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Energetic and Exergetic Analysis for Reconstruction of a Direct District Heating Substation

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***Abstract*— Different concepts of direct district heating thermal substations are analysed for a building that should implement energy efficiency measures. These measures should reduce the installed heating capacity for 45.3 %. The building, connected to a small district heating network, has a radiator central heating system equipped with thermostatic valves. These valves are not compatible with the present substation, which is in a poor condition and which is designed for constant water flow with variable supply temperature. A thermal substation is a part of a network and the network should be designed hierarchically. A direct substation without temperature control (one level of district heating supply temperature control) could be implemented if all buildings in the system are of the same class of energy efficiency. Oppositely, a substation with an additional control loop should be applied.**

***Keywords*— substation, energy efficiency, simulation, energy, exergy**

I. INTRODUCTION

The building sector is responsible for nearly half of the final energy use in the EU. The largest share of this is linked with space heating and domestic hot water preparation [1]. In the Republic of Serbia, the specific average annual energy consumption for heating of non-residential objects is 194 kWh/m^2 [2]. Improving energy efficiency of public buildings in a technically and economically optimal way is a great challenge. Many roads are open for engineers and each particular case has its own optimal solution at given moment. This solution is shaped by many influences: scientific progress in designing building insulation materials and energy technologies, fluctuations in energy, material, and fuel prices etc.

The management of the public hospital “Studenica” in Kraljevo has been trying to improve the energy efficiency (EE) of their buildings. Their goal is to achieve the class C of EE (i.e. to spend less than 120 kWh/m^2 annually [3]) for all four objects, which have the total space area of 47000 m^2. The topics of the paper emerged while suggesting the solution for the reconstruction of a direct heating substation for the Children’s Dispensary building. Table 1 shows the main technical data for the building, which has has two pipe water heating system with sectional radiators equipped with two-way radiator valves with pre-setting and thermostatic heads. All radiator are equipped with lockshield valves.

The building is connected to a district heating (DH) network that comprises all four buildings. The network operating temperatures are 90 °C for the forward pipe and 70 °C in the return. The DH system was initially designed to have a constant supply temperature in the primary side and constant flow with variable temperature in the secondary side. These facts were overlooked by the company that installed radiator thermostatic valves. Their implementation turn the secondary side of the network to a system with variable flow and variable supply temperature. Figure 1 shows the layout of the present substation. The substation is in a poor condition and needs renovation, its control valves are out of the function and it has two centrifugal constant-speed pumps, each with a power of 4 kW. To increase the EE, the technical staff of the hospital has changed the primary side of the DH network. Nowadays it has a variable supply temperature with constant flow. This is achieved by the implementation of a control loop with a three-way regulating valve after a shell and tube heat exchanger used to heat DH water by heat exchange with steam at 5 bar. The regulating valve is controlled by the outdoor ambient temperature.

TABLE I MAIN ENERGY DATA FOR THE CHILDREN’S DISPENSARY BUILDING IN THE PUBLIC HOSPITAL “STUDENICA” IN KRALJEVO

	Present	After the implementation of EE measures
Heating power requirement	318074 W	174111 W
Specific annual energy consumption	241.63 kWh/m^2	112.11 kWh/m^2
Branch 1 – heating power requirement	182306 W	98081 W
Branch 2	135768 W	76030 W
The exponent for thermal output for sectional radiators		n=1.33
Average indoor temperature		23 °C
Nominal supply and return DH water temperatures		90/70 °C
The excess area of radiators		5% (installed 333978 W)

Figures 2 and 3 show the layouts of two proposed solutions for the substation. Figure 2 depicts the configuration without an automatic control (DTSS1). Its principle is based on the temperature control in the boiler house, whereas the corrections would be performed by the thermostatic radiator valves. The main components of the substation are: a hydraulic flow divider and a centrifugal pump with four different control modes. Figure 3 shows the layout of the other analysed system (DTSS2). The substation has a control loop according to the outdoor ambient temperature. This arrangement enables a constant flow in the primary and variable flow in the secondary side of the network. The temperature of the DH supply water is firstly adjusted in the boiler house, and then, in the second stage, by this control loop inside the building. Imprecisions caused by sun light and internal heat gains would be adjusted by the thermostatic radiator valves inside the building.

