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Simulative comparison of concepts for simultaneous control of heat flow and outlet temperature of heat exchangers for highly flexible use in the test facility "District LAB"

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Abstract

An important measure for decarbonising the heating sector is the transformation of existing district heating (DH) systems into low-emission heating grids based on renewable heat sources. The test facility for DH applications "District LAB (D-LAB)" is currently being set up in order to support the transition by enabling the experimental investigation of various transformation measures. It consists mainly of a Flexible Heating Grid (FHG), which connects several decentralised Hardware-in-the-Loop (HIL) and is fed by a central generation plant. The HIL units in the FHG should be able to map almost any heat producer or consumer, so that a wide range of investigation scenarios is possible. In order to fulfil this requirement, the Heat Exchanger (HEx) that connects the HIL units with the FHG must extract or feed a defined heat flow from the grid and at the same time ensure a defined secondary-side outlet temperature. In a literature research conducted to the best of our knowledge, it turned out that in all technical applications only one outlet temperature is controlled. Therefore a suitable control concept had to be developed. This has been done by extensive simulative investigations, which are presented in this paper. Two control concepts, (I) "decoupled PID controller", (II) "Characteristic Field (CF)-Based Control", were self-developed and compared with each other. In order to represent a large spectrum of possible operating conditions with regard to the transformation of DH systems, 48 investigation scenarios based on target value steps were defined and used for the comparison. Subsequently, the average performance using the Root Mean Square Error (RMSE) as well as the time dependant step responses were examined. It turned out that, the CF-based concept appears to be more suitable for use in the D-LAB. It is conceivable that these results can also be transferred to other test facilities in which both, the heat flow and one outlet temperature need to be controlled.

Keywords: District heating, Hardware-in-the-loop, Control concepts, Thermal-hydraulic-simulation

Introduction

The German government's climate targets envisage a 65% reduction in greenhouse gas emissions compared to 1990 by 2030 and climate neutrality by 2045 (Erstes Gesetz 2021). Due to its large share of the German final energy demand of approx. 57% in 2018 (BDEW 2019) and the longevity of the infrastructure, the building heating sector in particular plays an important role in achieving these goals. A number of recent scientific studies, which have been summarised in the current BDEW meta-study (Maaß et al. 2021), show a far-reaching need for action in the building heating sector and conclude that the addition of new district heating (DH) systems and the transformation of existing ones is essential for achieving the targets. In particular, the transformation of existing systems is of great importance. It includes a number of technical measures, such as the reduction of grid temperatures, the substitution of generation plants with renewable technologies, the integration of heat storage systems, replacement of out-dated customer substations, as well as digitalisation and decentralisation measures. These measures partly interact with each other or are even conditional on each other, which poses technical challenges, especially against the background of maintaining supply security. The objective of the joint project "EnEff:Wärme: UrbanTurn—Transformation of the urban district heating supply" (FKZ: 03EN3029A-F) (Bundesministerium fur Wirtschaft und Klimaschutz 2022), which was launched in February 2021, is to contribute toward solving the technical challenges. As part of the project, the experimental facility for DH applications "District LAB (D-LAB)" is to be designed, built, and commissioned by Fraunhofer IEE in Kassel. Subsequently, empirical experiments are to be carried out there as part of "UrbanTurn", but also beyond this, in order to support the transformation of DH systems towards carbon-free heat supply solutions. The planned structure and the most important components of the D-LAB can be seen in Fig. 1.

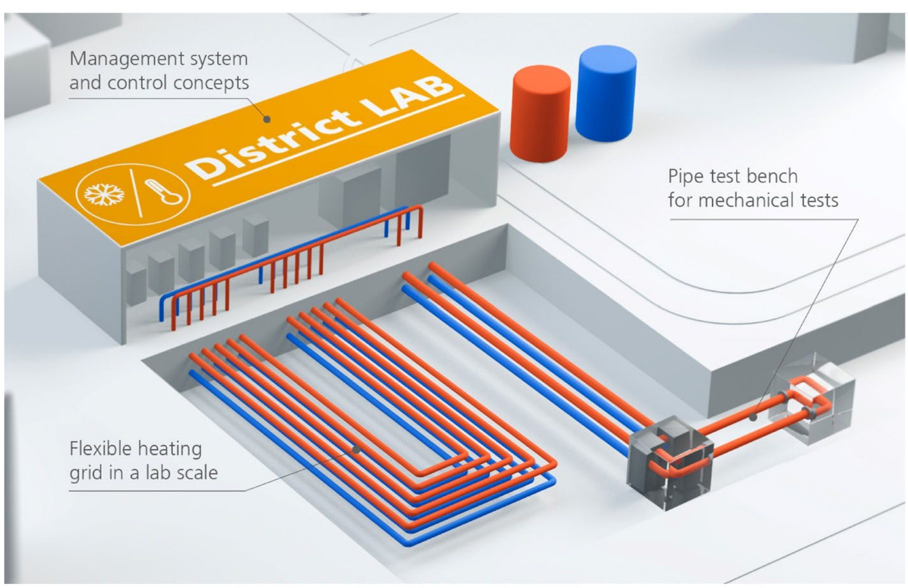

Fig. 1 Schematic representation of the structure of planned test facility D-LAB (Fraunhofer Institute for Energy Economics and Energy System Technology (IEE) 2022)

It can be seen that the D-LAB consists of a Flexible Heating Grid (FHG) on a lab scale, a pipe test bench for mechanical tests and a management system for testing different control concepts. The relevant part of the test facility for this work is the FHG. It consists of buried pipes connected to Hardware-in-the-Loop (HIL) units, various heat sinks and sources (heat pump, boiler, re-cooling plant) and storages. The HIL units are also connected to a cold and hot secondary circuit. In this way, they can act as (almost) any heat source or sink in the grid. The FHG thus enables the implementation and holistic analysis of various, complex DH supply scenarios, such as lowering the temperature level in an existing DH grid. In order to create the broadest possible spectrum of test applications, five HIL units, two of which will be built in a second construction phase, can represent consumers, producers as well as prosumers from the commercial or private sector through different heat flow levels. Further detailed information on the D-LAB can be found in Fraunhofer Institute for Energy Economics and Energy System Technology (IEE) (2022) or Kallert et al. (2021).

