Heat flow metering in building practice - A critical field study for a large industrial building complex

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Abstract. Increasingly complex concepts for the heating and cooling supply of buildings require both intelligent and transparent operational management strategies. One way of sequencing and coordinating different generator components is to include information about heat flows on the consumption side. In addition to heat meters, modern pumps also provide heat flow detection. The present study compares the heat flow detection via heat meters and pumps for multiple hydraulic circuits in the operating phase of a large industrial demonstration object. In particular, the influence of typical errors in the installation of the temperature measurement and their elimination are quantified.

1. Introduction
The energy transition in buildings is changing the design of systems for heating and cooling. On the supply side, the implementation of renewable energy sources often leads to multivalent systems with different temperature levels (e.g. solar heat, heat pumps, cogeneration). On the consumer side, the growing awareness of building owners and operators for comfort requirements lead to more complex HVAC-systems.

In a typical system, supply and consumer side are decoupled by tanks or other hydraulic components such as hydraulic switches. Generators are usually activated by the superior building automation system (BAS) based one or more temperature measurements in a buffer tank. Once activated, generators are controlled by internal loops e.g. to provide constant outlet temperatures. In case of multiple generators, sensors in different heights of a tank may be used to realize a sequential activation with increasing load. However, by decoupling the control of generation and consumer end, mapping of a suitable generator to a certain load level on a certain temperature level is not straightforward. A possible solution is to involve information about the thermal load in the control of the supply side [1]. Figure 1 drafts two possible use cases: a) Some heat generators like combined heat and power (CHP) units (“gen_1”) have a minimum output power under which they operate in unfavorable modes. With information from the load side (“cons_1/2”) these units can be blocked from the generator cascade. b) Distributed generators (“gen_1” and “gen_3”) can be operated more intelligent with information about the operating grade and load. To establish such concepts, heat metering on the consumer end in an adequate spatial resolution is necessary. Today, in many buildings, only information about final energy consumption of gas and electricity is available. Without detailed heat meter infrastructure, modern pumps with heat metering functionality may close this information gap, since pumps...
are part of many hydraulic subsystems anyway. In existing installations, substituting pumps to high energy efficiency models might offer new control options.

The heat flow $\dot{Q}$ is defined as $\dot{Q} = \dot{m} \cdot c \cdot \Delta T$ with the mass flow $\dot{m}$, the specific heat capacity of fluid $c$ and the temperature difference between supply and return flow $\Delta T$. Normative basis for heat metering [2, 3]. While heat meters are subject to these standards and, unlike the pump, provide a calibrated value, for pumps, heat flow measurement is an additional feature. Due to three measured input variables and the calculation of sensor signal differences heat metering is sensitive to the accuracy and the errors of both measurement and installation. A comprehensive overview of errors in practical installation is given in [4, 5]. Practical guidance is provided in [6].

To assess the quality of heat metering for control strategies the present study evaluates temperature and flow measurements and the resulting power and energy by heat meters and pumps in a large scale comparative field study. In contrast to measurements on the test bench under laboratory conditions this includes on-site effects. Since from experience the quality of the implementation is lacking in many practical installations two careful on-site inspections during commissioning have been carried out. Their effects are evaluated separately.

The study is based on the 2020 realized factory and an office building of the pump manufacturer wilo aiming towards a “zero emission campus”. The supply and demand side of the heat and cold system are largely equipped with heat meters and pumps with a heat metering functionality.

2. Methodology
In this section, the hydraulic systems evaluated and measurement devices are presented.

2.1. Hydraulic systems
The hydraulic system in the demonstration object can be divided into 104 circuits on the heating side whereof 74 are selected for this study and 43 circuits on the cooling side which are not included since there are no sufficient data yet. Depending on the type of connected load or generator the circuits are mixed or unmixed (Figure 2). The pipe diameter varies between 15 and 200 mm. Temperature levels vary between 70 and 90 °C in supply flows and between 30 and 70 °C in return flows. In circuits with Thermally Activated Building Systems (TABS) temperatures between 20 and 30 °C are observed.

Each circuit is equipped with temperature sensors in supply and return flow to provide data for building automation (BA) and visualization (cf. Figure 2). Since the primary goal of the research project is a detailed energy balance the demonstration object is equipped with about 110 heat meters. In mixed circuits both temperature sensors (cf. Figure 2) and flow meters are placed in the unmixed part. Moreover, about 90 pumps with temperature measurement devices.
and heat metering functionality are installed. In mixed circuits supply temperature and flow differ between heat meters and pumps. Figure 2 depicts the existent mixed or unmixed circuit types (“T-number”) with their different implementation of sensors, meters and pumps. In the evaluation each circuit is denoted with “#number”. Depending on the device, data is recorded as Change of Value (COV) or with a fixed sampling rate. For the present study data in a 1-minute-resolution is extracted from the automation database.