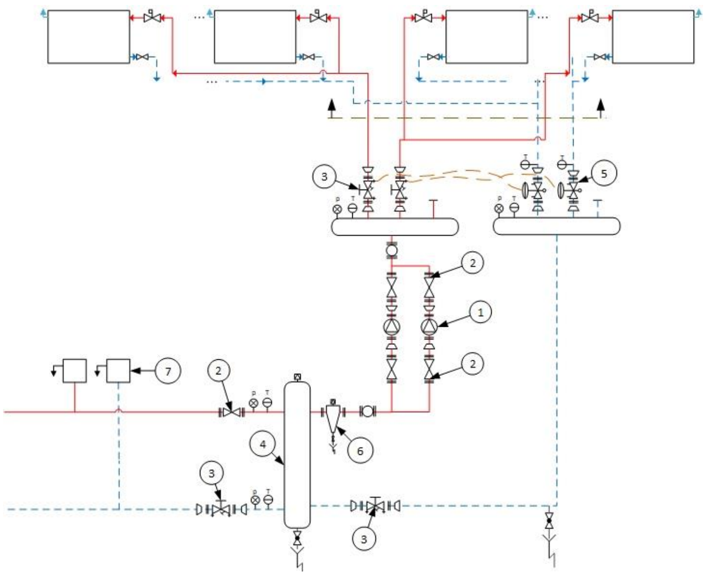

Fig. 1 Direct thermal substation without temperature control DTSS1. 1 – circulatory pump, 2 - shut-off valves, 3 –static balancing valves, 4 – hydraulic flow divider, 5 - dynamic pressure controller, 6 – filter, 7 – venting tank.

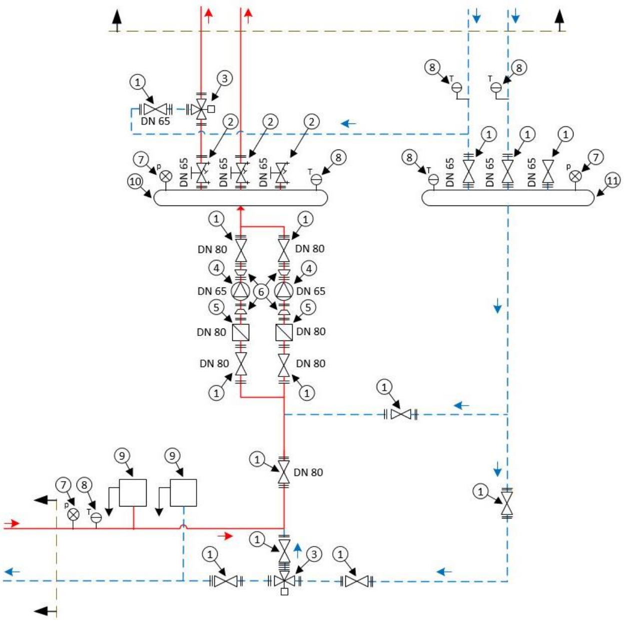

Fig. 2 The layout of the present direct DH substation. 1 – shut-off valves, 2 –static balancing valves, 3 – three-way mixing valves, 4-pump, 5 – filter (strainer), 6 – pipe-diameter reduction, 7 – manometer, 8 – thermometer, 9 – venting tank.

The goal of the paper is to choose:

- technically suitable configuration for the direct substation, and
- proper balancing strategy (static or dynamic) for the substation and its subnetwork.

To prevent the noise from the operation of thermostatic valves and to account for unpredicted pressure drops in the hydronic systems, manufacturers suggest the use of dynamic pressure control (shown in Figs. 2 and 3). Compared to the static balancing, also shown in Figs. 2 and 3, does the dynamic pressure control make an additional and unnecessary pressure drop? This question is the core for the second goal.

