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Economical heat production and distribution

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Abstract: A reliable supply of heat, provided by means of district heating systems, depends on faultless and stable operation. Economic success further requires high quality monitoring and control. The paper deals with an approach to the monitoring and control of district heating systems while focusing on economic success. In this respect it is necessary to take into account a possible usage of various energy sources, with regard to energy consumption prediction and operational economic optimum, throughout the planning as well as in the managing, monitoring and maintenance of the district heating systems. In order to ensure cost-effective management of a heating system, optimal system control measures must be adopted – requiring modeling and a prediction of the heating system's future operational state.

Key-Words: District Heating, Heat Consumption Prediction, Economical Production, Heat Distribution

1 Introduction

An economical management of complex district heating systems (DH) must embrace a rationalization of the operations of all components involved in the process of heat production and distribution. In this article one possible approach to cost-effective management of district heating systems is described. The management is based on determining the optimum supply temperature, the optimum flow-pressure conditions in the pipe network and the optimum heat production in the near future (a few hours to a few days in advance).

Economical management should be based on an accurate knowledge of production and distribution capacities, as well as predictions on the future consumption of heat from the energy system. The aim of the management is to fully meet consumers' needs, whilst preserving the lowest possible variable costs of production and distribution of heat. Economical management requires accurate prediction of future heat consumptions as well as an assessment of the risk of exceeding the limit values for heat consumption in the future. The forecast of the required variables is carried out with the INTELPRED software package [1], [2], [3]. The calculated values are then forwarded to the economic module, which determines the optimum economic profile of heat production $f(\Phi(t))$, supply temperature $f(T_s(t))$ and return temperature $f(T_r(t))$, taking into account the relevant boundary conditions.

2 Modeling of the district heating system

A district heating system can be divided into three elements: consumption points, the hot water network and production sources. An accurate knowledge of the operations of all system elements and of their interconnection is a prerequisite for the achievement of optimum results.

2.1 Consumption points

The operation quality of a substation and a data exchange with the control centre can to a large extent influence the operating efficiency of the whole DH system. To achieve the optimum substation operation parameters, it is of crucial importance to correctly plan, execute and control the secondary system and elements of the substation.

2.1.1 The consumption-point heat-flow model

Heat from hot water systems is used for:

- heating (with radiators, radiant floor heating, convectors)
- air-conditioning systems, process energy consumption,
- hot water production,
- cooling (absorption chillers).

Consumption points are divided into j categories, with regard to the consumption characteristics. Every category comprises i consumption points from which the data on the system's operating states can be obtained via a remote monitoring and control system. Consumption points belonging to the category j from which the data cannot be obtained are approximated with the factor p. The factor p is calculated as the ratio between the heat flow of all consumption points belonging to category j and the heat flow at consumption points of category j which are connected to the remote monitoring and control system [4]. The mathematical model of heat flow at consumption points can be expressed as:

$$\Phi_{\mathrm{cp}} = \sum_{j=1}^{K} \left(\sum_{i=1}^{N} \Phi_i \right) \cdot p_j \tag{1}$$

$$\mathrm{i} = 1, 2, 3, \ldots, \mathrm{N}, \quad \mathrm{j} = 1, 2, 3, \ldots, \mathrm{K}$$

Data on heat consumption in the district heating system, together with weather data and day type, are recorded in the data base at 30-minute intervals.

2.1.2 Consumption-point heat-flow prediction

The INTELPRED software package is used for heat consumption prediction. It enables energy consumption forecasting in all types of district heating systems. INTELPRED is based upon methods of simulated neural networks and genetic algorithms. On the basis of available data on the operation of the selected district heating system, it creates a model of system operation and response to control measures. In so doing, it determines the connections between the individual environmental variables' values (weather data, day type) and energy consumption in the system. On the basis of the system's current state and the given projected future values of certain environmental variables, the software forecasts future system operation and assesses the risk of exceeding the set energy consumption limit values in the future. The estimated forecasts and risk of exceeding the heat consumption limit values in the future form the basis for the determination of the economically most appropriate heating system control.

