

A CONTROL SYSTEM FOR DISTRIBUTED PUMPING IN A THERMAL ENERGY DISTRIBUTION SYSTEM

Description

TECHNICAL FIELD

[01] The present disclosure is directed to a control system and a method for distributed pumping in a thermal energy distribution system, in particular for use in a heating, cooling, ventilating, and/or air-conditioning (HVAC) system of a building.

BACKGROUND

10 [02] For instance, a thermal energy distribution system for heating and/or cooling may be a hydronic system for transporting thermal energy between a thermal energy source and a thermal energy transfer element, e. g. a heat exchanger. Typically, such thermal energy distribution systems comprise at least two system branches being arranged in parallel to each other, wherein each of the system branches comprises at least one thermal energy transfer element, e. g. a liquid-air heat exchanger. The system branches may be fed by a feeder branch, wherein the feeder branch comprises a thermal energy source for providing a supply flow of thermal energy (hot or cold) into the parallel system branches.

[03] Typically, the fluid flow through a system branch is controlled by a valve. The valve is typically closed-loop temperature-controlled, so that the opening degree of the valve allows a certain fluid flow through

the system branch to achieve a target temperature by means of the thermal energy transfer element that is installed in that system branch.

[04] EP 3 734 396 B1 describes a so-called "distributed pumping" system, in which the flow through the system branches is controlled by speed-controlled pumps rather than valves. As opposed to using valves for regulating a flow in a system branch, distributed pumping by a pump in each consumer branch has the advantage of lower pressure losses due to the inevitable hydraulic resistance added by valves. Distributed pumping can thereby save pumping energy.

[05] Furthermore, a flow regulation by valves has the disadvantage that additional pressure compensating valves or smart pressure independent balancing control valves (PICVs) are necessary to avoid that parallel system branches affect each other.

[06] It is, however, a technical challenge to perform the distributed pumping, i. e. to control the speed-controlled pump(s) in each system branch, in such a way that the full capacity range of a thermal energy transfer element in a system branch is efficiently used.

SUMMARY

[07] The control system and method for distributed pumping according to the present disclosure provides a solution to the problem of performing the distributed pumping, i. e. the controlling of the speed-controlled pump(s) in each system branch, in such a way that the full capacity range of a thermal energy transfer element in a system branch is efficiently used.

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[08] According to a first aspect of the present disclosure, a control system is provided for distributed pumping in a thermal energy distribution system, wherein the thermal energy distribution system comprises at

least two system branches being arranged in parallel to each other,
wherein

- a pump assembly is installed in one of the system branches comprising a thermal energy transfer element and at least one temperature
5 sensor for providing a measured temperature value that is affected by an output power of the thermal energy transfer element, and
 - the pump assembly is configured to control and provide a fluid flow through said system branch, wherein the output power of the thermal energy transfer element scales non-linearly with the fluid flow through
10 said system branch,
- characterised in that
- the control system is configured to provide a pump actuation signal for operating the pump assembly in a closed-loop control with the measured temperature as a feedback signal to control the fluid flow through
15 said system branch, wherein the control system is further configured to apply a non-linear correction function in the closed-loop control such that the output power of the thermal energy transfer element scales linearly with the pump actuation signal.

20 [09] Thus, it is the inventive idea to use a non-linear correction function to compensate for the non-linear scaling of the output power of the thermal energy transfer element with the fluid flow. As a result, the full capacity range of the thermal energy transfer element can be efficiently used. In absence of the non-linear correction function, the control sensitivity for the output power of the thermal energy transfer element would
25 undesirably change with the speed setting of the pump assembly, because the fluid flow through said branch naturally scales linearly with the pump speed.

30 [10] It should be noted that "linear scaling" between a variable x and a variable y may be defined herein as an evenly distributed sample of

value pairs (x, y) having an absolute value of a sample Pearson correlation coefficient (PCC) of $|r_{xy}| \geq 0.95$. Analogously, "non-linear scaling" between a variable x and a variable y may be defined herein as an evenly distributed sample of value pairs (x, y) having an absolute value of a sample PCC of $|r_{xy}| < 0.95$. For example, if $|r_{pq}| < 0.95$ for the value pairs $\{(\Phi_{\min}, q_{\min}), (20\%\Phi_{\max}, 20\%q_{\max}), (40\%\Phi_{\max}, 40\%q_{\max}), (60\%\Phi_{\max}, 60\%q_{\max}), (80\%\Phi_{\max}, 80\%q_{\max}), (\Phi_{\max}, q_{\max})\}$, wherein $\Phi_{\min}$ and $\Phi_{\max}$ is the minimum and maximum output power Φ of the thermal energy transfer element, and wherein $q_{\min}$ and $q_{\max}$ is the minimum and maximum fluid flow, the output power Φ of the thermal energy transfer element shall be considered herein to scale non-linearly with the fluid flow q . Similarly, for instance, if $|r_{p\omega}| \geq 0.95$ for the value pairs $\{(\Phi_{\min}, \omega_{\min}), (20\%\Phi_{\max}, 20\%\omega_{\max}), (40\%\Phi_{\max}, 40\%\omega_{\max}), (60\%\Phi_{\max}, 60\%\omega_{\max}), (80\%\Phi_{\max}, 80\%\omega_{\max}), (\Phi_{\max}, \omega_{\max})\}$, wherein $\omega_{\min}$ and $\omega_{\max}$ is the minimum and maximum pump speed, the output power Φ of the thermal energy transfer element shall be considered herein to scale linearly with the pump speed ω . It should be noted that the sample of value pairs (x, y) should be evenly distributed over the full variable range. Furthermore, for an acceptable error on the PCC to give meaningful results, the sample size should be at least 5, preferably 10 or higher.