The previous goals are assessed by performing exergy assessment. It can easily identify the causes of irreversibilities at the component level of the system. This enables the proposal of more efficient components, leading to an increase in energy performance of the system. Regarding DH system efficiency, exergy analysis [4] has shown that it is necessary to strive for a larger temperature difference between the forward and return temperatures of the network, and to decrease these temperatures to cut both energy and exergy loses. The hospital can achieve both of these goals by applying the EE measures on its buildings. E.g. for the analysed building, the designed forward and return temperatures are 90°C and 70°C, respectively. The reduced heating demand and the exponent for thermal output for space heating appliances (both given in Table 1) show that the nominal temperature regime for the insulated building is 69.2/49.2 °C.

The exergy analysis is strongly dependent on the reference temperature (t_o) [5]. The authors [4] performed steady-state exergy analysis of the DH system by applying an average outdoor temperature as their reference temperature. In [5], the authors performed hourly based calculations, and took an hourly based reference temperature for the exergy analysis. Their reference temperature varies hourly throughout the year. In this paper, the reference state at 0 °C and 1 bar has been taken. The dynamic behaviour of the reference temperature has not been taken into account because the primary goal of the analysis is the performance of the substation, not of the entire heating system.

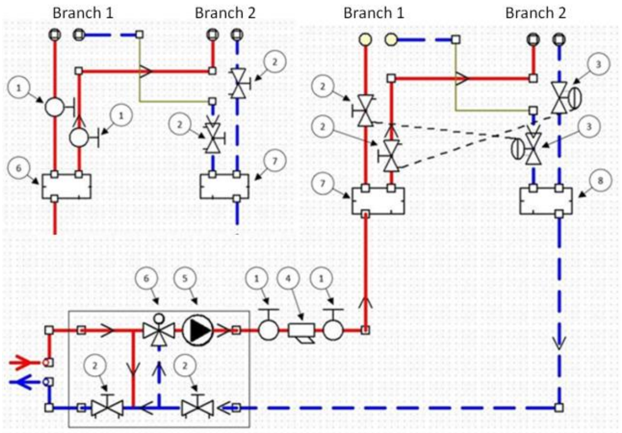

Fig. 3 Direct thermal substation with temperature control DTSS2. 1 – shut-off valves, 2 - static balancing valves, 3 - dynamic pressure controller, 4 – filter, 5 - circulatory pump, 6 – three-way regulating valve. Two different regulating schemes for the branches are shown in the figure.

II. MODELLING

A model is developed to evaluate and compare dynamic performances of the analysed substations (DTSS1 and DTSS2) and of the building. The model is developed in Modelica language, which is the object-oriented language for physical system modelling.

All the elements are modelled based on energy and mass balances. The core of the physical modelling is the calculation of basic temperature-dependent thermodynamic properties. Water density and specific heat capacity are calculated according to Refs. [6] and [7]. The pressure drop is taken into account by the flow factor k_v, which represents the water flow in m^3/h, at a pressure drop across the valve (or other component) of 1 bar i.e:

$$\Delta p = 10^5 \left(\frac{\dot{V}}{k_v}\right)^2, \qquad (1)$$

where V is the volume flow rate in m^3/h and the pressure drop Δp in Pa. Table 2 shows the properties of the modelled components.

TABLE III COMPUTATIONAL PARAMETERS

Component	Modelling characteristic
Balancing valves	k_v value is chosen to achieve minimum pressure drop of 3000 Pa
Butterfly and globe valves	k_v value is chosen according the diameter (the same as for the pipe)
Three-way valves	k_v value is chosen according to the minimum authority (0.25), the valve is controlled according to the water outlet temperature
Strainer (filter)	Singularity Δp coefficient 5
Differential pressure control valves	according to the set differential pressure (10 kPa is the minimum pressure drop for the size of the analysed system)
Pipes	pressure drop is calculated according to the Williams-Hazens equation [8]

The building thermal needs are modelled according to the procedure shown in Fig. 4. The inputs into this sub-model are weather conditions and supply temperature of the DH system. The water mass flow rate and the outlet temperature are calculated based on the thermal output of sectional radiators and energy balance.

