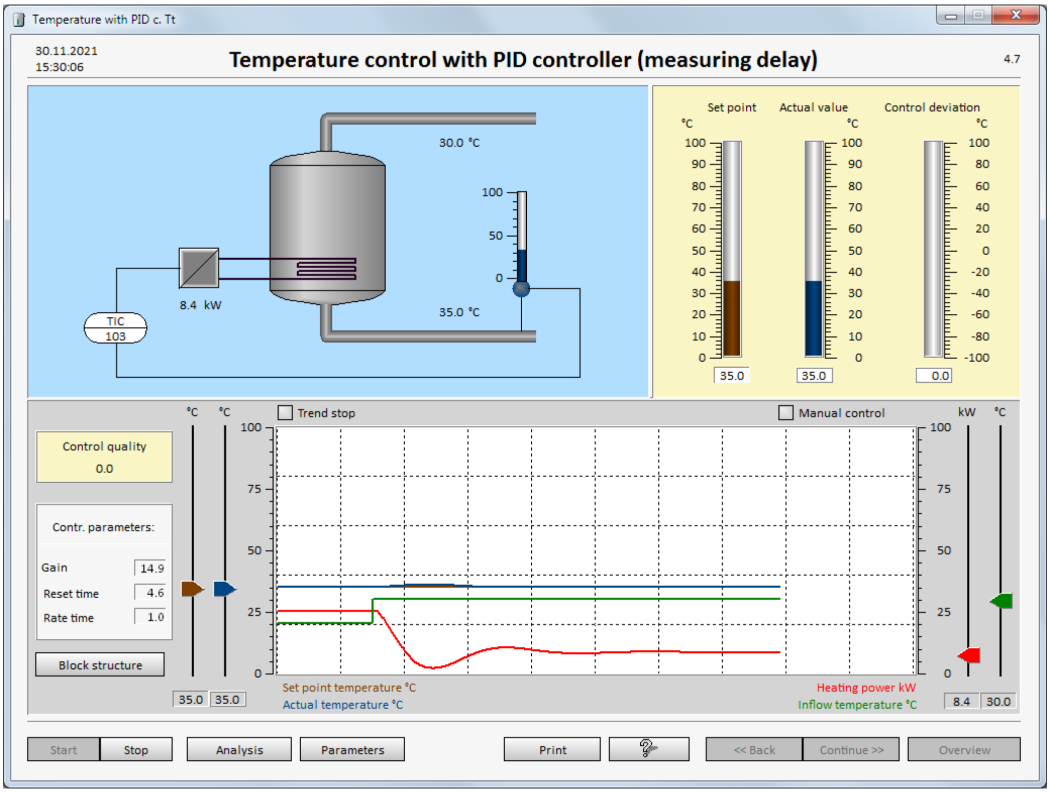
Command response with 20% overshoot

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



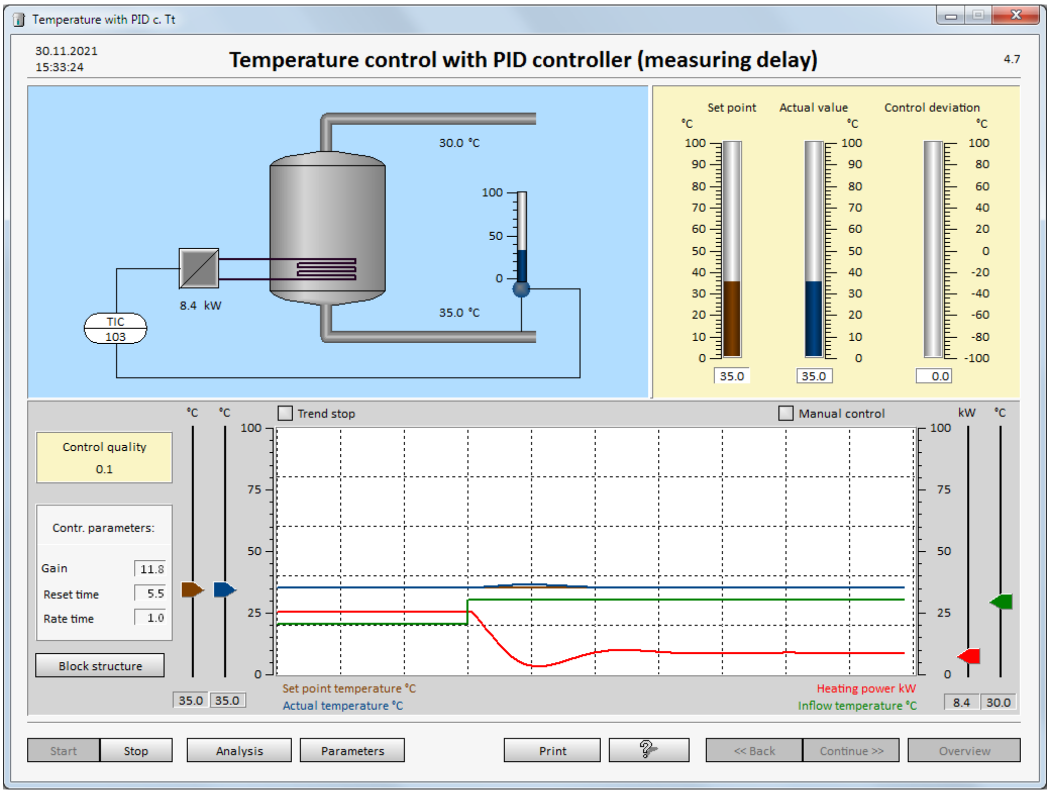
Command response aperiodic

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



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.



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 thumb values for good controller parameters.

The settings for the controller parameters differentiate between disturbance and command behavior. Different controller parameters are calculated.

If you want to cover both cases (disturbance and control behavior) with your controller parameters, 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 setpoint (reference value). The flow rate of the salt solution is regarded as the input variable (manipulated 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“.

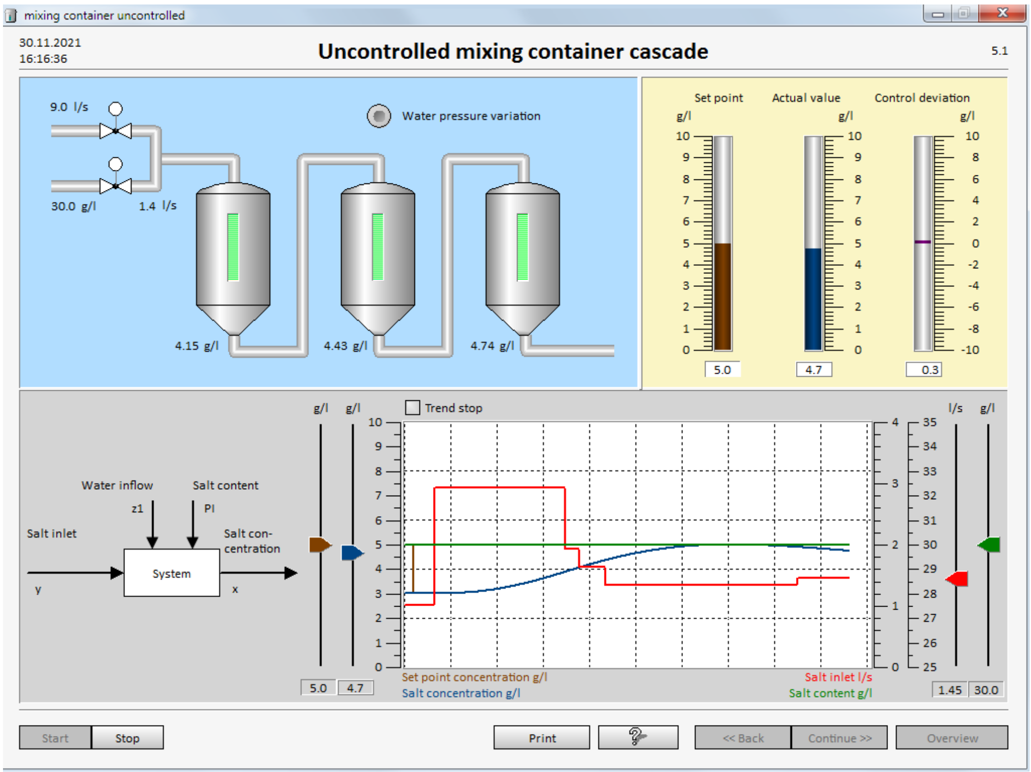
Press „Start“.

You can change the values for the setpoint (setpoint 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 setpoint concentration (reference variable) to 5g/l and then try to bring the salt concentration (controlled variable) in the third container to the setpoint concentration by adjusting the salt inlet (manipulated variable).

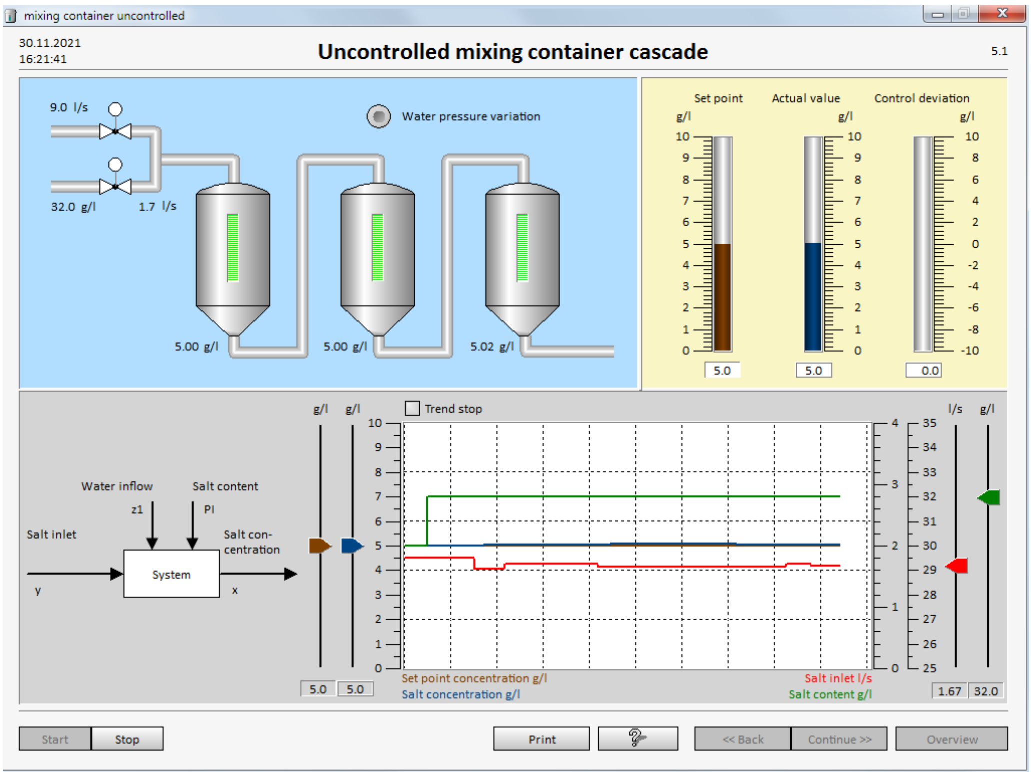
In this case one speaks of command response. The setpoint is adjusted and an attempt is made to bring the actual value (controlled variable, salt concentration) back to the new setpoint (setpoint concentration).



Since the system is a very slow process, it is very difficult to bring the control loop to the new setpoint.

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

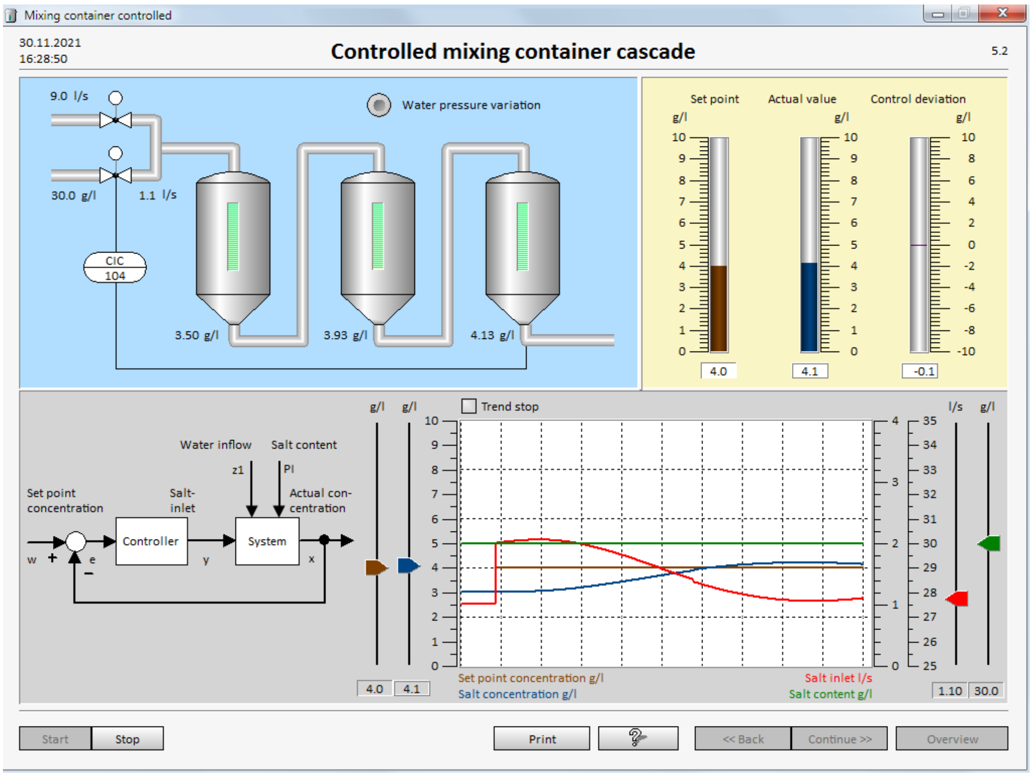
7.2.1 Closed-loop Controlled System

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 bringing the actual value to the setpoint.

Task 3.

Press „Start“ and set the setpoint to 4g/l.



With a small overshoot, the actual value goes to the setpoint after a long period of time.

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

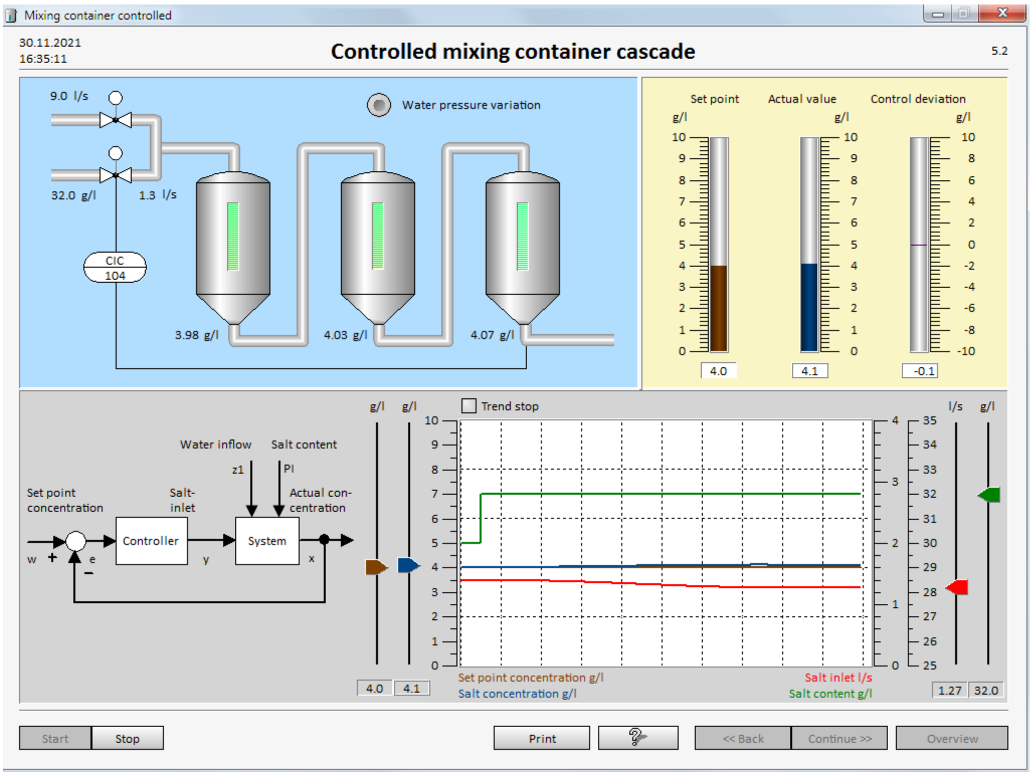
Task 4.

Investigate the disturbance behavior.

Set the setpoint 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.

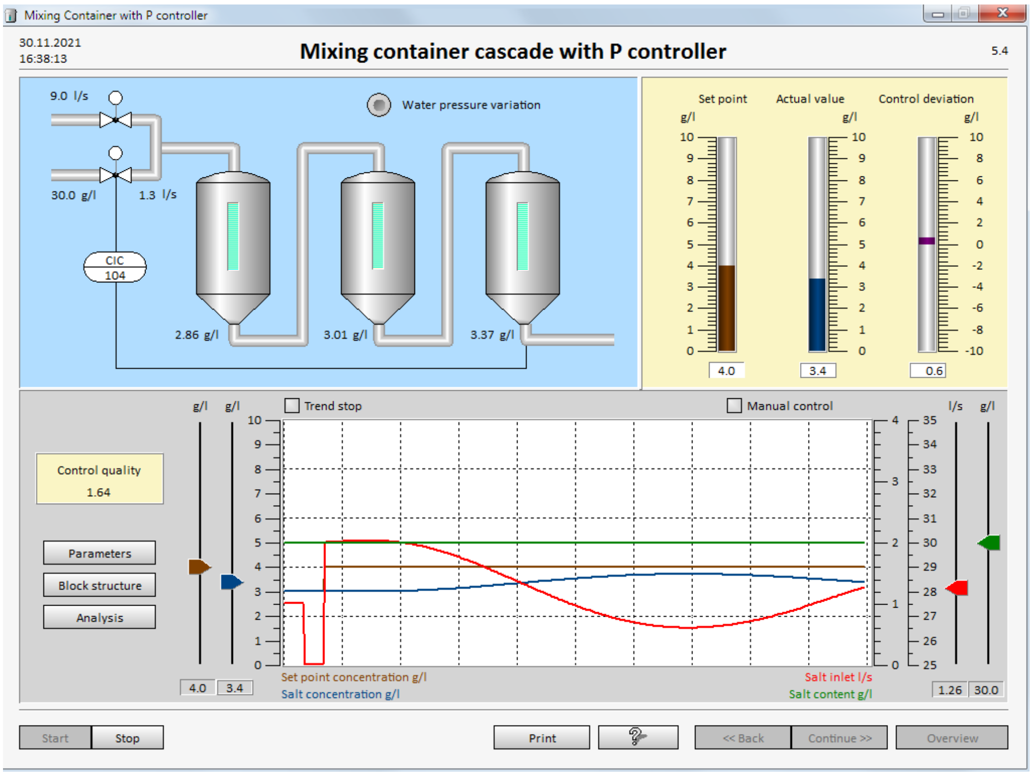
7.2.2 Closed-loop Control with P Controller

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

Press „Start“.

Task 5.

Change the setpoint 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 setpoint (reference variable). We get a steady-state control error.

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

w = reference variable (setpoint) 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 setpoint 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 (setpoint - 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 setpoint and actual value must be different, i.e. steady-state control error.

7.2.3 Closed-loop Control with I Controller:

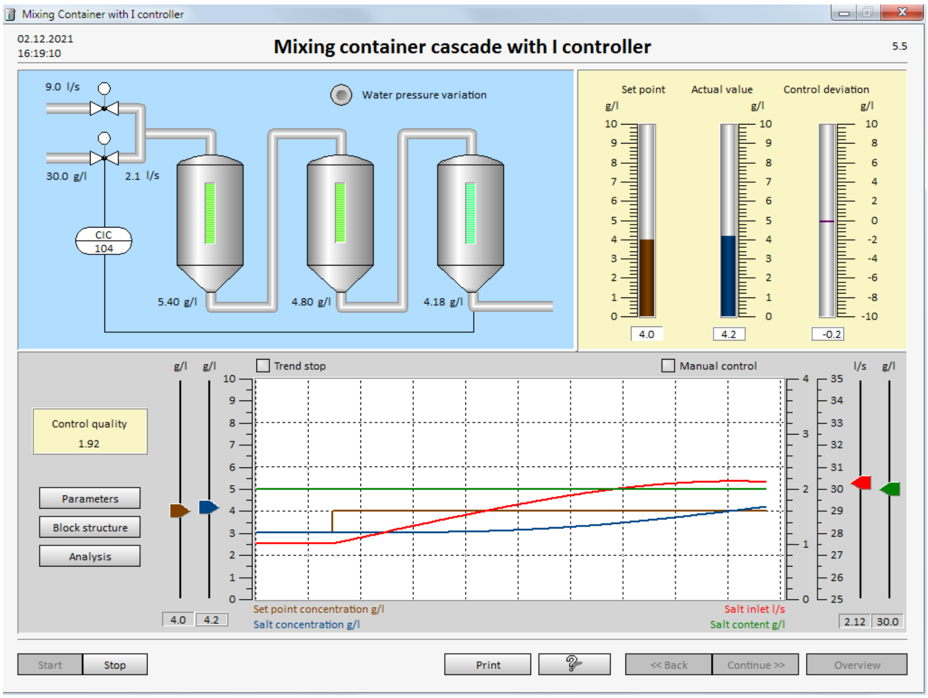
Go to „Overview“ and select item 5.5 „Closed-loop control with I controller“.

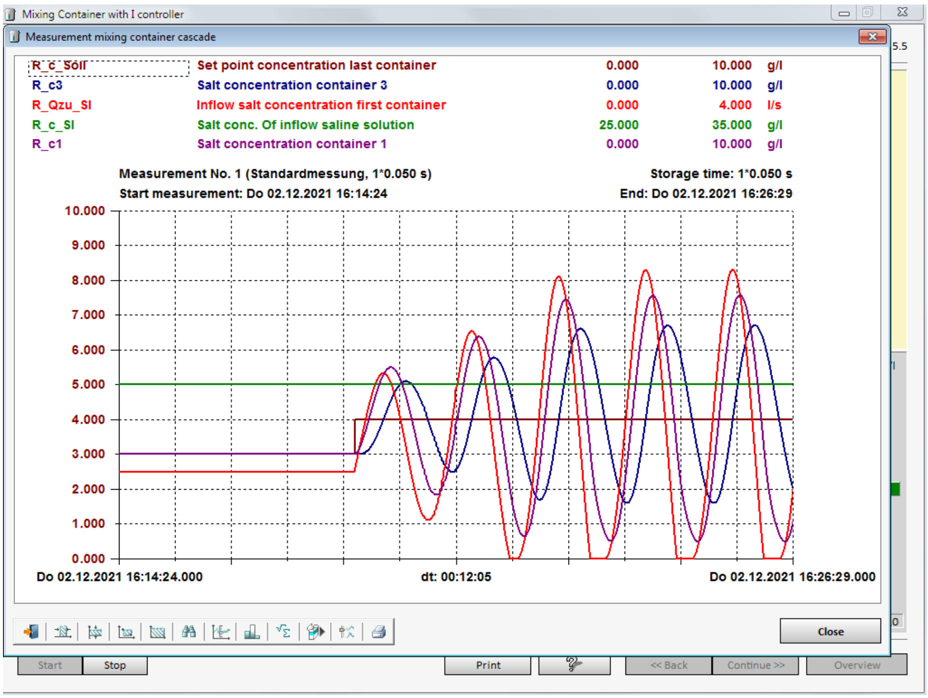
Press „Start“.

Task 6.

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

Change the setpoint 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“.

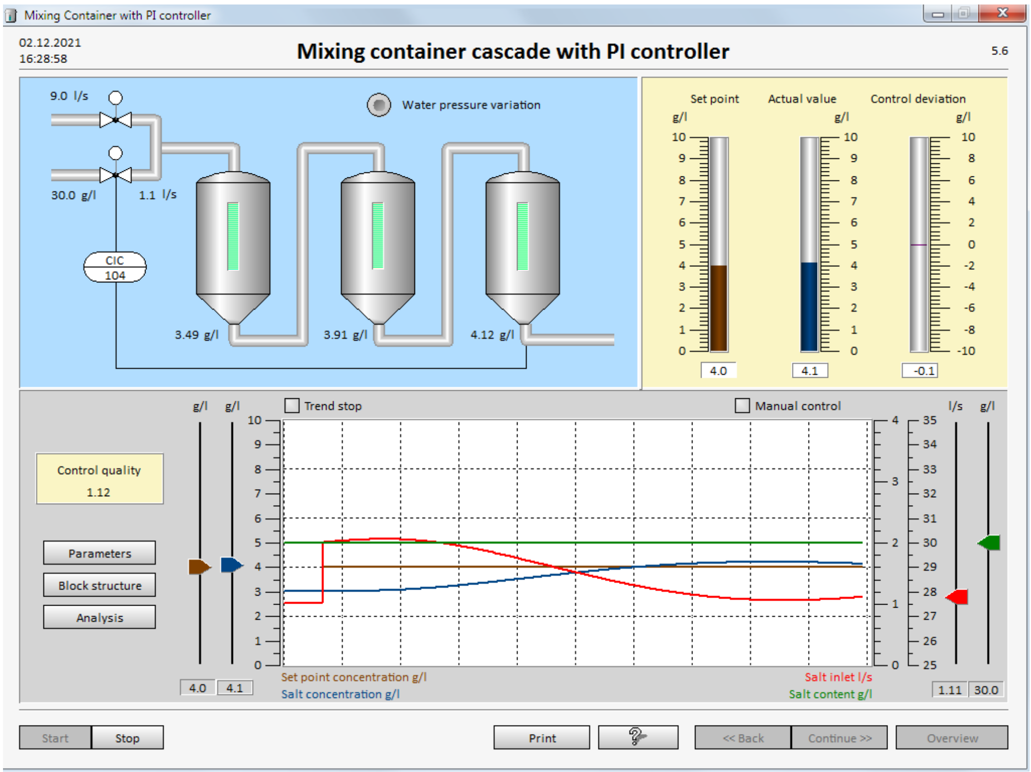
Press „Start“.

Task 7.

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

Examine command response.

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



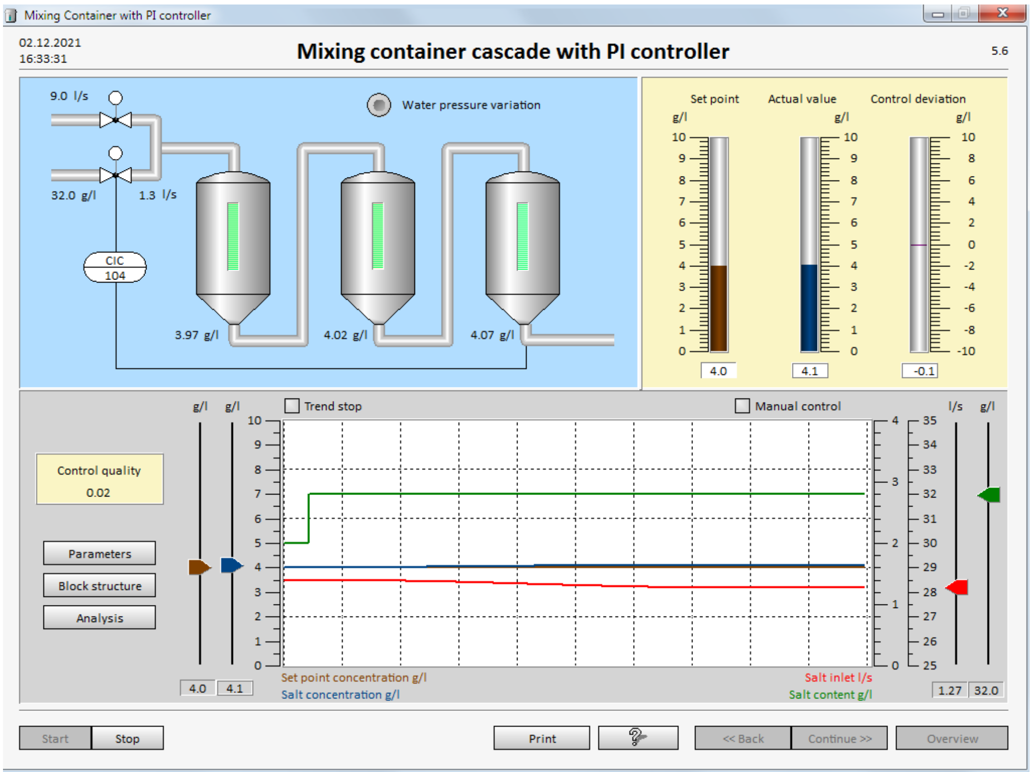
The control loop with the PI controller and the set parameters swings to the setpoint with a small overshoot. The actual value (controlled variable, salt concentration) reaches the setpoint (reference variable).

Task 8.

Investigate the disturbance response.

Let the control loop settle to the setpoint 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 bring the actual value back to the setpoint.

Task 9.

