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Chiller Pump Control using Temperature Sensor Feedback

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Abstract— **In commercial chilled water systems, one of the most prevalent system topology is the Primary/Secondary topology. In this topology, the primary and secondary circuits of the hydronic cooling system are hydraulically decoupled by a common pipe also referred to as the bypass. This allows the primary circuit to ensure minimum chiller flow without interfering with the secondary side. To maximize heat transfer and achieve optimal performance, the flow in the primary and secondary systems must equalize and thus leave no flow in the bypass line when the minimum chiller flow requirement is fulfilled. To achieve this goal in a robust and responsive manner a simple and cost-effective feedback method is proposed, where 3 temperature sensors constitute the control feedback for the primary pump control. Closed-loop stability is proven and automatic sensor calibration is proposed. The method is verified through lab test on a setup emulating by-pass of the Primary/Secondary topology.**

I. Introduction

Energy optimization of Heating, Ventilation, and Air Conditioning (HVAC) systems is a topic receiving increasing attention. Especially, chiller plant optimization with the aim of reducing the power consumption of both chillers and in the distribution is of high interest. That is, energy usage and thus optimization potential is high in these applications. The building sector energy consumption related to cooling only, amounts to a noticeable $12.000GW$ in 2016 [1].

In this work we consider chiller pump control in a Primary/Secondary topology. In this topology the water flow though the chillers is decoupled from the flow trough the Air Handling Units (AHUs) using a bypass [2], [3]. Flow from the return to the supply through the bypass leads to low temperature between supply and return on the secondary side, also known as the low ΔT syndrome [4]. In [4], [5] the undesired flow direction issue is solved by installing a check valve in the bypass. Though, this is a simple and good solution, a check valve can lead to over pressurizing the secondary side and is not energy optimal. Active control on the secondary side has also been proposed for solving the low ΔT problem [6], [7].

In [8] it is argued that no flow in the bypass improves overall system efficiency. However, the bypass is needed to ensure minimum flow requirement for the chillers. Therefore, we proposed a control approach that ensures no flow in the bypass while leaving room to ensure minimum flow requirements of the chillers. For the control, a temperature sensor configuration is used. In [9] a 5 temperature sensor setup is proposed for controlling the bypass flow as well. The approach in [9] uses the temperature sensors for flow estimation, whereas in our work direct control of the temperature values ensure zero flow in the bypass.

The starting point of the work is a variable flow Primary/Secondary system with a structure shown in Fig. 1. The proposed control ensures a proper balance between primary and secondary flows to ensure maximum heat transfer and avoid the low ΔT syndrome. These conditions are achieved while utilizing a minimum amount of temperature sensors and without the usage of any valves at the bypass (e.g. motorized valve, check valve). Two sensor configurations are investigated. The first one leads to globally asymptotically stable control for any positive controller parameters in the propose PI controller. Only local stability is proven for the second sensor configuration, but this configuration is well suited for energy calculation. The proposed control is inherently robust to sensor inaccuracies ensuring that the control objective is achieved even with sensor inaccuracies up to a certain magnitude. Though, the control is inherent robust, a method for in-system calibration of the temperature sensors is proposed to further increase robustness. The calibrated readings are especially suited for energy calculations, which typically requires high grade temperature sensors.

The paper starts, in Section II, with a presentation of the hydronic cooling system under consideration, along with the derivation of a dynamic model of the bypass dynamics. The control structure is presented and stability analysis is carried out in Section III, and the in-system calibration algorithm is presented in Section IV. Test results from a lab test with the proposed controller and calibration method is presented in Section V. Finally, the paper ends with some concluding remarks.

II. Chiller Systems

A model of the bypass in a chilled water circulation system is derived in this section. A sketch of chilled water system is shown in Fig. 1. Here, the chilled water supply consists of two chillers, producing chilled water for a water distribution system. A bypass line is placed between the chillers (primary) and distribution (secondary) side of the system to enable the required minimum flow through the chillers under any condition. Differential pressure sensors across the chiller evaporators provide feedback for the chiller minimum flow control. In this paper, the control of the bypass flow will be in focus, and the minimum flow control will not be treated here.

