Basics of optimal design of district heating pipelines diameters and design examples of Estonian old non-optimised district heating networks

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Abstract
Basics of optimal design of district heating pipelines diameters are presented in this article. Current work gives examples of new pipelines economic optimisation. The Estonian old non-optimised district heating networks are compared with new optimised networks. Heat distributions cost influencing factors are considered.

Keywords
district heating network, optimal design, efficiency, heat losses, economic optimisation, distribution cost

Introduction
During the last years essential changes have taken and are still taking place both in the economic and engineering environment of the energy sector. In the Estonian energy network prices on electricity and heat for all consumer groups have increased significantly.

Structure and volumes of heat consumption have changed significantly. In many settlements the district heating network developed on the basis of the boiler house of the dominating industrial enterprise and by now the network has been separated from the enterprise that often has either changed the production structure or is not in operation anymore. District heating networks are over-dimensioned. The over-dimensioning and poor causes high heat losses (around 18.5% [1]), for instance in Finnish district heating networks the heat losses are in the range of 6–7% [1] and in Sweden - 7.9% [2]. The relative heat losses in Russian DH networks are higher - 15-30% [3].The technical conditions of Estonian district heating networks that are 20-40 years old are out of date.

Poor condition of networks decrease futures of centralised heating and consumers make choice for the local heating. Often the local heating is not effective solution for regional heat supply-system and decrease potential of combined heat and electricity production.

In the present article basics of pipes internal diameters optimisation methodology and also some real examples of Estonian old non-optimised district heating networks design are presented. The optimisation purpose is to get minimal distribution costs of heat.

Basics of optimal design of district heating pipelines diameters

The question of how to select the optimal diameter of pipes in which a fluid is transported, represents a classical optimisation problem [4-7]. Fig. 1 shows qualitatively how an economic optimum can be found for the diameter of district heating pipe. Total cost is the sum of costs for pipeline installation, for heat losses, and for pumping power. Of these three cost elements, the cost of pipeline installation and heat losses increase their values strongly with diameter, while the pumping power drops rapidly ($K_{pumping} \sim D_s^5$) with increasing diameter.

Optimisation of this kind usually assumes that the flow rate is constant when the diameter is varied. This method was developed to be as simple as possible yet complete and accurate enough for design calculations [7].

The heat distribution total cost $k$ consists from pipes, pumps and network building cost $k_r$, heat distribution losses cost $k_{sk}$ and pumping cost $k_p$.

The annual expenses of network investments is calculated as

$$k_s = (k_1 + k_2 \cdot D_s) \cdot a, \text{ kr/m}$$

where

$k_1$ - pipes cost per length, kr/m;

$k_2$ - pipes cost per surface area, kr/m²;

$D_s$ - internal diameter of pipe, m;

$a$ - annuity factor, -
The annual pumping cost is calculated as
\[ k_p = k'_p \cdot \frac{\tau}{\eta_p} \cdot \frac{\Delta P}{L} \cdot V, \text{ kr/m} \]  \hspace{1cm} (2)
where
- \( k'_p \) - pumping cost, kr/(kW·h);
- \( \tau \) - pump operation time, h/year;
- \( \Delta P \) - friction losses, Pa/m;
- \( \eta_p \) - pump efficiency, -
- \( V \) - water flow rate, m³/s

The friction losses is calculated as
\[ R_l = \frac{\Delta P}{L} = \frac{\lambda}{D_s} \cdot \frac{1}{2} \cdot \rho \cdot \omega^2, \text{ Pa/m} \]  \hspace{1cm} (3)
where
- \( \lambda \) - friction factor;
- \( \rho \) - water density, kg/m³;
- \( \omega \) - water velocity, m/s

Pumping cost take into account pumping energy losses transformation to heat is calculated as
\[ k'_p = k_e - \eta_p \cdot k_s, \text{ kr/(kW·h)} \]  \hspace{1cm} (4)
where
- \( k_e \) - electricity cost, kr/(kW·h);
- \( k_s \) - heat cost, kr/(kW·h);
- \( \eta_p \) - pump efficiency, -

The distribution heat losses expenses is calculated as
\[ k_{dh} = k_s \cdot K \cdot 10^{-3} \cdot \int \theta \, d\tau, \text{ kr/m} \]  \hspace{1cm} (5)
where
- \( k_s \) - heat cost, kr/(kW·h);
- \( K \) - pipes heat transfer coefficient, W/(m·K);
- \( \int \theta \, d\tau \) - water distribution temperature and outdoor temperature difference duration, °C·h/year.

