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Analysis of energy recovery from surplus water pressure of municipal heat distribution network

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Abstract. The correct operation of a heating network system depends on appropriate water parameters of a network, especially a water pressure. The heating source provides the water pressure depending on the worst conditioned water main in the network. The structure of the water heating network depends largely on the landform features and, in many situations, a pressure zone with the pressure reducing valves is required. This excess pressure gives an opportunity for energy recovery during reduction of the pressure from the system. This can be done by substituting the existing mechanical pressure reducing valve by a water turbine combined with an electrical generator. In the paper, an example of a heating system is analysed and possible recovered energy is calculated assuming a specific value of energy conversion system efficiency. The real tests of the prototype reducer showed possibilities to achieve satisfying efficiency of an energy conversion. The presented economic analysis confirmedpotential of the proposed system.

1. Introduction

A heat distribution network has gained high importance during the last few years due to environmental care, safety and reliability aspects [1]. The district heating allows to reduce pollutant and thermal emissions in a city. Furthermore, centralized production eliminates combustion systems and increases safety of afinal user.

In order to provide the correct operation of a heating network the appropriate working medium (water) parameters (pressure, temperature and flow rate) have to be provided [2]. These parameters change seasonally according to the outside temperature. The parameters of a heat source depend also on a hydraulic network structure and landform features and they can be calculated taking into account pressure, flow, and thermal losses in the distribution system. The system enlargement requires higher water pressure at the point of a heat source what often causes places (network nodes or mains) where the pressure has to be reduced. This situation creates an opportunity to recover energy what can be identified by analyzing the piezometric graphs. These graphs present the water pressure distribution and pressure relations in the network for specific points (heat sources, pipes and nodes) taking into account ageodesic profile along with the network route. The additional parameters like: the saturation pressure of water for a specific temperature point, a pressure limit of the installation elements or the pressure, necessary to fill the installation with water, are also presented. The graphs include: the pressure losses in the heat source,the circulating pomp pressure, the pressure losses in a specific

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network segment, the available pressure of each node as well as the connection technique of the node with the heat network and pressure stabilization method applied in the network.

The heat distribution network is not well investigated yet from the energy recovery point of view. In scientific literature, the water supply systems are indicated as main infrastructures that offer hydropower potential [3,4]. The surplus energy resulting from excess pressure is located in lower topographic areas [5,6]. It is also shown that the pressure reduction can decrease the leakage problem [7], however the optimal location of the reducer is difficult due to the complex network topology and asymmetric water demand [8].

This paper presents the hydropower potential of the heat distribution network on an example of the Cracow city. The analysis of energy recovery from surplus water pressureincludes two possible solutions that distinguish places of energy recovery (nodes or mains). Furthermore, the example solution of the eco-reducer device and its main features are described. Finally, the economic analysis of the proposed installation is done.

2. Description of analysed heat network

The analyzed Cracow heat network covers the most of the city area. It contains three heat sources: EDF Kraków S.A. (EDF), Power Plant Skawina S.A. (Skawina) and Heat and Power Station ZE-7 ArcelorMittal Poland S.A. Cracow (ArcelorMittal),which power supply contribution equal respectively: 72.3%, 24.2% and 3.5%. The network is based on the eight water mains with the diameter range from 600 mm up to 1000 mm. The diameters of network pipes are reducedhowever they are not lower than 40 mm. The network topology is mixed due to the different arrangements of the network parts (radial branched, multi-ring, network couplers etc.). The network length is estimated at about 780 km, with the 8300 heated buildings and the total thermal power equals 1572 MW. The height difference between the highest and lowest network point is 73m which requires providing the high water pressureat the heat source.

The water parameters variationof the main supplier (EDF) with the main distinction for one-year period are presented below (Figure 1 – 3).The heating season begins inOctober and lasts till April. The presented variation is typical for the heat system and it is the most significant for water flow. The average water parameters at the supply point for the all heat sources (in season and out of season) are listed in Table 1. The average water flow rate supplied by the biggest source (EDF) in the heating season equals 12500 t/h and 1250 t/h out of season. The differences of the other parameters (temperature and pressure) are significantly smaller.