[11] Optionally, the pump actuation signal may define a pump speed ω , a pump motor torque τ , or a pump power. Most preferably, the pump actuation signal is a dimensionless relative value ranging between 0 and 1 or between 0% and 100%, which sets the pump speed to a value between $\omega_{\min}$ for a zero signal and $\omega_{\max}$ for a signal of 1 or 100%. In a similar way, the pump actuation signal may set the pump motor torque or the pump power within the respective available range.

[12] Optionally, the pump assembly may be a single-stage or multi-stage centrifugal pump with a speed-controlled, motor torque-controlled or power-controlled electric drive motor and a control module

located within an electronics housing of the pump assembly, wherein the control system is at least partly integrated into the control module of the pump assembly. This is highly advantageous, because there is no need for a superordinate control system that coordinates the operation of the pumps across the parallel system branches. Thus, there is no hardware adaptation needed except for the pump assembly to replace an existing valve or pump assembly or to update an existing pump assembly. The control module within an electronics housing of the pump assembly provides a standalone solution to perform distributed pumping efficiently in a decentralised manner for each system branch individually. The measured temperature value provided by the at least one temperature sensor is typically a readily available input variable in an HVAC system to control the room temperature that is affected by the thermal energy transfer element. The measured temperature value may be communicated to the control module via a wired or wireless communication, preferably via a communication network among smart devices, e. g. smartphone, smart station, smart temperature sensor, smart pump assembly, etc.

[13] Optionally, the control system may comprise a controller being configured to provide a controller output signal for reducing a difference between the measured temperature value and a reference temperature value, wherein the control system is configured to apply the non-linear correction function for converting the controller output signal to the pump actuation signal. This embodiment is useful in cases when there is no need for pressure independency between the system branches, e. g. in the simple case of a pump assembly being used to replace a two-way valve in a mixing loop. It is in this case simply trusted or known to a high degree that the fluid flow through the system branch scales linearly with the pump speed.

[14] However, if pressure independency between the system branches is important, because the system branches affect each other, it cannot be simply trusted or known to a high degree that the fluid flow through the system branch scales linearly with the pump speed. In that case, a further controller is advantageous. In addition to the first controller being configured to provide a first controller output signal for reducing a difference between the measured temperature value and a reference temperature value, the control system may then preferably comprise a second controller being configured to provide the pump actuation signal as a second controller output signal for reducing a difference between an actual flow value and a reference flow value, wherein the control system is configured to apply the non-linear correction function for converting the first controller output signal to the reference flow value. The actual flow value may be received as a measured value from a flow meter or as a value estimated on the basis of a current operating point of the pump assembly. As a flow meter is an expensive extra hardware item, it is preferred to estimate the actual flow value on the basis of a current operating point of the pump assembly, e. g. defined by the current electrical power consumption of the pump assembly. This is yet another advantage of distributed pumping over a valve-controlled flow.

[15] Thus, preferably, the control system may be configured to estimate the actual flow value based on a determined power consumption of the pump assembly and/or a measured pressure difference between a pressure upstream of the pump assembly and a pressure downstream of the pump assembly.

[16] Optionally, the control system may be configured to set an upper limit and/or lower limit to a controller output signal, to the pump actuation signal and/or to the reference flow value to prevent a saturation or wind-up of the closed-loop control. This is beneficial to ensure that the input variable and/or the output variable of the non-linear correction

function is within specified limits to reduce the risk of controller wind-up and saturation.

[17] Optionally, the control system may be configured to receive a supply line temperature value measured upstream of the thermal energy transfer element in said system branch and a return line temperature value measured downstream of the thermal energy transfer element in said system branch, wherein the control system is configured to estimate the output power of the thermal energy transfer element based on an estimated actual flow value and a difference between the supply line temperature value and the return line temperature value. This is particularly advantageous in order to define and/or tune the non-linear correction function. If the output power of the thermal energy transfer element cannot be measured or estimated, the non-linear correction function must be based on nominal values given in the specifications of the thermal energy transfer element. However, the real output power of the thermal energy transfer element may differ from the nominal value depending on the particular setup and it may change over time. It is therefore highly desirable to have a measurement or estimation of the actual output power of the thermal energy transfer element. The output power Φ of the thermal energy transfer element may be estimated as $\Phi = \rho \cdot c \cdot q \cdot (T_{sup} - T_{ret})$, wherein q is the estimated or measured fluid flow through the system branch, T_{sup} is the supply line temperature, T_{ret} is the return line temperature, ρ is the density of the fluid and c is the specific heat of the fluid. Typically, the pumped fluid is water and the density ρ of water and the specific heat of water is known.

[18] Optionally, the control system may be configured to tune the non-linear correction function, preferably upon pump assembly installation in said system branch, based on the output power of the thermal energy transfer element. This is particularly advantageous, because the actual output power of the thermal energy transfer element may in fact differ

from a nominal value depending on the particular setup, or it may have changed over time. As described above, the actual output power of the thermal energy transfer element may be estimated based on an estimated actual flow value and a difference between the supply line temperature and the return line temperature.

