Control aspects of decentralized solar thermal integration into district heating networks

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Abstract

This paper consists of two parts. In the first part a numerical model describing the thermo hydraulic behavior of district heating (DH) networks has been used to investigate the pressure and temperature profile within a solar assisted system. The network description is based on a graph-theoretical method and the Newton algorithm was used for solving the system of nonlinear equations. A direct integration without heat storage is implemented here for an existing network topology in South Germany. The simulation shows that critical differential pressure driven operation of the district pump is not realizable with a reasonable number of pressure transmitters. The volume flow driven control provides more stability but has to be optimized by means of pressure measurements. The second part of the paper presents the new test facility built for decentralized solar heat integration. It also gives an overview about the design topics that will be investigated during the next test period: component suitability for bidirectional heat exchange, station control, net metering and handling both solar and load sides.

Keywords: decentralized solar heat integration, district heating, hydraulics control, testing

1. Introduction

District heating networks with low temperature levels offer good integration potentials for solar thermal energy. Different commercial tools have been used for design and operational optimization of DH or solarthermal energy systems.

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A commercial tool containing all component models of both subsystems, which enables dynamic simulation studies, is not available. In research, only few references about system simulations of thermal networks in combination with solar collector models were found ([1],[2]). The target of the co-simulations was to predict the solar gains with different solar system sizes. The hydraulic behavior of the network and the interaction between different head sources (pumps) has not yet been deeply discussed. In at least three of the available documents describing DH sites with decentralized solar energy feed-in, control is considered as a key reason for poor system reliability and low solar gains ([3],[4][5]).

The first part of the paper presents simulation results obtained with the program spHeat [6], which was first developed within the European project POLYCITY as part of the CONCERTO initiative for energy efficient cities [7]. It was designed to run hydraulic and thermal simulations of networks with multiple loop topologies. spHeat has been further developed to enable the integration of distributed solar thermal (ST) heat surplus into the network model. In accordance to [8] “distributed” or “decentralized” means that the solar plant is not closely located to another major heat generator like a biomass or fossil fuel fired plant. The feed-in principles described in [8] and [9] are shown in Fig. 1. The feed-in return flow is the most challenging concept from a hydraulic point of view. The additional pump has to overcome the pressure differential between both lines.

The simulation study carried out in this paper only focuses on this integration scheme. The purpose of the study is to investigate the effect of the integration on the flow control characteristic. By means of static simulations, some weaknesses of two “conventional” control ways are shown. In the second part of the paper a new test facility for heat substations is introduced. It will be used to implement the feed-in schemes discussed above, to test the suitability of different components (pumps, valves) for bidirectional heat transfer, to test control algorithms and to validate the substation model developed.

![Fig. 1 Decentralized supply principles](image)

### 2. The simulation framework

#### 2.1. Network description

The studied network is located in Sonnenberg near Stuttgart in Germany. Sonnenberg is subdivided into two quarters; Southeast and Southwest (Fig. 2). As it currently stands, construction is completed in the Southeast quarter and residences are already occupied.

The quarters’ heat demand is partially supplied by a geothermal plant located at the southern end of the quarter, with distribution via a DH network. Water is heated from 40 to 70°C. One of the measures to enhance the primary energy factor of the whole system consists of integrating renewable energy sources. In several Canadian and Swedish sites decentralized solar thermal collectors has been successfully integrated. The first monitoring results prove the system operability but the solar gains remain lower than expected. In Sonnenberg, the lack of areas to install large collector fields near the heating plant makes central solar integration difficult to realise. The decentralised principle of heat supply is considered to be more realistic.
2.2. Model development

