Minimization of Mass Flow in District Heating Network Equipped with One Stage Domestic Hot Water Production Substations

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Abstract

The paper presents the possibilities of decreasing the mass flow in district heating system supplying district heating substations for residential buildings. In majority of district heating system in Western, Eastern and Central Europe the type of district heating substation with two stages of domestic hot water preparing is deeply rooted. The main aim of the paper is to show lack of arguments for grounds to use this technical solution in contemporary district heating networks. On the basis of computer simulation, the possibilities of decrease the mass flow and electrical energy consumption in heating (power) plant have been presented.

Keywords: *district heating system, domestic hot water, DHW priority, energy saving*

1. Introduction

In majority of district heating systems in Western, Eastern and Central Europe the type of district heating substation with two stage of domestic hot water preparing is deeply rooted (Burd, 1994, EUROHEAT & POWER, 2008). At present we can notice scientific papers concerning optimization of two stage district heating substations (Kimmo Yliniemi et al., 2009). The main aim of this technical solution in the past was decreasing the return network water temperature in district heating system. So the mass flow in district heating system could be smaller. Numerous research aimed at optimizing the mass flow lead to improving the control systems in district heating substation (Gustafsson et al., 2010). Another direction is search for optimal algorithms for district heating control (Maunu Kuosa et al., 2013). Two stage hot domestic water production needs enough high temperature of water returning from the space-heating section in a district heating exchanger station. In contemporary space-heating installations the maximal temperature of water is significantly smaller than in the past. The majority of heating installation are equipped with thermostatic valves for indoor temperature control. Procedures for dimensioning heating installation (EN 12831) give over-surfaced heaters (about 25÷30%) in installations (Zarski, 2012). In this standard internal heat gains in heated rooms are not taken into account. The cause of this is a significant decrease in the return water temperature in a heating installation. Critical conditions for two stage DHW production occur at the minimal supply water temperature. It is on the right side of the so called "breaking point" in temperature regulation curve. In this area we can notice a pure quantitative model of regulation, because of constant supply water temperature (about 70 °C). At surplus supply, the temperature of the water mass flow, in the primary section for space-heating, decreases. It is strongly non linear function - quasi-hyperbolic (Zarski, 2006). Temperature of return water in the primary circuit and the secondary (installation) circuit is practically the same. In contemporary district heating networks with modern district heating substations it is not possible to control the mass flow in a power or boiler plant (Maunu Kuosa et al. , 2013). The mass flow is forced by control valves settings according to weather conditions and hot domestic water actual demands. It generates troubles in power plant with district heating network cooperation (Zarski, 2012). For some time in Poland several District Heating Companies have tried to replace two stage water production system with one stage ones. In existing district heating substations, designed in 70..90. XX. century, a decrease in hot domestic water consumption (from 120 kg/day to about 50 kg/day per person) caused over-surfacing of hot water heat exchangers – in fact, only the second stage of water preparing is good enough (Zarski, 1998). The author's own contribution is to prove that two stage domestic hot water substations have no advantages in comparison with one stage heat exchanger stations in contemporary district heating systems.

2. Domestic hot water volume flow rate

Domestic hot water consumption can be considered at different time periods. A year is a period for balancing water production for settlement heat consumption and for economic analysis. Consumption of hot water per day is a significant index. This value is different in other countries, according to the kind of a building function (residential, commercial, industry, etc.). Typical warm water consumption values can be found in domestic regulations or we can assume these on the basis of practice and experience. Hot water consumption is rather irregular. Hot water consumption in residential building, is of different character, it is different in office or for commercial use. There are not universal rules for day time water distribution. Periods shorter than a day to balance the distribution of warm water may be: an hour, 20 minutes, 4 minutes, 1 minute. The shorter time the larger flow of water. Fig. 1. and 2. illustrate typical DHW distribution in residential building at time periods of 1 minute and 20 minutes.