In with pipe optimal diameter value heat losses expenses are higher than pumping cost. The influence of heat losses expenses to the optimum placement is small: move the total cost curve little beat to the left to the smaller diameters and higher water velocities direction. It is also possible to analytically evaluate the optimal diameter and friction losses. The heat losses expenses did not much affect value of optimal diameter and because that, we did not take them into account in next calculation.

Economically optimal diameter of pipe is evaluated from next equation
\[ \frac{dk}{dD} = d \left( \frac{(k'_p + k_s) \cdot a + k'_p \cdot \frac{\tau}{\eta_p} \cdot \frac{\lambda}{k'_p} \cdot \frac{\Delta P}{L} \cdot \sqrt{V}}{D_s} \right) = 0 \]  \hspace{1cm} (6)

The optimal internal diameter of pipe:
\[ D_{s,\text{opt}} = \left[ \frac{40 \cdot \lambda \cdot \rho \cdot \tau \cdot \frac{1}{k'_p} \cdot \frac{\Delta P}{L}}{\pi^2 \cdot \rho \cdot \Delta P_{\text{max}}^{1/2}} \right] \cdot \sqrt{V}, \text{ m} \]  \hspace{1cm} (7)

If pressure drop in the district-heating network is limited with definite value \( \Delta P_{\text{max}} \) (Pa), the internal diameter of pipes must be at least next value, depending to the water flow \( G \) (kg/s):\[ D_s \geq \sqrt{\frac{8 \cdot \lambda \cdot L \cdot G^2}{\pi^2 \cdot \rho \cdot \Delta P_{\text{max}}}}, \text{ m} \]  \hspace{1cm} (8)

Optimal water velocity:
\[ \omega_{\text{opt}} = \sqrt[1/3]{\frac{8 \cdot \pi \cdot \lambda \cdot \rho \cdot \tau}{5 \cdot \pi \cdot \lambda \cdot \rho}} \cdot \frac{k'_p}{k_s}, \text{ m/s} \]  \hspace{1cm} (9)

Optimal friction losses:
\[ R_{l,\text{opt}} = \frac{\Delta P}{L} = \frac{8 \cdot \pi \cdot \lambda \cdot \rho}{\pi^2 \cdot \rho \cdot \Delta P_{\text{max}}^{1/2}} \cdot \left[ \frac{40 \cdot \tau \cdot \frac{\lambda}{\eta_p} \cdot \frac{1}{k'_p} \cdot a}{\Delta P} \right]^{1/6}, \text{ Pa/m} \]  \hspace{1cm} (10)

In practise, if you designs network, the optimal values of pipes diameter, friction losses, water velocity and supplied heat load are presented by the power equations:
\[ R_{l,\text{opt}} = C_1 \cdot D_{s,\text{opt}}^{n_1}, \text{ Pa/m} \]  \hspace{1cm} (11)
\[ \omega_{\text{opt}} = C_2 \cdot D_{s,\text{opt}}^{n_2}, \text{ m/s} \]  \hspace{1cm} (12)
\[ Q_{\text{opt}} = C_3 \cdot D_{s,\text{opt}}^{n_3}, \text{ kW} \]  \hspace{1cm} (13)
\[ D_{s,\text{opt}} = C_4 \cdot Q_{\text{opt}}^{n_4}, \text{ m} \]  \hspace{1cm} (14)

Where values of constants \( C_1, C_2, C_3, C_4 \) and powers \( n_1, n_2, n_3, n_4 \) are depending of heat distribution cost.

In the next calculation examples, the optimal values of pipelines diameters, water velocities, friction losses and heat loads were received using the graphical method. Optimal values are compared with the networks real operation data.
Example of district heating pipelines diameters optimal design

The purpose of pipe internal diameter is to get minimal distribution costs of heat. Classical optimisation usually assumes that the maximum load flow rate is constant when the diameter is varied. This method was developed to be as simple as possible yet complete and accurate enough for design calculations.

Example of pipes diameter optimisation is presented on the figure 2. In this example the values of main parameters are the next: supplied heat load is 1000 kW, lifetime of network is 30 years, network pipes and building costs are presented in the table 1, loan rate is 10%, cost of electricity according to night tariff is 0.74 kr./KWh and to day tariff is 1.27 kr./KWh, total pumping efficiency is 0.72, cost of heat is 450 kr./MWh. The temperature regime in network is 110/70°C and the design outdoor temperature is -22°C. The network operation time is 8760 hours per year.

