Feasibility study of collector-distributor district heating system

D O Romanov, Y V Yavorovsky, E V Zhigulina and A Y Shelginsky

Department of industrial heat engineering systems, National Research University "Moscow Power Engineering Institute", Krasnokazarmennaya str. 14, Moscow, 111250, Russia

E-mail: dimrom09@yandex.ru

Abstract. One of the ways to improve efficiency of district heating systems is to use thermo-hydraulic dispatchers (THD) along with distributed variable speed pumps (DVSP) for reducing electricity consumption. First part of this paper deals with the application of THD at consumers to evaluate its technical and economic advantages. Although the result of the analysis shows that savings are quite small for Moscow conditions, the solution still might be applicable due to low additional capital expenditures. The second part of the paper uses the obtained result and summarizes previous works in this field to introduce collector-distributor district heating system which extensively incorporates THD and DVSP. Feasibility study of the proposed system was performed in comparison with a conventional district heating system. Electricity saving potential of collector-distributor district heating system is estimated to be 42-129 MW*hr/yr, while discounted payback period of additional capital expenditures is less than 2 years.

1. Introduction

District heating systems, in general, have branch or ring structures requiring significant amount of electricity for pumping a heat carrier. Usually required hydraulic head of central circulating pumps is defined by the most distant consumer from the heat supply source. It leads to redundant power of the pumps which is wasted by throttle valves in substations and consumers located closer to the heat supply source. In order to make district heating systems more efficient, new designs and concepts of hydraulic network are being proposed. New hydraulic scheme of district heating system based on distributed variable speed pumps (DVSP) and hydraulic connector was investigated both analytically and experimentally in [1-8]. It was shown in [1] that DVSP system consumes at least 31% less than conventional system. Similar research works [2-4] showed that savings reach almost 50%. Hybrid scheme, in which both DVSP and throttling valves are used, is considered in [5]. In this case, annual electricity consumption is estimated to be 28.5% less than in conventional system.

The hydraulic scheme with DVSP can be also applied to district cooling systems. District cooling system with cooled water storage and DVSP is shown in [6]. The cooled water storage in the system can be considered as large hydraulic connector. The analysis showed that the system allows for 10% of electricity saving in comparison with conventional district cooling system. District heating and cooling system with DVSP was considered in [7] and, in result, annual equivalent costs were reduced by 20.8-27.7%. An interesting idea of coupling district heating system with district cooling system by means of energy bus system was proposed in [8]. Energy bus system consists of heat pumps, ring topology pipe network, DVSP, hydraulic connectors, and heat and cold consumers. The results showed that this system can utilize waste or low-exergy heat during the whole year. Moreover, DVSP along

with hydraulic connectors allow for electricity saving as well as thermal and hydraulic decoupling of sources and consumers.

Thermohydraulic dispatcher (THD) is a device similar to hydraulic connector, but the difference is that usually THD has several manifolds adjusted to connect several consumers or (and) sources with their own pipe network. Several papers concerning experimental research of THD and its potential application to district heating systems have been recently published [9-13]. Different schemes of heat substation (direct connection, indirect connection, scheme with THD) were analyzed and electricity saving effect was calculated as well as capital costs in [11]. Different types of heat substation connection to heat supply network (conventional scheme, DVSP scheme, THD-based scheme) were analyzed in [13]. So, before performing overall analysis of THD implementation in district heating systems, which is the end goal of this paper, analysis of consumers, namely, space heating (SH) systems connected to THD is needed to be done.

2. Methods

Figure 1 shows two ways of organizing SH systems at consumers' side. Conventional system is depicted on the left side, while the system with THD is on the right side of Figure 1. The latter suggests replacement of automatic balancing valve along with partner valve with variable frequency pump. This allows for avoiding interdependence of SH loops. If a wet rotor pump is applied, then showed in Figure 1 sensor, frequency converter, and controller are not needed, as they are integrated into the pump. The electricity consumption of two schemes differs by the value that is throttled in the balancing valve. So, electric output that is reduced can be estimated by equation (1):

$$\Delta N = \frac{0.0278 \cdot V^3}{\eta \cdot kvs^2} \tag{1}$$

V – volume flow rate, m^3/hr.
η – coefficient of performance (COP) of pump.
kvs – amount of flow through a fully-open valve under pressure difference of 1 bar, m^3/(hr·bar$^{0.5}$).
0.0278 – coefficient for conversion to kW.
The reduction of electricity consumption can be calculated by equation (2):