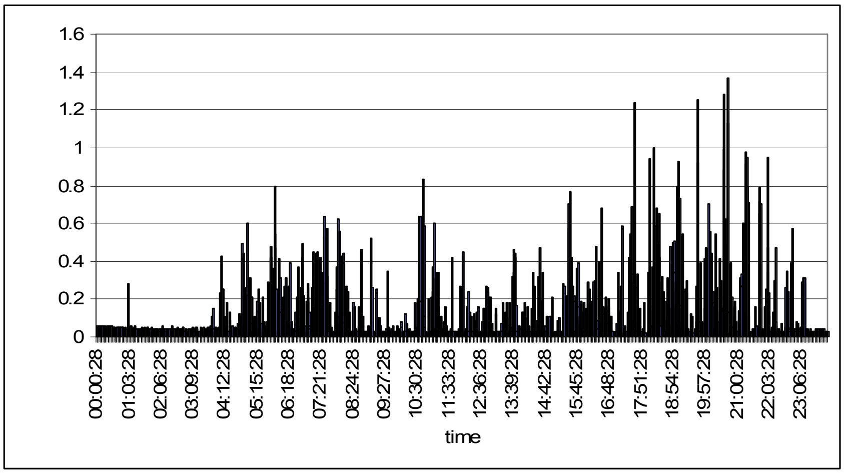

Fig. 1. Typical distribution of DHW (vertical axis – kg/s) in residential building – time period: 1 minute, maximum: 1.37 kg/s (Zarski, DHS Manual)

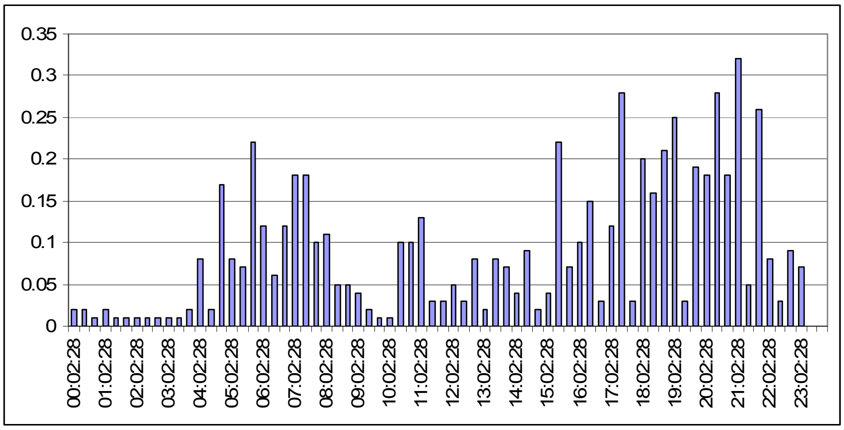

Fig. 2. Typical distribution of DHW (vertical axis – kg/s) in residential building – time period: 20 minute, maximum: 0.32 kg/s (Zarski, DHS Manual)

As we can notice the maximum of 1 min. flow is about 4.3 times larger than that calculated in 20 minutes of time period. The maximum domestic hot water flow occurs in short time periods. If we have tools for stabilization of DHW temperature we can design a heat exchanger for 20 min. mass flow, whose capacity will be smaller 4.3 times that designed for one minute flow. In European Union countries (in Poland since 2005) the maximum flow of DHW is calculated according to standard EN 806-3: Specification for installations inside buildings conveying water for human consumption. Pipe sizing. This standard also covers the system of pipes, fittings and connected appliances installed for supplying potable water. The time of exceeding hourly average value is about 3÷4 hours. Daily water consumption divided by number 24 gives the average hourly water consumption

$$m_h = \frac{m_d}{24} \tag{1}$$

where:
m_d – daily water consumption, kg/day,
m_h – hourly water consumption, kg/h.

Maximum mass flow in 20 minutes time period can be calculated from formula (Zarski, DHS Manual)

$$m_{20} = N_{20} \cdot m_h \tag{2}$$

where:
m_{20} – maximum mass flow of DHW in 20 minutes time period, kg/h or kg/s,
N_{20} – peaking factor, calculated as

$$N_{20} = 10.96 \cdot (n_f)^{-0.231} \tag{3}$$

where:
n_f – number of flats.

Volume flow rate is calculated as

$$q_{20} = \frac{m_{20}}{\rho} \tag{4}$$

ρ – domestic hot water density, kg/m^3.

The mass flow calculated according to Formula (2) is a parameter for heat exchanger dimensioning.

According to Euroheat & Power standard (EUROHEAT & POWER, 2008) the maximum volume of flow rate of DHW for heat exchanger selection is calculated in dependence on the number of apartments at max-min range. It is presented in Fig. 3.