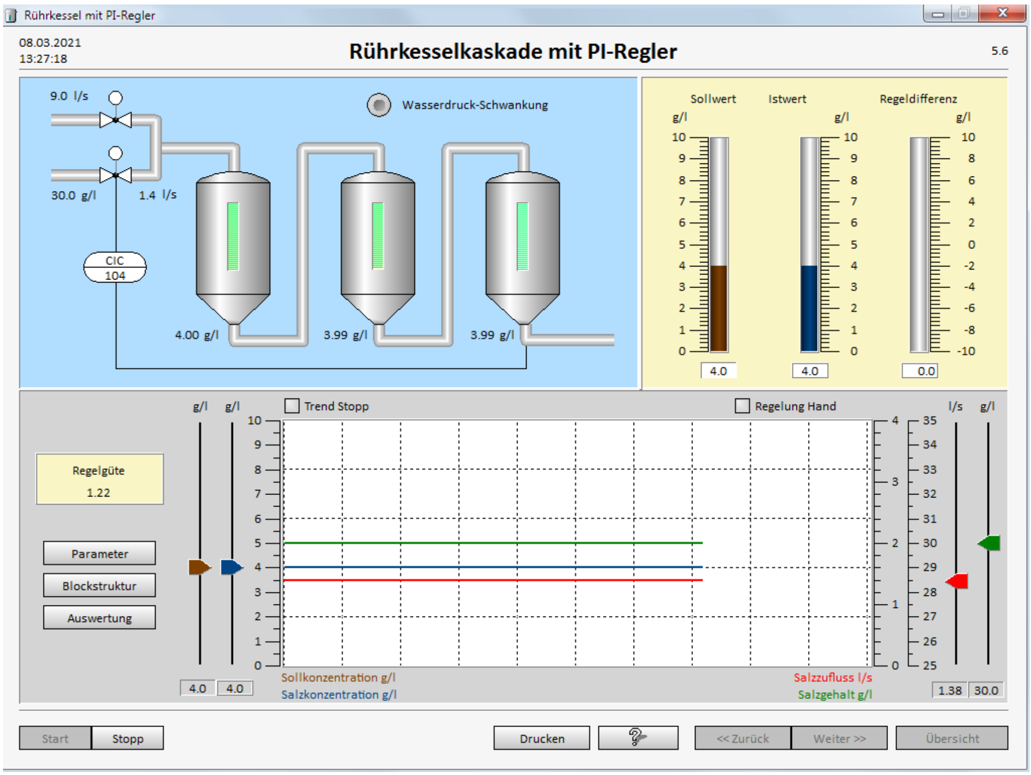
The number in the box labeled "Control quality" indicates a value about the quality of the steady control loop. The smaller the number, the faster the control loop has settled and the actual value has reached the setpoint.

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 press “Stop” and then “Start” again. The setpoint 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 setpoint 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:

- Press „Stopp“ and „Start“
- Set controller parameters
- Set setpoint to 4g/l
- Wait until control loop has settled

In general:

Since the PI controller has an I component (integrator), it also applies here that the controller brings the actual value to the setpoint 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.

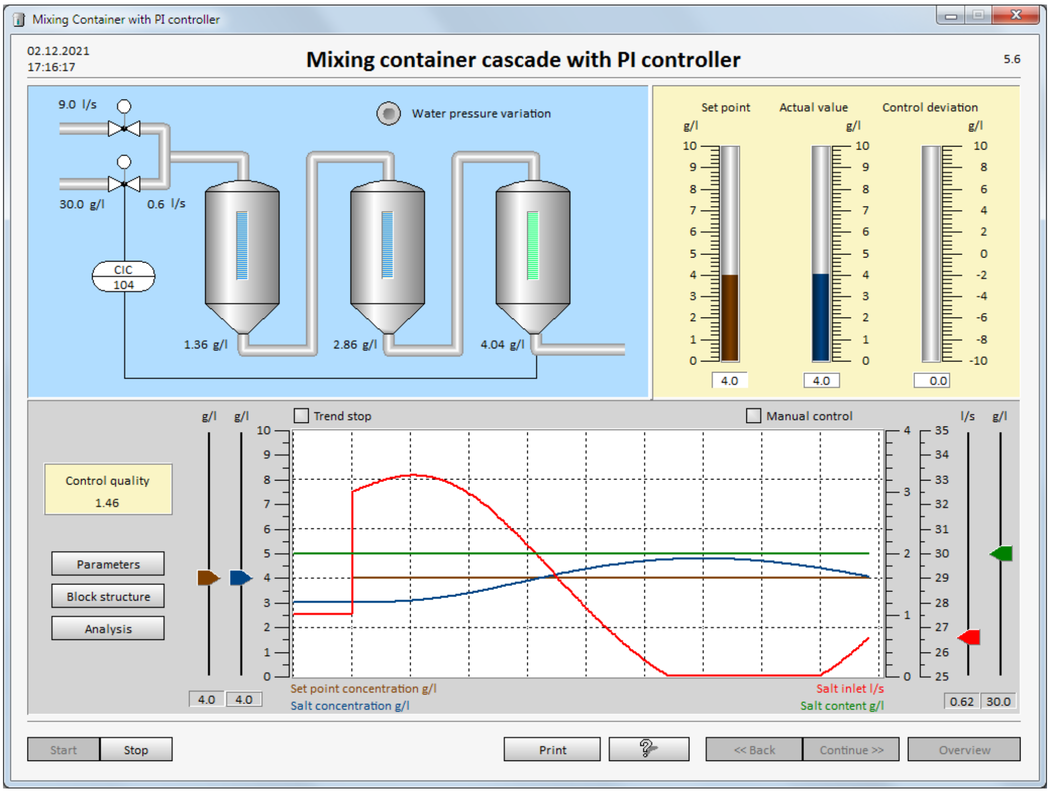
In order for a control loop to settle to a value, the control signal must be constant (output of the controller). The output value of an integrator is only constant when the input value of the integrator is equal to zero, i.e. when the setpoint and actual value are the same.

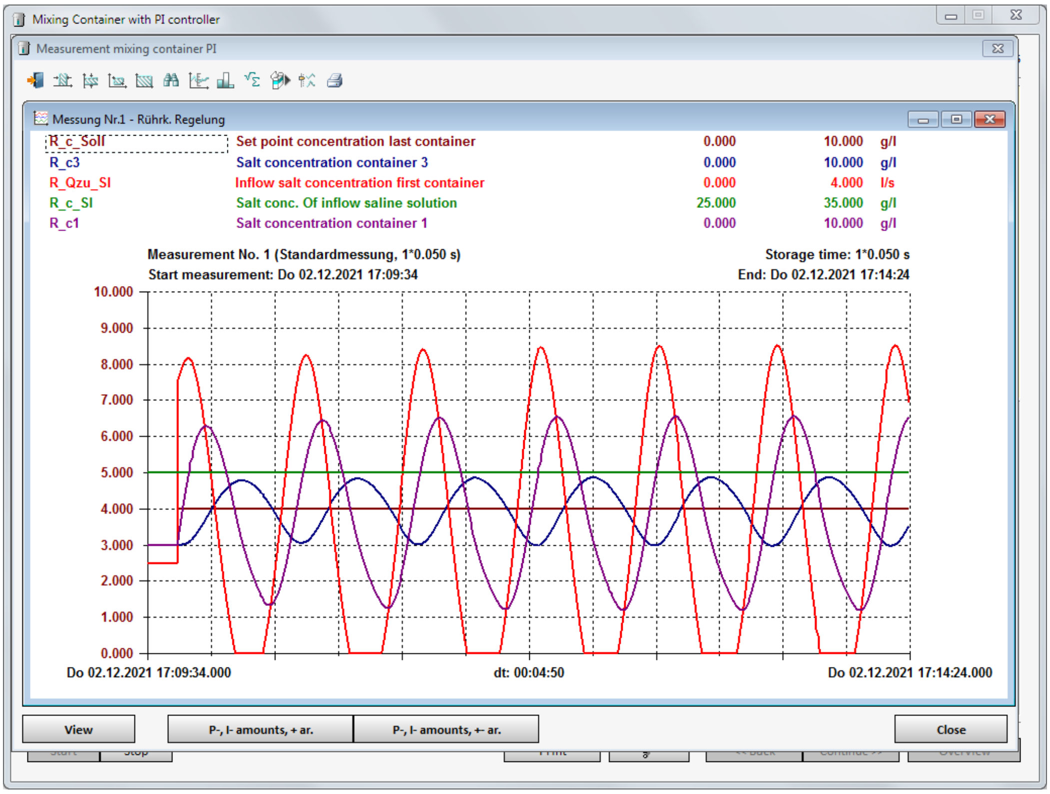
Task 10.

Restart the mixing container cascade with PI controller.

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

Enter a setpoint jump 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 setpoint and remains at the setpoint.
- 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

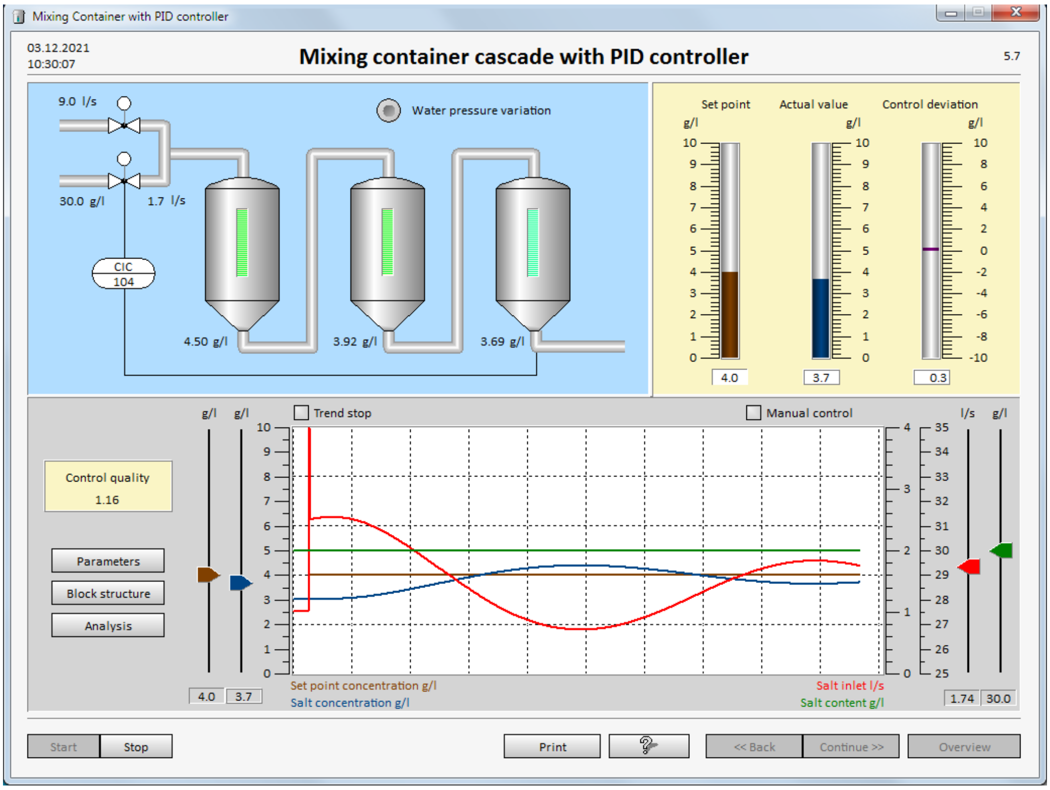
Go to „Overview“ and select item 5.7 „Closed-loop control with PID controller“.

Press „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 setpoint 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 setpoint.

As you can see in the trend diagram, the sudden change in the setpoint 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 goes to 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:

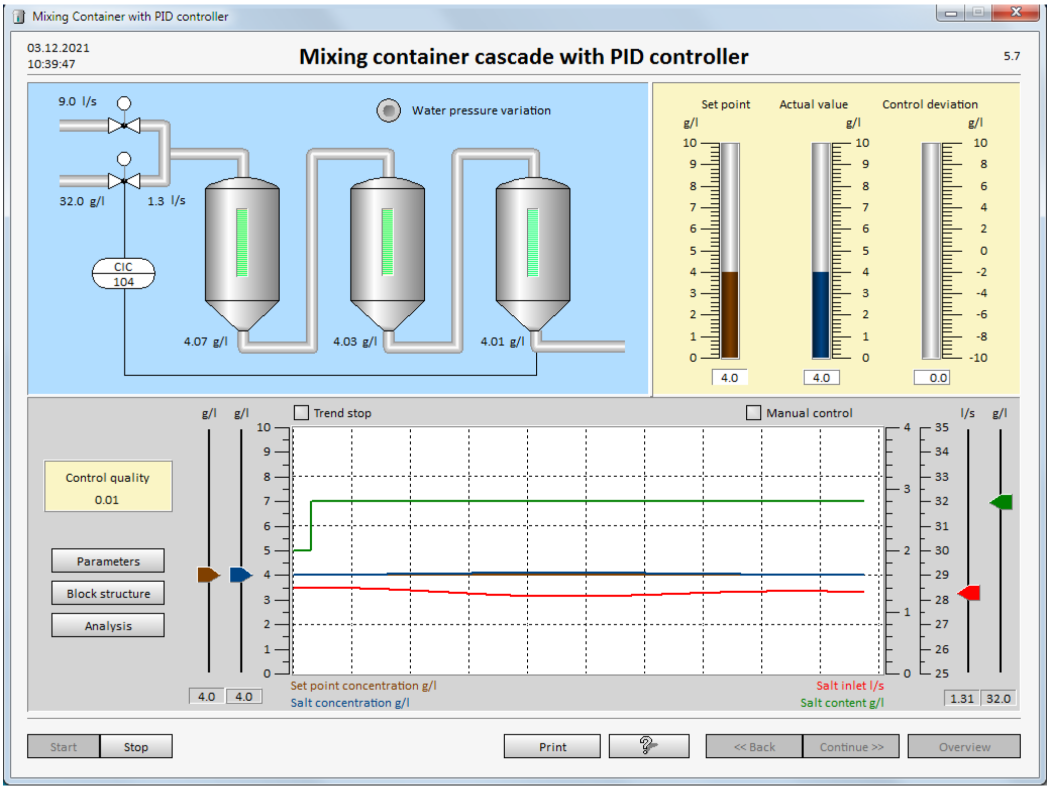
In the trend display it can happen that the peak is not shown. You can, however, see that the peak is present via "Analysis" (display of the stored signal values) and selection of a corresponding time range.

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 setpoint 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 setpoint concentration (reference variable) again after a period of time.

Note:

In practice, the PI controller is mainly used as a controller. If a PID controller is used, the D component is often turned away 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 setpoint and actual value. If the change increases, i.e. the difference between setpoint and actual value increases, the D component adds a calculated value to the control signal. If the change between setpoint and actual value becomes smaller, i.e. the difference between setpoint and actual value decreases, the D component subtracts a calculated value from the control signal. In principle, the D component takes into account the trend as to whether the difference between setpoint and actual value is increasing or decreasing. If the difference increases, the D component amplifies the control signal; if the difference between setpoint and actual value is smaller, the control signal is reduced.

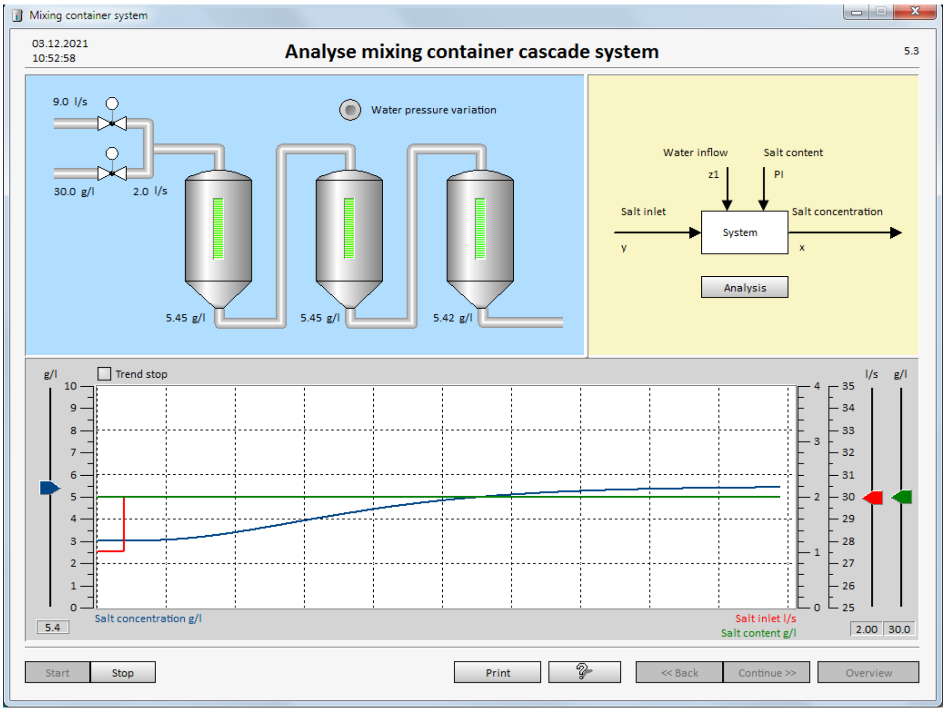
7.3 Examine Controlled System

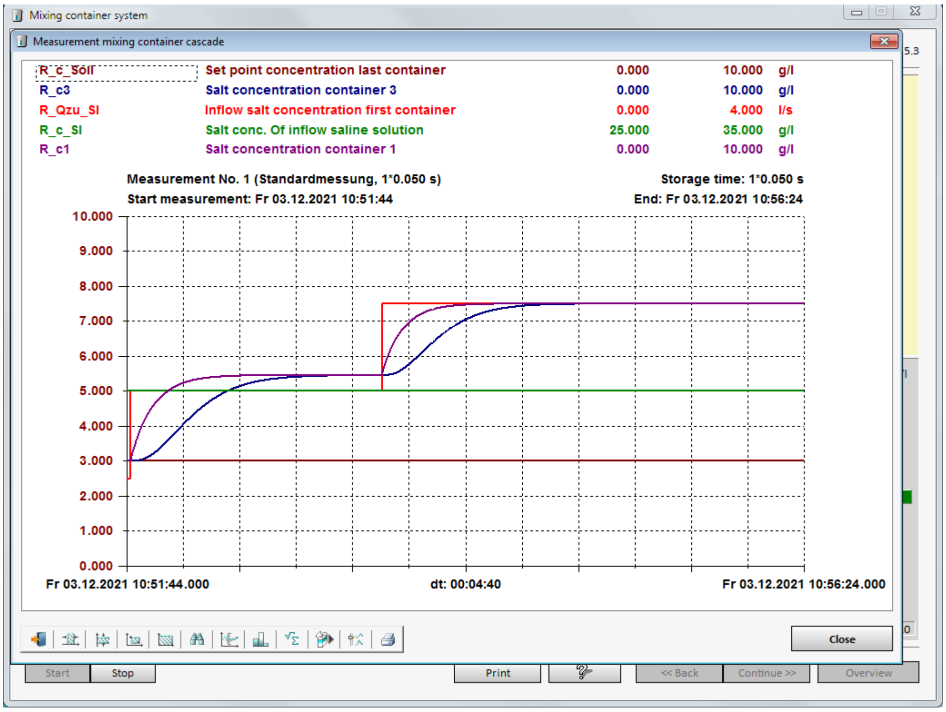
Select item 5.3 „Examine controlles system“. Press „Start“.

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 jumps. 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 jumps 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

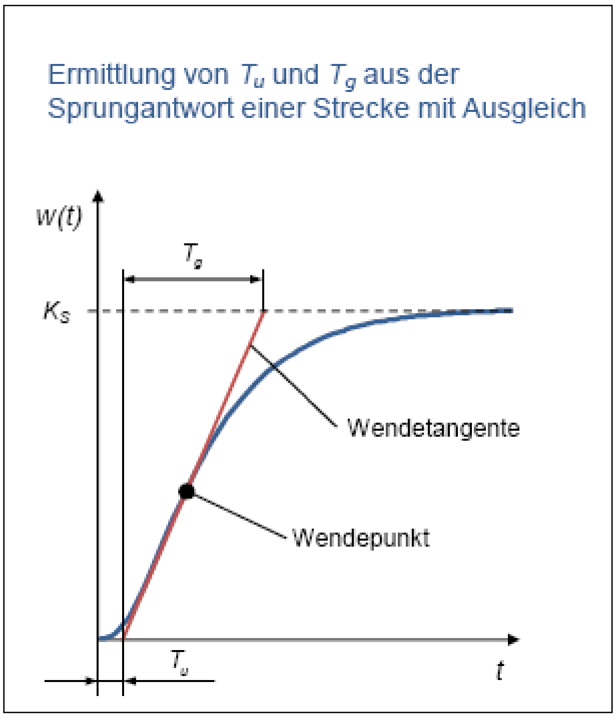
The mixing container cascade is a system with self-regulation.

After a finite time, a system with self-regulation swings 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 jump in the control signal (sudden change in the control signal by 1):



The parameters Ks, Tg and Tu can be determined from this step response. The controlled system gain Ks (final value of the actual variable) results from the abrupt change in the control signal by 1. If you change the manipulated variable larger, you have to divide the resulting gain of the system by the change in the control signal 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:

Regler-verhalten	Gütekriterium: Überschwingung nach Gegenseite mit 20% von x_m, kürzeste Schwindungsdauer		Gütekriterium: aperiodischer Regelvorgang mit kürzester Dauer	
	Störung	Führung	Störung	Führung
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	$K_P \approx \frac{1,2}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2 \cdot Tu$ $T_v \approx 0,42 \cdot T_u$	$K_P \approx \frac{0,95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1,35 \cdot T_g$ $T_v \approx 0,47 \cdot T_u$	$K_P \approx \frac{0,95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2,4 \cdot T_u$ $T_v \approx 0,42\, T_u$	$K_P \approx \frac{0,6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$ $T_v \approx 0,5 \cdot T_u$

Für Regelstrecken *ohne Ausgleich* ist statt $\frac{T_g}{K_S \cdot T_u}$ der Ausdruck $\frac{1}{K_{IS} \cdot T_u}$ einzusetzen.

The setting 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“.

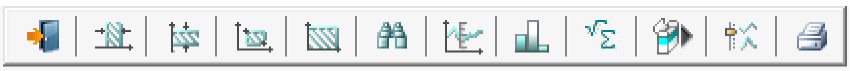
Press „Start“. Enter a jump in the salt inlet from 1g/l to 2g/l.

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.

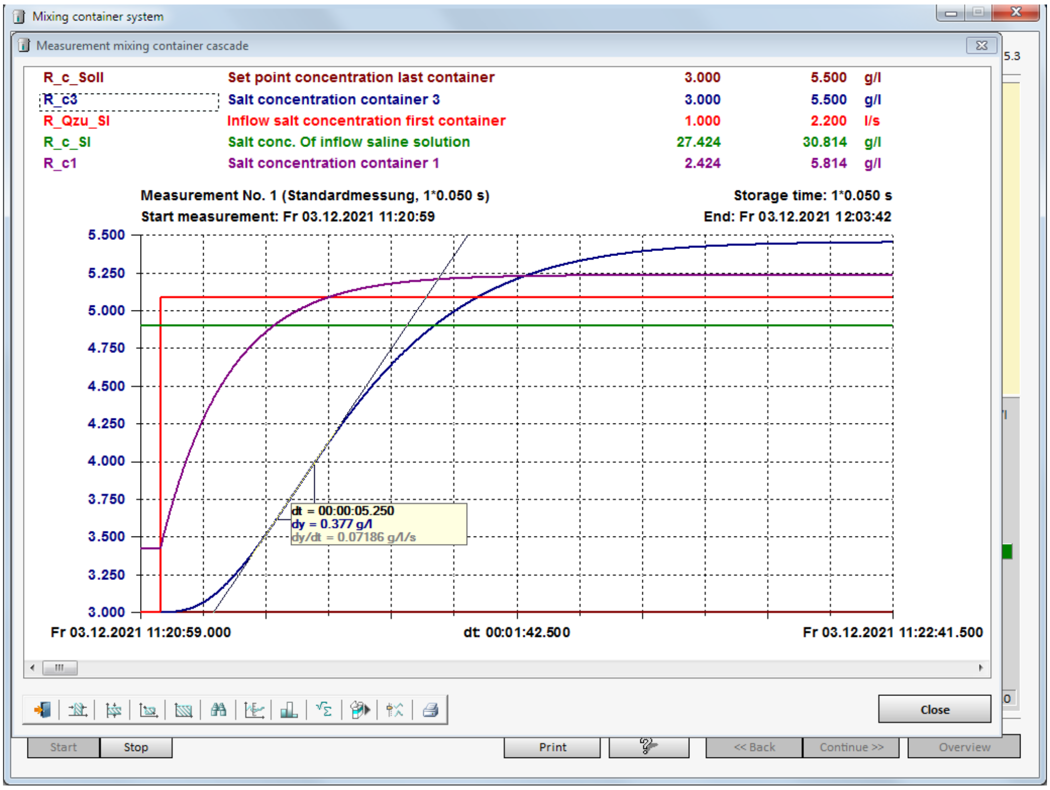
With the help of the button bar in the window, time and value segments (zooming) can be selected.



Try to find the area of interest for the evaluation with the jump 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.



Signal curve for the salt concentration

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

By clicking on the blue curve, the associated measured value and the time are displayed. By holding and pulling 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) / Jump height = (5,5 – 3) / 1 = 2,5

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

So: 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

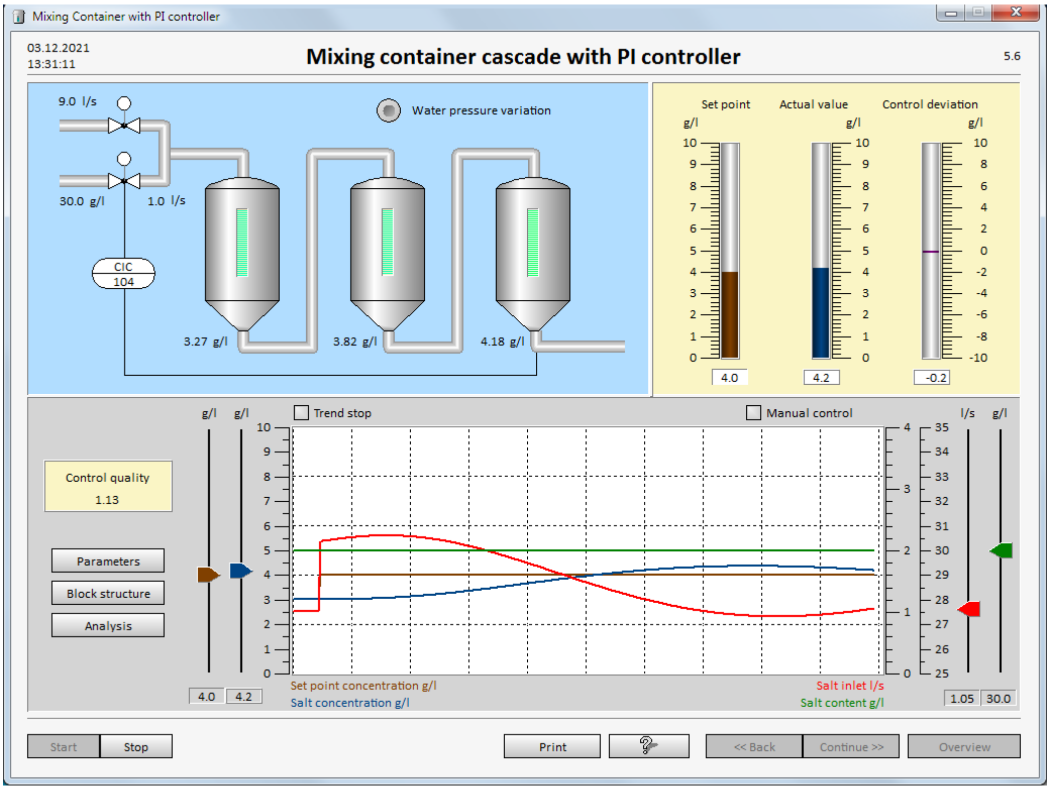
K = 1,2*Tb / (Ks*Te)	2,28
Tn = 2 * Te	14,60
Td = 0,42 * Te	3,07

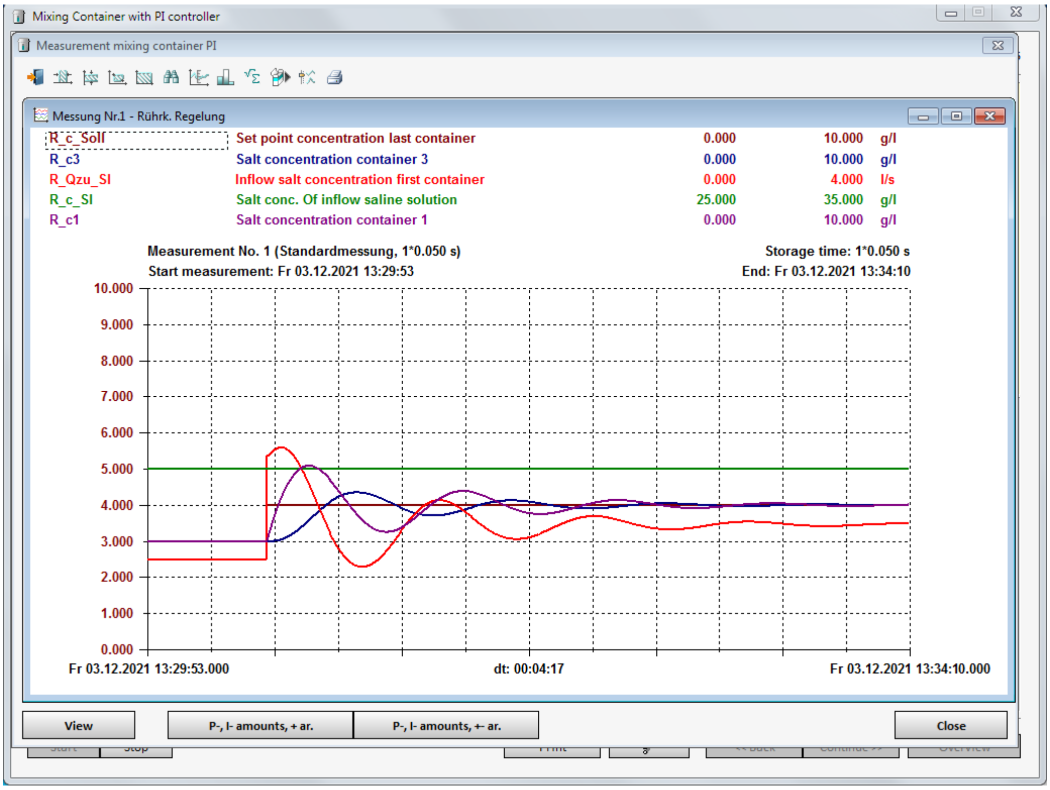
Disturbance response aperiodic

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

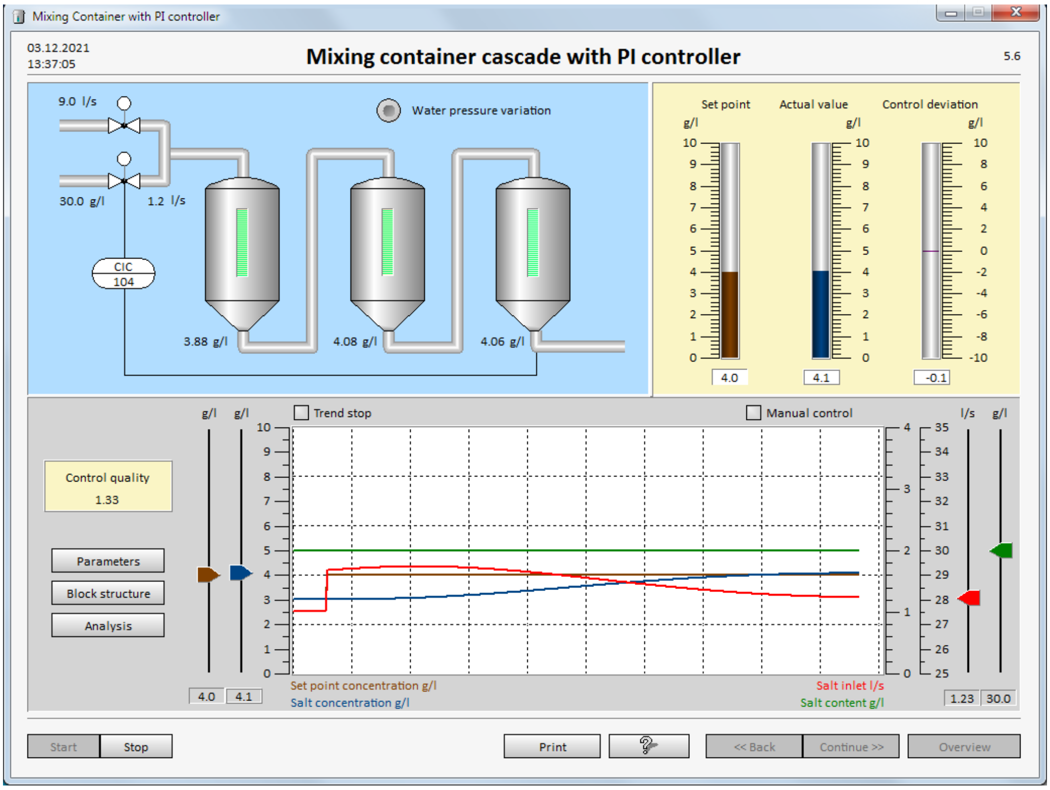
Task 15.