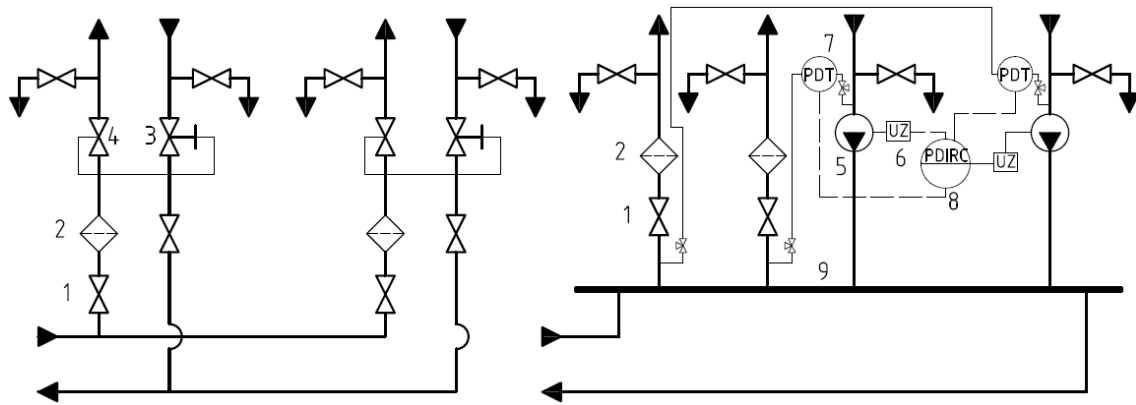$$\Delta E = \Delta N \cdot \tau \cdot 24 \tag{2}$$

ΔE is the reduction of electricity consumption, kW·hr.
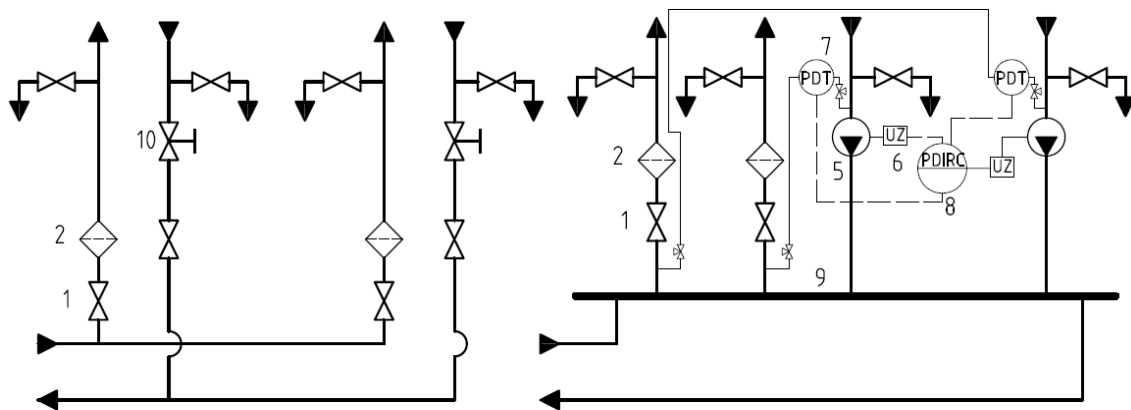τ is duration of heating period.

While Figure 1 suits for two-pipe SH system where radiators are connected in parallel, Figure 2 represents one-pipe SH system (connection of radiators in series).The difference between one-pipe and two-pipe SH systems lies in using different balancing valves. However, aforementioned principles are correct for one-pipe SH system as well.