The prediction leads to a time-dependent function of heat consumption:

$$f(\Phi_{cp}(t)) \tag{2}$$

The minimum supply temperature T_{st} and the maximum hot water network return temperature T_{rt}, which depend on the outdoor temperature, are determined with technical conditions laid down by the heat supplier. With regard to the prediction of time-dependent outdoor temperature T_o the following functions can be defined:

$$f(T_{st}(t)) \tag{3}$$

$$f(T_{rt}(t)) \tag{4}$$

On the basis of functions (2), (3) and (4) the function of volume flow (according to technical conditions) may be thus calculated:

$$f(q_{vt}(t)) \tag{5}$$

2.2 The hot water network

Hot water networks are generally complex piping networks, composed of numerous straight sections, junctions or loops. Specialized software packages enable static hydraulic analysis of different types of piping networks [5]. The data obtained are crucial for the design of the hot water network, the determination of the optimum configuration of pumping stations, the detection of critical points in the system and the assessment of possibilities for consumption extension [6], [7], [8]. For optimum management of the system the pipe network models must be simplified by grouping into individual units. In this way the model can be simplified by 80-95%, without any significant deterioration in accuracy [5]. However, it is important to preserve some important characteristics of the network, such as the volume of the medium in the pipe network, time lags, volume flow, heat losses and pressure conditions. The simplified model must agree with the real model to a certain level of accuracy, especially as regards pressure conditions and heat transfer dynamics.

2.2.1 A heat flow model for the distribution of heat

The paper assesses the possibility of heat storage in the hot water network for the purposes of optimization of production and distribution of heat. The mathematical model for the distribution of heat flow at the heat source threshold can be expressed as:

$$\Phi_{\mathrm{ds}} = \Phi_{cp} + \Phi_{hl} + \Phi_{ak} + \Phi_{hlak} \tag{6}$$

2.2.2 A corrected consumption-point heat-flow model

In a corrected consumption-point heat-flow model the heat distribution time delay needs to be taken into account t_K (from the source to the last consumption point), with regard to volume flow. The delay may be determined with:

- a simulation of operating states of the system in a system for hydraulic analysis of pipe networks,
- measurements of time delays in different operating states.

$$t_K = f(q_{vt}) \tag{7}$$

Functions (3) and (4) are then corrected with the time delay:

$$f(T_{st}(t+t_K)) \tag{8}$$

$$f(T_{rt}(t+t_K)) \tag{9}$$

On the basis of functions (2), (8) and (9) the corrected time-dependent function of volume flow may be calculated:

$$fq_{vt}((t+t_K)) \tag{10}$$

The changes of time delay due to corrected volume flow are minimal and can therefore be disregarded. The volume flow depending on the chosen supply temperature T_s and return temperature T_r of the hot water network can be expressed as:

$$q_v = \frac{T_{st} - T_{rt}}{T_s - T_r} \cdot q_{vt} \tag{11}$$

The heat flow equation for consumption points goes as follows:

$$\Phi_{cp} = q_v \cdot \rho \cdot c_p \cdot (T_s - T_r) \tag{12}$$

2.2.3 The heat flow model for heat losses

This model features the distribution of hot water by means of a double-pipe hot water network. Heat losses can be divided into two groups: losses in the supply pipe and those in the return pipe. When calculating heat losses it is necessary to take into account the effects of the return pipe on losses in the supply pipe and vice versa. A mathematical model for heat flow due to heat losses at T_{st} and T_{rt} for pre-insulated pipes laid directly into the ground, expressed in a simplified manner, is as follows:

$$\Phi_{hl} = L \cdot \lambda \cdot (T_{st} + T_{rt} - 2 \cdot T_{so}) \tag{13}$$

The pipe heat conductivity coefficient λ for the individual hot water network may be determined on the basis of:

- pipe producers' data, with regard to measurements and quality of insulation of individual pipe segments,
- measurements and calculations that are based upon the heat that was produced and sold within a period of several years.

On the basis of heat losses and T_s and T_r during the years 2003 and 2004 in the hot water network TOM (Toplotna oskrba Maribor d.o.o.) the calculated pipe heat conductivity coefficient amounts to λ = 0.313 W/mK. Producer's data: λ_2 = 0.363 W/mK for series 2 hot water pipes and λ_3 = 0.296 W/mK for series 3 hot water pipes, the average pipe diameter being 244 mm. The hot water network pipeline L has a length of 22843 m. The volume of water in the pipe network amounts to 2137 m^3.