In Fig. 1, q_S is the chiller flow generated by the primary pumps, which will form the actuators in this work, q_F is the secondary flow generated by the secondary pumps, and q_B

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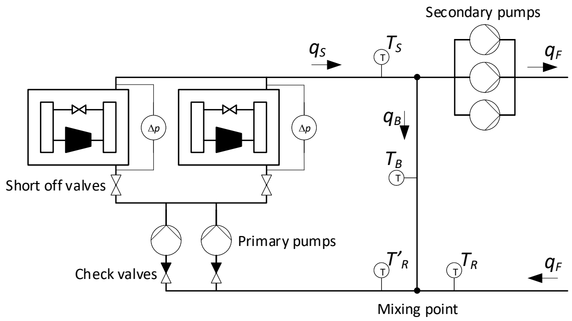

Fig. 1. Sketch of the chiller setup that is controlled in this work.

is the bypass flow resulting from the imbalance between q_S and q_F. The temperatures, T_S and T_R are the supply and return temperatures, respectively. The bypass temperature is denoted T_B, and depends on the bypass flow q_B as well as the temperatures T_S and T_R. The control objective in this paper is to adjust the primary flow q_S such that the bypass flow q_B equals zero and thereby ensuring maximum heat transfer between primary and secondary side. The bypass flow along with the primary and secondary flows are not measured. The idea is to use the bypass temperature T_B as a measure for the flow. To that end, a model of the relation between the flows and the temperatures is derived.

By defining one control volume encapsulating the bypass and a lumped value for the bypass temperature, the dynamic of the temperature is described by the following two expressions

$$CV\dot{T}_B = C|q_B|(T_S - T_B) + B(T_a - T_B)\ ,\ q_B > 0 \quad \text{(1a)}$$

$$CV\dot{T}_B = C|q_B|(T_R - T_B) + B(T_a - T_B)\ ,\ q_B \leq 0, \quad \text{(1b)}$$

where C is the specific heat capacity of water, V is the volume of water inside the bypass, T_a is the ambient temperature, and B the heat transfer coefficient between the water inside the bypass and the surroundings. We assume that the losses to the surroundings are small leading to the following assumption

Assumption 1 *The heat losses to the surroundings are negligible, meaning that $B = 0$ in* (1).

Moreover, the supply temperature T_S is typically controlled by the chiller controllers to a piecewise constant reference value and the return temperature is generated by the cooling systems. The cooling system dynamic is typically very slow and therefore, we will assume that the return temperature T_R and the secondary flow q_F are piecewise constant leading to the following assumption

Assumption 2 *The supply temperature T_S, the return temperature T_R, and the secondary flow q_F are piecewise constant, with $T_S < T_R$ and $q_F > 0$.*

Combining (1a) and (1b), and using Assumption 1 leads to the following model of the bypass dynamic

$$V\dot{T}_B = -|q_B|T_B + |q_B|\mathbb{1}_{q_B>0}T_S + |q_B|\mathbb{1}_{q_B\leq 0}T_R\ , \quad (2)$$

where the function $\mathbb{1}_{x>y}$ is 1, when $x > y$ is fulfilled, otherwise it is 0. The goal for the proposed control approach is to control the bypass temperature to the mean of T_S and T_R. This goal leads to the following control error

$$e_T = \frac{T_S + T_R}{2} - T_B \quad (3)$$

Under Assumption 2 the error dynamics become

$$V\dot{e}_T = -\,|q_B|e_T + Gq_B \quad (4)$$

where $G = -\frac{T_S - T_R}{2} > 0$ as $T_S < T_R$ in cooling systems.

The idea pursued in the paper is to use the temperature T_B or equivalently the temperature error e_T to control the bypass flow q_B. To establish the relation between the temperature error e_T and the bypass flow q_B, we evaluate the uncontrolled dynamics of (4) under different values of q_B. First it is recognized that $e_T = G = -\frac{T_S - T_R}{2}$ when $q_B > 0$ and $e_T = -G = \frac{T_S - T_R}{2}$ when $q_B < 0$ are stable equilibrium's for (4). Finally, for $q_B = 0$ any value of e_T is a stable equilibrium for (4). These arguments are collected in the following Lemma.

