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The Analysis of Efficiency and Optimization of District Heating Networks in Estonia

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

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Eesti kaugkütte soojusvõrkude efektiivsuse analüüs ja optimeerimine

ALEKSANDR HLEBNIKOV

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CONTENTS

INTRODUCTION

Topicality of the theme

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 networks 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 heat insulation 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 % [32]. The relative heat losses in Russian DH networks are 15–30% [2] and Latvian DH networks are 16% [25]. The Estonian district heating networks are 20–40 years old and there technical condition is bad so they need to be renovated in near future to ensure efficient and reliable heat supply.

Poor condition of DH networks and not reliable heat supply can decrease futures of district heating and consumers can make a choice for different heat supply alternative. Often the decentralised heating is not effective solution for regional heat supply strategy and decreases potential of combined heat and power production.

Objective estimation of district heating networks actual conditions and technical-economical argumentation for networks renovation should be carried out to increase combined heat and electricity production.

Main characteristic parameters of the Estonian district heating networks and their difference from the optimal values are estimated in the current work for the first time and compared one to another and with the typical modern Nordic networks. Networks efficiency influencing factors are considered. Current work gives the actual efficiency of pipes thermal insulation in Tallinn and other Estonian towns. To evaluate the actual conditions of the thermal insulation was created a model, based on the heat losses, determined by the using district heating network heat balances.

The objective of the current work was to estimate main characteristic parameters of the Estonian district heating networks and their difference from the optimal values.

The examples of economic optimisation of new pipelines are presented in this work. The Estonian old non-optimized district heating networks are compared with new optimized networks. Old networks efficiency increasing potential was found out.

Preservation of district heating systems in working order and their renovation are the basic preconditions for combined heat and power generation, and thus for reduction of fuel consumption and environment pollution.

Improvement of district heating systems efficiency also plays decisive role for ensuring competitiveness of district heating utilities, which in turn serves as a precondition for utilisation of opportunities and advantages provided by district heating systems both for power generation and reduction of the environmental impact, as well as improvement of the comfort and life quality of heat consumers.

Goal of the work

Considering the aforesaid, the purpose of the given research work is detailed and objective estimation of the present condition of the Estonian district heating networks, and also determination how much can be their efficiency increased after carrying out of full optimization and reconstruction and how big can be efficiency increasing potential. Moreover, the analysis of damages statistics of district heating systems is made and indicative parameters allowing to define a real condition of DH networks are developed

Tasks to be solved

For the purpose of achieving the above posed goal the following tasks were set and solved in the following sequence within the present work:

– the model suitable for optimization of old Estonian heating systems is made;

– for each considered district heating system main characteristic parameters describing the efficiency are found for present conditions and after optimization and reconstruction;

– the potential of the energy savings, received as a result of full reconstruction of old district heating systems is found;

– the optimization model of the district heating systems, made in the given work, has been used for optimization and development of reconstruction plans for more than twenty old district heating systems;

– the analysis of damages statistics of old district heating systems has been made and indicative parameters allowing to estimate the general condition of a district heating system has been obtained in the given work.

Methodology of research

Researches on increase in efficiency of old district heating systems are based on the networks optimization model made within the given work which in turn contains thermal, hydraulic and economic models.

At carrying out of analyses it is considered more than twenty Estonian district heating systems with small, average and big loading. District heating systems with annual thermal loading from less than 5000 MWh to over 100000 MWh have been considered.

On the basis of the valid working parameters thermal and hydraulic models have been made for each considered district heating system and optimization of networks has been carried out.

Scientific novelty

Novelty of the work consists in the creation of the new methodology allowing objectively to estimate the valid condition of old district heating systems, to estimate potential of their efficiency increasing and to develop the proved plan of reconstruction of a district heating system.

The developed methodology on optimization of old district heating systems, in difference from optimization models developed in Denmark, Sweden, Finland and other western countries, allows to consider much more technical features specific to old Estonian district heating systems, such as various types of the network pipes lining (a underground network in the concrete channel, an air network), various heat insulation materials (old glass wool, stone wool, asbestos), change in properties of heat insulation materials during the time, various temperature modes of a network, various hydraulic modes of a network, various types of pipes, thermal expansion compensators, armature, changes of a pipes roughness.

Practical significance

The analysis of the accumulated practical experience and results of research carried out within the present work and main drawn conclusions and recommendations can be applied in practice in the course of planning, analysing and implementing reconstruction and upgrades of district heating systems of large and small cities.

The results of this work were applied already for the many real DH networks reconstruction plans (over 20 DH networks) and cities heat supply long-term development concepts (Narva, Tallinn, Türi, Võru, Kuressaare, Kiviõli, Jüri etc.)

During researches for each district heating system have been made the thermal models necessary for an estimation of the valid efficiency of thermal insulation, and the hydraulic models necessary for definition of hydraulic modes. The received results have compared to optimum values. Diameters of pipes of the considered district heating systems have been optimized for minimization of heat distribution costs. All calculations are made proceeding from the valid heat loadings and considering possible increase in loading at expansion of district heating networks.

For each considered district heating system key parameters defining their valid efficiency are found, and also the analysis of factors influencing the district heating systems efficiency is made. Efficiency of the Estonian district heating systems have compared to efficiency of modern nordic district heating systems. Final result of researches became definition of the major characteristic parameters of district heating systems after full optimization and reconstruction. Greater practical achievement of work is that the possible potential of the energy savings received at reconstruction of old heating systems is certain, and also economically proved plans of reconstruction of district heating systems are developed. Preservation of district heating systems in working order and renovation are the basic precondition for combined heat and power generation, accordingly for fuel consumption and environment pollution reduction.

Application of the present work results can help to avoid mistakes and wrong decisions in the course of planning district heating systems efficiency improvements.

The results of the work studies are used in the following study subjects of the Bachelor's and Master's studies at Tallinn University of Technology: "Heat supply systems" and "District heating networks"

Approbation

The results of the research have been reported at the following worldwide international conferences: 5th Baltic Heat Transfer Conference 19–21 September, 2007 Saint Petersburg, Russia and the 11th International Symposium on District Heating and Cooling, August 31 to September 2, 2008 in Reykjavik, ICELAND. Except for this results of researches are published in editions of the Estonian and Lithuanian academies of sciences.

Personal contribution

The research included in the current work is based upon the author`s long-term research experience in the field of development of the rehabilitation projects for old district heating networks.

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ABBREVIATIONS, TERMS AND SYMBOLS

Roman symbols

a – networks hydraulic conductivity
A – surface area of the distribution pipes
A_s – the constant factor depending on a roughness of walls of pipelines
C_{net} – factor of network
d – internal diameter of the pipeline
d_a – the average diameter of the district heating network pipes
d_{ekv} – internal equivalent diameter of the channel
d_k – external diameter of thermal insulation
$D_{s,opt}$ – optimal value of pipes diameter
D_t – external diameter of a pipe
G – the mass flow rate of the heat-carrier
H – the real depth of pipes axis
H_s – the fictitious thickness of ground considering thermal resistance of a ground surface
H_t – the resulted depth of pipes axis
H_0 – pressure head of the pump accordingly at $V_0 = 0$
H_1 – pressure head of the pump accordingly at $V_1 \neq 0$
i – pipe index
k – the total cost of heat distribution
k_p. – pumping cost
k_t, – pipes and network construction cost
k_{sk} – distribution heat losses cost
K – heat transfer coefficient of a pipe
K_o – overall heat transfer coefficient
K_p – heat transfer coefficient of a supply pipe
K_t – heat transfer coefficient of a return pipe
$K_{p,t} = K_{t,p}$ – heat transfer coefficient considering heat exchange between supply and return pipes
l – length of the pipeline
L_1 – length of pipe number 1
L_i – length of pipe number i

$\dot{m}_1$ – mass flow rate in pipe number 1

$\dot{m}_i$ – mass flow rate in pipe number i

n – total number of pipes

N – capacity of the pump at a mode differing from nominal

N_n – capacity of the pump at a nominal mode

ΔP_0 – total pressure loss in the pipe network

ΔP_1 – pressure loss in pipe number 1

p_d – dynamic pressure

q – heat losses of a underground network

q_{dp} – the distribution parameter

q_{hlf} – the heat loss factor

Q – the annual quantity of the heat supplied to the district heating network

Q_{hlf} – the annual distribution heat loss

$Q_{opt.}$ – optimal value of supplied heat load

Re – Reynolds's number

R_{k-o} – thermal resistance of the channel and ground

R_l – specific pressure drop on length

$R_{l,opt.}$ – optimal value of friction losses

$R_{p,is}$ – thermal resistance of insulation of a supply pipe

$R_{t,is}$ – thermal resistance of insulation of a return pipe

S – the characteristic of resistance representing pressure drop at unit of the flow of the heat-carrier

S_0 – conditional internal resistance of the pump

t_p – water temperature in a supply pipe

t_t – water temperature in a return pipe

$t_{\tilde{o}}$ – temperature of external air

Δt – temperature difference of supply and return water

V – the flow rate of the heat-carrier

W – velocity of the heat-carrier

W_{opt} – optimal value of water velocity

Greek symbols

α – convective heat transfer coefficient from water to an internal surface of a pipe

α_0 – the convective heat transfer coefficient from the ground surface to air

α_i – the factor considering a share of pressure losses in local resistance from resistance on length

α_{kkp} – convective heat transfer coefficient from a surface of thermal insulation covering layer to air

α_{ksp} – convective heat transfer coefficient from a air to channel wall

β_k – heat losses coefficient for a underground channel lining network

$\beta_{õ}$ – heat losses coefficient for a air lining network

ξ – total factor of local resistance on a site of the pipeline

η_n – nominal efficiency coefficient of the pump

η_p – pump efficiency

Θ – difference between water average temperature and outdoor temperature

λ – hydraulic friction factor

λ_{hk} – heat conductivity coefficient of a bitumen

λ_{is} – heat conductivity coefficient of thermal insulation

$\lambda_{is.kk}$ – heat conductivity coefficient of a covering layer

λ_{ks} – heat conductivity coefficient of a channel wall

λ_p – heat conductivity coefficient of a ground

λ_{ts} – steel heat conductivity coefficient

ν – kinematic viscosity of a liquid

ρ – density of the heat-carrier

τ – water average temperature and outdoor temperature difference duration time

Abbreviations

CHP – combined heat and power generation
DH – district heating
DHEMOS – open source dynamic simulation of district heating networks
EEK – the Estonian crone
EU – European union
MS EXCEL – calculations editor for computer
THERMIS – computer program for district heating networks calculations
VBA (VISUAL BASIC) – computer-programming environment

1 EFFICIENCY OF DISTRICT HEATING SYSTEMS AND THEIR OPTIMIZATION

The average level of heat losses in district heating networks in Estonia are still very high and is around 19% and at least 2–3 times higher than in modern networks with similar heat sypply density. From the above it follows that is a high potential for increasing the efficiency of district heating networks.

Therefore the reduction of heat transmission losses is one of the most important directions in the process of improving the efficiency of district heating networks. The technical conditions of Estonian district heating networks are 20–40 years old are bad and need to be renovated step by step in near future to ensure efficient and reliable heat supply.

Improvement of efficiency of district heating systems also plays decisive role for ensuring competitiveness of district heating utilities, which in turn serves as a precondition for utilisation of opportunities and advantages provided by district heating systems both for power generation and reduction of the environmental impact, as well as improvement of the comfort and life quality of heat consumers.

The tendency to increase combined heat and power production in the energy supply of cities has intensified building of district heating systems in many countries.

In Estonia we can use potential of existing DH networks for CHP production. Our DH networks need renovation. Renovation and extending of the present networks requires big investments every year. Because the economical age of the pipelines is long and the heat loads as well as the supply systems develop all the time, the network should be carefully dimensioned according to the economic optimality.

Design of a DH system is a very complex analytical problem, which includes several variables that affect the total economy of the system and also to the selection of other design parameters. Temperature levels, pipe diameters and the investments timing are factors that affect strongly the profitability of the system.

The temperature levels of the supply and return water are the most important variables, because they have an effect on most of the parameters. Determination of the most profitable temperatures is a systems theoretic problem, which involves precise analysis of all the three main parts of the system: the plants, the network and the consumers. In this work it has been developed a simple model for analysing the network before renovation plan development and the temperature levels are given different as input data. The old pipelines wich situated in the underground ducts will be changed by the preinsulated pipes with optimaly selected diameters according to the real heat load and potential of heat demand grooving.

The question of how to select the optimal diameter of pipes in which a fluid is transported, represents a classical optimization problem [4,5,6]. Total heat transportation cost is the sum of costs for pipeline installation, for heat losses, and for pumping power. Of these three cost elements, the costs 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 diameter increasing.

Classical optimization 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.

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.

Pipe sizes are usually determined on the basis of simple criteria, such as maximum pressure loss or maximum flow velocity. Many of investigators have addressed the issue of pipe size determination, trying to improve on these simple criteria [16]:

Aamot and Phetteplace (1976) [7] presented a method that relies on establishing the ratio between the heat losses and the pumping cost and then finds the lowest cost pipe diameter by minimising the sum of capital, heat loss and pumping costs. Their work only addressed a single pipe segment and did not include the effect of varying load over the yearly cycle.

Szepe and Calm (1979) [8] presented a model for single pipe segments that neglected heat losses and time varying loads, but used geometric programming theory to achieve additional insight into their simplified problem. In later work, Phetteplace (1981) included the effect of annual load variations, but only single pipe segments were addressed.

Frederiksen (1982) [5] provided a detailed analysis of the heat generating station and the consumers systems, but simplified the transmission network to a single supply and return pipe.

Many of investigators have addressed multiple pipe networks. Stoner (1974) [9] discussed models that are capable of modelling either steam or water networks. Although the models do not determine optimum diameters, he gave a procedure for achieving an optimal design by sensitivity analysis, but did not discuss how this process would be accomplished for networks of more than one pipe.

Zinger et al.(1976) [10, 37] described a computer program for calculating flows and pressure levels in branched networks of hot water pipes. Their program accounts for pressure drops in consumers equipment and throttling devices placed in the network. Diameters are assumed to be known and they did not discuss how to determine them.

Morofsky and Verma (1979) [11] developed a feasibility analysis and costing tool for district energy systems, not intended for detailed design. They found the appropriate pipe sizes by finding those that absorbed all of the available pressure difference. They started the search for pipe size at the smallest available discrete pipe diameter and then calculated pressure losses. If the pressure losses were more than the available pressure difference, they increased the pipe size to the next discrete size and repeated the calculation. They proceeded in this fashion until they reached a discrete pipe diameter that did not result in pressure losses greater than the available pressure difference.

McDonald and Bloomster (1977) [12] discussed a model for laying out and sizing the piping network for a city heated with geothermal water. Pipe diameter is determined using a "simple search" of feasible pipe sizes by minimizing the sum of the annual capital cost, heat loss cost and pumping cost. They provided no information on how to handle network constraints or consider annual load variations.

Bøhm (1986) [13] noted that, in the case of consumers directly connected to the network, the "classical" approach of determining the optimal diameter by finding the minimum of the sum of the capital, heat loss and pumping costs results in pressures that are too high at the heating plant. He suggested the use of Munser`s (1980) [15] method, which proportions the total available pressure loss in a network according to the next equation:

$$\Delta P_1 / \Delta P_0 = \frac{L_1}{\sum_{i=1}^{n} L_i \cdot \left(\dot{m}_i / \dot{m}_1 \right)^{1/3}} \tag{1.1}$$

where

ΔP_1 – pressure loss in pipe number 1, Pa

ΔP_0 – total pressure loss in the pipe network, Pa

L_1 – length of pipe number 1, m

L_i – length of pipe number i, m

$\dot{m}_1$ – mass flow rate in pipe number 1, kg/s

$\dot{m}_i$ – mass flow rate in pipe number i, kg/s

n – total number of pipes,

i – pipe index.

This equation is intended for use on "linear networks" that do not have branches.

Koskelainen (1980) [6, 14] developed a method that is able to solve for optimal diameters in a branched network. His method consists of successively assuming that the objective function and constraints locally are linear and repeatedly solving the problem with a linear programming algorithm. He gives an example where his "optimal" network has a cost that is 16,4 % less than one sized using a head loss design rule.

Phetteplace (1995) [16] developed a rational design method that yields the optimal pipe sizes for an application based on case-specific parameters values. This method allows for the inclusion of all major costs and can account for such factors as escalation of energy prices, seasonal energy costs, increases in heat losses over system life, variation in seasonal heat demand, load management strategy, the effect of the heat consumer, etc. Each of the major constraints on the design of a realistic district heating network is derived and considered, This method is felt to be practical for sizing much of the piping of a district heating system.

The next step in optimization is dynamic simulation models of district heating networks today are also very popular. One type of mathematical model involves a full physical modelling of the network [17, 18] and in other type of model – DH network is replaced by a simplified one (Bøhm.B., Larsen.H., [19]). Also we can find more information and practical examples about DH network and all DH system optimization [22, 23, 24].

There are many commercial programs for DH calculations, for example the THERMIS [21] is one popular program and also we can find very good open source software, for example the DHEMOS (Open Source Dynamic Simulation of District Heating Networks) [20].

As we can see there are many methods for the DH network optimization. In this work is used the classical optimization method with some changers developed specialy for old networks renovation. This method was developed to be as simple as possible yet complete and accurate enough for design calculations. The one very important purpose of the current investigations is to find the energy saiving potential of old DH networks in Estonia due to optimization and renovation.

2 THEORETICAL ALGORYTHMS FOR THE DH NETWORK OPTIMIZATION MODEL

2.1 Classical model for hydraulic calculations

2.1.1 The primary goals and formulas of hydraulic calculation

At designing of district heating networks the primary goal of hydraulic calculation consists in definition of pipes diameters under the set charges of the heat-carrier and had differences of pressure in all network or in its separate sites.

While district heating networks is in operation, there is a necessity of the decision of return tasks by definition of the heat-carrier flows on a network sites or pressure in separate points at change of hydraulic modes. Results of hydraulic calculation are used for construction of piesometric schedules, a choice of schemes of user's inputs, selection of the pump equipment, definition of a district heating network cost and other purposes.

At movement of the heat-carrier on pipes, pressure losses are caused by hydraulic resistance of friction and local resistance of the pipeline:

$$\Delta P = \Delta P_l + \Delta P_k \text{, Pa.} \tag{2.1}$$

Hydraulic resistance on length of the pipeline are defined under Weisbach-Darcy formula [33]:

$$\Delta P_l = \lambda \cdot \frac{l}{d} \cdot \frac{\rho \cdot W^2}{2} \text{, Pa,} \tag{2.2}$$

where

λ – hydraulic friction factor;
l – length of the pipeline, m;
d – internal diameter of the pipeline, m;
ρ – density of the heat-carrier, kg/m^3;
W – velocity of the heat-carrier, m/s.

The hydraulic friction factor generally depends from Reynolds's number (Re) and a relative equivalent roughness of a pipe (k_{ekv} / d). A roughness of a pipe name ledges and the roughnesses influencing at turbulent movement of a liquid on linear losses of pressure. In real pipes these ledges and roughnesses are various under the form, size and are non-uniformly allocated on length.

For an equivalent roughness k_{ekv} conditionally accept a uniform granular roughness which ledges have the identical form and the sizes, and losses of pressure on length are the same, as well as in real pipes. The size of an equivalent roughness of pipes walls in view of corrosion is recommended to be accepted: for steam lines – 0,2 mm; for old DH water networks – 0,5–1 mm and for new DH water network pipes – 0,2 mm [34, 35, 36].

For external networks the turbulent mode of heat-carriers movement is characteristic.

The mode of water flow characterizes Reynolds's number:

$$\mathrm{Re} = \frac{W \cdot d}{\nu}, \tag{2.3}$$

where ν – kinematic viscosity of a liquid, m^2/s.

At $\mathrm{Re}\, k_{ekv} / d \le 23$ [33] pipes are considered hydraulicaly smooth. In this case the laminar boundary layer covers a roughness of walls, that is thickness of a boundary layer is more than k_{ekv}, and hydraulic resistance are caused only by friction forces in a liquid and depend on Reynolds's number.

For hydraulicaly smooth pipes at turbulent movement the hydraulic friction factor can be defined under the formula of Murin [33]:

$$\lambda_s = \frac{1{,}01}{(\lg \mathrm{Re})^{2,5}}. \tag{2.4}$$

For hydraulicaly rough pipes at $\mathrm{Re}\, k_{ekv} / d \ge 560$, when solving influence on hydraulic resistance on all length of the pipeline is rendered with friction forces of a liquid about a pipes wall, the hydraulic friction factor depends only on a relative equivalent roughness and is defined under the formula of professor Šifrinson [33]:

$$\lambda_k = 0{,}11 \cdot \left(\frac{k_{ekv}}{d} \right)^{0,25}. \tag{2.5}$$

In transition region of the hydraulic resistance, described change of a complex $\mathrm{Re}\, k_{ekv} / d = 23 \div 560$, the formula of professor Altshul is recommended [33]:

$$\lambda_k = 0{,}11 \cdot \left(\frac{k_{ekv}}{d} + \frac{68}{\mathrm{Re}} \right)^{0,25}. \tag{2.6}$$

Under the later formula (2.6) hydraulic friction factor is defined precisely enough for all three regions of hydraulic resistance (smooth, transitive and rough). At $\mathrm{Re}\, k_{ekv} / d \le 10$ results of calculation coincide with Murin's data, and at $\mathrm{Re}\, k_{ekv} / d \ge 500$ with Šifrinson's data.

Local hydraulic resistance are defined under formula of Weisbach [33]:

$$\Delta P_m = \xi \cdot \frac{\rho \cdot W^2}{2}, \text{ Pa}, \tag{2.7}$$

where

ξ – total factor of local resistance on a site of the pipeline [33].

It is possible to replace local losses of pressure by equivalent hydraulic resistance on length if in the equation (2.2) instead of l to substitute l_{ekv} – equivalent length of local resistance, that is such length of the rectilinear pipeline, linear losses of pressure in which are numerically equal to losses of pressure in local resistance.

Solving in common the equations (2.2) and (2.7), we shall receive:

$$l_{ekv} = \xi\, d / \lambda \text{, m.} \tag{2.8}$$

For characteristic in DH networks local resistances values of equivalent lengths are resulted in the literature [33].

Hydraulic calculation of the branched out pipelines is convenient for making on a method of average specific losses of pressure, following forms of record of full hydraulic resistance therefore are often used:

$$\Delta P = \Delta P_l + \Delta P_m = \Delta P_l \cdot \left(1 + \frac{\Delta P_m}{\Delta P_l}\right) = R_l \cdot l \cdot (1+\alpha) = R_l \cdot (l + l_{ekv})\text{, Pa,} \tag{2.9}$$

where

α – the factor considering a share of pressure losses in local resistance from resistance on length;

R_l – specific pressure drop on length, Pa/m.

From the formula (2.2) follows, that:

$$R_l = \frac{\lambda}{d} \cdot \frac{\rho W^2}{2} = 6{,}27 \cdot 10^{-2} \cdot \frac{\lambda}{d^5} \cdot \frac{G^2}{\rho}\text{, Pa/m,} \tag{2.10}$$

where

G – the mass flow rate of the heat-carrier, t/h

Where in formulas (2.7) and (2.10) dynamic pressure is defined as follows:

$$p_d = \frac{\rho \cdot W^2}{2}\text{, Pa.} \tag{2.11}$$

2.1.2 Metodology of hydraulic calculation

Hydraulic calculation is made on separate sites of a network. A district heating network divide into sites. The calculating site of the branched out network can be named the pipeline in which the flow of the heat-carrier does not change. The calculating site is situated, as a rule, between the next branches. Sometimes the calculating site should be divided on two or the several, if in its limits it is required to change diameters of pipes.

Hydraulic resistance of each site depends on four key parameters which are internal diameter of a pipe, the flow rate of the heat-carrier, length of a site and factor of local resistance.

$$\begin{aligned} \Delta P_1 &= R_1 \cdot l_1 \cdot (1+\alpha_1) = f(d_1, G_1, l_1, \xi_1) \\ \Delta P_2 &= R_2 \cdot l_2 \cdot (1+\alpha_2) = f(d_2, G_2, l_2, \xi_2) \\ &\dots\dots\dots\dots\dots\dots \\ \Delta P_n &= R_n \cdot l_n \cdot (1+\alpha_n) = f(d_n, G_n, l_n, \xi_n) \end{aligned} \tag{2.12}$$

In precomputations, when diameters of pipes are not known, the share of pressure losses in local resistances can be roughly certain under formula of Šifrinson:

$$\alpha_k = 0{,}01 \cdot \sqrt{G}\,, \tag{2.13}$$

where

G – the biggest flow rate of the heat-carrier in the beginning of the branched out network, t/h

If the district heating system already exists, lengths and diameters of sites, local hydraulic resistance are known. Knowing the valid thermal loadings and temperature modes of a network, it is possible to define precisely enough flow rates of the heat-carrier on separate sites.

Knowing these data it is possible to define precisely thermal loadings, velocities of the heat-carrier, specific pressure losses upon friction for each separate site and pressure in various units of a network: at consumers and in central points.

If a district heating system is on the project stage, using the design loadings of consumers it is possible to define optimum diameters of all sites of a network. Knowing diameters and lengths of all sites, loading of sites, it is possible to define pressure drop on sites and knowing a lay of land it is possible to construct the piesometric schedule of a network and to choose suitable pumps.

The methodology of pipes diameters optimization of a district heating system is resulted further in chapter 2.3. At optimum internal diameters of pipes, cost of heat distribution on a network will be minimal.

2.1.3 Bases of the network hydraulic mode

The hydraulic mode defines interrelation between the charge of the heat-carrier and pressure in various points of system at present time.

The calculated hydraulic mode is characterized by distribution of the heat-carrier according to calculated thermal loading of subscribers. Pressure in central points of a network and on user's inputs equally to calculated. Evident representation about this mode gives the piesometric schedule constructed according to hydraulic calculation.

However during in network operation the flow rate of water in system changes, owing to change of consumers loading. Calculation of a hydraulic mode enables to define redistribution of flows and pressure in a network.

Calculation of a hydraulic mode is based on the basic equations of hydrodynamics [34, 37, 38]. In DH networks square-law dependence of pressure drop from the flow rate, as a rule, takes place:

$$\Delta P = S \cdot V^2 \text{, Pa,} \tag{2.14}$$

where

S – the characteristic of resistance representing pressure drop at unit of the flow of the heat-carrier, Pa/(m^3/h)^2;

V – the flow rate of the heat-carrier, m^3/h.

Value of the characteristic of resistance can be found from the joint decision of the equations (2.14), (2.9) and (2.10):

$$S = \frac{\Delta P}{V^2} = \frac{R_l \cdot (l + l_{ekv})}{V^2} = A_s \cdot \frac{(l + l_{ekv})}{d^{5,25}} \cdot \rho \text{, Pa/(m}^3\text{/h)}^2\text{ ,} \qquad (2.15)$$

where A_s is the constant factor depending on a roughness of walls of pipelines:

$$A_s = 0{,}0894 \cdot \frac{k_{ekv}^{\ 0,25}}{Z^2}, \qquad \text{m}^{0,25}\text{h}^2\text{/s}^2\text{ ,} \qquad (2.16)$$

where $Z = 3600$ s.

Table 2.1 Factor depending on a roughness of a pipe wall [33]

Equivalent roughness k_{ekv}, m	0,0002	0,0005	0,001
A_s, m^{0,25}h^2/s^2	$8{,}15 \cdot 10^{-10}$	$10{,}3 \cdot 10^{-10}$	$12{,}15 \cdot 10^{-10}$

As follows from the equations (2.15) and (2.16), the characteristic of resistance depends on the geometrical sizes of a network, a roughness of pipes walls and density of the heat-carrier. At known flow rates and to pressure losses corresponding them, the characteristic of resistance can be found from the equation (2.14).

By development of a hydraulic mode often use the linear unit of pressure named by a pressure head. The graphic representation of pressure losses from the flow rate is the characteristic of a network. The characteristic of a DH network represents the square-law parabola, which is passing through the beginning of coordinates (fig.2.1). Crossing of the characteristic of a network with the characteristic of the pump (point A) defines an operating mode of the pump on the given network.

During of operation, the characteristic of a network resistance changes owing to with addition of new subscribers, switching-off of a part of loading, at change of a roughness of pipes walls.

Further we shall define the characteristic of resistance of the branched out network consisting from of some consecutive and in parallel-connected sites. The general pressure losses ΔP in the network consisting of consistently connected sites with constant flow rate V, develop of losses of pressure on each site:

$$\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 \text{, Pa,} \qquad (2.17)$$

where

ΔP_1, ΔP_2, ΔP_3 – pressure losses on separate sites of a network, Pa.

Having expressed losses of pressure through the flow and characteristics of resistance under the formula (2.14), we shall receive:

$$S \cdot V^2 = S_1 \cdot V^2 + S_2 \cdot V^2 + S_3 \cdot V^2, \text{ Pa}, \tag{2.18}$$

where

S – the characteristic of networks resistance, Pa/(m^3/h)^2;

S_1, S_2, S_3 – the characteristic of networks separate sites resistance, Pa/(m^3/h)^2.