The influence of water temperature regime to the pipe optimal diameter value is presented on the figure 3. With increasing of supply and return water temperatures difference, pipes optimal diameter decreasing. The value of pipes optimal diameter is mainly affected by the temperatures difference. The water flow is determinate by the heat load and depends from the difference of supply and return water temperatures. The growing of water average temperature did not have big influence to the pipes diameter optimal value - little beat move total distribution cost curve to the left in smaller diameters and higher water velocities direction. Also, we can conclude that changes in heat losses cost practically did not influence the optimal diameter value. The total cost curve moves vertically up when heat losses increasing and down, when decreasing, at the same time the value of optimal diameter practically did not change.

The pipes and network building cost influence to the pipes diameter optimal value is presented on the figure 4. In this example, pipes and network building cost growing up two times. The growing of this cost element causes moderate decreasing of the pipes optimal diameter.

The pumping cost influence to the pipes diameter optimal value is presented on the figure 6. The pumping cost depends from the electricity cost, which in this example growing up two times. The pumping cost near the diameter optimal value is small comparing to the other costs (pipes and network building, heat losses). As we can see from the drawing (Fig.6), even when the electricity prices doubling, pipes optimal diameter have only a little growing. The total cost curve moves little beat right to the bigger diameters direction.

<table>
<thead>
<tr>
<th>Pipes diameter DN (mm)</th>
<th>Minimal cost (kr/m)</th>
<th>Maximal cost (kr/m)</th>
<th>Average cost (kr/m)</th>
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<tr>
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</table>

Table 1. The pipes and network building average cost in Estonia

Fig. 2. Example of pipes diameter optimisation

Fig. 3. Influence of water temperature regime to the diameter optimal value

Fig. 4. Influence of pipes and network building cost to the diameter optimal value
**Results and conclusions**

If we have the optimal diameter value the heat losses cost is higher than pumping cost. Heat losses cost have only small influence to the optimal diameter value. Changes in the heat losses practically did not influence the optimal diameter value, of course heat distribution cost growing. The total cost curve moves vertically up when heat losses increasing and down, when decreasing, at the same time the value of optimal diameter practically did not change.

We can conclude, that the value of pipes optimal diameter is mainly affected by the water temperatures difference. The water flow is determinate by the heat load and depends from the difference of supply and return water temperatures. Other costs did not have so big influence to the diameter optimum value, mainly move total cost curve in vertical direction up or down with very small decreasing or increasing of optimum value.

The growing of pipes and network building cost causes moderate decreasing of the pipes optimal diameter.

The pumping cost depends from the electricity cost. The pumping cost near the diameter optimal value is small comparing to the other costs (pipes and network building, heat losses). Even, when the electricity prices doubling, pipes optimal diameter value has only a little growing. The total cost curve moves little beat right to the bigger diameters direction.

We can conclude that diameter optimal value mainly depends from pumping and network building costs relation. The pumping power drops rapidly ($K_{\text{pumping}} \sim D_s^3$) with diameter increasing and at the same time, pipes and network building cost grows moderately.

The water velocities and friction losses in pipes of Estonian old district heating networks as rule are much lower than optimum values. This situation exists because old networks where designed for much bigger load and take into account growing potential. In present time the heat load of consumers is 20-30 % less than designed (in some cases is up to 2 times less).

Pumping costs in old networks with over dimensioned pipes are much lower than in new optimised networks. At the same time heat losses in old networks with over dimensioned and badly insulated pipes are times higher. The saving in heat losses gives great increasing of total DH distribution cost.

As rule of thumb many district heating networks in Denmark and in other European countries have been designed by applying a friction loss of 100 Pa/m [4,7]. Estonian old networks are designed also by applying similar friction loss of about ~80 Pa/m [10], but real friction loss are much less [8,9].

On the figure 6 the optimal diameter depending to the heat load is presented. Next figures Fig. 7, 8 and 9 presents real and optimised values of heat load, water velocity and friction loss depending to pipe diameter. The example is given for typical Estonian network witch situated in Võru town.

As Fig. 9 shows, real friction losses in pipes are mainly less than optimal values and in some old pipes mainly with small diameters (about 50 mm) are higher. The friction loss optimal value is not constant for all diameters, as rule of thumb say. For the smaller diameters friction losses optimal values are higher than for bigger diameters. Similar tendency was presented by the G.Phetteplace in [7].

Received results are practically useable in DH pipelines design and in renovation of old district heating networks.

**Fig. 5. Influence of pumping cost to the diameter optimal value**

**Fig. 6. Optimal diameter depending to heat load $D_s = f(Q)$ in Võru town DH network**

**Fig. 7. Optimal heat load depending to pipe diameter $Q = f(D_s)$ in Võru town DH network**
Fig. 8. Water velocity depending to pipe diameter \( \omega = f(D_s) \) in Võru town DH network

Fig. 9. Friction losses in Võru town DH network depending to pipe diameter \( R_i = f(D_s) \)

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