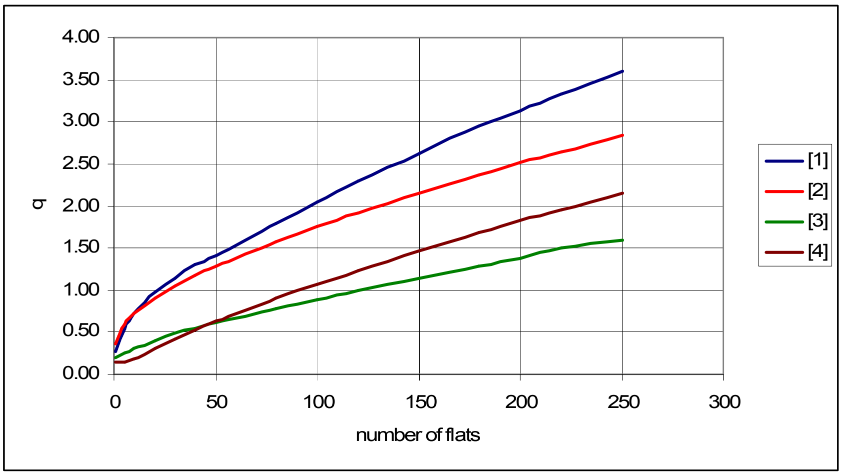

Fig. 3. Flow capacity of warm water (q [dm^3/s]) in residential buildings derived from different formulas, 1 – EN 806, 2 – upper slope (Euroheat), 3 – lower slope (Euroheat), 4 – author's proposition

These curves can be extrapolated by an exponential formula for larger number of apartments.

3. One or two stage of DHW production

Urban district heating systems in Central and Eastern Europe were built in the 60s of the XX. century. It is the history of the development of district systems, but is important that two stages of domestic hot water production stemmed from those conditions. Designed operating temperature of the systems was high: supply water of 150 °C, return water of 70 °C in case of direct connection and 80 °C at indirect connection (only special buildings like hospital, nursery, etc.). Previously, the heating season began and ended at the outdoor temperature of 10 °C. The operating temperature for the heating space was assumed to be 18 °C. Heating installation in buildings were designed at operating temperature (supply/return) 95/70 °C (exceptionally 90/70 °C). Figure 4. presents typical operating temperature diagram based on these figures.

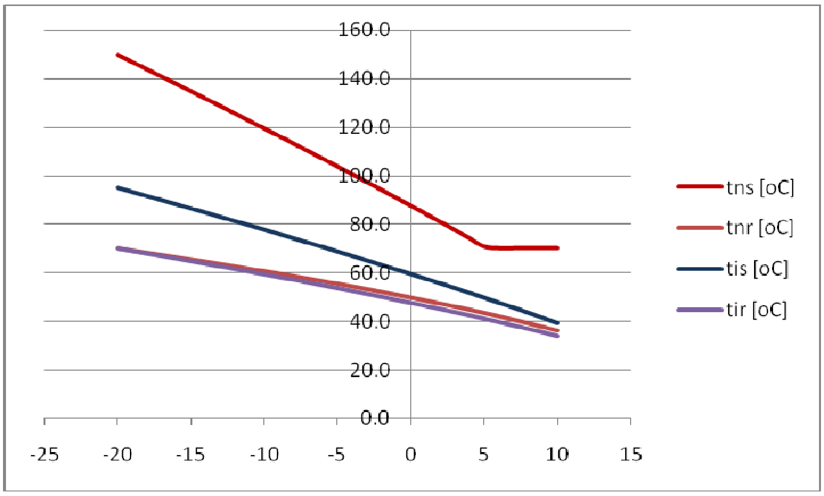

Fig. 4. Operating temperature diagram in past district heating systems and building installations (3. climatic zone in Poland) (Zarski, 2012)

Denotations:
t_{nso} – designed supply temperature of district heating water, °C,
t_{nro} – designed return temperature of district heating water, °C,
t_{iso} –designed supply temperature of installation water, °C,
t_{iro} – designed return temperature of district heating water, °C,
t_{ns} – actual supply temperature of district heating water, °C,
t_{nr} – actual return supply temperature of district heating water, °C,
t_{is} – actual supply temperature in installation, °C,
t_{ir}– actual return temperature from installation, °C.

The so called "breaking point" occurred at about 6 °C outdoor temperature. The supply temperature on the right side of the breaking point was constant because of domestic hot water demands. We can notice that the minimal temperature in return pipelines of district heating networks was about 38-39 °C. That allowed to use the potential of heat carried by the return water from the space-heating section for the first stage of domestic water heating. Heating installation in buildings were not equipped with thermostatic valves. The supply temperature in installation from the 70s of the XX. century was shaped by using a control valve in the heating section as the function of outdoor temperature, at the beginning simple direct control valves, later control valves with electrical actuators. The idea of two stage domestic hot water preparing is shown in Fig. 5.