An important issue that has come up in the course of designing the D-LAB relates to the control concept of the Heat Exchanger (HEx) connected to the FHG within each HIL unit. As already mentioned it is necessary that the HIL units can imprint almost any heat demand and availability profile at different temperature levels on the FHG and thus should allow a realistic representation of the consumers and producers in a DH grid. Therefore, it is required to control the outlet temperature as well as the transferred heat flow simultaneously. In order to implement this requirement technically, a special design of the HIL units is needed (see chapter Structure of the Hardware-in-the-Loop Units).

In this paper, first it will be explained whether comparable approaches exist for such control tasks. Also, the structure of the Hil units and the limitation of the simulation models for the investigation will be presented. Subsequently a basic approach is explained, which then is used to build up the control concepts for the comparison. Following this the structure and the signal flow of the two self-developed control concepts are presented in detail. Afterwards a description of the steps required to set up the simulation model for the comparison of the concepts is given. The next section presents the results. For this purpose, various investigation scenarios are first defined and the necessary parameter variations are explained. The steps for the required processing of results are stated and the results are presented. Finally, the results are interpreted by formulating a conclusion and an outlook.

Related approaches

The design and also the controlled variables of the HIL units differ from conventional sub-stations, as they are commonly used in DH systems. In these, the primary-side mass flow is usually controlled via a throttle valve in such a way that the secondary-side outlet temperature meets a target value. This target value can be constant or varied over time depending on the local ambient temperature. The transferred heat is not controlled in these systems, but measured for the purpose of determining the consumption values for final billing. Also in other technical application areas, no comparable use case could be identified within the scope of a literature research carried out to the best of our knowledge. Although publications were found, that deal with the design of controllers for HEx, these exclusively focus on the control of one of the outlet temperatures. Some examples are:

- In Padhee (2014) a simulation study is carried out by Padhee to determine which control concept performs best in controlling the outlet temperature of a shell or a tube HEx. A mathematical model of the HEx is developed using experimental data. This transient model is then used for an evaluation of three concepts, “feedback PID”, “feedback PID plus feed-forward” and “internal model controller”. The results show that the internal model controller performs best as it provides barely any overshoot and the fastest settling time.
- Duka and Oltean show in Duka and Oltean (2012) that the target value tracking as well as the disturbance rejection of the outlet temperature of a tank, which acts as a HEx, can be done with a PI controller. Also they show that this PI controller is the linear case of a fuzzy logic controller. Based on this they developed two nonlinear fuzzy logic controllers both of which outperform the PI controller in the tasks of target value tracking and disturbance rejection. Finally they conclude that nonlinear fuzzy logic controllers in general will perform better than PI or PID controllers in controlling the outlet temperature of a HEx.
- In Díaz et al. (2001) Díaz et al. present the simulation of the dynamic behavior and the controlling of the outlet temperature of a HEx located in a test facility by using two artificial neural networks. One artificial neural network is used to simulate the HEx the other is used for the control task. Also an I controller is used to compensate errors in the steady state. The results show that the neural network controller performs better as it has a less oscillating behavior and thus is able to reach steady states at operating points where PI and PID controllers are not able to.

Against the background of the control task presented, these publications seem to have only limited relevance. Therefore in this paper, a simulative comparison of two self-developed control concepts for the described task will be carried out for determining which of the concept fits best to the requirements of the D-LAB. This information will be valuable for the ongoing planning process of the D-LAB. On top of that, the methodical approach as well as the results itself might be useful for other test facilities which deal with comparable objectives.

Structure of the hardware-in-the-loop units

As already described in the previous chapter, each of the HIL units should draw out or feed in a defined heat flow at a defined outlet temperature via the HEx connected to the FHG. The objective is that the HIL unit is able to reproduce the behaviour of any DH grid participants within the FHG of the test facility. Examples for this may be space heating and domestic hot water preparation for single or multi-family houses as well as solar thermal systems or industrial waste heat gains.

In order to achieve this technically, each HIL unit is connected to the FHG via a HEx to act as a grid participant. Furthermore, the HIL units are connected to two secondary circuits, the Cold Circuit (CC) and the Hot Circuit (HC), via two additional HEx. These secondary circuits allow every HIL unit to take or remove heat via the D-LAB’s central heat sources and sinks. Upstream of each of the three HEx, there is a throttle valve that is used to control the mass flows from FHG, CC or HC. In addition, all three HEx are connected via a hydraulic circuit located inside the HIL unit. This circuit has various pumps and valves that can be used to adjust the secondary mass flows through each HEx, as well as the direction of flow. For the sake of completeness, it should be noted that the HIL units also have a decentralised heat pump and a storage. In the context of this paper, the focus is on the control concept of the HEx connected to the FHG, therefore only the components within the scope of the investigation are modelled. The principle structure of the HIL units as well as the highlighting of the scope of this paper can be seen in Fig. 2.

Control concepts for the comparison

As described in the previous chapter, it is necessary to develop new control concepts for the HEx of the D-LAB which are capable of controlling the heat flow and outlet temperature simultaneously. Accordingly, there are two variables to be controlled and no simple PID-controller could be used. These variables can be influenced by the mass flows through both primary and secondary side of the HEx which turns both mass flow rates to manipulated variables. An obvious solution for a two-variable control is a cascaded control with two PI or PID controllers. However, it can be assumed that the heat capacity of the HEx has a significant influence on the time response of the system. This influence is identical for temperature and heat flow control, which is the reason that they have a similar time behaviour. For a cascaded control, it is essential that the inner control loop is significantly faster than the outer one (Heinrich and Schneider 2019). Therefore, it cannot be used in the present case.

On the basis of further considerations and the execution of various simulations, it turned out, that a decoupling of the two control loops with a feed forward control for the secondary side represents a good basis. This is possible because secondary side inlet and outlet temperatures, and thereby their difference ΔT_{sec}, as well as the required heat flow $\dot{Q}$ can be assumed to be known in the context of the control task and there is an analytical relationship between these variables and the secondary side mass flow rate $\dot{m}_{sec}$. Here