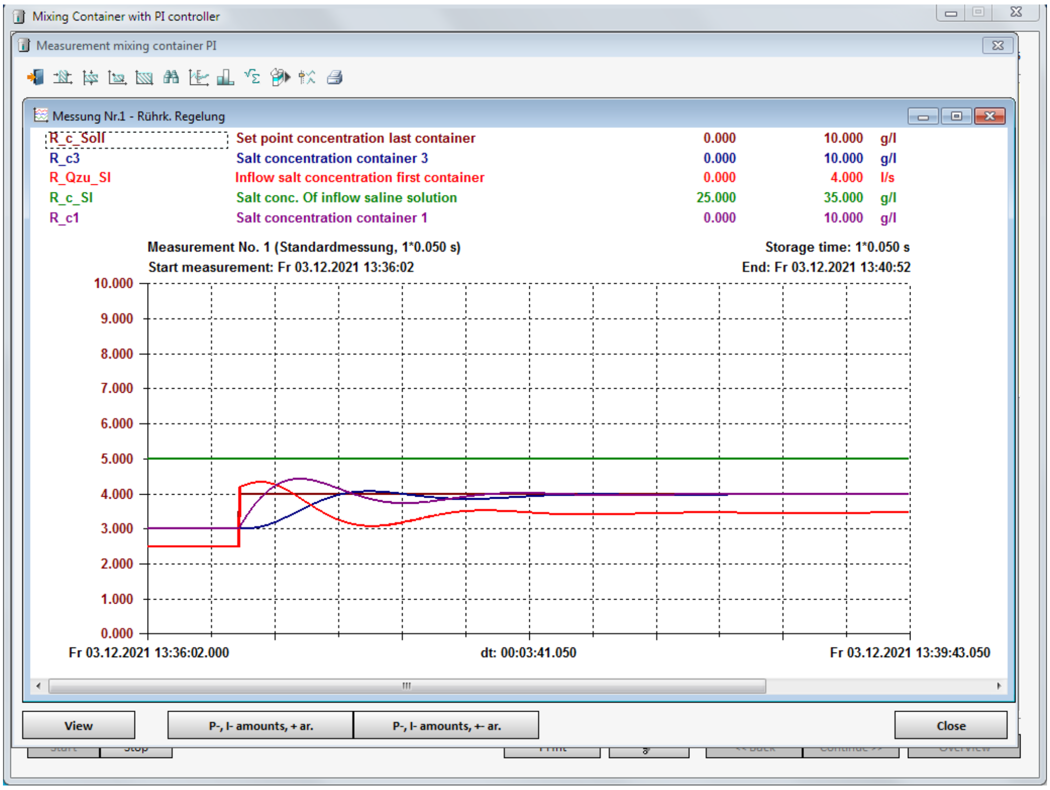
Investigate the control behavior and the disturbance behavior for the mixed container cascade with the parameters determined according to Chien/Hrones/Reswick for the PI controller and the PID controller.



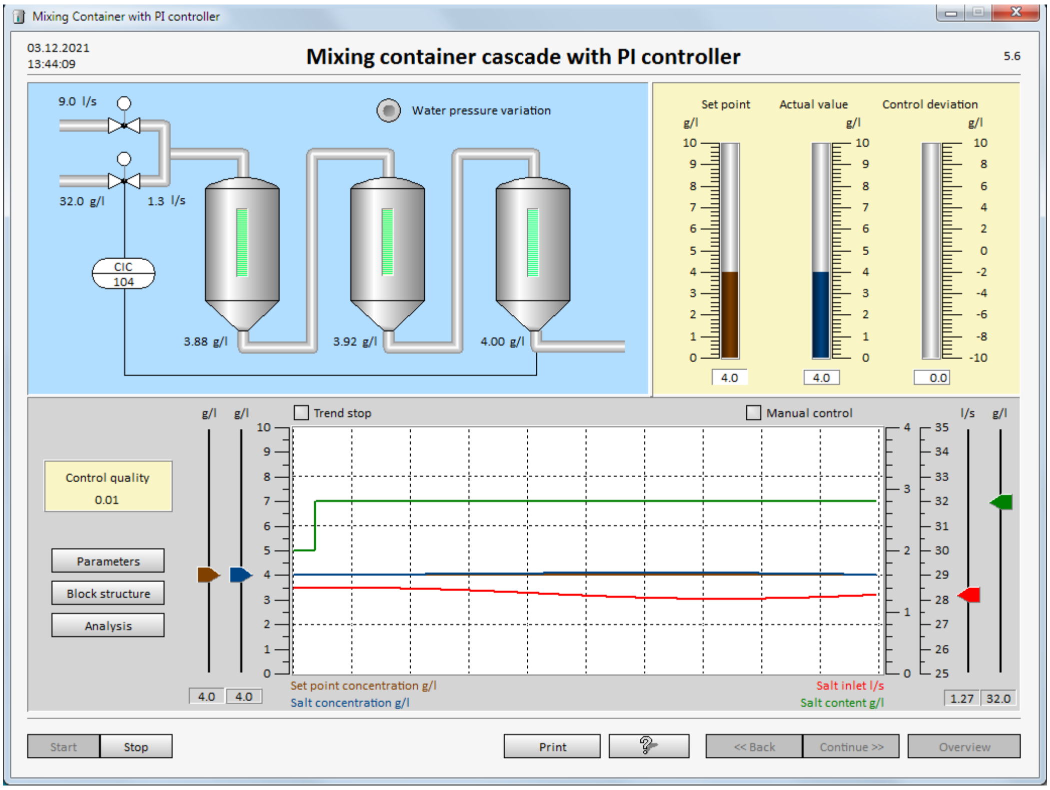


Command response with 20% overshoot / Change of the setpoint from 3g/l to 4g/l.

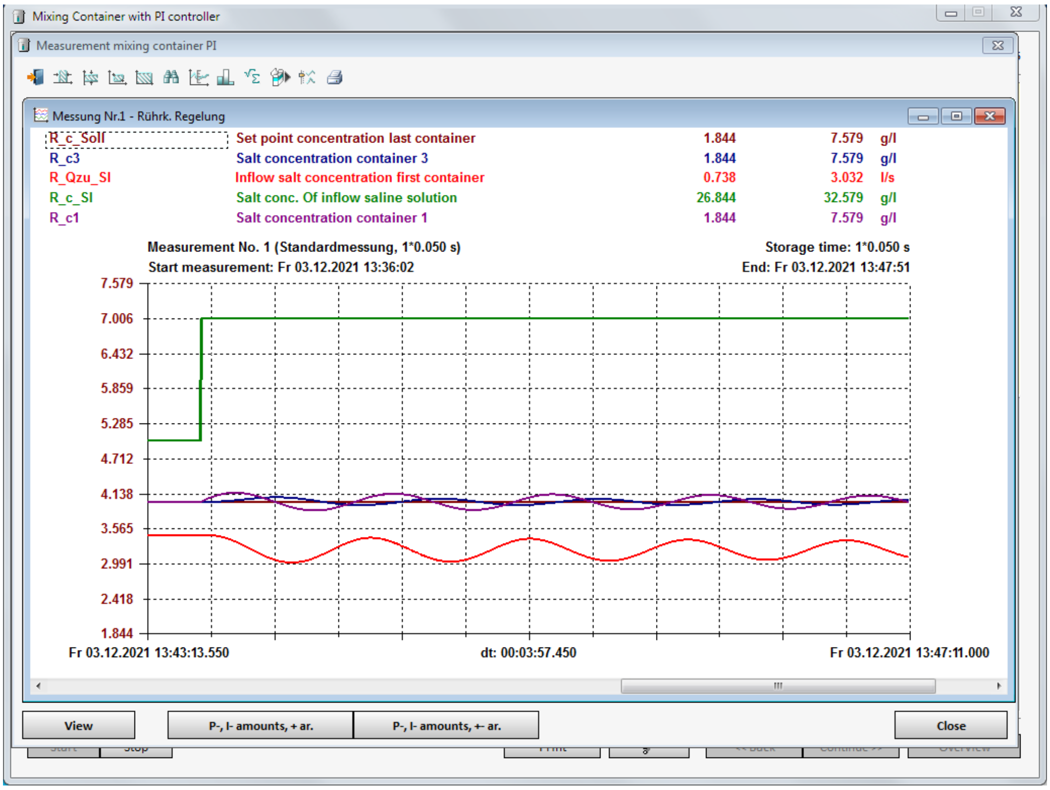




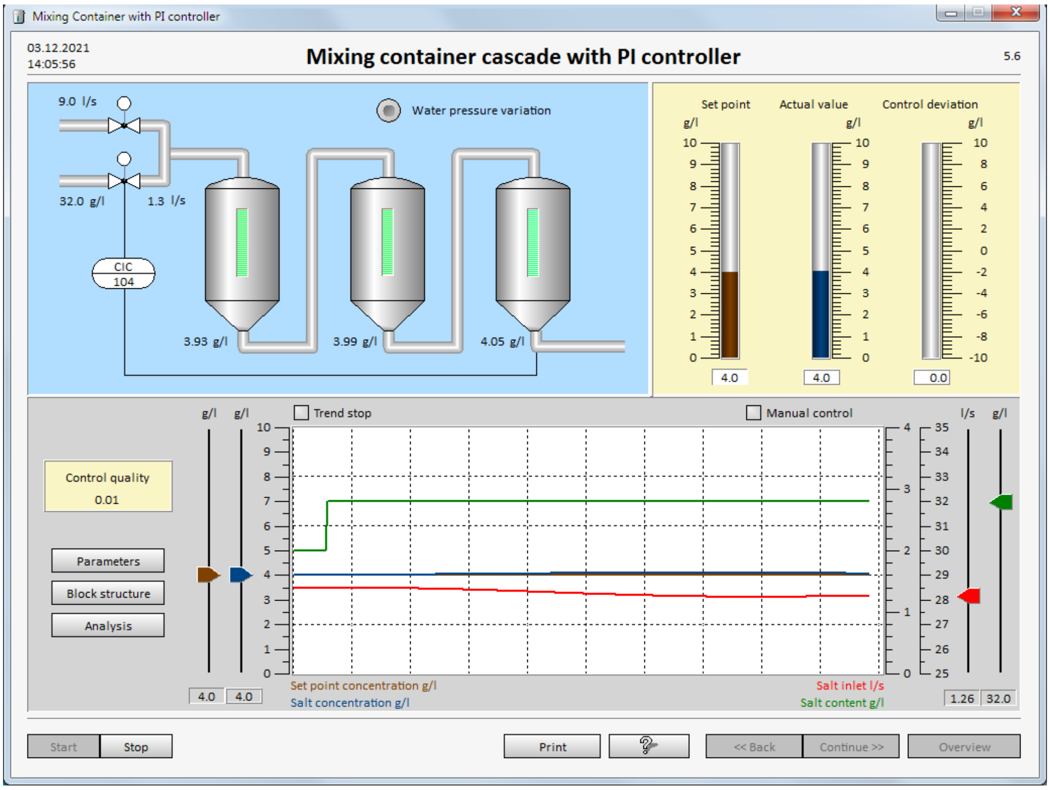
Command response aperiodic / Change of the setpoint from 3g/l to 4g/l.

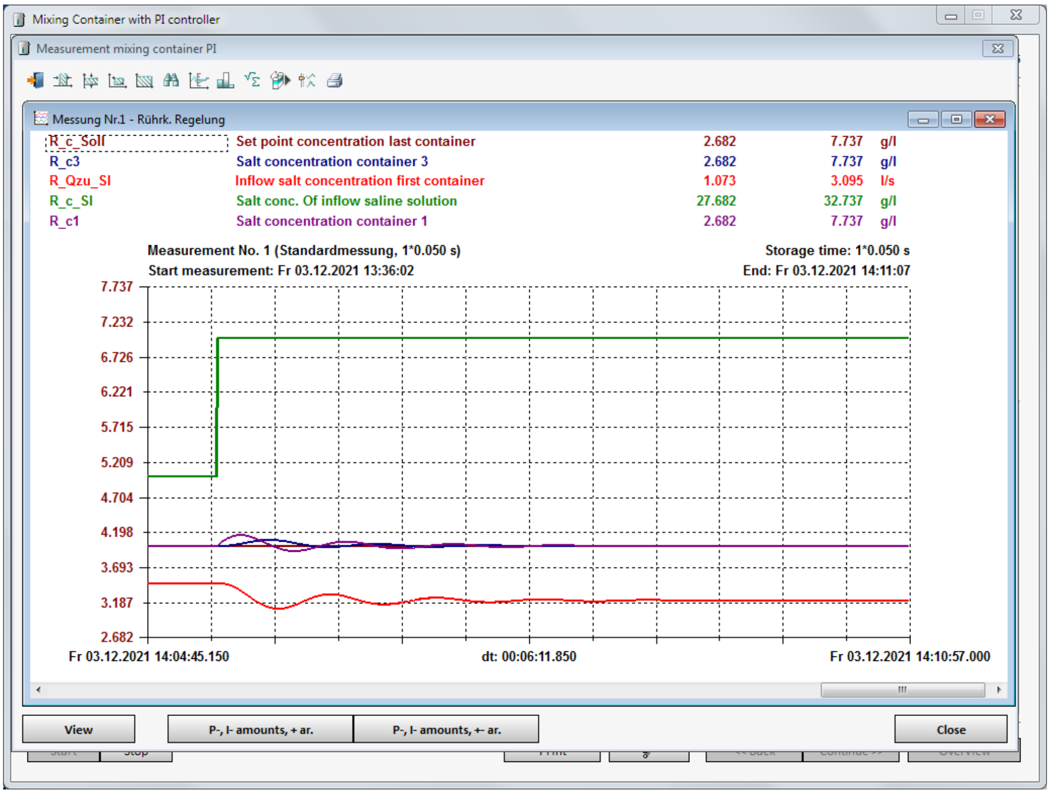


Disturbance response with 20% overshoot / Change of the disturbance input (salt content) from 30l/s to 32l/s.

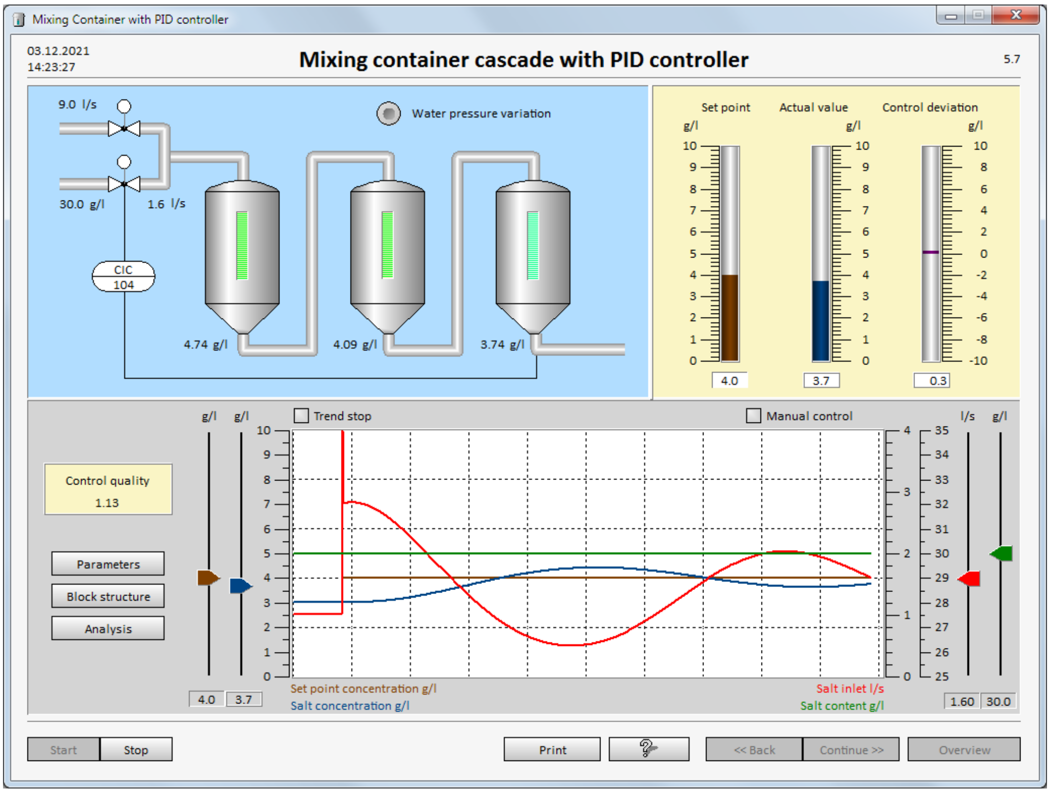


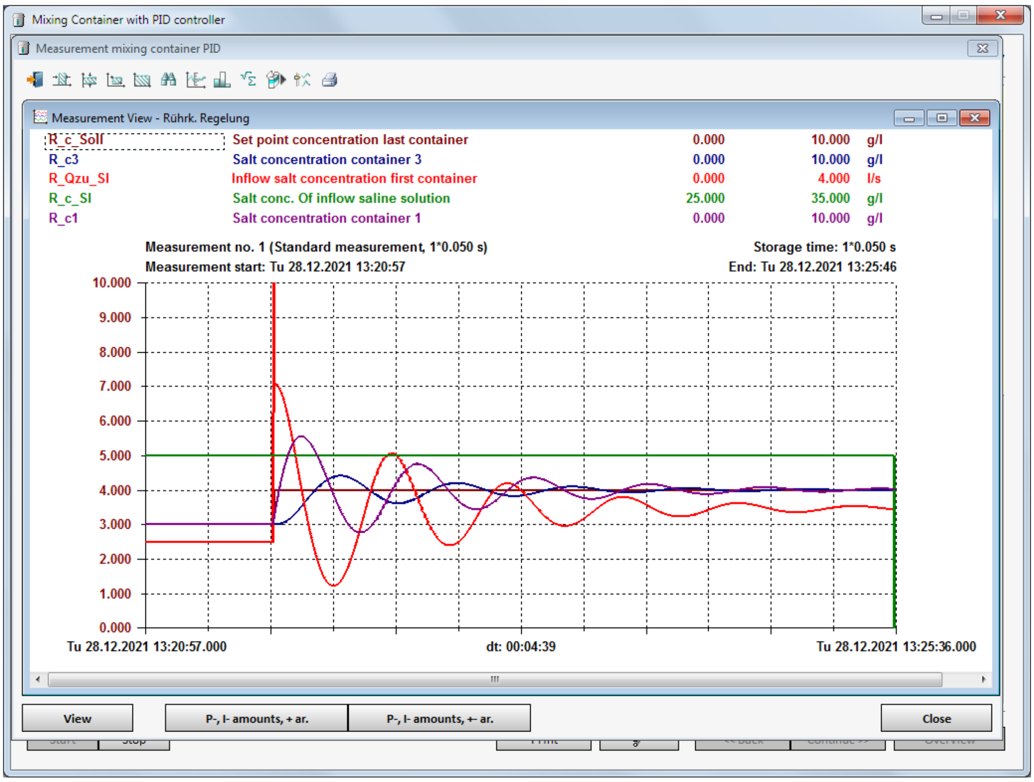
The disturbance is not controlled with these parameters



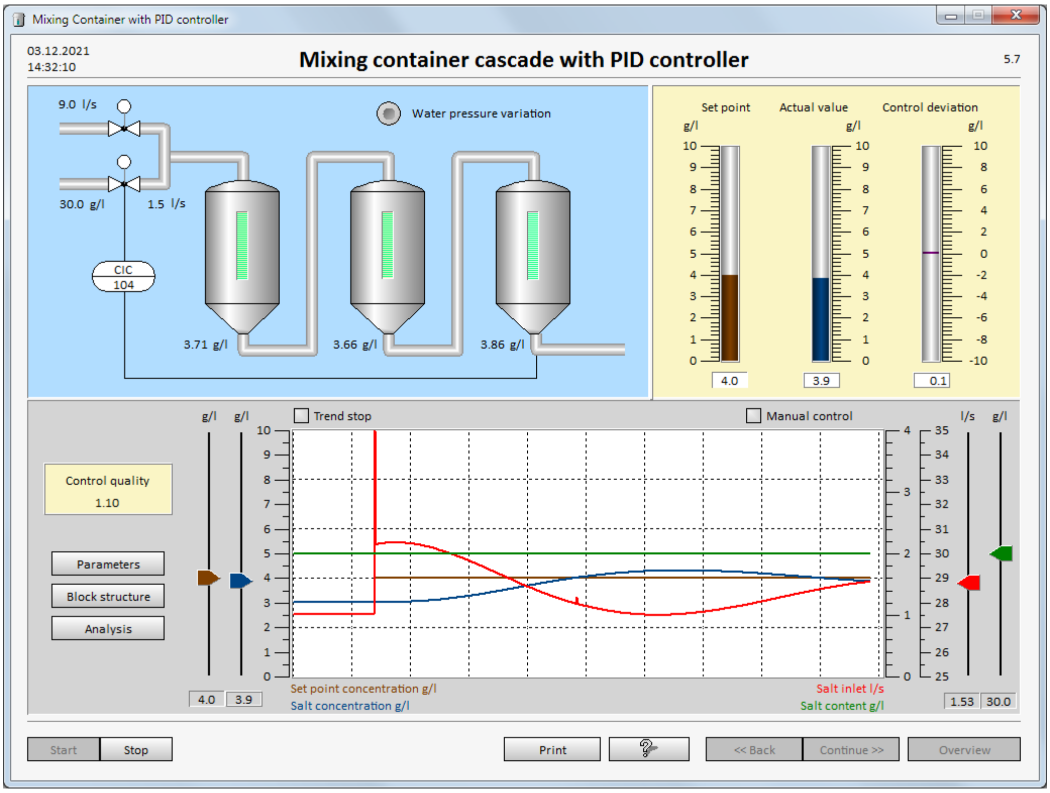


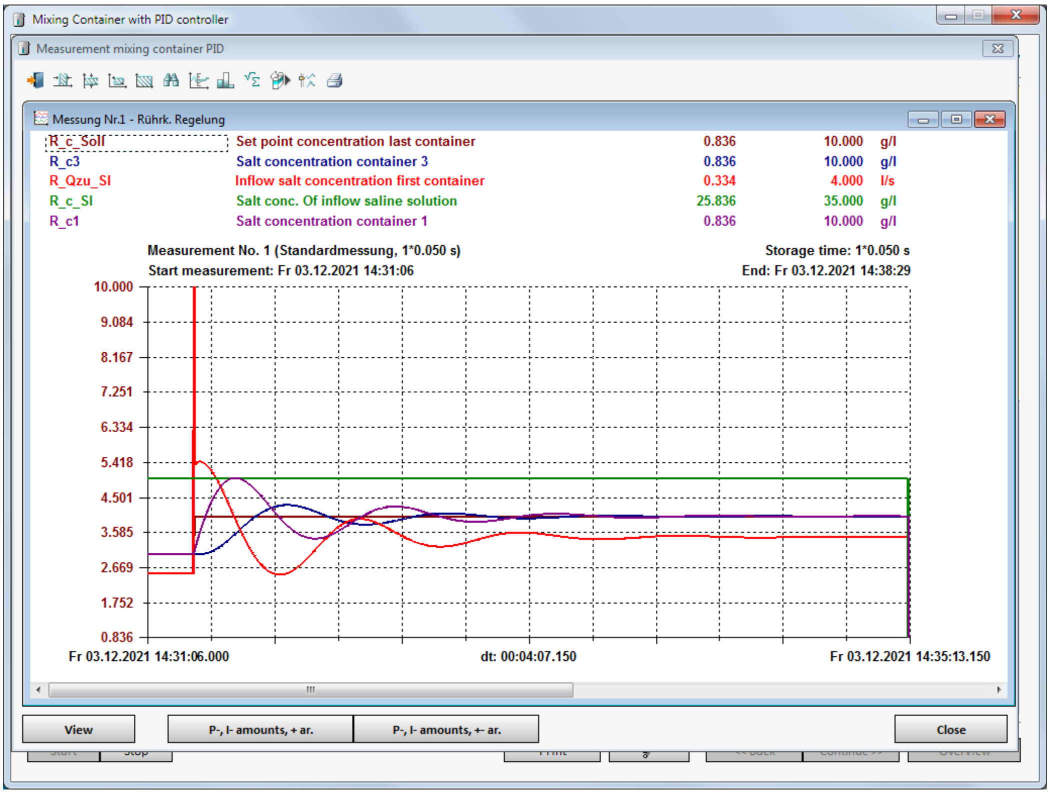
Disturbance response aperiodic / Change of salt content from 30l/s to 32l/s.