The variation of temperature T_{so} at a depth of 1m, depending on the season, is shown in figure 1:

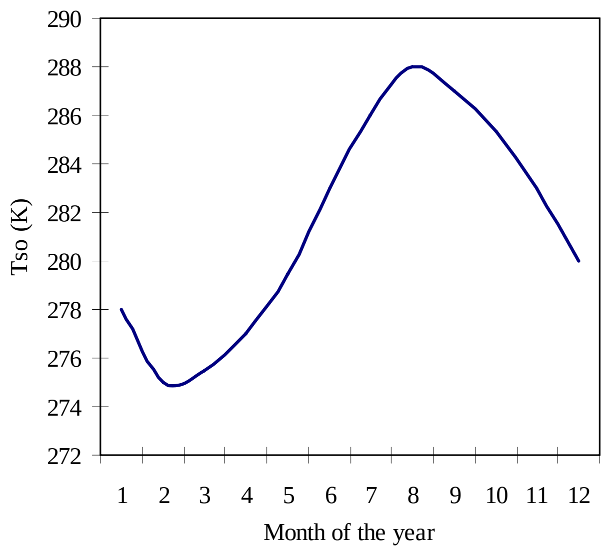

Figure 1: T_{so} at a depth of 1m, depending on the month

2.2.4 A heat flow model for heat storage

For the storage of heat in the pipe network at low consumption rates in the network it is necessary to install a bypass on appropriate segments – enabling volume flow $q_{v,bp}$. The degree of opening of the bypass is regulated via a remote monitoring and control system, depending on the heat storage needs. Heat storage in the hot water network may be expressed for the supply and return pipes jointly:

$$\Phi_{ak} = q_{v,bp} \cdot \rho \cdot c_p \cdot (T_s + T_r - T_{st} - T_{rt}) \tag{14}$$

2.2.5 The heat flow model for heat losses due to heat storage

Heat losses due to heat storage in the hot water network may be expressed for the supply and return pipes jointly:

$$\Phi_{hlak} = L \cdot \lambda \cdot (T_s + T_r - T_{st} - T_{rt}) \tag{15}$$

2.3 Production sources

Heat may be produced separately or be co-generated together with electricity (CHP). In both cases it is important to have the optimum management of energy production with respect to profit, with all technical boundary conditions provided for. The aim of the optimum production control is to produce as much heat as possible from low-cost and environment-friendly sources. To achieve this goal, two elements are extremely important, namely:

- choice of the right configuration of production sources at the time of planning the installation, considering the hourly profile of consumption in the hot water network; and
- establishment of an optimum energy-production plan, in accordance with high-quality short-term and long-term prediction of heat consumption.

The heat flow model of heat production is shown below as the sum total of all production sources:

$$\Phi_{\mathrm{pr}} = \sum_{i=1}^{n} \Phi_{pri} \tag{16}$$

3 Cost-effective production and distribution of heat

The basis of cost-effective production and distribution of heat, with regard to a known future consumption rate, is a balance equation between the heat flow model for heat production (16) and the heat flow model for heat distribution (6) within any given period of time, taking into account all relevant boundary conditions:

$$\sum_{j=1}^{m} \Phi_{prj} \cdot t_j = \sum_{j=1}^{m} \Phi_{dsj} \cdot t_j \tag{17}$$

Certain simplifications are carried out:

- considered time period: 24 hours;
- time interval t – 30 min;
- the number of time intervals m – 48;
- all parameters are average values of the given time interval.

Using a numerical simulation of the balance equation (17), with regard to all boundary conditions, the possible control measures for heat production and distribution within a period of 24 hours are simulated. The chosen time-dependant combination of control measures should ensure the maximum of the variable part of the profit function within the chosen time frame:

$$C(t) = C_{ds}(t) - C_{pr}(t) \tag{18}$$

Variable revenue due to heat distribution may be expressed as:

$$C_{ds} = \sum_{j=1}^{m} (\Phi_{cpj} \cdot c_S + (-\Phi_{hlj} \pm \Phi_{akj} - \Phi_{hlakj}) \cdot c_C) \cdot t_j \tag{19}$$

Variable costs due to heat production may be expressed as:

$$C_{pr} = \sum_{j=1}^{m} (\sum_{i=1}^{n} \Phi_{pri} \cdot c_{pri}) \cdot t_j \tag{20}$$

Figure 2 shows the daily profile for heat production (unbroken line) and the daily profile for heat consumption (broken line). In the graph the principle of heat storage inside the pipe network is evident, enabling us to avoid initiation of a third heat source. A similar principle is used to avoid switching on a second boiler during summer operations.

Figure 3 shows the consumption of heat in the network of the company TOM. The broken line represents the hourly profile of heat production for the year 2004 and the unbroken one the hourly profile of heat production for the year 2003. The graph shows that up to a heat demand of approx. 6.5 MW, heat was produced from a cheaper source in comparison with 2003.