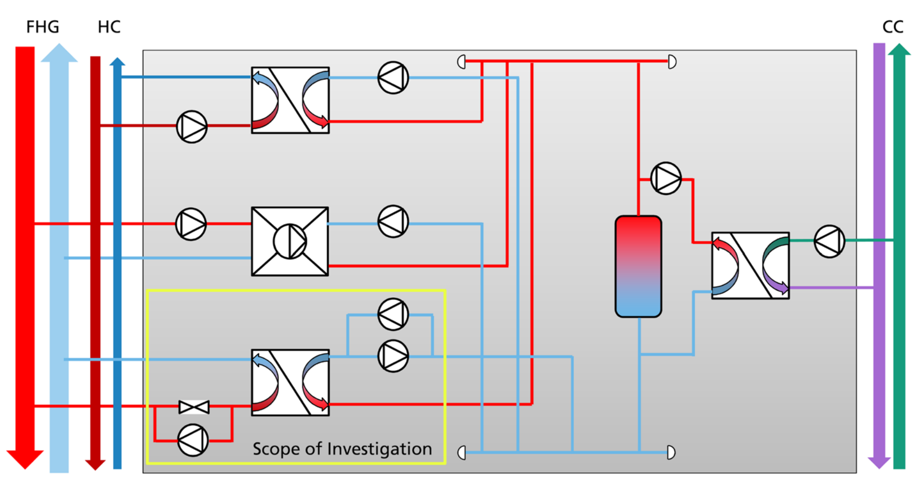

Fig. 2 Schematic representation of a HIL unit and scope of this investigation [own representation]

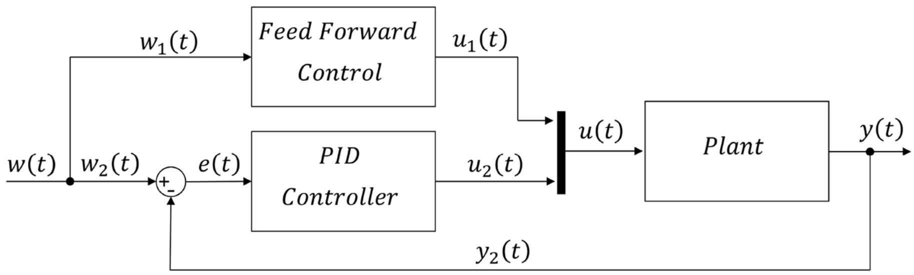

Fig. 3 Schema of the concept "decoupled PID controller" [own representation]

$c_{p,sec}$ is the specific heat capacity at constant pressure of the fluid on the secondary side. The relationship is given in Eq. (1):

$$\dot{Q} = \dot{m}_{sec} \cdot c_{p,sec} \cdot \Delta T_{sec} \quad (1)$$

Starting from these considerations and the results from the literature review shown in chapter Related Approaches, in particular (Padhee 2014) and (Díaz et al. 2001), two self-developed and more advanced control concepts, the "decoupled PID controller" and the "characteristic field (CF) based" concepts, for the overall control task were developed. Both concepts are explained in detail in the following chapters.

The control concept "decoupled PID controller"

The first self-developed control concept used for the comparison essentially consists of a PID controller and a feed-forward control. Both serve to determine a part of the manipulated variable vector $u(t)$ consisting of the primary and secondary side mass flow specifications for the controlled system (Plant). The reference variable vector $w(t)$, which contains various target and actual values of thermal state variables (e.g., heat flow and temperatures), functions as the input signal. As usual with controls, the PID controller uses the control deviation $e(t)$ to determine the manipulated variable $u_2(t)$, the primary side mass flow rate. The control deviation results from the difference of a part of the reference variable vector $w_2(t)$ and the relevant part of the controlled variable vector $y_2(t)$. These are target and actual values of the secondary side outlet temperature to be controlled. The other part of the manipulated variable, the secondary side mass flow rate $u_1(t)$ is determined by the feed-forward control explained in the previous chapter on the basis of Eq. 1, taking into account the reference variable vector. This structure is intended to enable the decoupling of the two control variables thermal heat flow and outlet temperature and is shown schematically in Fig. 3.

The control concept "characteristic field based control"

The main difference between the first and the second self-developed control concept used for the comparison is the substitution of the PID controller by a lookup table in which the Characteristic Field (CF) of a HEx is stored and the addition of an I controller. This structure is shown schematically in Fig. 4.

In this concept the lookup table uses a part of the reference variable vector $w_{2,1}(t)$ as input variable and thus calculates a part of the manipulated variable vector $u_{2,1}(t)$ by linear interpolation of the CF. Since a small error is always to be expected with this

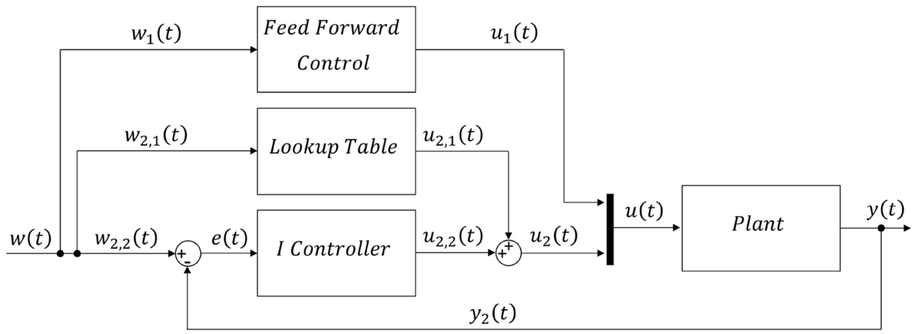

Fig. 4 Schema of the concept "characteristic field based control" [own representation]

procedure, an I controller is added for compensation. For this purpose, it uses the control deviation $e(t)$, which results from the difference between the corresponding part of the controlled variable vector $y_2(t)$ and the reference variable vector $w_{2,2}(t)$. The output is the manipulated variable $u_{2,2}(t)$. This is then added to the output signal of the lookup table to obtain the required manipulated variable $u_2(t)$ for the controlled system.

Simulation model realisation

The simulative comparison of the two self-developed control concepts is used as main method within this investigation. The simulation models are built and the simulations are carried out in MATLAB (The Mathworks inc: MATLAB 2022) with the Simulink extension (The Mathworks inc: Simulink 2022) using component models from the CARNOT toolbox (CARNOT Toolbox 2021). In the following explanations, the implementation and the structure of the simulation model are discussed. For this purpose, the parameterisation of the thermo-hydraulic component models and the procedure for determining the CF for one of the control concepts are shown. Subsequently, the procedure for the tuning of the controllers is presented. Finally, considerations regarding the suitability of the concepts in relation to the capabilities for realising feed-in and feed-out situations are described.

Thermo-hydraulic component models

For the investigation, thermo-hydraulic component models of the CARNOT toolbox (CARNOT Toolbox 2021) are used to model the controlled system. In particular, these are models for HEx and thermo-hydraulic sources. It should be noted that the HEx model is based on the NTU method (Verein Deutscher Ingenieure 2006) and is thus suitable for the simulation of plate and tube heat HEx. In the D-LAB, plate HEx will be used according to the current planning status. The parameters used for the HEx model are shown in Table 1.