2.2. Temperature measurement and on-site checks
The temperature sensors of the BAS, of the heat meters and of the pumps differ in type of sensor and wiring (cf. Figure 2). As input for the heat metering, pumps are equipped with two analog inputs for external temperature sensors. Additionally, some pumps have an integrated temperature sensor. The evaluation compares up to four different temperature measurements in a pipe sector of about 1 to 3 m. Depending on the pipe diameter temperature measurements are either implemented by direct immersion or by perpendicular thermowells. Insufficient insertion of the sensor head to the end of the thermowell is a known fault in on-site implementations [4]. Therefore, two careful on-site inspections of the professionally installed temperature sensors have been conducted to compare

a) Initial state without inspection)

b) After first inspection and revision

c) After second inspection and revision

Each data evaluation period in winter 2020/21 lasts between 1 and 3 months.

2.3. Flow metering
For flow detection two different methods are applied. While ultrasonic flow rate sensors as part of the heat meter provide a directly measured value, pumps calculate the flow based on characteristic curves of electric power input and pump speed, based on manufacturer calibration.

3. Results and discussion
3.1. Temperatures
In an initial step, relevant deviations between temperature measurements within a pipe section were observed in time series analysis. For the representation in Figure 3 mean values per device, flow direction and period are compared and sorted by range. The three states a) to c) refer to the status of revision. A band of ±0.5 K around the mid-range was defined to indicate conformity between different measures.

In the initial state a) without inspection about 10 % of the supply measurements exceeded the ±3 K limit. During the two inspections typical faults in the implementation of temperature sensors, mainly too short insertion of the temperature sensors in the thermowell but also inverted sensors between supply and return or temperature measurement in the mixed and flow detection in the unmixed part or vice versa have been found and corrected. The implementation was done by a professional service provider for the building owner, not by the university as part of the research project. By each step the temperatures are grouped closer together but even after two revisions 3 supply and 1 return measurements remain out of the ±3 K band. Figure 3 shows that, due to the influence of cable length, the Pt 100 sensors of the heat meter measure warmer temperatures than the Pt 1000 sensors of the pumps and BA. The sensors of the heat meter are supplied calibrated in pairs by the manufacturer and are not suitable for measuring absolute temperatures.

For heat metering, the temperature difference $\Delta T$ is the relevant measure, which is depicted in Figure 4 for circuit type T-1 in one plot per circuit. To provide information about both distribution and frequency, the temperature differences are plotted against each other in a kernel density estimate (KDE) plot where a darker color indicates a higher frequency in this area. The closer the colored areas run along the angle bisector the better the two $\Delta T$ match. To illustrate the effect of revisions the initial state a) is separated. After the second revision the temperature
Concerning the flow, states 3.2. Flow of pumps in circuit #05) and supply temperatures are not permanently stable. Moreover, particular circuits are not regulated properly yet (e.g. on-off-operation circuits (e.g. #04, #15, #69) are mainly operated at relatively small temperature differences around 10 K. Moreover, particular circuits are not regulated properly yet (e.g. on-off-operation of pumps in circuit #05) and supply temperatures are not permanently stable.

3.2. Flow
Concerning the flow, states a) to c) are taken into account since there have been no changes to the devices. Figure 5 shows different patterns of conformity between measured and estimated flow. While for e.g. circuits #3, #4 and #13 both measurements run along the angle bisector, #05 has a distinct offset and #14 a scattered distribution.

3.3. Power
For the resulting thermal power state again states a) and c) before and after revision is differentiated (cf. Figure 6). The influence of the more accurate temperature measurement can be clearly identified e.g. for circuits #02, #03 or #15.

3.4. Energy
Figure 7 compares the percentage deviation of registered energy between heat meter and pump for circuit types T-1 and T-7. Comparing states a) to c) it can be shown that by revising the

Figure 3. Comparison of temperature measurements as difference from mid-range [K].
temperature measurement the conformity between heat meter and pumps can be increased from 8 % to 36 % related to a ±10 % threshold.

The remaining deviations can be traced back to various reasons: 1) Differences in flow between measured and estimated, based on pump calibration curve value. This topic has to be investigated separately taking also into account the influence of calming sections. 2) Circuits with TABS are typically operated in mixed circuits with a temperature difference of just a few Kelvin. Additionally, some TABS circuits are operated with permanently running pumps and closed valves which leads to an “apparent” heat consumption due to temperatures in the measuring tolerance. 3) In one circuit leak flows are detected by the flow meter at no pump speed.
4. Conclusion and Outlook

The present study provides an overview over the measurement of temperature, flow, power and energy in a large scale application. By comparing multiple measurements in a pipe section, errors could be detected and revised for more reliable heat flow metering. It can be assumed that the type and extent of the defects found is representative of many other buildings where such a comparison is not possible. This underlines, firstly, the need for robust product design of cabling and sensor fixation for a precise, easy and fail-safe installation on site and secondly, checks of the implementation as part of the commissioning phase as described in e.g. [7].

Introducing heat flows for control tasks opens up more options for innovative operation strategies. However, faulty heat flow metering would disturb the supply concept and in case of a malfunction fall-back strategies to a simpler temperature based operation may be obligatory. Overall, the development of operating concepts that are as straightforward as possible and backed up with simulations should remain the top priority. Namely for the renovation case, metering with high efficiency pumps is an innovation with great potential. Future work will also include the cooling circuits as well, where the correct measuring of $\Delta T$ is even more crucial.

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