This result was achieved thanks to the choice of a suitable combined heat and power production facility (gas engine CHP: P_{el} = 3 MW, Φ_{th} = 3 MW) and the storage of surplus heat in the pipe network. Savings resulting from heat production and distribution management with heat storage in the pipe network are represented by the difference in price of energy produced within the range of 7000-8760 hours in the year 2004, reduced by the costs of heat losses due to heat storage.

4 Conclusion

Consumers are demanding ever improving services at lower prices. The market for energy sources has been steadily opening. Heat producers and distributors must be ever more competitive, which is possible with greater efficiency and flexibility. The required return on investment can be achieved by taking good organizational measures and by cutting heat production and distribution costs.

In the last two years our development work in collaboration with the Faculty of Mechanical Engineering, Ljubljana, and the Faculty of Chemistry and Chemical Engineering, Laboratory of Heating Engineering, Maribor, has been directed towards the development of products and services for the cost-

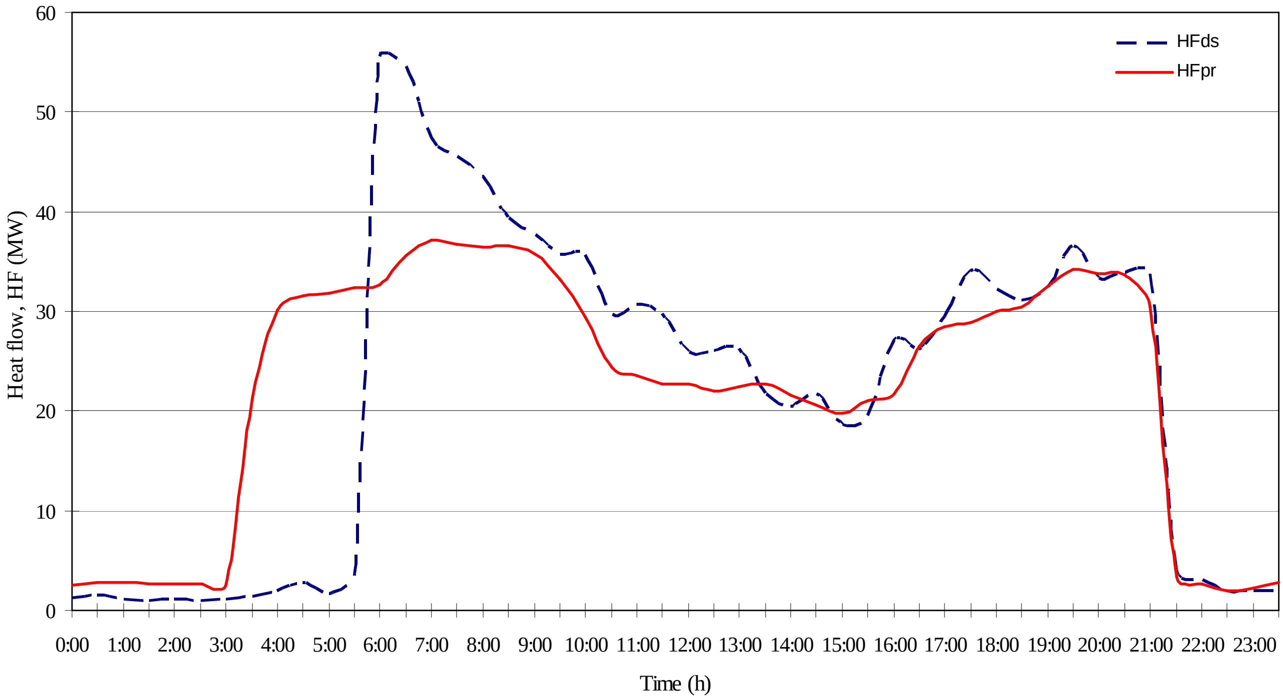

Figure 2: An example of cost-effective management of heat production and distribution at TOM