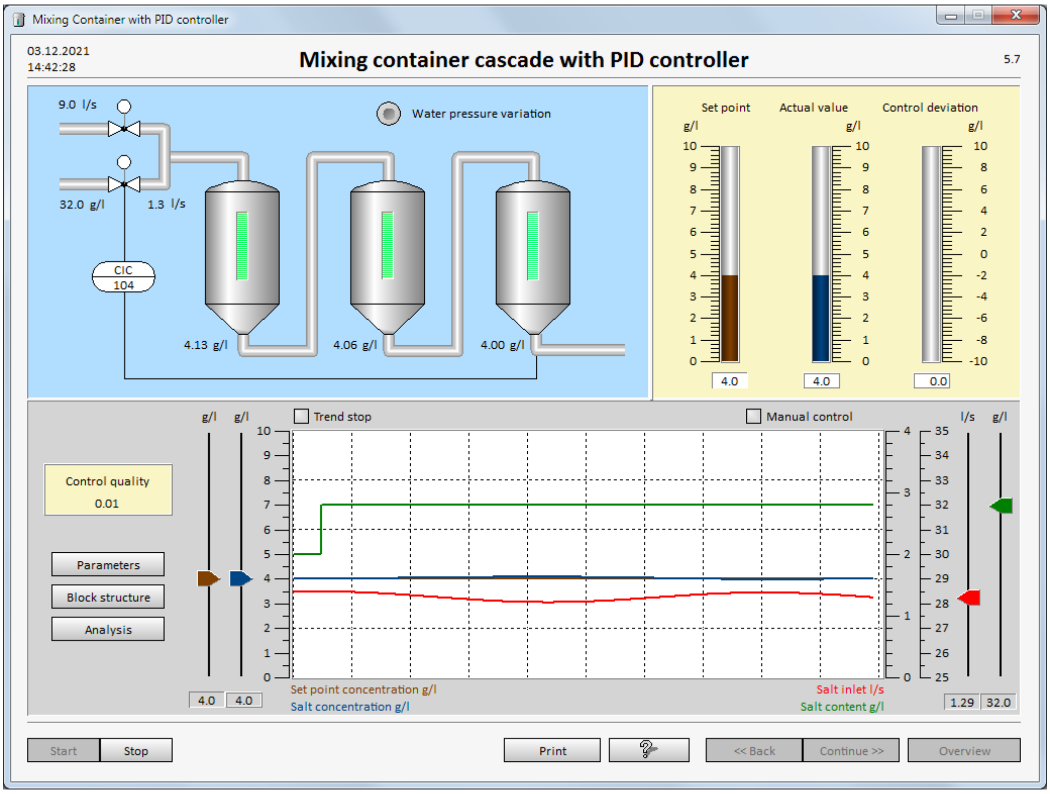
Command response with 20% overshoot / Change of the setpoint from 3g/l to 4g/l.

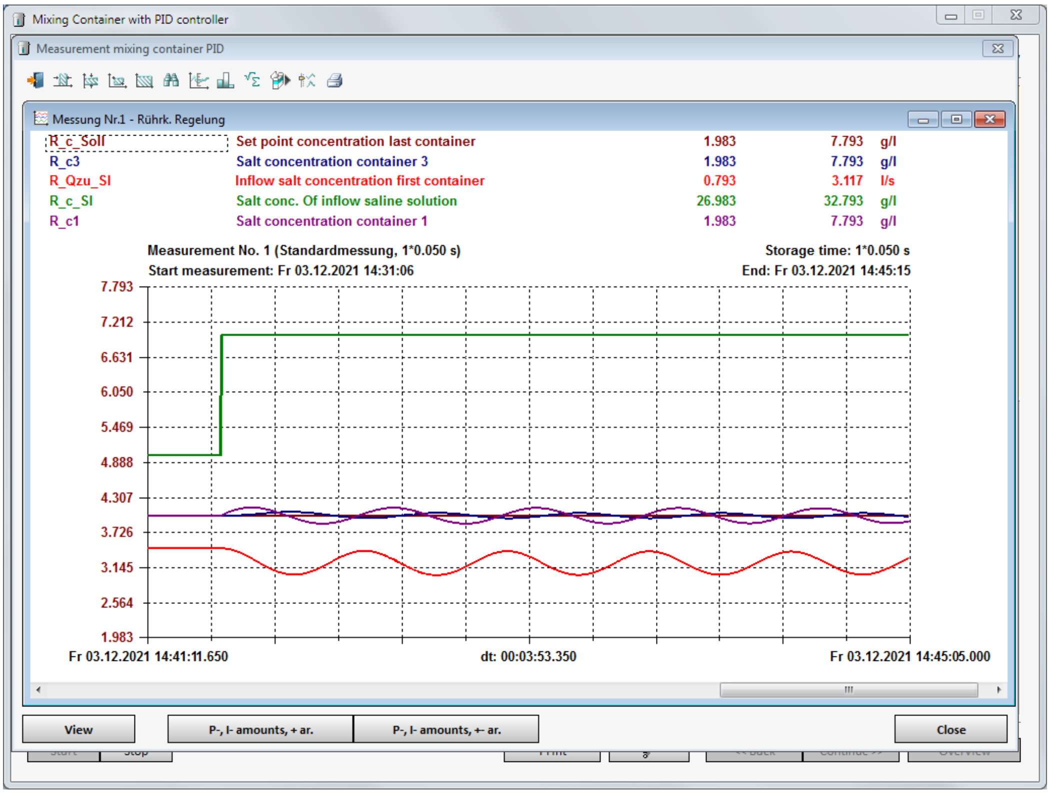




Command response aperiodic

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





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 loop, 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 much earlier than in the third tank. The inner control loop therefore reacts much more quickly to control disturbance, so that the control is accelerated. Another advantage is that large control deviations, such as occur in a single-loop control loop, are avoided in the first boiler due to the inner circle.

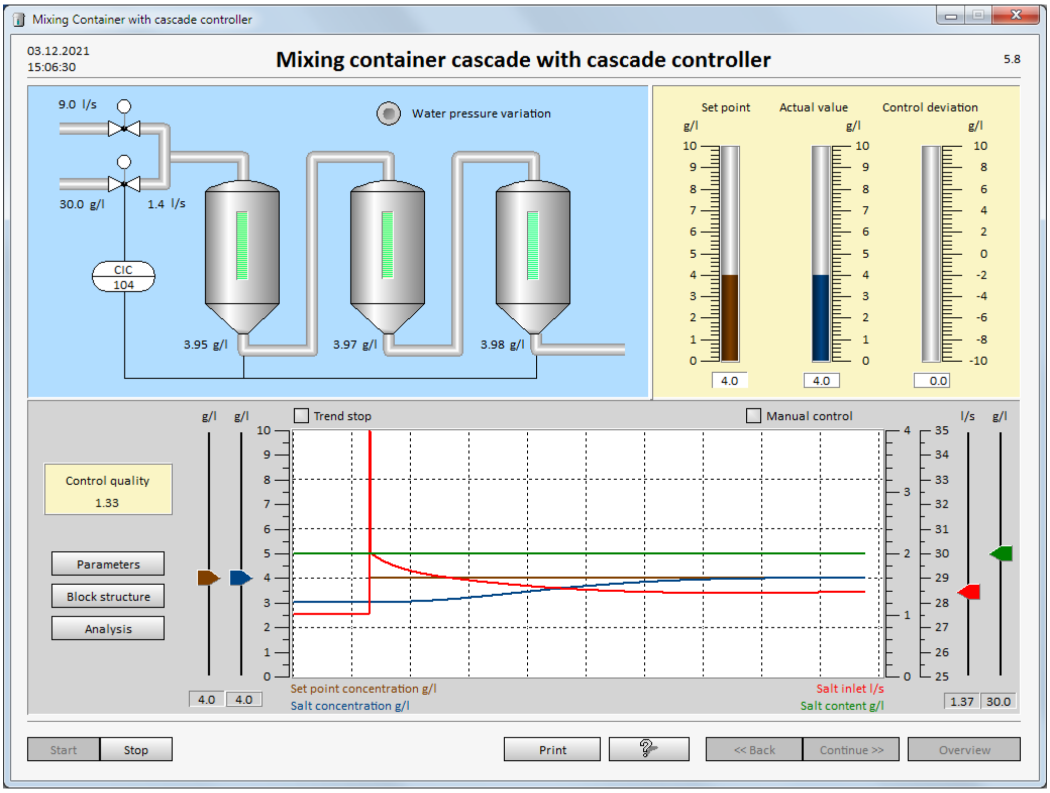
Task 16.

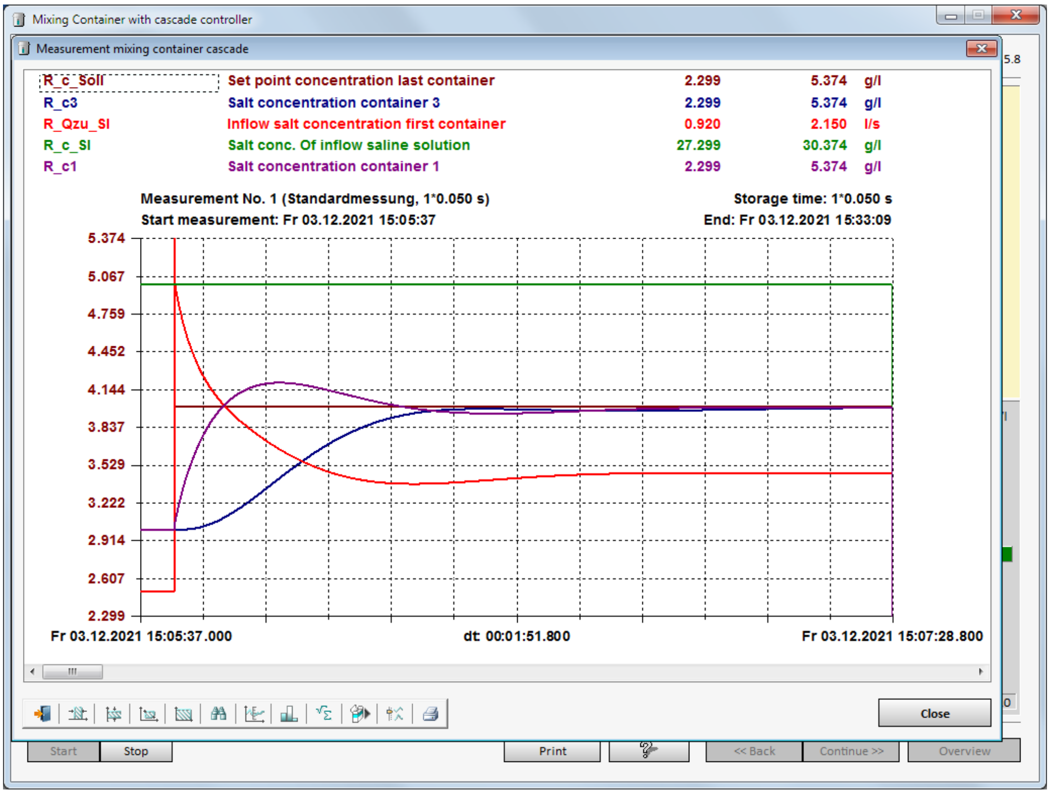
Select the item 5.8 „Closed-loop control with cascade controller“ for the mixed container cascade an press „Start“.

Enter a jump in the setpoint concentration from 3g/l to 4g/l.

Observe the control behavior.

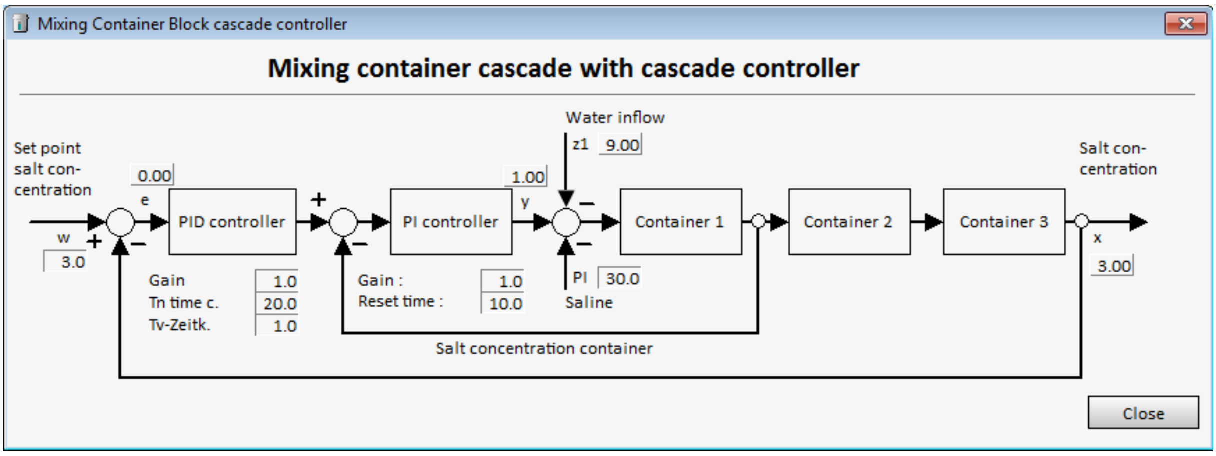
With the set values of the two controllers, the behavior of the control is very good. The actual value (salt concentration in the 3rd container) goes quickly and without overshooting to the setpoint (setpoint concentration).


Mixing Container with cascade controller
03.12.2021
15:06:30
Mixing container cascade with cascade controller
5.8
9.0 l/s
Water pressure variation
30.0 g/l
1.4 l/s
CIC
104
3.95 g/l
3.97 g/l
3.98 g/l
Set point
Actual value
Control deviation
g/l
4.0
4.0
0.0
Trend stop
Manual control
Control quality
1.33
Parameters
Block structure
Analysis
Set point concentration g/l
Salt concentration g/l
Salt inlet l/s
Salt content g/l
1.37
30.0
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)
Storage time: 1*0.050 s
Start measurement: Fr 03.12.2021 15:05:37
End: Fr 03.12.2021 15:33:09
5.374
5.067
4.759
4.452
4.144
3.837
3.529
3.222
2.914
2.607
2.299
Fr 03.12.2021 15:05:37.000
dt: 00:01:51.800
Fr 03.12.2021 15:07:28.800
Close
Start
Stop
Print
<< Back
Continue >>
Overview

The inner control loop (with PI controller) tries to adjust the salt inflow to bring the salt concentration of the 1st container to the manipulated variable of the outer controller (PID controller). The output of the PID controller is the reference variable for the inner control loop. Since the salt concentration continues 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 outputs the setpoint (setpoint concentration). The outer controller specifies a reference value for the inner control loop that 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 the control signal of the external controller goes to the setpoint concentration as a reference variable makes it possible to achieve good and fast control loop behavior.



8 Liquid Level Control (Control Training II)

A container with inflow and outflow is simulated as a controlled system. The size of the outlet 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 setpoint. The valve position represents the input variable of the system, the level the output variable. The inflow acts as a disturbance variable.

The valve is controlled by a motor that is driven by a three-point controller. By activating the motor, the valve can open, close or remain in the set position. The three-position controller issues the "open" and "closed" commands. The valve setpoint position is the setpoint for the three-point controller. The actual value of the valve follows the setpoint with a time delay because the motor moves the valve to the desired position by opening or closing.

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

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

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

8.1 Uncontrolled System (Manual Control)

Select in control Training II the item 5.1 „Uncontrolled system“.

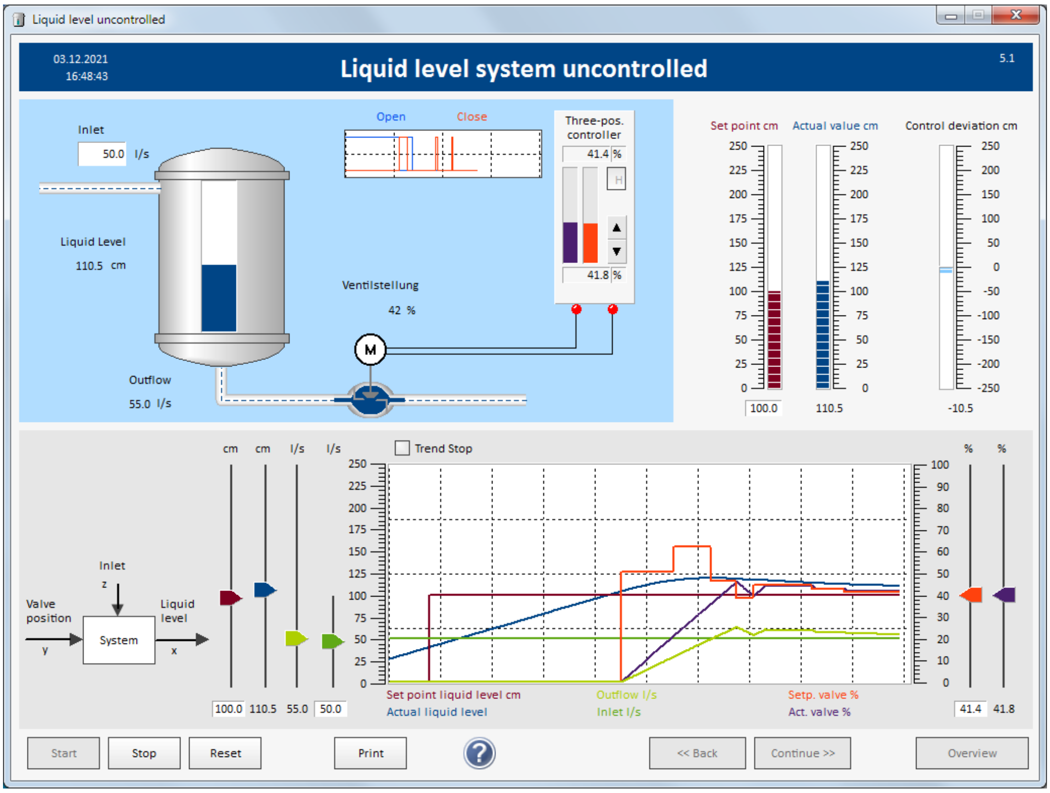
Press “Start”. You can now change the values for the setpoint (reference variable, actual liquid level cm), the control signal (setpoint valve) and the disturbance signal (inlet l/s) using the slider or by entering values below the slider.

Task 1.

Set the inlet to 50l/s and let the container fill up. Set the setpoint (reference variable, setpoint liquid level) to 100cm. By adjusting the control signal (setp. valve %) you can now try to bring the actual value (controlled variable, actual liquid level) to the setpoint (reference variable, setpoint liquid level).

The actual valve position lags behind the desired valve position (compare red and purple signal in the trend display).

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

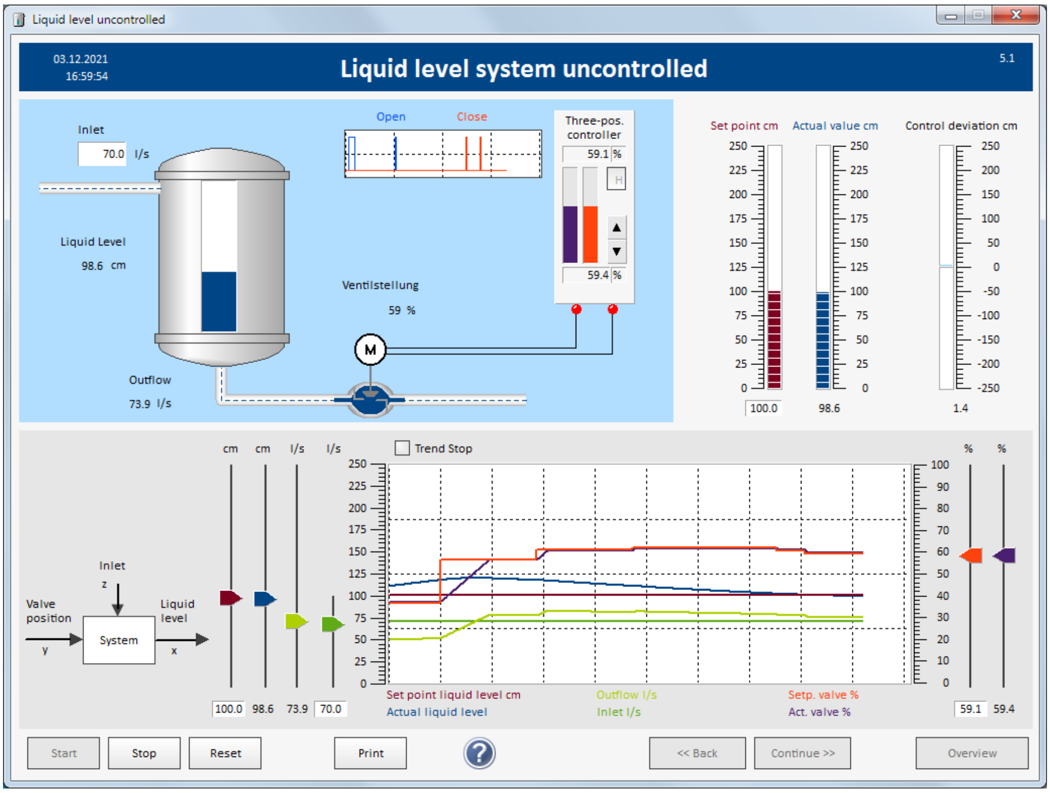


This type of control is known to as command response. The setpoint is adjusted and an attempt is made to bring the actual value (controlled variable) back to the new setpoint (reference variable) by adjusting the control signal.

It can be observed with this system that the actual valve position lags behind 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 inlet 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 more flows out of the container and the level drops.

Changing the inflow is a disturbance for 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

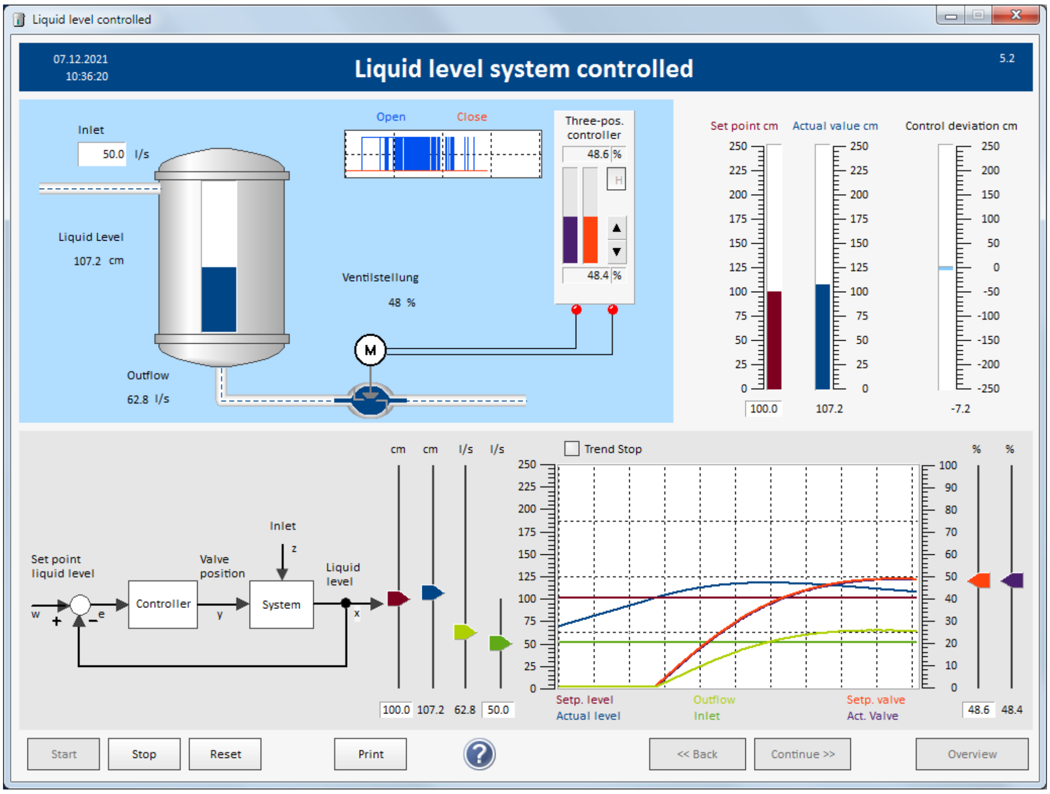
Go to „Overview“ and select item 5.2 „Controlled system“.

Here you can see how the system behaves in principle if, instead of manual control by the user, a controller takes on the task of bringing the actual value to the setpoint.

Task 3.

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

What will happen?



Only when the level of 100cm is reached by the inlet does the controller begin to output a control signal greater than 0. As long as the level was below the setpoint level, the valve remained closed.

If the actual level exceeds the setpoint level, the valve was opened so that more flows out and the level drops again.

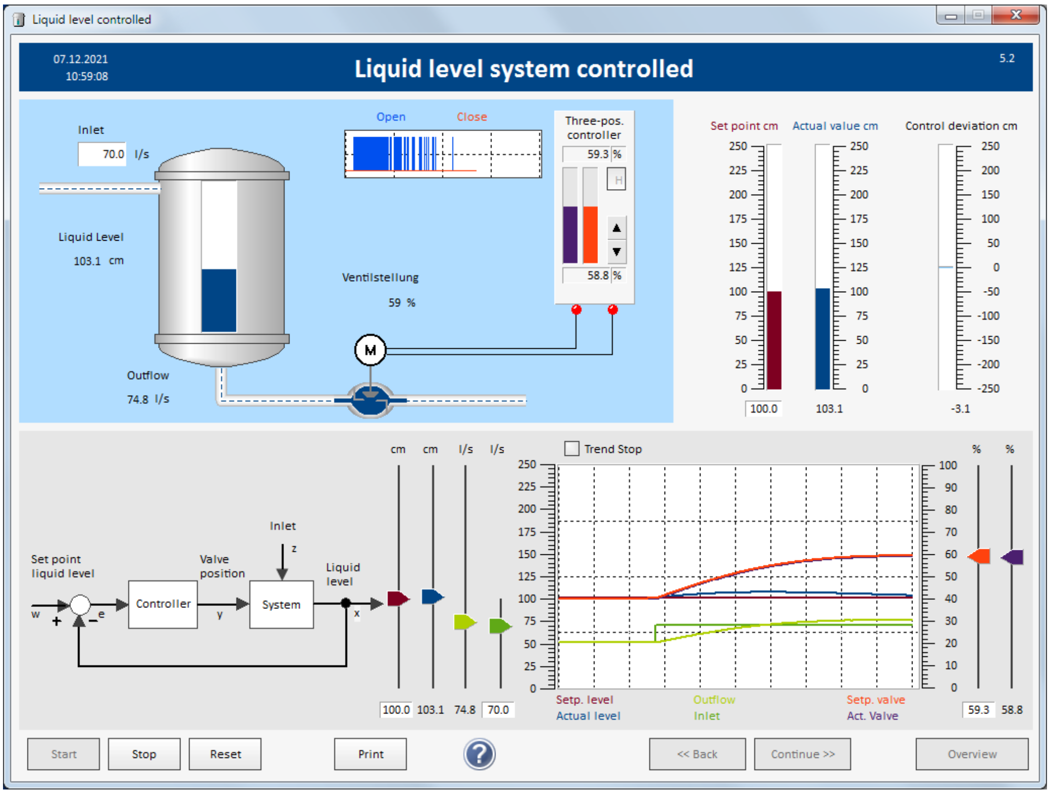
With an overshoot, the controller manages to bring the actual level to the setpoint.

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

Task 4.

Change the inlet to 70l/ s.

What will happen?



The level begins to rise.

The controller tries to open the valve further so that more flows out of the container.

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

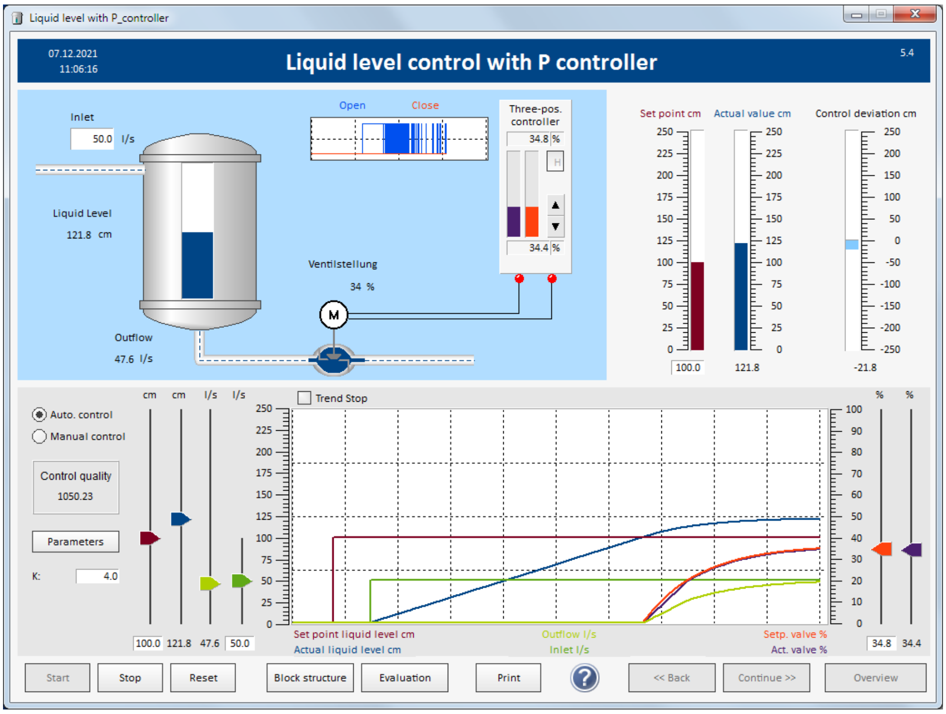
Go to „Overview“ and select item 5.4 „Closed-loop control with P controller“.