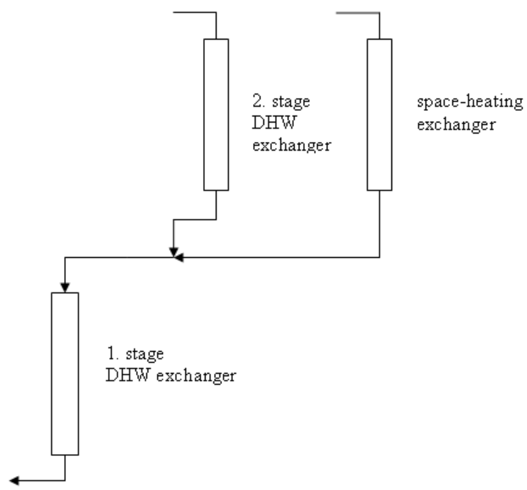

Fig. 5. Idea of two stage domestic hot water production

The return water from the space-heating section, after mixing with return water from 2. stage of DHW preparing, supplied 1. stage heat exchanger. At these parameters we could warm water in 1. Stage to about 30 °C. It was enough to divide the thermal capacity of DHW exchangers into 50%/50%. In contemporary district heating systems in Poland, Germany and Scandinavian countries the operating supply temperature of district heating systems is lower: in Poland extreme 130 °C, more often 120 °C, in some towns 105÷110 °C, in Scandinavia not higher than 60-80 °C, with a trend to decrease to 50 °C (Denmark). The space temperature is now of 20 °C, internal installations are designed at maximum 70 °C supply temperature, the heating season begins and ends at 12÷15 °C. Figure 7. illustrates a diagram of contemporary operating temperature in average conditions, in Poland. As can we notice the minimal temperature of return water from the space-heating section is not higher than 32 °C. On the right side of the breaking point (being moved to outdoor temperature of 1 °C) in primary circuit for space heating supply temperature is higher than required by heating installation. As a result this fact a mass flow in primary circuit decreases (control valve closes). Using simulation tools (Hexact, 2013) we can calculate real return water temperature in primary section. In table 1. real temperature of return network water is presented.

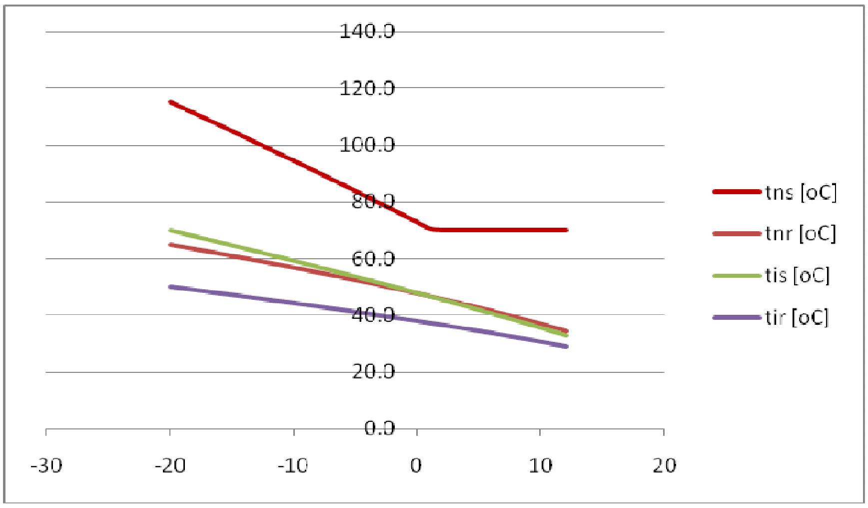

Fig. 6. Typical contemporary operating temperature diagram in district heating systems and building installations (3. climatic zone in Poland) (Zarski 2012), denotation as above

Tab. 1. Real return temperature in space-heating section (grey) (Hexact, 2013), denotation as above

t_e [°C]	t_{ns} [°C]	t_{nr} [°C]	t_{is} [°C]	t_{ir} [°C]
1	70.5	41.9	46.8	37.3
2	70.0	39.9	45.6	36.6
3	70.0	38.8	44.4	35.9
4	70.0	37.7	43.2	35.2
5	70.0	36.7	42.0	34.5
6	70.0	35.7	40.8	33.8
7	70.0	34.6	39.5	33.0
8	70.0	33.6	38.3	32.3
9	70.0	32.6	37.0	31.5
10	70.0	31.6	35.7	30.7
11	70.0	30.6	34.4	29.9
12	70.0	**29.5**	33.0	29.0