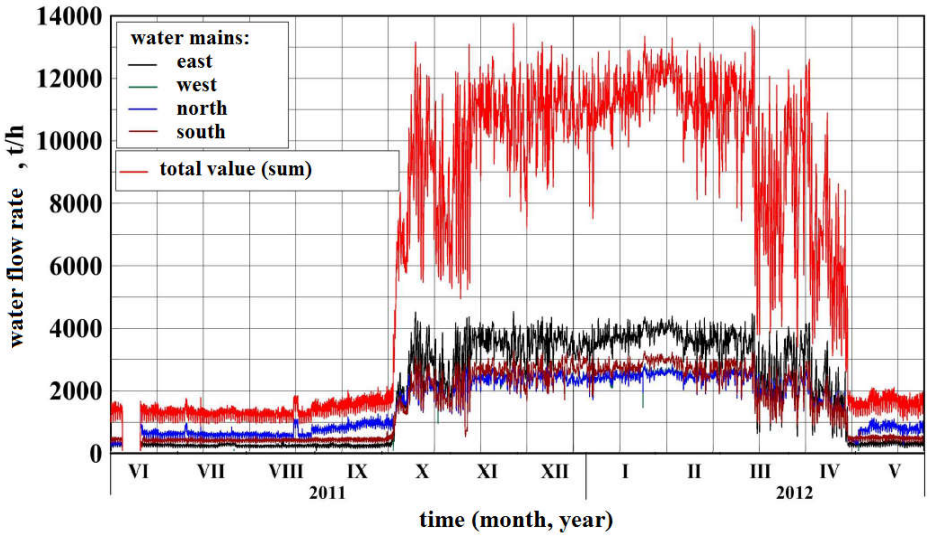


Figure 1. The water flow rate in the mains supplied by the EDF in one-year period.

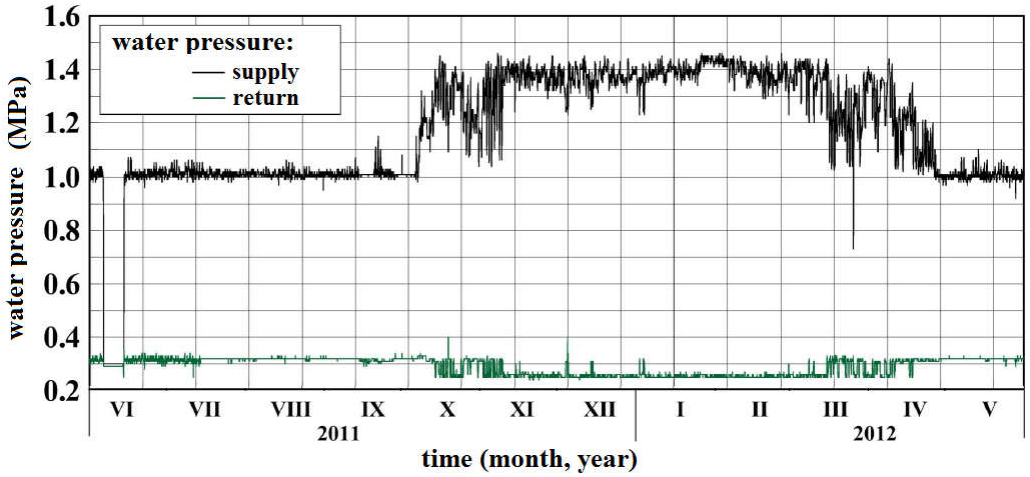


Figure 2. Water pressure variation at the supplier point (EDF) in one-year period.