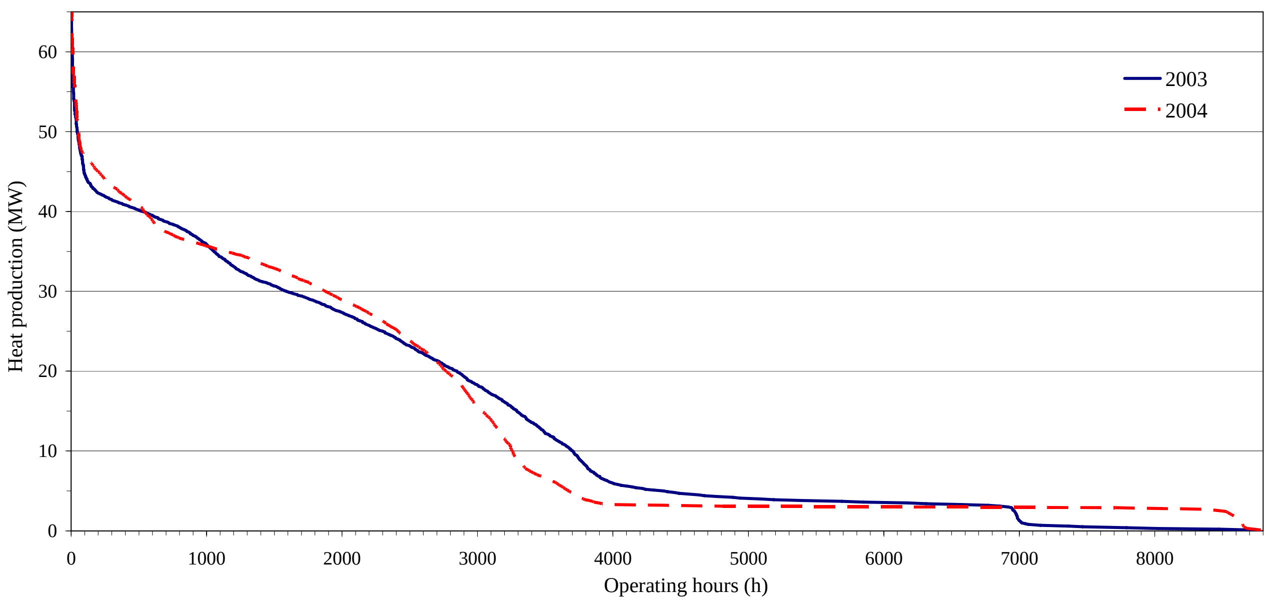

Figure 3: Hourly profile of heat production in the TOM network

effective management of heat production and distribution. The results of this collaboration are the aforementioned software package for the monitoring and control of consumption points, the software package for long-term and short-term prediction of heat consumption and the software package which allows calculations of the maximum variable part of profit and the determination of control measures within a certain time frame, whilst ensuring stability in the operation of the system.

All of the operational tests are being executed on a medium-sized district heating system (Φ_{pr} = 94 MW), in cooperation with the company TOM. Operational testing of the software package for the monitoring and control of consumption points and the software package for long-term and short-term prediction of heat consumption has been concluded. The development of phase 1 of the economic module and the determination of a schedule for different control measures are scheduled to be concluded by autumn 2005. The commencement of commercial use of the entire system for cost-effective heat production and distribution is planned for the 2006/07 heating season.

The cost-effective heat production and distribution described above enables the highest savings levels in:

- systems in which heat is generated by using several different sources and fuels;
- systems, where a base load consumption of power from CHP plants is provided for.

The peak heat loads of heat generation facilities can effectively be reduced – which, when building new or renovating already existing sources, leads to savings in investment into production sources for covering these peak loads.

The development of a system for cost-effective pumping stations management is currently being planned in combination with the dynamic control of pressure conditions.

Nomenclature:

c_C variable part of cost price of heat (EUR/J)
c_p specific heat capacity (J/kgK)
c_{pr} variable part of heat production expenditure via source i (EUR/J)
c_S variable part of selling price of heat (EUR/J)
C_{ds} variable revenue from the distribution of heat (EUR)
C_{pr} variable expenditure due to production of heat (EUR)
K number of consum. characteristics categories
L hot water network pipeline length (m)
m number of time intervals
n number of production sources
N number of category j consumption points
p category j remote control factor
q_v volume flow at T_s and T_r (m^3/s)
$q_{v,bp}$ volume flow through the bypass (m^3/s)
q_{vt} volume flow at T_{st} and T_{rt} (m^3/s)
t time interval (s)
t_K time delay of heat distribution (s)
T_o outdoor temperature (K)
T_r chosen return temperature (K)
T_{rt} maximal return temperature (K)
T_s chosen supply temperature (K)
T_{so} soil temperature at a depth of 1m (K)
T_{st} minimal supply temperature (K)

Greek letters:

Φ_{ak} heat flow for heat storage (W)
Φ_{cp} heat flow at consumption points (W)
Φ_{ds} distribution heat fl. at the source threshold (W)
Φ_{hl} heat flow for heat losses (W)
Φ_{hlak} heat fl. due to heat losses because of storage (W)
Φ_{pr} heat flow of heat production(W)
λ pipe conductivity coefficient (W/mK)
ρ density (kg/m^3)

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