COP of pump = 0.6 and was assumed to be constant value. Although this value might change, it was shown in [14] that pump efficiency change can be neglected if speed change is less than 33%. Density of water = 1000 kg/m^3. Duration of heating period in Moscow is 205 days. Discount rate = 0.08. For the sake of simplicity, calculations were performed under condition that balancing valves are fully open during the whole heating period. So, calculated values of electricity economy can be considered as minimum ones. However, during heating period it is most likely that thermal and hydraulic regimes of consumers change and so does the valve opening. So, the goal of the analysis is to show minimal energy saving potential.
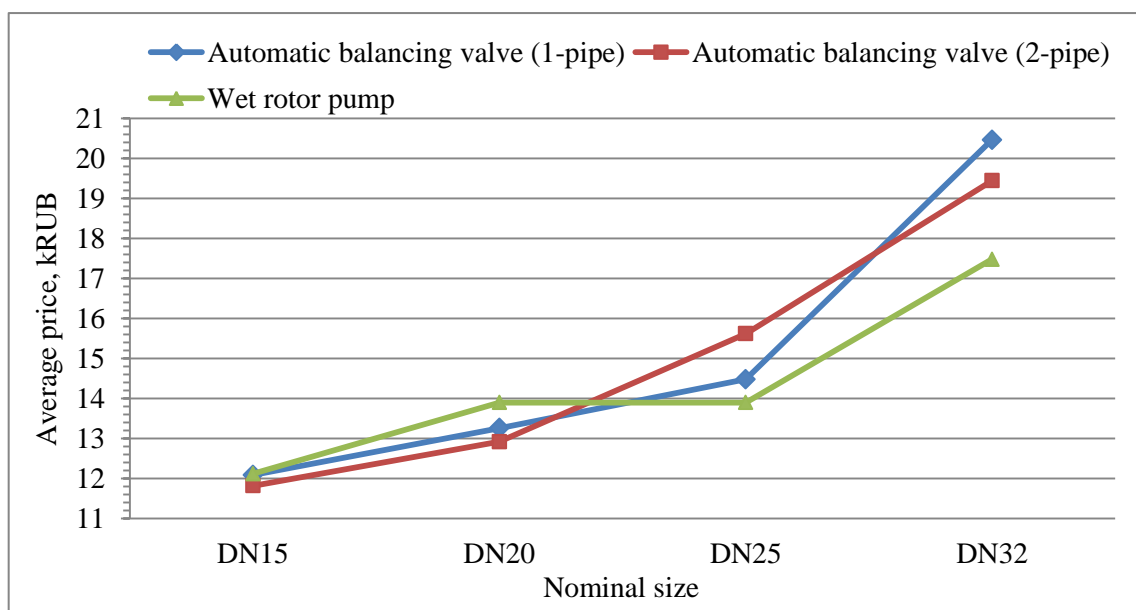
Average prices of automatic balancing valves (for one-pipe and two-pipe systems) and wet rotor pumps were received from manufacturers. These values are represented in Figure 3.

Figure 1. Principal schemes of space heating system (conventional scheme – on the left, scheme with THD – on the right); 1 – shut-off valve, 2 – strainer, 3 - automatic balancing valve (two-pipe version), 4 – partner valve, 5 – pump, 6 - variable speed drive, 7 – pressure difference sensor, 8 - programmable logical controller, 9 – THD.

Figure 2. Principal schemes of space heating system (conventional scheme – on the left, scheme with THD – on the right); 10 – automatic balancing valve (one-pipe version).

Figure 3. Average prices of automatic balancing valves and wet rotor pumps replacing them.

3. Results

The results of calculations are shown in Table 1, in which ΔE is electricity economy during a year, ΔOPEX is decrease of operational expenditures due to electricity economy. It turned out that economic effect of replacing balancing valves with wet rotor pumps varies from 130 to 510 RUB/yr for a single SH loop. Although these values are very small, it is worth noting that a multi-family building usually has many SH loops. And taking into consideration the whole district, it is possible to get much higher overall economic effect. Moreover, the estimated effect doesn't account for dynamic operation of SH system, which can also lead to higher values. Analyzing Figure 3 and Table 1 one can draw a conclusion that discounted payback periods of additional capital expenditures in comparison with conventional SH system for small diameters (DN15 and DN20) are 1-7 years. However, the average prices of automatic balancing valves DN25 and DN32 are even higher than those of wet rotor pumps; therefore in this case, installation of the pumps along with THD instead of automatic balancing valves leads to reducing operational expenditures as well as capital ones.