For each, primary and secondary side, one simple thermo-hydraulic source model is used to realise the limitation to the scope of investigation shown in Fig. 2. This is possible as the simple source models determine the thermo-hydraulic state variables (pressure, mass flow rate, temperature and flow media) for both inlet sides as entered by the user. Mass flows and temperatures are considered time-variable, while pressures and flow media are considered as constants. Water is used as the primary and secondary

Table 1 Parameterisation of the HEx component model

Parameter	Value	Unit
Flow type	Counter flow	–
Constant heat transfer	12,500	W/K
Exponent mass flow primary/secondary	0/0	–
Heat loss to ambient	3	W/K
Heat capacity	6000	J/K

media. The pressures are set to 10 *bar* on both sides to prevent evaporation of the water on high temperatures. It should be noted that in this setup, the simple source models take over the tasks of the pumps and valves shown in Fig. 2 by the targeted and time-variable determination of the mass flows. The typical transient time behaviour of these components is taken into account in a simplified way via PT1 elements (see also chapter Setup of the Simulation Model for the Comparison). This modelling approach was chosen as the planning of the experimental facility had not progressed far enough at the time the model was created and the time behaviour of the components was therefore unknown.

Determination of the characteristic field

For the investigation of the CF-based control concept, a CF of the controlled system, i.e., the HEx, is required. This is determined using the thermo-hydraulic component models described in the previous chapter. For this purpose, a great number of simulations with different primary and secondary inlet temperatures and mass flow rates are carried out systematically and automatically.

All thermo-hydraulic component models of the CARNOT Toolbox (CARNOT Toolbox 2021), i.e., also the HEx model, are based on transient calculation methods. However, the numerical values of the state variables are required for the steady state to build the CF. The purpose of this is that the steady state is also to be determined by the control concept in the final application. Therefore, the simulation duration for the automatic simulation runs is selected in such a way that reaching the steady state within the HEx model is ensured. For this purpose, a simulation duration of 400 *s* per run is used and the results of the last time step are used for further processing. This numerical value for the simulation duration was validated with the parameter sets with the minimum temperature differences, since the longest duration until the stationary state is reached is to be expected here. It turned out that the steady state in this specific case was reached after less than 35 *s* which is much faster than the duration chosen for the automated simulations. It is therefore safe to expect that the steady state has been reached in all cases at the end of the simulation period.

For the creation of the CF and the associated simulations with systematic variation of the entry states, some considerations for the reduction of the number of dimensions are useful. The reason for this is that, the number of grid points of the CF and thus the computational effort for its determination increases exponentially with the number of dimensions. The simple thermo-hydraulic source models allow the specification of primary and secondary mass flows and inlet temperatures, on the basis of

Table 2 Grid points of the CF

Variable	Minimum	Maximum	Step size	Number of steps
$\dot{Q}$	100 W	60000 W	1000 W	60
ΔT_{in}	5 °C	90 °C	5 °C	18
ΔT_{sec}	5 °C	40 °C	5 °C	8

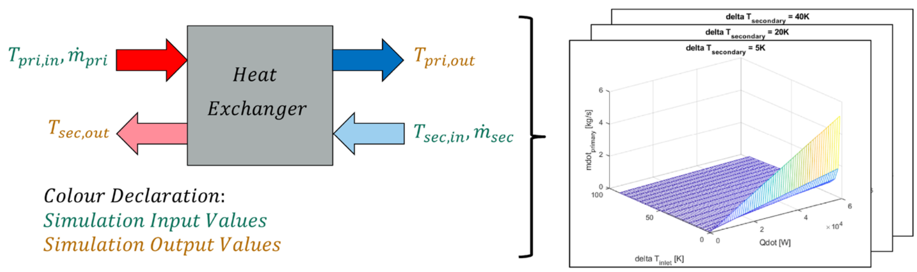

Fig. 5 Schematic of the procedure for determining the CF of the HEx [own representation]

which the HEx model determines the outlet temperatures. This subsequently allows the calculation of the transferred heat flow. Without further dimension reduction, this would result in a CF according to Eq. (2):

$$\dot{Q} = f\left(T_{pri,in}, T_{sec,in}, \dot{m}_{pri}, \dot{m}_{sec}\right) \tag{2}$$

This would correspond to a CF with five dimensions. In addition, the heat flow in the intended control structure is a reference variable and the primary-side mass flow is the manipulated variable to be calculated. In order to address these facts, the absolute temperature values can be substituted by temperature differences by means of Eq. (3), neglecting the temperature dependence of the specific heat capacity of the water:

$$\begin{aligned} \Delta T_{in} &= T_{pri,in} - T_{sec,in} \\ \Delta T_{sec} &= T_{sec,out} - T_{sec,in} \end{aligned} \tag{3}$$

Furthermore, the secondary-side mass flow can be described according to Eq. (4) via its dependence on the heat flow and secondary-side temperature difference:

$$\dot{m}_{sec} = \frac{\dot{Q}}{c_{p,sec} \cdot \Delta T_{sec}} \tag{4}$$

This reduces the number of dimensions according to Eq. (5) to four:

$$\dot{m}_{pri} = f\left(\dot{Q}, \Delta T_{in}, \Delta T_{sec}\right) \tag{5}$$

To realise this consideration in the simulation model, it is necessary to select a temperature level to which the temperature differences refer. For the creation of the CF, a temperature of 50 °C was used within this work. Overall, the operating behaviour was

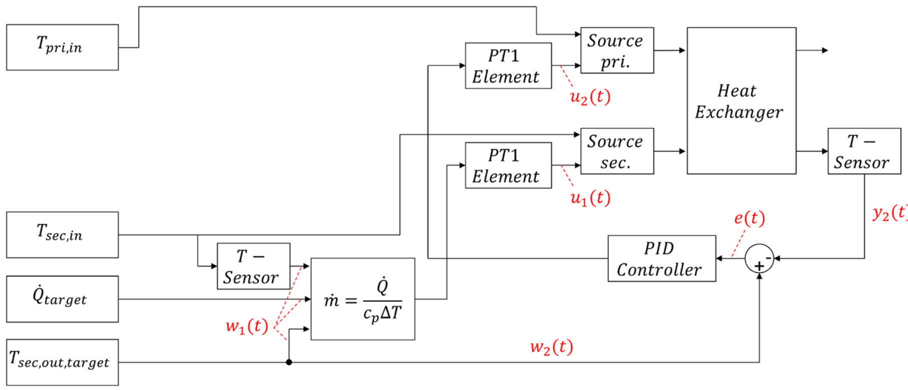

Fig. 6 Model structure of the control concept "decoupled PID controller" [own representation]