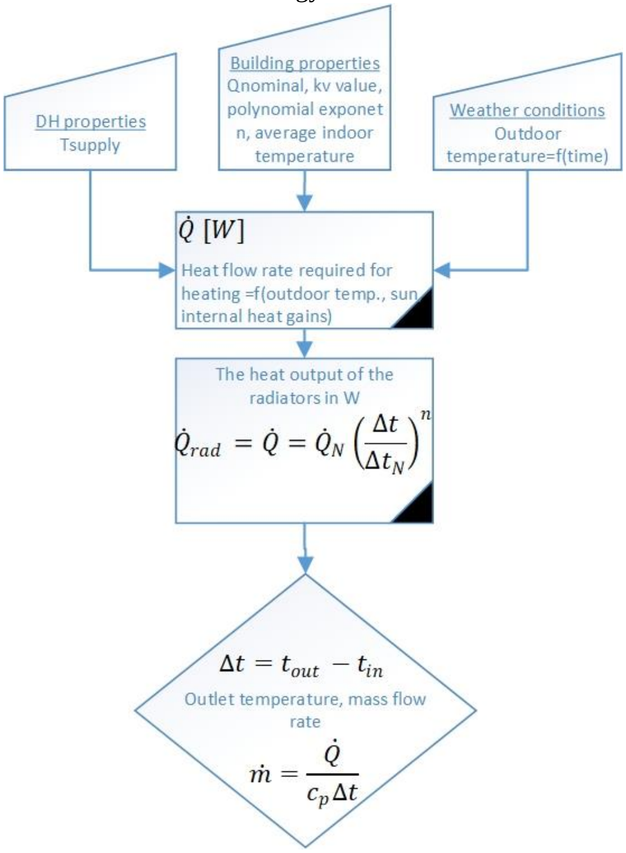

Fig. 4 Algorithm for calculation of the outlet temperature and mass flow rate from the building.

The circulatory pump is modelled to simulate the following control modes:

- constant-curve control,
- constant-pressure control,
- proportional-pressure control, and
- adjustment of the pump performance to the heat demand of the system.

The power of the circulatory pump is calculated according to

$$Ppump = \frac{\Delta p \dot{V}}{\eta_M \eta_P}, \qquad (2)$$

where η_M=0.55 is the efficiency of the electric motor, and η_P=0.6 is the efficiency of the pump circuit. These values are taken from the Ref. [9].

The model is validated only for the time-independent mode by comparing the model results and the results of the software Hecos [10]. The results of the model coincided with the results of the software, which is a reliable tool for sizing central heating systems.

III. EXERGY ANALYSIS

Exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment [11]. The reference temperature T_o is defined as a restricted dead-state with thermo-mechanical equilibrium. Compared to physical exergy all other forms are considered negligible. The physical component of the physical exergy in J/kg of a flowing water is

$$e_{ph} = (h - h_o) - T_o(s - s_o). \tag{3}$$

In the previous equation, h in J/kg is the enthalpy, and s in J/kgK is the entropy of water stream, which is calculated according to Ref. [12]. The subscript $_o$ designates the reference state. The change in specific physical exergy of the flowing water is

$$\Delta e_{ph} = c(T - T_o) + \frac{p}{\rho} - \frac{p_o}{\rho_o} - T_o(s - s_o). \tag{4}$$

This change is caused by the net exergy transfer through the process boundaries and by the exergy destruction within the system due to irreversibilities. The exergy destruction rate in W is the difference between all the input and output exergy rates, i.e.