From last expression follows, that

$$S = S_1 + S_2 + S_3, \text{ Pa/(m}^3\text{/h)}^2. \tag{2.19}$$

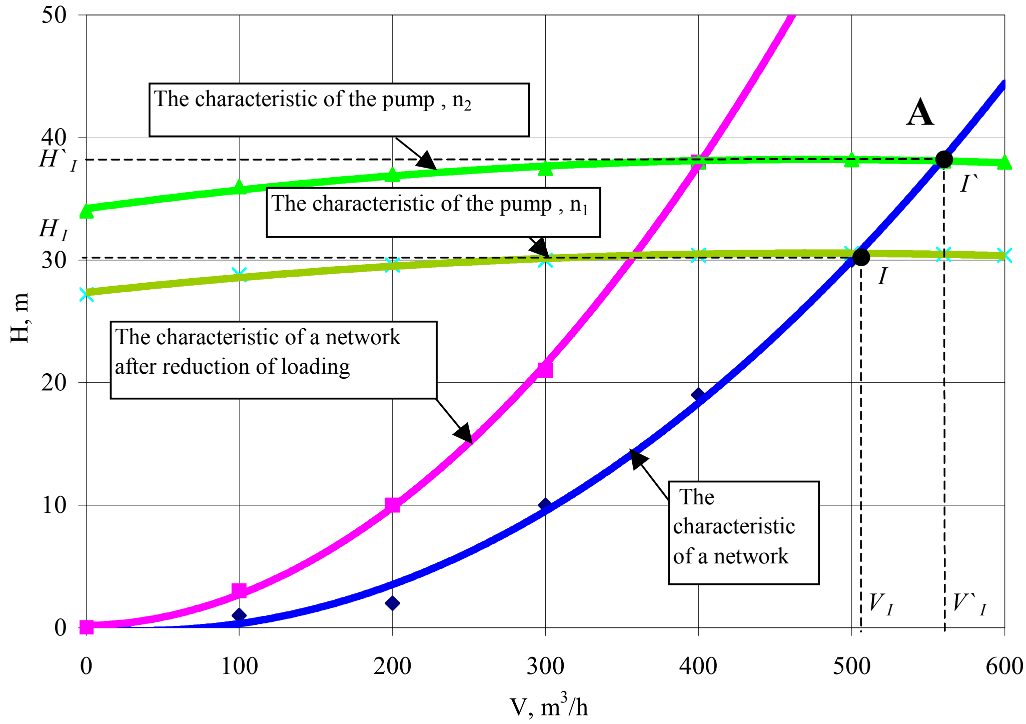


Figure 2.1 The characteristic of a network and the pump

Hence, the total resistance characteristic of consistently connected sites of a network is equal to the sum of resistance characteristics of these sites.

At parallel connection the general flow in a network is equal to the sum of flow rates on branches.

$$V = V_1 + V_2 + V_3, \text{ m}^3\text{/h}. \tag{2.20}$$

The flow rate of water according to expression (2.14) can be presented in the next form:

$$V = \sqrt{\frac{\Delta P}{S}};\quad V_1 = \sqrt{\frac{\Delta P_1}{S_1}};\quad V_2 = \sqrt{\frac{\Delta P_2}{S_2}};\quad V_3 = \sqrt{\frac{\Delta P_3}{S_3}}\quad, \text{m}^3/\text{h}. \qquad (2.21)$$

In view of equality of pressure losses in parallel-connected sites of a network ($\Delta P = \Delta P_1 = \Delta P_2 = \Delta P_3$), expression (2.20) will become next:

$$\sqrt{\frac{1}{S}} = \sqrt{\frac{1}{S_1}} + \sqrt{\frac{1}{S_2}} + \sqrt{\frac{1}{S_3}},\quad \text{m}^3/(\text{h}\cdot\text{Pa}^{0,5}). \qquad (2.22)$$

The size $1/\sqrt{S}$ represents the hydraulic parameter named by conductivity, equal to the flow rate of water at pressure difference in 1 Pa:

$$a = 1/\sqrt{S} = V/\sqrt{\Delta P},\ \text{m}^3/(\text{h}\cdot\text{Pa}^{0,5}). \qquad (2.23)$$

In view of dependence (2.23) we shall receive expression (2.22) in a following kind:

$$a = a_1 + a_2 + a_3,\ \text{m}^3/(\text{h}\cdot\text{Pa}^{0,5}), \qquad (2.24)$$

where

a – networks conductivity, m^3/(h·Pa^{0,5});

a_1, a_2, a_3 – conductivity of networks separate sites, m^3/(h·Pa^{0,5}).

Thus, total conductivity of in parallel-connected sites is equal to the sum of conductivities of these sites.

On the basis of equality (2.19) and (2.24) the characteristic of resistance of the branched out network on known conductivity or characteristics of resistance of its separate sites is defined. By means of the received dependences networks hydraulic mode calculation is made.

2.1.4 Calculation of the hydraulic mode

2.1.4.1 Calculation of a hydraulic mode of a network with one heat supply source

In the automated system with regulators for heating and regulators of temperature for hot water supply the water flow at subscribers is defined only by size of their thermal loading. The constancy of the set flow on heating input is supported by adjustment of a regulator: at reduction of had pressure in input the degree of opening of the regulator valve increases.

Calculation of a hydraulic mode of such system [33, 37] is reduced to definition of pressure losses at known flow rates of water.

In case of automatic regulators absence on inputs, change of flows and pressure in a network causes redistribution of flows in the main pipelines and on user's inputs. Calculation of a hydraulic mode enables to define flows of water and pressure losses corresponding them at the changed operating conditions of system.

As initial data serve: the scheme of a network, piesometric schedule and pressure on collectors of thermal power station. We shall consider the scheme of the thermal network having n subscribers (fig. 2.1). Characteristics of resistance of the main sites we shall designate accordingly – S_I, S_{II}, S_{III}, ..., S_N and characteristics of resistance of subscribers in view of branches – S_1, S_2, S_3, ..., S_n.The total flow of water is equal a network *V*, the flow of water on user's inputs – V_1, V_2, V_3, ..., V_i. (with an index corresponding its number).

Since the first subscriber, we shall write down conditions of equality of pressure losses in parallel sites of network AS_1A ... AS_nA:

$$\Delta P_1 = S_1 \cdot V_1^2 = S_{1-n} \cdot V^2 \text{, Pa,} \tag{2.25}$$

where

S_{1-n} – the characteristic of a networks resistance from the subscriber 1 up to *n* -th, inclusive with all branches, defined under formulas (2.19 and 2.24).

From the equation (2.25) we shall find the relative flow of water at the subscriber 1:

$$V_1 = V_1 / V = \sqrt{S_{1-n} / S_1} \text{, m}^3\text{/h.} \tag{2.26}$$

For user's input 2 it is possible to write down:

$$\Delta P_2 = S_2 \cdot V_2 = S_{2-n} \cdot (V - V_1)^2 \text{, Pa,} \tag{2.27}$$

where

S_{2-n} – networks characteristic of resistance (2.19) and (2.24) from the subscriber 2 up to n-th inclusive with all branches.

But, on the other hand, difference of pressure in unit *A* is equal:

$$\Delta P_1 = (S_{II} + S_{2-n}) \cdot (V - V_1)^2 = S_{1-n} \cdot V^2 \text{, Pa.} \tag{2.28}$$

From the joint decision of the equations (2.27) and (2.28) we shall find the relative flow of water at the second subscriber:

$$\overline{V_2} = \frac{V_2}{V} = \sqrt{\frac{S_{1-n}}{S_2} \cdot \frac{S_{2-n}}{S_{II-n}}}\,, \tag{2.29}$$

where $S_{II-n} = S_{II} + S_{2-n}$

By analogy for any *m*-th subscriber of the system consisting from *n* consumers, we shall receive:

$$\overline{V_m} = \frac{V_m}{V} = \sqrt{\frac{S_{1-n}}{S_m} \cdot \frac{S_{2-n}}{S_{II-n}} \cdot \frac{S_{3-n}}{S_{III-n}} \cdot \frac{S_{m-n}}{S_{M-n}}}\,. \tag{2.30}$$

Thus, if the total flow of water and the characteristic of resistance are known for all separate sites of a network it is possible to find the flow rate of water through any user's installation.

The characteristic of the centrifugal pump at constant turns will be following:

$$H = H_0 - S \cdot V^2 \text{, m} \tag{2.31}$$

where

H_0 and H – pressure head of the pump accordingly at $V_0 = 0$ and $V \neq 0$, m;
S_0 – conditional internal resistance of the pump, m·s²/m⁶.

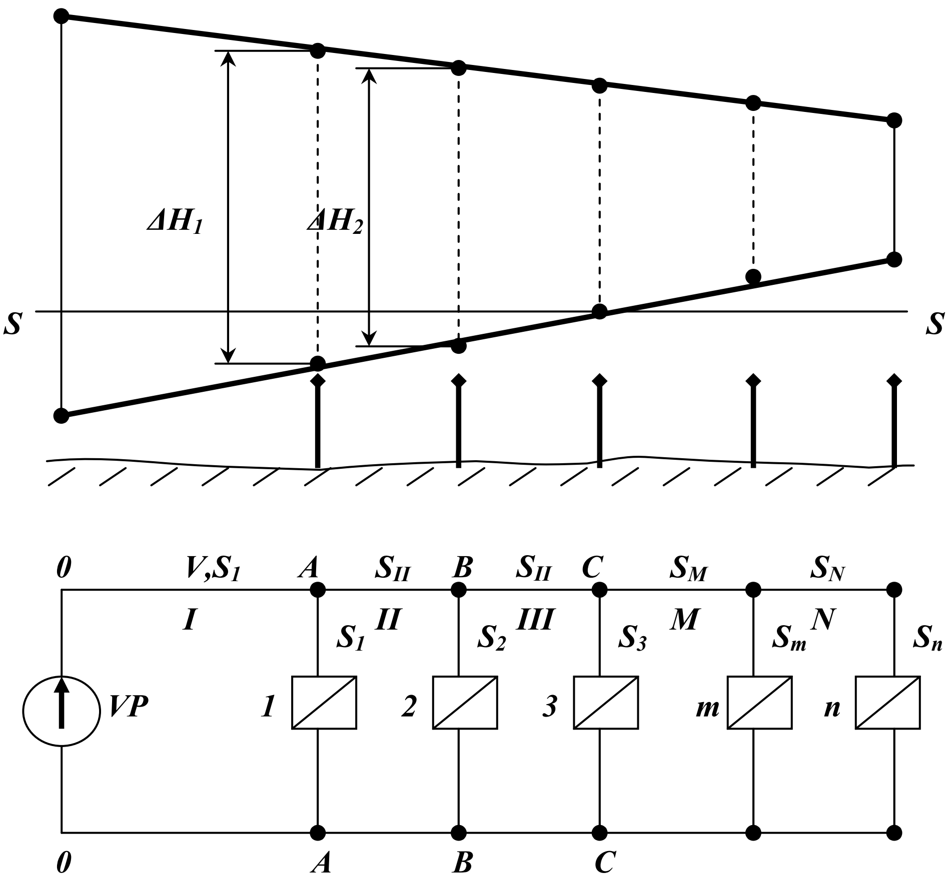


Figure 2.2 The scheme of a DH network with one heat source and piesometric schedule (where ΔH_1 and ΔH_2 valid heads of water in mH$_2$O accordingly at consumers 1 and 2)

Power of the pump at a nominal mode and at a mode differing from nominal at various flows of water (water density ρ =1000 kg/m^3) [38]:

$$N_n = g \cdot V_n \cdot H_n / \eta_n \text{, kW,} \tag{2.32}$$

$$N = N_n \cdot \left[x + \frac{V}{V_n} \cdot (1 - x) \right] \text{, kW,} \tag{2.33}$$

where

N_n and N – capacity of the pump at a nominal mode and at a mode differing from nominal, kW;
g=9,81 m/s^2 – acceleration of a gravity;
V_n – the nominal flow of water, m^3/s;
H_n – the nominal pressure head of pump, m;
η_n – nominal efficiency coefficient of the pump;
$x = N_x / N_n$ – factor of idling;
N_x – capacity of idling, kW.

The characteristic of the pump can be changed changing of turns number.

At reduction of turns number the characteristic of the pump to be displaced to the left and downwards, the point of crossing with the characteristic of a network to be displaced to the left and the flow rate will decrease.

At increase of turns number, the characteristic of the pump to be displaced to the right and upwards, the point of crossing with the characteristic of a network to be displaced to the right and the charge will increase (fig. 2.1).

Change of the pump rotation frequency is possible owing to presence of the frequency converter for the pumps electric motor. The characteristic of the pump will need to be recounted for new frequency of rotation. The characteristic is recalculated on all points separately [38]:

$$H`_I = H_I \cdot (n_2 / n_1)^2, \quad V`_I = V_I \cdot (n_2 / n_1), \quad N`_I = N_I \cdot (n_2 / n_1)^3 . \qquad (2.34)$$

On the basis of a hydraulic mode calculation a lot of the questions connected with operation of a heat supply system is solved, namely: the opportunity of connection of new subscribers to an existing network, emergency reservation of system, is checked work of a network at the maximal hot water supply.

2.1.4.2 Calculation of a hydraulic mode of a ring network with two heat supply sources

The hydraulic mode of ring networks with several heat sources is very sensitive to change of the heat-carrier flow rate on separate sites [34, 38]. The principle of calculation of such systems is based on Kirchoff equations (with reference to DH network), namely:

$$1)\ \Sigma V = 0, \qquad (2.35)$$

where ΣV – the algebraic sum of water flows in any point, m^3/h;

$$2)\ \Sigma S \cdot V^2 = 0, \qquad (2.36)$$

where $\Sigma S \cdot V^2$ – the algebraic sum of pressure losses for any closed contour, Pa.

There are two various conditions of calculation. For the automated inputs flows of water at subscribers and characteristics of resistance of main sites of a ring network are known. For not automated inputs the had pressure in point of a water supply to a network ring and characteristics of resistance of all sites is known. It is required to find distribution of the water flow in both cases on a networks sites.

Let's consider the first case, networks with one heat source when on user's inputs are installed regulators of the flow on an example of the elementary ring networks (fig. 2.3). We shall be set by any flows and directions of water streams, as shown in the network scheme. Thus we shall agree to consider positive inflow of water to point and pressure loss for the flow, which is passing in a contour clockwise, and negative – a drain of water from point and a pressure loss for the flow, which is passing counter-clockwise.

According to first equation of Kirchoff, flows (m^3/h) of the heat-carrier will be the following:

$$V_I = V_1 + V_{II}; \quad V_{II} = V_2 - V_{III}; \quad V_{IV} = V_3 + V_{III};$$
$$V = V_1 + V_{IV} = V_1 + V_2 + V_3 \tag{2.37}$$

Usually at any way chosen direction of streams the second equation of Kirchoff is not observed, therefore:

$$\Sigma\, S \cdot V^2 = S_I \cdot V_I^2 + S_{II} \cdot V_{II}^2 - S_{III} \cdot V_{III}^2 - S_{IV} \cdot V_{IV}^2 \pm \Delta P = 0, \tag{2.38}$$

where ΔP - difference in pressure losses, Pa.

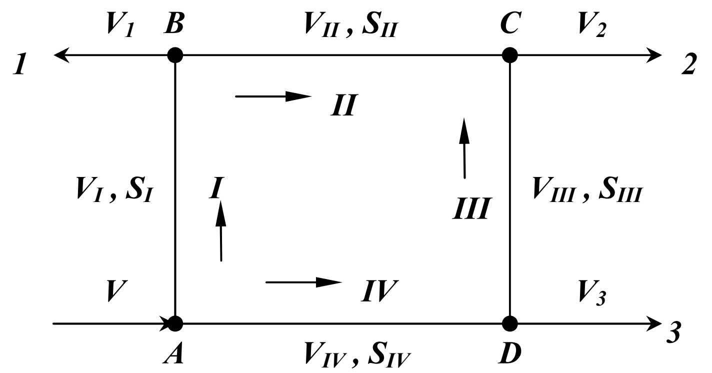


Figure 2.3 The scheme of a ring network with one source of heat

Positive value of distinction of a pressure ($\Delta P > 0$), testifies to an overload of sites *I* and *II* in a direction of an hour hand and insufficient loading of sites *III* and *IV*. The negative size of distinction of pressures specifies the return. For elimination of distinction of pressures at $\Delta P > 0$ it is necessary to reduce flows on sites *I* and *II*. With movement of water clockwise, and on sites *III* and *IV* to increase by the same size of the flow of distinction. After introduction in the equation (2.38) the flow of equalizing ΔV the second equation of Kirchoff is carried out:

$$S_I \cdot (V_I - \Delta V)^2 + S_{II} \cdot (V_{II} - \Delta V)^2 - S_{III} \cdot (V_{III} + \Delta V)^2 - S_{IV} \cdot (V_{IV} + \Delta V)^2 = 0 \quad (2.39)$$

Solving this equality concerning equalizing flow ΔV and neglecting insignificance of size ΔV^2, value of the equalizing flow we define parity:

$$\Delta V = \frac{\Delta P}{2 \cdot \Sigma SV}, \text{ m}^3\text{/h}, \quad (2.40)$$

where ΣSV size is always positive.

Entering this amendment ΔV to the equation (2.39), repeatedly spend verifying calculation and specify value of new, more exact amendment on a parity (2.40).

So as a result of several specifications define finally flows of water on sites and a point of a watershed in a ring.

At a feed of a network from two and more sources an arrangement of a point of a watershed define similarly (fig. 2.4).

We shall be set any way by a point of a watershed (point *B*) and we shall work out second equation of Kirchoff:

$$S_I \cdot V_I^2 + S_{II} \cdot V_{II}^2 - S_{III} \cdot V_{III}^2 - S_{IV} \cdot V_{IV}^2 - g \cdot \rho \cdot (H_1 - H_2) = \Delta P, \quad (2.41)$$

where $H_1 - H_2 = \Delta H$, m – difference of pressures of the network pumps installed on heat source № 1 and heat source № 2.

Having defined equalizing water flow under the formula (2.40), make specification of an arrangement of a point of a watershed. At positive value of distinction of pressure ($\Delta P > 0$) the point of a watershed will be displaced aside heat source № 2 (a point *C*) as overloaded there are sites I, II and flows of water on these sites should be reduced. At negative values of distinction of pressure ($\Delta P < 0$), use of equalizing flows of the heat-carrier displaces a point of a watershed aside heat source № 1 (a point *A*).

If in intermediate points of a network there are pump substations, at a choice of a point of a watershed their pressures summarize with pressures of network pumps of heat source in a direction of movement of the heat-carrier.

Position of a point of a watershed influence the characteristic of resistance of a network sites and units and had pressures on collectors of heat sources stations. The increase in a pressure of the network pump at constant hydraulic characteristics of a network displaces a point of a watershed in a direction from thermal power station (fig. 2.5). Replacement of pipes by bigger diameter or reduction of networks loading increases radius of action of heat sources station. Hence, any change of loadings and characteristics of a network causes change of had pressures in a network and on user's inputs. Changing position of a point of a watershed, it is possible to achieve economic loading of heat sources stations.

Calculation of distribution of a stream in a ring network without regulators of the water flow make on second equation of Kirchoff a method of consecutive approximation. As flows of water at subscribers in advance are not known, are set by a share of the water flow acting in a point of a watershed at the left (α) and on the right ($1-\alpha$).

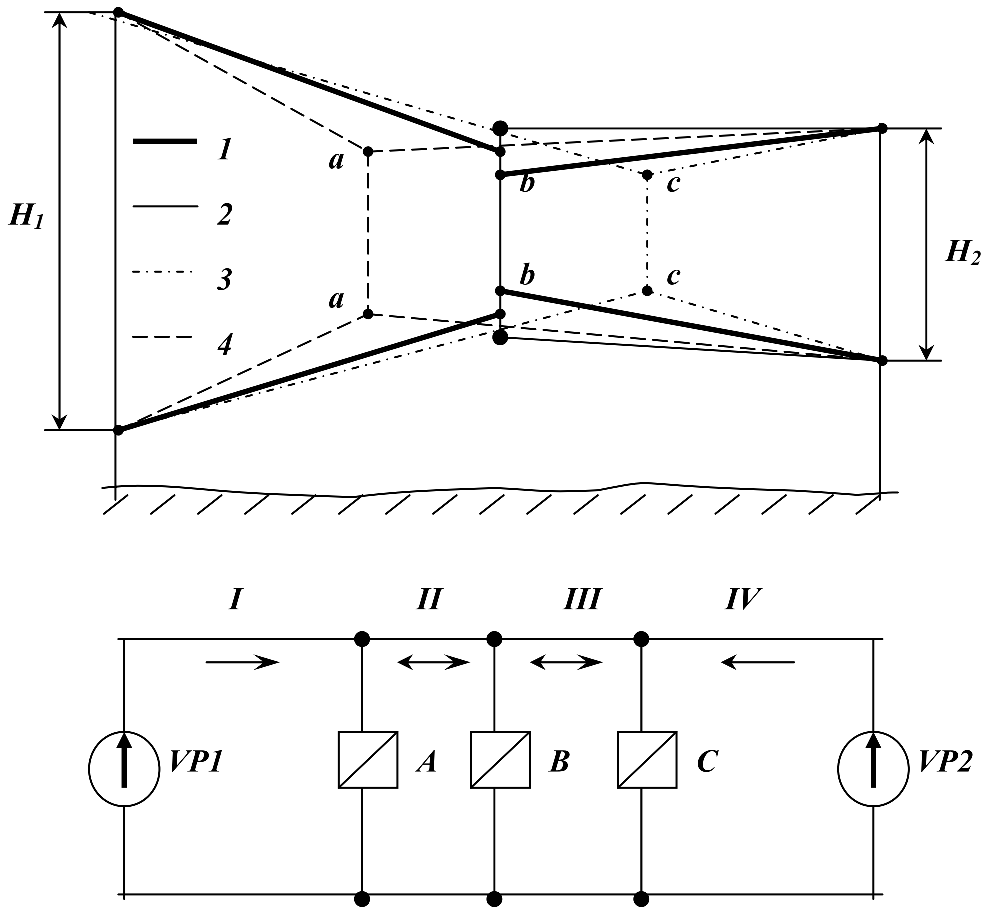


Figure 2.4 The ring network with two heat supply sources and piesometric schedule (1 – at any way chosen watershed in a point B in at $\Delta P > 0$; 2 – at any way chosen watershed in a point B in at $\Delta P < 0$; 3 – at displacement of a watershed in a point C; 4 – at displacement of a watershed in a point A)

Further define characteristics of resistance of systems sites (Fig. 2.4):

$$S = S_{A-1-II-2} \quad \text{ja} \quad (-S) = S_{A-IV-3-2}\text{, Pa·h}^2\text{/m}^6, \qquad (2.42)$$

where signs "+" and "–" correspond to movement of water clockwise and against.

Then find flows of water under formulas:

$$V = \sqrt{\frac{\Delta P_A}{S}}; \quad (-V) = \sqrt{\frac{\Delta P_A}{(-S)}}\ , \mathrm{m^3/h}, \tag{2.43}$$

where ΔP_A – difference of pressure (Pa) in a water supply point to a ring.

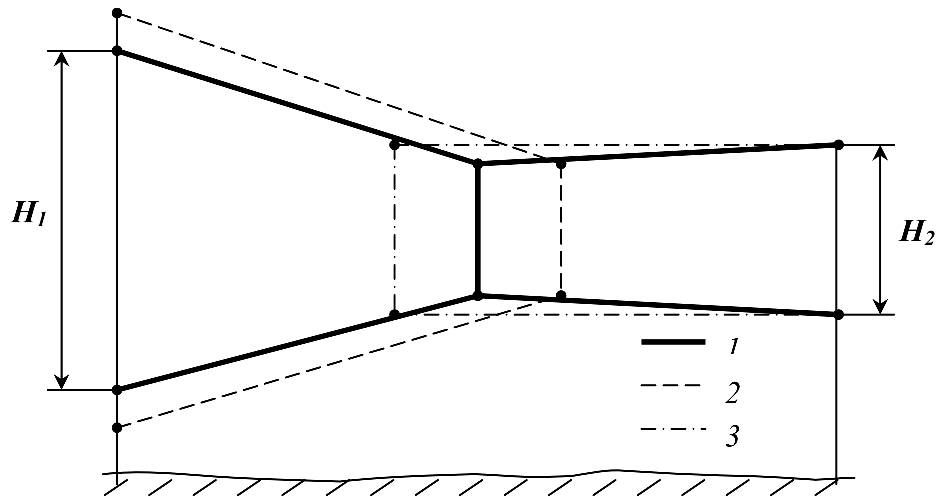


Figure 2.5 Schedules of a watershed point change in networks (1 – at a starting position of a point of a watershed; 2 – at change of a pressure of the network pump; 3 – at reduction of a network resistance)

Further check performance of second equation of Kirchoff at positive distinction of pressure reduce a share of the water flow α, at negative a share of the water flow α increase. It is possible, having left α same to move a point of a watershed to unit *B* or *C*. Change of sizes α make until second equation of Kirchoff will be satisfied.

Using the above-stated dependences, within the limits of the given work applied computer programs in MS EXCEL and VBA (VISUAL BASIC) environment [52,53], for performance of hydraulic calculations of networks have been created. Programs completely consider all technical features of Estonian old district heating systems.

Using the created programs hydraulic calculations of the considered networks have been made. For hydraulic calculation of networks of the city of Tallinn, databases of AS Tallinna Küte and program TERMIS have been used [21].

2.2 Model for DH network heat losses calculations

In the given chapter the description of model for calculation of heat losses of a network is given. The created thermal model allows to make the analysis of efficiency of existing thermal insulation of old networks, knowing the valid heat losses and a design of a network.

By means of the created thermal model it is possible to define heat losses of DH networks of different types: in the underground channel, underground from the preinsolated pipes, an air lining.

Efficiency of thermal insulation of six DH networks has been in detail considered: Võrusoo and Võrukivi networks in Võru, Kuressaare network, Orissaare network, Terme and Vabriku networks in Türi.

For each considered network the thermal model has been made, by means of which, proceeding from the valid heat losses, the valid efficiency of existing thermal insulation of a underground network in the channel lining has been certain. The valid coefficients of a heat transfer have been received.

Calculations are made on months. Empirical formulas for calculation of the heat losses of the considered networks are found. Dependence of efficiency of thermal insulation on humidifying during the winter, autumn and spring periods are certain. Advice by calculation of heat losses, in view of seasonal humidifying of insulation, in those old networks where the account of heat losses is not present is given.

2.2.1 Heat losses calculation for different types of district heating networks lining

2.2.1.1 Heat losses of a underground network laying in the concrete channel

For heat losses calculation of an underground network it is necessary to know value of a heat transfer coefficient of insulation depending on diameter of pipes, lengths of sites, temperatures of the heat-carrier and temperature of air.

For definition of a heat transfer coefficient it were necessary to know what thermal insulation materials are used, their thickness, depth of the channel lining, thermal and physical properties of a ground. On the basis of these data it is possible to define thermal resistance of all separate layers of insulation. Besides it is necessary to consider a heat exchange between a submitting and return pipe, which partially compensates heat losses.

The scheme of the underground network, which is lying in the concrete channel, is given in figure 2.6.

Knowing the separate thermal resistances and considering a heat exchange between pipes [29, 31, 33], the heat transfer coefficients of pipes are certain.

At the given arrangement of pipes the heat transfer coefficient of a supply pipe is defined as follows [36, 46]:

$$K_p = \frac{1/R_{p,is} \cdot (1/R_{t,is} + 1/R_{k-o})}{1/R_{p,is} + 1/R_{t,is} + 1/R_{k-o}}, \text{ W/(mK)}. \qquad (2.44)$$

The heat transfer coefficient of a return pipe is defined as follows:

$$K_t = \frac{1/R_{t,is} \cdot (1/R_{p,is} + 1/R_{k-o})}{1/R_{p,is} + 1/R_{t,is} + 1/R_{k-o}}, \text{ W/(mK).} \quad (2.45)$$

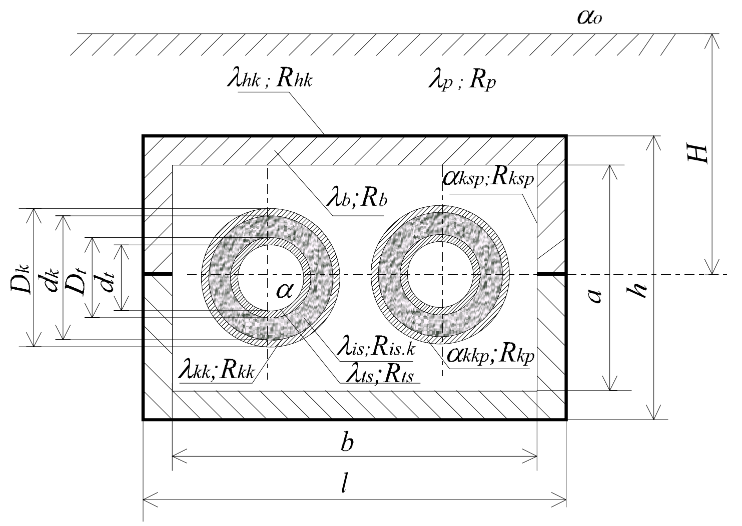


Figure 2.6 The underground network lying in the concrete channel

The heat transfer coefficient considering heat exchange between supply and return pipes is defined as follows:

$$K_{p,t} = K_{t,p} = \frac{1/R_{p,is} \cdot 1/R_{t,is}}{1/R_{p,is} + 1/R_{t,is} + 1/R_{k-o}}, \text{ W/(mK),} \quad (2.46)$$

where

$R_{p,is}$ – thermal resistance of insulation of a supply pipe, (mK)/W;

$R_{t,is}$ – thermal resistance of insulation of a return pipe, (mK)/W;

R_{k-o} – thermal resistance of the channel and ground, (mK)/W.

