OPERATIONAL OPTIMIZATION IN DISTRICT HEATING SYSTEMS USING THERMAL INERTIA OF BUILDINGS

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Summary. Evolution of energy market and development of IT result in new challenges for operational optimization in modern district heating networks. Among the solutions which can help in such optimization, thermal load shifting with the use of inertia of buildings has been identified as one which requires additional research. Two mathematical models for simulation of transient behavior of buildings connected to DH systems have been described, and the more simplified model has been validated by comparing results.

The simplified model for simulation of building’s behavior can be used in global operational optimization of DH systems, and the methodology demonstrated in this article can help DH operators in assessing, what kind of power limitation can be used under certain conditions for a group of buildings with certain properties, in order not to affect the comfort of the customers nor make significant errors in simulation. The results can prove useful for DH system operators in the near future.

1. INTRODUCTION

The aim of this paper is to discuss the topic of operational optimization in District Heating (DH) systems, identify new challenges which arose in this subject and outline possible solutions. The focus is on hot water DH networks, as this technology is much more popular than steam DH, and its modeling as well as flexibility potential are different.

District heating is a mature technology, and most of its problems have been solved over the years by standardized solutions which in turn became popular all around the world. Preinsulated pipelines are a good example of this trend – once developed in Scandinavia, currently the same technology is found in the networks in Poland, Italy, Russia, China and USA.

There are also significant similarities between DH networks in terms of control and operation. Years of experience have lead the operators to a conclusion that the most profitable way of heat distribution is decreasing the heat losses by lowering the supply temperature as much as possible, but without the risk of breaking hydraulic constraints on pressures and flows. In the large modern networks, it is achieved by setting the temperature of supply according to outdoor temperature (with the use of a “regulation table” or “heating curve”) and then controlling the pressures and flows in the network with the use of pumps located both at the heat source and in the crucial parts of distribution grid. That approach is a result of several assumptions and constraints which have been treated as certain for years, such as:
– stable price and accessibility of fuels
– stable price of electricity produced by Combined Heat and Power (CHP) plants
– simple priorities regarding the tradeoffs: always better to produce as much electricity in cogeneration as possible, always better to minimize heat losses by maximizing the flow rather than minimize pumping cost by increasing the temperature of supply

Under aforementioned assumptions, it was never needed to utilize some inertia of the system for moving the production in time – unless in case of very high peaks of the demand, when power increase meant switching to different fuels or decreasing the cogeneration factor; but such situations are rare and in fact quite difficult to cope with (very high peaks of the demand usually occur after longer periods of high demand, so it might not be possible to accumulate energy shortly before). On top of that, poor computational capacity of IT hardware, rare readings of heat meters and low penetration of telemetry devices made more sophisticated analyses of network’s transient behavior impossible almost until the end of XXth century.

In recent years the situation has dramatically changed – both in terms of technical possibilities and needs or business drivers. Sophisticated hydraulic and thermal models of the grids, remote control of pumping stations or valves, and telemetric systems providing thousands of measurements almost in real time are now a standard in large DH networks all around the world – including old systems in Polish cities.

What is more important, a strong need for flexibility and dynamic scheduling of production has emerged. It is to a huge extent a result of rapidly changing situation on electricity market and fuel market.

The prices and availability of different fuels are much more dynamic than in the past, and the environmental regulations have become difficult to predict, so many heat producers try to diversify their fuel mix and use distributed or renewable energy sources. It makes the models based on centralized heat production and replicable hydraulic situation in the grid useless. Each production unit could have different limits in terms of DH water temperatures, available power at given moment etc., and its input to the grid changes the hydraulic situation. Simple pumping strategies based on keeping the pressure difference at “critical substation” and copying the approach used previously at the same outdoor temperature are no longer valid when multiple heat sources are connected to the network.

Even more significant impulse for changes comes to most DH systems from electricity market. Massive use of intermittent sources, rapid changes in demand and new market models result in a totally new approach to the value of electricity. For example on Polish Power Exchange, where a large share of energy produced by CHP plants is traded, the price of MWh changes every hour, with daily variations of 50 % and more.
Illustrative example of this situation is shown in Fig. 1. Even larger variations of electricity value should be considered for producers who offer ancillary services to the Transmission System Operator.