[19] Optionally, the non-linear correction function may be an exponential function or a polynomial function of a controller output value, wherein the non-linear correction function ($F_\theta(u)$) is parametrised by a set of at least two parameters ($\theta = [\theta_1, \theta_2]^T$). The preferred embodiment with an exponential correction function may be referred to as "equal-percentage" correction. For example, the non-linear correction function may be denoted as $F_\theta(u)$, wherein u is the controller output value as input variable and θ is a parameter vector $\theta = [\theta_1, \theta_2]^T$ containing the at least two parameters θ_1, θ_2 . The parameters θ_1, θ_2 may be tuned to achieve the best linear scaling of the actual output power of the thermal energy transfer element with the pump actuation signal. For example, the non-linear correction function may take the form $F_\theta(u) = \theta_1 \exp(\theta_2 u)$ or $F_\theta(u) = \theta_1 u + \theta_2 u^n$, wherein $n \geq 2$, e. g. $n = 6$, may be a pre-determined exponent.

[20] Optionally, the control system may comprise an autotuning mode, wherein the control system is in the autotuning mode configured to operate the pump assembly in $K \geq 2$ batch runs (indexed by i), wherein the pump actuation signal (ω, τ, P) differs between the batch runs so that corresponding actual flow values ($q_{i=1}, \dots, q_{i=K}$) are distributed over a full flow range (q_{min}, q_{max}) of the pump assembly, wherein the control system is configured to determine, at the respective actual flow value ($q_{i=1}, \dots, q_{i=K}$) for each batch run i , a relative output power value ($\frac{\Phi_{i=1}}{\Phi_{max}}, \dots, \frac{\Phi_{i=K}}{\Phi_{max}}$) of the thermal energy transfer element relative to a maximum output power (Φ_{max}) of the thermal energy transfer element, wherein the control system is configured to tune the non-linear correction

- function ($F_\theta(u)$) by determining at least two parameters ($\theta = [\theta_1, \theta_2, \dots]^T$) of the non-linear correction function $F_\theta(u)$, for which a difference between the actual flow values ($q_{i=1}, \dots, q_{i=K}$) and the non-linear correction function ($F_\theta(\bar{u})$) at the relative output power values ($\bar{u} = \left[\frac{\Phi_{i=1}}{\Phi_{max}}, \dots, \frac{\Phi_{i=K}}{\Phi_{max}} \right]^T$)
- 5 is minimal. The non-linear correction function $F_\theta(u)$ is supposed to compensate how the relative output power value scales with the fluid flow q . Therefore, the parameter vector $\theta = [\theta_1, \theta_2, \dots]^T$ may be determined for an exponential correction function by last squares minimisation problem $\min_\theta \left| \log \bar{q} - \log F_\theta(\bar{u}) \right|^2$, wherein $\bar{u} = [u_{i=1}, \dots, u_{i=K}]^T$ is a vector of relative
- 10 output power values and $\bar{q} = [q_{i=1}, \dots, q_{i=K}]^T$ is a vector of estimated or measured fluid flow values determined in each batch run i . In case of a polynomial correction function, the least squares minimisation problem may be denoted as $\min_\theta \left| \bar{q} - F_\theta(\bar{u}) \right|^2$ subject to $\partial_u F_\theta(\bar{u}) \geq \epsilon$, wherein $\partial_u F_\theta(u_i) = [\theta_1, n\theta_2 u_i^{n-1}]^T$ is the derivative with respect to u solved in u_i .
- 15 The constraint ensures that the slope of the identified curve is always larger than a margin ϵ in the batch runs. This condition is beneficial to ensure stability of the control loop over the full control range when the non-linear correction function is applied.

[21] Optionally, the control system may be configured to apply a

20 branch-specific non-linear correction function for each of the system branches of the thermal energy distribution system. As the pump assemblies and/or the thermal energy transfer elements may differ among the parallel system branches, it may be beneficial to apply individually tuned non-linear correction functions for each system branch.

25 [22] Optionally, the control system may be configured to tune each branch-specific non-linear correction function, preferably upon pump assembly installation in the respective system branch, based on the output power of the thermal energy transfer element in the respective system branch. Even if the pump assemblies and/or the thermal energy

transfer elements may be nominally identical among the parallel system branches, the individual setup may differ and thus how the output power of the thermal energy transfer element actually scales with the fluid flow through the respective system branch. It therefore beneficial to tune
5 each branch-specific non-linear correction function.

[23] According to another aspect of the present disclosure, a pump assembly is provided, wherein the pump assembly comprises a single-stage or multi-stage centrifugal pump with a speed-controlled, motor torque-controlled or power-controlled electric drive motor and a control
10 module located within an electronics housing of the pump assembly, wherein the control module comprises a control system as described above. In this standalone embodiment, the control system is fully implemented into a control module of the pump assembly that is installed at the respective system branch for distributed pumping. Thus, there is no
15 need to change the existing hardware setup, except for replacing an existing valve or an existing pump by the inventive pump assembly. Alternatively, an existing pump assembly may be updated, so that the control module of the pump assembly is able to perform the inventive control system's tasks. Preferably, each system branch is equipped with such an
20 inventive pump assembly.

[24] According to another aspect of the present disclosure, a thermal energy distribution system is provided that comprises at least two system branches being arranged in parallel to each other, wherein at least one of the at least two system branches comprises
25 - a thermal energy transfer element,
- at least one temperature sensor for providing a measured temperature value that is affected by an output power of the thermal energy transfer element,
- a pump assembly being configured to control and provide a fluid
30 flow through said system branch, and

- a control system as described above.

[25] Optionally, the thermal energy distribution system may further comprise

- 5 - a supply line temperature sensor installed in said at least one system branch upstream of the thermal energy transfer element for providing a supply line temperature value, and
- a return line temperature sensor installed in said at least one system branch downstream of the thermal energy transfer element for
- 10 providing a return line temperature value.