Thermal resistance of thermal insulation of a pipe consists of following parts:

$$R_{is} = R_{tsp} + R_{ts} + R_{is.k} + R_{is.kk} + R_{kkp}, \text{ (mK)/W,} \quad (2.47)$$

where

R_{tsp} – thermal resistance of an internal surface of a pipe, (mK)/W;

R_{ts} – thermal resistance of a pipes wall, (mK)/W;

$R_{is.k}$ – thermal resistance of a layer of thermal insulation, (mK)/W;

$R_{is.kk}$ – thermal resistance of a covering of a layer of thermal insulation, (mK)/W;

R_{kkp} – thermal resistance of an external surface of a covering, (mK)/W.

Thermal resistance of the channel and ground consists of following parts:

$$R_{k-o} = R_{ksp} + R_{ks} + R_{hk} + R_p \text{, (mK)/W,} \tag{2.48}$$

where

R_{ksp} – thermal resistance of an internal surface of the channel: (mK)/W,

R_{ks} – thermal resistance of a wall of the channel, (mK)/W;

R_{hk} – thermal resistance of a layer of a waterproofing of the channel, (mK)/W;

R_p – thermal resistance of a ground and surface of ground, (mK)/W.

Heat losses of a supply and return pipe will be the following:

$$q_p = K_p(t_p - t_{\tilde{o}}) - K_{p,t}(t_t - t_{\tilde{o}}) \text{, W/m,} \tag{2.49}$$

$$q_t = K_t(t_t - t_{\tilde{o}}) - K_{t,p}(t_p - t_{\tilde{o}}) \text{, W/m,} \tag{2.50}$$

where

K_p – heat transfer coefficient of a supply pipe, W/(mK);

K_t – heat transfer coefficient of a return pipe, W/(mK);

$K_{p,t} = K_{t,p}$ – heat transfer coefficient considering heat exchange between supply and return pipes, W/(mK);

t_p – temperature of water in a supply pipe, $^\circ\mathrm{C}$;

t_t – temperature of water in a return pipe, $^\circ\mathrm{C}$;

$t_{\tilde{o}}$ – temperature of external air, $^\circ\mathrm{C}$.

If coefficients of a heat transfer of a supply and return pipe are equal, heat losses of an underground network can be found as follows:

$$q = q_p + q_t = 2 \cdot (K_1 - K_o) \cdot \left(\frac{t_p + t_t}{2} - t_{\tilde{o}} \right) = 2 \cdot U \cdot \Theta \text{, W/m,} \tag{2.51}$$

where

$K_1 = K_p = K_t$, $K_o = K_{p,t} = K_{t,p}$, $U = K_1 - K_o$, $\mathrm{W/(m \cdot K)}$,

$\Theta = \dfrac{t_p + t_t}{2} - t_{\tilde{o}}$, °C.

Further formulas for definition of thermal resistance are resulted. The basic thermal resistance are thermal resistance of a layer of thermal insulation and further thermal resistance of a ground follows on size. Other thermal resistances, in comparison with them, are insignificant.

Thermal resistance of an internal surface of a pipe:

$$R_{tsp} = \frac{1}{\pi \cdot d_t \cdot \alpha}, \text{ (mK)/W}, \tag{2.52}$$

where

d_t – internal diameter of a pipe, m;

α – convective heat transfer coefficient from water to an internal surface of a pipe, W/(m^2K).

On an internal surface of a pipe convective heat transfer is very intensive. Owing to it, thermal resistance of an internal surface of a pipe will be very small in comparison with other resistances.

Thermal resistance of a pipes wall will be very small, owing to good heat conductivity of steel:

$$R_{ts} = \frac{1}{2\pi \cdot \lambda_{ts}} \cdot \ln \frac{D_t}{d_t}, \text{ (mK)/W}, \tag{2.53}$$

where

λ_{ts} – steel heat conductivity coefficient, W/(mK);

D_t – external diameter of a pipe, m.

In the further calculations the coefficient of heat conductivity of steel is taken equal λ_{ts} = 63 W/(mK), at temperature 50°C [45].

The basic thermal resistance of a thermal insulation layer will be the following:

$$R_{is} = \frac{1}{2\pi \cdot \lambda_{is}} \cdot \ln \frac{d_k}{D_t}, \text{ (mK)/W}, \tag{2.54}$$

where

λ_{is} – heat conductivity coefficient of thermal insulation, W/(mK);

d_k – external diameter of thermal insulation, m.

As thermo insulation material in old networks glass wool is used. Further factors influencing on efficiency of fibrous thermo insulation materials are resulted in [49, 50, 51]. Mineral wool is a fibrous material in which the ratio of length of fibres to their diameter makes l/d > 400. The coefficient of heat conductivity of thermo insulation material depends on temperature of a material, density, porosity, and diameter of fibres. Influence of temperature growth on increase of heat conductivity increases with increase in density of a material.

The heat flow which is passing through a fibrous material, consists of three parts: heat conductivity on fibres of a material, molecular heat conductivity in gas filling space between fibres and heat exchange by radiation in gas between fibres. Distribution of a heat flow between these parts depends on heat conductivity of fibres, heat conductivity of gas being between fibres, porosity, diameter of fibres, an emissivity, etc.

The majority of fibrous materials absorb humidity from air. The quantity of the absorbed moisture depends on physical properties of a fibres material, properties of substance which connecting fibre, temperature and humidity of an environment. First the absorbed moisture accumulates on a surface of fibres in the form of adsorption layer, further fills all volume of a fibrous material. Humidifying of a fibrous material considerably increases its heat conductivity. Relative humidity of air can reach in the underground channel up to 100 %. At contact with a cold wall of the channel damp air is cooled also moisture condensed. Drops of a liquid get on pipes thermal insulation and humidify it, that sharply increasing its heat conductivity. The moisture also can to get in the underground channel through the waterproofing, damaged from an old age.

At increase in porosity of a thermo insulation material up to p=0,98, the effective coefficient of heat conductivity will reach the minimal value. It speaks that at materials with in greater density (ρ > 100 kg/m^3), the basic part of a heat flow goes on fibres. At reduction of density and growth of porosity, the share of a thermal stream going on fibres decreases and at increase in porosity up to 1 comes nearer to zero. The molecular part of a heat flow increases with increase in porosity and reaches the maximal value equal to heat conductivity of filling gas. However the increase in molecular heat conductivity occurs more slowly, than reduction of heat conductivity on fibres and consequently effective heat conductivity does not increase. At the further increase in porosity (p > 0,98), heat conductivity again starts to increase owing to an intensification of heat exchange by radiation.

Increase in heat conductivity of a fibres material increases effective coefficient of heat conductivity. It is especially appreciable at more dense fibrous materials. At increase in diameter of fibres, effective heat conductivity increases due to increase in molecular heat conductivity and an intensification of heat exchange by radiation.

As pipes thermal insulation in old networks basically layers from mineral wool with density 135–170 kg/m^3 were used [40]. At installation layers were squeezed and as a result it density increased approximately in 1,5 times and reached 200 kg/m^3. As a result with increase in density of a material heat conductivity increased also. In following figure 2.7 the coefficient of heat conductivity of mineral wool depending on density and volumetric humidity is resulted [35].

At drawing up of thermal model for old networks for both pipes the thickness of thermal insulation 40 mm were accepted (one layer of insulation with initial thickness of 50 mm) for pipes DN25–200 and for pipes of bigger diameter since DN 250–80 mm (two layers of insulation) were accepted. For the new and reconstructed sites the valid thickness of thermal insulation has been taken.

Calculations of heat losses (fig.2.7) are made for three different conditions of mineral wool: for completely dry material with heat conductivity 0,05 W/(mK), for a damp material with heat conductivity 0,08 W/(mK) (W = 15%) and 0,145 W/(mK) (W = 35%).

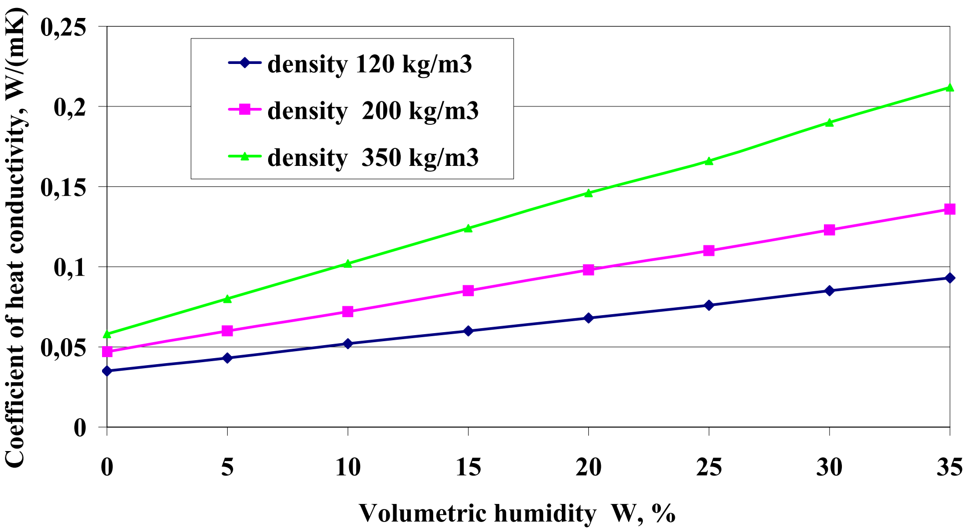


Figure 2.7 Coefficient of heat conductivity of mineral wool depending on volumetric humidity at temperature 30°C [35].

These values of heat conductivity substantially conditional. Except for humidifying insulation can be still and other problems raising heat conductivity: old glass wool of local manufacture can be non-uniform density, at installation used insulation with thickness less than normative, wire fixed insulation have collapsed from corrosion and insulation has sagged.

The layer of mineral wool is covered as a rule by ruberoid and fixed by a steel wire. Thermal resistance of a covering layer will be the following:

$$R_{is.kk} = \frac{1}{2\pi \cdot \lambda_{is.kk}} \cdot \ln \frac{D_k}{d_k}, \text{ (mK)/W}, \qquad (2.55)$$

where

$\lambda_{is.kk}$ – heat conductivity coefficient of a covering layer, W/(mK);

D_k – external diameter of a covering layer, m.

The coefficient of heat conductivity of roofing material (ruberoid) is taken λ_{kk} = 0,17 W/(mK) [36], at temperature 30 °C. Thickness of a ruberoid is 3 mm.

Thermal resistance of an external surface of a thermal insulation covering layer is the following:

$$R_{kkp} = \frac{1}{\pi \cdot D_k \cdot \alpha_{kkp}}, \text{ (mK)/W}, \qquad (2.56)$$

where

D_k – external diameter of a thermal insulation covering layer, m;

α_{kkp} – convective heat transfer coefficient from a surface of thermal insulation covering layer to air, W/(m^2 K).

The convective heat transfer coefficient from a surface of thermal insulation covering layer to air is taken α_{kkp} = 8 W/(m^{2}K) [41].

Thermal resistance of a wall of the channel and ground consists of following parts:

$$R_{k-o} = R_{ksp} + R_{ks} + R_{hk} + R_p \text{, (mK)/W,} \tag{2.57}$$

where

R_{ksp} – thermal resistance of an internal surface of the channel, (mK)/W;

R_{ks} – thermal resistance of a channel wall, (mK)/W;

R_{hk} – thermal resistance of a waterproofing of the channel, (mK)/W;

R_p – thermal resistance of a ground and surface of a ground, (mK)/W.

Thermal resistance of an internal surface of the channel is the following:

$$R_{ksp} = \frac{1}{\pi \cdot d_{ekv} \cdot \alpha_{ksp}} \text{, (mK)/W,} \tag{2.58}$$

where

α_{ksp} – convective heat transfer coefficient from a air to channel wall, (m^2 K)/W;

d_{ekv} – internal equivalent diameter of the channel, m.

The convective heat transfer coefficient from air to a channel wall is taken α_{ksp} = 8 W/(m^{2}K) [41].

Equivalent diameter is certain as follows:

$$d_{ekv} = \frac{4F}{P} = \frac{4ab}{2(a+b)} \text{, m,} \tag{2.59}$$

where

a and *b* – the internal sizes of the channel, m;

F – the area of an internal section of the channel, m^2;

P – internal perimeter of the channel, m.

The internal sizes of usually used channels are the following: DN32-DN80 – a = 0,4 m and b = 0,75 m; DN100–DN150 – a = 0,5 m and b = 1,0 m; DN175–DN250 – a = 0,65 m and b = 1,25 m; DN300–DN400 – a = 0,84 m and b = 1,5 m; DN500–DN600 – a = 1,3 m and b = 2,4 m [42,43].

The thermal resistance of a channel wall is the following:

$$R_{ks} = \frac{1}{2 \cdot \pi \cdot \lambda_{ks}} \cdot \ln \frac{D_{ekv.v}}{D_{ekv.s}}, \text{ (mK)/W,} \tag{2.60}$$

where

λ_{ks} – heat conductivity coefficient of a channel wall, W/(mK);

$D_{ekv.v}$ – external equivalent diameter of the channel, m;

$D_{ekv.s}$ – internal equivalent diameter of the channel, m.

The heat conductivity coefficient of ferro-concrete is taken following: λ_{ks} =1,55 W/(mK) [36].

The external sizes of usually used channels are the following: h = 0,6 m and l = 0,95 m; DN100–DN150 – h = 0,7 m and l = 1,2 m; DN175–DN250 – h = 0,89 m and l = 1,49 m; DN300–DN400 – h = 1,075 m and l = 1,74 m; DN500–DN600 – h = 1,5 m and l = 2,6 m [42,43].

After installation the concrete channel is covered from the external side with bitumen for a waterproofing. Thickness of bitumen makes ~5 mm. Thermal resistance of a waterproofing layer will be the following:

$$R_{hk} = \frac{1}{2\pi \cdot \lambda_{hk}} \cdot \ln \frac{D^{hk}_{ekv.v}}{D^{hk}_{ekv.v}}, \text{ (mK)/W,} \tag{2.61}$$

where

λ_{hk} – heat conductivity coefficient of a bitumen, W/(mK);

$D^{hk}_{ekv.v}$ – external equivalent diameter of a waterproofing layer, m;

$D^{hk}_{ekv.s}$ – internal equivalent diameter of a waterproofing layer, m

The heat conductivity coefficient of bitumen is $\boldsymbol{\lambda_{hk}}$ = 0,3 W/(mK) [36].

If depth of the channel lining is small (*H/D*$_{ekv}$< 2), then temperature of a surface of ground can essentially exceed natural temperature of ground. For prevention of errors at calculation of heat losses it is necessary to use temperature of external air. In this case thermal resistance of a ground and its surface will be the following:

$$R_p = \frac{1}{2\pi \cdot \lambda_p} \cdot \ln\left[\frac{2H_t}{D_{ekv}} + \sqrt{\frac{4H_t^2}{D_{ekv}^2} - 1}\right], \text{ (mK)/W,} \tag{2.62}$$

where

D_{ekv} – external equivalent diameter of the channel, m;

λ_p – heat conductivity coefficient of ground W/(mK),

H_t – the resulted depth of an axis of pipes, m.

The resulted depth of an axis of pipes is the following:

$$H_t = H + H_s = H + \frac{\lambda_p}{\alpha_0}, \text{ m}, \tag{2.63}$$

where

H_t – the resulted depth of pipes axis, m;

H – the real depth of pipes axis, m;

H_s – the fictitious thickness of ground considering thermal resistance of a ground surface, m;

λ_p – heat conductivity coefficient of a ground, (mK)/W;

α_0 – the convective heat transfer coefficient from the ground surface to air, W/(m^2K).

The convective heat transfer coefficient from a surface of the ground to air is taken α_0 = 15 W/(m^2K) [34, 35] at speed of a wind 3,2 m/s.

Thickness of a layer of the ground covering the channel makes 0,7 m and thermal resistance of a ground is found under the formula (5.19).

If depth of the channel lining is big ($H / D_{ekv} > 2$), then temperature of a ground surface is practically identical with natural temperature of ground. At calculation of heat losses it is necessary to use natural temperature of a ground on depth of a pipes axis. In this case thermal resistance of a ground and its surface will be the following:

$$R_p = \frac{1}{2\pi \cdot \lambda_p} \cdot \ln \frac{4H_t}{D_{ekv}}, \text{ (mK)/W}, \tag{2.64}$$

The heat conductivity coefficient of a ground is taken the following: λ_p = 1,85 (mK)/W for stony and sandy ground at humidity of 6 %, λ_p = 2,38 (mK)/W at humidity of 30 % and λ_p = 2,9 (mK)/W for completely wet ground. At the best, heat conductivity of a ground can will decrease till λ_p = 0,91 (mK)/W, at humidity of a ground of 1,3 % [35]. Mid-annual value of heat conductivity makes λ_p = 2,38 (mK)/W.

Further the heat transfer coefficient for a pipe of a underground network (5.8) is counted up at different humidity of a ground and thermal insulation. Results of calculations are brought in figure 2.8.

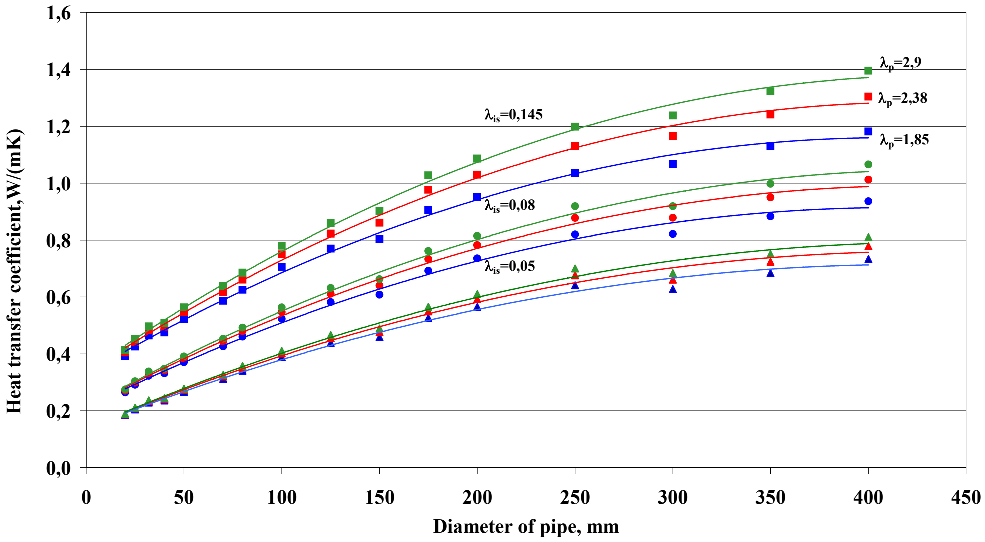


Figure 2.8 The heat transfer coefficient for a pipe of a underground network at different humidity of a ground (λ_{pin} = 1,85; 2,38; 2,9 W/(mK)) and thermal insulation (λ_{is} = 0,05; 0,08; 0,145 W/(mK))

Apparently from figure 2.8, the possible increase in heat conductivity of a ground 1,85–2,9 W/(mK) increases the general heat transfer coefficient of a pipe depending on diameter (DN20–400) by 2,6–10,6 % at completely dry mineral wool – λ_{is} = 0,05 W/(mK), on 3,8–13,8 % at partially damp (W=15%) mineral wool – λ_{is} = 0,08 W/(mK) and on 5,8–18,1 % at strongly damp (W=35%) mineral wool - λ_{is} = 0,145 W/(mK). In the further calculations heat conductivity of ground is taken λ_{pin} = 2,38 W/(mK).

2.2.1.2 Heat losses of a underground network from the preinsulated pipes

The scheme of a underground DH network from the preinsulated pipes with the indication of all thermal resistances is given in figure 2.9.

Network heat losses consist of supply and return pipe heat losses. At the same time it is necessary to consider a thermal exchange between pipes. In this case heat exchange between pipes goes through a ground between pipes.

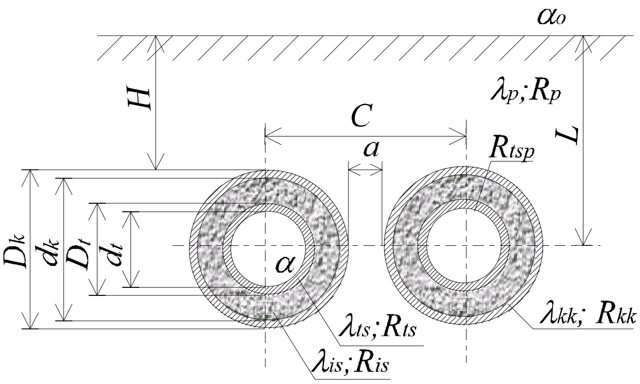


Figure 2.9 Underground network from the preinsulated pipes

Heat losses of a underground network from the preinsulated pipes are defined under formulas 2.49, 2.50 and 2.51, brought in point 2.2.1.1. Also it is necessary to consider heat exchange between pipes and a ground in other way [29].

The heat transfer coefficient of a supply pipe will be the following [3, 27, 28]:

$$K_p = \frac{R_{t,is} + R_{t,pin}}{(R_{p,is} + R_{p,pin}) \cdot (R_{t,is} + R_{t,pin}) - R_c^2}, \text{ W/(mK)}. \tag{2.65}$$

The heat transfer coefficient of a return pipe will be the following:

$$K_t = \frac{R_{p,is} + R_{p,pin}}{(R_{p,is} + R_{p,pin}) \cdot (R_{t,is} + R_{t,pin}) - R_c^2}, \text{ W/(mK)}. \tag{2.66}$$

The heat transfer coefficient considering heat exchange between supply and return pipes is defined as follows:

$$K_{p,t} = K_{t,p} = \frac{R_c}{(R_{p,is} + R_{p,pin}) \cdot (R_{t,is} + R_{t,pin}) - R_c^2}, \text{ W/(mK)}, \tag{2.67}$$

where

$R_{p,is}$ – thermal resistance of a supply pipe insulation, (mK)/W;

$R_{t,is}$ – thermal resistance of a return pipe insulation, (mK)/W;

$R_{p,pin}$ – thermal resistance of the ground around supply pipe, (mK)/W;

$R_{t,pin}$ – thermal resistance of the ground around return pipe, (mK)/W;

R_c – thermal resistance considering heat exchange between supply and return pipes, (mK)/W.

Thermal resistance of a pipe consists of the following parts

$$R_{is} = R_{tsp} + R_{ts} + R_{is.k} + R_{is.kk} \text{ , (mK)/W,} \tag{2.68}$$

where

R_{tsp} – thermal resistance of a pipes internal surface, (mK)/W;

R_{ts} – thermal resistance of a pipes wall, (mK)/W;

$R_{is.k}$ – thermal resistance of a thermal insulation layer, (mK)/W;

$R_{is.kk}$ – thermal resistance of a thermal insulation covering layer, (mK)/W;

These thermal resistances can be defined under formulas resulted in chapter 2.2.1.1. As thermal insulation it is used polyurethane foam by heat conductivity λ_{is} = 0,03 W/(mK) [30]. The preinsulated pipe from above is covered by a blanket of polythene with heat conductivity λ_{kk} = 0,43 W/(mK) [30]. Thickness of thermal insulation is taken in accordingly standard [39].

Thermal resistance of a ground and its surface at $L/D_k > 1$:

$$R_p = \frac{1}{2 \cdot \pi \cdot \lambda_p} \cdot \ln \frac{4 \cdot L_t}{d_t} \text{ , (mK)/W,} \tag{2.69}$$

where

L_t – the resulted depth of a pipe, m.

For the account of a ground surface thermal resistance it is necessary to use the resulted depth of a pipes axis.

$$L_t = L + \frac{\lambda_p}{\alpha_o} \text{ , m,} \tag{2.70}$$

where

L – the valid depth of pipes, m.

Thickness of a ground layer up to a preinsulated pipe surface makes H = 0,7 m and proceeding from it depth of a pipes axis is certain. The distance between surfaces of the preinsulated pipes in a horizontal plane makes a = 0,15 m

Thermal resistance of a ground and its surface at $L/D_k < 1$:

$$R_p = \frac{1}{2 \cdot \pi \cdot \lambda_p} \cdot \ln \left[\frac{2 \cdot L_t}{D_k} + \sqrt{\left(\frac{2 \cdot L_t}{D_k} \right)^2 - 1} \right] \text{, (mK)/W.} \tag{2.80}$$

Thermal resistance considering heat exchange between supply and return pipes:

$$R_c = \frac{1}{2 \cdot \pi \cdot \lambda_p} \cdot \ln \sqrt{1 + (2H_t / C)^2} \text{ , (mK)/W,} \tag{2.81}$$

where
C – distance between axes of a supply and return pipe, m.

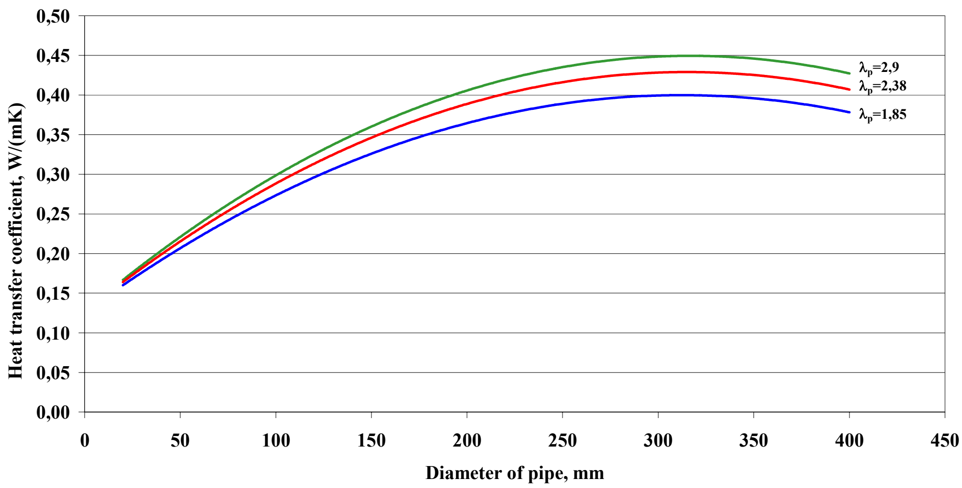


Figure 2.10 Heat transfer coefficient of the underground preinsulated pipe at different heat conductivity of a ground λ_{pin} = 1,85; 2,38; 2,9 W/(mK)

Apparently from figure 5.4, the possible increase in heat conductivity of a ground λ_{pin} = 1,85–2,9 W/(mK) increases the general heat transfer coefficient of a pipe depending on diameter (DN20–400) by 4,2–13,0 % at completely dry polyurethane foam – λ_{is} = 0,03 W/(mK). Influence of humidifying of a ground at the preinsulated pipes renders greater influence on a heat transfer than at a channel lining. At a channel lining this change under identical conditions makes 2,6–10,5 %. This conclusion is fair only in case of dry insulation in a channel-lining network.

2.2.1.3 Heat losses of an air lining network

At calculation of an air lining network heat losses it is necessary to define separately heat losses of a supply and return pipe. The thermal exchange between pipes does not occur. The scheme of an air-lining network with the indication of all thermal resistances is given in figure 2.11.

The heat transfer coefficient of an air lining network pipe:

$$K = 1 / R_{\Sigma} \text{, W/(mK)}, \qquad (2.82)$$

where

R_{Σ} – total thermal resistance of a pipe, (mK)/W.

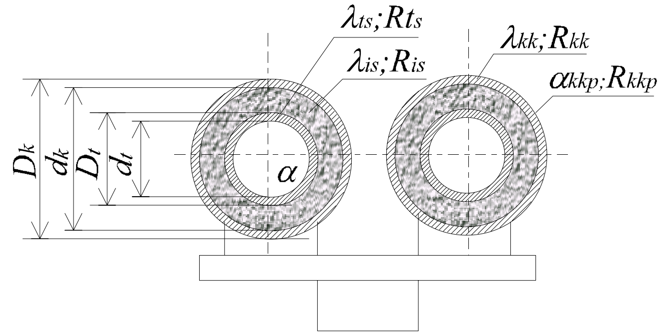


Figure 2.11 Air lining network

Total thermal resistance of a pipe consists of following parts:

$$R_{\Sigma} = R_{tsp} + R_{ts} + R_{is.k} + R_{is.kk} + R_{kkp}\text{, W/(mK).} \tag{2.83}$$

Heat losses of one pipe will be the following:

$$q = K(t_{sk} - t_{\tilde{o}})\text{, W/m,} \tag{2.84}$$

where

K – heat transfer coefficient of a pipe, W/(mK);

t_{sk} – temperature of the heat-carrier, $^{\circ}\mathrm{C}$;

$t_{\tilde{o}}$ – temperature of external air, $^{\circ}\mathrm{C}$.

Heat losses of an air-lining network consisting of two pipes:

$$q = q_p + q_t = K_p(t_p - t_{\tilde{o}}) + K_t(t_t - t_{\tilde{o}})\text{, W/m,} \tag{2.85}$$

where

K_p – heat transfer coefficient of a supply pipe, W/(mK);

K_t – heat transfer coefficient of a return pipe, W/(mK);

t_p – water temperature in a supply pipe $^{\circ}\mathrm{C}$,

t_t – water temperature in a return pipe, $^{\circ}\mathrm{C}$;

$t_{\tilde{o}}$ – temperature of external air, $^{\circ}\mathrm{C}$.