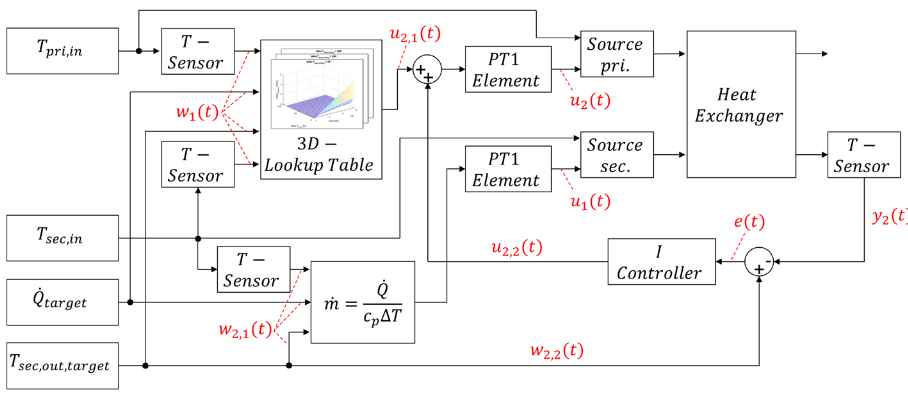

Fig. 7 Model structure of the "CF-based" control concept [own representation]

determined on the basis of 8640 simulation runs with the grid shown in Table 2. A schematic representation to visualise the described procedure is given in Fig. 5.

Setup of the simulation model for the comparison

To compare the self-developed control structures, a simulation model was built that contains the two concepts presented in chapter control concepts for the comparison. The parameterisation of the thermo-hydraulic components and the basic structure are identical. The two systems are shown schematically in Figs. 6 and 7. On the left side, the input variables are indicated, which can change in a time-dependent manner. In the lower left area, the feed-forward control used for the decoupling is drawn. In the upper right area, the controlled system consisting of HEx and primary and secondary sources is shown. In addition, temperature sensors that provide the actual values to the control structures can be seen in the illustration. Measurement errors are also taken into account here. Since the detailed design of the sensors is still pending, it is assumed in accordance with DIN IEC 751 (TMH GmbH 2022) that the measurement accuracy of the sensors in the temperature range occurring in the D-LAB is $\pm 0.43\,K$. In addition, based on the guidelines of the German Calibration Service [Deutscher Kalibrierdienst (DKD)] (Physikalisch-Technische Bundesanstalt 2018a, b), it is assumed that the largest part occurs in the form of systematic deviations and that these can be eliminated using appropriate calibration measures. As a remaining random measurement error, a random equally distributed noise in the range of $\pm 0.1\,K$ is considered in the temperature sensor model. In addition, the sensors contain a PT1 element for mapping the time response of the sensors and the low-pass filtering of the measured values, as it is assumed that such filters are also used in the experimental setup. Furthermore, it can be seen in the figures that PT1 elements were used for the simplified modelling of the time behavior of the pumps and valves in the D-LAB. For this purpose, the manipulated variables of the control structures are delayed via PT1 elements. The time constants of the PT1 elements are important variables which is the reason for varying them between the simulations (cf. chapter Investigation scenarios). In addition, the figures show the model-realisation of the two different control structures explained in Figs. 3 and 4. They are given via the red colored vector descriptions to provide a direct link between the figures.

Tuning of the controllers

To finalise the modelling, the parameterisation of the controllers used must be determined. In a first approach, the controlled systems were linearised and the PID tuner app from the MATLAB Control Systems Toolbox (The Mathworks inc 2022) was then used to determine these parameters. The parameter set obtained in this way resulted in a fast controller reaction if the time constants of the PT1 elements were set $\tau = 0\,s$. With an increase of the time constants, however, an oscillating response behaviour appeared, which makes the parameter set unsuitable. Therefore, the "Frequency Response Based" tuning method of the toolbox was used in the second step. It turned out that the parameterisation obtained in this way, did not result in an oscillation of the controllers for greater time constant values and thus in a significantly better behaviour. The parameterisation obtained in this way was used for the further steps and can be seen in Table 3. In addition, a parameterisation based on the Ziegler-Nichols method (Ziegler and Nichols 1942) was determined for comparison purposes. This also proved to be stable against larger time constants but led to larger overshoots compared to the parameterisation from the "Frequency Response Based" tuning method. Due to this behavior it was not used.

Withdrawal vs. feed-in performance

In the D-LAB test facility, the HEx for which the control concept is to be designed has to be capable of both extracting and supplying heat to and from the FHG. In the previous explanations, only the case in which heat is extracted from the grid has been described.

Table 3 Tuning of the used controllers

Parameter	PID controller	I controller
P	0.0341	–
I	0.0105	0.00005
D	0.0234	–
N	3	–

This is due to the fact that the performance of the concepts is completely identical when feeding in or taking out. Only the signal routing must be adapted accordingly. This results from the fact that, by definition, heat is always transferred from hot to cold. Therefore, under the condition of otherwise identical state variables, in particular temperatures and mass flows, extraction and supply are physically identical. This fact was also verified with the simulation model. As a result, the focus in the following is also on the withdrawal situation.

Results

Extensive simulations with different parameter configurations were carried out with the model described in the previous chapter. In the following explanations, the underlying investigation matrix (see Table 4) as well as the thought processes for setting it up are initially described. This is followed by an explanation of the steps taken to process the simulation results. Then the comparison of the results is presented. This is done on the one hand on the basis of a specially defined comparison factor and on the other hand on the basis of the representation of the time behaviour of the step responses.