[26] According to another aspect of the present disclosure, a method is provided for distributed pumping in a thermal energy distribution system, wherein the thermal energy distribution system comprises at least

15 two system branches being arranged in parallel to each other, wherein at least one of the system branches comprises a thermal energy transfer element, at least one temperature sensor, and a pump assembly being configured to control and provide a fluid flow through said system branch, wherein the method comprises

- 20 - receiving from the temperature sensor a measured temperature value that is affected by an output power of the thermal energy transfer element,
- providing a pump actuation signal for operating the pump assembly in a closed-loop control with the measured temperature as a
- 25 feedback signal to control and provide, by the pump assembly, the fluid flow through said system branch, wherein the output power of the thermal energy transfer element scales non-linearly with the fluid flow through said system branch, wherein a non-linear correction function is applied in the closed-loop control such that the out-
- 30 put power of the thermal energy transfer element scales linearly with the pump actuation signal.

[27] Optionally, the pump actuation signal may define a pump speed, a pump motor torque, or the pump power.

[28] Optionally, a controller may provide a controller output signal for reducing a difference between the measured temperature value and a reference temperature value, wherein the non-linear correction function is applied for converting the controller output signal to the pump actuation signal.

[29] Optionally, a first controller may provide a first controller output signal for reducing a difference between the measured temperature value and a reference temperature value, wherein a second controller provides the pump actuation signal as a second controller output signal for reducing a difference between an actual flow value and a reference flow value, wherein the non-linear correction function is applied for converting the first controller output signal to the reference flow value.

[30] Optionally, the actual flow value may be estimated based on a determined power consumption of the pump assembly and/or a measured pressure difference between a pressure upstream of the pump assembly and a pressure downstream of the pump assembly.

[31] Optionally, an upper limit and/or lower limit may be set to a controller output signal, to the pump actuation signal and/or to the reference flow value to prevent a saturation or wind-up of the closed-loop control.

[32] Optionally, a measured supply line temperature value may be received from a supply line temperature sensor installed in said system branch upstream of the thermal energy transfer element, and wherein a measured return line temperature value may be received from a return

line temperature sensor installed in said system branch downstream of the thermal energy transfer element, wherein the output power of the thermal energy transfer element is estimated by the pump assembly based on an estimated actual flow value and a difference between the
 5 supply line temperature value and the return line temperature value.

[33] Optionally, the method may further comprise tuning the non-linear correction function, preferably upon pump assembly installation in said system branch, based on the output power of the thermal energy transfer element.

10 [34] Optionally, the non-linear correction function may be an exponential function or a polynomial function of a controller output value, wherein the non-linear correction function is parametrised by a set of at least two parameters. The preferred embodiment with an exponential
 15 correction function may be referred to as "equal-percentage" correction.

[35] Optionally, the pump assembly may be operated in an autotuning mode in which the pump assembly performs $K \geq 2$ batch runs (indexed by i), wherein the pump actuation signal differs between the batch runs so that corresponding actual flow values ($q_{i=1}, \dots, q_{i=K}$) are
 20 distributed over a full flow range (q_{min}, q_{max}) of the pump assembly, wherein a relative output power value ($\frac{\Phi_{i=1}}{\Phi_{max}}, \dots, \frac{\Phi_{i=K}}{\Phi_{max}}$) of the thermal energy transfer element relative to a maximum output power (Φ_{max}) of the thermal energy transfer element is determined at the respective actual
 25 flow value ($q_{i=1}, \dots, q_{i=K}$) for each batch run, wherein the non-linear correction function ($F_{\theta}(u)$) is tuned by determining at least two parameters ($\theta = [\theta_1, \theta_2, \dots]^T$) of the non-linear correction function $F_{\theta}(u)$, for which a

difference between the actual flow values ($q_{i=1}, \dots, q_{i=K}$) and the non-linear correction function ($F_{\theta}(\bar{u})$) at the relative output power values ($\bar{u} = \left[\frac{\Phi_{i=1}}{\Phi_{max}}, \dots, \frac{\Phi_{i=K}}{\Phi_{max}} \right]^T$) is minimal.

[36] Optionally, a branch-specific non-linear correction function may
5 be applied for each of the system branches of the thermal energy distribution system.

[37] Optionally, each branch-specific non-linear correction function may be tuned, preferably upon pump assembly installation in the respective system branch, based on the output power of the thermal energy transfer element in the respective system branch.
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[38] According to another aspect of the present disclosure, a computer program is provided comprising instructions which, when the program is executed by a control system, cause the control system to carry out the method described above.

[39] The method disclosed herein may be implemented in form of
15 compiled or uncompiled software code that is stored on a computer readable medium with instructions for executing the method. Alternatively, or in addition, one or more method steps may be executed by software in a cloud-based system and/or a building management system (BMS), e. g. in the control system disclosed herein.
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[40] The control system and method described herein may be implemented and integrated in local decentral system branch control units located at, in or close to the pump assemblies of the system branches.
25 Alternatively, or in addition, the control system and method described herein may be implemented and integrated in at least one central control unit controlling the pump assemblies in the system branches via a

network, e. g. as part of a building management system (BMS). It is also possible to implement the control system and method described herein at least partially in a remote cloud computing environment. A cloud computing environment may be particularly useful in case of geograph-
5 ically widely spread thermal energy distribution system, such as a district heating or cooling system.