If coefficients of a heat transfer of a supply and return pipe are equal, heat losses of an air-lining network can be found as follows:

$$q = q_p + q_t = 2 \cdot K \cdot \left(\frac{t_p + t_t}{2} - t_{\tilde{o}} \right) = 2 \cdot K \cdot \Theta\text{, W/m.} \tag{2.86}$$

Heat transfer coefficient of an air-lining network at different heat conductivity of thermal insulation is given in figure 2.12.

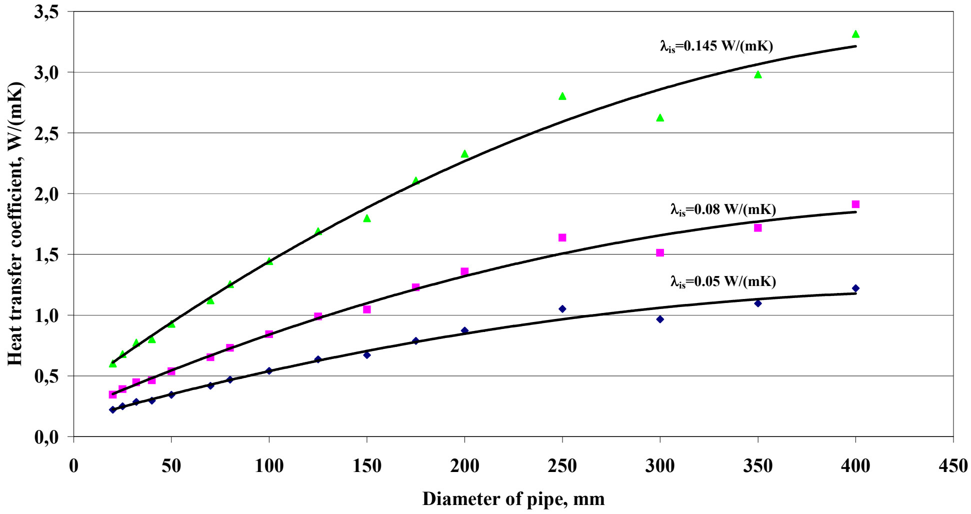


Figure 2.12 Heat transfer coefficient of an air-lining network at different heat conductivity of thermal insulation (λ_{is} = 0,05; 0,08; 0,145 W/(mK))

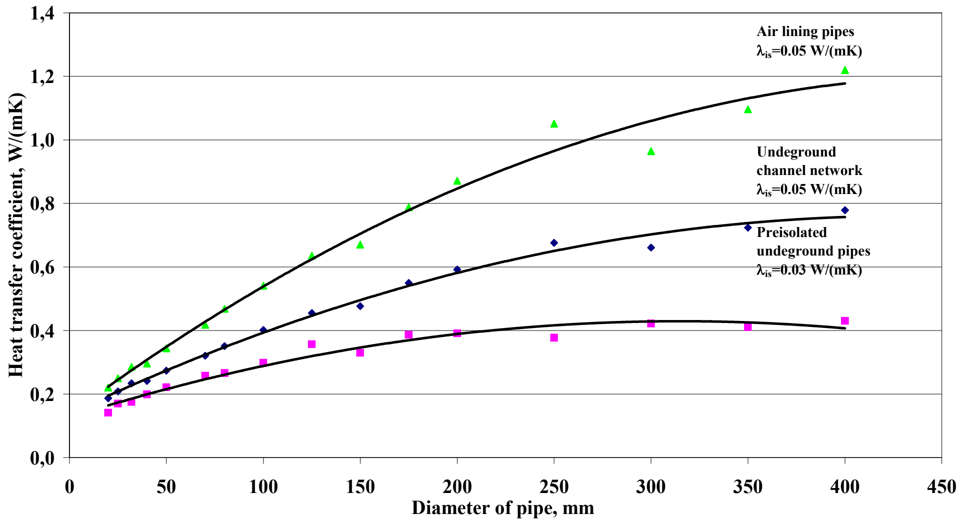


Figure 2.13 Heat transfer coefficient of pipes for various lining

Apparently from figure 2.12, dependence of a heat transfer coefficient of an air lining pipes on heat conductivity of insulation will be much stronger than in an underground network. Thermal resistance of a ground in an underground network smoothes growth of a heat transfer coefficient. Heat transfer coefficient of a various lining pipes is given in figure 2.13.

Apparently from figure 2.13 heat transfer will be the biggest at pipes of an air lining network, pipes of a underground network in the concrete channel further follow and the smallest heat transfer will be at the underground preinsulated pipes.

2.2.2 Definition of the empirical formula of DH network heat losses

For definition of all district heating networks heat losses it is necessary to know values of pipes heat transfer coefficients, length and diameters of all sites, temperature of the heat-carrier and temperature of air.

Heat losses of all networks will be the following:

$$Q_{sjk} = Q_k + Q_{\tilde{o}} + Q_e = \\ = 2 \cdot \left(\sum_{i=1}^{n} K_{k,i} \cdot L_{k,i} + \sum_{i=1}^{m} K_{\tilde{o},i} \cdot L_{\tilde{o},i} + \sum_{i=1}^{f} K_{e,i} \cdot L_{e,i} \right) \cdot \Theta \cdot 10^{-6}, \quad \text{MW}, \tag{2.87}$$

where

K_k – heat transfer coefficient of underground channel pipeline, W/(mK);

$K_{\tilde{o}}$ – heat transfer coefficient of air lining pipes, W/(mK);

K_e – heat transfer coefficient of preinsulated underground pipes, W/(mK);

L_k, $L_{\tilde{o}}$, L_e – lengths of sites, m.

Θ – difference between water average temperature and outdoors temperature, ^{o}C.

In addition it is necessary to consider that pipes supports and armature are not isolated, also it increases heat losses. For this purpose normative heat losses coefficients are used. Heat losses of all networks, in view of this, will be the following:

$$Q_{sjk} = \beta_k \cdot Q_k + \beta_{\tilde{o}} \cdot Q_{\tilde{o}} + Q_e, \text{ MW}, \tag{2.88}$$

where

β_k = 1,25 – heat losses coefficient for a underground channel lining network [44,45],

$\beta_{\tilde{o}}$ = 1,3 – heat losses coefficient for an air lining network [44,45].

In the further calculations empirical formulas for definition of heat losses are made. Formulas are made both on the basis of calculation, and on the basis of the valid operational data of a network. For each network the coefficient is found, having multiplied which on a difference of average temperature of the heat-carrier and external air it is possible to define capacity of a network heat losses at any moment.

The valid heat transfer coefficients for underground networks of a channel lining received by means of the given method can be used with sufficient accuracy in heat losses calculations of all old networks of the given type.

From the analysis of the received data strong dependence of a heat transfer coefficient on a season is observed. The pipes heat transfer coefficient of old underground channel lining network strongly increases during the rainy period in the spring and in the autumn and in the winter at thawing a snow on a place of a network lining.

At the reconstructed district heating systems such big change of a heat transfer coefficient it is not observed, there is only a little change caused basically by the increase in heat conductivity of a ground during the damp period of year.

In an end result, borders in which the pipes heat transfer coefficient of old underground lines in the channel lining in current of year can change are certain. Considering these changes it is possible to estimate heat losses of old networks precisely enough.

Definition of a heat transfer coefficients in more detail considered in following chapters in which many district heating systems are considered and compared.

2.3 Model for district heating network optimization

2.3.1 Basics of district heating networks pipes internal diameters optimization

The question of how to select the optimal diameter of pipes in which a fluid is transported, represents a classical optimization problem [4, 5, 6]. Fig. 2.14 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, heat losses, and 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 diameter increasing.

Optimization 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.

Dynamic simulation models of district heating networks today are also very popular [17, 18, 19]. One type of mathematical model involves a full physical modelling of the network [18] and in other type of model - DH network is replaced by a simplified one [19].

The total cost of heat distribution $\boldsymbol{k}$ consists from pipes and network construction cost $\boldsymbol{k_t}$, distribution heat losses cost $\boldsymbol{k_{sk}}$ and pumping cost $\boldsymbol{k_p}$.

The annual expenses of network investments per 1 meter of DH network length is calculated as

$$k_t = (k_t^{"} + k`_t \cdot D_s) \cdot a \text{, EEK/m,} \tag{2.89}$$

where

$k_t^{"}$ – pipes cost per length, EEK/m;

$k`_t$ – pipes cost per surface area, EEK/m^2;

D_s – internal diameter of pipe, m;

a – annuity factor, –.

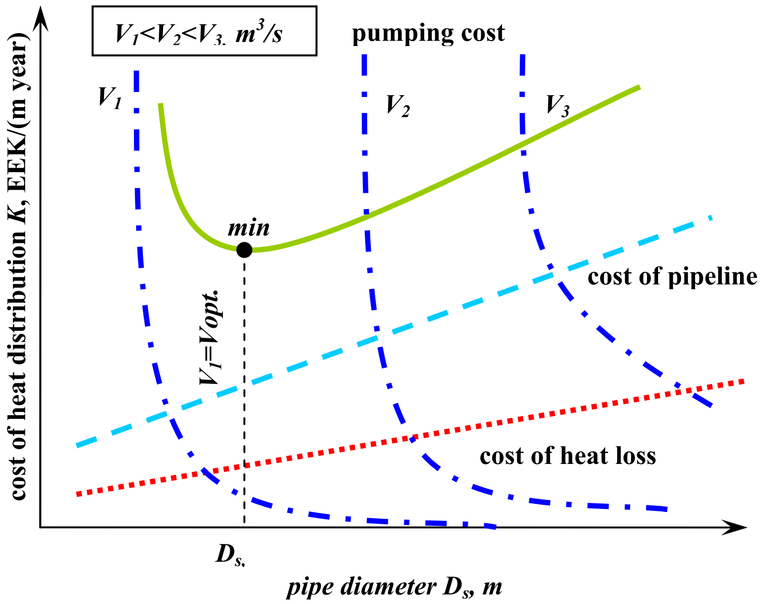


Figure 2.14 Pipe diameter economic optimization

The annual pumping cost per 1 meter of DH network length is calculated as

$$k_p = k`_p \cdot \frac{\tau}{\eta_p} \cdot \frac{\Delta P}{L} \cdot V \text{, EEK/m,} \tag{2.90}$$

where

$k`_p$ – pumping cost, EEK/(kW·h);

τ – pump operation time, h/year;

$\frac{\Delta P}{L} = R_l$ – friction losses, Pa/m;

η_p – pump efficiency, –;

V – water flow rate , m³/s.

The friction losses per 1 meter of DH network length is calculated as

$$R_l = \frac{\Delta P}{L} = \frac{\lambda}{D_s} \cdot \frac{1}{2} \cdot \rho \cdot W^2 \text{, Pa/m,} \tag{2.91}$$

where

λ – friction factor;

ρ – water density, kg/m³;

W – water velocity, m/s.

Pumping cost take into account pumping energy losses transformation to heat is calculated as

$$k_p^{'} = k_e - k_s \cdot (1 - \eta_p) \text{, EEK/(kW·h),} \tag{2.92}$$

where

k_e – electricity cost, EEK/(kW·h);

k_s – heat cost, EEK/(kW·h);

η_p – pump efficiency, –.

The distribution heat losses expenses is calculated as

$$k_{sk} = k_{s\cdot} \cdot K \cdot 10^{-3} \cdot \int \theta \, d\tau \text{, EEK/m,} \tag{2.93}$$

where

k_s – heat cost, EEK/(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 a 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 equation.

Economically optimal diameter of pipe is evaluated from next equation:

$$\frac{dk}{dD_s} = \frac{d}{dD_s}\left((k_t^{"} + k`_t \cdot D_s) \cdot a + k`_p \cdot \frac{\tau}{\eta_p} \cdot \frac{8}{\pi^2} \cdot \lambda \cdot \rho \cdot \frac{V^3}{D_s^5} \right) = 0 \ \Rightarrow \tag{2.94}$$

The optimal internal diameter of pipe:

$$D_{s,opt} = \left[\frac{40}{\pi^2} \cdot \lambda \cdot \rho \cdot \frac{\tau}{\eta_p} \cdot \frac{k`_p}{k`_t \cdot a} \right]^{1/6} \cdot \sqrt{V} \text{, m.} \tag{2.95}$$

If pressure drop in the district heating network is limited with definite value $\Delta P_{\max}$ (Pa), the internal diameter of pipes must be at least next value, depending to the water flow G (kg/s):

$$D_s \geq \sqrt{\frac{8 \cdot \lambda \cdot L \cdot G^2}{\pi^2 \cdot \rho \cdot \Delta P_{\max}}} \text{, m.} \tag{2.96}$$

Optimal water velocity:

$$W_{opt} = \left[\frac{8}{5 \cdot \pi} \cdot \frac{\eta_p}{\lambda \cdot \rho \cdot \tau} \cdot \frac{k`_t \cdot a}{k`_p} \right]^{1/3} \text{, m/s.} \tag{2.97}$$

Optimal friction losses:

$$R_{l,opt} = \frac{\Delta P}{L} = \frac{8}{\pi^2} \cdot [\lambda \cdot \rho]^{1/6} \cdot \left[\frac{40}{\pi^2} \cdot \frac{\tau}{\eta_p} \cdot \frac{k`_p}{k`_t \cdot a} \right]^{-5/6} \text{, Pa/m.} \tag{2.98}$$

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:

$$R_{l,opt.} = C_1 \cdot D_s^{n_1} \text{ , Pa/m;} \tag{2.99}$$

$$W_{opt.} = C_2 \cdot D_s^{n_2} \text{ , m/s;} \tag{2.100}$$

$$Q_{opt.} = C_3 \cdot D_s^{n_3} \text{ , kW;} \tag{2.101}$$

$$D_{s,opt} = C_4 \cdot Q^{n_4} \text{ , m.} \tag{2.102}$$

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.

2.3.2 Example of district heating pipelines internal diameters optimization

The purpose of pipe internal diameter optimization is to get minimal costs of heat distribution. Classical optimization 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 optimization is presented on the figure 2.15. 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 the average for the 2005 year, loan rate is 10%, cost of electricity according to night tariff is 0,74 EEK/kWh and to day tariff is 1,27 EEK/kWh, total pumping efficiency is 0,72, cost of heat is 450 EEK/MWh (in 2005 year). The temperature mode in network is 110/70^{o}C and the design outdoor temperature is -22^{o}C. The network operation time is 8760 hours per year. For calculations for a basis have been taken average temperatures of external air in Harjumaa.

Apparently from figure 2.15, the site of optimum value of diameter is expressed not sharply. Near to an optimum, in a direction of diameter increasing, there is smooth and not a sharp change. From this it is possible to draw a following conclusion, that at reconstruction of a district heating system it is expedient to choose a pipe with for the size bigger diameter to provide a stock on increase in loading in the future. Thus additional expenses will not be very much bigger.

The influence of water temperature mode to the pipes optimal diameter value is presented on the figure 2.16. With increasing of supply and return water temperatures difference, pipes optimal diameter decreasing. In the given example together with increase in a difference of heat-carrier temperatures his average temperature also increases. 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.

With increase in a difference of temperatures, total costs of heat distribution essentially decrease. For example at a temperatures difference of the heat-carrier in $\Delta t = 60^0 C$ degrees, at a temperature mode 130/70^{o}C, total costs of heat distribution will decrease at 1,52 times in comparison with costs at a difference of temperatures in $\Delta t = 25^0 C$ degrees at a temperature mode of 95/70^{o}C.

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.

From figure 2.16 it is visible, that cost of heat distribution decreases at increase in a difference of the heat-carrier temperatures, despite of increase in average temperature of the heat-carrier and to increase in heat losses (W/m^2).

There is such situation, that at a greater difference of temperatures and higher average temperature of the heat-carrier, optimum diameter decreases. It speaks that the charge of the heat-carrier essentially decreases at greater temperature drop, and despite of increase in heat losses from unit of a surface (W/m^2), heat losses from one running metre of a pipe will decrease owing to reductions of diameter and the specific area of a surface.

Hence reduction of temperature drop of the heat-carrier, with a view of reduction of average temperature and heat losses, only due to reduction of temperature of supply water at constant temperature of return water, will not reduce costs of heat distribution to a new network with optimized diameters of pipes and effective thermal insulation. It is expedient to increase a difference of temperatures of the heat-carrier together with reduction of return water temperature.

The temperature of return water depends on heat supply systems of consumers (depends on the surface area of radiators, with increase in the surface area of radiators temperature drop of the heat-carrier will increase also temperature of return water will decrease).

The smaller temperature of return water also will increase efficiency of thermal pumps working in a district heating network.

Reduction of supply water temperature at constant temperature of return water will increase pumping costs because for transfer of the same quantity of heat the greater flow rate of the heat-carrier is required. Simultaneously the average temperature of the heat-carrier and heat losses will decrease.

Apparently from researches, in the new optimized district heating systems with effective thermal insulation the increase in heat-carrier pumping costs will cost more, than cost of heat losses reduction.

It is fair for the new optimized district heating system with effective thermal insulation, however in case of with an old network with ineffective thermal insulation the situation can be another: at reduction of temperature of supply water the heat losses in money value decrease more, than costs on pumping will increase. It is confirmed with researches lead by Aris Žigurs in Latvia in the city of Riga [25]:

"The results of the transition from the temperature schedule of 130/70^{o}C to the temperature schedule of 115/70^{o}C at the heat supply areas of HS Daugavgriva and HS Vecmilgravis show (table 2.2) that the flow of the network water will increase by approximately 27–28%, and the lowering of the forward temperature of the heat carrier reduced heat loss in DH network, heat loss in the network will decrease by approximately 5%. If the forward temperature of heat carrier is lowered by 2^{o}C in summer the heat loss can be reduced by ~2,2%. However, irrespective of the fact that the relative decrease of the heat loss is lower than the relative increase in power consumption, when the absolute values of the changes are recalculated and transformed into monetary values it can be concluded that the changes of the temperature is useful, because the costs savings from the reduction of the heat loss exceed the increase of power costs twice. The economic effect from reduction of losses by introducing a lower temperature schedule is 3 to 4 times higher than increase of power consumption costs for transportation of the heat carrier."

The pipes and network building cost influence to the pipes diameter optimal value is presented on the figure 2.17. 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 with 95 mm up to 92 mm at increase in total cost at distribution of heat at ~50 %.

Table 2.2 Results of the transition from the temperature schedule of 130/70^{o}C to the temperature schedule of 115/70^{o}C at the heat supply areas of HS Daugavgriva and HS Vecmilgravis [25]

Heat supply area	Increase of electricity consumption for network pumps, MWh_{el}/heating per.	Decrease of heat loss, MWh_{heat}/heating per.
HS Daugavgriva	46,9	213,4
HS Vecmilgravis	154,4	431,0

The pumping cost influence to the pipes diameter optimal value is presented on the figure 2.18. 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, 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 (95 mm – 99 mm) and total cost will increase only for 10–15 %. Such insignificant increase speaks that in the field of optimum diameter costs on pumping make the least part from total cost.

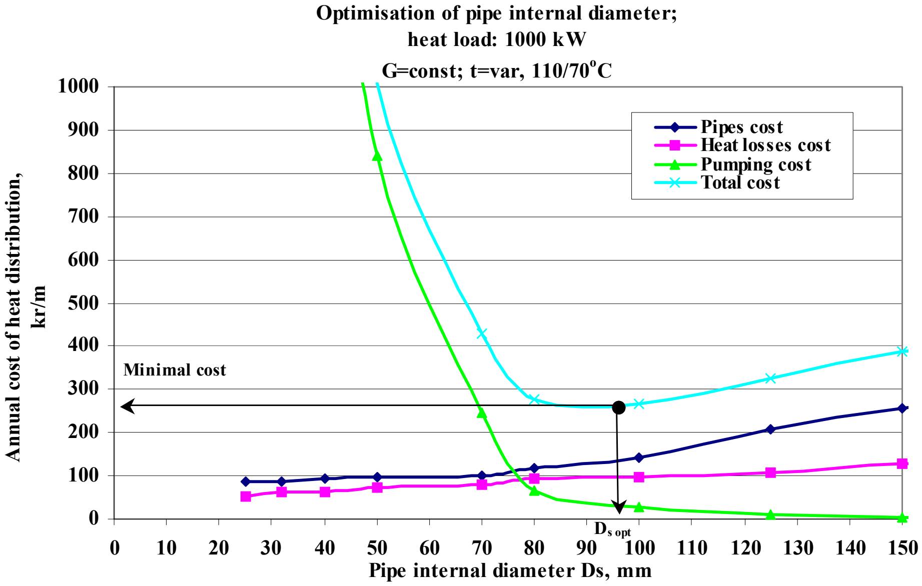


Figure 2.15 Example of pipes diameter optimization

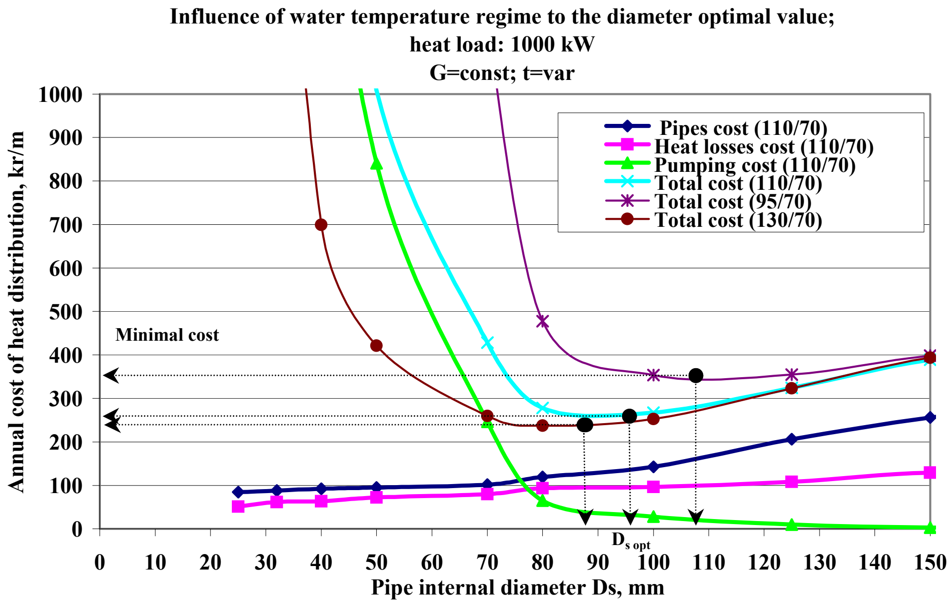


Figure 2.16 Influence of water temperature mode to the diameter optimal value

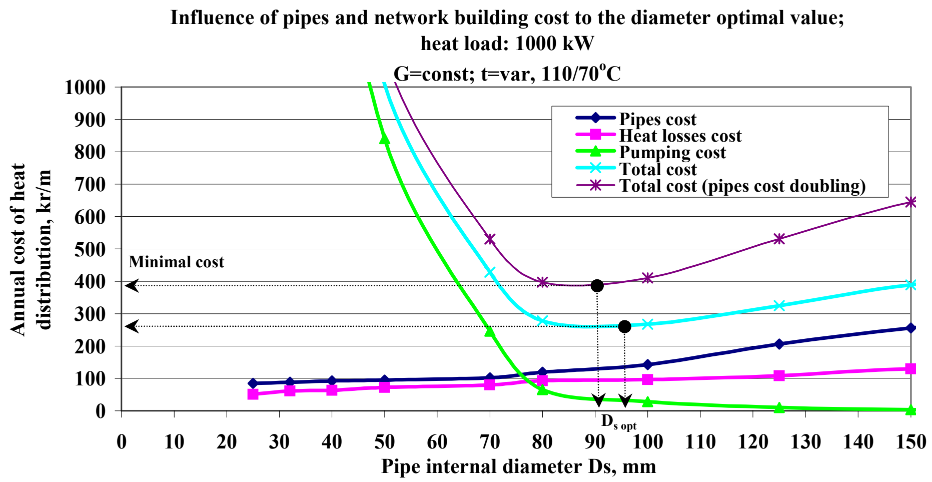


Figure 2.17 Influence of pipes and network building costs to the diameter optimal value

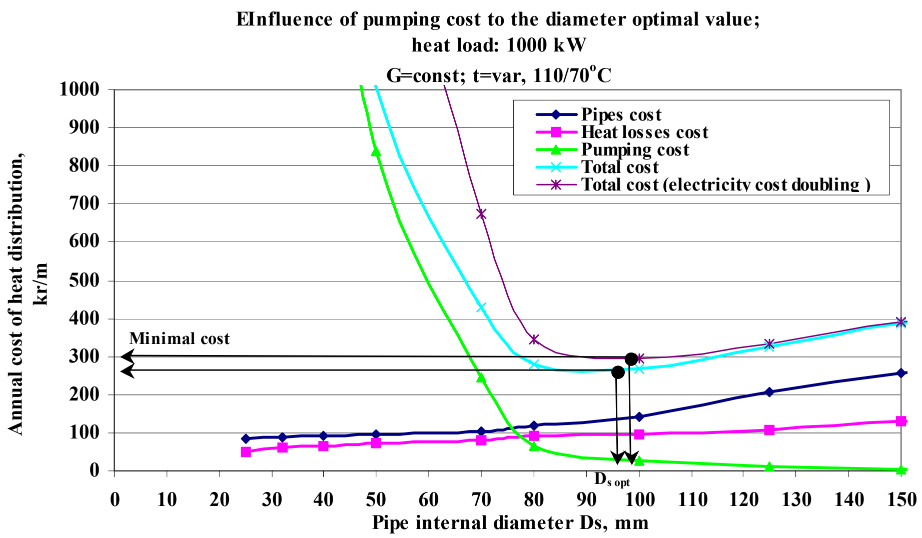


Figure 2.18 Influence of pumping cost to the diameter optimal value

3 DEFINITION OF THE VALID EFFICIENCY OF THERMAL INSULATION IN THE OLD DISTRICT HEATING SYSTEMS

Efficiency of thermal insulation of six district heating systems has been considered. It were following district heating systems: in Võru city the Võrusoo and Võrukivi networks, Kuressaare network, Orissaare network, in Türi city the Terme and Vabriku networks.

For each considered district heating system the thermal model has been made and on the basis of which, using the valid data on heat losses, have been found heat transfer coefficients of an underground pipelines system.

Except for this, advice by calculation of a network pipes heat losses in view of seasonal change of a networks pipes heat transfer coefficient are given where the valid heat losses are not known.

3.1 The description of considered district heating systems

Võrusoo and Vabaduse district heating networks in Võru city

Since of 1987 the district heating systems Võrusoo and Vabaduse are incorporated in one network. Boiler-house Vabaduse has become operational since 1971 year. During with 1975 for 1980 the district heating system strongly extended. Approximately the one-fourth part of a network has age more than 35 years and three fourth have age of the order of 25 years. Boiler-house Võrusoo has become operational since 1984. The age of Võrusoo district heating system makes more than 25 years.

The maximal consumed thermal power makes 30 MW of what heating makes 22 MW and hot water supply makes 8 MW. The temperature mode of a network makes 120/70 ^{o}C at temperature of external air –22 ^{o}C. Qualitative-quantitative regulation is used. The amount of heat released by a boiler-house in a network makes ~70000 MWh, consumption makes ~55000 MWh and networks heat losses make ~15000 MWh (21%).

Relative heat losses during the summer period, when there is only a loading of hot water supply, make 40–50 %. During the heating period, relative heat losses are within the limits of 12–20 %.

At old underground network in the concrete channel, practically there is no drainage for removal of rainwater. There where the drainage has been constructed, ceramic pipes owing to age have already collapsed also drainage does not work. The bitumen waterproofing of channels owing to age also has collapsed and does not carry out the tasks. It is the big problem as a level of subsoil waters is very high and there are marshy places. A ground in a place of a network lining is basically sandy and stony.

The length of a underground pipelines in the concrete channel makes 13061 m (74,5 %), the length of an old air pipelines makes 1034 m (5,9 %), the length of the reconstructed air pipelines network makes 774 m and length of the reconstructed network from the preinsulated pipes makes 2655 m (15,2 %). The total length of a network makes 17524 m. The area of a pipes surface makes 17051 m^2 and the volume of pipes makes 757 m^3. There is a two pipes system.

The waterproofing layer of air pipelines basically was kept, however thermal insulation has sagged and also external air in some places freely gets under insulation and carries away heat. Basically air pipelines are in a satisfactory condition.

Võrukivi district heating network in Võru city

The age of Võrukivi district heating system makes more than 25 years.

The maximal consumed thermal capacity makes 1,1 MW of what heating makes 0,7 MW and hot water supply makes 0,4 MW. The temperature mode of a network makes 105/70 ^oC at temperature of external air –22 ^oC. Qualitative-quantitative regulation is used. The amount of heat released by a boiler-house in a network makes ~2500 MWh, consumption makes ~2100 MWh and networks heat losses make ~400 MWh (16%).

At old underground network in the concrete channel, practically there is no drainage for removal of rainwater.

The length of a underground pipelines placed in the concrete channel makes 143 m (17,3 %), the length of an old air pipelines makes 110 m (13,3%)and length of the reconstructed network from the preinsulated pipes makes 574 m (69,4 %). The total length of a network makes 827 m. The area of a pipes surface makes 528 m^2 and the volume of pipes makes 12,5 m^3. There is a two pipes system.