Table 1. Feasibility study of single SH loop of the scheme with THD in comparison with conventional scheme.
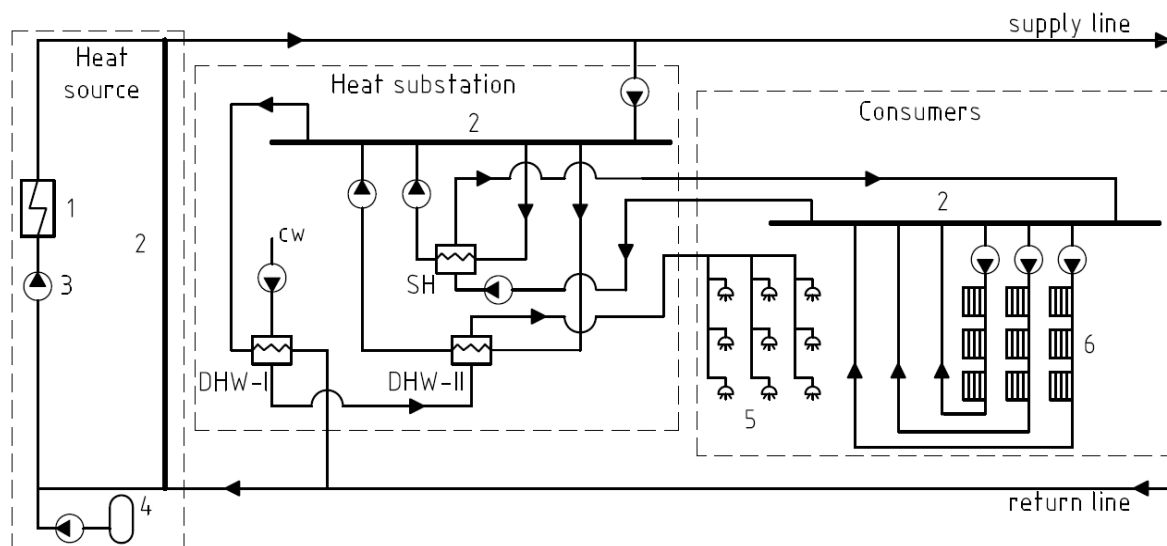
	V (m³/hr)	kvs (m3/hr·bar0.5)	ΔN (W)	ΔE (kW·hr/yr)	Tariff (RUB/kW·hr)	ΔOPEX (RUB/yr)	Discounted payback period (yr)	
							1-pipe SH	2-pipe SH
DN15	0.62	1.6	4.3	21.2	6.1	130	1	3
DN20	0.97	2.5	6.7	33.1	6.1	200	4	7
DN25	1.55	4	10.8	52.9	6.1	320	_	_
DN32	2.44	6.3	16.9	83.4	6.1	510	_	_