Table 4 Investigation scenarios

Scenario name	$T_{pri,in}$[°C]	$\dot{Q}$-Level	f_p [−]	τ [s]	Scenario name	$T_{pri,in}$[°C]	$\dot{Q}$-Level	f_p[−]	τ[s]
1-Q	80	Low	1	1	9-Q	80	High	1	1
1-T	80	Low	1	1	9-T	80	High	1	1
1-TQ	80	Low	1	1	9-TQ	80	High	1	1
2-Q	130	Low	1	1	10-Q	130	High	1	1
2-T	130	Low	1	1	10-T	130	High	1	1
2-TQ	130	Low	1	1	10-TQ	130	High	1	1
3-Q	80	Low	1	2	11-Q	80	High	1	2
3-T	80	Low	1	2	11-T	80	High	1	2
3-TQ	80	Low	1	2	11-TQ	80	High	1	2
4-Q	130	Low	1	2	12-Q	130	High	1	2
4-T	130	Low	1	2	12-T	130	High	1	2
4-TQ	130	Low	1	2	12-TQ	130	High	1	2
5-Q	80	Low	1,5	1	13-Q	80	High	1,5	1
5-T	80	Low	1,5	1	13-T	80	High	1,5	1
5-TQ	80	Low	1,5	1	13-TQ	80	High	1,5	1
6-Q	130	Low	1,5	1	14-Q	130	High	1,5	1
6-T	130	Low	1,5	1	14-T	130	High	1,5	1
6-TQ	130	Low	1,5	1	14-TQ	130	High	1,5	1
7-Q	80	Low	1,5	2	15-Q	80	High	1,5	2
7-T	80	Low	1,5	2	15-T	80	High	1,5	2
7-TQ	80	Low	1,5	2	15-TQ	80	High	1,5	2
8-Q	130	Low	1,5	2	16-Q	130	High	1,5	2
8-T	130	Low	1,5	2	16-T	130	High	1,5	2
8-TQ	130	Low	1,5	2	16-TQ	130	High	1,5	2

Investigation scenarios

The comparison of the two control concepts "decoupled PID controller" and "characteristic field (CF) based control concept" is to be made by considering their step responses. Since there are two variables to be controlled (heat flow and secondary side outlet temperature), this results in three basic simulation scenarios:

- Step response of the heat flow at constant outlet temperature
- Step response of the outlet temperature at constant heat flow
- Response to simultaneous steps of heat flow and outlet temperature

It should be noted that the steps should only be made when the controlled system is in a steady state. This is not the case at the beginning of the simulation, as the initialisation state is usually not stationary. Simulations with various parameterisations have shown that the steady state is reached approx. $200\,s$ after the start of the simulation. Accordingly, the time for the steps of the target values is set to $400\,s$ after the start of the simulation. A total simulation time of $600\,s$ is used.

In order to make the comparison of the two self-developed control concepts as comprehensive as possible, the comparisons of the step responses are to be carried out at different operating points. This applies to the temperature level of the inlet temperatures, more precisely their difference, as well as the heat flow level. For both parameters, two levels each are determined for the investigation based on a typical transformation scenario for DH grids, which should later be analysed in D-LAB:

Temperature:

- Low-temperature grid with a supply temperature of $80\,°C$
- Conventional grid with a flow temperature of $130\,°C$
- The secondary side inlet temperature is constant $40\,°C$

Heat flow:

- Low heat flow level:
  - At constant heat flow level: 10 kW
  - Step: From 1 kW to 10 kW
- High heat flow level:
  - At constant heat flow: 50 kW
  - Step: From 5 kW to 50 kW

Furthermore, considerations regarding the robustness of the control concepts are to be included in the comparison. For this purpose, the time constants of the PT1 elements and the parameterisation of the HEx models (cf. Table 1) are adapted. For the time constants τ, numerical values of $1\,s$ and $2\,s$ are considered, which are changed equally in all PT1 elements. For the sake of illustration, it should be noted that the output signal of a

PT1 element requires a time duration of 5τ after a step to match the new input signal by 99.3%.

On top of that, the parameterisation of the HEx models is changed with the factor f_p. This is to model that the HEx in reality never correspond exactly to what is stored in the characteristic diagram. f_p is also varied on two levels. On the first level its value is $f_p = 1$ and on the second $f_p = 1.5$. This corresponds to a deviation of the parameters by 50 % compared to the values in Table 1. Altogether, the described parameter variation results in an investigation matrix with $3 \times 2 \times 2 \times 2 \times 2 = 48$ different scenarios. Each scenario received its own name using a consecutive numbering together with a letter for the type of step. Here Q corresponds to a heat flow step, T to a temperature step and TQ to the case where both steps take place. The entire investigation matrix can be seen in Table 4.

Processing of the results

As already described, the first 200 s of the simulation time are spent settling into a steady state. After 400 s, the step or steps of the target values take place and consequently also the desired and to be evaluated step responses. The settling process before the steps should not be included in the comparison of results. Therefore, this data is removed from the time series and the time values are then reinitialised so that the steps take place at time $t = 0\,s$.

In addition, a synchronisation of all resulting time series is necessary in order to make them comparable with each other. This is needed as a solver with variable step size (ode15s) has been used for the simulations in order to optimise their durations in Simulink. For details please refer to the MATLAB/Simulink documentation (The Mathworks inc 2022). This choice has the consequence that initially each time series of the simulation results has a different time vector as the solver calculates the required step-size and thereby the time vector by itself within the simulation. For synchronisation, a new common time vector is first determined, which is composed of the intersection of the time vectors of all simulations. This is to counteract a possible loss of information. Then the result time series are projected onto this new common time vector. The time series that result after the application of the measures described are used for the further comparison of results.

Comparison of results

The first way to compare the results in this work is the usage of a measure for the average controller performance, the RMSE, with the definition given in Eq. (6).

$$RMSE_{j,k}(x) = \sqrt{\frac{\sum_{i=1}^{n}(x_{actual,j,k,i} - x_{target,k,i})^2}{n}} \tag{6}$$
$$j \in \{CF, PID\},\ k \in \{1-Q, ..., 16-TQ\},\ x \in \{\dot{Q}, T_{sec,out}\}$$

With the RMSE, the actual values of the controls are compared with their target values and the mean square deviation is determined. By doing so, the deviations become sign-independent and there is a stronger weighting of large deviations compared to small ones. This behaviour appears to be well suited for the desired evaluation of the control concepts. A low RMSE value indicates that target and actual values match well and vice versa. It has turned out that the resulting RMSE numerical value is not that well suited for a result interpretation without further effort. Therefore, a comparison factor f_c was defined with the following Eq. (7):

$$f_{c,k} = \frac{\overline{RMSE}_k(x) + RMSE_{CF,k}(x)}{\overline{RMSE}_k(x) + RMSE_{PID,k}(x)} \tag{7}$$

The mean values of the RMSE within one scenario k are defined by Eq. (8):

$$\overline{RMSE}_k(x) = \frac{RMSE_{CF,k}(x) + RMSE_{PID,k}(x)}{2} \tag{8}$$

This allows the direct comparison of the performance of the control concepts. Based on the definition, $f_{c,k} = 1$ means that the RMSE values in scenario k are identical, which corresponds to an identical performance. $f_{c,k} < 1$ means that the CF-based concept has achieved a lower RMSE value and thus a better performance in scenario k. Similarly, $f_{c,k} > 1$ means that, the concept with decoupled PID controller has a better performance in scenario k. The results for all scenarios are shown in Fig. 8.