Kuressaare district heating network

Kuressaare networks boiler-house has become operational since 1965 year. The age of the oldest parts makes more than 45 years. District heating network is reconstructed in 80–90s years.

Two boiler-houses work in the united network. Capacity of boiler-house Kalevi makes 35 MW, and Luha boiler-house – 16MW.

The maximal consumed thermal capacity makes 51 MW of what heating makes 34 MW and hot water supply makes 17 MW. The temperature mode of a network makes 120/70 ^oC at temperature of external air –19 ^oC. Qualitative-quantitative regulation is used. The amount of heat released by a boiler-house in a network makes ~82000 MWh, consumption makes ~62000 MWh and networks heat losses make ~20000 MWh (24%).

The length of a underground pipelines in the concrete channel makes 20973 m (76,6 %), the length of an old air pipelines makes 4156 m (15,2 %), and length of the reconstructed network from the preinsulated pipes makes 2237 m (8,2 %). The total length of a network makes 27366 m. The area of a pipes surface makes 25689 m^2 and the volume of pipes makes 1043 m^3. There is a two pipes system.

Orissaare district heating network

Orissaare network has become operational since 1970 year. District heating network is totally reconstructed in 1993–96 years.

The maximal consumed thermal capacity makes 2 MW of what heating makes 1,9 MW and hot water supply makes 0,1 MW. The temperature mode of a network makes 95/70 ^oC at temperature of external air –19 ^oC. Qualitative-quantitative regulation is used. The amount of heat released by a boiler-house in a network makes ~ 3500 MWh, consumption makes ~3080 MWh and networks heat losses make ~420 MWh (12%).

The length of a underground pipelines in the concrete channel makes 916 m (57 %), the length of an air pipelines makes 43 m (2,6 %)., and length of the network from the preinsulated pipes makes 648 m (40,3 %). The total length of a network makes 1606 m. The area of a pipes surface makes 1540 m^2 and the volume of pipes makes 60 m^3. The network is in very good conditions. There is a two pipes system.

Terme district heating network in Türi city

Terme network has become operational since 1972 year. During with 1980 for 1990 years the district heating system strongly extended.

The maximal consumed thermal capacity makes 6,9 MW of what heating makes 6,1 MW and hot water supply makes 0,8 MW. The temperature mode of a network makes 90/70 ^oC at temperature of external air –22 ^oC. Qualitative-quantitative regulation is used. The amount of heat released by a boiler-house in a network makes ~18300 MWh, consumption makes ~10980 MWh and networks heat losses make ~7320 MWh (40%). There is a mainly two pipes system and partly four pipes system.

The length of a underground pipelines in the concrete channel makes two pipes system – 4810 m (61,4 %) and four pipes system – 1271 m (16,2 %), the length of an old air pipelines makes 1328 m (17 %), and length of the reconstructed network from the preinsulated pipes makes 419 m (5,4 %). The total length of a network makes 7828 m. The pipes surface area makes 5582 m^2 and the volume of pipes makes 173 m^3.

Vabriku district heating network in Türi city

Vabriku network has become operational since 1982 year.

The maximal consumed thermal capacity makes 8 MW of what heating makes 7 MW and hot water supply makes 1 MW. The temperature mode of a network makes 90/70 ^{o}C at temperature of external air –22 ^{o}C. Qualitative-quantitative regulation is used. The amount of heat released by a boiler-house in a network makes ~15000 MWh, consumption makes ~ 12000 MWh and networks heat losses make ~3000 MWh (20%).

The length of a underground pipelines placed in the concrete channel makes 4409 m (87,5 %), the length of an old air pipelines makes 241 m (4,8 %) and length of the reconstructed network from the preinsulated pipes makes 390 m (7,7 %). The total length of a network makes 5040 m. The area of a pipes surface makes 4286 m^2 and the volume of pipes makes 153 m^3. There is a two pipes system.

In figure 3.1 the valid relative heat losses of networks on months are given.

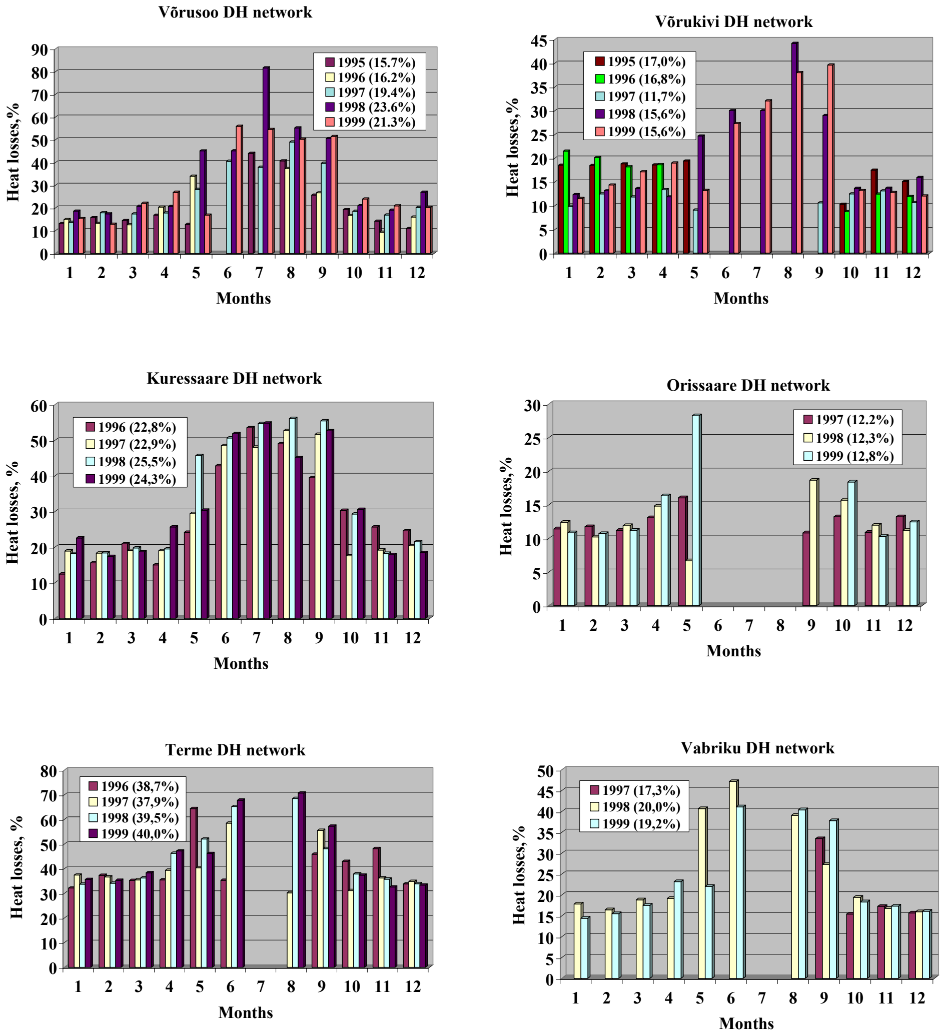


Figure 3.1 Relative heat losses of district heating systems

3.2 The valid efficiency of thermal insulation of a underground network lying in the concrete channel

Using model for heat losses calculation and knowing the valid heat losses, the valid heat transfer coefficients of the pipes, which are lying in the underground concrete channel, have been received.

The valid heat losses are received as a difference of heat quantity supplied in a network from a boiler-house and quantities of heat received by consumers.

Knowing the valid heat losses, types of a pipes lining, lengths and diameters of pipes, thickness of thermal insulation, the valid temperature of the heat-carrier and air, thermal insulation efficiency of an underground network is estimated.

For definition of thermal insulation efficiency the model for heat losses calculation has been used at the certain assumptions and simplifications.

In the first have assumed, that the preinsulated pipes polyurethane foam insulation heat conductivity coefficient does not change and is constant in current of year (λ_{is} = 0,03 W/(mK)), as pipes are tight also a moisture does not get in thermal insulation.

In the second, change of ground heat conductivity in current of year has not been considered. The coefficient of heat conductivity of a stony and sandy ground for all year is taken equal λ_p = 2,38 W/(mK). The coefficient of heat conductivity of stony and sandy ground can change in current of year, at change of ground humidity, within the limits of 1,85–2,9 W/(mK). Change of ground heat conductivity at effective thermal insulation does not render very big influence on a heat transfer coefficient.

Hence, for a network part made from the preinsulated pipes with polyurethane insulation, heat losses basically will depend on one variable, which will be temperature of air. The heat transfer coefficient of an underground network lying in the concrete channel and an air network depend on heat conductivity of thermal insulation, which it will be necessary to define.

Change of insulation heat conductivity, event in current of year owing to change of humidity and temperature of thermal insulation, for the considered networks is resulted in figure 3.2. As we see, heat conductivity of thermal insulation of old underground networks in current of year considerably changes and the reason of it basically is change of humidity.

The moisture can get in the underground concrete channel through the destroyed waterproofing, through connection of concrete elements, through chambers of a network, which are below a level of channels. Owing to insulation humidifying its heat conductivity can increase up to five times λ_{is} = 0,05–0,25 W/(mK) during the rainy periods of year.

Heat conductivity essentially increases during the rainy spring and autumn periods of year, and in the winter period during a thawing weather when the snow thaws. In the end of spring, in the summer, in the beginning of autumn thermal insulation practically completely dries up. Heat conductivity of dry thermal insulation makes λ_{is} = 0,05– 0,07 W/(mK) and this value coincides with data on heat conductivity of the glass wool brought in the literature [35].

In figures 3.3 (on a running meter) and 3.4 (on square meter) change of a heat transfer coefficient of an underground network in current of year is resulted. The diameter of a pipe there is less and coefficient of a heat transfer on unit of the area will be bigger. The coefficient of a heat transfer increases for one running metre of a pipe with growth of diameter.

Heat losses of an underground network lying in the concrete channel are shown in figure 3.5.

Value of annual average heat conductivity coefficient is resulted in figure 3.6.

Apparently from figures, average annual values of the heat transfer coefficients received for some years, practically coincide. Old underground networks pipes heat transfer coefficients considerably exceed the same values for the preinsulated pipes.

Proceeding from the received results it is possible to draw following conclusions that at an estimation of heat losses of old underground networks it is necessary to use different values of heat conductivity coefficient for the different periods of year. In figure 3.7 advised values of heat conductivity coefficients for the various periods of year are resulted.

Further formulas for heat losses power calculation of the considered networks are resulted. Factors in formulas consider the valid efficiency of thermal insulation, length and diameters of networks sites. For calculation of network heat losses in formulas it is necessary to substitute a difference of average temperature of the heat-carrier and air. These formulas allow to estimate heat losses also for the future.

Theoretically calculated and valid formulas for definition of heat losses of networks are resulted in a following kind: $Q_{sjk}=C_{net}\cdot\Theta$, where Θ is difference between average temperature of water and outdoor temperature. Values of factor C_{net} and used values of heat conductivity coefficients λ are resulted in table 3.1.

It is clearly visible, that efficiency of thermal insulation of old networks is far from an ideal, in comparison with value of new stone wool heat conductivity 0,05 W/(mK), average annual efficiency of old thermal insulation more than twice below. During rainy autumn and springtime, in the winter during a thawing weather, efficiency of thermal insulation decreases in comparison with new dry insulation more than three times.

The reason of low efficiency of old thermal insulation is that old thermal insulation from glass wool was condensed from influence of a moisture and heat has sagged, the waterproofing of channels is damaged, the drainage has collapsed and as a result water gets in the channel and humidifies thermal insulation.

Exception is completely reconstructed heating network Orissaare, there efficiency of thermal insulation is approximately equal to efficiency of dry new stone wool.

Table 3.1 Theoretically calculated and valid factors C_{net} for network heat losses formulas.

DH network	Theoretically calculated values		Year	Real C_{net}	Year
	C_{net}	λ			
Võru city,	0,0183	0,05	1997 – 1999	0,031	1995
Võrusoo	0,0243	0,08		0,0313	1996
and	0,0335	0,145		0,0354	1997
Vabaduse				0,0349	1998
networks				0,0323	1999
Võru city,	0,0008	0,05		0,0014	1995
Võrukivi	0,0011	0,08	1995 – 1996	0,0018	1996until
network	0,0016	0,145	summer	0,0010	summer
				0,00091	1996autumn
	0,0006	0,05		0,00086	1997
	0,0007	0,08	1996	0,00085	1998
	0,0009	0,145	autumn-1999		1999
			after partly		
			renovation		
Kuressaare	0,0338	0,05	1996 – 1999	0,0464	1996
network	0,0468	0,08		0,0407	1997
	0,0678	0,145		0,0444	1998
				0,0428	1999
Orissaare	0,0012	0,05	1997-1999	0,00144	1997
network	0,0015	0,08		0,00134	1998
	0,0021	0,145		0,00134	1999
Türi city,	0,0084	0,05	1996 – 1999	0,0132	1996
Terme	0,0117	0,08		0,0144	1997
network	0,0172	0,145		0,0143	1998
				0,0143	1999
Türi city,	0,0054		1998 – 1999	0,0082	1998
Vabriku	0,0072			0,0071	1999
network	0,0098				

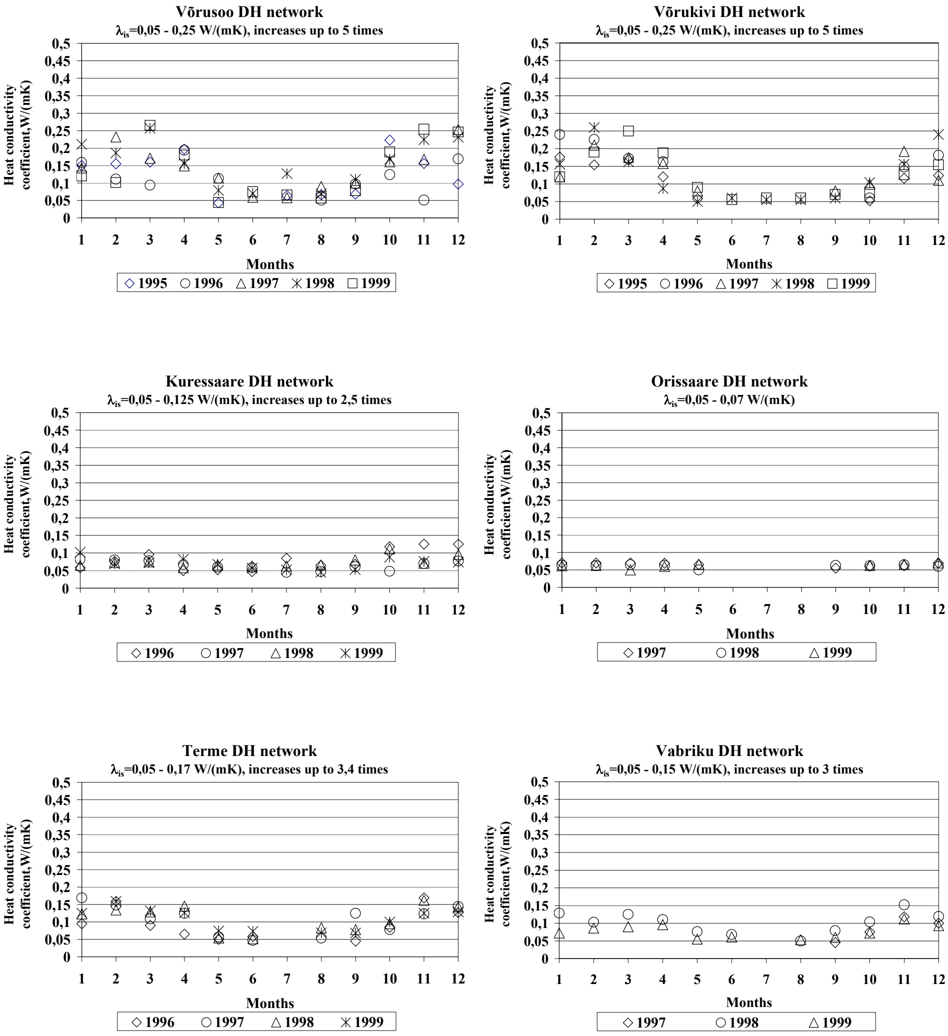


Figure 3.2 Changes in insulation heat conductivity of old underground networks

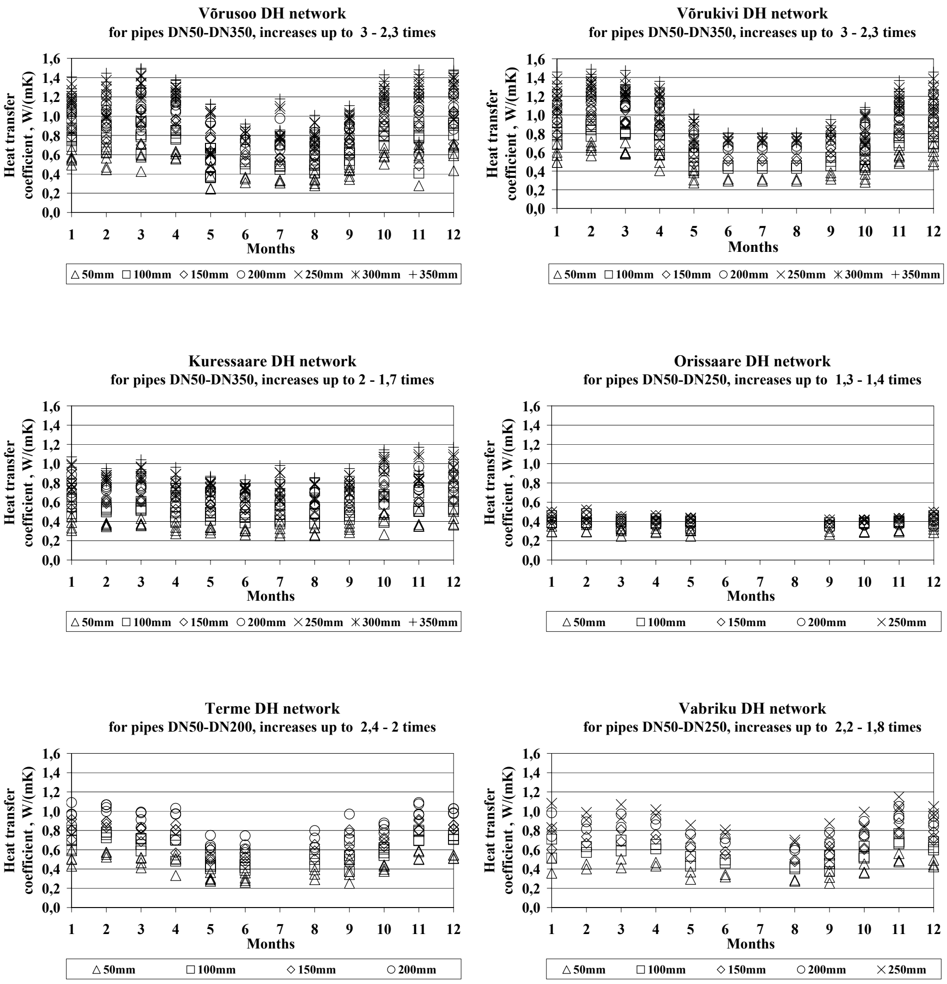


Figure 3.3 Changes in insulation heat transfer coefficient of an old underground network (on a running meter)

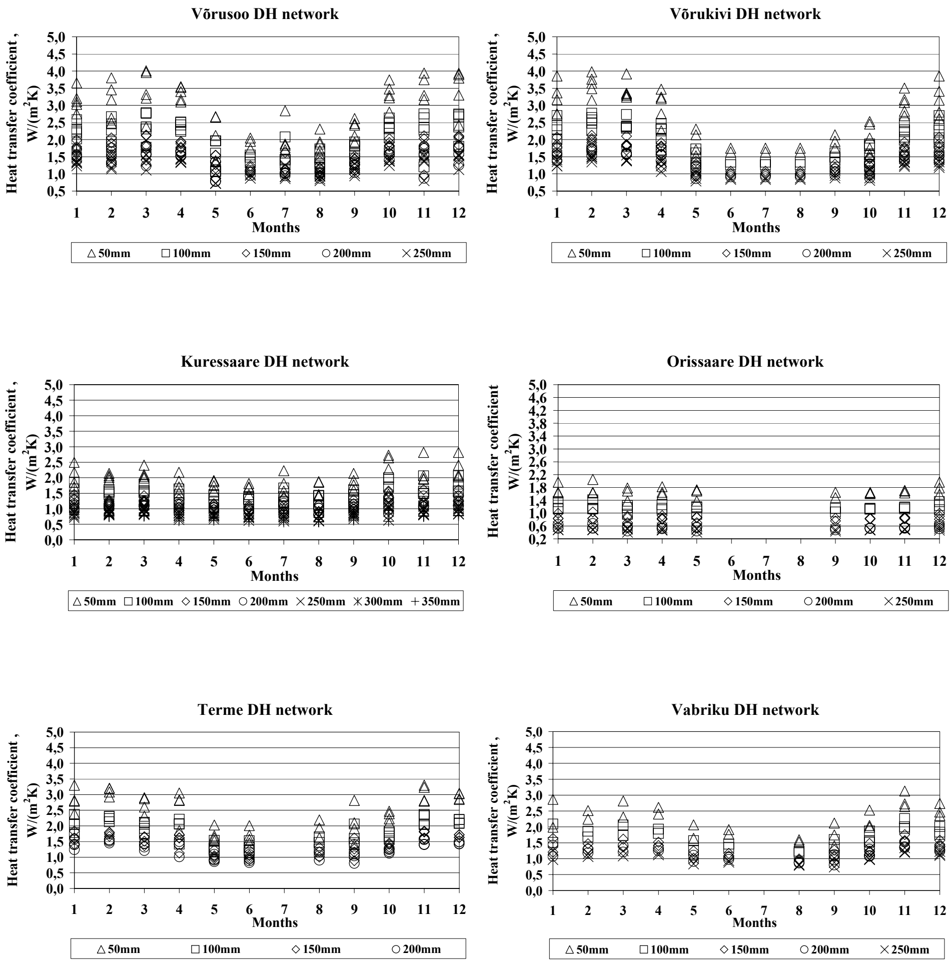


Figure 3.4 Changes in insulation heat transfer coefficient of an old underground network (on square meter)

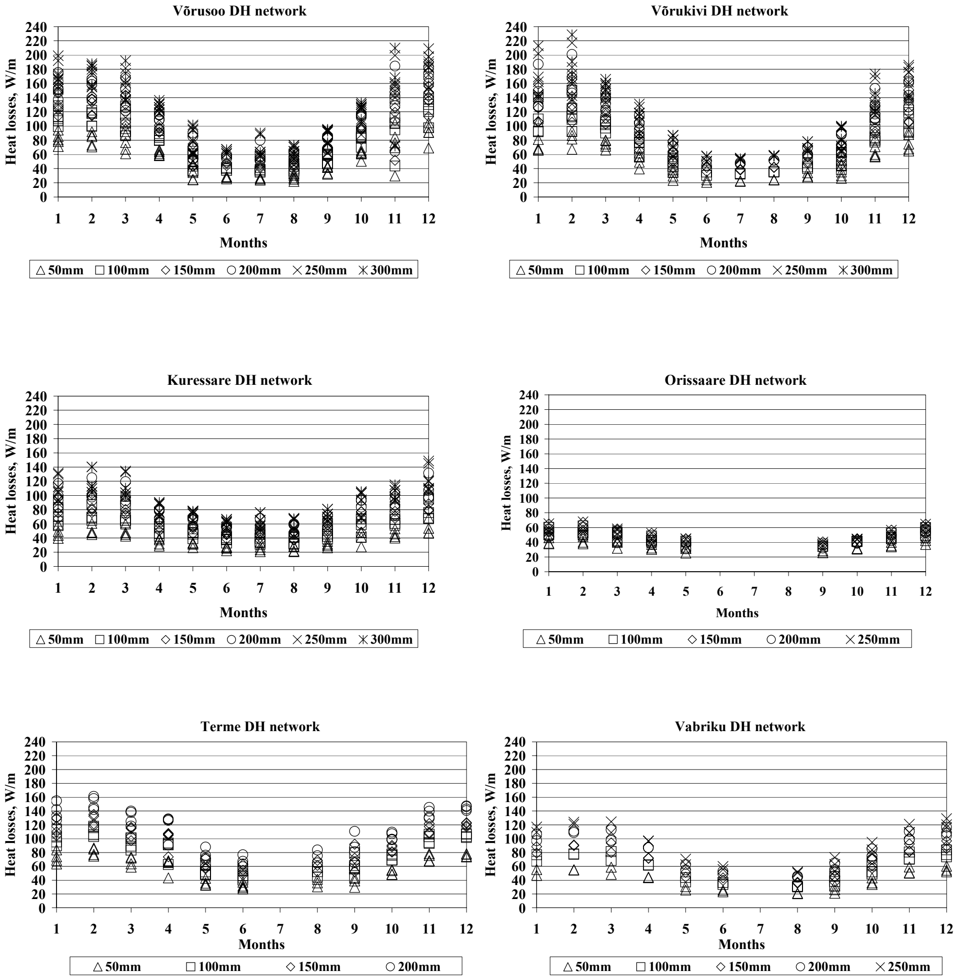


Figure 3.5 Heat losses of an old underground network

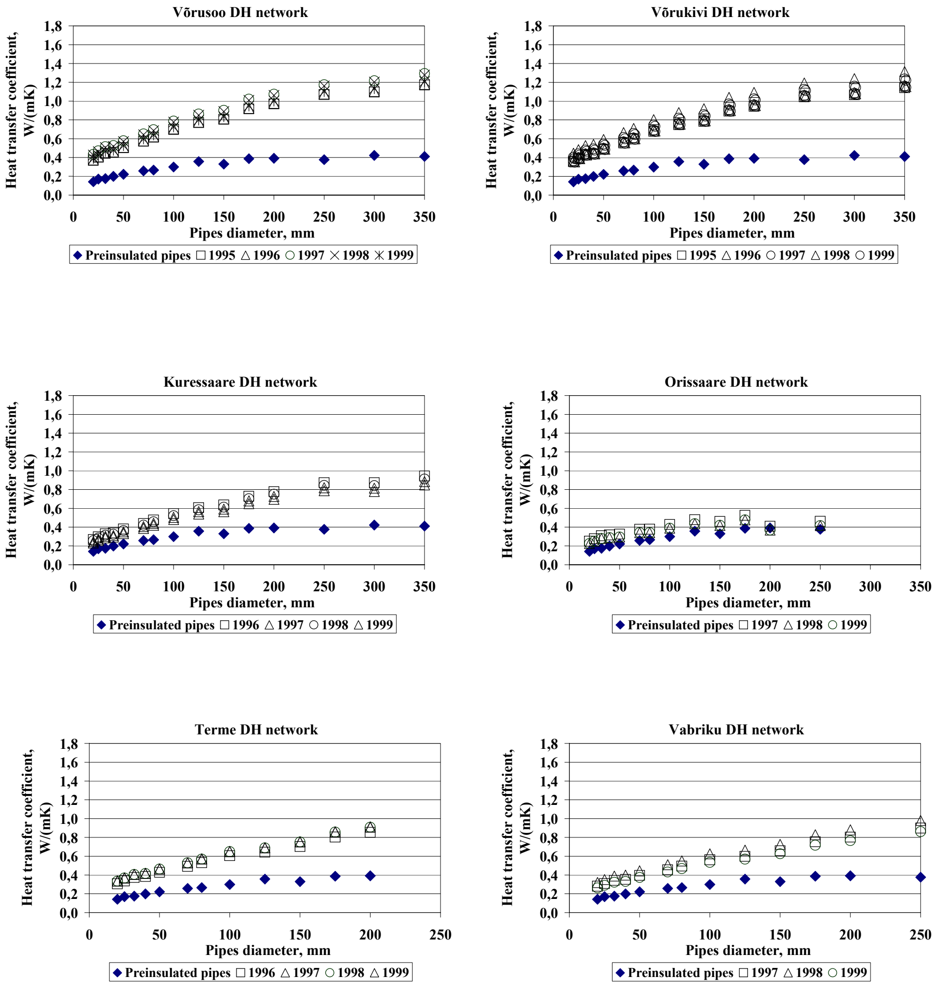


Figure 3.6 Value of average annual coefficient of heat conductivity

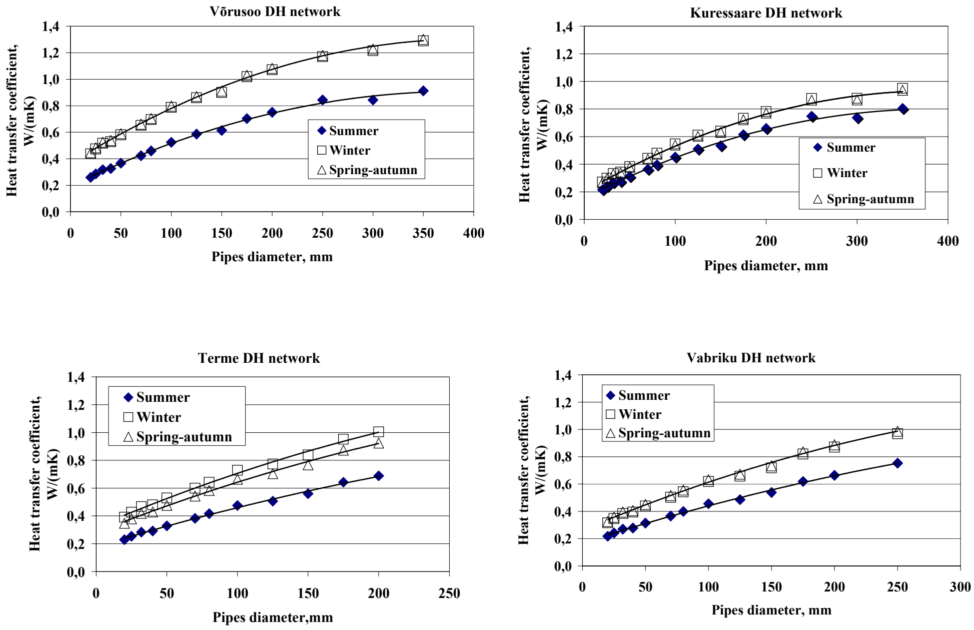


Figure 3.7 Advised values of heat conductivity coefficients for the various periods of year

3.3 The analysis of the received results and conclusions

The purpose of the given research was to determine the valid efficiency of thermal insulation of old thermal networks. The analysis is made with use of thermal model of a network and the valid data on heat losses of a network.