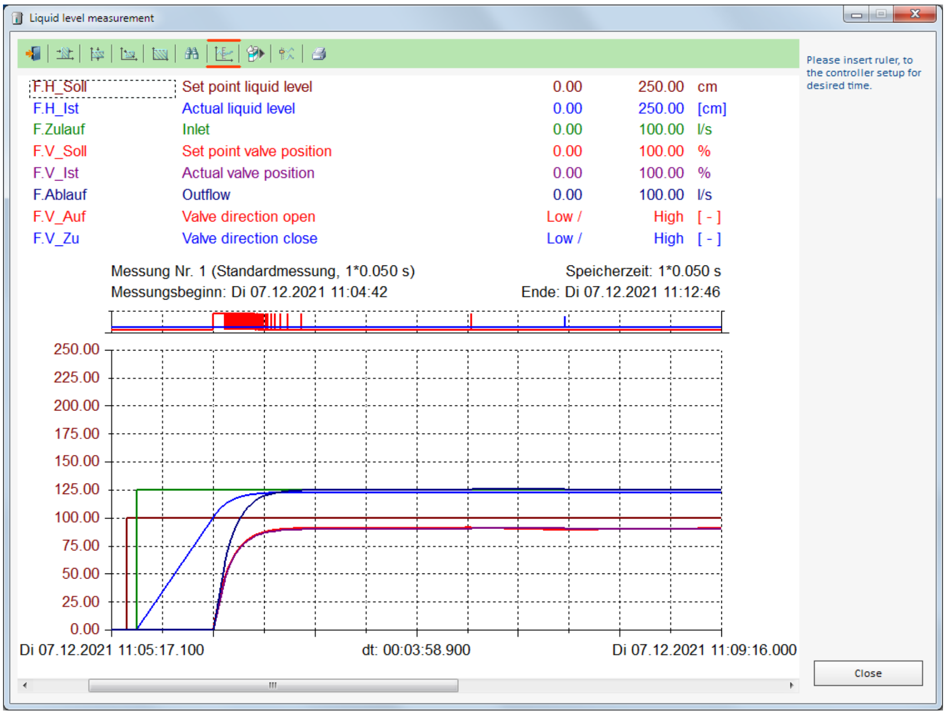
Press „Start“.

Task 5.

Set K to 4, the setpoint to 100cm and the inlet 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 inlet has been set to 50l/s. If the actual level exceeds the setpoint 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 setpoint (reference variable). We get a steady-state control error.

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

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

Reason:

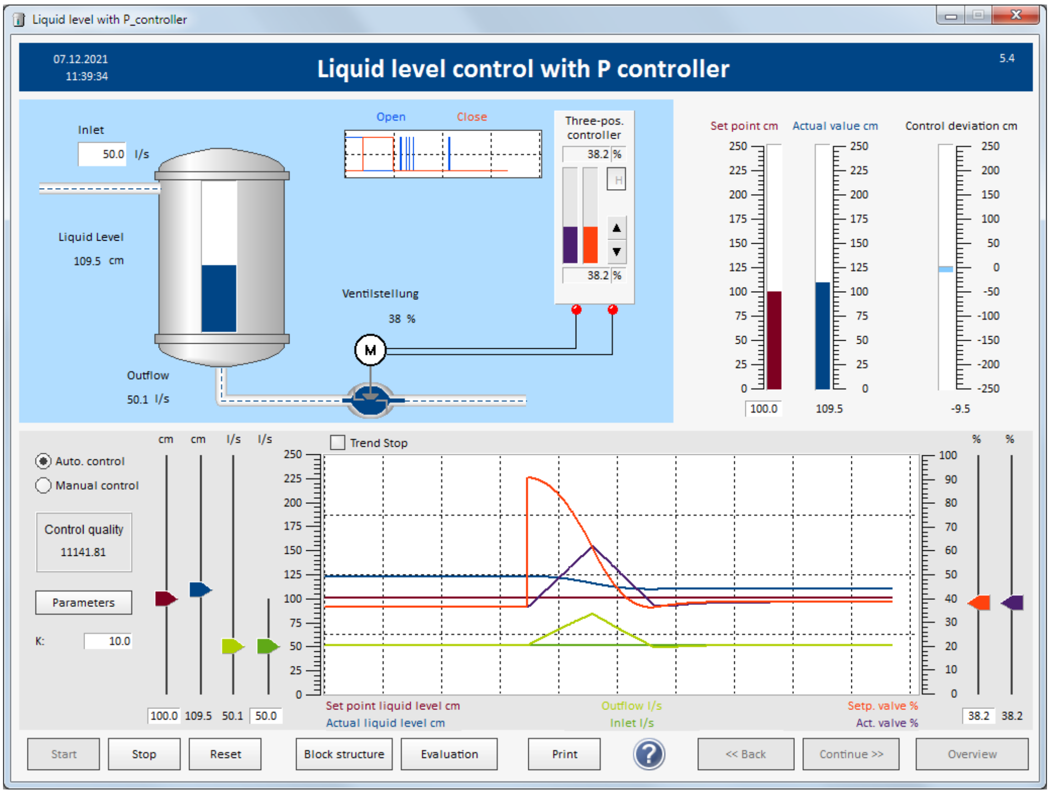
The P controller works like an amplifier. The input signal to the controller x-w (setpoint - actual value) is multiplied by the specified gain factor (in our case 4). In order for the P controller to output a control signal (valve position) not equal to zero, the setpoint and actual value must be different,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

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

Task 6.

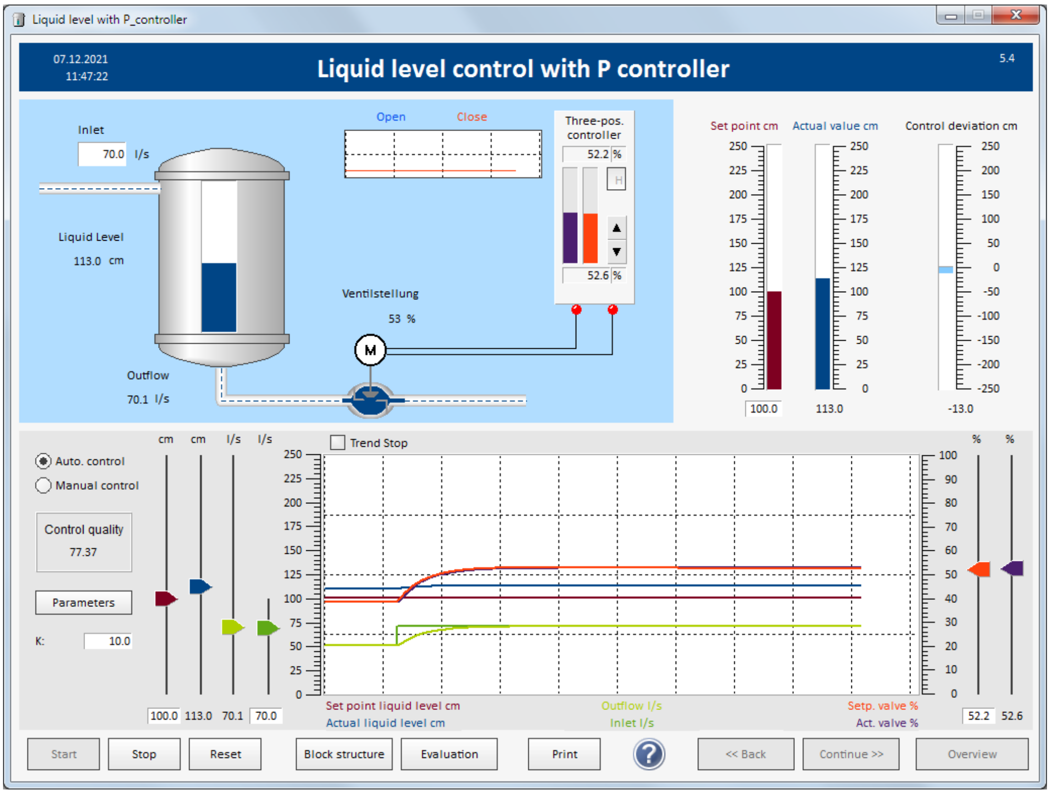
Change the gain of the P controller from 4 to 10 and wait until the control loop has settled again.

What will happen?



The control error between the setpoint 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 bring the actual value to the setpoint 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 setpoint 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“.

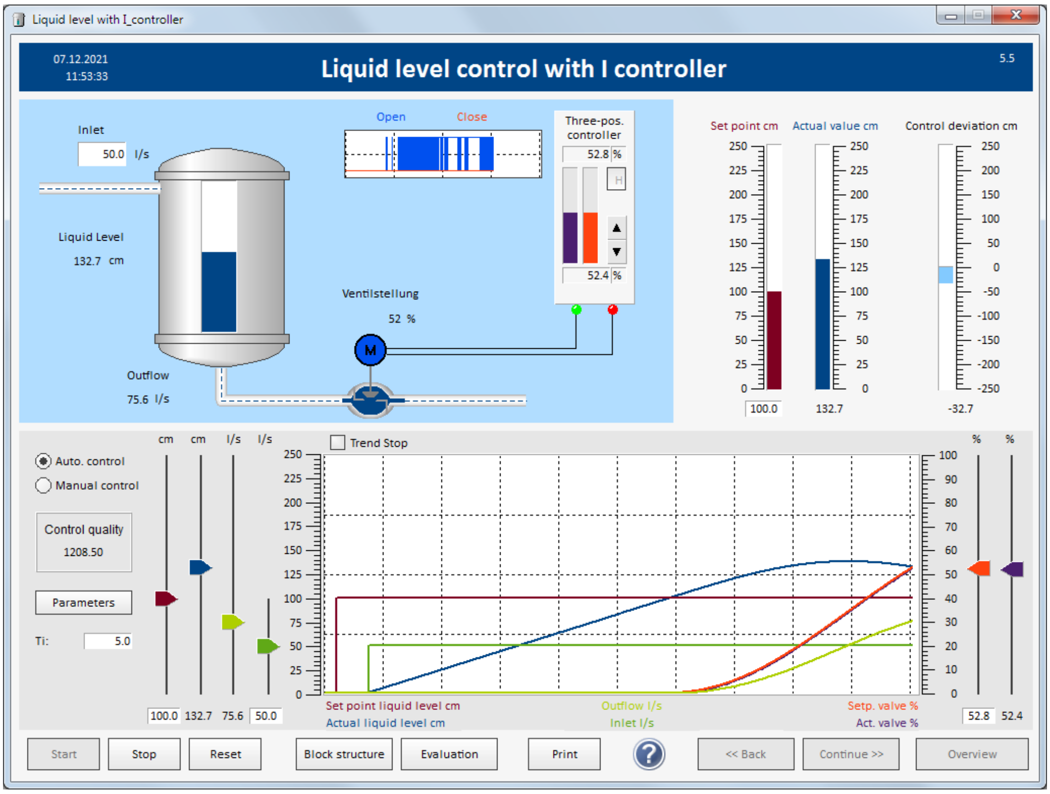
Press „Start“.

Task 7.

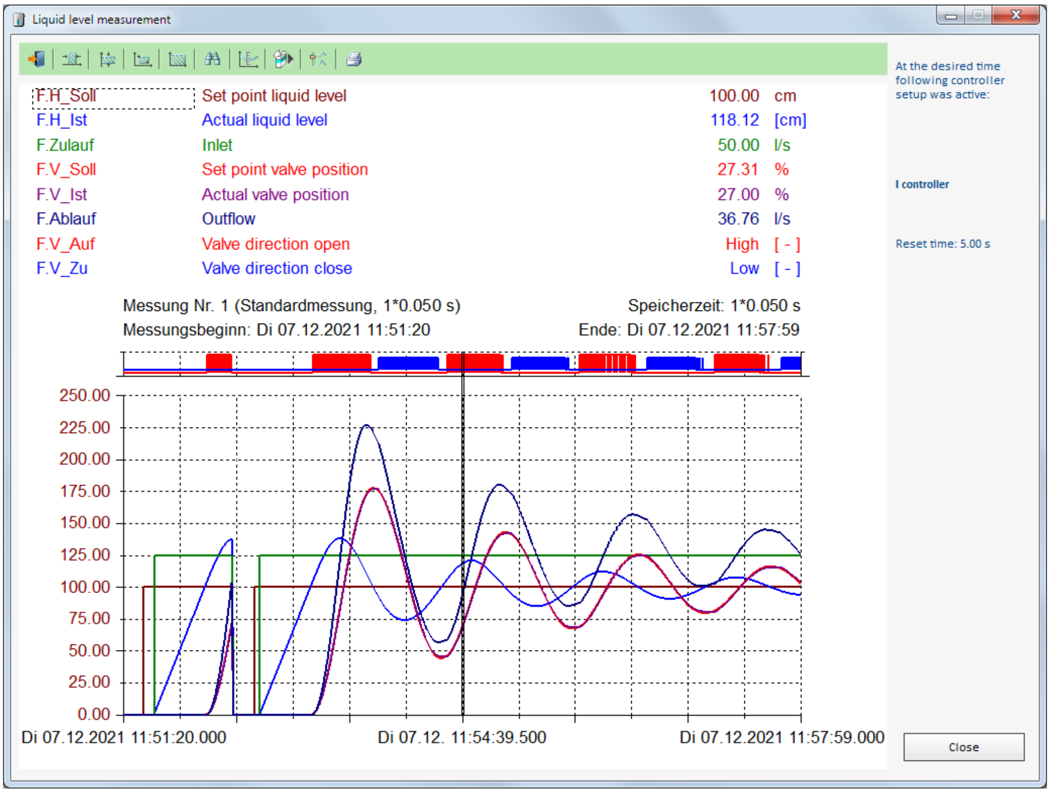
Set the controller parameter Ti to 5.

Change the setpoint to 100cm and the inlet 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 setpoint.



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

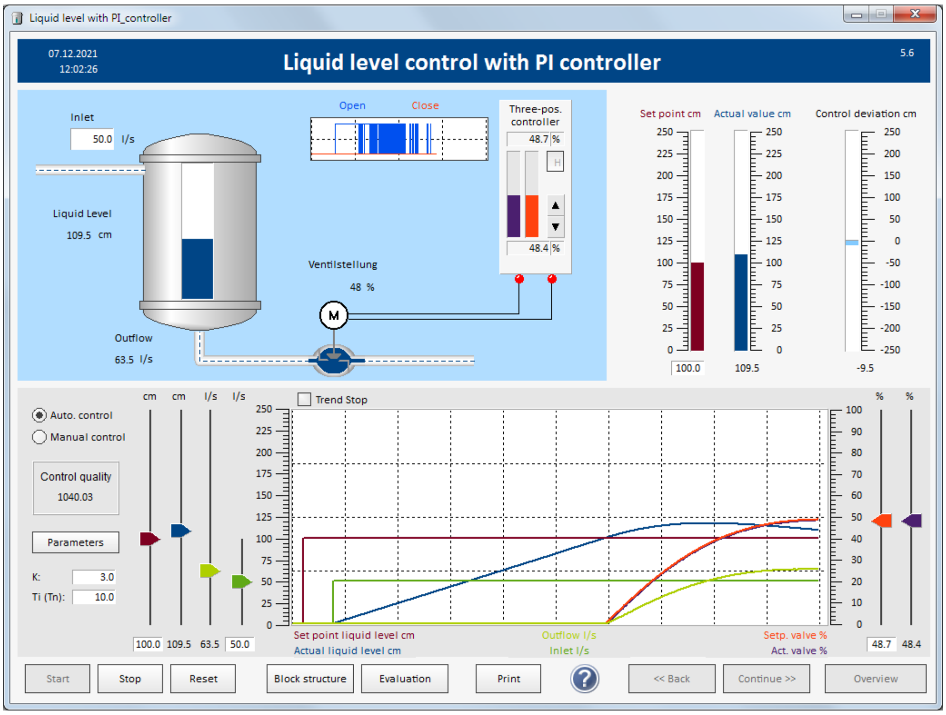
Go to „Overview“ and select item 5.6 „Closed-loop control with PI controller“.

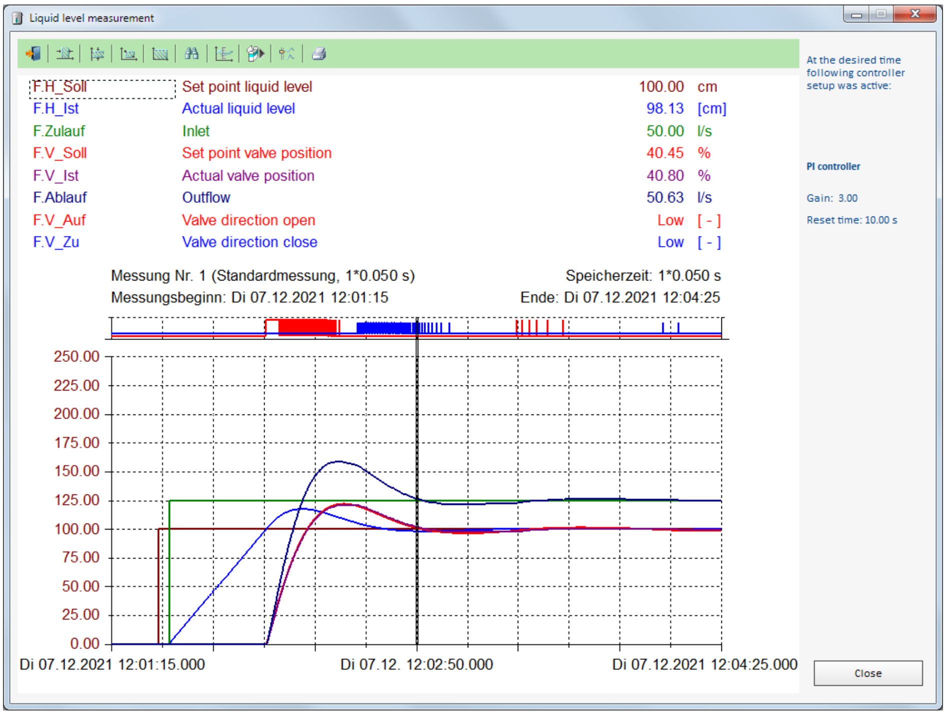
Press „Start“.

Task 8.

Leave the controller parameters on: Gain K = 3, Reset time Ti = 10.

Change the setpoint to 100cm and the inlet to 50l/s. Observe the settling behavior.





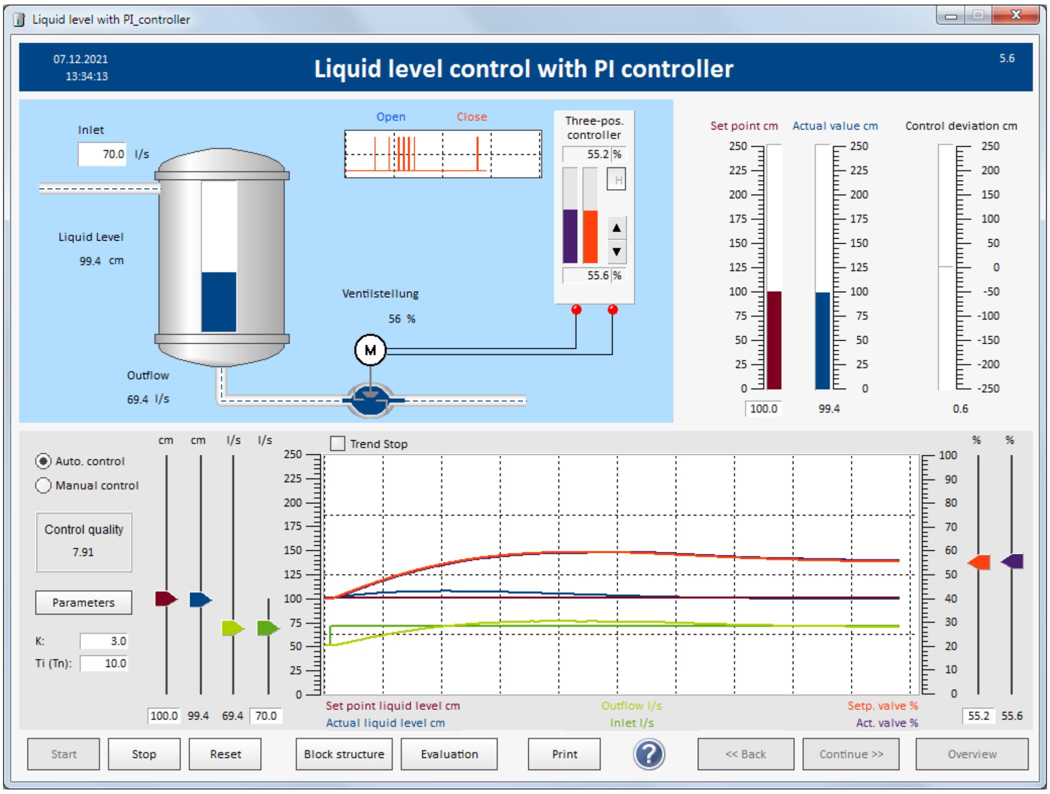
The actual value (controlled variable, actual level) reaches the new setpoint (reference variable, setpoint level) with the PI controller and the set parameters with overshoot.

Since the setpoint 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 inlet 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 setpoint again.

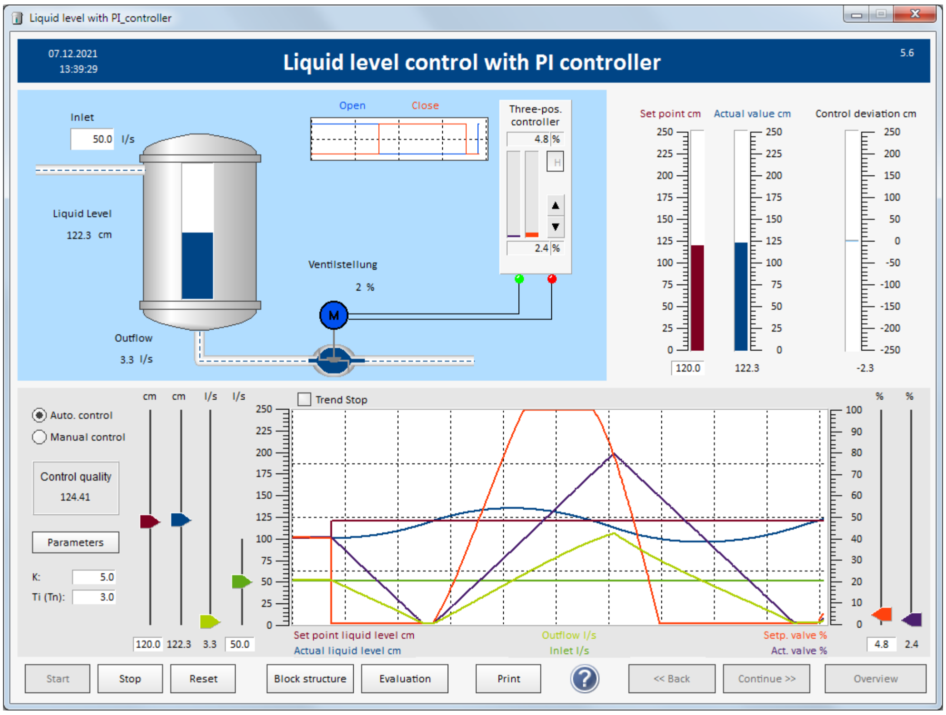
Since the control loop reacts to a change in the disturbance value, one speaks of disturbance response in this case.

Task 10.

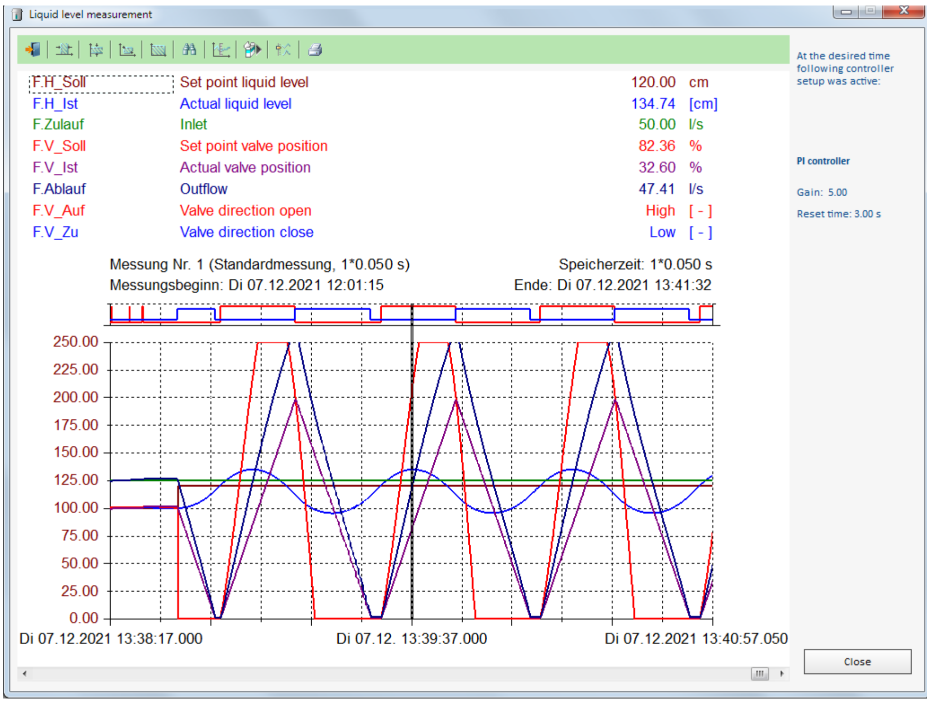
Let the system settle with the specified parameters of the PI controller to the setpoint 100cm with an inlet of 50l/s.

Change the controller parameters to K = 5 and Ti = 3.

Enter a jump in the setpoint level from 100cm to 120cm. What will happen?



With these controller parameters, the control loop becomes unstable and the actual level oscillates around the setpoint level.

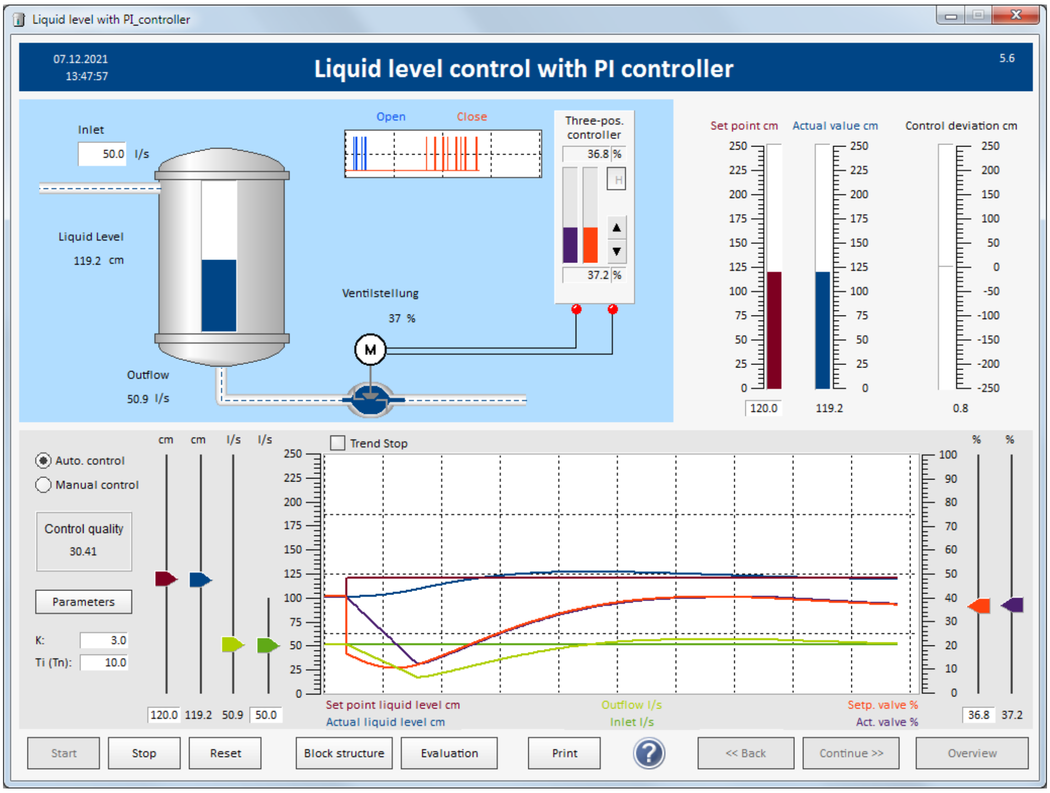


Task 11.

Let the system settle with the specified parameters K = 3 and Ti = 10 of the PI controller to the setpoint 100cm with the inlet 50l/s.

Enter a jump in the setpoint level from 100cm to 120cm.

Determine the control quality for this jump.



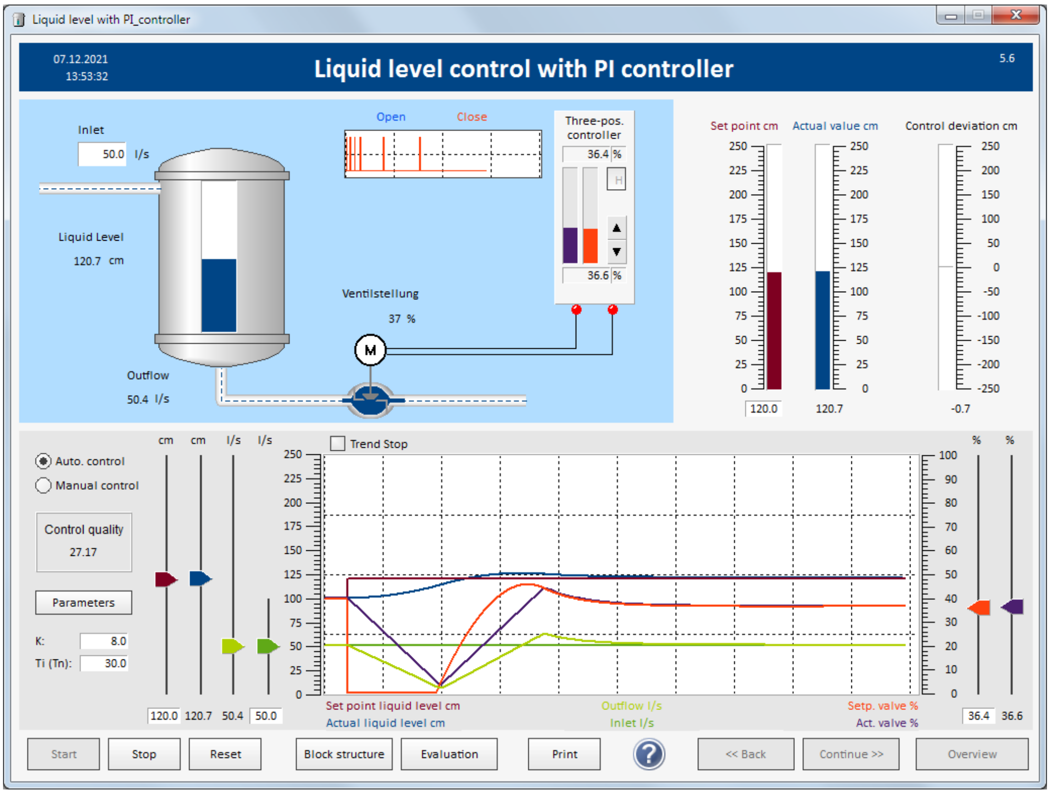
The control quality after settling is approx. 31.71.