$$\dot{E}_{destroyed} = \dot{E}_{in} - \dot{E}_{out}\,. \tag{5}$$

The exergy rate of electrical power in W is equal to it, whereas the exergy rate of heat flow rate in W is

$$\dot{E}_Q = \dot{Q}(1 - \frac{T_o}{T}). \tag{6}$$

For the analysis, the exergy efficiency is defined in two ways: (i) as the ratio of the sums of all input and output exergy streams (7) and (ii) as the ratio between the useful exergy flow rate (exergy of heat flow rate) and invested exergy flow rate (8):

$$\varepsilon = \frac{\dot{E}_{in}}{\dot{E}_{out}}, \tag{7}$$

$$\varepsilon = \frac{\dot{E}_Q}{(\dot{E}_{water\ ,in} - \dot{E}_{water\ ,out}) + P_{pump}}, \tag{8}$$

IV. RESULTS

The present DH network supplies the system with hot water temperature that linearly depends on the outdoor ambient temperature: t_{supply} (°C) = 70 – $t_{outdoor}$(°C) (regime 3). The subsequent analysis is carried out for this temperature regime and for two others: t_{supply} (°C) = 50 – $t_{outdoor}$(°C) (regime 1) and t_{supply} = 70 °C (regime 2). The static pressure in the substation is taken to be 3 bar. The regime 2 correlates well with the reduced heating demand of the building for which the nominal temperature regime is 69.2/49.2 °C (see Table 1 and Fig. 4). Figure 5 shows the temperatures in the return line depending on the supply temperatures for all three temperature regimes. Without an additional temperature regulation, DTSS1 can work in the whole range of outdoor temperatures only if the supply temperature for the entire network is controlled linearly between 70 °C and 50 °C. Figure 6, for this temperature regime and for DTSS1, shows different behaviour of a circulatory pump.

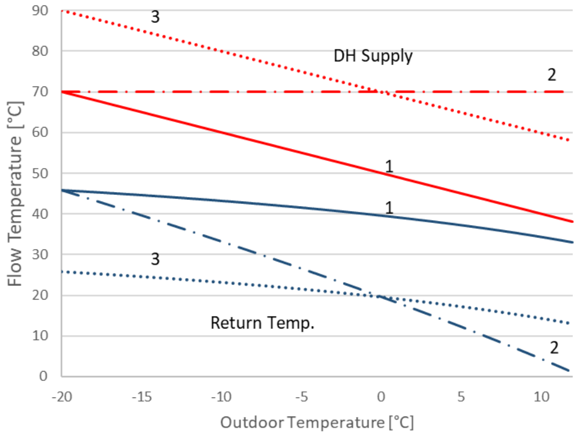

Fig. 5 Return temperatures of the DH system from the building depending on the supply temperatures. There are 3 pairs of lines for three different supply temperatures.

The present substation has two 4 kW centrifugal pumps that can only operate at constant-speed. Because of the reconstruction and substantial decrease in energy consumption (the present piping is going to be over-sized), the solutions DTSS1 and DTSS2 would require circulatory pumps with powers 128 W and 140 W, respectively. These powers would be a bit larger if the concept with differential pressure control valves is applied (see Figs. 2 and 3). The addition of dynamic pressure controllers would increase the pressure drop in the system by 10 kPa. The pump behavior depends on the implemented control mode. Three different modes are shown in Fig. 5. To stress the importance of the adjustment of the pump performance to the heat demand in the system, the pump power of 750 W is simulated in DTSS1 that works under the regime 1 in Fig. 5. Line 3 illustrates the optimal pump duty. That is the minimum pump power required for the operation in DTSS1. If the pump is controlled in this manner, both DTSS1 and DTSS2 would not require dynamic differential pressure control nor the use of overflow valves in the substation. These valves should be included in the substations if the pump operates in constant-power and constant-pressure control modes. In these cases, the excess pressure drops that should be applied by thermostatic radiator valves are shown in Fig. 7. This unwanted exergy destruction would make noise if the constant-power mode is applied. The exergy destruction made by circulatory pump, which is shown in Fig. 6, is caused by the irreversibilities in the electric motor and in the pump circuit due to the friction.