SUMMARY OF THE DRAWINGS

10 [41] Embodiments of the present disclosure will now be described by way of example with reference to the following figures of which:

Figs. 1a,b show schematically two different embodiments of a thermal energy distribution system as disclosed herein;

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Fig. 2 shows a top diagram displaying an example of how the thermal output power of the thermal energy transfer element scales with the fluid flow in the associated system branch, a middle diagram displaying an example of how the fluid flow in the associated system branch
20 scales with a controller output (the non-linear correction function being applied and not applied), and a bottom diagram displaying an example of how the thermal output power of the thermal energy transfer element scales with a controller output (the non-linear correction function being applied and not applied);

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Figs. 3a,b shows schematically two embodiments of a control system and method as disclosed herein; and

Figs. 4a,b shows schematically two further embodiments of a control
30 system and method as disclosed herein.

DETAILED DESCRIPTION

[42] Fig. 1 shows a thermal energy distribution system 1 in form of a HVAC system comprising a chiller 3 for providing chilled water. In case of a heating system, the system 1 could comprise a boiler as thermal energy source instead of chiller 3. A primary pump 5 pumps the chilled water in a primary circuit along a bypass line 6 to feed three secondary parallel system branches 7 of the thermal energy distribution system 1. The three system branches 7 are connected to the primary circuit in parallel to each other, so that the flow of chilled water through the primary circuit is split among the three system branches 7. Each of the system branches 7 comprises at least one speed-controlled pump 9 for distributed pumping. This means that a water flow q through the respective system branch 7 is not controlled by a valve, but by the speed of the respective pump 9 installed in said system branch 7. However, a non-return valve 11 in form of a check valve is installed in each system branch 7 in order to prevent an undesirable back-flow through the respective system branch 7.

[43] A thermal energy transfer element 13, e. g. here in form of a liquid-air heat exchanger, is installed in each system branch 7. The chilled water pumped by the associated pump 9 through the thermal energy transfer element 13 may be used to cool air that is ventilated into an air-conditioned room. A temperature sensor (not shown in Figs. 1a,b) may be installed in the air-conditioned room and/or integrated in the thermal energy transfer element 13 to provide a measured temperature value T . The measured temperature value T is affected by an output power of the thermal energy transfer element 13, i. e. the measured temperature value T decreases when the output power of the thermal energy transfer element 13 increases and vice versa. The measured

temperature value T is typically used for closed-loop controlling the output power of the thermal energy transfer element 13 to achieve a selectable reference temperature as target temperature.

- 5 [44] The thermal energy distribution system 1 further comprises a control system 15 for distributed pumping. As shown in Fig. 1a, the control system 15 may be fully implemented for each system branch 7 independently in a local control module 16 of a pump assembly that comprises the pump 9 in said system branch 7 (it is only shown for one system branch 7 as an example). The pump assembly may be a single-stage or multi-stage centrifugal pump 9 with a speed-controlled, motor torque-controlled or power-controlled electric drive motor and a control module 16 located within an electronics housing of the pump assembly, wherein the control system 15 is fully integrated into the control module 16 of the pump assembly. The control system 15 being part of a control module 16 located within an electronics housing of the pump assembly provides a standalone solution to perform distributed pumping efficiently in a decentralised manner for each system branch 7 individually.
- 20 [45] The control system 15 receives the measured temperature value T provided by a temperature sensor and/or the thermal energy transfer element 13 as a feedback variable in a closed-loop control. It is preferred, as shown in Fig. 1a, that the control system 15 further receives or determines a power consumption P of the pump 9 to estimate the water flow q through the respective system branch 7. Alternatively, a flow meter could be installed in the system branch to provide a measured value of the water flow q . As will be explained in view of Fig. 3a, estimating or measuring the water flow q is not needed if there is no requirement for pressure independence between the system branches 7, e. g. in the simple case of a pump assembly being used to replace a two-way valve in a mixing loop.
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[46] The control system 15 provides a pump actuation signal as output to set the operating point of the pump 9. Most preferably, the pump actuation signal is the set pump speed ω . Alternatively, the pump actuation signal may be a set motor torque τ or a set pump power P . If the pump actuation signal is the pump power P , for example, the pump speed ω may be used to estimate the flow. As the output power of the thermal energy transfer element 13 scales non-linearly with the water flow q through the system branch 7, the control system 15 applies a non-linear correction function in the closed-loop control such that the output power of the thermal energy transfer element scales linearly with the pump actuation signal ω , τ , P . Thereby, the full capacity range of the thermal energy transfer element 13 is efficiently close-loop controlled.

[47] Fig. 1b shows an embodiment of the thermal energy distribution system 1 with a superordinate control module 17, e. g. as part of a building management system (BMS) or a cloud-based control system. The control system 15 is partly implemented in said superordinate control module 17 and partly within the local control module 16 of the pump assembly, wherein the superordinate control module 17 collects the temperature value T from the different system branches 7 and provides a controller output signal u for each pump 9. So, the closed-loop control is performed by the superordinate control module 17. Another part of the control system 15 is still locally implemented in the pump assembly, similar to in Fig. 1a, where the controller output signal u is received as input rather than the measured temperature value T .