Six district heating networks have been considered: Võrusoo and Võrukivi in Võru city, Kuressaare, Orissaare, Terme and Vabriku in Türi city. For each considered district heating network the thermal model has been made.

Data have been entered into thermal model of a network: lengths and diameters of pipes, thickness of thermal insulation, type of a lining and other data on a design of a network.

After the thermal model of a network has been made the valid temperatures of the heat-carrier and air, and also the valid heat losses have been entered in it. Efficiency of pipes thermal insulation has been as a result certain.

The final result had been estimated coefficient of heat conductivity of thermal insulation at which calculated by means of thermal model heat losses coincided with the measured heat losses. Calculations are made on months.

During work it was found out, that value of coefficient of heat conductivity strongly depends on a season is more exact from a changing humidity. During the rainy spring and autumn period, in the winter and in the spring at thawing a snow, the coefficient of heat conductivity of insulation strongly increased from for humidifying.

The coefficient of heat conductivity increased during the damp period of year for example in Võrusoo and Võrukivi networks up to five times 0,05 – 0,25 W/(mK), while during the dry summer period of year was much less 0,05 – 0,07 W/(mK).

The reason of such substantial growth of heat conductivity is seasonal humidifying of thermal insulation of an underground network.

In Kuressaare district heating network heat conductivity of insulation during the rainy period of year increases up to 2,5 times: 0,05 – 0,125 W/(mK), and in dry period practically does not change: 0,05 – 0,06 W/(mK).

Heat conductivity of pipes insulation in Terme network in Türi city during the rainy period increases in 3,4 times: 0,05 – 0,17 W/(mK), during the dry period is within the limits of 0,05 – 0,07 W/(mK) and in the second Vabriku network heat conductivity during the rainy period increases in 3 times: 0,05 – 0,152 W/(mK), during the dry period is within the limits of 0,05 – 0,07 W/(mK).

In completely reconstructed district heating system Orissaare, seasonal change of heat conductivity of thermal insulation is very insignificant: 0,05 – 0,068 W/(mK) and is caused by growth of temperature during the heating period. During the dry period is within the limits of 0,05 – 0,06 W/(mK). Growth of heat conductivity of insulation owing to humidifying of thermal insulation does not occur. As we see, value of heat conductivity coefficient in current of year practically does not change and coincides with data for new dry thermal insulation from mineral wool [35].

By means of thermal model of a network, pipes heat transfer coefficients of an underground network and there change depending on the period of year are certain.

For example in Võrusoo DH network, for pipes DN50 the heat transfer coefficient increases in 2,95 times: 0,24 – 0,72 W/(mK) and for pipes DN350 – 2,28 times: 0,66 – 1,50 W / (mK). Hence the increase in a heat transfer coefficient in the spring and in the autumn during the rainy period, in the winter and in the spring at thawing a snow, can reach three times. With reduction of a pipe diameter, change will increase.

The heat transfer coefficient in Võrukivi DH network increases for pipes DN32 in 2,76 times: 0,23 – 0,64 W/(mK) and for pipes DN70 – 2,46 times: 0,32 – 0,79 W/(mK).

In Kuressaare DH network, for pipes DN50 the heat transfer coefficient increases in 2 times: 0,252 – 0,504 W/(mK) and for pipes DN300 – 1,78 times: 0,62 – 1,1 W/(mK). Hence the increase of a heat transfer coefficient in the spring and in the autumn during the rainy period, in the winter and in the spring at thawing a snow, can reach up to two times (1,7 – 2 times).

The heat transfer coefficient in Terme DH network increases for pipes DN50 in 2,35 times: 0,25 – 0,59 W/(mK) and for pipes DN200 – 1,97 times: 0,55 – 1,1 W/(mK). The increase will make 2 – 2,4 times.

The heat transfer coefficient in Vabriku DH network increases for pipes DN50 in 2,22 times: 0,25 – 0,56 W/(mK) and for pipes DN250 – 1,82 times: 0,63 – 1,15 W/(mK). The increase will make 1,8 – 2,2 times.

As have shown researches, heat transfer coefficients of underground network pipes, during the rainy period can increase in 1,7 – 3 times. The average increase of a pipes heat transfer coefficient in old networks makes two times.

In totally renovated Orissaare network, for pipes DN50 the heat transfer coefficient increases only in 1,3 times: 0,24 – 0,36 W/(mK) and for pipes DN250 – 1,4 times: 0,35 – 0,52 W/(mK). The small increase of a heat transfer coefficient occurs only in some rainy months of the heating period due to humidifying a ground and increase in heat conductivity of insulation at increase in its temperature.

In the given research the overall heat transfer coefficients describing efficiency of thermal insulation of all network, consisting of parts with a different design and efficiency of thermal insulation also are certain. The heat transfer coefficient is given on unit of the area.

The overall heat transfer coefficient for Võrusoo network is in the limits 1,82 – 2,08 $W/(m^2K)$.

The overall heat transfer coefficient for Võrukivi network after partly reconstruction in 1997 year is in the limits 1,61 – 1,72 $W/(m^2K)$, before reconstruction was considerably above – 2,65 $W/(m^2K)$.

The overall heat transfer coefficient for Kuressare network is in the limits 1,58 – 1,81 $W/(m^2K)$.

For the Terme network in Türi town the overall heat transfer coefficient is 2,36 – 2,56 W/(m^2K) and for Vabriku network the overall heat transfer coefficient is 1,7 – 1,9 W/(m^2K).

The overall heat transfer coefficient for Orissaare totally renovated network is considerably below than in other networks and is in the range 0,87 – 0,94 W/(m^2K). The coefficient of a heat transfer in network Orissaare, practically coincides with calculated values for the preinsulated pipes and efficiency of thermal insulation is at the same level as at modern networks. At other considered old networks efficiency of thermal insulation below in 2 – 2,5 times than at modern networks.

Results of the given researches are presented in my articles of many scientific conferences.

By means of thermal model of the network developed in given work, the thorough estimation of thermal insulation efficiency for several tens Estonian networks is lead.

Novelty of the developed thermal model consists that it allows determining precisely enough values of pipes heat transfer coefficients in old district heating networks. For the first time the valid data by efficiency of thermal insulation of old networks have been obtained and using obtained data it is possible to count precisely enough heat losses of networks where the valid data on heat losses are absent.

4 EXAMPLES OF DISTRICT HEATING SYSTEMS OPTIMIZATION MODEL APPLICATION

4.1 The description of investigated district heating networks

During the given research, hydraulic modes of Estonian old district heating systems with different capacity have been analysed.

Usual old district heating systems in which the most part passes in the underground concrete channel have been chosen. In total 14 district heating systems of different capacity have been considered:

- distributed heat up to 5000 MWh/year: Haiba, Imavere, Ardu;
- distributed heat in an interval 5000 – 10000 MWh/year: Räpina, Koeru, Sindi;
- distributed heat in an interval 10000 – 50000 MWh/year: Viimsi, Haabneeme;
- distributed heat in an interval 50000 – 100000 MWh/year: Keila, Võru, Kiviõli;
- distributed heat over 100000 MWh/year: Tallinn city district heating networks (Lasnamäe, Mustamäe, Kesklinn).

For each considered district heating system the full hydraulic model has been made.

At definition of the heat-carrier flow rate, for a basis have taken the valid thermal loadings of consumers. The valid loadings have been received knowing the valid consumption of heat for the last 3–5 years.

Hydraulic models have been made both for winter, and for summer loadings.

Calculations of hydraulic modes are made both for the old not optimized network, and for new optimized.

During hydraulic calculations valid velocities and specific hydraulic resistances of the heat-carrier have been found for each part of an old network. After, during networks optimization optimum values of velocities and specific hydraulic resistances of the heat-carrier have been found.

4.2 Results of optimization

4.2.1 District heating networks with heat output up to 5000 MWh/year

District heating systems with heat distribution up to 5000 MW/year are the smallest considered systems, such as Haiba, Imavere, Ardu networks.

The considered district heating networks are constructed in 1970–80 years of the last century. Basically it is underground networks placed in the concrete channel. As thermal insulation glass wool by thickness 50 mm is used.

The given networks have small length which makes 500–2000 m: Haiba networks length is 597 m, Imavere - 1905 m and Ardu – 982 m.

District heating systems with small heat output can be compact, as Haiba and Ardu networks in which thermal loading for small networks is enough big, accordingly 4,5 MWh/m and 3,5 MWh/m and stretched, as Imavere, which length is enough big - 1905 m, and heat loading is small 1,7 MWh/m in year.

For carrying out of hydraulic calculations, schemes of old networks have been restored, lengths and diameters of all parts are certain.

Thermal loadings of a network parts have been certain knowing the valid loadings of consumers. On thermal consumption of last years the greatest loadings have been found at the minimal calculation temperature of external air.

In figure 4.1 the valid heat loading of a network parts depending to pipe diameter is shown and dependence of optimum loadings values of a pipe diameter $D_{s,opt.} = f(Q)$ is shown.

In figure 4.2 the valid and optimum values of water velocities depending to pipe diameter are shown $W_{opt.} = f(D_s)$.

In figure 4.3 the valid and optimum values of friction losses depending to pipe diameter are shown $R_{l,opt.} = f(D_s)$.

Results presented in figures 4.1 and 4.3 are received both for the biggest winter loading, and for the least summer loading.

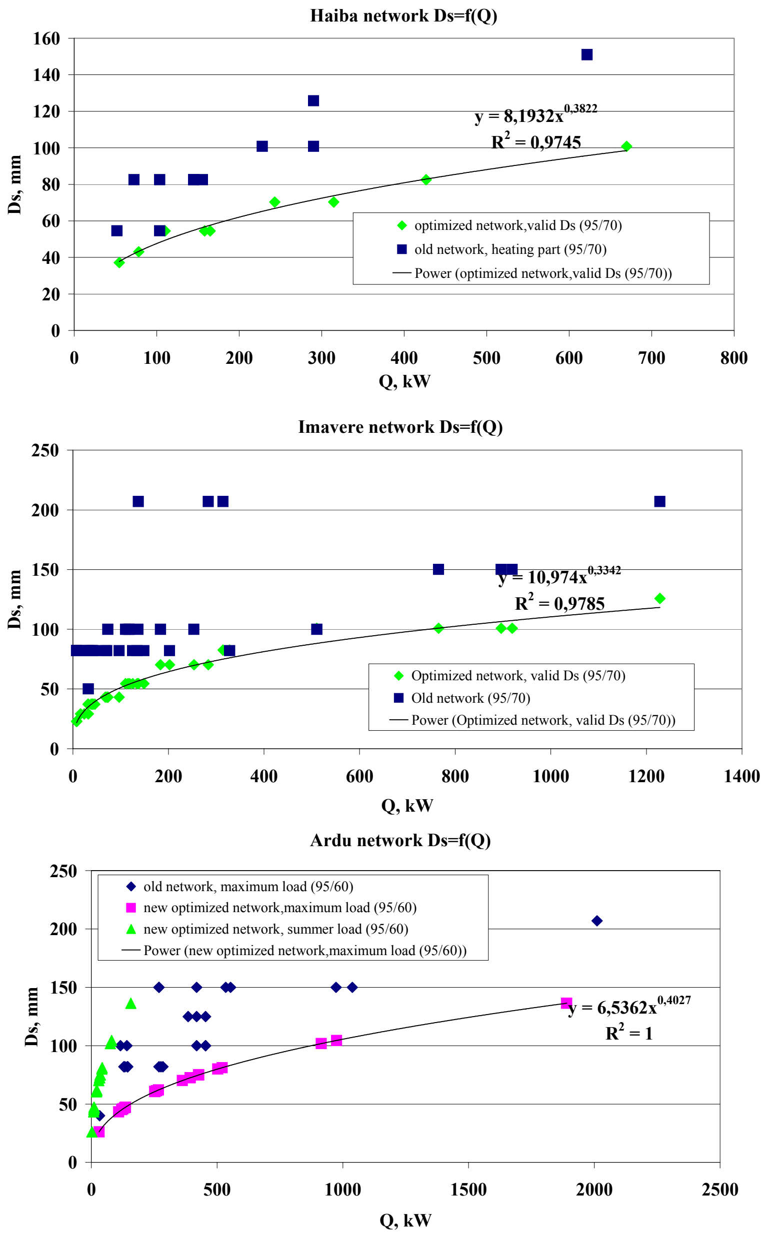


Figure 4.1 Valid and optimal values of internal diameter depending to heat load $D_s = f(Q)$ *(Haiba, Imavere, Ardu)*

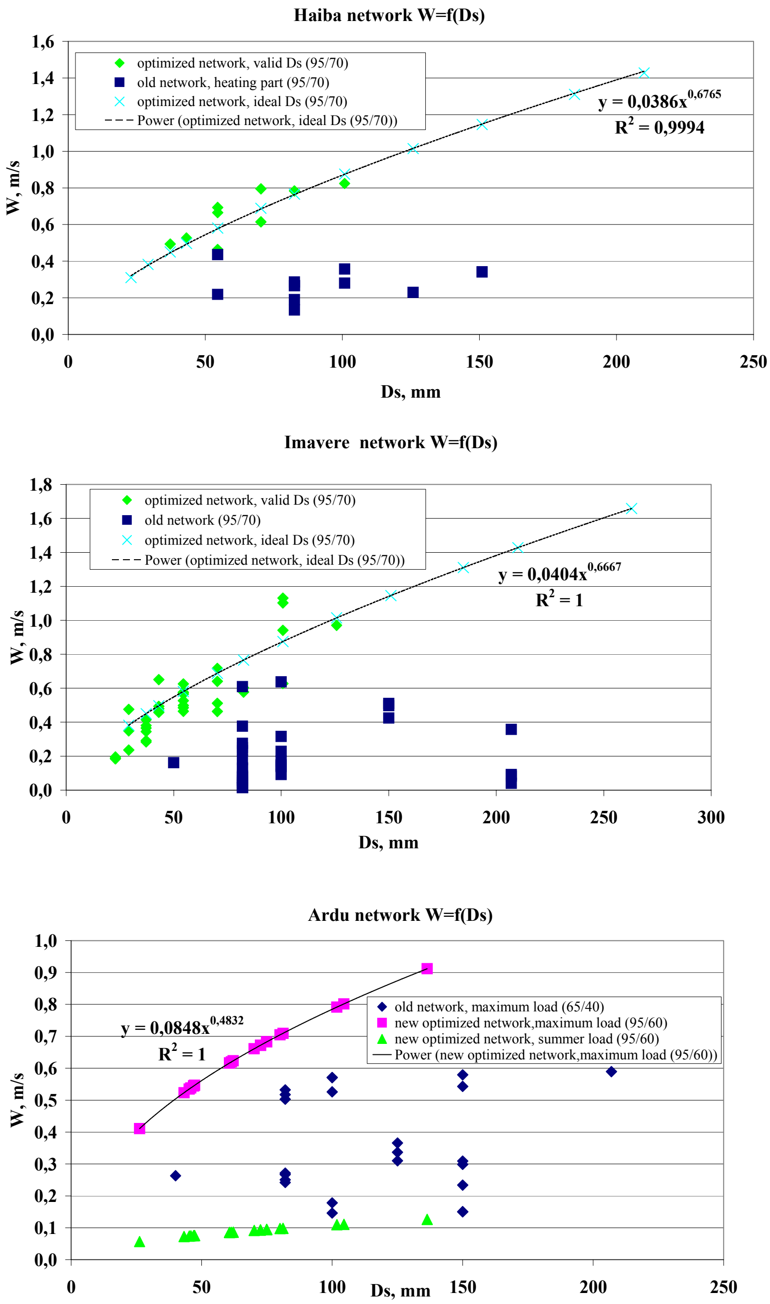


Figure 4.2 Valid and optimal values of water velocity depending to pipe diameter $W = f(D_s)$ *(Haiba, Imavere, Ardu)*

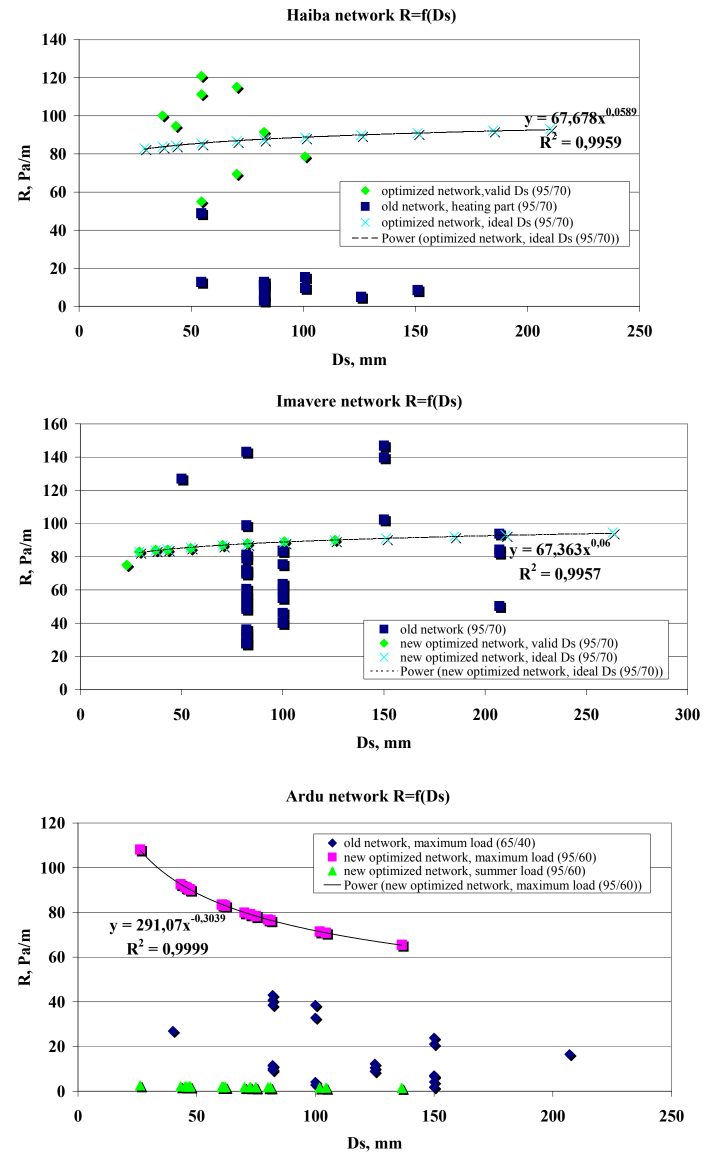


Figure 4.3 Valid and optimal values of friction losses depending to pipe diameter $R_l = f(D_s)$ *(Haiba, Imavere, Ardu)*

4.2.2 District heating networks with heat output in an interval 5000–10000 MWh/year

In following group district heating systems of bigger settlements and cities, in which heat distribution makes 5000–10000 MWh/year, are given.

In the given group district heating systems of Räpina, Sindi cities and Koeru settlements are considered. These are typical networks of small cities and the rural centres.

The given networks length makes in Räpina network – 1732 m, Koeru – 2390 m and Sindi – 2139 m.

For the considered small networks the loading are enough big and make for the Räpina network – 3,1 MWh/m in year, for Koeru network – 4,1 MWh/m and for Sindi network – 4,5 MWh/m in year.

In figure 4.4 the valid heat loading of a network parts depending to pipe diameter is shown and dependence of optimum loadings values of a pipe diameter $D_{s,opt.} = f(Q)$ is shown.

In figure 4.5 the valid and optimum values of water velocities depending to pipe diameter are shown $W_{opt.} = f(D_s)$.

In figure 4.6 the valid and optimum values of friction losses depending to pipe diameter are shown $R_{l,opt.} = f(D_s)$.

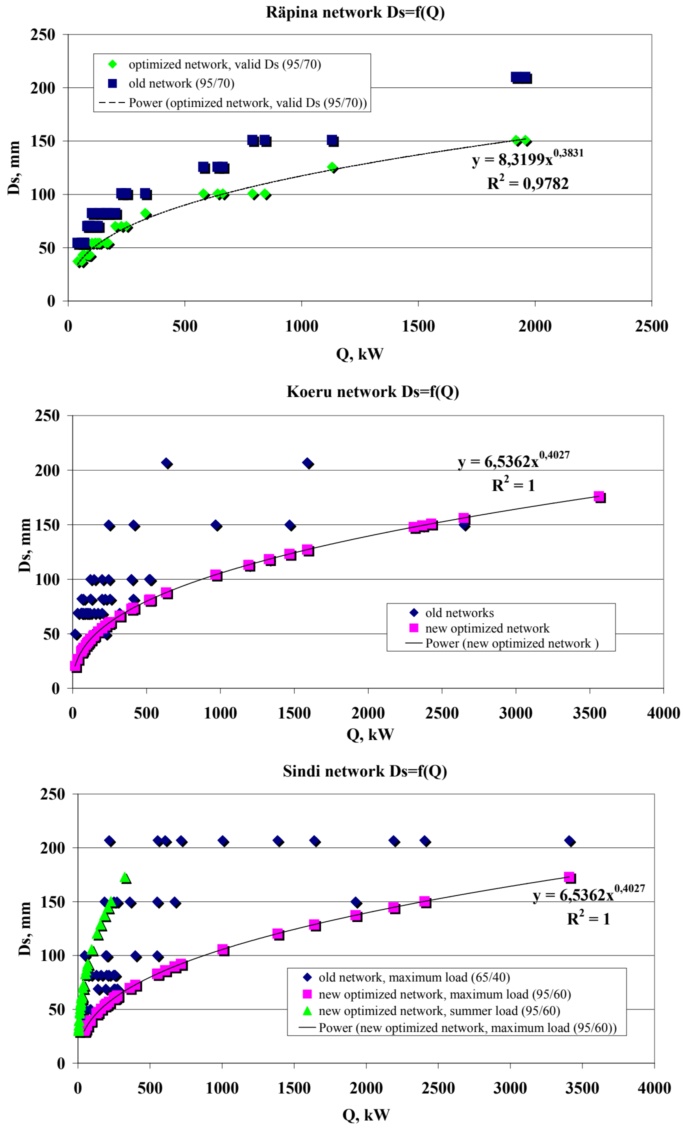


Figure 4.4 Valid and optimal values of internal diameter depending to heat load $D_s = f(Q)$ (Räpina, Koeru, Sindi)

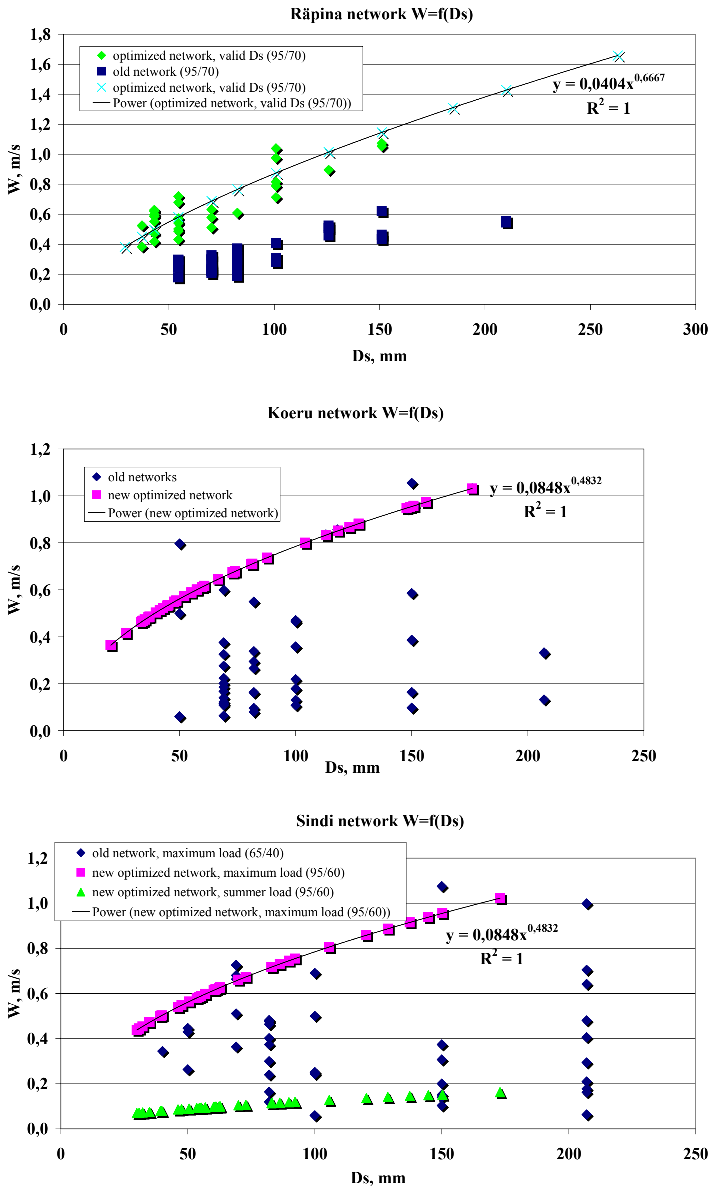


Figure 4.5 Valid and optimal values of water velocity depending to pipe diameter $W = f(D_s)$ *(Räpina, Koeru, Sindi)*

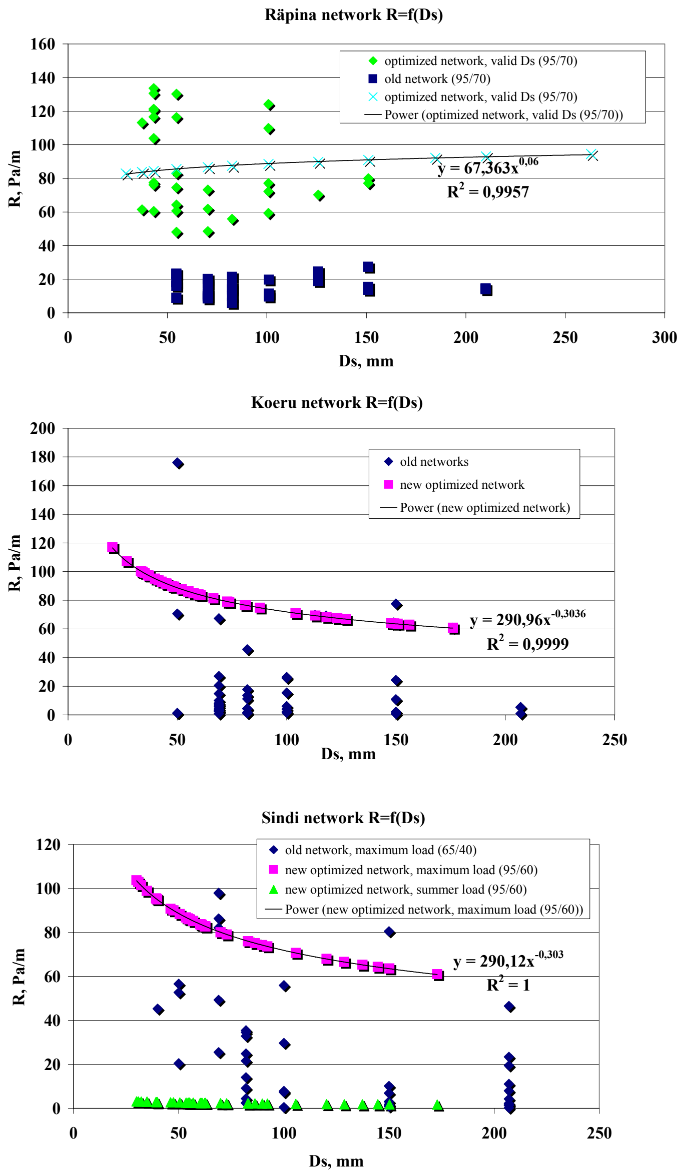


Figure 4.6 Valid and optimal values of friction losses depending to pipe diameter $R_l = f(D_s)$ *(Räpina, Koeru, Sindi)*

4.2.3 District heating networks with heat output in an interval 10000–50000 MWh/year

This group includes district heating networks of two quickly developing settlements Viimsi and Haabneeme.

Lengths of district heating networks are the following: Viimsi – 3921 m and Haabneeme – 4800 m. Specific thermal loadings are the following: in Viimsi – 2,7 MWh/m year and in Haabneeme – 3,6 MWh/m year.