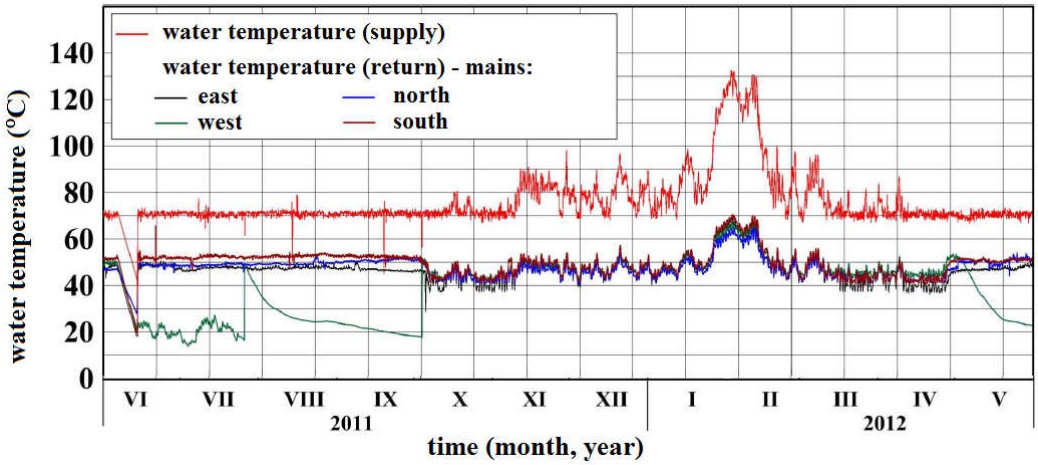


Figure 3. Water temperature variation of the mains supplied by the EDF in one-year period.

Table 1. The average water parameters at the supply point of heat sources in season / out of season.

heat source	flow rate (t/h)	supply pressure (MPa)	return pressure (MPa)	temperature (°C)
EDF	12500 / 1250	1.42 / 1	0.25 / 0.33	80÷130 / 70
Skawina	3800 / 550	1.34 / 0.85	0.4 / 0.43	
ArcelorMittal	660 / 50	0.8 / 0.78	0.2 / 0.18	

3. Calculations of surplus energy possible to recovery

As mentioned in Introduction, a possibility and potential amount of energy can be assessed by analyzing the piezometric graphs of the mains. When the pressure difference between the supply and return main at its end point is higher than 0.25 MPa then it is possible to recover energy from the surplus pressure.This process can be realized directly at the supply point of the main and branch points or in the network nodes.These two variants are analyzed below. Furthermore, it is possible to substitute the existing mechanical pressure reducing valve by a special device.

The energy of the excess pressure of water can be converted into the power P according to the following formula [9]:

$$P = 277{,}6 \cdot M \cdot \Delta p \cdot \eta \quad (1)$$

where M is the mass water flow rate (t/h), Δp is the surplus of pressure difference (MPa), and $\eta$is theefficiency of the device.

In the paper, it is proposed to convert water energy into electrical energy which is convenient to transfer and utilize or sell. This can be done with water turbine integrated with an electrical generator, so called the eco-reducer. Optionally, the power electronic converter that converts parameters of electrical energy to the desired one can be applied. Thus, the total efficiency of the eco-reducer equals the product of the individual efficiencies of its elements (2), where η_t is the turbine efficiency, η_g is the generator efficiency, and η_c is the converter efficiency. In the further analysis, the total average efficiency of the eco-reducer, which equals 50%, is assumedand is justified in chapter 4.

$$\eta = \eta_t \cdot \eta_g \cdot \eta_c \tag{2}$$

3.1. Variant I – energy recovery fromnetwork nodes

This solution analyzes the energy recovered in the network nodes and in the existing pressure reducing point in the mains.It is assumed that pressure difference exceeding 0.2 MPa in the nodes can be utilize to produce electrical energy. Additionally, only the nodes where the generated electrical power equal or higher than 1 kW are considered because of the technical realization and cost-effectiveness.

In the analyzed system there are about 4000 network nodes, however the number of the nodes that fulfill a power limit in the season equals 116. The detailed list of the nodes number depending on a range of power recovery and season is presented in table 2. From this table follows that it is possible to recovery 355 kW/h in season. Unfortunately, this energy reduces drastically to 15 kW/h that can be recovered from the 10 nodes out of season.

Table 2. Number of nodes and total power depending on the power range and season.

Power range (kW)	<0.25	0.25÷0.5	0.5÷1	1÷1.5	1.5÷2.5	2.5÷5	>5
in the heating season							
Number of nodes	3154	503	173	30	38	32	16
Total power (kW)	283	174	115	37	73	121	124
out of the heating season							
Number of nodes	3876	31	29	7	3	-	-
Total power (kW)	105	10.5	20	8	7	-	-

Additionally, the existing 11 pressure reducing points in the mains can be utilized. The available power of each main in season and out of season is given in table 3. It follows that the mainsallow to generate 194 kW/h in season and 20 kW/h out of season.