[48] The top plot of Fig. 2 shows an example of how the output power Φ of the thermal energy transfer element 13 scales non-linearly with the water flow q through the system branch 7. The middle plot shows in a dashed line that the water flow q through the system branch 7 scales linearly with the pump actuation signal ω if no correction function is applied. The pump actuation signal ω is in the shown example a relative

pump speed ranging from zero to 1 for maximum pump speed $\omega_{\max}$. In case of the pump actuation signal being the motor torque τ or the pump power P , the water flow q through the system branch 7 does not scale linearly with the pump actuation signal τ , P , which makes the correction slightly more complicated, but not less beneficial. In any case, if no correction function is applied, a controller output signal u is simply used as the pump actuation signal ω , τ , P . The solid line in the middle plot shows that the water flow q through the system branch 7 scales non-linearly with the pump actuation signal ω after a non-linear correction function is applied. The resulting effect of applying the non-linear correction function is visible in the bottom plot of Fig. 2. The dashed line shows that the output power Φ of the thermal energy transfer element 13 would scale non-linearly with the pump actuation signal ω , i. e. the controller output signal u , if no correction function were applied. After applying the non-linear correction function, the solid line in the bottom plot shows that the output power Φ of the thermal energy transfer element 13 scales linearly with the pump actuation signal ω over the full control range $[0, 1]$ from minimum to maximum.

[49] The non-linear correction function $F_{\theta}(u)$ may be an exponential function or a polynomial function of the controller output value u , wherein the non-linear correction function $F_{\theta}(u)$ is parametrised by a set of at least two parameters $\theta = [\theta_1, \theta_2]^T$. For example, the non-linear correction function may be denoted as $F_{\theta}(u)$, wherein u is the controller output value as input variable and θ is a parameter vector $\theta = [\theta_1, \theta_2]^T$ containing the at least two parameters θ_1, θ_2 . As will be explained in more detail in view of Figs. 4a,b, the parameters θ_1, θ_2 may be tuned to achieve the best linear scaling of the actual output power Φ of the thermal energy transfer element 13 with the pump actuation signal ω , τ , P . For example, the non-linear correction function may take the form $F_{\theta}(u) = \theta_1 \exp(\theta_2 u)$ or $F_{\theta}(u) = \theta_1 u + \theta_2 u^n$, wherein $n \geq 2$, e. g. $n = 6$, may be a pre-determined exponent.

[50] Fig. 3a shows schematically a very simple embodiment of the control system 15 and method by way of processing blocks 31, 33. In this embodiment, estimating or measuring the water flow q is not needed,
 5 because there is no requirement for pressure independence between the system branches 7, e. g. in the simple case of a pump assembly being used to replace a two-way valve in a mixing loop. The thermal energy transfer element 13 comprises here a heat exchanger 19, a fan 21 and a temperature sensor 23 downstream of the heat exchanger 19. The pump
 10 9 pumps chilled water through the heat exchanger 19 which cools the air that is blown along the heat exchanger 19 by the fan 21. The pump 9 thus causes a pressure differential Δp between a supply line 25 and a return line 27 of the system branch 7. The temperature sensor 23 is arranged to measure the temperature T affected by the thermal energy
 15 transfer element 13 and is fed back in a closed-loop control to minimise a deviation from a selectable or pre-determined reference temperature T_{ref} . A PI controller 29 determines a controller output value u in order to minimise the difference $T - T_{ref}$. In correction block 31, the non-linear correction function $F_{\theta}(u)$ is applied to convert the controller output value
 20 u into a pump actuation signal ω , τ , P . However, before the pump actuation signal ω , τ , P is used to command the pump 9, an upper limit and/or lower limit is in saturation block 33 set to the pump actuation signal ω , τ , P to reduce the risk of a saturation or wind-up of the closed-loop control.

[51] Fig. 3b shows an embodiment of the control system 15 and
 25 method that allows for estimating or measuring the water flow q in order to achieve a pressure independence between the system branches 7. This is due to the fact that the pump operation in other parallel system branches 7 may affect the pressure differential Δp in this system branch 7. Therefore, the control system 15 comprises two PI controllers 29, 35,
 30 wherein a first one 29 of the two PI controllers 29, 35 determines a controller output value u in order to minimise the difference $T - T_{ref}$ in the

same way as in the embodiment of Fig. 3a. The second PI controller 35 determines the pump actuation signal ω , τ , P as a second controller output signal such that a difference between an actual flow value q and a reference flow value q_{ref} is minimised. In this embodiment, the non-linear
5 correction function $F_{\theta}(u)$ is applied in correction block 31 and the limitation is applied in saturation block 33 for converting the first controller output signal u to the reference flow value q_{ref} .

[52] The embodiments of the control system 15 and method shown in Figs. 4a,b allows for a tuning of the non-linear correction function $F_{\theta}(u)$,
10 preferably at the time of installation of the pump assembly or whenever the output power of the output power Φ of the thermal energy transfer element 13 has changed or behaves differently than expected. Without tuning, the non-linear correction function $F_{\theta}(u)$ may rely on nominal values provided by a manufacturer of the thermal energy transfer element
15 13. The behaviour of true output power of the output power Φ of the thermal energy transfer element 13 may, however, differ from the nominally expected behaviour depending on the actual setup, or it may change over time. It is therefore beneficial to tune the non-linear correction function $F_{\theta}(u)$ at least once upon installation of the pump assembly,
20 sporadically and/or periodically, or on demand. The only additional information that the control system 15 needs to tune the non-linear correction function $F_{\theta}(u)$ is a supply line temperature T_{sup} and a return line temperature T_{ret} in the respective system branch 7. Often, the thermal energy transfer element 13 and/or the pump assembly 9 may be already
25 equipped with a supply line temperature sensor 37 and a return line temperature sensor 39, so that the supply line temperature T_{sup} and a return line temperature T_{ret} can be readily provided to the control system 15. Otherwise, the control system 15 may comprise the supply line temperature sensor 37 and a return line temperature sensor 39. The control system
30 15 comprises an autotuning mode, in which the pump assembly is oper-