In Fig. 8 the yellow coloured plots on the left show the heat flow comparison factors, while the green coloured plots on the right contain the outlet temperature comparison factors. For orientation, the described critical value $f_{c,k} = 1$ is highlighted. The following observations and conclusions can be made from the left-hand diagrams in Fig. 8, which show the performance in terms of the heat flow rates:

- The comparison factors within the three diagrams show moderate variances.
- The performance of the two control concepts is similar in scenarios with a heat flow step, whereby it is noticeable that from scenario 9 onwards, the CF-based concept

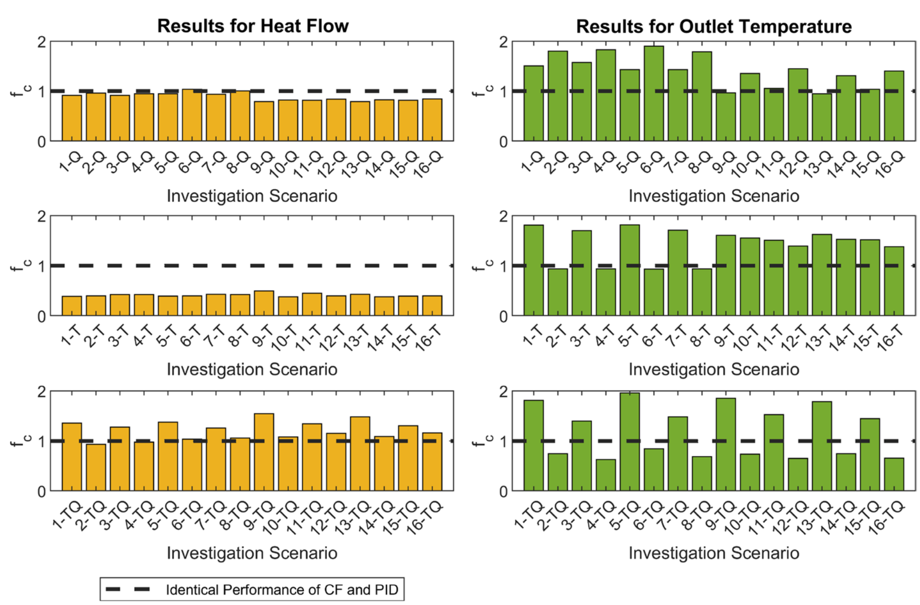

Fig. 8 Results of the comparison factors for heat flow (left side) and outlet temperature (right side) sorted by step types. Top: Q-steps; Middle: T-steps; Bottom: TQ-steps [own representation]

always performs a little better. The explanation for this can be derived from Table 4, as the heat flow level is consistently higher from scenario 9 onwards.
- The performance of the two control concepts differs in scenarios with temperature steps. Here, the CF-based concept shows a significantly better performance.
- The performance of the two control concepts differs in scenarios with temperature and heat flow steps, whereby the concept with PID controller shows better comparison factors in scenarios with odd numbering. In scenarios with even numbering the performance advantage of the concept with PID controller is smaller up to non-existing. In Table 4 the temperature level can be identified as the cause, as this consistently changes between the even and odd-numbered scenarios.

The following observations and conclusions can be made for the right-hand diagrams in Fig. 8, which show the performance with regard to the outlet temperatures:

- The comparison factors within the three diagrams show large variances.
- The performance of the concept with decoupled PID controller is generally better in the scenarios with heat flow steps. However, this advantage is reduced significantly in some cases from scenario 9 onwards. The identified reason for this is the heat flow level, as this is high in scenario 9 and low below (cf. Table 4).
- The behaviour from the previous point is reversed in scenarios with temperature steps.
- In the scenarios with heat flow and temperature steps, an alternating behaviour is visible. In the scenarios with odd numbering, the performance of the concept with PID controller is better. In the scenarios with even numbering, the performance of the map-based scenario is better. The temperature level can be identified from Table 4 as explanation for this behaviour, as it consistently changes between the even and odd numbered scenarios.

Overall, it should be noted that the performance rated with the compare factor of the two self-developed concepts differs significantly depending on the scenario. Therefore, it also seems to be useful to look at the time dependant behaviour. For this purpose, in Fig. 9 plots of the errors are given for step responses of all scenarios for outlet temperature and heat flow of both control concepts over time. In addition, the respective mean values as well as the 10th and 90th percentile are plotted. This gives an impression of the usual error range as a function of time.

In the plots on the right side it can be seen that, the concept with PID controller produces some over- or undershoots shortly after the steps at $t = 0\,s$ which results in large error values. In both graphs of the PID controller, massive oscillations are recognisable, the amplitude of the errors exceeds the height of the steps in some cases. But it also can be seen that the desired target values are reached after a relatively short time which results in small error values after the initial oscillations. In contrast, the concept with the CF, shown in the plots on the left side, reacts more slowly and it therefore takes considerably more time until the target values are reached with sufficient accuracy after the steps. On the other hand, almost no oscillatory behaviour occurs with this concept and only a few slight overshoots in the top plot can be detected.