Lemma 1 *Under Assumption 1, the relations between the bypass flow q_B and the equilibrium of* (4) *are*

- *for $q_B > 0$ $e_T = G = -\frac{T_S - T_R}{2}$ is asymptotically stable equilibrium.*
- *for $q_B < 0$ $e_T = -G = \frac{T_S - T_R}{2}$ is asymptotically stable equilibrium.*
- *for $q_B = 0$ any e_T is stable equilibrium.*

Lemma 1 means that the control error e_T can be used as an indicator for the bypass flow, and therefore be used for manipulating the supply flow q_S such that the bypass flow equals zero. We use that from Lemma 1 $e_T = 0$ is only a stable equilibrium if $q_B = 0$.

The relation between the bypass flow q_B and the supply flow q_S is found from mass conservation at either of the two mixing points in Fig. 1. The relation is

$$q_B = q_S - q_F\ , \quad (5)$$

where q_F is piecewise constant according to Assumption 2. The supply flow is generated by centrifugal pumps. The relation between the pumps speed ω, the pumps flow q_S, and the pumps pressure Δp for a parallel pump installation with equal sized pumps, is described by the following polynomial

$$\Delta p = -a_{h2}\left(\frac{q_S}{n}\right)^2 + a_{h1}\frac{q_S}{n}\omega + a_{h0}\omega^2\ , \quad (6)$$

where a_{h2}, a_{h1}, a_{h0} are constants describing the pumps, ω is the pumps speed, and n is the number of running pumps. The pumps flow q_S is forced to be larger than zero by non-return valves installed at the pumps, hence $q_S \geq 0$ always. The hydraulic load of the system is given by the hydraulic resistance of the chillers and shut-off valves, see Fig. 1

$$\Delta p = r|q_S|q_S\ , \quad (7)$$

where $r|q_S|$ is the flow dependent hydraulic resistance of the primary part of the system in Fig. 1. The hydraulic resistance r depends on the position of the shut-off valves, which by nature is piecewise constant. Combining (6) and (7) and considering the positive solutions leads to

$$q_S = n\frac{a_{h1} + \sqrt{a_{h1}^2 + 4(a_{h2} + n^2 r)a_{h0}}}{2(a_{h2} + n^2 r)}\omega = K\omega \tag{8}$$

If the sensors T_S, T_R, and T_B shown in Fig. 1 are used as input to the control the model formed by (4) and (8) can be used for setting up a control solution. A control solution based on a PI control structure using the controller error (3) will be analyzed in Section III.

In cases where energy is to be measured along with the control of the bypass flow, it is important to measure the supply and return temperature at the same side of the bypass. In this case, the sensors T_S, T_R', and T_B are used in the control. Again a PI control structure will be used but with the control error

$$e_T' = \frac{T_S + T_R'}{2} - T_B\ . \tag{9}$$

To be able to analyse the impact of this controller error the relation between T_R and T_R' needs to be established.

The energy conservation at the lower mixing point in Fig. 1 leads to $T_R' q_S = T_B q_B + T_R q_F$ for $q_B > 0$ and for $q_B \leq 0$ $T_R' = T_R$. The energy conservation together with mass conservation at the mixing points (5), leads to the following expression for T_R'

$$T_R' = \left(T_B\frac{q_B}{q_F + q_B} + T_R\frac{q_F}{q_F + q_B}\right)\mathbb{1}_{q_B>0} + T_R\mathbb{1}_{q_B\leq 0}\ . \tag{10}$$

It easy to see that $q_B \leq 0$ means that $T_R' = T_R$. For the case where $q_B > 0$ we will analyze the implication of $e_T' = 0$. By adding and subtracting e_T in (9) the control error e_T' can be rewritten to

$$e_T' = e_T - \frac{1}{2}\left(e_T + G\right)\frac{q_B}{q_F + q_B}\mathbb{1}_{q_B>0}\ , \tag{11}$$

where $G = -\frac{T_S - T_R}{2}$ as previously.

The error e_T' is analyzed under the equilibrium condition ($\dot{e}_T = 0$), where the equilibrium values for e_T are given by Lemma 1. It is easy to see that $e_T' = e_T$ when $q_B \leq 0$. In the case where $q_B > 0$ Lemma 1 means that $e_T = \frac{T_S - T_R}{2} = -G$, which shows that $e_T' = e_T$ at the equilibrium. Hence, e_T' can only equal zero when $e_T = 0$ at equilibrium.