From this analysis follows that possible energy recovery in this variant equals 549 kW/h in heating season and only 35 kW/h out of the season.

Table 3. Power recovery value from specific main in season and out of season.

Main number	1	2	3	4	5	6	7	8	9	10	11
Power in season (kW)	50	10.8	6.1	36	37.3	8.6	3.8	2	16.7	16.4	6.3
Power out of season (kW)	-	-	-	6.1	6.8	1.1	1.4	-	3.6	1	-

3.2. Variant II – energy recovery from water mains

The second variant considers the energy recovery mainly directly at the heat supply points of the main and branch points. The target is to provide the pressure difference between the supply and return main at its end point which equals 0.25 MPa. It is assumed to eliminate all existing pressure reducing points

in the mains. Thissolutionis presented on an example of the east main of the EDF supplier (Figure 4). The actual hydraulic conditions of the heat network are modified significantly.

The detailed analysis of the piezometric graphs showed that in the heat season it is possible to recover 857 kW/h thanks to the eco-reducers which power range from 3.5÷161 kW. Naturally this value decreases to 93 kW/h out of season and the power range of eco-reducers is 6÷44 kW. However, there is still some pressure excess in some network nodes which can be utilized. This is possible only in the heating season and this power does not exceed 27 kW (Table 4).

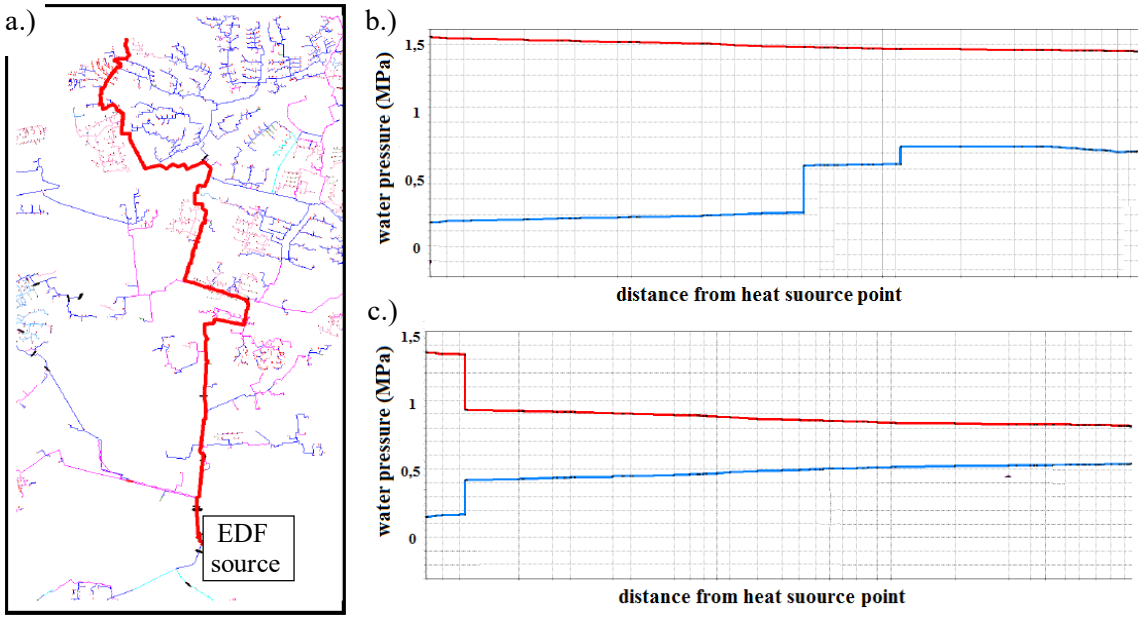


Figure 4. The east main of the EDF source: main route (a), actual piezometric graph (b), modified piezometric graph according to the Variant II (c).

Table 4. Power recovery value for Variant II in season and out of season.

Time period	Value of power recovery (kW)			
	mains	branches	nodes	total
Heating season	668	189	27	884
Out of heating season	93	-	-	93

3.3. Variants comparison

The above presented variants should be compared taking into account several criteria. Firstly, the power value that can be recovered and a possibility of its utilization have to be analyzed. Then, the number of eco-reducers and the range of the nominal power needs to be assessed. Finally, troublesomeness of the installation and network reliability are also important. This comparison is presented in Table 5.