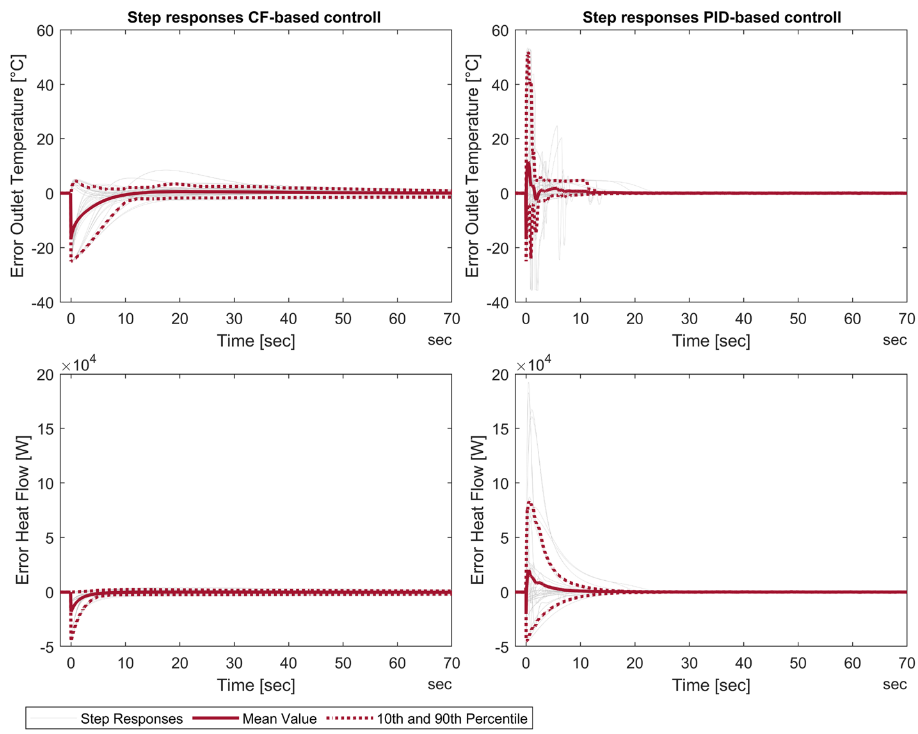

Fig. 9 Step responses as well as mean values and 10th/90th percentiles of all scenarios [own representation]

Discussion of the results

Based on the illustrations and observations described in the previous chapter, a discussion will take place at this point with the aim of deciding which concept is better suited for application in the D-LAB.

First of all, it should be noted that the exclusive consideration of the compare factor in the present case does not allow a final identification of a more suitable concept. The reason for this is that depending on the scenarios, large differences in performance were determined whereby sometimes one concept was rated better than the other and vice versa. Nevertheless, the observation allows conclusions, such as that the delays caused by the PT1 elements and the deviations in the parameterisation of the HEx only have a minor influence on the compare factor. The largest deviations are caused by other primary-side inlet temperatures and by changing the heat flow level. The explanation for this behaviour is most likely the fact that the heat transfer behaviour of the HEx is non-linear. This fact can be counteracted by the lookup table in the CF-based concept, whereas the concept with a decoupled PID controller is adapted for one operating point and therefore delivers poorer control performance due to the non-linearity at other, in particular distant, operating points. Since a very flexible use of the HEx is planned in D-LAB, this would be a benefit for the CF-based concept. This interpretation can be verified by the plot of the time sequences, especially the distance of the percentiles to the extreme values of the individual representations in Fig. 9. While there is hardly any distance in the CF-based concept, it is partly very large in the concept with the decoupled PID controller, which supports the interpretation.

Furthermore, the observation and comparison of the time curves, especially the mean values and the percentiles, allows the conclusion that the CF-based concept results in a slower but also more stable control behaviour. This is advantageous for the application in D-LAB as the planned experiments contain profiles for space heating or solar thermal gains, which require rather slow changes of heat flow and temperatures over time. In addition, because the planning has not yet been completed, it is unknown how large the maximum possible flow rates of the valves or pumps will be. The fast response of the PID-based concept is mainly possible due to large mass flows and it is questionable whether these will be feasible at all.

For the reasons mentioned above, this paper concludes that the CF-based concept is more suitable for the application in D-LAB.

Conclusion and outlook

Fraunhofer IEE is planning to build the District LAB (D-LAB) test facility to conduct empirical studies to support the decarbonisation of the heating sector e.g., by transforming existing district heating (DH) networks. Within the test facility, Hardware-in-the-Loop (HIL) units are to be used to represent any grid participant (consumer, producer or prosumer) that are connected via Heat Exchanger (HEx) to a Flexible Heating Grid (FHG). Example applications for the HIL-units are space heating and domestic hot water preparation of single or multi-family houses as consumers, and solar thermal energy and industrial waste heat as producers. In order to be able to realise this task technically, it is necessary that both, the outlet temperature and the heat flow rate of the HEx connected to the FHG are controllable variables. This requires a special control concept. Within the scope of a literature research carried out to the best of our knowledge, no comparable application case was found. The literature dealt exclusively with the control of outlet temperatures. However, the concepts found for this could serve as a basis for the construction of own control concepts specially developed for the application case. As a result, two control concepts "decoupled PID controller" and "characteristic field (CF) based controller" were developed and subsequently compared with each other by simulation. The MATLAB software with the Simulink extension and blocks from the CARNOT toolbox were used for the simulations. The methods used and the structure of the models used were explained in detail.

For the actual concept comparison, 48 different investigation scenarios were developed, which cover a broad spectrum of the experiments to be expected later in the D-LAB within the framework of the investigations on the transformation of DH grids. In all investigation scenarios, the aim was to quantitatively and qualitatively compare the step responses of outlet temperature and/or heat flow. For the quantitative comparison, a comparison factor based on the Root Mean Square Error (RMSE) was defined, which allows comparing the mean square control errors of the two concepts. Furthermore, the errors of the step responses of the concepts as well as their 10th and 90th percentiles were presented in order to be able to compare the qualitative differences of the two concepts. It has been shown that the control behaviour of the concepts is very different depending on the scenario. This influence is more significant for the "decoupled PID controller" concept. Furthermore, the control behaviour of the two concepts is very different from each other. The CF-based concept shows a more stable but also slower control behaviour without large overshoots, while the "decoupled PID controller" concept shows the opposite behaviour. Therefore, the conclusion is drawn that the CF-based control concept appears to be better suited for application in the D-LAB compared to the concept using the decoupled PID controller. The underlying rationale for this is that the CF-based concept has a more stable time response. The strong overshoots of the concept with decoupled PID controller appear to be problematic for the application.

Since step responses served as the object of comparison in this paper, this conclusion initially applies only to this case. The heat flow and temperature steps used are extreme cases, as the target values change spontaneously. This is not the case in real operating cases that are to be simulated by the HEx in the D-LAB test facility, e.g., profiles for space heating or solar thermal. Here, performance and temperature requirements change constantly over the course of several hours and no steps are to be expected. For this reason, further investigations are required using real test profiles like those which are planned in the D-LAB. In addition, it is conceivable to determine an optimisation of the controller tunings within the scope of further extensive simulation studies, whereby they can be better adapted to the application. These should be carried out with the presented simulation model and used as a basis for the final selection of the control concept for the test facility. However, this does not make sense at the present project state, as it would require precise knowledge of the time behaviour of the sensors and actuators. Nevertheless, it is conceivable that the methods presented and the results of the comparison can be used for other test facilities with similar objectives and as a basis for further investigations.

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