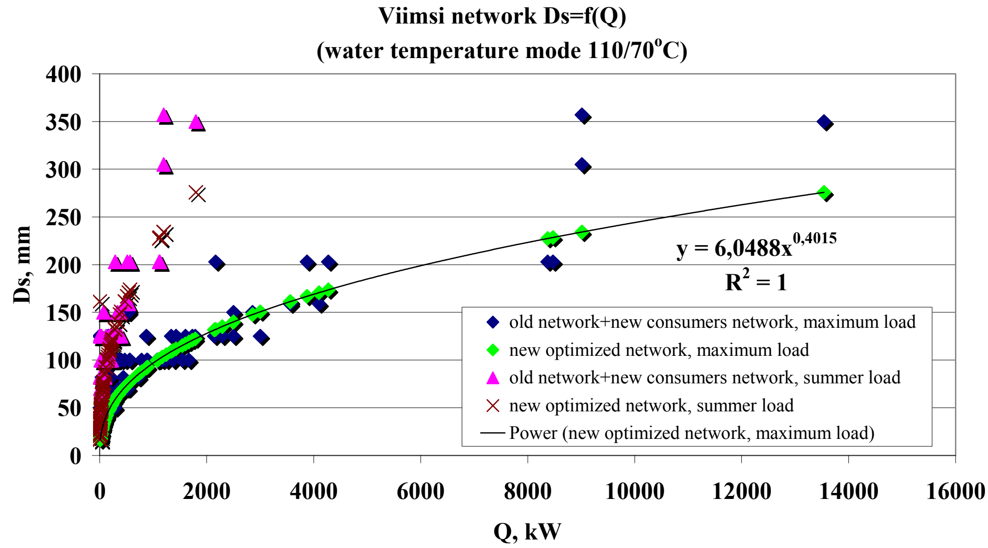
As a result of rapid development of settlements, length and loadings of district heating systems can in the future considerably will increase. Specific thermal loading can increase up to 5–6 MWh/m year.

Calculations are made both for existing networks, and in view of loading growth and expansion of networks.

In figure 4.7 the valid heat loading of a network parts depending to pipe diameter is shown and dependence of optimum loadings values to a pipe diameter $D_{s,opt.} = f(Q)$ is shown.

In figure 4.8 the valid and optimum values of water velocities depending to pipe diameter are shown $W_{opt.} = f(D_s)$.

In figure 4.9 the valid and optimum values of friction losses depending to pipe diameter are shown $R_{l,opt.} = f(D_s)$.



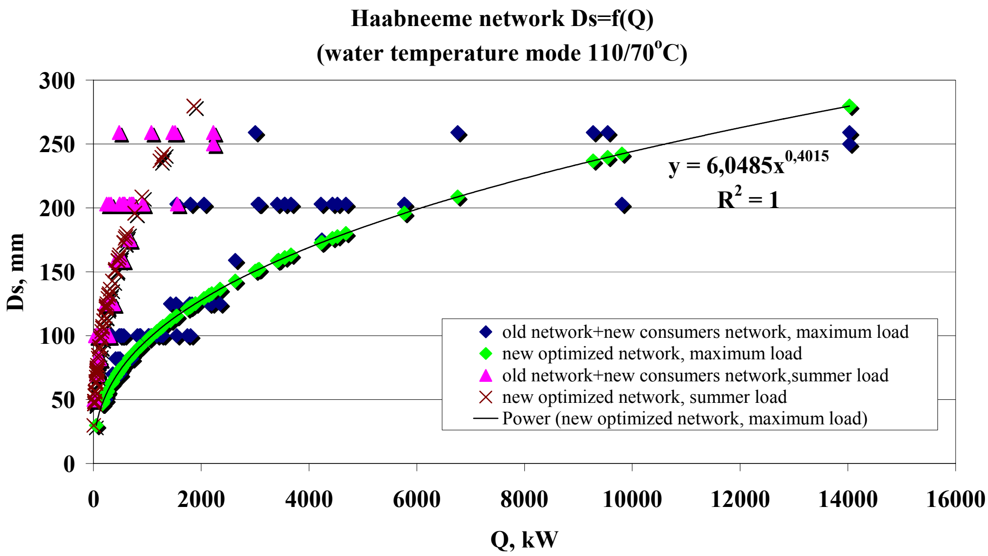
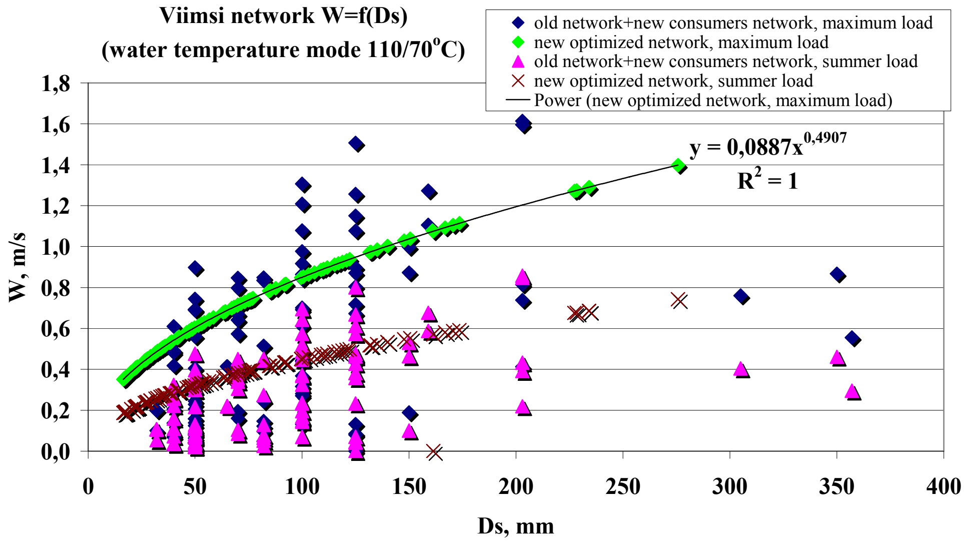


Figure 4.7 Valid and optimal values of internal diameter depending to heat load $D_s = f(Q)$ *(Viimsi, Haabneeme)*



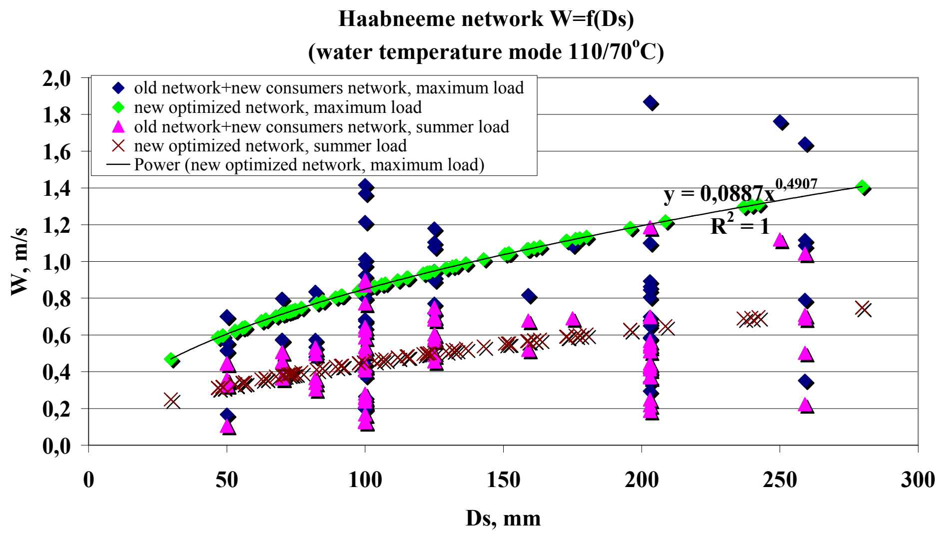
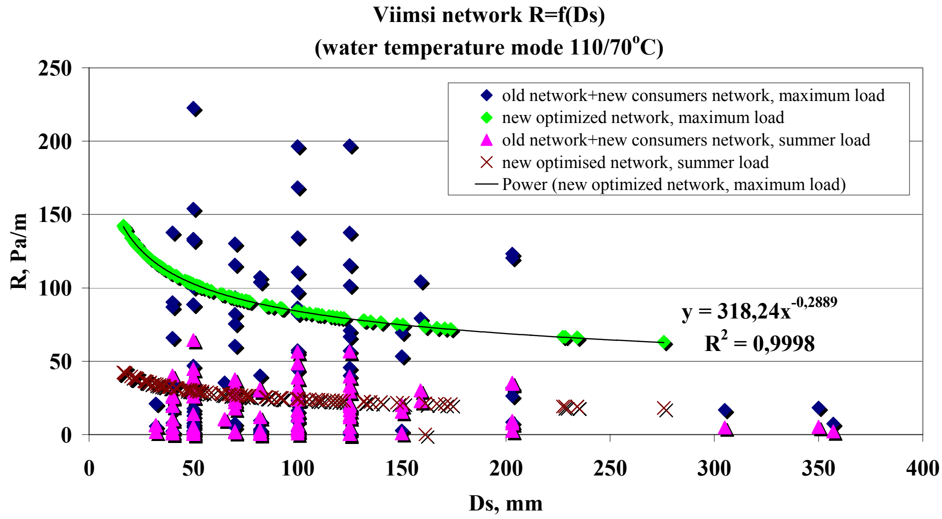


Figure 4.8 Valid and optimal values of water velocity depending to pipe diameter $W = f(D_s)$ *(Viimsi, Haabneeme)*



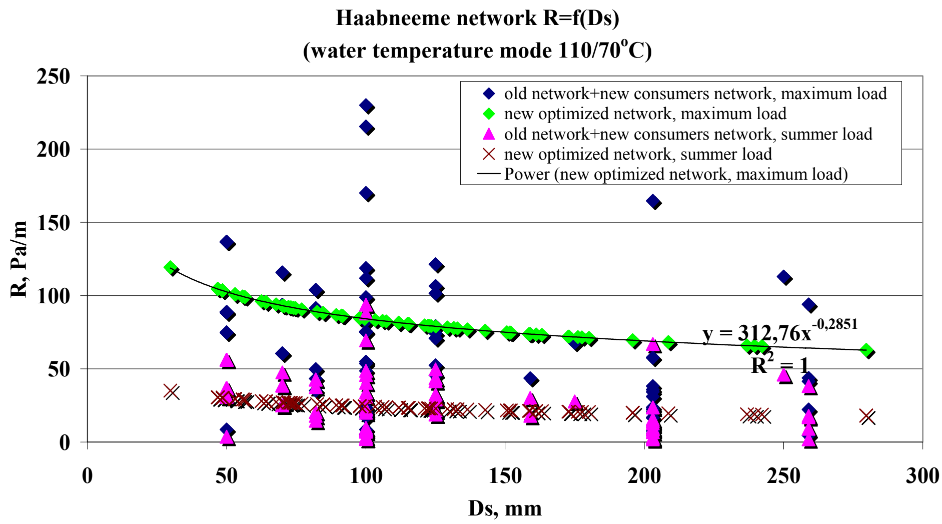


Figure 4.9 Valid and optimal values of friction losses depending to pipe diameter $R_l = f(D_s)$ *(Viimsi, Haabneeme)*

4.2.4 District heating networks with heat output in an interval 50000 – 100000 MWh/year

The given group includes district heating networks of enough big towns, such as Keila, Võru and Kiviõli.

Lengths of district heating networks are the following: Keila – 11916 m, Võru – 20083 m, Kiviõli – 11004 m.

Specific thermal loadings is enough big and are the following: in Keila network – 5,0 MWh/m year, Võru – 3,8 MWh/m, Kiviõli – 5,1 MWh/m.

In the near future fast development of towns and district heating networks it is not supposed.

Hydraulic calculations and optimization are made for different temperature modes of the heat-carrier.

In figure 4.10 the valid heat loading of a network parts depending to pipe diameter is shown and dependence of optimum loadings values of a pipe diameter $D_{s,opt.} = f(Q)$ is shown.

In figure 4.11 the valid and optimum values of water velocities depending to pipe diameter are shown $W_{opt.} = f(D_s)$.

In figure 4.12 the valid and optimum values of friction losses depending to pipe diameter are shown $R_{l,opt.} = f(D_s)$.

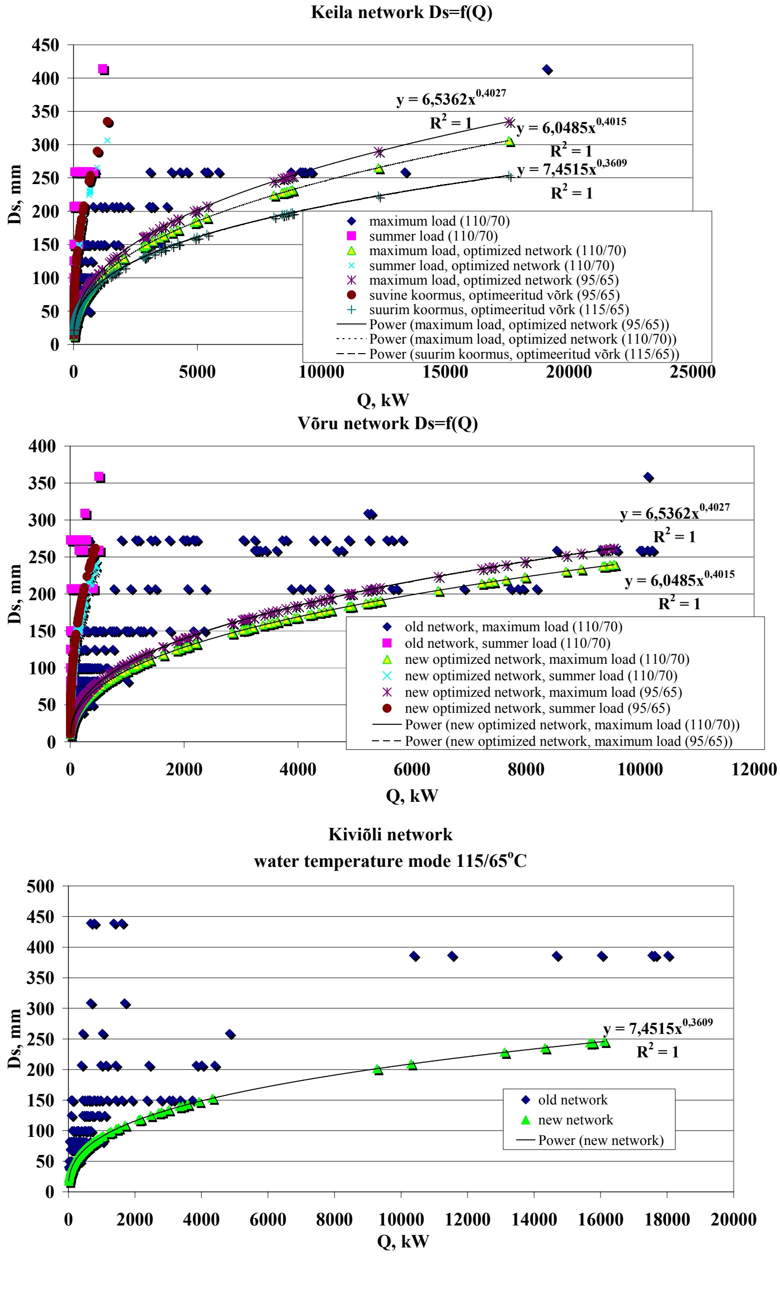


Figure 4.10 Valid and optimal values of internal diameter depending to heat load $D_s = f(Q)$ *(Keila, Võru, Kiviõli networks)*

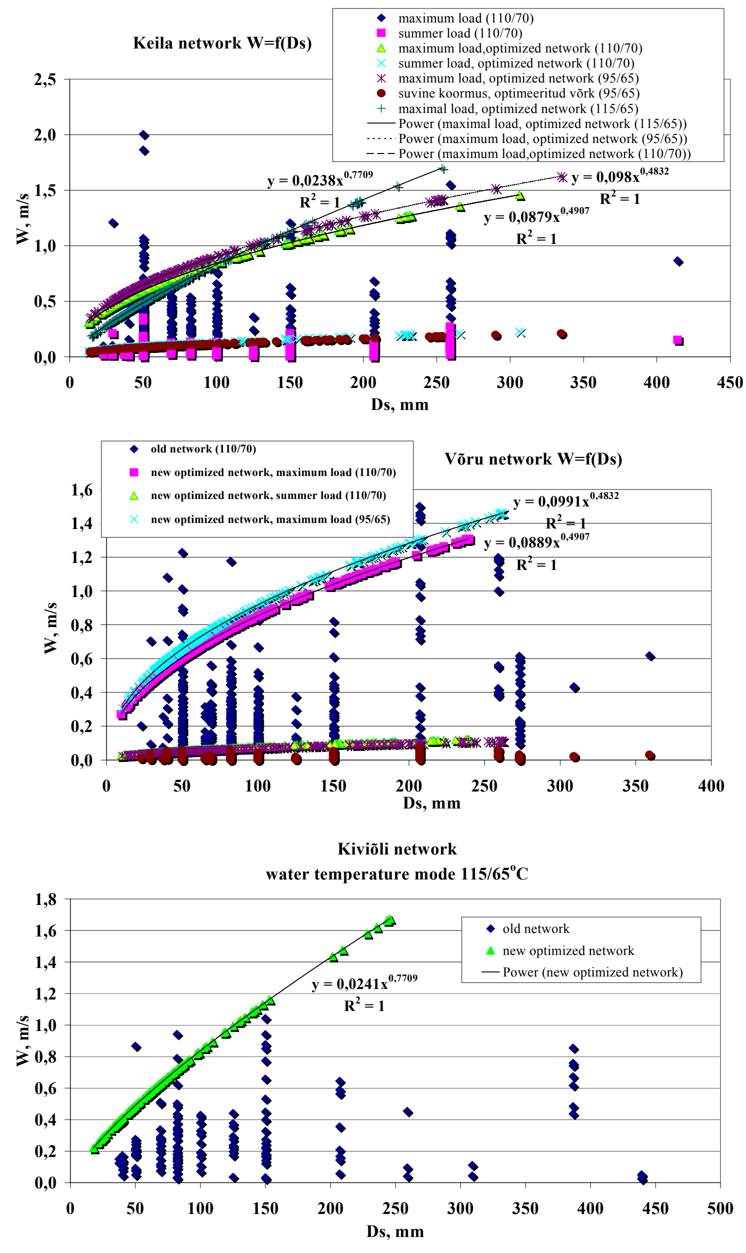


Figure 4.11 Valid and optimal values of water velocity depending to pipe diameter $W = f(D_s)$ *(Keila, Võru, Kiviõli networks)*

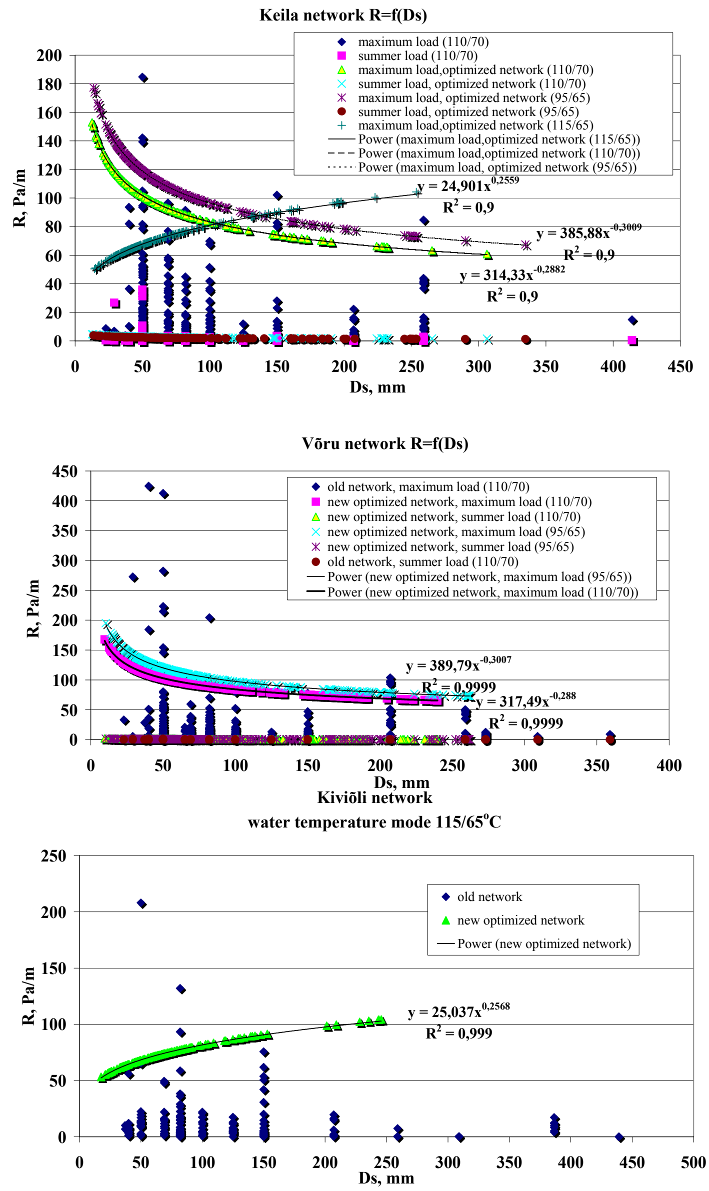


Figure 4.12 Valid and optimal values of friction losses depending to pipe diameter $R_l = f(D_s)$ *(Keila, Võru, Kiviõli networks)*

4.2.5 District heating networks with heat output over 100000 MWh/year

These are district heating networks of big cities with length of 50–200 km kilometres and with annual heat distribution over than 100000 MWh.

The given group includes the biggest district heating systems of Estonia, networks of Tallinn city: Kesklinn, Mustamäe-Õismäe, Lasnamäe. Kesklinna and Lasnamäe networks are connected through heat exchangers in pump station Laagna.

Lengths of district heating networks are the following: Kesklinna network – 82902 m, Lasnamäe network– 86561 m, Mustamäe-Õismäe network – 144036 m.

Specific thermal loadings is more than in small towns and are the following: Kesklinna network – 5,4 MWh/m year, Lasnamäe – 5,6 MWh/m, Mustamäe-Õismäe – 6,0 MWh/m.

In figure 4.13 the valid heat loading of a network parts depending to pipe diameter is shown and dependence of optimum loadings values to a pipe diameter $D_{s,opt.} = f(Q)$ is shown.

In figure 4.14 the valid and optimum values of water velocities depending to pipe diameter are shown $W_{opt.} = f(D_s)$.

In figure 4.15 the valid and optimum values of friction losses depending to pipe diameter are shown $R_{l,opt.} = f(D_s)$.

Hydraulic calculations and optimization are made for valid temperature mode of the heat-carrier.

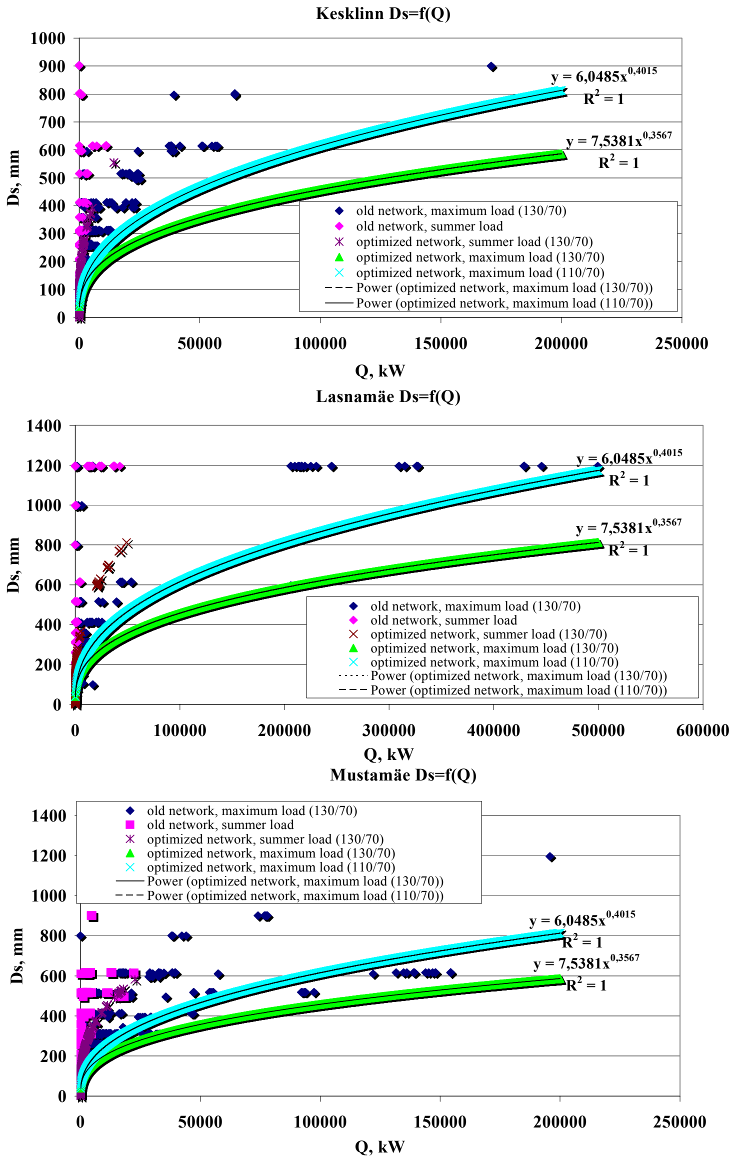


Figure 4.13 Valid and optimal values of internal diameter depending to heat load $D_s = f(Q)$ *(Kesklinna, Lasnamäe and Mustamäe-Õismäe networks)*

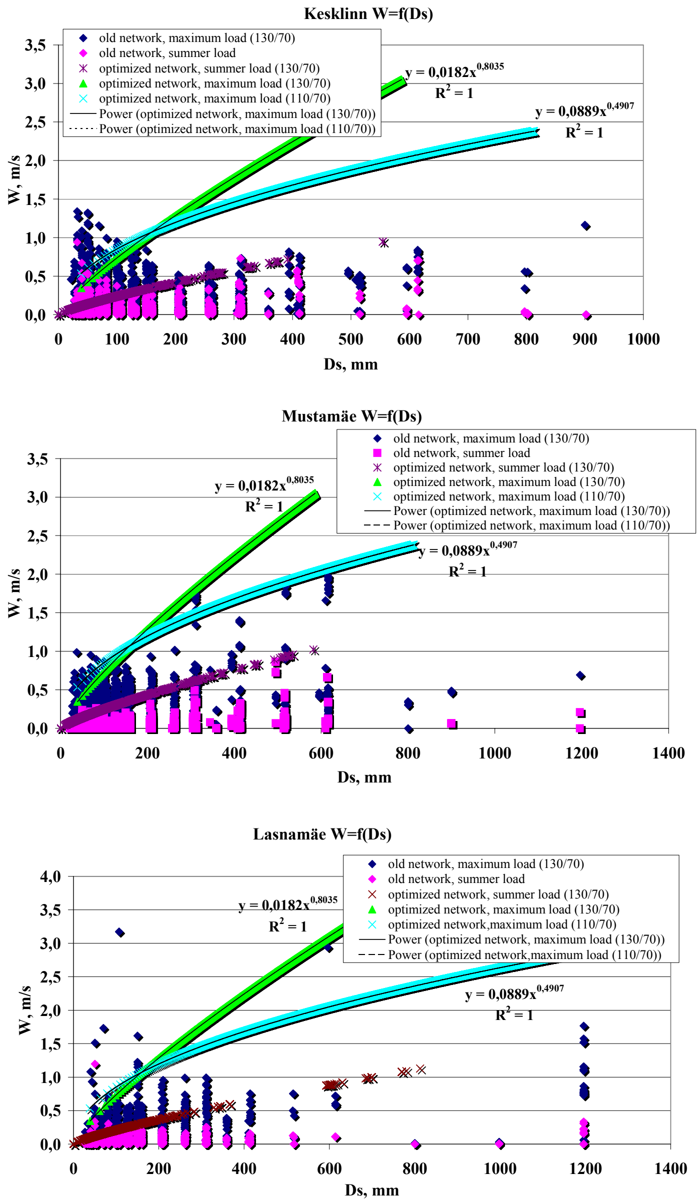


Figure 4.14 Valid and optimal values of water velocity depending to pipe diameter $W = f(D_s)$ *(Kesklinna, Lasnamäe and Mustamäe-Õismäe networks)*

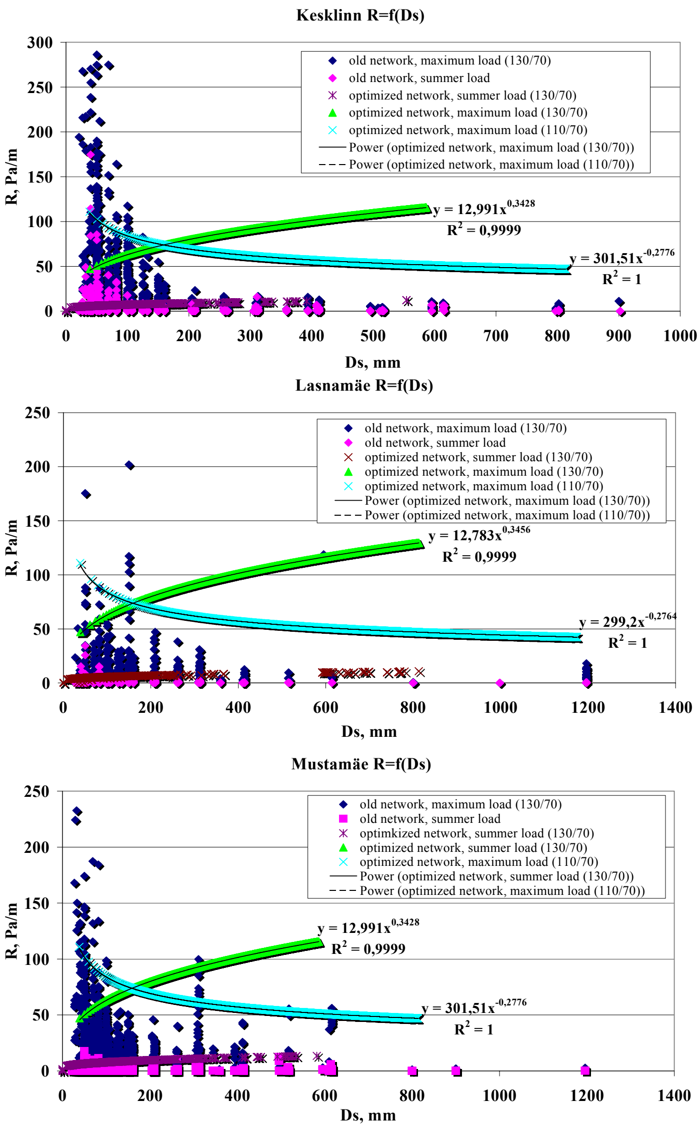


Figure 4.15 Valid and optimal values of friction losses depending to pipe diameter $R_l = f(D_s)$ *(Kesklinna, Lasnamäe,Mustamäe-Õismäe)*

4.3 Conclusions by results of the networks optimization calculations

At optimum internal diameter of a pipe, cost of heat losses will be bigger than costs of heat-carrier pumping and in very insignificant degree influence the optimum value: displace a curve of total costs a little to the left, aside smaller diameters and bigger velocities.