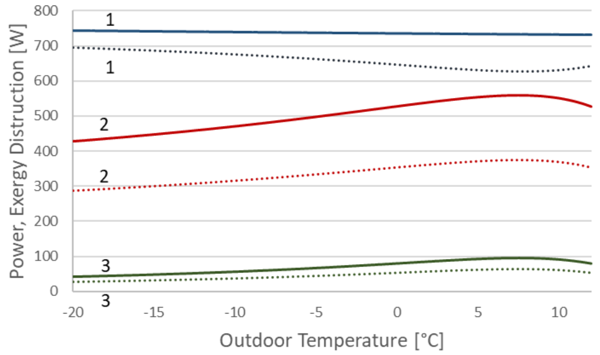

Fig. 6 The circulatory pump power (solid lines) and exergy destruction (dotted lines) for three different control modes: 1- constant power, 2 – constant-pressure control, and 3 – system with the optimized pump duty point.

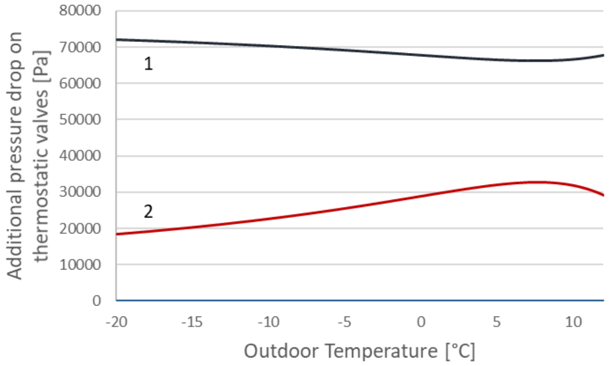

Fig. 7 The additional pressure drop that should be achieved on the thermostatic radiator valves if the pump is controlled by the constant power (line 1 for the case 1 in Fig. 6) and constant pressure (line 2 for the case 2 in Fig. 6).

Figure 8 shows the exergy balance for the heating system equipped with DTSS1 at the average outdoor temperature during the heating season 5.4°C [13], supplied by the DH system represented by the line 1 (regime 1) in Fig. 5. Compared with the exergy of DH supply and return, the power used for pumping is very small. Typically, this power is in the range from 1% to 3% of the total energy supplied [5]. In this case, it is even smaller due to the use of the present piping, which is in good condition and over-sized for the heating demand of the insulated building. The useful exergy is very small due to the small average temperature 23 °C in the building. Conversely, compared to the useful exergy, exergy destruction is substantial as can be seen in Figs. 8 and 9. The latter figure shows the exergy destruction for the whole range of outdoor temperatures for the building heating system equipped with DTSS1 working at the DH supply temperature shown as line 1 in Fig. 5 (regime 1). The main cause for the exergy destruction is the heat exchange at finite temperature difference in the building. The exergy destruction due to the pressure drop depends on the applied substation and the pump operation mode but compared with exergy destruction due to the heat exchange, it is very small because water is essentially incompressible under normal operating conditions. In both analysed substations, the biggest exergy losses are due to the mixing of water flow streams at different temperatures. These exergy losses are of the same magnitude for hydraulic divider in DTSS1 and three-way mixing valve in DTSS2 and depends on the enthalpies of the incoming and outgoing flows.

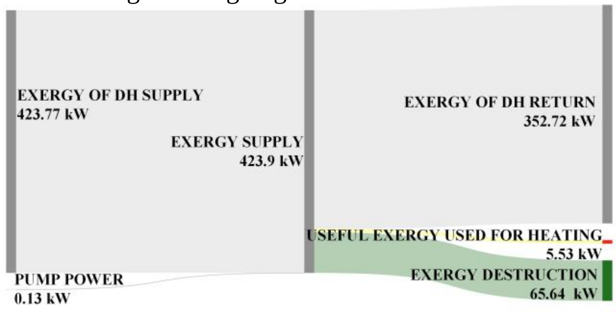

Fig. 8 The exergy balance for the central heating system of the analysed building with DTSS1 supplied with hot water at 64.6 °C (see line 1 in Fig. 5) with the optimally sized pump working at constant speed.