Logical development of obtained results and previous works can be represented by collector-distributor district heating system which includes DVSP and THD installed at heat supply source, heat substation and consumers. The system suggests that losses of electric energy are minimal due to replacement of throttling valves with variable frequency pumps. At the same time, such system allows for implementing different control strategy (either supply temperature control or flow control, or combination of both). Figure 4 shows the principal scheme of collector-distributor district heating system, while the principal scheme of conventional system is shown in Figure 5. In Figure 4, heat substations are connected to the network according to DVSP scheme [1], while SH and DHW heat exchangers are connected to the heat substation through THD, and radiators are connected to heat exchangers through THD as well. Shown in Figure 4 features of the system are two-stage DHW system, indirect connection of SH system through the heat exchanger and one-pipe SH system. But it is not necessary to follow only these features, therefore one-stage DHW system, direct connection of SH system without heat exchanger, two-pipe SH system are also possible depending on reference data for design, technical restrictions, and economic calculations.
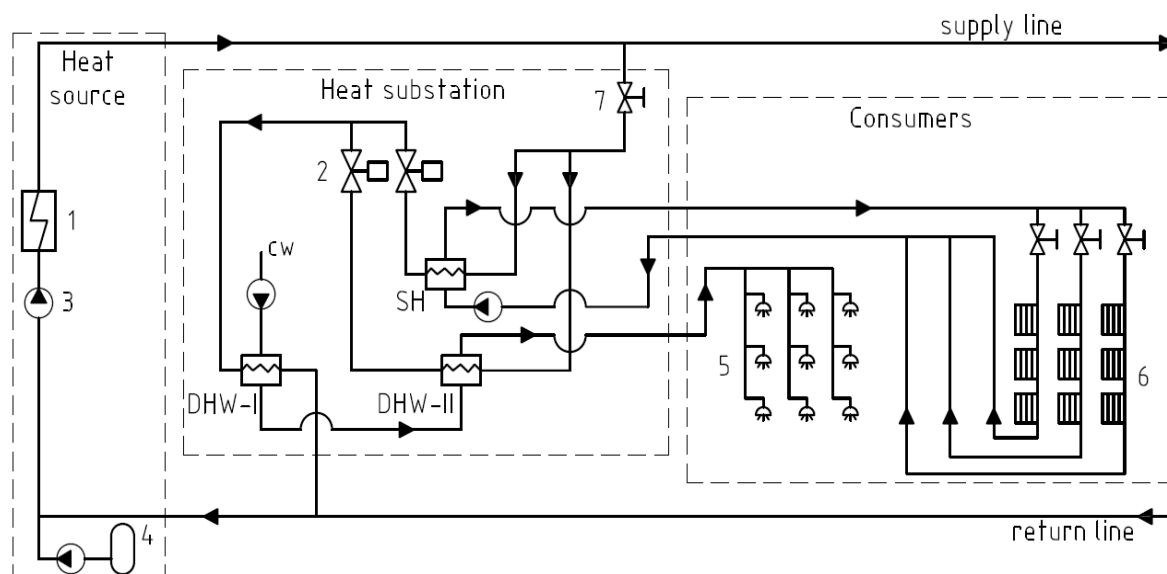
In [4], it was shown that energy saving effect of DVSP system increases if pressure losses at consumers decrease. So, collector-distributor district heating system embodies this principle by using THD at heat substation and consumers, thus allowing for decreasing pressure losses at heat substations and consumers which leads to greater overall saving effect.

Based on the previous results, feasibility study of collector-distributor district heating systems in comparison with conventional district heating systems was performed. One-pipe SH system, indirect connection of SH and DHW systems through THD, one-stage DHW system were chosen for calculations. Systems with 3 different total heat outputs were considered: 2.4 MW, 7.2 MW, and 14.4 MW. The results of calculations can be seen in Table 2, 3, and 4, in which ΔCAPEX is increase of capital

expenditures. Analysing the results, it is clear that the network and source have the greatest electricity saving effect, while consumers have the least one. Overall result demonstrates that collector-distributor district heating system has less operational expenditures and more capital expenditures than conventional system. Electricity economy varies from 42 to 129 MW*hr/yr. However, discounted payback period of additional capital expenditures for all three cases is less than 2 years which is a good indicator for choosing collector-distributor district heating system over the conventional one.

Figure 4. Principal scheme of collector-distributor district heating system. 1 – heat supply source, 2 – THD, 3 – pump, 4 – water tank, 5 – tapping points, 6 – radiators. SH – space heating system heat exchanger. DHW-I – domestic hot water supply heat exchanger (the first stage). DHW-II – the second stage, cw – cold water.

Figure 5. Principal scheme of conventional district heating system. 1 – heat supply source, 2 – control valve, 3 – pump, 4 – water tank, 5 – tapping points, 6 – radiators, 7 – balancing valve. SH – space heating system heat exchanger. DHW-I – domestic hot water supply heat exchanger (the first stage). DHW-II – the second stage, cw – cold water.