As we see the real return temperature is close to the return installation temperature. By mixing the return space heating water with return 2. stage exchanger water we **decrease** the supply temperature of 1. stage DHW exchanger. Practically 2. stage heat exchanger must warm water at almost full range (80÷90%). In heating installation equipped with thermostatic valves (at heaters) real return temperature from space heating section is stronger low. It is about 20÷25 °C. A mass flow in heating section is significantly smaller than in 2. stage DHW section (less than 10÷15%). If the surface area of the heaters it is over-surfaced than the temperature of return water is close to the temperature of heating space (20 °C). Table 2. gives results of the simulation (Zarski, 2006) in case of 10% over-surfacing of heaters. It is a normal margin of the surface area. The return temperature in the space-heating section (in primary circuit) will achieve about 20 °C because of small mass flow. In two stage domestic hot water production, heat exchangers in the second stage must deliver 100% of heat for warming water up. In existing heating substations with two stage of DHW production in Poland two heat exchangers work only at high temperature of supply water. At low supply temperature second stage of DHW takes over the total heat demand for water preparation.

Tab. 2. Real return temperature in installation in case of heaters over-surfacing (10%) design temperature: 70/50 °C, (Hexact, 2013), denotation as above

t_e [°C]	t_{is} [°C]	t_{ir} [°C]
1	46.8	25.0
2	45.6	24.2
3	44.4	23.3
4	43.2	22.5
5	42.0	21.7
6	40.8	21.0
7	39.5	20.5
8	38.3	20.2
9	37.0	20.0
10	35.7	20.0
11	34.4	20.0
12	33.0	20.0

4. Domestic hot water priority in one stage of district heating substation

Domestic hot water demands are rather irregular. The maximal values occur in short time periods. Priority of hot domestic water function assumes possibility of decreasing of heating installation capacity in maximum DHW consumption periods by limitation of opening of control valve in space-heating section. Contemporary buildings built in accordance to new thermal and saving energy standards have a large value of time constant. It is a range from 15 (light construction class) to over 200 h (heavy construction class). So time of growing cold of building is long in case of installation switching off. In time period of maximum HDW consumption lasting 1÷2 hours we can not notice a temperature falling even in shut-off heating installation case. If only in this time supply temperature falls at 2÷3 K, the result will be unseen. Figure 7. shows diagram (Harvey, 1993) consisting of characteristics of components of a complex heating system: heater (heat exchanger)and control valve with linkage. This characteristics is built according to the typical shape of a control valve plug – with logarithmic profile. Dependence of thermal capacity-plug lift is linear. It is optimal model for regulation of heating systems. Using the above diagram we can calculate the decrease in the space-heating capacity and the decrease in the mass flow of heating medium in dependence on the valve plug lift. If we assume fulfilling of 60% of the heat demand, the lift plug of control valve will be the same: 60%. In the break point of regulation curve temperature of installation of water (at design parameters 70/50 °C) will be 39/34 °C. Then if we decrease thermal capacity to 60%,the supply temperature after heat exchanger will be 37 °C. After another cycle of water flow in an installation, the supply temperature will be about 35 °C, at the next circle 33 °C, etc. This temperature decline is small and the indoor temperature would significantly change only in long time period. In tight and "warm" contemporary buildings this time will be about 8÷100 h. This is also compensated by heat gains (internal and external), not calculated in heat load estimation (EN 12831). This process allows us to decrease the total mass flow in district heating substations.

Total mass flow in common (connection) section with priority of DHW may be calculated as

$$m_{nw} = x \cdot m_{nh} + m_{nDHW} \tag{5}$$

where:
x –mass flow decreasing factor,
m_{nh} – mass flow in primary space heating circuit, kg/s,
m_{nDHW} – mass flow in primary domestic hot water circuit, kg/s.

Correlation between dimensionless plug lift and dimensionless mass flow (at constant differential pressure) shown in Table 3. (logarithmic profile of valve plug).