III. Controller Design

Firstly, control using the sensor configuration T_S, T_R, and T_B is analyzed. With this configuration, the error is given by (3) and the system dynamics is given by (4). We seek to control the error to zero using a standard PI controller, meaning that the controller dynamics is given by

$$\dot{z} = e_T \tag{12a}$$
$$\omega = -k_p(e_T + \tau z)\ , \tag{12b}$$

where $k_p, \tau > 0$ are controller constants. At the equilibrium $e_T = 0$ and the bypass flow q_B equals zero. Due to mass conservation (5) and the relation between speed and flow (8) the equilibrium value for the integrator term is $\bar{z} = -\frac{1}{Kk_p\tau}q_F$. Defining the variable $\zeta = z - \bar{z}$ and combining (4), (8), and (12) leads to the following error dynamic for the closed loop system

$$\dot{\zeta} = e_T \tag{13a}$$
$$V\dot{e}_T = -|Kk_p(e_T + \tau\zeta)|e_T - GKk_p(e_T + \tau\zeta) \tag{13b}$$

Stability of the system (13) is analyzed using the Lyapunov function candidate $W = GKk_p\tau\zeta^2 + Ve_T^2$. Note that W is larger than zero at any point, where $\zeta, e_T \neq 0$ as $G, K, k_p, \tau, V > 0$. The derivative along the solutions of (13) leads to

$$\dot{W} = -|Kk_p(e_T + \tau\zeta)|e_T^2 - GKk_p e_T^2 < 0 \quad \forall e_T \neq 0\ ,$$

which shows that for any ζ and $e_T = 0$ the derivative of the Lyapunov function $\dot{W} = 0$. Then, using LaSalle's invariant principle [10], it is possible to show that the only invariant set for $\dot{W} = 0$ is when $e_T = 0$ and $\zeta = 0$, hence the closed loop system (13) is stable for any $k_p, \tau > 0$. These arguments is collected in the following lemma.

Lemma 2 *Under Assumptions 1 and 2, the sensor configuration T_S, T_R, and T_B, , with system dynamics described by* (4), (8), *and* (12), *is stable for any $k_p > 0$ and $\tau > 0$.*

Secondly, we turn our attention to the systems with the sensor configuration T_S, T_R' and T_B. The difference between this sensor configuration and the previously analyzed is that the control error is now given by (9) where the return temperature T_R' is given by (10). The flow through the bypass is considerably smaller than the primary flow in the chillers and secondary flow of the loads. Therefore, in the following analysis of the feedback structure we put the following assumption on the bypass flow

Assumption 3 *The bypass flow is small, such that $|q_B| << q_F$ where $0 < q_F$ is the forward flow, see Fig. 1.*

Again a PI controller will be used for controlling the system

$$\dot{z} = e_T' \tag{14a}$$
$$\omega = -k_p(e_T' + \tau z)\ , \tag{14b}$$

where $k_p, \tau > 0$ are controller constants. The control error e_T' is given by (11). Rearranging this error expression to

$$e_T' = \left(1 - \frac{1}{2}\frac{q_B}{q_F + q_B}\mathbb{1}_{q_B>0}\right)e_T - \frac{1}{2}G\frac{q_B}{q_F + q_B}\mathbb{1}_{q_B>0}$$

shows that for $0 \leq q_B << q_F$ then $1 - \frac{1}{2}\frac{q_B}{q_F + q_B} \approx 1$ and $\frac{q_B}{q_F + q_B} \approx \frac{q_B}{q_F}$. This means that under Assumption 3 the error e_T' simplifies to

$$e_T' = e_T + f(q_B) \quad , \quad f(q_B) = -\frac{1}{2}\frac{G}{q_F}q_B\mathbb{1}_{q_B>0}\ . \tag{15}$$

Introducing the error expression (15) in the controller output equation (14b) and solving for the deviation of the controller output around the equilibrium point $q_B = 0$ leads to the following expression for f

$$f(q_B) = h(q_B)(e_T + \tau\zeta) \ , \tag{16}$$

where

$$h(q_B) = h_0 \mathbb{1}_{q_B>0} = \frac{Kk_p \frac{1}{2}\frac{G}{q_F}}{1 - Kk_p \frac{1}{2}\frac{G}{q_F}} \mathbb{1}_{q_B>0} \ . \tag{17}$$