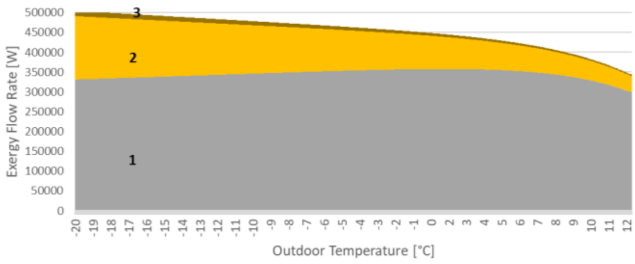

Fig. 9 Exergy flow rates at the exit of DTSS1 for the building heating system working at the DH supply temperature under the regime 1 (see Fig.5): 1 - return water flow, 2 – exergy destruction, 3 – useful exergy used for heating.

Figure 10 shows the change of the exergy efficiency of the building heating system equipped with DTSS1. The efficiencies calculated by equation (7) differ among applied temperature regimes, whereas when calculated by equation (8), they cannot be distinguished in the scale of Fig. 10. This means that the exergy efficiency of the heating system is primarily influenced by the exergy destruction due to the heat exchange in the sectional radiators.

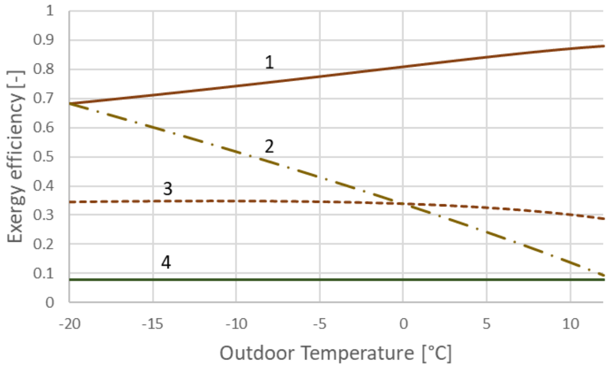

Fig. 10 Exergy efficiency of the building heating system equipped with DTSS1 for the three examined temperature regimes shown in Fig. 5: 1,2, and 3 are exergy efficiencies calculated by eq. (7) for the regimes 1,2, and 3 in Fig. 4. 4 – is the exergy efficiency calculated by eq. (8) for all three temperature regimes.

V. CONCLUSIONS

The analysis has been performed primarily to answer what kind of thermal substation should be implemented in the Children's Dispensary building of the Public Hospital "Studenica" in Kraljevo and could be useful for thermal engineers with the same kind of doubts. The main conclusions of this modest analysis are:

- A thermal substation could not be designed independently of the entire DH system. It is a part of a network and the network should be designed hierarchically: from the top to the bottom.
- Direct substation without temperature regulation (DTSS1), i.e. DH network with the supply water temperature controlled only in the boiler house, could be implemented if all other buildings in the system have similar specific energy requirements for space heating (W/m^2), i.e. if they are of the same class of EE. If the objects are not of the same class, a substation with an additional control loop should be implemented.
- Compared with the exergy destruction caused by the heat exchange in a radiator heating system, the exergy destruction due to the balancing and dynamic pressure control is substantially smaller.

In both analysed substations DTSS1 and DTSS2, the largest exergy losses are due to the mixing of different flow streams (supply and return). The type of the substation should be selected based on the required operation, after the implementation of a techno-economic analysis rather than exergetic one.

- Regardless of the type of the substation, the applied circulatory pump should adjust its performance according to the heat demand of the system. In this kind of operation, thermostatic radiator valves would perform only small flow corrections in different rooms. With this mode of pump operation, the system does not need flow control for preventing the noise that can arouse from the operation of thermostatic radiator valves. Nevertheless, the static balancing of the system should be applied. The selected mode of operation of the circulatory pump directly influences the pressure drop in the system.
- The improvement of energy efficiency in a building with oversized radiator central heating system that is in good condition can lead to the increase in energy and exergy efficiencies of the system as well as to the possibility for the inclusion of alternative energy sources.

ACKNOWLEDGMENT

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