Table 5. The comparison of the proposed variants of the energy recovery in heating network.

	The solution of the energy recovery	
	Variant I	Variant II
Advantages	- Narrow power range of the eco-reducers (easy to standardize) - Small dimensions (pipe diameter: 50÷150 mm) - Possibility of utilizing energy on installation place - Small noise level	- Higher power to recovery - High power of the individual eco-reducer - Small number of eco-reducers
Drawbacks	- Smaller total power value than in Variant II - High number of eco-reducers	- Wide range of the eco-reducer dimensions (pipe diameter: 200÷800 mm) - Significant modification of present hydraulic conditions - Limited possibility of utilizing energy on installation place - Higher noise level - Eco-reducer failures can limittransfer of heating energy to consumers

4. Technical solution of eco-reducer

The eco-reducer aim is to convert energy of the excess water pressure into electrical energy. Thus, the main elements of the device are a water turbine and an electrical generator.

Taking into account the water parameters a recommended solution is the Francis turbine. However, due to investment costs and simplicity of a mechanical system, a better choice is to apply the vortex water pump adapted for turbine work [10]. The permanent magnet synchronous machine, which provides high efficiency over a wide range of generated power, is selected as the electrical generator. As mentioned before, it is convenient to use the power electronic converter that matches parameters of electrical energy to the desired ones. What is more, this converter allows to work with variable speedsand adjusts the turbine speed according to actual water parameters in order to achieve the best efficiency[11].

The prototype eco-reducer of 2 kW power was installed and tested in a real node network (Figure 5a). The detailed device features are presented in paper [9]. The important result is the energy conversion efficiency which value reaches 60% and it exceeds 50% in a wide range of the water flow variation (Figure 5b). This confirms correctness of the average efficiency value, which equals 50%, and which is assumed in the analysis.

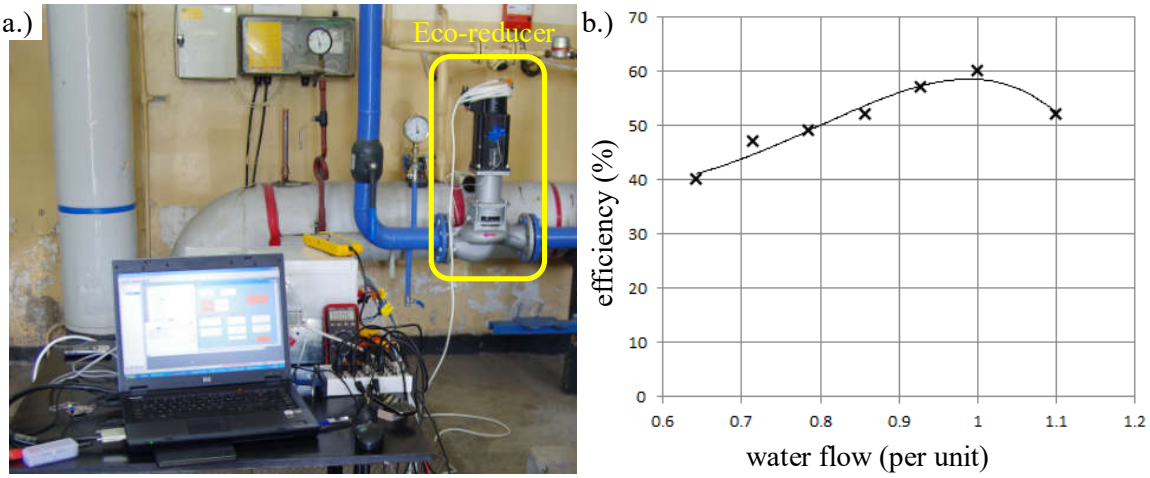


Figure 5. The eco-reducer tests: research benchin the real network node (a), energy conversion efficiency as function of the per unit water flow (b).

5. Economic analysis

The economic analysis requires additional assumptions. The heating season which lasts six months(4500 hours) is analyzed. The estimated cost of the 1 kW eco-reducer is 1200 Euro for a standardized device and 1700 Euro if an extra design process is necessary. The price for the 1 kW recovered energy is 10 Euro cents. Additionally, the correction factor, which equals 0.7, and which considers the water flow variations is introduced.