To obtain a closed loop model of the system we combine the bypass dynamics (4), the controller dynamics (14) around the equilibrium $q_B = 0$, and the expression (16). Using that $h(q_B) \geq 0$ for all q_B the closed loop dynamics becomes

$$\dot{\zeta} = e_T + h(e_T + \tau\zeta)$$
$$V\dot{e}_T = -Kk_p(1+h)|x|e_T - GKk_p(1+h)(e_T + \tau\zeta) \ .$$

where $x = e_T + \tau\zeta$. We use the state transformation $x = e_T + \tau\zeta$ of the integrator state ζ, which leads to

$$\dot{x} = -k_p'|x|e_T + \tau e_T - \left(Gk_p' - \tau h\right)x \tag{18a}$$

$$\dot{e}_T = -k_p'|x|e_T - Gk_p'x \ , \tag{18b}$$

where $k_p' = \frac{Kk_p}{V}(1+h)$. Stability of (18) is analyzed using the Lyapunov function candidate $W = \frac{1}{2}k_p'x^2 + \frac{1}{2}\frac{\tau}{G}e_T^2$. $W > 0$ for all $x, e_T \neq 0$ as $k_p' > 0$ for all q_B and $\tau, G > 0$. The derivative of W along the solution to (18) is given by

$$\dot{W} = -k_p'\left(Gk_p' - \tau h\right)x^2 - k_p'\frac{\tau}{G}|x|e_T^2 - {k_p'}^2|x|xe_T \ . \tag{19}$$

Here it is used that the function $h(q_B)$ can be written as

$$h(x) = \int_{-\infty}^{x} h_0 \delta_{\xi=0} d\xi \ , \tag{20}$$

where h_0 is given by (17) and $\delta_{x=y}$ is the Dirac delta function. From (20) it is easy to verify that $\dot{k'}_p x^2 = \frac{Kk_p}{V}h_0\delta_{q_B=0}x^2 = 0$ for all x as $q_B = k_p'x$. It is clear that the system is stable for all level curves given by

$$x = \sqrt{2}\frac{R}{\sqrt{k_p'}}\cos(\theta) \quad , \quad e_T = \sqrt{2}\frac{R}{\sqrt{\tau/G}}\sin(\theta) \tag{21}$$

where $\dot{W} < 0$ on the curve. From (19) $\dot{W} < 0$ for all x, e fulfilling

$$\frac{\tau}{G}e_T^2 + k_p'xe_T + \left(Gk_p' - \tau h\right)|x| > 0 \ . \tag{22}$$

As $\frac{\tau}{G} > 0$, it is clear that for $Gk_p' - \tau h > 0$, the inequality (22) is fulfilled for $|e| < \bar{e}$. Hence there exist a small enough radius R of the level curves (21), such that (22) is fulfilled on the level curve. Therefore, there exist a neighborhood around the equilibrium where the system is stable.

In Fig. 2, the curve formed by $\dot{W} = 0$ (yellow lines) together with the level curves of the Lyapunov function candidate (blue and red curve lines) in a vector field plot are shown. The parameters used for the plot are $k_p = 0.1$, $\tau = 1$, $G = 2.5$, $V = 0.01$, $K = 1$, and $q_F = 60$. The level curves which does not intersects with the curves $\dot{W} = 0$ are stable level curves, hence the region formed by the interior of level curve depicted by the red curve is the region of stability proved by the Lyapunov function candidate. We summarize the result in the following lemma.

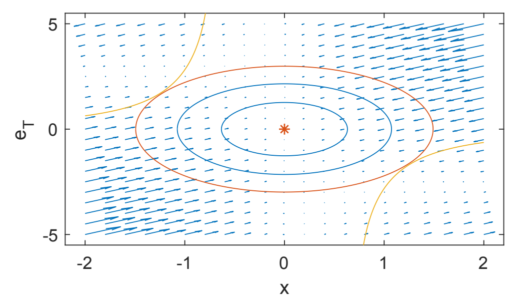

Fig. 2. Velocity plot with level curves of the Lyapunov function candidate for the transformed system and the stability boundaries calculated by $\dot{W} = 0$.