Also capital expenditures of consumers might be less than in conventional system which is shown in the ΔCAPEX column of the tables. It can be seen in Table 2 that capital expenditures on consumer units and heat substation in collector-distributor system is equal to those of the conventional one. So, the system with total heat output of 2.4 MW has smaller payback period than others.

Table 2. Feasibility study of collector-distributor district heating systems in comparison with conventional district heating systems. Total heat output is 2.4 MW.

Elements of collector-distributor system	ΔE (kW·hr/yr)	ΔOPEX (kRUB/yr)	ΔCAPEX (kRUB)
Consumers (21 units; one-pipe SH loop; THD and wet rotor pump instead of balancing valve DN15)	445	3	1
Heat substation (3 units; THD+indirect SH, 0.3 MW; THD+one stage DH, 0.5 MW)	2244	14	0
Network and supply source (DVSP scheme; 2.4 MW)	39011	238	291
Total	41701	254	292

Table 3. Feasibility study of collector-distributor district heating systems in comparison with conventional district heating systems. Total heat output is 7.2 MW.

Elements of collector-distributor system	ΔE (kW·hr/yr)	ΔOPEX (kRUB/yr)	ΔCAPEX (kRUB)
Consumer (39 units; one-pipe SH loop; THD and wet rotor pump instead of balancing valve DN20)	1291	8	25
Heat substation (3 units; THD+indirect SH, 0.9 MW; THD+one stage DHW, 1.5 MW)	9594	59	465
Network and supply source (DVSP scheme; 7.2 MW)	83030	506	429
Total	93915	573	919

Table 4. Feasibility study of collector-distributor district heating systems in comparison with conventional district heating systems. Total heat output is 14.4 MW.

Elements of collector-distributor system	ΔE (kW·hr/yr)	ΔOPEX (kRUB/yr)	ΔCAPEX (kRUB)
Consumer (48 units; one-pipe SH loop; THD and wet rotor pump instead of balancing valve DN25)	2539	15	-28
Heat substation (3 units; THD+indirect SH, 1.8 MW; THD+one stage DHW, 3.0 MW)	29289	179	597
Network and supply source (DVSP scheme; 14.4 MW)	97629	596	527
Total	129457	790	1096

4. Discussion

There are 3 possible operating regimes of THD:

- mixing regime (when total flow rate in primary circuits is less than that in secondary circuits);
- nominal regime (when total flow rate in primary circuits is equal to that in secondary circuits);
- bypassing regime (when total flow rate in primary circuits is bigger than that in secondary circuits).

It is worth pointing out that THD should work in nominal regime. Otherwise, electricity saving effect may not be reached. Therefore, when changing flow rates in secondary circuits, flow rates in primary circuits should be changed accordingly. This can create some difficulties for control system of collector-distributor district heating system. At the same time, regulation method of a system based on multiple distributed pumps was described in [15] and can be used for collector-distributor district heating system as well. The system is likely to have both flow control and supply temperature control strategies because variable frequency pumps have limited range of regulation. Nevertheless, regulating algorithms of collector-distributor district heating system should be further investigated.

Dynamic operation of the proposed system was neglected in this paper, but it is important for a hydraulic network to cope with changing flow rates and heat loads. So, dynamic models are necessary for more accurate calculations and developing control strategies. Although some models have been developed in [1,16], this subject can also be further investigated and new improved models can be developed.

5. Conclusion

After having analyzed the possibility of connecting SH system through THD and replacing automatic balancing valves with DVSP, it was clear that this solution is feasible for Moscow conditions, especially for diameters of balancing valves DN25 and DN32. For DN15 and DN20, discounted payback period is 1-7 years.

Then collector-distributor district heating system including THD and DVSP was proposed in this paper. Its feasibility study shows that it is possible to save 42 - 129 MW*hr/yr of electric energy in district heating systems of 2.4 - 14.4 MW heat output. The savings can be higher if dynamic operation and flow control strategy are taken into account. At the same time, additional capital investments in comparison with conventional system are relatively low and the discounted payback period is less than 2 years.

The concept of using THD along with DVSP might be also applicable to district cooling systems or to district heating and cooling systems. Another possible area of its implementation is low temperature district heating. These subjects might be of great interest for future research works.

Acknowledgements

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