ated in $K \geq 2$ batch runs (indexed by i), wherein the pump actuation signal ω , τ , P differs between the batch runs so that corresponding actual flow values $(q_{i=1}, \dots, q_{i=K})$ are distributed over a full flow range (q_{min}, q_{max}) of the pump assembly. The control system 15 determines, at the respective actual flow value $(q_{i=1}, \dots, q_{i=K})$ for each batch run i , a relative output power value $(\frac{\Phi_{i=1}}{\Phi_{max}}, \dots, \frac{\Phi_{i=K}}{\Phi_{max}})$ of the thermal energy transfer element 13 relative to a maximum output power Φ_{max} of the thermal energy transfer element 13 among the K batch runs. The non-linear correction function $F_{\theta}(u)$ is tuned by determining at least two parameters $(\theta = [\theta_1, \theta_2, \dots]^T)$ of the non-linear correction function $F_{\theta}(u)$, for which a difference between the actual flow values $(q_{i=1}, \dots, q_{i=K})$ and the non-linear correction function $(F_{\theta}(\bar{u}))$ at the relative output power values $(\bar{u} = [\frac{\Phi_{i=1}}{\Phi_{max}}, \dots, \frac{\Phi_{i=K}}{\Phi_{max}}]^T)$ is minimal. The non-linear correction function $F_{\theta}(u)$ is supposed to compensate how the relative output power value scales with the fluid flow q . Therefore, the parameter vector $\theta = [\theta_1, \theta_2, \dots]^T$ is determined for an exponential correction function by least squares minimisation problem $\min_{\theta} ||\log \bar{q} - \log F_{\theta}(\bar{u})||^2$, wherein $\bar{u} = [u_{i=1}, \dots, u_{i=K}]^T$ is a vector of relative output power values and $\bar{q} = [q_{i=1}, \dots, q_{i=K}]^T$ is a vector of estimated or measured fluid flow values determined in each batch run i . In case of a polynomial correction function, the least squares minimisation problem is denoted as $\min_{\theta} ||\bar{q} - F_{\theta}(\bar{u})||^2$ subject to $\partial_u F_{\theta}(\bar{u}) \geq \epsilon$, wherein $\partial_u F_{\theta}(u_i) = [\theta_1, n\theta_2 u_i^{n-1}]^T$ is the derivative with respect to u solved in u_i . The constraint ensures that the slope of the identified curve is always larger than a margin ϵ in the batch runs. This condition is beneficial to ensure stability of the control loop over the full control range when the non-linear correction function is applied.

[53] The embodiment shown in Fig. 4b differs from the embodiment shown in Fig. 4a in the same way as the embodiment of Fig. 1b differs from the embodiment of Fig. 1a. The first PI controller 29 is implemented

in a superordinate control module 17, e.g. as part of a building management system (BMS) or a cloud-based control system. The control system 15 is thus partly implemented in said superordinate control module 17, which collects the temperature value T and provides a controller output
5 signal u. So, the closed-loop control is performed by the superordinate control module 17. Another part of the control system 15 is still locally implemented in the local control module 16 located in or at the pump assembly, where the controller output signal u is received as input rather than the measured temperature value T.

10 [54] Where, in the foregoing description, integers or elements are mentioned which have known, obvious or foreseeable equivalents, then such equivalents are herein incorporated as if individually set forth. Reference should be made to the claims for determining the true
15 scope of the present disclosure, which should be construed so as to encompass any such equivalents. It will also be appreciated by the reader that integers or features of the disclosure that are described as optional, preferable, advantageous, convenient or the like are optional and do not limit the scope of the independent claims.

20 [55] The above embodiments are to be understood as illustrative examples of the disclosure. It is to be understood that any feature described in relation to any one embodiment may be used alone, or in combination with other features described, and may also be used in combination with one or more features of any other of the embodi-
25 ments, or any combination of any other of the embodiments. While at least one exemplary embodiment has been shown and described, it should be understood that other modifications, substitutions and alternatives are apparent to one of ordinary skill in the art and may be changed without departing from the scope of the subject matter described herein, and this application is intended to cover any adapta-
30 tions or variations of the specific embodiments discussed herein.

[56] In addition, "comprising" does not exclude other elements or steps, and "a" or "one" does not exclude a plural number. Furthermore, characteristics or steps which have been described with reference to one of the above exemplary embodiments may also be used in combination with other characteristics or steps of other exemplary embodiments described above. Method steps may be applied in any order or in parallel or may constitute a part or a more detailed version of another method step. It should be understood that there should be embodied within the scope of the patent warranted hereon all such modifications as reasonably and properly come within the scope of the contribution to the art. Such modifications, substitutions and alternatives can be made without departing from the spirit and scope of the disclosure, which should be determined from the appended claims and their legal equivalents.