![Profile of electricity price on Polish Power Exchange](source: POLPX)

The same amount of electricity (which corresponds in general to the same cost of fuel, labor etc.) brings to the CHP plant owner completely different benefit, depending on the time when it was fed into the grid. As no feasible way of electricity storage is widely known, an obvious conclusion for every CHP operator trading electricity at variable prices, is to optimize production by shifting in time the heat delivery. The average cogeneration factor is no longer the most important KPI, if sometimes the price of electricity drops below the price of heat, and on some other times the electricity is so valuable that even production in pseudo-condensation mode becomes extremely beneficial. All the circumstances described so far lead to one important conclusion: the operation of DH systems, especially those fed by CHP plants, should be dynamically optimized on a daily basis, with a special focus on flexibilities enabling heat load shifting. Such optimization is possible due to progress in IT and telecommunication, and can bring a huge change in benefits due to the situation on fuel and electricity market.

2. CURRENT STATE OF RESEARCH

There are many remarkable works dedicated to the topic in question, including case studies and experiments. Mateusz Słupiński [1] has described the process of production scheduling for a CHP plant, with a strong focus on changing prices of electricity, using the German dedicated software BoFiT.

The advantage of using such commercial solutions is ease of use and high reliability, but the models implemented in BoFiT are not designed for hydraulic calculations, and do not include all the flexibilities available in a real grid. Pengfei Jie, Neng Zhu and Deying Li [2] presented
their own algorithm in MATLAB, created for operational optimization in one existing DH network with the use of four different strategies. Significant potential for savings in an existing Chinese network has been demonstrated. Linn Sarinen [3] also performed a case study on an existing DH network (Nyköping, Sweden) with the use of a dynamic model created in MATLAB. Benonysson et al [4] have proposed a model for finding an improved profile of supply temperature in order to use the thermal inertia of the DH network for peak shaving. Their work presents promising results in case of a small network with one heat source. Similar work has been made in Modelica software environment by Daniele Basciotti, Florian Judex, Olivier Pol and Ralf-Roman Schmidt [5]. There are many works [6, 7] dedicated to thermal energy storage tanks and modeling of their operation. Bujalski [8] has created a model for finding optimal schedule of operation for a CHP plant containing many different production units, equipped with a storage tank. The solution has been successfully tested in a very large existing CHP plant. A. Campos Celador, M. Odriozola and J.M. Sala [9] have studied the influence of the way in which hot water tanks are modeled, on the results of long-term simulation of operation of a CHP plant. Their work provides a good outlook on three types of approach to modeling the hot water tanks in DH. Sergio Rech, Andrea Toffolo and Andrea Lazzaretto [10] described a non-linear model of CHP plant with thermal energy storage tanks operating at variable temperature, which included investment costs in the long-term optimization.

Each of the aforementioned works contributes to the research in operational optimization of DH by providing and demonstrating partial solutions. Some works focus on thermal energy storage in the grid, others on hot water tanks or utilizing the thermal inertia of buildings. Some algorithms use the electricity prices as main input, other serve only avoiding the use of peak boilers. No holistic study, taking into account all three ways of heat storage, pumping optimization, management of the risk of failures and uncertainties of demand forecasting, is known to the author. This is probably because of very high complexity of the problem, and because most DH operators as well as heat consumers are used to traditional operation modes. Introduction of one heat storage technique (which is usually a hot water tank) stops some operators from thinking about parallel use of other techniques. Some innovative ideas (for example utilizing the thermal inertia of buildings) are not explored due to legal regulations (for example controlled tariffs for end users in Poland, which do not allow setting variable prices of heat depending on time of the day). The objective of current study is to make a step towards global optimization with the use of all available flexibilities, by focusing on buildings – as one of elements that has been explored less than the others so far.

3. EQUATIONS GOVERNING THE OPERATION OF DH SYSTEMS

A DH system comprises heat sources, pipelines, pumping stations, storage tanks, valves and buildings with their substations. There are already comprehensive models and commercial solutions for simulation of operation of CHP plants, pumping stations and distribution networks. A lot can be done in order to unite them and make necessary simplifications in a
way allowing for global optimization of DH systems. However, the equations which should be used (describing the hydraulic and thermodynamical relationships) are well known and have been described in works such as [11] or [12]. In this article, the focus will be on buildings and substations – which require very careful modeling, because of their large number in the system on one hand, and need to simulate transient states on the other hand.

In most district heating systems, the substations connect the buildings to the DH network via heat exchangers with automatic valves. It means that the substations consume certain heating power, depending on their needs, independently from the available pressure difference and supply temperature – of course, within a range of pressures and temperatures.

The acceptable range of pressure difference between supply and return line available at the substation results from nominal power and equipment used. Minimum pressure difference is the one at which the substation can reach desired heating power with fully open regulation valve. Maximum pressure difference is the one at which equipment can be damaged. At any pressure difference between the values mentioned, required flow (and thus heating power) can be reached by control of the regulation valve.