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 setpoint.

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 setpoint level of 100 cm.

The setpoint 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 inlet = 50l/s to the target level = 100cm
- Set controller parameters
- Set the setpoint 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 setpoint.

8.2.5 Closed-loop Control with PID Controller

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

Press „Start“.

Keep the set parameters K = 3, Ti = 10 and Td = 2. Enter 100cm as the setpoint level and set the inlet to 50l/s.

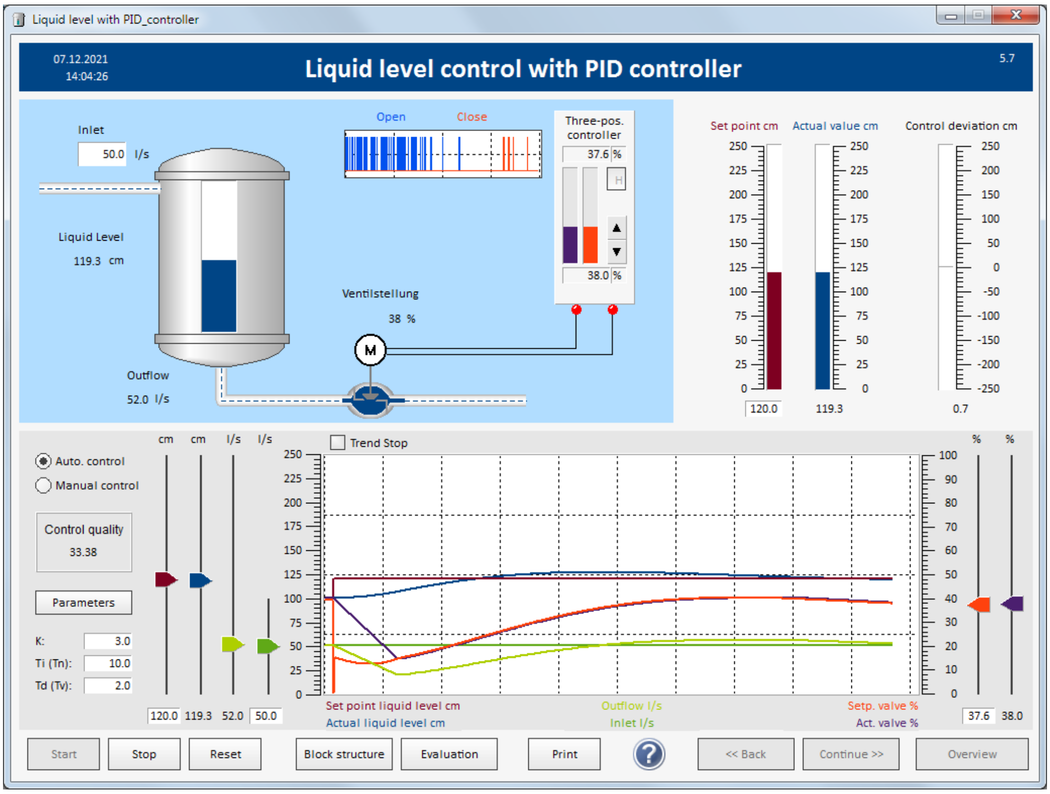
Wait until the control loop has settled.

Task 13.

Investigate the command response with the preset parameters:

Gain K = 3, Reset time Ti = 10, Derivative time Td = 2

Change the setpoint to 120cm.



The control loop goes into a stable state with overshoot. The actual value reaches the setpoint.

As can be seen in the trend diagram, the sudden change in the setpoint 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.

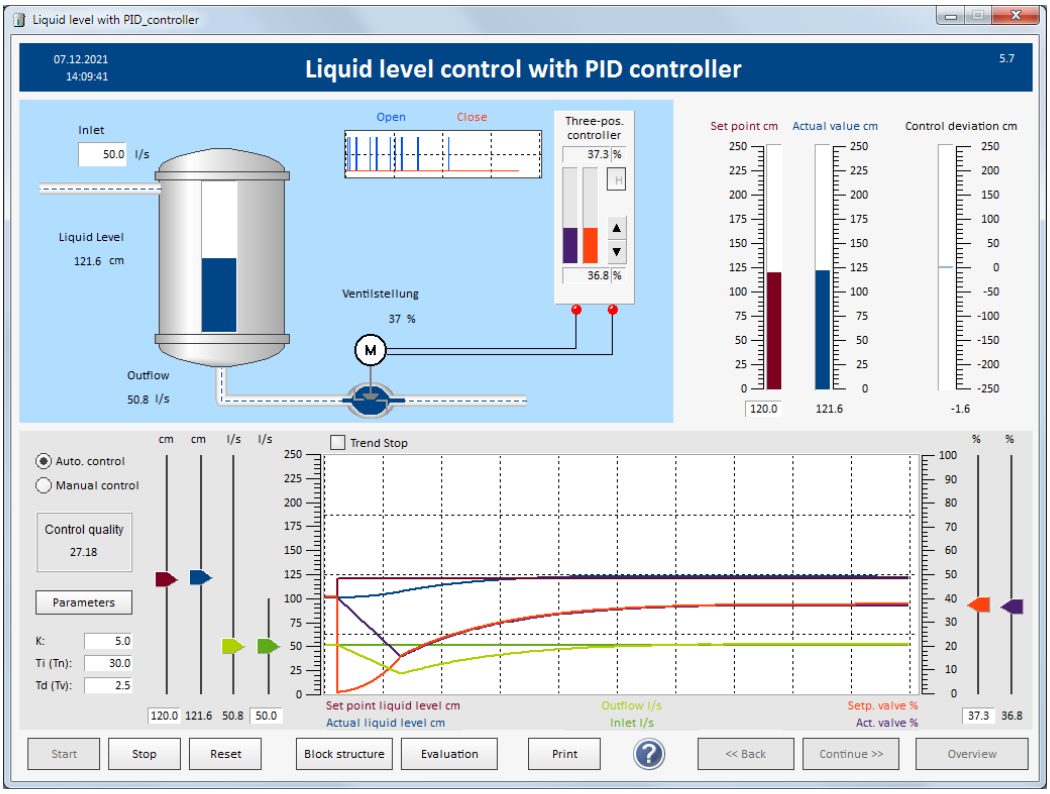
The control quality is over 33.5.

Since the valve is controlled by pulses (opening, closing), the actual value fluctuates slightly around the setpoint.

Task 14.

Carry out the tests with further controller parameters in order to improve the control quality:

- Let the system settle with an inlet = 50l/s to the setpoint level = 100cm
- Set controller parameters
- Set the setpoint 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.

Note:

In practice, PI controllers are mainly used. In many cases, the D component is turned away in the PID controller, so that the controller then 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, with the D component, you have the option of making the control faster (but this is often very difficult).

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

9 Engine Speed Control (Control Training II)

This process is the simulation of an engine, the speed of which 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.

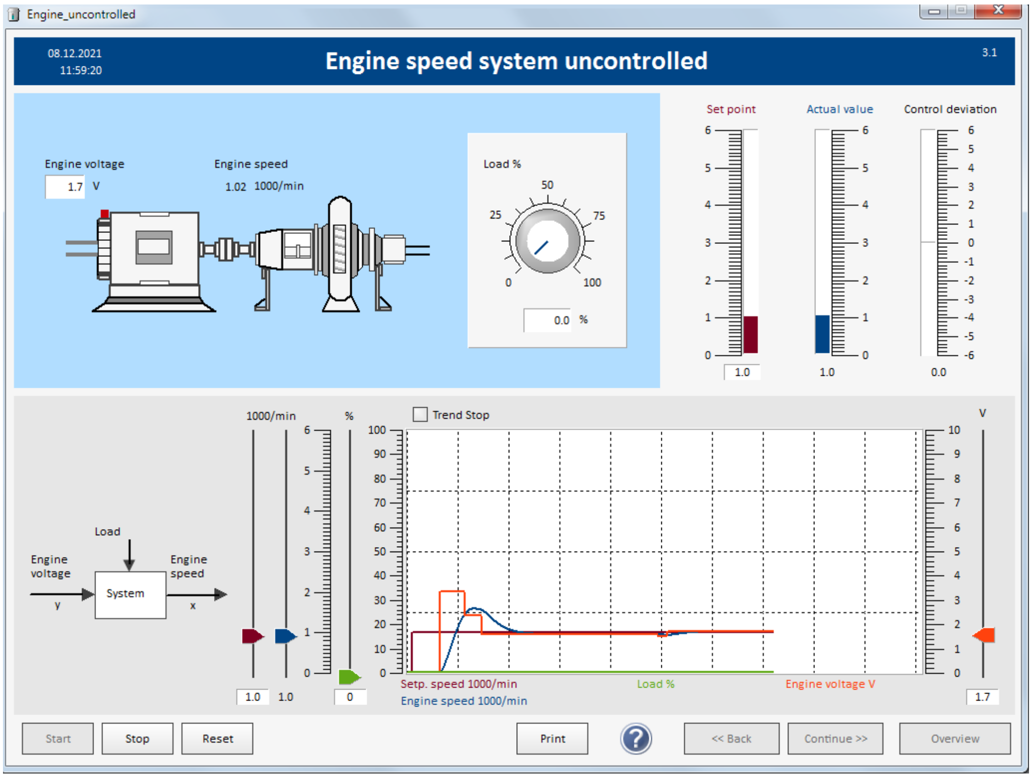
9.1 Uncontrolled System (Manual Control)

Select item 3.1 „Uncontrolled system“. Press „Start“.

You can now change the values for the setpoint (reference variable, setpoint 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.

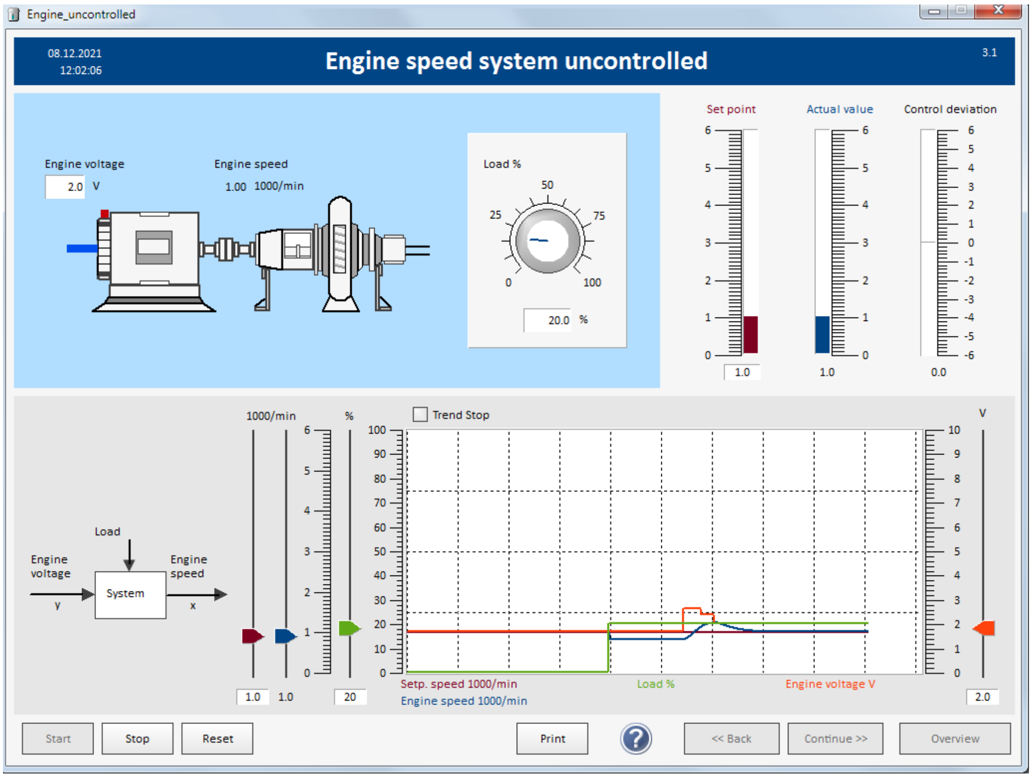
Set the setpoint (setpoint speed, reference variable) to 1 (corresponds to 1000/min) and try to bring the actual value (Engine speed) to the setpoint speed (reference variable) by adjusting the engine voltage (control signal).



This type of control is known as command response. The setpoint is adjusted and an attempt is made to bring the actual value (controlled variable) back to the new setpoint (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

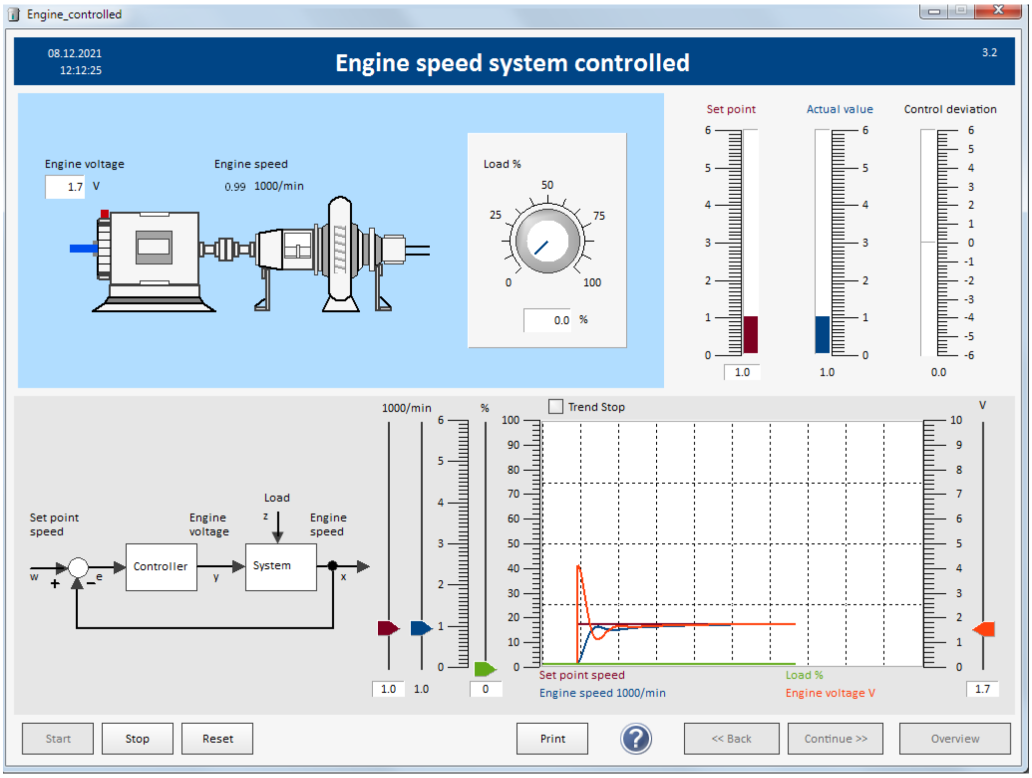
9.2.1 Closed-loop Controlled System

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 bringing the actual value to the setpoint.

Task 3.

Press „Start“ and set the setpoint to 1 (1000/min). What will happen?

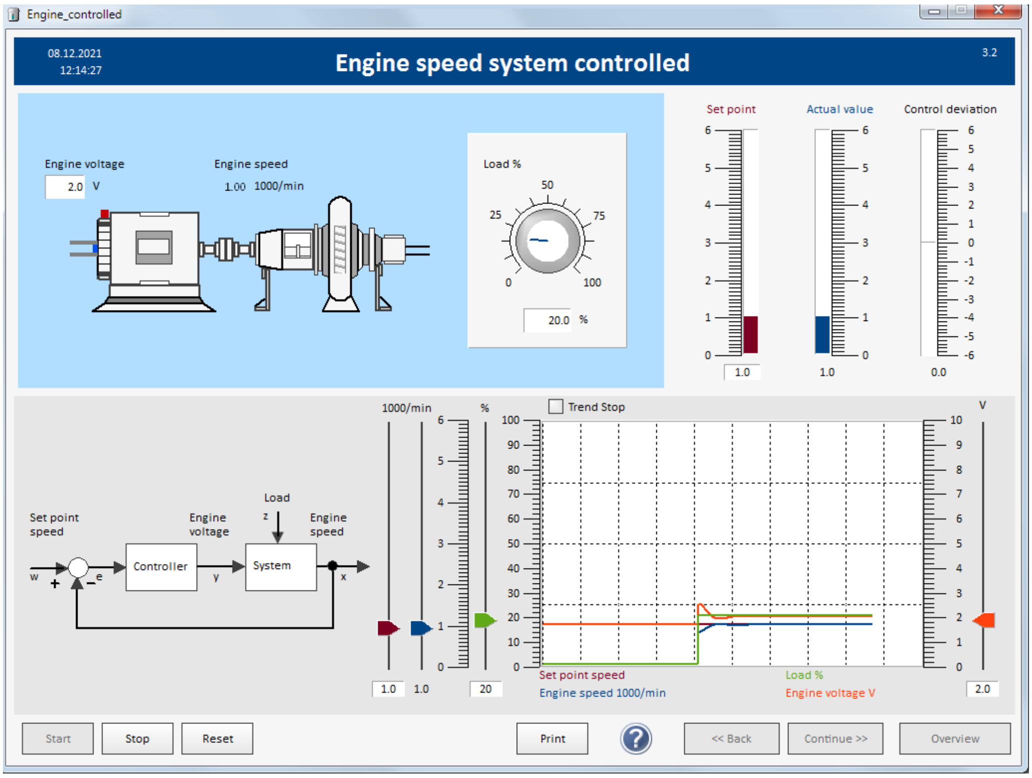


The actual value (engine speed) goes to the setpoint after a short time (command response).

Task 4.

Change the load from 0% to 20%.

What will happen?



The speed becomes lower.

The controller tries to bring the actual value (engine speed) back to the setpoint by increasing the engine voltage (control signal).

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

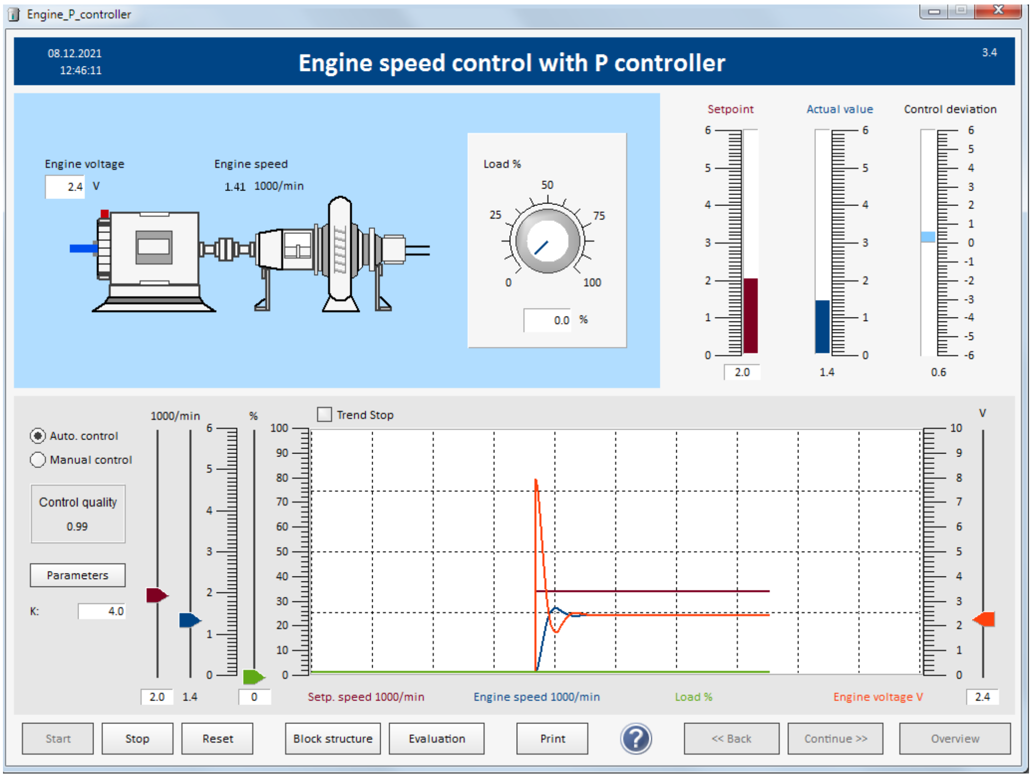
9.2.2 Closed-loop Control with P Controller

Go to „Overview“ and select item 3.4 „Closed-loop control with P controller“.

Press „Start“.

Task 5.

Change the setpoint 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 setpoint (reference variable, setpoint speed). We get a steady-state control error.

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

w = reference variable (setpoint) and x = controlled variable (actual signal).

Reason:

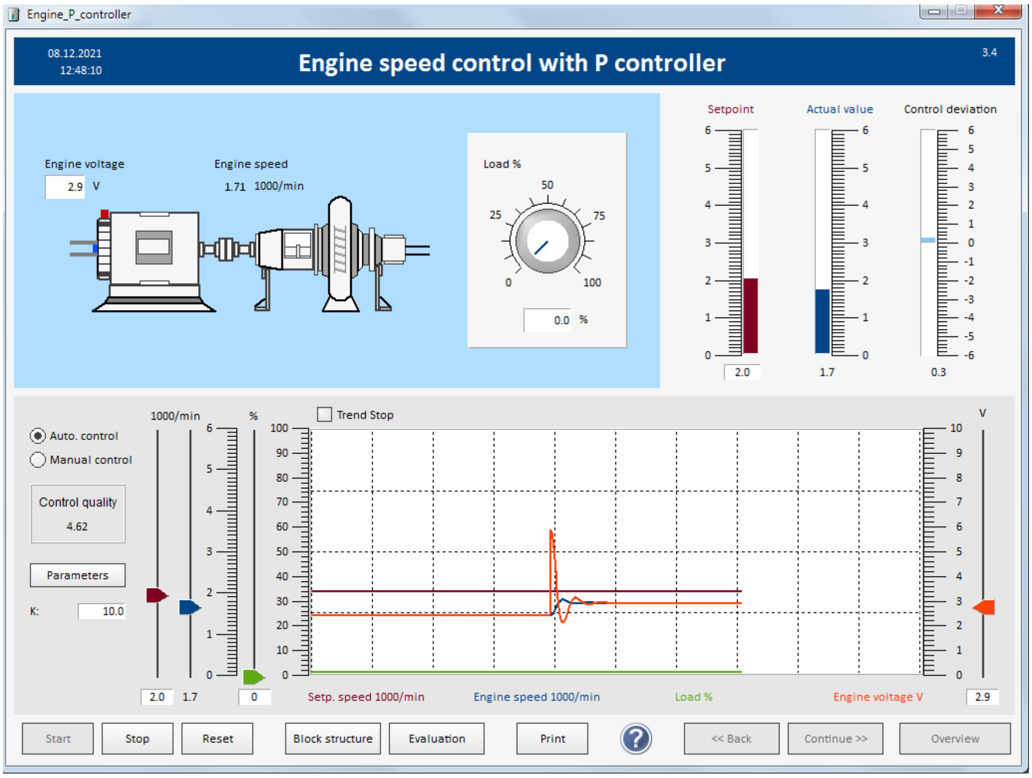
The P controller works like an amplifier. The input signal to the controller w - x (setpoint - actual value) is amplified with the specified amplification factor (in our case 4). In order for the P-controller to output a control signal (an engine voltage) that is not equal to zero, setpoint and actual 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 setpoint 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 bring the actual value to the setpoint 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:

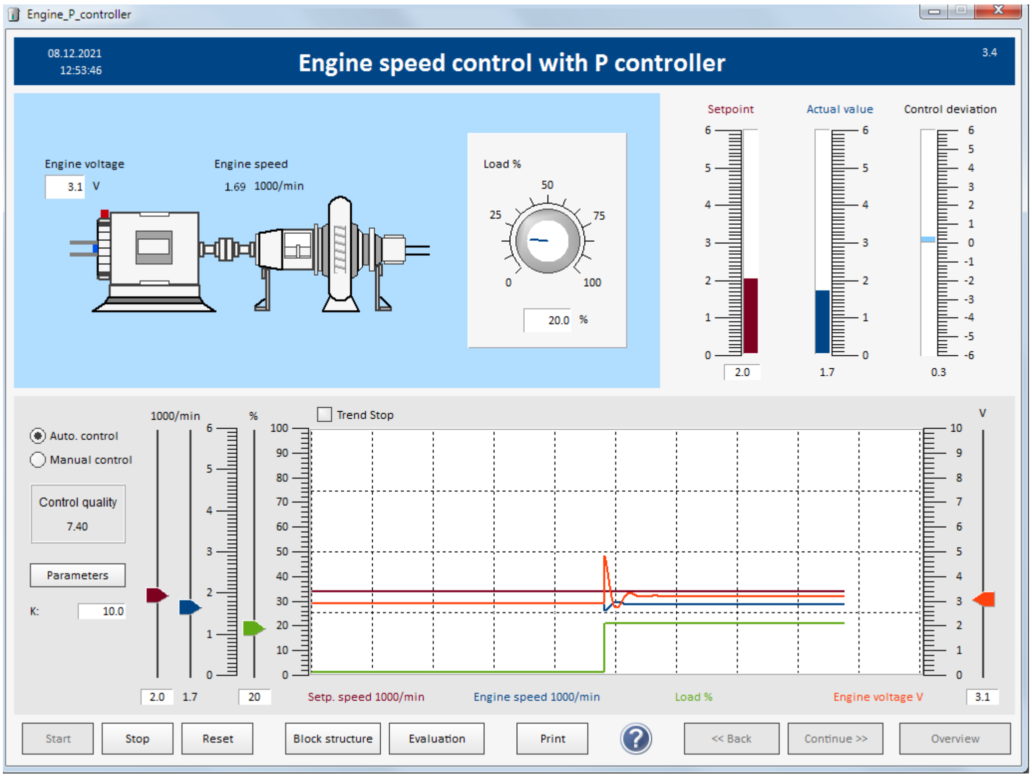
Control signal y = K * (w – x) = 10 * (2 – 1,71) = 2,9

(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 setpoint and disturbance variable (command response and disturbance response).

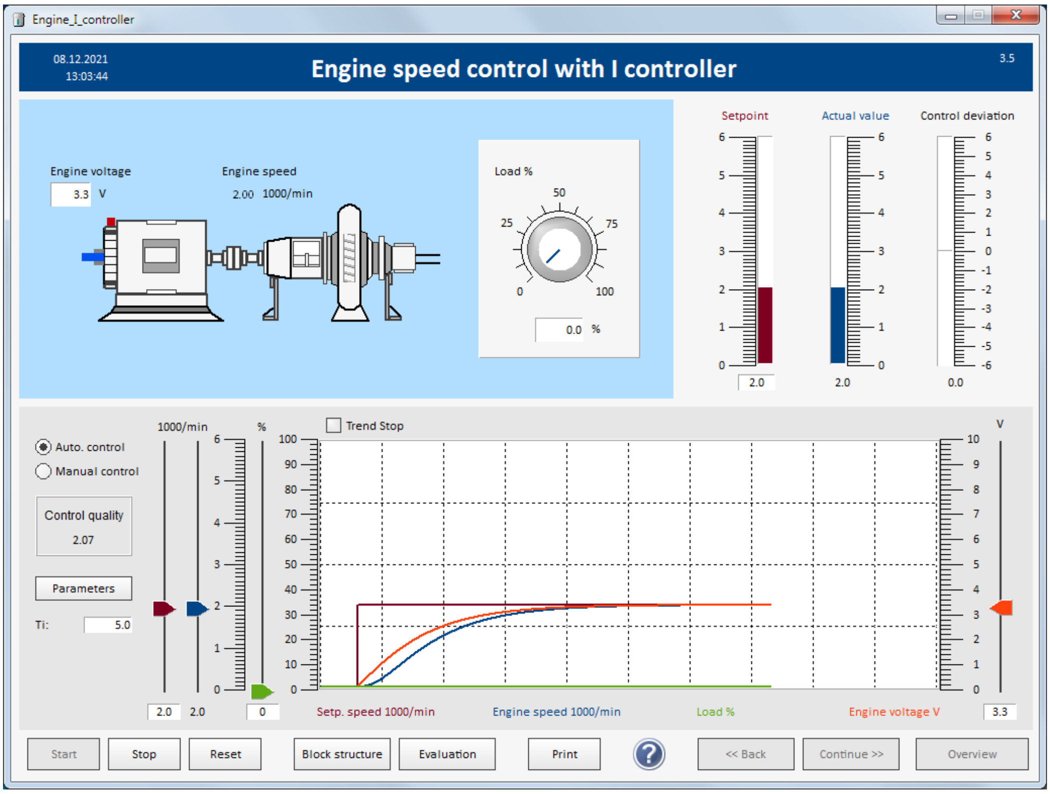
9.2.3 Closed-loop Control with I Controller:

Go to „Overview“ and select item 3.5 „Closed-loop control with I controller“.