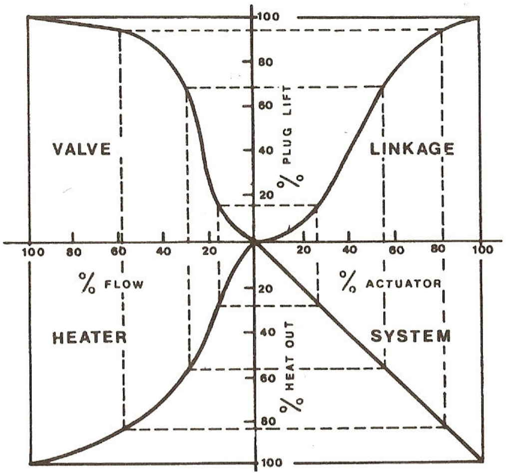

Fig. 7. Characteristics of complex heating system (Harvey, 1993)

Tab. 3. Dimensionless correlation between plug lift and mass flow in case of logarithmic plug profile (on the basis Harvey, 1993), bold letters – preferred values (Zarski, 2013)

Plug lift [%]1	Mass flow [%]
0	0
10	12
20	18
30	20
40	24
50	28
60	**30**
70	34
80	40
90	50
100	100

Mass flow of heating medium in a single district heating substation is calculated according to domestic hot water demands. In a district heating system with a large number of DHS time shift of maximum DHW demands in return (mixing) nodes allows to use for calculations of thermal balance the mass flow only for central heating needs. This is confirmed by the operation experience in large and medium sized district heating systems.

5. Advantages of decreasing district heating mass flow at domestic hot water priority in one stage district heating substation

In case of DHW priority we can expect smaller energy consumption for pumping the heating medium. If we assume the time of exceeding hourly average hot domestic water demands as 3 hours per day, we may calculate the rate of energy saving in a year. In Fig. 9. Shows pressure diagram in both cases: with and without domestic hot water priority in a branch of district heating network (design DHN in Torun). Total heating capacity: 87.78 MW. Control system in power plant should stabilize differential pressure in the farthest substation (using telemetry), not in a heat source! Result of simulation are shown in Table 4.

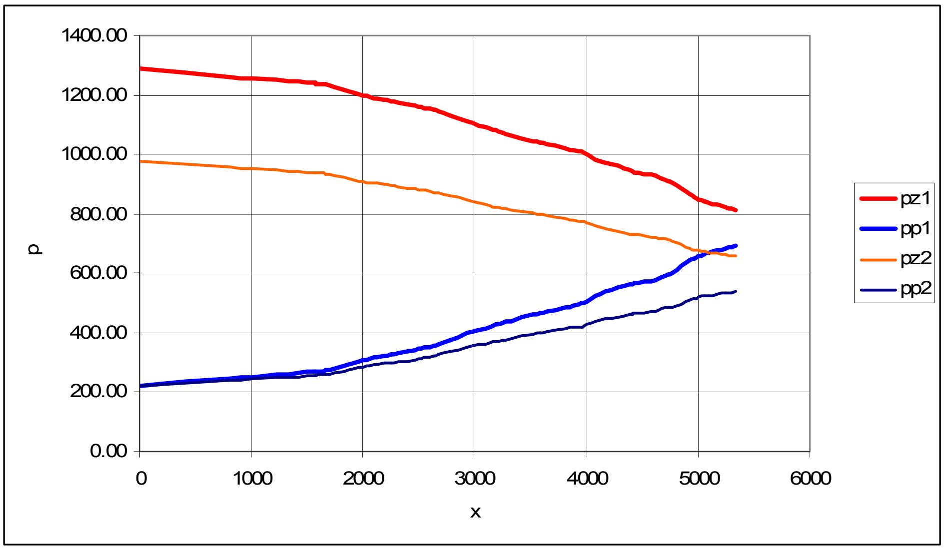

Fig. 8. Pressure diagram in district heating network with and without domestic hot water priority p_z – pressure in supply pipeline, p_p – pressure in return pipeline, index "1" – without DHW priority, index "2" – with DHW priority, p – pressure [kPa], x- distance [m]

Tab. 4. Energy consumption in a year for pumping water with and without DHW priority

	Without DHW priority	With DHW priority
Total mass flow, t/h	1411.95	1225.16
Differential pressure, kPa	1066.95	754.78
Electrical energy consumption (efficiency of 70%), kWh	253195	412483
Annual energy saving, kWh		159288
Annual energy saving, %		**38.6**

6. Conclusions

In the author's opinion in contemporary district heating system we have no condition for two stage domestic hot water production. District heating substations with one stage of DHW production is simpler and cheaper than the one with two stages. The total mass flow in district heating substation with one stage of DHW and domestic hot water production is not larger than in a two stage station. Priority DHW function gives significant rate of saving electrical energy for pumping water in urban district heating systems. For example, the annual energy saving rate is about 40%. It is a **significant** value, regarding technical, economic and environmental requirements and international regulations.

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