The network description in spHeat is based on a graph-theoretical method. The main components of the graph are edges (pipes) and nodes (consumer or plant) as shown in Fig. 3. The Newton algorithm [10] was used for solving the system of nonlinear equations. The model is based on a quasi-dynamic approach, where the flow and pressure are calculated using a static flow model in the sub-program spHydro. The temperature is calculated dynamically in spThermo depending on the flow velocity and several boundary conditions like ground and ambient temperatures. The backward-difference method is implemented to solve the differential equations of heat transfer along the pipes. In spHeat the network is divided into feed and return levels. Both sub-networks are calculated separately and the resulting return temperature at each house station is determined based on an energy balance equation. The plant head elevation dictates the mass flow distribution in the network and therefore the temperature propagation. In the case of decentralised integration, supplementary head elevations from return to supply influence the flow direction and have to be taken into account. The separation of the network into its two levels is not suitable.
\[ \Delta \rho = k_v \dot{V}^m + k_x \dot{V}^n \quad (1) \]

with the flow dependent coefficient \( k_v \) of heat exchanger, the valve travel dependent coefficient \( k_x \) and the corresponding exponents \( m \) and \( n \). In the case of feed-in return flow eq.1 is replaced by eq.2 describing the head elevation through the pump shown in Fig. 1:

\[ \Delta \rho = \Delta \rho \cdot \rho h . \quad (2) \]

![Fig. 4 Merging feed and return sub-networks (a substation model corresponds to each two nodes)](image)

3. The simulation study

In DH networks hot water is pumped by variable speed pumps to the different stations. Open loop control of the head elevation in the supply plant is still applied in many installations, leading to unnecessary high pressure differentials during the low demand season. The optimization potential for the pump energy consumption was shown by operating in closed loop mode [12]. Closed loop algorithms use the measured pressure differential at a critical consumer (generally the most distant) to adapt the head elevation of plant pumps.

A second -more advanced- closed loop algorithm uses the plant’s pressure differential as control variable. In this case the total volume flow is feed-forwarded to the pump drive. The required head elevation is calculated in a way to approximate the supply characteristic curve (see [13]):

\[ \Delta \rho = f(\dot{V}) \quad (3) \]

the curve which theoretically guarantees a minimum \( \Delta \rho \) at the critical consumer. Costs for sensor maintenance and signal transmission can be avoided. The influence of decentralized heat integration on these two closed loop operation modes is discussed on the basis of static hydraulic calculations of the network in Sonnenberg. For this study a constant size has been assumed for all substations. Fig. 5 shows the pressure differential between feed and return lines along the network. The same course is also represented in Fig. 6. The critical consumer C56 at the left bottom side of the figure has the minimum value of 0,5bar around its heat exchanger and fully opened valve.
Assuming that consumer C56 has heat surplus to be feed-in with a constant volume flow of 3l/s, the critical station moves to node C50. Keeping the same pump frequency leads to unnecessary high pressures (blue continuous curve in Fig. 6). If the pressure differential of node C50 is then used as control variable, the plant pump frequency is reduced to match the minimum value of 0.5bar at this node (red dot). This may lead to insufficiently supplied stations (red curve). The critical consumer changes its location dependant on a) the feed-in point and b) the demand of all other consumers. Pressure differential driven control with a reasonable number of pressure transmitters doesn’t guarantee a satisfying/safe operation.

By varying the consumer valves’ travel (i.e. the demand volume flow) and adapting the central head elevation the supply characteristic curve of Sonnenberg can be determined in spHeat (continuous blue curve in Fig. 7). The pressure drop caused by the supplying unit (heat exchanger, storage tank, valves etc.) is not considered. A second order polynomial approximation of this curve may be used in the second closed loop control method to determine the necessary head elevation:

\[ \Delta p = a \cdot V^2 + b \]  

(4)
Where \( a \) and \( b \) are discussed in [14]. Assuming solar heat integration in the same node C56 and following the characteristic curve (w/o integration) also leads to unnecessary high pressures as shown in Fig. 8. The head level increases for almost all nodes through the decentralised integration.

![Fig. 7 The central pump characteristic curve](image1)

Fig. 7 The central pump characteristic curve

Fig. 7 also shows the supply characteristic curves obtained in spHeat for two different integration points (dashed for node C56 and dotted for node C23 in the middle top side of the network). In both cases a constant feed-in flow rate of approx. 3l/s has been applied. To minimise the consumption of the major pump, a slightly ‘adapted’ characteristic curve should be applied.