There is also a temperature range acceptable for the substations to work properly. In general, the minimal accepted supply temperature is that at which the heat exchanger in the substation meets its required heat load, utilizing the maximum flow of district heating water (that means fully open valve). If the district heating water temperature is higher than the minimal value, or the heat load at the substation is lower than nominal, the flow of district heating water through the heat exchanger is throttled by an automatic valve. Thus, modern substations operate properly with any supply water temperature higher than a given minimal value and lower than the maximal value chosen due to some security or material reasons.

Normally the heating power will be set adjusted to keep the desired indoor temperature in the building. However, there can be situations when heating power is limited for a certain period of time (which means cooling down the building), and then increased again (to reheat it). Such situations are especially interesting for optimization, and will be discussed in details.

4. MATHEMATICAL MODEL OF THERMAL INERTIA OF THE BUILDING

The heat balance of each building can be written as:

\[
\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} = C \frac{dT_{\text{in}}}{dt} \quad (1)
\]

If the sum of heat delivered to the building is higher than the sum of heat lost from the building (at a given moment), its internal temperature increases, in the opposite case it
decreases. The heat lost from the building is mainly the sum of heat conducted to the surrounding air through the walls, windows, roof etc., heat conducted through the foundation to the ground and heat required to increase the temperature of fresh air coming to the house (which replaces warm air leaving the house through ventilation system). Assuming that the temperature inside the building is uniform in all its volume, sum of heat lost from the building at a given moment can be written as:

\[ \dot{Q}_{out} = \dot{Q}_{\text{cond}, \text{air}} + \dot{Q}_{\text{cond}, \text{ground}} + \dot{Q}_{\text{ventilation}} \]

\[ \dot{Q}_{out} = U_{\text{walls etc.}} \cdot (T_{in} - T_{out}) + U_{\text{foundation}} \cdot (T_{in} - T_{ground}) + \dot{m}_{\text{vent}} \cdot c_p \cdot (T_{in} - T_{out}) \]

(2)

For simplicity, it can be assumed that the temperature difference between the building and the ground is proportional to the temperature difference between the building and the surrounding air. The reality is more complicated, but as it is very difficult to model the changes of the temperature during the year, and in the end heat lost to the ground is not a very significant share of total heat loss, such simplification is chosen. Based on new assumption, the heat lost to the ground is equal to:

\[ \dot{Q}_{\text{cond}, \text{ground}} = U_{\text{foundation}} \cdot (T_{in} - T_{ground}) = U_{\text{foundation}} \cdot \sigma \cdot (T_{in} - T_{out}) \]

\[ = \bar{U}_{\text{foundation}} \cdot (T_{in} - T_{out}) \]

And thus, (2) can be rewritten as:

\[ \dot{Q}_{out} = U_{\text{walls etc.}} \cdot (T_{in} - T_{out}) + \bar{U}_{\text{foundation}} \cdot (T_{in} - T_{out}) + \dot{m}_{\text{vent}} \cdot c_p \cdot (T_{in} - T_{out}) \]

\[ \dot{Q}_{out} = (U_{\text{walls etc.}} + \bar{U}_{\text{foundation}} + \dot{m}_{\text{vent}} \cdot c_p) \cdot (T_{in} - T_{out}) \]

(3)

In fact, all the coefficients in (3) can vary: heat loss coefficients are dependent on the temperature, wind speed etc., and mass flow of ventilation air depends on the behaviour of inhabitants or automatic controllers. However, for most buildings some average values of those numbers can be defined and treated as constants. Under this assumption, (3) becomes:

\[ \dot{Q}_{out} = U_{\text{building}} \cdot (T_{in} - T_{out}) \]

(4)

The heat coming into the building is a sum of heat from space heating installation and all other heat sources (including solar radiation, electric devices, hot water, cooking, people etc.). The solar gains can be calculated according to the rules given in [13]. As the heat input from people, electric devices etc. is intermittent and difficult to model, and in general independent from outdoor temperature, in this work it will be treated as stable
additional heating power linked to every building. Under aforementioned assumptions, (1) can be rewritten as:

$$\dot{Q}_{gains} + \dot{Q}_{SH} - U_{building} \cdot (T_{in} - T_{out}) = C \frac{dT_{in}}{dt} \tag{5}$$

If we assume that the outdoor temperature is stable in time, (5) can be rewritten as:

$$\dot{Q}_{gains} + \dot{Q}_{SH} - U_{building} \cdot \theta = C \frac{d\theta}{dt} \tag{6}$$