Lemma 3 *Under Assumptions 1, 2, and 3, the sensor configuration T_S, T_R', and T_B, with system dynamics described by* (4), (8), (11), *and* (14), *is stable in a region around the equilibrium formed by $x, e_T = 0$ for any $k_p > 0$ and $\tau < \frac{GKk_p}{Vh_0}$.*

IV. In-system Calibration

In practices the temperatures T_S, T_R (T_R'), and T_B are measured with imperfect sensors, leading to sensor readings θ_S, θ_R (θ_R'), and θ_B, respectively. From Lemma 1 the control error (3) will be bounded between $-G = \frac{T_S - T_R}{2}$ and $G = -\frac{T_S - T_R}{2}$ independent on the flow q_B. That is, after the effect of the initial bypass temperature is eliminated. Evaluating the controller errors (3) and (9), it is easily seen that the individual magnitudes of the sensor reading errors of θ_S, θ_R (θ_R'), and θ_B must be smaller than $\frac{T_R - T_S}{4}$ to ensure that the system works.

To improve robustness even further while allowing the use of low-grade sensors and enable improved energy metering, in-system sensor calibration is proposed. A periodic in-system calibration will besides eliminating the inherent sensor inaccuracies, also compensate for effects caused by installation, system controller inaccuracies and long-term drifting. Effects that are not taken into account with the use of costly factory calibrated sensors.

From Lemma 1, it is clear that for $q_B > 0$, $T_B = T_S$ and for $q_B < 0$ $T_B = T_R$ after a transient phase. Thus, a matching of offsets in a sensor pair can be performed when a given bypass flow direction is present and known. As the matching will be done during regular system operation and periodically, the proposed algorithm manipulates the feedback signal to the controller in order to force either a positive or negative q_B.

The manipulation is done by adding an offset $\delta\theta$ to the measured supply temperature θ_S, such that $\dot{\delta\theta} = c$, where

c controls the speed and sign of the ramp. The ramp speed is chosen slow enough for the controller to be able to track the change. The required magnitude of the injected offset is related to the system $\Delta T = T_R - T_S$ and sensor inaccuracy. Evaluating the feedback error (3) with the sensor offset

$$e_T = \frac{\theta_S + \delta\theta + \theta_R}{2} - \theta_B \tag{23}$$

and using that according to Lemma 1 $T_R \leq T_B \leq T_S$, implies that eventually the control error e_T will differ from 0. Here, it is used that saturation of T_B implies saturation in θ_B. The flow direction can be determined by looking at the imperfect temperature feedback. Define ϵ_S, ϵ_R, and ϵ_B as sensor offsets, such that $\theta_S = T_S + \epsilon_S$, $\theta_R = T_R + \epsilon_R$, and $\theta_B = T_B + \epsilon_B$. Then the relation between the control error (23) and the flow direction is

$$e_T > 0|_{q_B<0} \quad , \quad e_T < 0|_{q_B>0} \ , \tag{24}$$

while clearly e_T must be impacted by the increasing magnitude of the offset $\delta\theta$

$$\left.\frac{de_T}{dt} > 0\right|_{\dot{\delta\theta}>0} \quad , \quad \left.\frac{de_T}{dt} < 0\right|_{\dot{\delta\theta}<0} \ . \tag{25}$$

When the two statements (24) and (25) hold true the bypass flow direction q_B is known and calibration values can be derived. We define calibration values $\theta_{S_{cal}}$ and $\theta_{R_{cal}}$ given by

$$\theta_{S_{cal}} = (\theta_B - \theta_S)|_{q_B>0} \, , \theta_{R_{cal}} = (\theta_B - \theta_R)|_{q_B<0} \ ,$$

meaning that

$$\theta_{S_{cal}} = \epsilon_B - \epsilon_S \quad , \quad \theta_{R_{cal}} = \epsilon_B - \epsilon_R \ . \tag{26}$$

The resulting compensated feedback is then

$$e_T = \frac{(\theta_S + \theta_{S_{cal}}) + (\theta_R + \theta_{R_{cal}})}{2} - \theta_B$$

To verify the effect of the matching with $\delta\theta = 0$, the control error with sensor offset and calibration values $\theta_{S_{cal}}$ and $\theta_{R_{cal}}$ is calculated

$$\begin{aligned} e_T &= \frac{(T_S + \epsilon_S + \theta_{S_{cal}}) + (T_R + \epsilon_R + \theta_{R_{cal}})}{2} - T_B - \epsilon_B \\ &= \frac{T_S + T_R}{2} - T_B \ , \end{aligned}$$

and thus the true T_B must be $\frac{T_S + T_R}{2}$. Hence, the control setup is exactly the same as analyzed in Section III.