Press „Start“.

Task 8.

Change the setpoint to 2 (1000/min). What will happen?



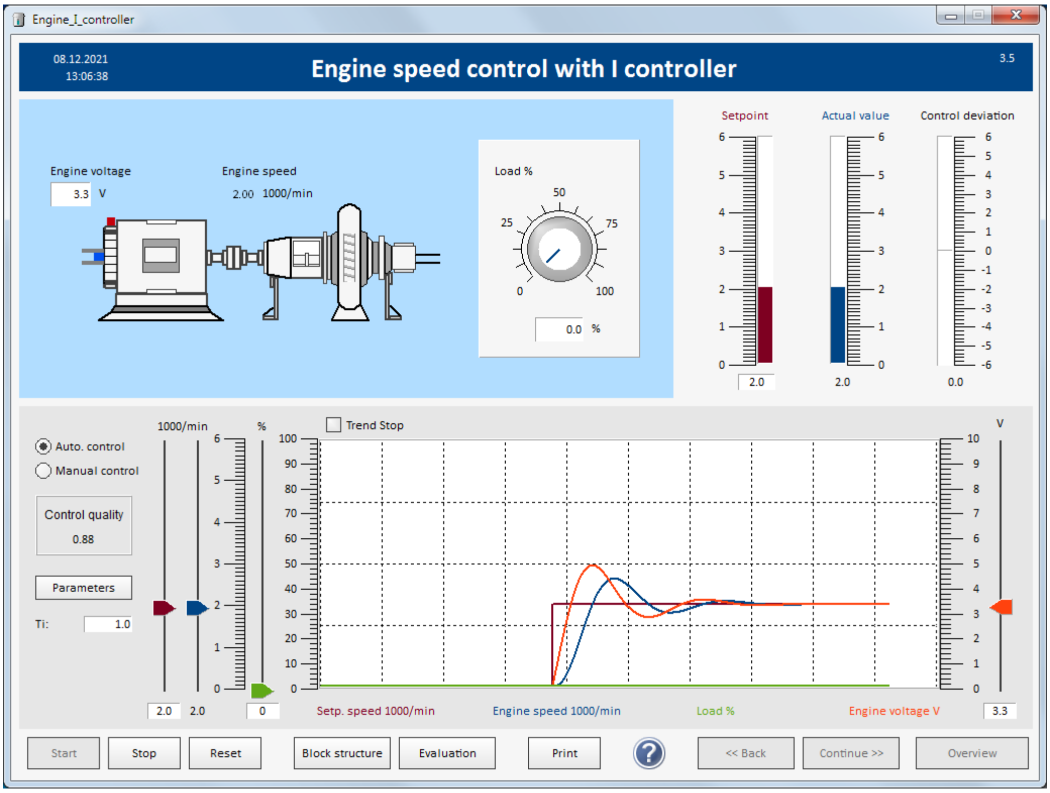
The engine speed is slowly increased by the I controller. The actual value reaches the setpoint after a long period of time.

Task 9.

Press „Reset".

Change the time constant Ti to 1 and specify a setpoint jump 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 setpoint 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“.

Press „Start“.

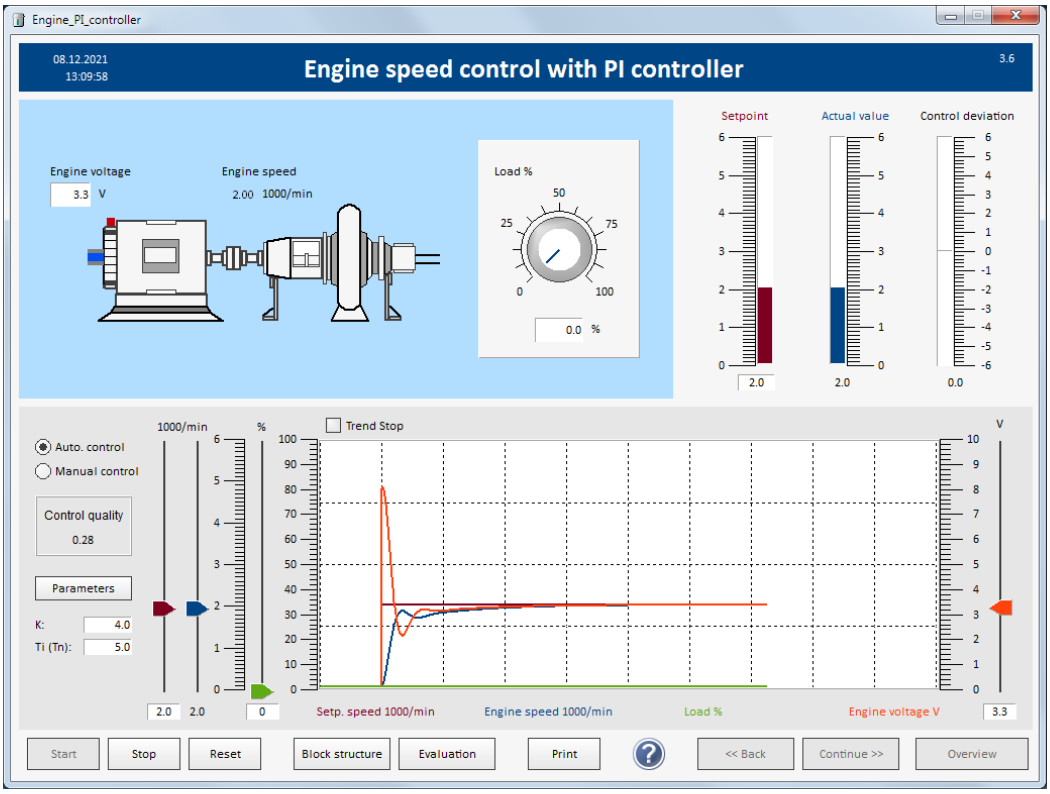
Task 10.

Keep the set parameters:

Gain K = 4, Reset time Ti = 5.

Change the setpoint 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 setpoint (reference variable, setpoint speed) without overshooting.

The value for the control quality reaches 0.28.

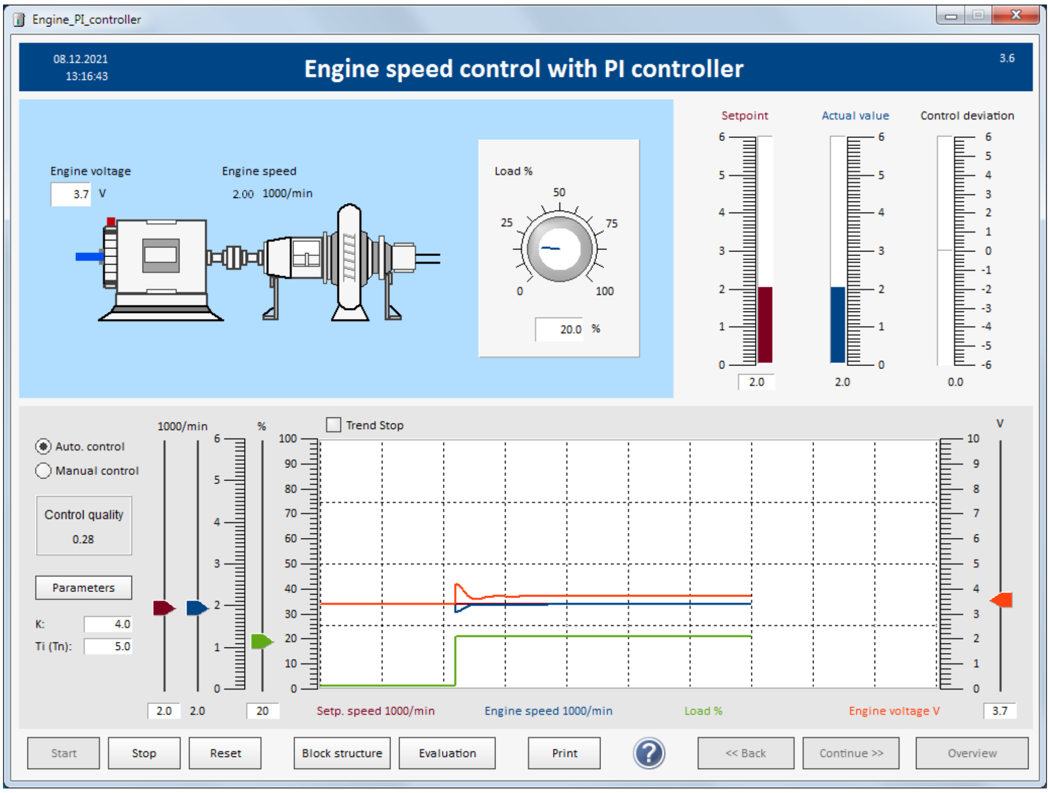
Since the setpoint has been changed, this is about the investigation of the command response.

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 setpoint again.

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

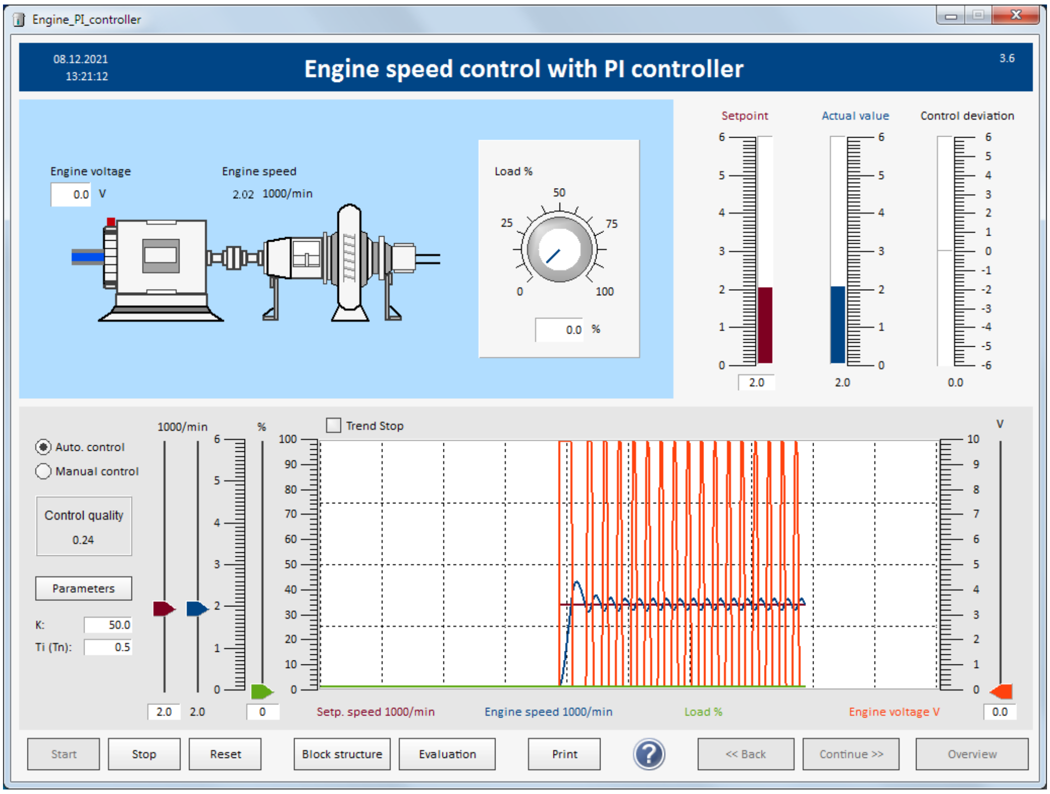
Task 12.

Press „Reset“.

Set the controller parameters to gain K = 50 and reset time Ti = 0.5.

Enter a setpoint jump 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 setpoint (reference variable, setpoint speed)

With these controller parameters, the PI controller is not suitable for this control loop.

Task 13.

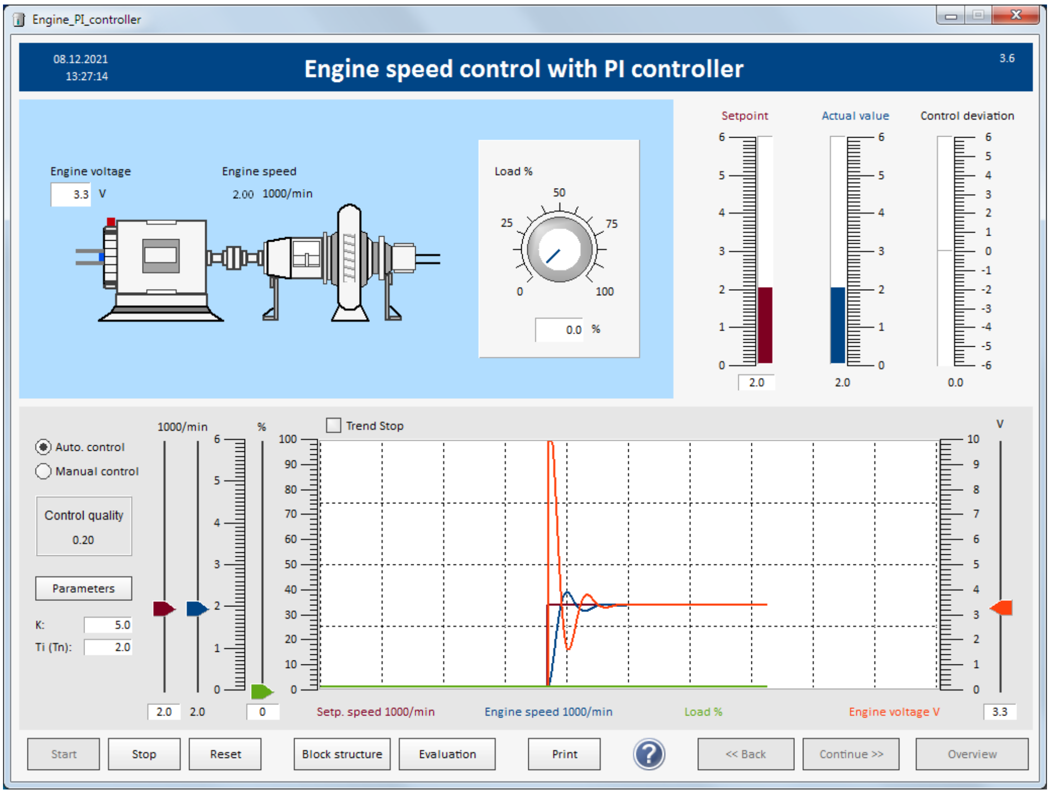
The number in the box labeled "Control quality" indicates a value about the quality of the steady-state control loop. The smaller the number, the faster the control loop has settled, i.e. the actual value has reached the setpoint and is no longer changing.

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 press "Reset". Setpoint speed (setpoint), engine speed (controlled variable), control signal (engine voltage) and disturbance (load) receive their initial values again.

Change the controller parameters and then set the setpoint 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:

- Press Reset
- Set the controller parameters
- Set setpoint 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“.

Press „Start“.

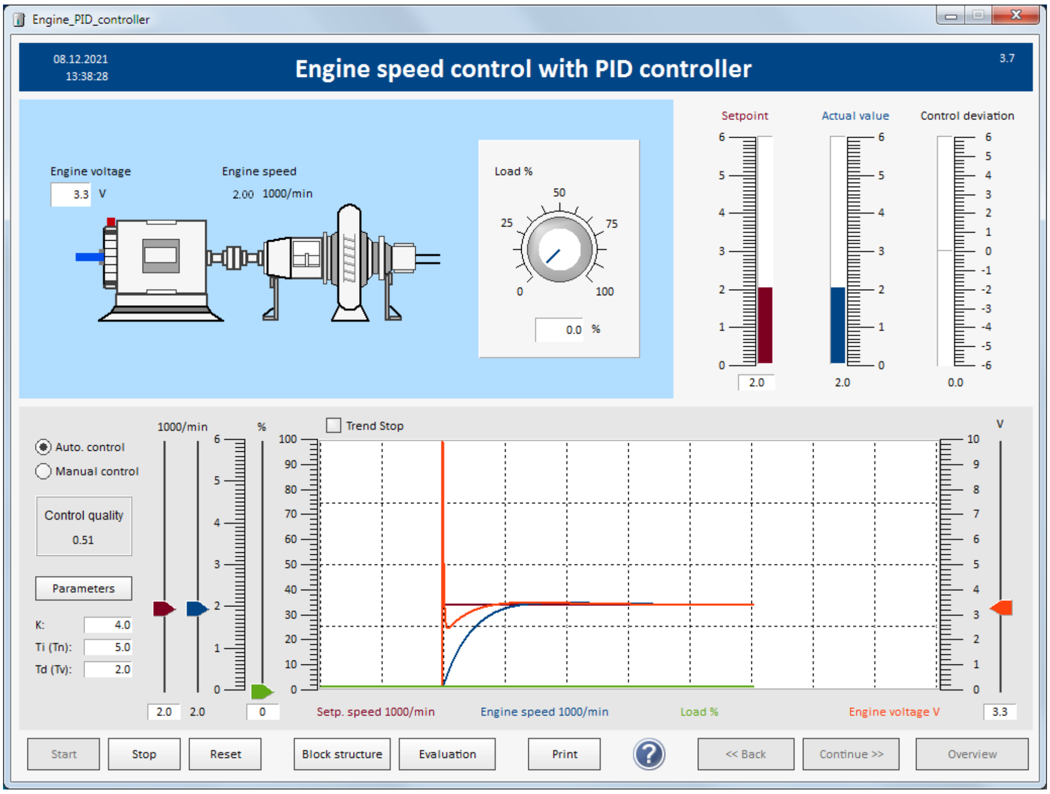
Task 14.

Investigate the command response with the preset parameters:

Gain K = 4, reset time Ti = 5, derivative time Td = 2.

Change the setpoint to 2 (1000/min).

Observe the behavior.



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

As can be seen in the trend diagram, the sudden change in the setpoint 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 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.

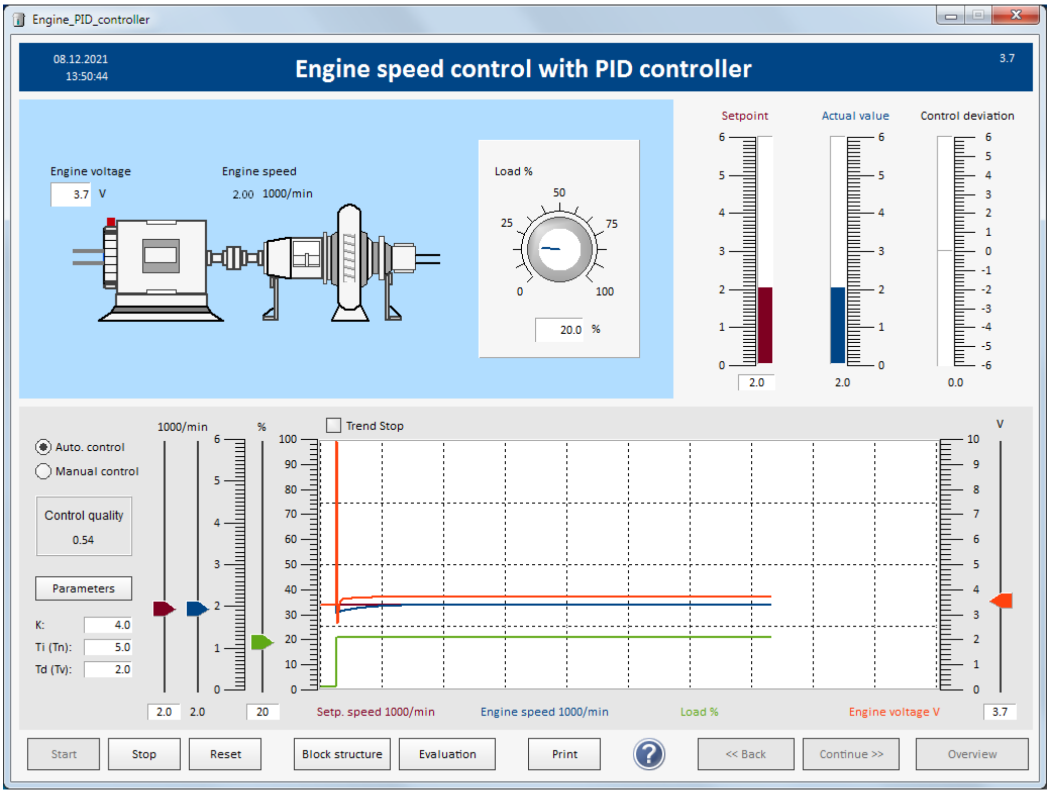
Investigate the disturbance response with the preset parameters:

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.

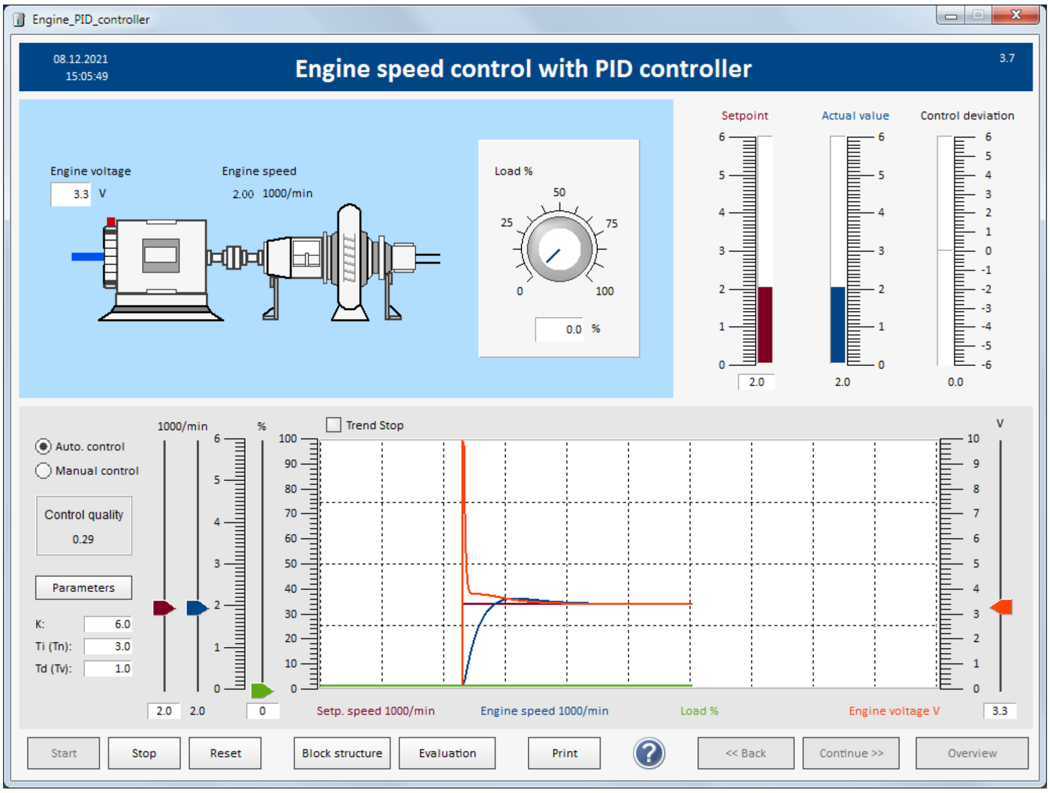


The controller controls the disturbance without overshooting.

Task 16.

Carry out tests for the command response with further controller parameters in order to improve the control quality:

- Press „Reset“
- Set the controller parameters
- Set the setpoint 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.

Note:

In practice, the PI controller is mainly used. In many cases, the D component is turned away in the PID controller, so that the controller then 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, with the D component, you have the option of making the control faster (but this is often very difficult).

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

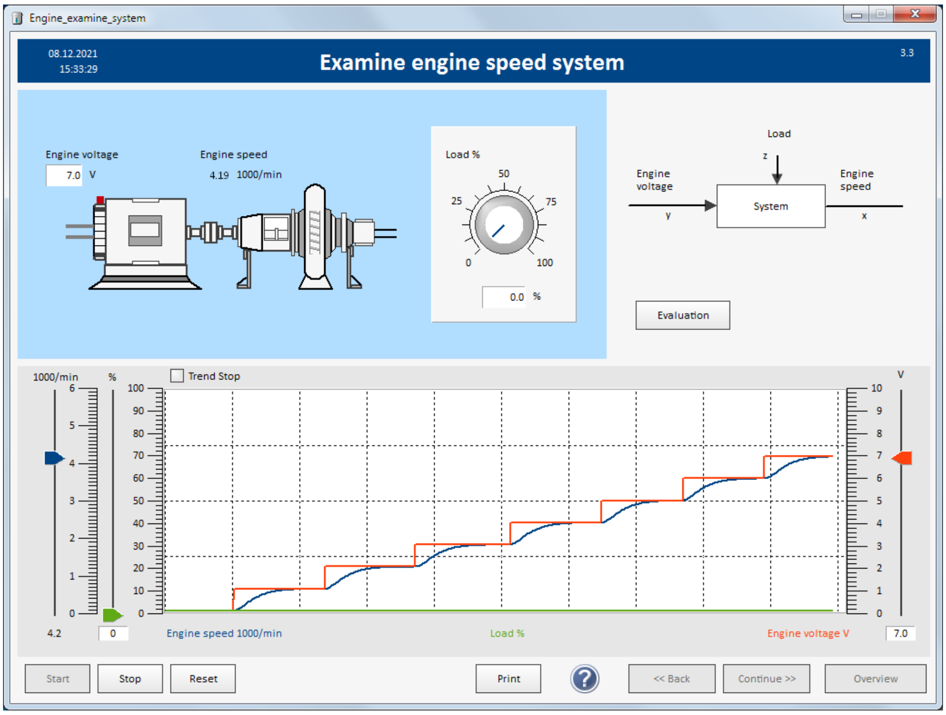
9.3 Controlled System

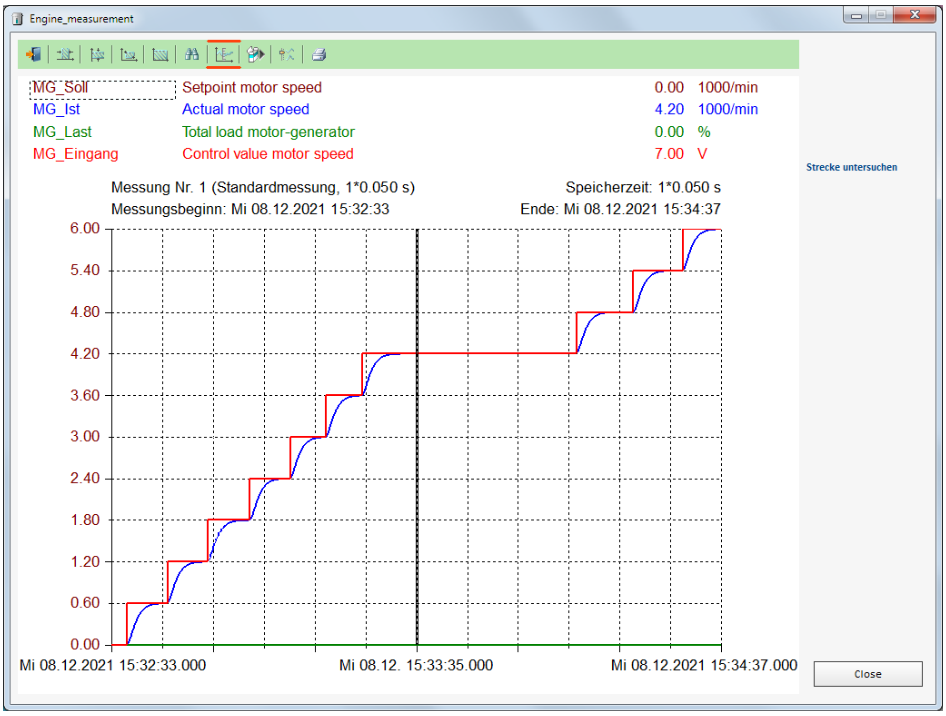
For engine speed control, select item 3.3 "Examine controlled system".

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.

Press “Start” and increase the control signal by 1V each time. 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 Ruling

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

A unit jump 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.

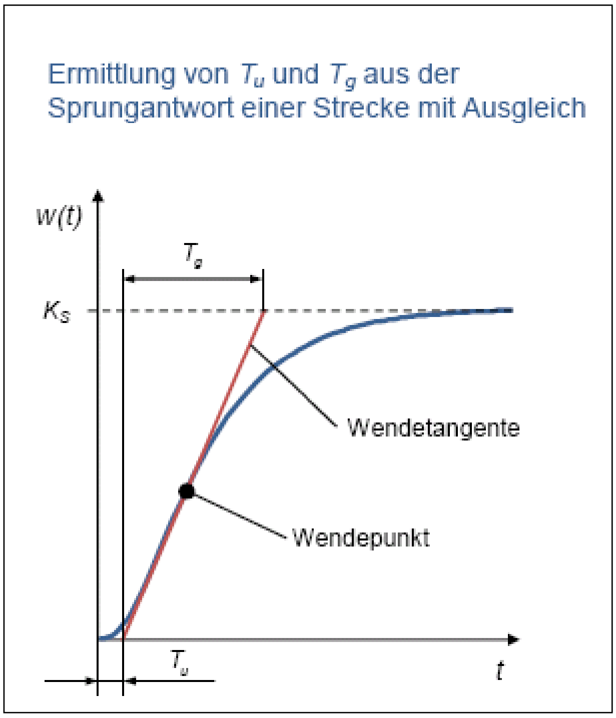
For the controller tuning rules for systems with self-regulation, the parameters Tu, Tg and Ks must be determined as shown in the figure below.