In a typical case, space heating is used to keep a preset indoor temperature. Based on (5), the condition for not changing the internal temperature is:

$$\dot{Q}_{gains} + \dot{Q}_{SH} - U_{building} \cdot (T_{in} - T_{out}) = 0$$
$$\dot{Q}_{SH} = U_{building} \cdot (T_{in} - T_{out}) - \dot{Q}_{gains} \tag{7}$$

However, in some cases the power of space heating installation can be lower or higher than in (7). In such cases, the temperature inside the building will vary from the present value. Solving (6) yields:

$$\theta(t) = \frac{\dot{Q}_{gains} + \dot{Q}_{SH}}{U_{building}} + k1 \cdot e^{-\frac{ut}{c}} \tag{8}$$

Coefficient $k1$ can be found by applying the equation at $t=0$:

$$\theta(t = 0) = \theta_0 \rightarrow k1 = \theta_0 - \frac{\dot{Q}_{gains} + \dot{Q}_{SH}}{U_{building}}$$
$$\theta(t) = \frac{\dot{Q}_{gains} + \dot{Q}_{SH}}{U_{building}} + \left(\theta_0 - \frac{\dot{Q}_{gains} + \dot{Q}_{SH}}{U_{building}}\right) \cdot e^{-\frac{ut}{c}} \tag{9}$$

From (9) it can be seen, that in general the temperature difference between the building and its surroundings tends to reach the value at which the sum of heat input is equal to heat loss. The pace of temperature changes is described by an exponential function, containing with a coefficient dependent on the difference between current indoor temperature and indoor temperature in steady state, and a time constant typical for a given building, the same in every conditions. In order to properly simulate the transient behaviour of a building under aforementioned assumptions, its time constant must be known.
Time constants of buildings vary depending on the materials and construction. They can reach from 10 hours to 200 hours and more [14].

When space heating is switched off and there are no heat gains, after one time constant the temperature difference between the building and its surrounding drops by approximately 63%. After 5% of the time constant, it drops by approximately 5% (about 1°C in moderate winter), which can be acceptable for some residential houses. Heat gains from solar radiation, electric appliances in the building and people make the process of decreasing temperature even slower. The limitation of heating, rather than switching it off, is also a solution for using the thermal inertia of buildings without noticeable change in thermal comfort of residents. If coordinated heating power limitation in many buildings is possible, and if proper models are used to make sure that the comfort of inhabitants is not changed (e.g. that the temperature deviation from preset value does not exceed 1°C), thermal inertia of the buildings can be efficiently used for optimization of heat production in DH.

5. UTILIZATION OF THERMAL INERTIA OF BUILDINGS

Typical case of using thermal inertia of buildings is a temporary decrease of their heating power by certain amount, and reheating afterwards. It is illustrated in Fig. 2 and can be divided into stages:

1. Balanced situation before the procedure. There is a certain temperature difference between indoor and outdoor, kept constant. The heating power of the substation is equal to the heat losses from the building and it can be forecasted based on weather data and historical measurements.

2. Using the inertia. The heating power of the substation is decreased by certain amount. The temperature difference between indoor and outdoor is slowly decreasing as the building is cooling down.

3. Reheating. The heating power limitation is stopped. The power of substations reaches maximum. The temperature difference between indoor and outdoor is slowly increasing as the building is heated back.

4. Balanced situation after the procedure. After reheating, the temperature difference between indoor and outdoor has reached the present value (typically it means that the outdoor temperature will reach the same value as at stage 1) and is kept at this level. The heating power of the substation is equal to the heat losses from the building and it can be forecasted based on weather data and historical measurements.
For a holistic model of DH system, allowing optimization, a simplification would be needed in order to simulate the thermal inertia of buildings – without knowing their parameters precisely and without using non-linear equations. In the next section, a simple model is proposed and its results are compared to the exact results calculated from the model described before (containing non-linear equations and basing on several parameters describing the building).

6. SIMPLIFIED MODEL

In many cases the DH operator does not know time constants nor heat loss coefficients of all the buildings. He can use only a forecast of heat demand (based on historical measurements from telemetry, available in many modern DH systems, and the share of space heating in total heating power (depending on domestic hot water needs which can be determined based on heat consumption during summer). Moreover, such forecast (and estimation of space heating share) can be done for a group of buildings at once – but they do not necessarily have the same time constants and heat loss coefficients. For simple simulations, a model using only forecasted heating power is needed. The easiest answer is to assume that total amount of energy consumed by the building during the procedure remains unchanged. It corresponds to a situation in which blue area and orange area in Fig. 2 are equal. It is valid for very small changes in indoor temperature (which means that the total amount of heat losses during the procedure, equal to total energy which needs to be delivered, remains the same in the scenario with and without power limitation). With such assumptions, whole procedure can be applied for simulations of each buildings behaviour or even group of buildings, also with different and unknown properties – as long as their predicted heat load and maximum power are known. The formulas for heating power become:
The time of end of reheating can be determined from the equation:

\[
\dot{Q}(t) = \dot{Q}_{predicted}(t) \text{ for } t < t_{\text{start of limitation}} \text{ and for } t > t_{\text{end of reheating}}
\]

\[
\dot{Q}(t) = \dot{Q}_{predicted}(t) - \Delta\dot{Q} \text{ for } t_{\text{start of limitation}} < t < t_{\text{end of limitation}}
\]

\[
\dot{Q}(t) = \dot{Q}_{max} \text{ for } t_{\text{end of limitation}} < t < t_{\text{end of reheating}}
\]

\( (10) \)

For constant predicted heating power during reheating time (which corresponds normally to constant weather conditions), the moment of end of reheating can be calculated easily:

\[
\Delta\dot{Q} \cdot (t_{\text{end of limitation}} - t_{\text{start of limitation}}) = \int_{t_{\text{end of limitation}}}^{t_{\text{end of reheating}}} (\dot{Q}_{max} - \dot{Q}_{predicted}(t)) \, dt
\]

\( (11) \)

The time of end of reheating can be determined from the equation:

\[
t_{\text{end of reheating}} = t_{\text{end of limitation}} + \frac{\Delta\dot{Q} \cdot (t_{\text{end of limitation}} - t_{\text{start of limitation}})}{\dot{Q}_{max} - \dot{Q}_{predicted \text{ for reheating time}}} \]

\( (12) \)

7. CALCULATIONS

In order to validate the simplified model (10) (12), parallel calculations using this model and using the precise model (1)-(9) were performed for different cases. The cases were scenarios of power limitation by certain percentage, performed on a building characterized by certain heat loss coefficient and time constant, for a certain time, at certain set difference between outdoor and indoor temperature. The stages of limitation and reheating have been modelled in both ways, and total energy consumption in both cases was determined (during total period of the procedure according to the simplified model). In case of the precise model, the temperature difference and heat losses were decreasing during limitation stage, and thus total energy consumption has been decreased compared to scenario without limitation. It is reflected by shorter reheating stage than in case of the one simulated with simplified model.

Two results were monitored in each case: lowest value of the temperature difference between indoor and outdoor during whole procedure according to the precise model and the difference in total energy consumption between the results of the precise model and the simplified model. As long as the temperature difference does not drop significantly (which means that the comfort is kept indoor) and the difference of energy consumption is minimal (which means that the estimation of resulting heating power is the same for both models), the procedure of power limitation and reheating can be safely performed by a DH operator using...
only the simplified model. It is crucial to know, in which cases (i.e. minimal time constants of the buildings, maximal power limitations and maximal durations of the procedure, all depending on desired temperature difference) the simplified model is enough for simulation of thermal inertia of buildings.

8. RESULTS

The results of calculations are shown in Fig. 3 and 4.

It can be seen, that both the maximum temperature drop and the error in calculations of total energy used depend highly on the duration of the procedure and on the time constant of the building. Of course there is also a high influence of the weather (difference between indoor and outdoor temperature) and of the percentage by which the heating power has been decreased. The calculations were performed for a building with total heat loss coefficient $U$ equal to 100 W/K, with internal heat gains at 400 W. The developed methodology can be used easily for any other building.

Fig. 3. Maximum temperature drop [K] during a procedure of decreasing the heating power of a building by 5%, at the difference between indoor and outdoor temperature equal to 40 K.
Fig. 4. Percentage error in calculating with the simplified model the total energy used during a procedure of decreasing the heating power of a building by 15%, at the difference between indoor and outdoor temperature equal to 20 K

The results show, that it is possible to utilize the thermal inertia of buildings for management of heating power demand, without significant influence on the comfort of residents, and to simulate such procedure with a very simple model without significant errors. However, for higher duration of the procedure, buildings with low time constant or severe power limitations are characterized by decreased accuracy of the simplified model results.

9. CONCLUSION

Main challenges of operational optimization in modern district heating networks have been outlined. Among new solutions, thermal load shifting with the use of inertia of buildings has been scrutinized.

The methodology has been developed and demonstrated. This methodology, for a given type of building and scenario of heating power limitation, makes it possible to determine the maximum temperature drop and error of the simplified model for simulation of energy consumption.

It can be used as a part of future solutions for optimization of district heating systems’ operation, sometimes referred to as Smart District Heating.

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