Evaluating $\Delta\theta$ with the compensation active, reveals that the measured $\Delta\theta = \theta_R + \theta_{R_{cal}} - \theta_S - \theta_{S_{cal}}$ obtained using the matched sensor feedback is given by

$$\Delta\theta = T_R + \epsilon_R + \theta_{R_{cal}} - T_S - \epsilon_S - \theta_{S_{cal}} = T_R - T_S \ .$$

Thus, true ΔT reading is achieved. Using sensor T'_R instead of T_R provides the chiller ΔT, which together with the chiller flow q_S is often used for energy metering. However, $T_R = T'_R$ when $q_B = 0$, which is the outcome of the proposed control. Therefore, as long as q_S is higher than the minimum flow requirement of the chiller, ΔT can also be obtained with the sensor configuration T_S, T_R and T_B.

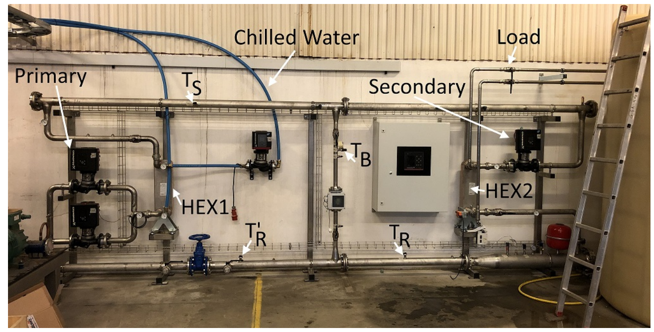

Fig. 3. The laboratory set-up used for testing the proposed feedback method and sensor matching algorithm.

The above described matching approach can as well be used for matching the sensor configuration with sensor readings θ_S, θ'_R, and θ_B. Hence, both the control robustness and sensor matching is obtainable with both sensor configurations analyzed in this paper.

V. Test Results

The proposed control and sensor matching algorithm is verified on the laboratory setup shown in Fig. 3. The system is feed with chilled water from a compressor running hysteresis control with a set-point of $10°C$ and $\pm 0.5°C$ hysteresis. A pump running at constant speed feeds the heat exchanger *HEX1* with chilled water and thereby emulating the evaporator of a chiller. The primary side pumps are subject to the developed control approach. The secondary side pump provides a flow of chilled water to remove energy from the heat exchanger *HEX2*. The secondary side pump and the HEX2 emulates the secondary side of the Primary/Secondary topology. *HEX2* receives water at $\approx 20°C$ from the building, the system is pressurized at 2 bar and the secondary flow is varied with a sinusoidal load-profile with a period of 1-hour.

The in-system calibration and the controller is tested in two situations. The results of these tests are shown in Figs. 4 and 5. In both figures, the first plot presents the actual ΔT and the measured $\Delta\theta$ and the second plot presents the flow in the bypass q_B together with the temperature offset $\delta\theta$ used for the sensor calibration. As discussed in Section II generally, it is desirable to know the primary side ΔT both for energy metering and performance optimization. Therefore, the temperature T'_R instead of T_R is used in the tests, meaning that the sensor matching calibrates the primary side ΔT.