- [57] List of reference numerals:
- 1 Thermal energy distribution system
 - 3 chiller
 - 5 primary pump
 - 6 bypass line
 - 7 system branch
 - 9 pump
 - 11 non-return valve
 - 13 thermal energy transfer element
 - 15 control system
 - 16 local control module
 - 17 superordinate control module
 - 19 heat exchanger
 - 21 fan
 - 23 temperature sensor
 - 25 supply line
 - 27 return line

	29	first PI controller
	31	correction block
	33	saturation block
	35	second PI controller
5	37	supply line temperature sensor
	39	return line temperature sensor
	q	fluid flow
	ω	pump speed
	Φ	output power of thermal energy transfer element
10	u	controller output signal
	T	Temperature
	Δp	differential pressure
	T_{ref}	reference Temperature
	T_{sup}	supply line Temperature
15	T_{ret}	return line Temperature
	q_{ref}	reference flow
	P	power consumption of pump assembly
	τ	motor torque

Claims

1. A control system (15) for distributed pumping in a thermal energy distribution system (1), wherein the thermal energy distribution system (1) comprises at least two system branches (7) being arranged in parallel to each other, wherein
 - a pump assembly is installed in one of the system branches (7) comprising a thermal energy transfer element (13) and at least one temperature sensor (23) for providing a measured temperature value (T) that is affected by an output power (Φ) of the thermal energy transfer element (13), and
 - the pump assembly is configured to control and provide a fluid flow (q) through said system branch (7), wherein the output power (Φ) of the thermal energy transfer element (13) scales non-linearly with the fluid flow (q) through said system branch,characterised in that
 - the control system (15) is configured to provide a pump actuation signal (ω , τ , P) for operating the pump assembly in a closed-loop control with the measured temperature (T) as a feedback signal to control the fluid flow (q) through said system branch (7), wherein the control system (15) is further configured to apply a non-linear correction function in the closed-loop control such that the output power (Φ) of the thermal energy transfer element (13) scales linearly with the pump actuation signal (ω , τ , P).
2. The control system (15) according to claim 1, wherein the pump actuation signal (ω , τ , P) defines a pump speed (ω), a pump motor torque (τ), or a pump power (P).
3. The control system (15) according to claim 1 or 2, wherein the pump assembly is a single-stage or multi-stage centrifugal pump (9) with

5 a speed-controlled, motor torque-controlled or power-controlled electric drive motor and a control module (16) located within an electronics housing of the pump assembly, wherein the control system (15) is at least partly integrated into the control module (16) of the pump assembly.

4. The control system (15) according to any of the preceding claims, wherein the control system (15) comprises a controller (29) being configured to provide a controller output signal (u) for reducing a difference between the measured temperature value (T) and a reference temperature value (T_{ref}), wherein the control system (15) is configured to apply the non-linear correction function ($F_{\theta}(u)$) for converting the controller output signal (u) to the pump actuation signal (ω, τ, P).

15 5. The control system (15) according to any of the claims 1 to 3, wherein the control system (15) comprises a first controller (29) being configured to provide a first controller output signal (u) for reducing a difference between the measured temperature value (T) and a reference temperature value (T_{ref}), wherein the control system (15) comprises a second controller (35) being configured to provide the pump actuation signal (ω, τ, P) as a second controller output signal for reducing a difference between an actual flow value (q) and a reference flow value (q_{ref}), wherein the control system (15) is configured to apply the non-linear correction function ($F_{\theta}(u)$) for converting the first controller output signal (u) to the reference flow value (q_{ref}).

30 6. The control system (15) according to claim 5, wherein the control system (15) is configured to estimate the actual flow value (q) based on a determined power consumption (P) of the pump assembly and/or a measured pressure difference (Δp) between a

pressure upstream of the pump assembly and a pressure downstream of the pump assembly.

- 5 7. The control system (15) according to any of the preceding claims, wherein the control system (15) is configured to receive a supply line temperature value (T_{sup}) measured upstream of the thermal energy transfer element (13) in said system branch (7) and a return line temperature value (T_{ret}) measured downstream of the thermal energy transfer element (13) in said system branch (7), wherein the control system (15) is configured to estimate the output power (Φ) of the thermal energy transfer element (13) based on an estimated actual flow value (q) and a difference between the supply line temperature value (T_{sup}) and the return line temperature value (T_{ret}).
- 10 8. The control system (15) according to any of the preceding claims, wherein the control system (15) is configured to tune the non-linear correction function ($F_{\theta}(u)$), preferably upon pump assembly installation in said system branch, based on the output power of the thermal energy transfer element.
- 15 9. The control system (15) according to any of the preceding claims, wherein the control system (15) comprises an autotuning mode, wherein the control system (15) is in the autotuning mode configured to operate the pump assembly in $K \geq 2$ batch runs, wherein the pump actuation signal (ω, τ, P) differs between the batch runs so that corresponding actual flow values ($q_1, \dots, q_K$) are distributed over a full flow range (q_{min}, q_{max}) of the pump assembly, wherein the control system (15) is configured to determine, at the respective actual flow value ($q_1, \dots, q_K$) for each batch run, a relative output power value ($\frac{\Phi_1}{\Phi_{max}}, \dots, \frac{\Phi_K}{\Phi_{max}}$) of the thermal energy transfer element (13) relative to a maximum output power (Φ_{max}) of the thermal en-
- 20 25 30

ergy transfer element (13), wherein the control system (15) is configured to tune the non-linear correction function ($F_\theta(u)$) by determining at least two parameters ($\theta = [\theta_1, \theta_2, \dots]^T$) of the non-linear correction function ($F_\theta(u)$), for which a difference between the actual flow values ($q_1, \dots, q_K$) and the non-linear correction function ($F_\theta(\bar{u})$) at the relative output power values ($\bar{u} = \left[\frac{\Phi_1}{\Phi_{max}}, \dots, \frac{\Phi_K}{\Phi_{max}} \right]^T$) is minimal.

10. The control system (15) according to any of the preceding claims, wherein the control system (15) is configured to apply a branch-specific non-linear correction function ($F_\theta(u)$) for each of the system branches (7) of the thermal energy distribution system (1).