![Fig. 8 The critical nodal differential pressure](image2)

Fig. 8 The critical nodal differential pressure

The same full line characteristic curve of Fig. 7 is shown in Fig. 9 (dpp 0bar) together with other characteristic curves obtained under different head elevations in the integration node 56. For integration in this node an extension of eq. 4 by \( c \) fulfills the requirement of minimum pressure differential at the critical node:

\[
\Delta p = a \cdot V^2 + b + c
\]

A value of -0.15bar was determined for \( c \) if solar heat is integrated in node C56. In the flow range of 10 to 20l/s the adaptation of eq. 4 into eq. 5 would lead to pump energy savings between 5 and 12%. Several simulations were...
performed to investigate the dependency of $c$ on the integration position (and on other parameters). Due to the nonlinear nature of the hydraulic system, no linear relationship could be found. Therefore tuning the curve parameters for existing integration nodes has to be performed in a practical way by varying the solar feed-in flow and reducing the head elevation to its required minimum value.

4. The test bench

4.1. The general layout

The test facility shown in Fig. 10 has already been built as part of a running EnEff:Wärme project. It was designed to develop and test heat substations under different operational conditions (differential pressure and feed temperature). The facility comprises two parts: one heated circuit which is connected to the large storage tank and one secondary circuit below the first part to simulate the consumer behavior.

The first part of the rig has been already built to emulate a small heating network with six connections. The connections allow the realization of several pipe loops as shown in Fig. 3. Hot water is heated up electrically and stored in the buffer tank. The estimated storage heat capacity is 35kWh. The differential pressure between return and supply line is maintained by a circulation pump with PI-controlled speed. Both discussed closed loop control algorithms of chapter 3 can be implemented in the current setup. The final hot water temperature is controlled by a PI-controlled 3-way mixing valve (on the left of the storage top side). The pipe pressure losses shown using the color
map in Fig. 5 are simulated through different valves along the supply and return line. In accordance to the network presentation in Fig. 5, the critical node is here simplified to a controllable valve (at the left end of Fig. 10).

The test object(s) can be connected close to measurement point for critical differential pressure or even closer to the pump. The cooling of the test objects is provided by a separate sub-network, which is cooled by a fan coil. Differential pressure up to 3.0bar and supply temperatures up to 100°C can be reached. The test rig is designed for small stations with up to 50kW transfer capacity and the expected flow rate does not exceed 4m³/h. First measurements were performed to compare different flow sensor technologies (as shown in Fig. 11) and to tune simple P-controllers.

![Fig. 11 Flow measurements with Vortex versus Ultrasonic (Reference) sensor](image)

4.2. The test topics

As mentioned in the introduction, the feed-in return flow principle is challenging from a hydraulic point of view. In the few works [2] found about this kind of integration, such as [2], the hydraulic aspect remains unexplored. Detailed measurements of installed substations have not been published yet. A setup of the first substation being designed to feed-in solar heated water into the network is shown in the right side of Fig. 10. The station is equipped with a transmitter for bidirectional flow and several control valves. The main topics for the test phase can be summarized in the following points:

- Which components are suitable for bidirectional heat exchange?
- How can the needed effort to feed-in surplus heat in DH networks be quantified?
- Under which operational conditions can decentralized heat integration be economic?
- Which feed-in principle is suitable under which operational conditions?

Furthermore control algorithms to overcome fast flow and temperature changes from solar side in direct integration circuits will be implemented. Cascade control and feed-forward of the solar side temperature are some of the planned schemes.

Heat metering also presents an important topic. Current costs for a bidirectional solution amount to around 2000€ with ultrasonic transmitters. The accuracy of valve bridges in combination with flow meters will be investigated (Fig. 12). Also constant flow valves for use in the feed-in direction will be considered. The strategy to adjust own load and surplus heat is also one of the key issues in decentralised solar heat integration. The integration of this kind of strategies in the supply management of the whole DH system will be addressed.
5. Conclusions

The extension of the district heating analysis tool spHeat is described in this paper. The separated models for supply and return sub-networks have been merged into one model. The integration of head sources became easier. First static calculations show that critical differential pressure driven operation of the district pump is much more difficult in the case of return→feed heat integration. For flow rate driven control and in a network with several integration candidates a trade-off between pump energy savings and curve tuning efforts has to be made. The shape of the optimal characteristic curve has to be determined separately for each integration node. The planned test rig for bidirectional heat transfer stations is presented. The first phase of the installation has been completed and the main development topics are discussed in the paper.

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References