The objective is to keep the bypass flow at zero by matching primary and secondary flows to maximize heat transfer. The controller accomplishes this despite offsets on the sensors within some bound G defined in Lemma 1. This is evident from Fig. 4, where offsets on sensors readings θ_S, θ'_R and θ_B are introduced. Here the offset does not exceed the bound defined by G, which means that the offset does not impact the control. This results in the system keeping $q_B = 0$ in the time frame 0 to 0.5 h. Between time 0.5 to 2.1 h the in-line sensor calibration is executed by manipulating $\delta\theta$. Decreasing $\delta\theta$ eventually causes the required positive bypass

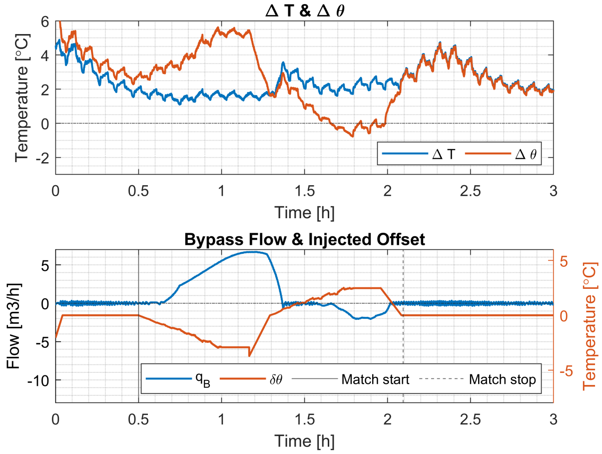

Fig. 4. Sensor matching with offsets $\epsilon_S = 0.25°C$, $\epsilon'_R = 0.5$ and $\epsilon_B = 0.5°C$ on sensors readings θ_S, θ'_R and θ_B respectively.

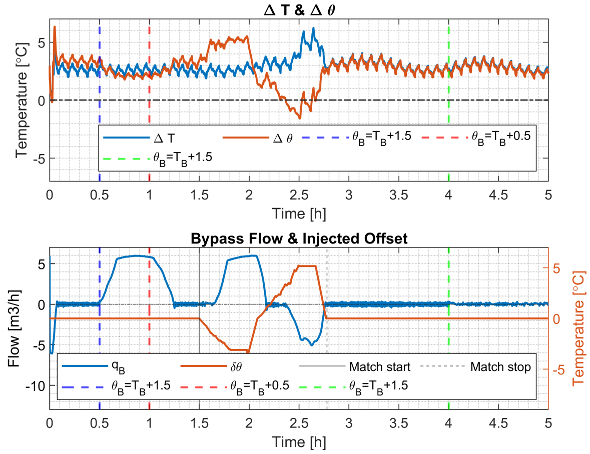

Fig. 5. Sensor matching with offsets $\epsilon_S = 0.25°C$, $\epsilon'_R = 0.5$ and $\epsilon_B = 0.5°C$ on sensors readings θ_S, θ'_R and θ_B respectively. An additional offset is imposed on θ_B prior and post matching.

flow q_B for matching θ_S/θ_B. This is seen between time 0.5 and 1.2 h. After the matching of θ_S/θ_B the procedure for matching θ_R/θ_B is executed. This leads to a negative bypass flow between time 1.7 to 2.0 h. The calibration leads to equivalent ΔT and $\Delta\theta$ after time 2.1 h. The bypass flow is as expected controlled to 0 after the calibration.

The results of the second test is shown in Fig. 5. Here, the offsets on sensors θ_S, θ_B and θ'_R are the same as in test 1. An additional offset is added to the bypass sensor θ_B, which leads to a violation of the robustness boundary defined by G. This additional bypass sensor offset is added at time 0.5 h (blue dashed line), causing loss of control and a bypass flow $q_B \neq 0$. At time 1 h (red dashed line) the additional bypass sensor offset is removed, and stability is re-established. Subsequently, a sensor matching is performed. Post sensor matching the bypass sensor offset is again increased at time 4 h (green dashed line). With the match sensors the additional offsets do not push the system into instability, which is evident by the fact that $q_B = 0$ also after time 4 h.

VI. Conclusion

This paper presents an alternative approach to control the bypass flow by chiller pumps. The optimal operation is obtained when the bypass flow equals zero. The proposed controller ensures this by using only temperature sensors, leading to a considerably less expensive solution compared to solutions that use flow sensors. The temperature differences in chilled water systems are low, meaning that slight offsets on the sensor readings can lead to reduced control performance. Therefore, an online calibration routine is developed. This online calibration not only increase robustness of the control but also makes energy metering possible with low-grade temperature sensors.

Further work includes extending the stability analysis of the sensor configuration T_S, T'_R, and T_B. Moreover, in practical systems the flow trough the chillers must be maintained above a certain threshold level. Implementing these constraints into the control is also part of the further work on the application.

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