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 use both terms.

The controller parameters can then be calculated from the setting table according to Chien/Hrones/Reswick:

Regler-verhalten	Gütekriterium			
	Überschwingung nach Gegenseite mit 20% von x_m, kürzeste Schwindungsdauer		aperiodischer Regelvorgang mit kürzester Dauer	
	Störung	Führung	Störung	Führung
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	$K_P \approx \frac{1{,}2}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2 \cdot Tu$ $T_v \approx 0{,}42 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 1{,}35 \cdot T_g$ $T_v \approx 0{,}47 \cdot T_u$	$K_P \approx \frac{0{,}95}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx 2{,}4 \cdot T_u$ $T_v \approx 0{,}42\, T_u$	$K_P \approx \frac{0{,}6}{K_S} \cdot \frac{T_g}{T_u}$ $T_n \approx T_g$ $T_v \approx 0{,}5 \cdot T_u$

Für Regelstrecken *ohne Ausgleich* ist statt $\frac{T_g}{K_S \cdot T_u}$ der Ausdruck $\frac{1}{K_{IS} \cdot T_u}$ einzusetzen.

[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:

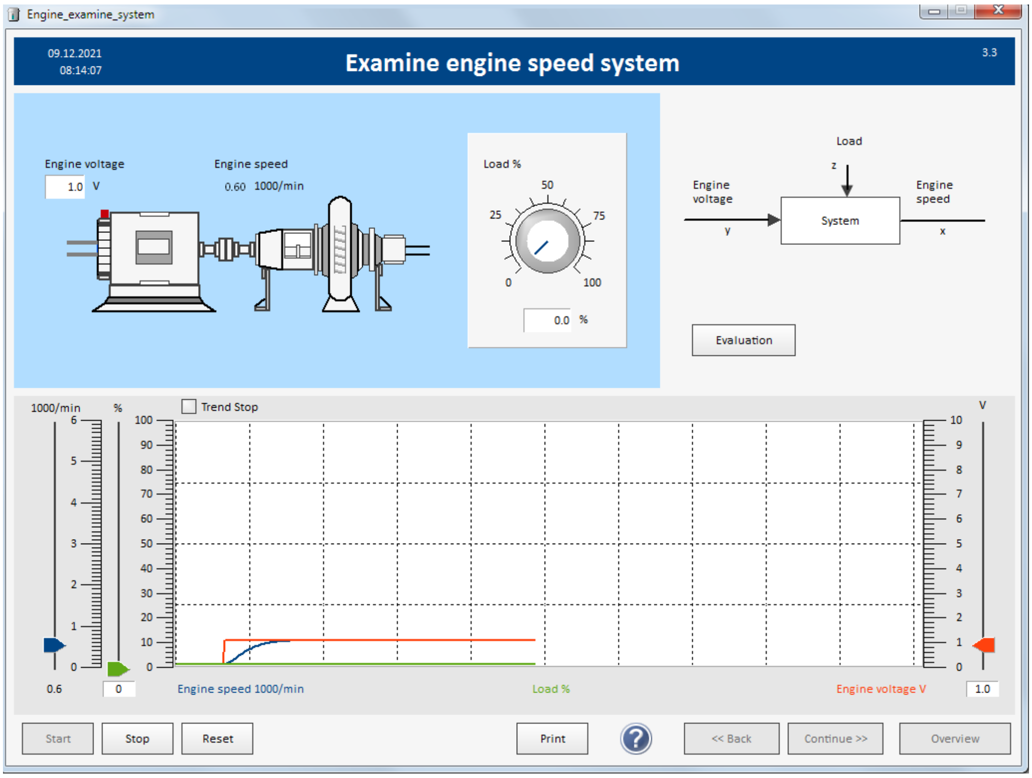
Tu = Te, Tg = Tb

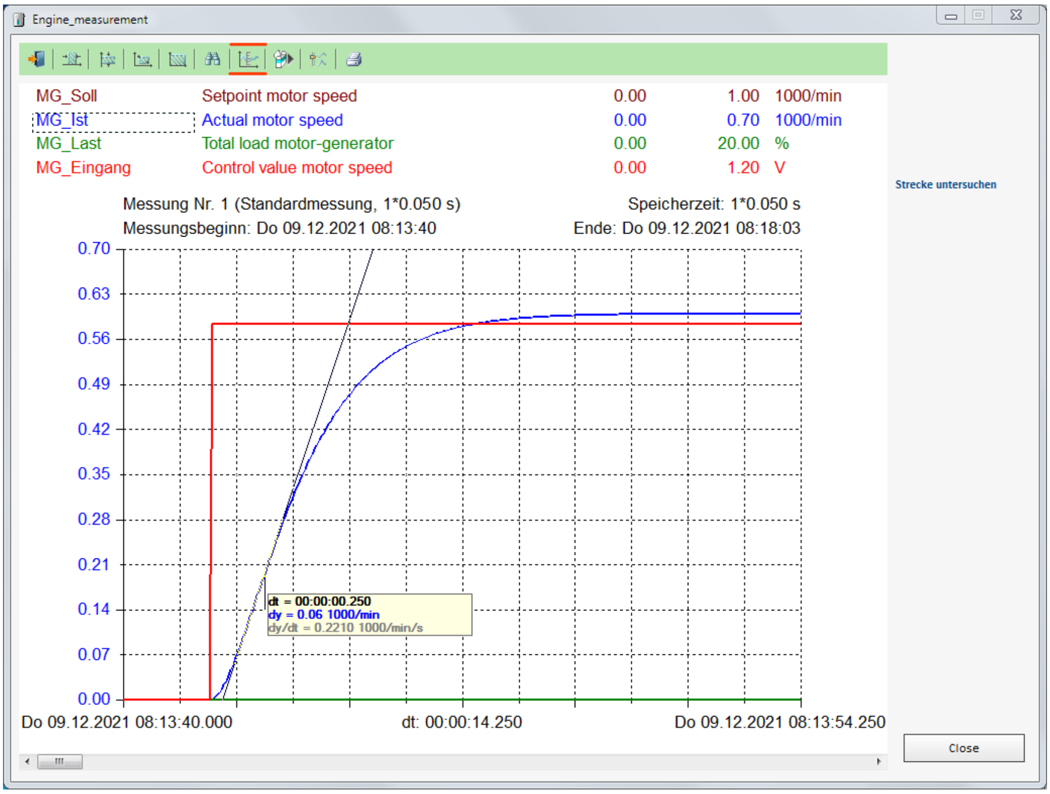
For the engine speed system, select point 3.3 "Examine controlled system”.

Task 18.

Press „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 holding and pulling.

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 jump 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.

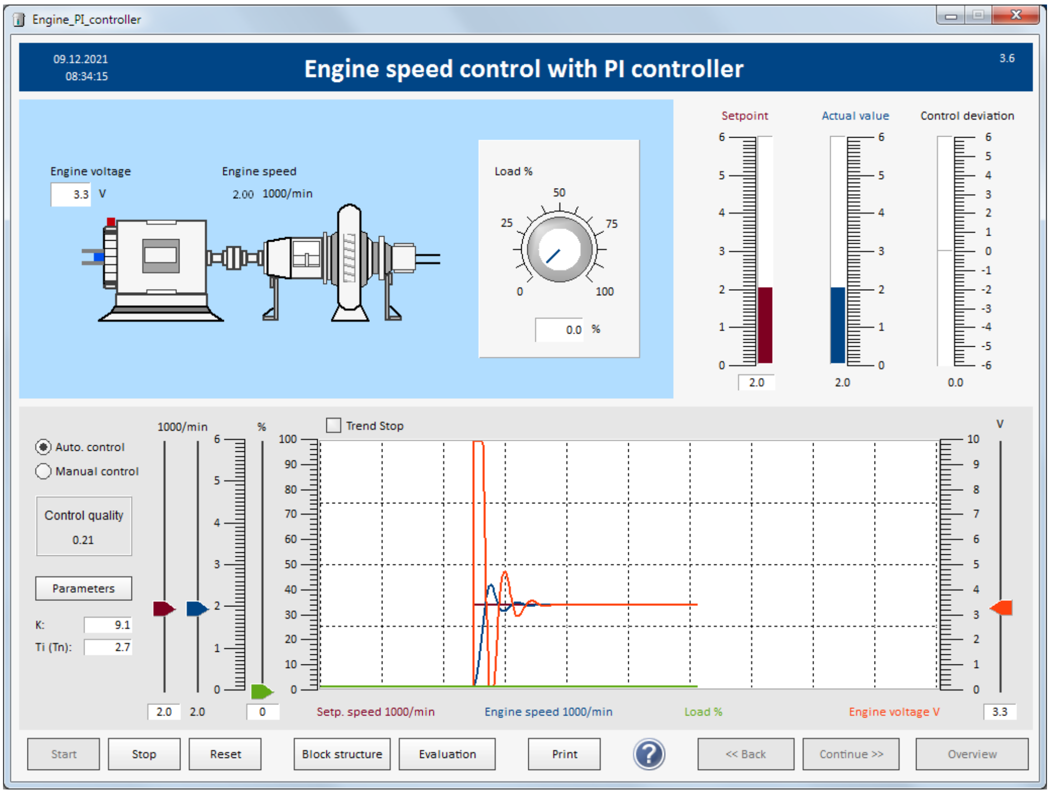
Also: Te = Tu = 0,3s Tb = Tg = 2,727s Ks = 0,6

By inserting the values in the table, we get for the PI controller:

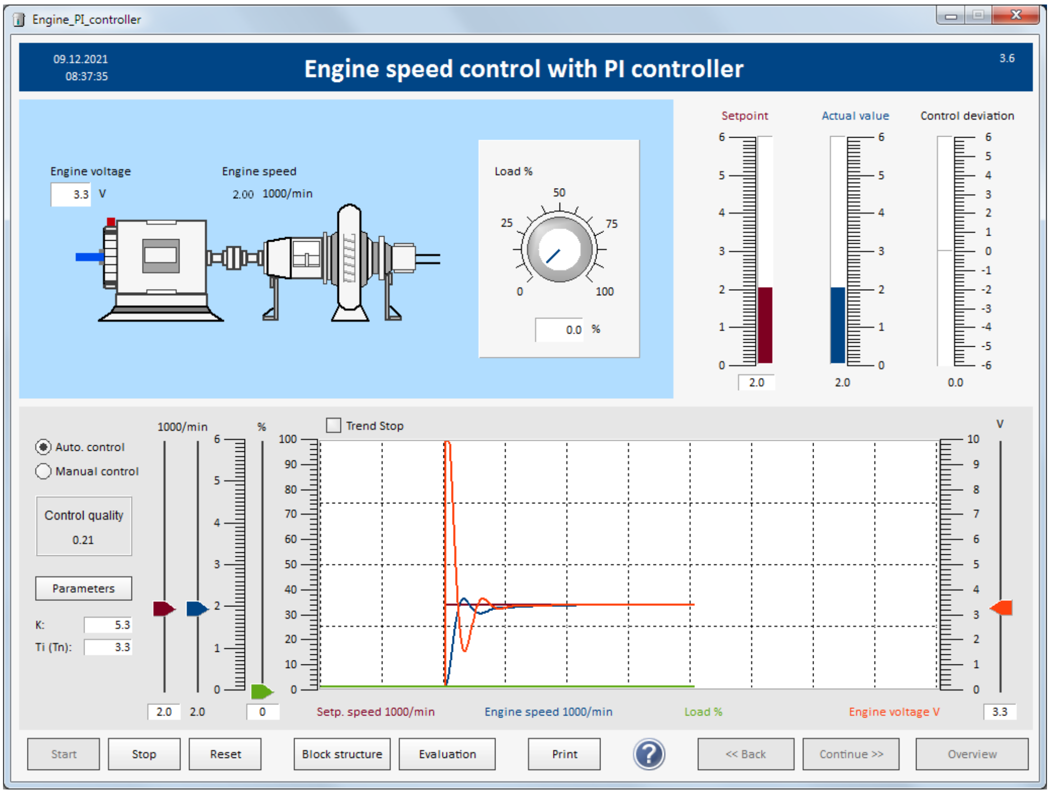
PI controller

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
Dusturbance 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 jump of the setpoint speed from 0 to 2 (1000/min)

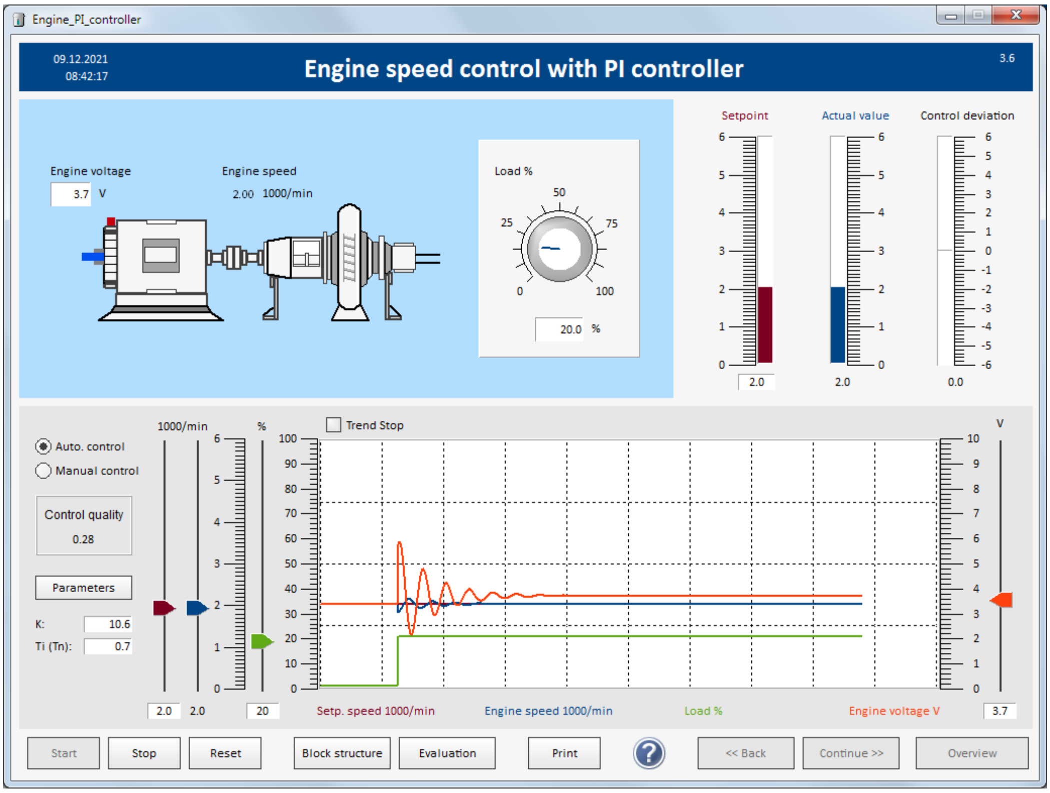


Command response with 20% overshoot

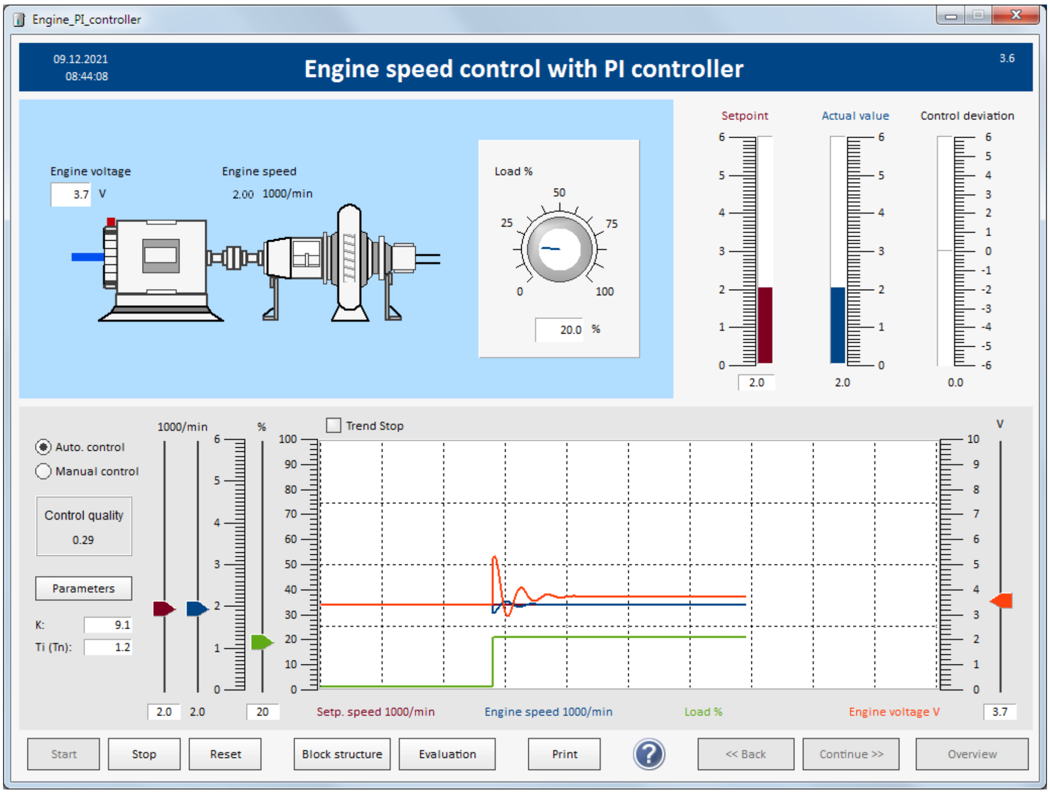


Command response aperiodic

For the disturbance the load was set from 0% to 20%.



Disturbance response with 20% overshoot



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

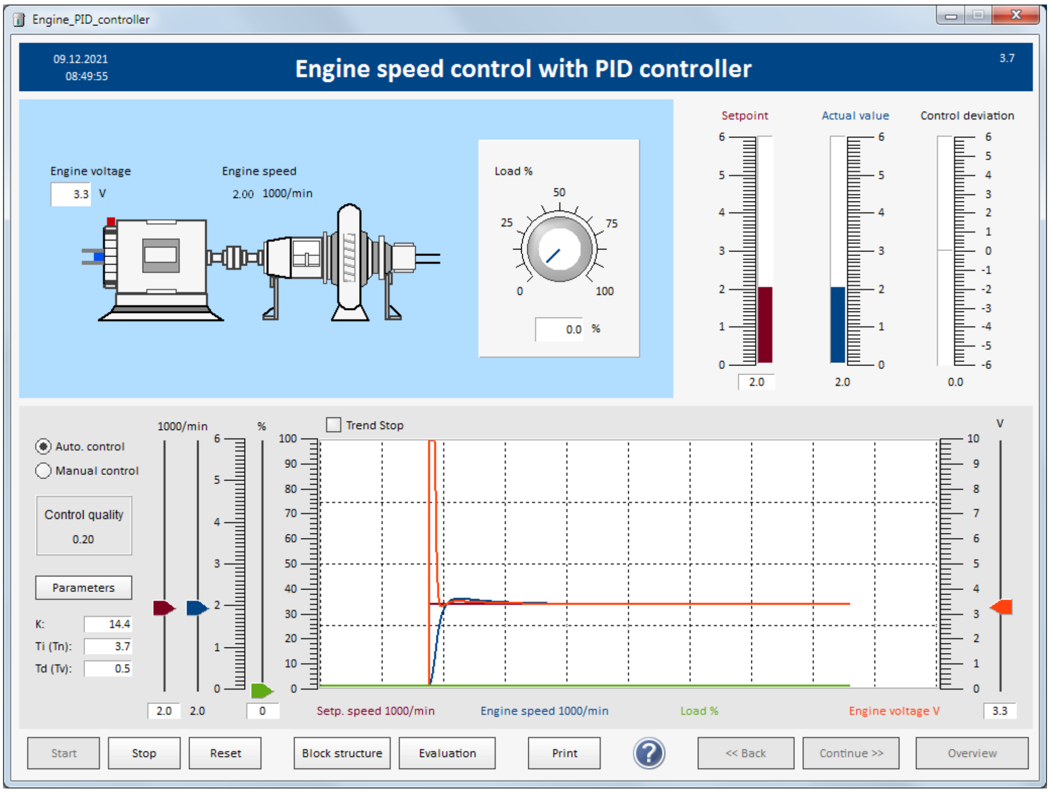
K = 1,2*Tb / (Ks*Te)	18,18
Tn = 2 * Te	0,60
Td = 0,42 * Te	0,13

Disturbance response aperiodic

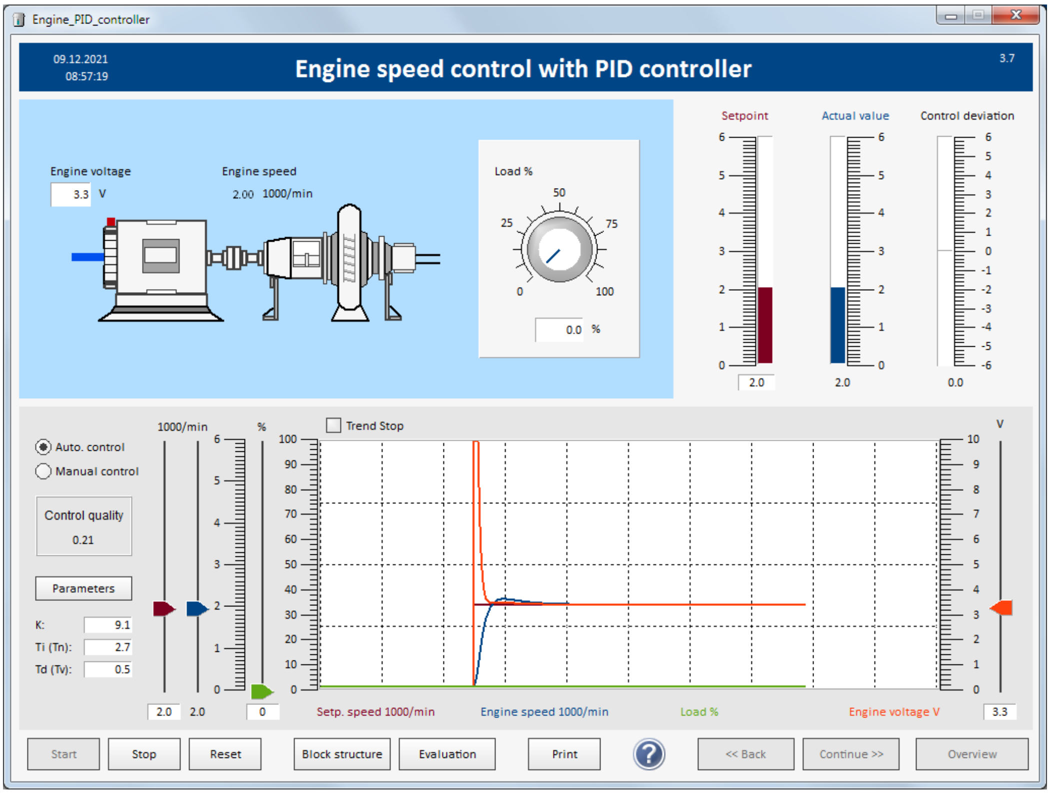
K = 0,95*Tb / (Ks*Te)	14,39
Tn = 2,4 * Te	0,72
Td = 0,42 * Te	0,13

With these controller parameters, the following control loop behavior results with a reference jump of the setpoint speed from 0 to 2 (1000/min).

The derivative time was taken as 0.5s, as the entry is limited to 0.5s



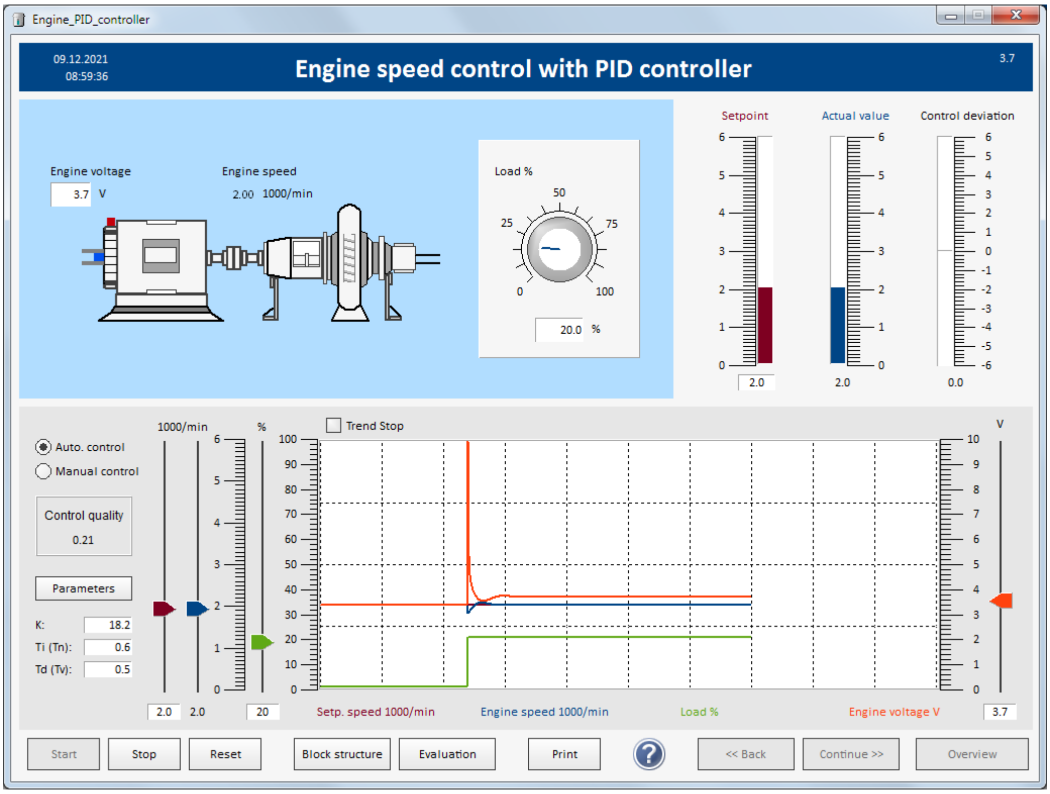
Command response with 20% overshoot



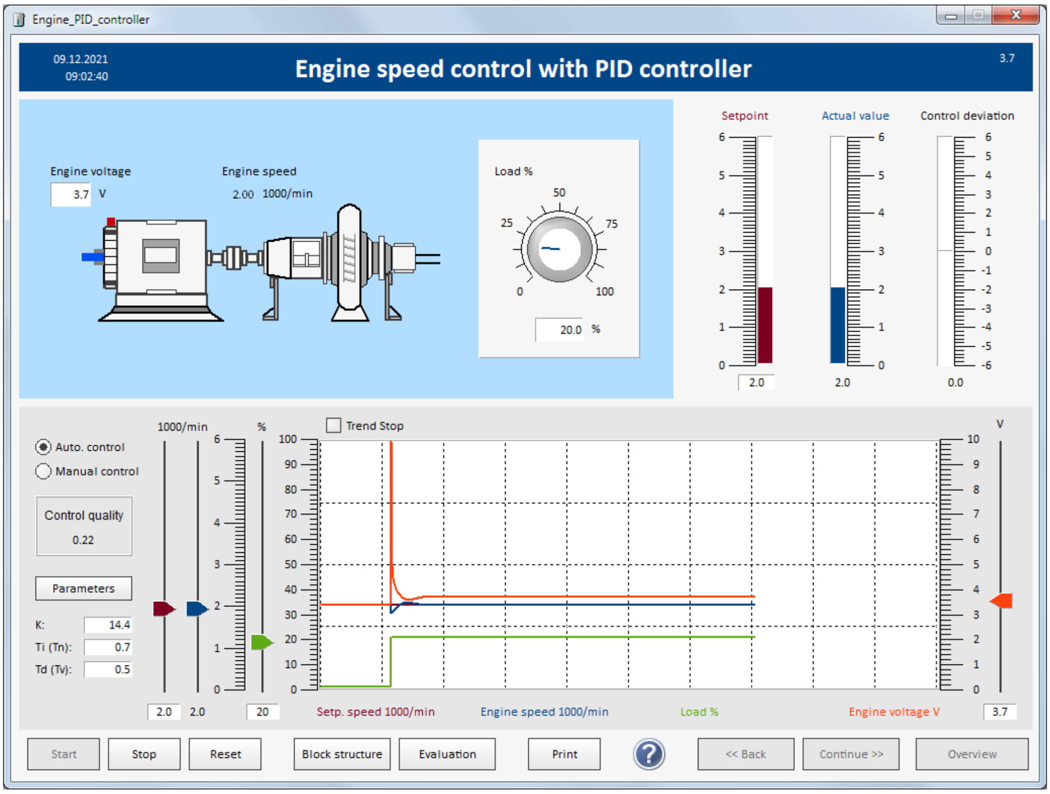
Command response aperiodic

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



Disturbance response with 20% overshoot



Disturbance response aperiodic

9.5 Assessment of the Controller Tuning Rules

Controller tuning rules are empirically determined methods that are suitable for calculating thumb values for good controller parameters.

The settings for the controller parameters differentiate between disturbance and command behavior. Different controller parameters are calculated.

If you want to cover both cases (disturbance and control behavior) with your controller parameters, 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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