Firstly, the Variant I is calculated. According to the data presented in chapter 3.1 the recovered energy equals: E = 549kW·4500h·0.7 = 1 729 330 kWh. Taking into account the energy price the income is 172 935 Euro. The number of the eco-reducers equals 127 (116 in nodes and 11 in mains), but there are only 15 different constructions considering a pipe diameter and power (Table 6). Thus, the system cost is:

C = (62kW·1700Euro + 347kW·1200Euro)+(124kW·1700Euro + 74kW·1200Euro)=821 400 Euro

Taking into account additional costs (nodes and mains adaptation), which equal 30% of installation costs, this investment should provide a return in 6 years (T=1.3·821 400 Euro/172 935 Euro ≈ 6 years).

Table 6. List of the eco-reducer nominal power matched to the Variant I.

Installation place	Network nodes									Existing reducing points					
Nominal power (kW)	2	3	4	5	6	7	9	11	15	3	8	10	16	37	50
Number of devices	57	21	14	9	4	4	3	2	2	2	2	2	2	2	1
Installed power (kW)	409									198					

The analogous calculations are performed for Variant II. In these case, the recovered energy is higher (according to chapter 3.2) and equals: E = 884kW·4500h·0,7 = 2 784 600 kWh. The drawback of this variant is the limited possibility of utilizing the recovered energy on a place. It means that a part of this energy needs to be sold. It assumed that 50% of energy is sold and the price for 1kW sold energy is 5 Euro cent.The income is calculated as: I = 2784600 kWh/2·0,1Euro + 2784600 kWh/2·0,05Euro = 208 845Euro. This Variant includes only 43 eco-reducers (7 in mains and 18 in branches and 18 in nodes), with 17 different nominal powers (Table 7). Thus the system cost is:

C = (439kW·1700Euro + 225kW·1200Euro)+(123kW·1700Euro + 64kW·1200Euro) + (6kW·1700Euro + 32kW·1200Euro) = 1 350 800 Euro

Taking into account additional costs (network adaptation), which equal 30% of installation costs, this investment should get a return in 8.5 years (T=1.3·1 350 800 Euro/208 845 Euro ≈ 8.5 years).

Table 7. List of the eco-reducer nominal power matched to the Variant II.

Installation place	mains					branches										nodes	
Nominal power kW	44	60	70	110	155	4	5	7	8	9	10	11	14	25	30	2	4
Number of devices	1	1	2	1	2	2	3	1	2	3	2	1	2	1	1	17	1
installed power kW	664					187										38	

It is important to point out that presented calculations consider only the heating season. As presented in chapter 3 there is some energy to recover also out of season inthe both Variants. However, the conversion efficiency of the eco-reducer decreases during an operation in the low power range (see Figure 5b). Taking into account this additional income it can be estimated that the return time for the Variant I is shortened to 5 years and for Variant II to 7 years.

6. Conclusions

The presented paper shows the possibilities of energy recovery in the heating network on an example of the Cracow city.The detailed analysis of the network structure and hydraulic parameters allowed to proposed the two variants of system realization.

Despite the fact that the recovery energy in the Variant I is lower, this solution has important advantages. First of all, the time of an investment return is shorter and lasts 5 years. The possibility of the energy utilizing on-place (e.g. by pumps of heat exchanger) reduces the electrical energy consumption ofthe specific node. This simplifiesa system implementation because it does not require any modifications ofan electrical installation andno extra legal and technical arrangements with an electrical energy supplier are needed. Furthermore, the investment costs are almost two times lower than in the Variant II. This solution is also simpler from a technical point of view. There are many similar installation places and a temporary system time-out resulting from a device failure is permissible. The application of eco-reducer in the mains, which is the base of the Variant II, requires implementing safety systems which are not included in the system costs. These features cause that the Variant I seems to be a better solution.

The prepared analysis requires to introduce a few assumptions. The important parameter, which has significant importance on the investment return time, is the eco-reducer efficiency as a function of power. The tests of the prototype device confirma possibility of achieving efficiency higher than 50% in a wide operating range.The precise design process can improve this parameter more.

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