Hence it is possible to draw a conclusion, that change of heat losses cost practically does not influence value of an optimum, only displaces a curve of total costs on a vertical upwards, at increase in heat losses and downwards, at reduction of heat losses.

By networks optimization, formulas for calculation of a pipes diameter optimum values, hydraulic losses, velocities of the heat-carrier and thermal loading are deduced using formulas (2.99), (2.100), (2.101) and (2.102):

$$R_{l,opt.} = C_1 \cdot D_s^{n_1},\ W_{opt.} = C_2 \cdot D_s^{n_2},\ Q_{opt.} = C_3 \cdot D_s^{n_3},\ D_{s,opt} = C_4 \cdot Q^{n_4}$$

Values of constants C_1, C_2, C_3, C_4 and exponents n_1, n_2, n_3, n_4 depend on cost of heat distribution in a network.

It is possible to draw a conclusion that values of constants and exponents depend basically on a temperature mode of the heat-carrier from which its flow depends. In the given research temperature drop of the heat-carrier within the limits of Δt =25 – 60°C are considered.

Cost of heat losses practically does not influence value of a pipes diameter optimum. With reduction of Δt value the optimum value of diameter will increase.

The increase of a network construction cost will displace a site of diameter optimum value aside smaller diameters and bigger velocities of the heat-carrier.

It is possible to draw a conclusion, that the site of an optimum basically is certain by a ratio of pumping costs of the heat-carrier and construction of a network.

The increase in pumping cost, owing to growth of electricity cost, displaces a site of an optimum aside bigger diameters and smaller velocities of the heat-carrier.

The increase in construction cost of a network displaces a site of an optimum aside smaller diameters and bigger velocities.

In existing Estonian district heating networks, velocity of the heat-carrier and specific hydraulic losses, as a rule, below 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) [46,47,48].

Pumping costs in old networks with over dimensioned pipes are much lower than in new optimized 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.

Despite of smaller cost of the heat-carrier pumping, total cost of heat distribution in old networks will be bigger, than in new networks, owing to over dimensioned diameters and considerably the worst thermal insulation.

As figures 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 [16].

In figures 4.16 – 4.19 and in table 4.1 values and functions for calculation of optimum values of diameter, velocity of the heat-carrier, specific pressure loss and thermal loading are resulted for heat-carrier different temperature modes.

Results are received at the today's prices for construction of networks and for electricity. Cost of heat influences cost on distribution of heat, but practically do not influence value of a diameter optimum.

The received dependences can be used at practical engineering calculations. For simplification of engineering calculations table 4.1 is made, in which formulas for calculation of diameter optimum values, specific hydraulic resistance, velocity of the heat-carrier and distributed heat amount are resulted. Dependences are given for different temperature modes of the heat-carrier.

By results of the lead researches a number of scientific articles is written (look the list of publications).

Apparently from the lead researches in chapter 3.2 on an example of optimization, value of an optimum depends basically on the flow rate of the heat-carrier, which depends from a difference of temperatures of the heat-carrier. Other changes in costs displace a curve of total costs only on a vertical upwards or downwards, at practically constant value of a diameter optimum.

Table 4.1 Constants and exponents for formulas by definition of optimum diameter, hydraulic resistance, velocity of the heat-carrier and heat loading.

Temperature difference, ^{o}C	$R_{l,opt.} = C_1 \cdot D_s^{n_1}$		$W_{opt.} = C_2 \cdot D_s^{n_2}$		$Q_{opt.} = C_3 \cdot D_s^{n_3}$		$D_{s,opt} = C_4 \cdot Q^{n_4}$	
	C_1	n_1	C_2	n_2	C_3	n_3	C_4	n_4
delta_25	810	-0,4034	0,1464	0,4266	0,0117	2,4266	6,2502	0,4121
delta_35	274,33	-0,2928	0,0844	0,4832	0,0094	2,4832	6,5362	0,4027
delta_40	301,51	-0,2776	0,0889	0,4907	0,0113	2,4907	6,0485	0,4015
delta_50	22,454	0,2796	0,0241	0,7709	0,0038	2,7709	7,4515	0,3609
delta_60	13,076	0,3429	0,0183	0,8035	0,0035	2,8035	7,5381	0,3567

The note: Cost of heat practically does not influence value of an optimum.

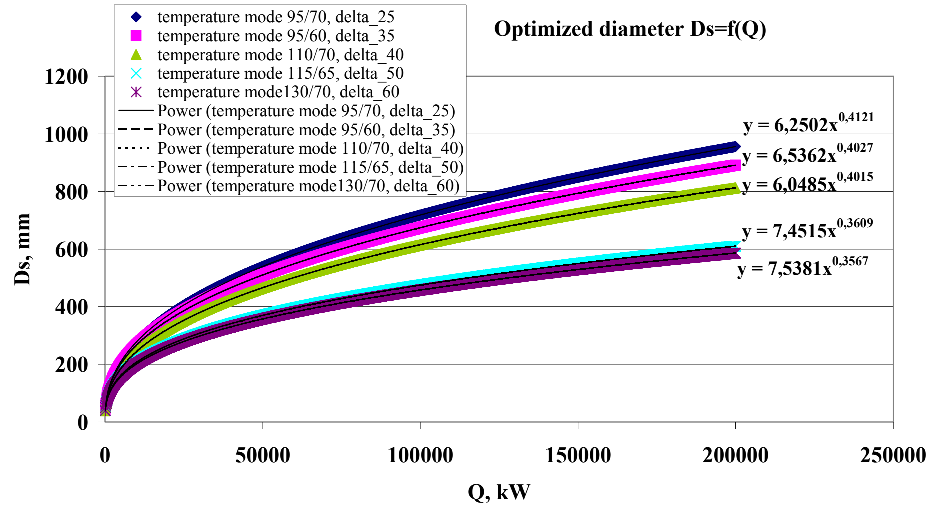


Figure 4.16 Optimal diameter depending to heat load $D_s = f(Q)$

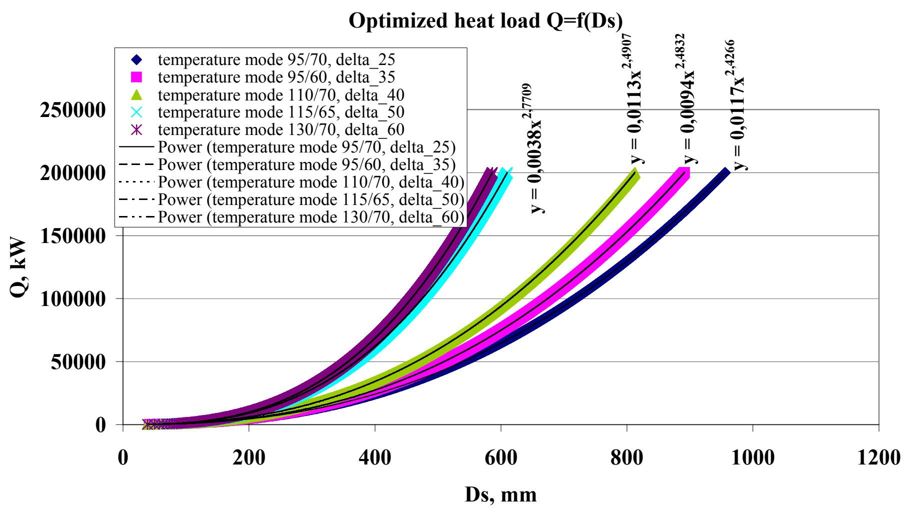


Figure 4.17 Optimal heat load depending to pipe diameter $Q = f(D_s)$

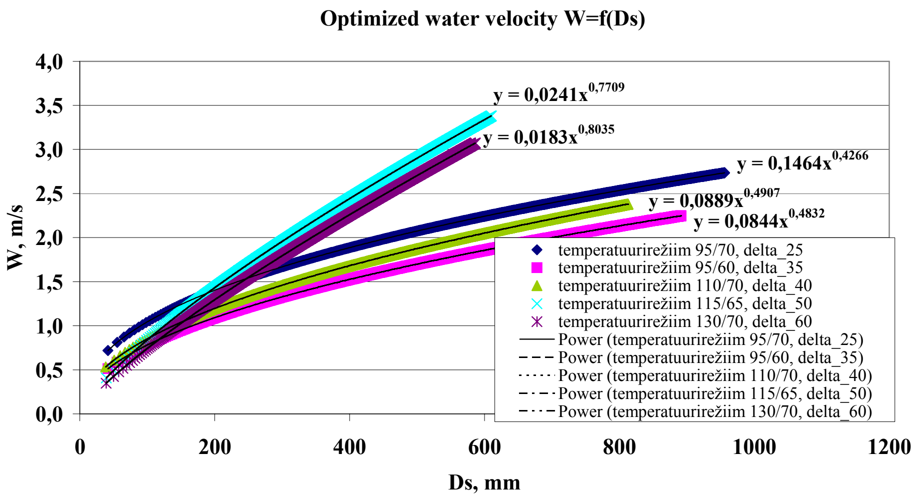


Figure 4.18 Optimal velocity of water depending to pipe diameter $W = f(D_s)$

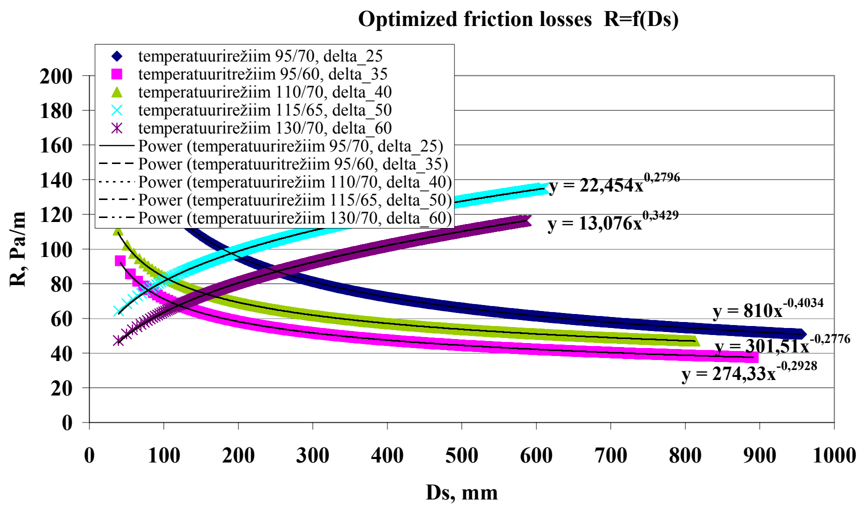


Figure 4.19 Optimal friction depending to pipe diameter $R_l = f(D_s)$

5 THE MAJOR CHARACTERISTIC PARAMETERS OF THE ESTONIAN DISTRICT HEATING NETWORKS AND THEIR DIFFERENCE FROM OPTIMAL VALUES

5.1 The major characteristic parameters of the district heating networks

The major characteristic parameter for estimating the efficiency of the district heating networks is heat loss factor q_{hlf}. The heat loss factor is a ratio between the heat loss and the quantity of heat supplied to the district heating network. The heat loss factor does not depend only on the efficiency of the pipe insulation. It depends on the following parameters:

- The overall heat transfer coefficient K_o, in W/(m^2·K), which characterizes the efficiency of pipe insulation;
- The specific surface area of the distribution pipes *A/L*, in m^2/m, which characterizes of the average size of the district heating pipes;
- The degree-hours number $\int \Theta d\tau$, in ^{o}C·h, which indicates the level of water/steam distribution temperature relative to the annual average of the outdoor temperature;
- The specific heats supply *Q/L*, in MW·h/m, which characterizes the concentration of the district heating demand,

where
A– surface area of the distribution pipes, m^2;
L– pipes length, m;
Θ – difference between water average temperature and outdoor temperature, ^{o}C;
τ – water average temperature and outdoor temperature difference duration time, h;
Q– the annual quantity of the heat supplied to the district-heating network, MW·h.

The overall heat transfer coefficient can be calculated on the basis of design data of the district networks or estimated from the heat loss measurements. In the present work the overall heat transfer coefficient is calculated on the basis of the annual heat losses. The annual heat losses are calculated as difference between the heat supplied to the district heating network and the heat measured at the consumers. The heat losses with DH water leakages are less than 1% and there are also take into account in calculations. The relative error of the heat-flow meters is within $\pm$ 2 % – $\pm$5 %, depending on the load.

The heat loss factor is given by:

$$q_{hlf} = \frac{Q_{hlf}}{Q} = \frac{K_o \cdot A \cdot \int \Theta \, d\tau}{Q} = K_o \cdot \frac{(A/L) \cdot \int \Theta \, d\tau}{(Q/L)}, \qquad (5.1)$$

where
Q_{hlf} – the annual distribution heat loss, MW·h;

Q – the annual quantity of the heat supplied to the district heating network, MW·h.

The real overall heat transfer coefficient K_o is given by:

$$K_o = \frac{q_{hlf}}{\left[\dfrac{(A/L)\cdot\int \Theta \, d\tau}{(Q/L)}\right]}, \text{ W/(m}^2\text{·K)}. \quad (5.2)$$

Calculated overall heat transfer coefficient is given by:

$$K_{ü,arv} = \frac{\sum_{i=1}^{n} K_{k,i}\cdot A_{k,i} + \sum_{i=1}^{m} K_{õ,i}\cdot A_{õ,i} + \sum_{i=1}^{f} K_{e,i}\cdot A_{e,i}}{\sum_{i=1}^{n} A_{k,i} + \sum_{i=1}^{m} A_{õ,i} + \sum_{i=1}^{f} A_{e,i}}, \text{ W/(m}^2\text{K)}. \quad (5.3)$$

where

K_k – heat transfer coefficient of underground canal pipelines, W/(m^{2}K);

$K_õ$ – heat transfer coefficient of on the ground pipelines, W/(m^{2}K);

K_e – heat transfer coefficient of underground preinsulated pipelines, W/(m^{2}K);

A_k, $A_õ$, A_e – pipes surface area $A_i = 2\cdot\pi\cdot D_{t,i}\cdot L_i$, m^2.

For analysing district heating network efficiency, the heat loss factor can be divided into two parts: the overall heat transfer coefficient and the distribution parameter. The distribution parameter is given by:

$$q_{dp} = \frac{q_{hlf}}{K_o} = \frac{(A/L)\cdot\int \Theta \, d\tau}{(Q/L)}, \text{ (m}^2\text{·K)/W}. \quad (5.4)$$

The average diameter of the district heating pipes d_a is given by:

$$d_a = \frac{A/L}{2\cdot\pi}, \text{ m}. \quad (5.5)$$

In following chapter 5.2 characteristic parameters of considered district heating systems are resulted. Results are received in two stages. During the first stage (in 2000 year) the estimation of thermal insulation efficiency has been made in networks of the Võru city, Türi, Kuressaare, Orissaare and Põlva. During the second stage (in 2000 – 2009 years) the estimation of thermal insulation efficiency and hydraulic modes has been made for more than 20 district heating networks.

The major characteristic parameters of the Estonian district heating networks are estimated for the first time according to presented methodology and compared one to another and with the typical modern Nordic networks.

Using the described method total overall heat transfer coefficients for the different district heating networks in Tallinn and small Estonian towns were calculated and analysis carried out. The results of the calculations are presented in figures 5.1 and 5.3. For the comparison the relevant data about Swedish district heating networks are provided. As shown in figures 5.1 and 5.3, the total overall heat transfer coefficients for the different underground ducts of the district heating pipes in Tallinn and small Estonian towns are much higher (up to 3 times) than the same coefficients for the pre-insulated district heating pipes with the same diameters.

The overall heat transfer coefficients certain during the first stage of researches are brought in figure 5.1. In figure 5.1 dependence of the overall heat transfer coefficient on average diameter of network pipes is resulted. The bottom curve corresponds to calculated heat transfer coefficient of the preinsulated pipes of the second class of thermal insulation. For comparison data on overall heat transfer coefficients for typical Swedish district heating networks are cited.

During the second stage of researches when the analysis of hydraulic modes of networks is made, the basic characteristics also are received.

In figure 5.3 the overall heat transfer coefficients received during the second stage of researches are resulted and in figure 5.4 loadings of networks are brought.

Also be certain with what values of parameters after carrying out of full optimization and reconstruction could. The considered district heating systems are grouped by heat loadings.

Apparently from research, at the majority of old district heating systems the overall heat transfer coefficients are within the limits of 1,5 – 2 W/(m^2 K). In Orissares totally renovated network, overall heat transfer coefficient is about 0,9 – 1,0 W/(m^{2}K), and it is in the same range that in modern western networks. On a design of a district heating system are very similar. The most part of district heating systems situated in the underground concrete channel – 73–87 %, the air part makes on length of 5–15 % and the reconstructed underground part from the preinsulated pipes makes 8–15 %. Average diameters of district heating systems pipes are similar and make 0,135–0,155 m.

Efficiency of heat insulation for typical Estonian networks, which is estimated by the overall heat transfer coefficient, is 2–3 times less than same value for the ordinary Swedish networks. For example in the Võrusoo network, overall heat transfer coefficient during last years is in the range 1,8–1,9 W/(m^{2}K), and this value is about 2 times higher than in Swedish networks.

Analysing the district heating networks efficiency we can also use the specific volume heat supply (*Q/V*) in MW·h/m^3, where *V* is total volume of district heating networks pipes. Figure 5.2 presents the specific volume heat supply for different district heating networks depending on the specific heat supply *Q/L*, MW·h/m.

In typical Swedish district heating systems specific volumetric heat supply makes 160 – 170 (MWh)/m^3 at specific heat loading 5 – 6 (MWh)/m and average diameter of pipes 140 – 150 mm. For the areas with one-family houses specific volumetric heat supply is in the range 300-500 MW·h/m^3 at specific heat loading 0,5 – 2,0 (MWh)/m and average diameter of pipes 25 – 65 mm.

As shown in figure 5.4, in Tallinn, the specific volume heat supply of the district heating networks are low and is in the range 14–63 MW·h/m^3 and for the local networks are in the range 150–202 MW·h/m^3. As shown in figure 5.2, in small Estonian towns, the specific volume heat supply of the district heating networks are in the higher range 59–233 MW·h/m^3, but lower than in optimized networks. Over-dimensioning of pipes and poor insulation increase network heat losses.

The results of calculations showed that in Tallinn and also in the local district heating networks the pipe diameters are over-dimensioned. The reason of the over-dimensioning is that the networks were designed taking into account the growth potential of the consumers in the future. Actually the heat consumption has decreased. The number of industrial customers has decreased; consumers started to save energy and some consumers are disconnected from the district heating network and use local heating.

The distribution parameter expresses the potential of the network to have a certain relative distribution loss. The overall heat transfer coefficient is a constant of proportionality, which expresses the heat loss reduction ability of the insulation. In Tallinn, the distribution parameters of the district heating networks are in the range 0,136 – 0,176 (m^2·K)/W. In the small local district heating networks the distribution parameters are in the range 0,057 – 0,086 (m^2·K)/W.

In table 5.3 generalizations on major characteristic parameters for the Estonian district heating systems is brought and shown on how many their efficiency can increase after optimization and full reconstruction. The relevant data for typical Swedish district heating networks are provided in table 5.2.

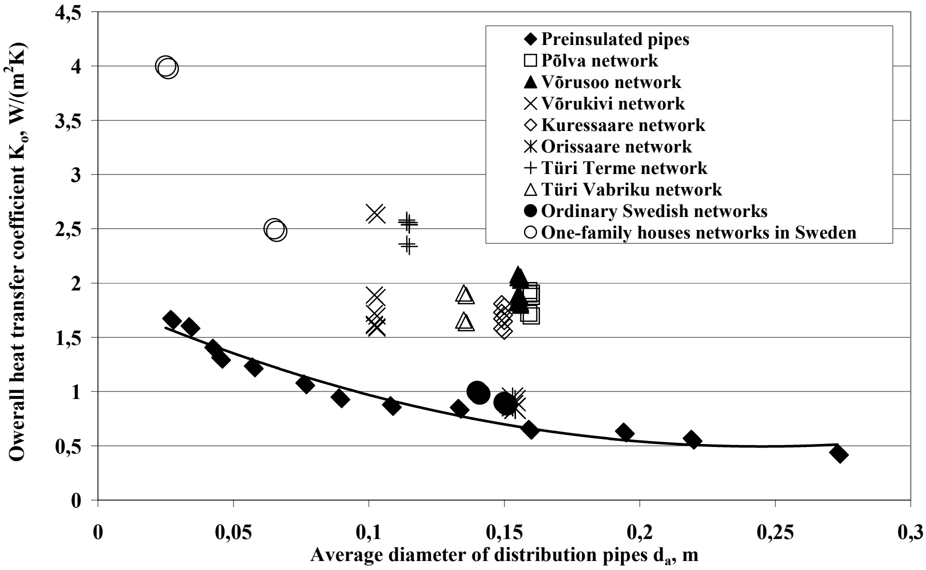


Figure 5.1 Total overall heat transfer coefficient for different district heating systems in small Estonian towns depending on the average diameter of pipes (1998-2002 years)

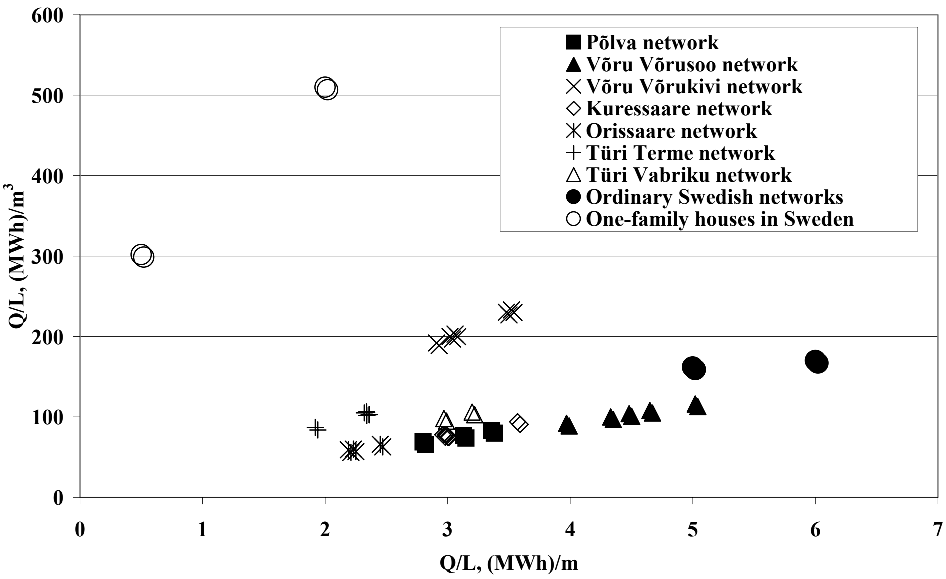


Figure 5.2 The specific volume heat supply for different parts of district heating systems in small Estonian towns depending on the specific heat supply (1998-2002 years)

Tabel 5.1 The major characteristic parameters for the small Estonian district heating networks (average)

Network	q_{hlf}	d_a, m	A/L, m^2/m	V/L, m^3/m	$\int\Theta \cdot d\tau$, $10^5 \cdot {}^oC \cdot h$	Heats supply Q/L, (MW·h)/m	Heats supply Q/V, $(MW \cdot h)/m^3$	Heat losses Q_{hlf}/L, (MW·h)/m	K_o, $W/(m^2 \cdot K)$	q_{dp}, $(m^2K)/W$
Põlva	0,245	0,159	0,999	0,041	4,25	2,80	69	0,69	1,72	0,142
Võrusoo (Võru)	0,213	0,155	0,973	0,043	4,63	3,97	92	0,85	1,89	0,113
Võrukivi (Võru)	0,156	0,102	0,639	0,015	4,42	2,91	192	0,45	1,61	0,097
Kuressaare	0,243	0,149	0,939	0,038	4,66	2,99	78	0,73	1,67	0,146
Terme (Türi)	0,400	0,114	0,713	0,022	5,13	2,34	106	0,94	2,56	0,156
Vabriku (Türi)	0,192	0,135	0,850	0,030	4,1	2,97	98	0,57	1,66	0,117
Orissaare	0,130	0,153	0,959	0,037	3,49	2,23	60	0,29	0,87	0,150

Tabel 5.2 The major characteristic parameters for the ordinary Swedish district heating networks [3]

Network	q_{hlf}	d_a, m	A/L, m^2/m	V/L, m^3/m	$\int\Theta \cdot d\tau$, $10^5 \cdot {}^oC \cdot h$	Q/L, (MW·h)/m	Q/V, $(MW \cdot h)/m^3$	Q_{hlf}/L, (MW·h)/m	K_o, $W/(m^2 \cdot K)$
ordinary networks	0,07-0,085	0,140-0,150	0,880-0,942	0,031-0,035	5,6	5–6	162–170	0,35–0,43	0,9–1,1
one-family houses networks	0,15–0,21	0,025–0,065	0,158–0,408	0,001–0,007	4,8–5,5	0,5–2,0	302–510	0,105–0,3	2,5–4,0

Table 5.3 The major characteristic parameters for the Estonian district heating networks before and after prospective optimization

DH network	Degree-hours, 10^5 °Ch	q_{hlf}	L, m	d_a, m	A/L, m^2/m	V/L, m^3/m	Q/L, MWh/m	Q/V, MWh/m^3	Q_{hl}/L, MWh/m	K_o, W/(m^2K)	q_{dp}, (m^2K)/W
a). Supplyed heat 5000 MWh/year											
Haiba											
old network	5,0	0,26	597	0,149	0,94	0,02	4,5	217	1,2	2,5	0,10
new optimized network	5,0	0,05	405	0,065	0,41	0,01	6,7	684	0,2	1,3	0,04
Imavere											
old network	3,3	0,24	1905	0,116	0,73	0,03	1,71	69	0,4	1,7	0,14
new optimized network	5,1	0,13	1599	0,055	0,35	0,01	1,99	336	0,2	1,4	0,09
Ardu											
old network	2,0	0,11	982	0,133	0,84	0,03	3,5	134	0,4	2,3	0,05
new optimized network	4,0	0,05	1212	0,080	0,50	0,01	4,6	526	0,2	1,2	0,04
b). Supplyed heat 5000-10000 MWh/year											
Räpina											
old network	3,1	0,20	1732	0,165	1,04	0,04	3,1	72	0,6	2,0	0,10
new optimized network	5,1	0,08	1374	0,083	0,52	0,01	3,6	317	0,3	1,1	0,07
Koeru											
old network	4,0	0,15	2390	0,113	0,71	0,02	4,1	201	0,6	2,2	0,07
new optimized network	4,0	0,08	2630	0,098	0,61	0,02	3,4	218	0,3	1,1	0,07
Sindi											
old network	2,4	0,12	2139	0,128	0,81	0,03	4,5	157	0,5	2,8	0,04
new optimized network	3,9	0,05	1889	0,085	0,53	0,01	5,3	464	0,2	1,3	0,04
c). Supplyed heat 10000-50000 MWh/year											
Viimsi											
old network	4,5	0,22	3921	0,124	0,78	0,03	2,7	97	0,6	1,6	0,13
new optimized network	4,5	0,11	3921	0,099	0,62	0,02	2,4	142	0,3	0,9	0,12
Haabneeme											
old network	5,0	0,21	4800	0,158	0,99	0,05	3,6	77	0,8	1,5	0,14
new optimized network	5,0	0,10	4800	0,124	0,78	0,03	3,1	113	0,3	0,8	0,12
d). Supplyed heat 50000-100000 MWh/year											
Keila											
old network	4,6	0,17	11916	0,137	0,86	0,03	5,0	149	0,8	2,2	0,08
new optimized network	4,6	0,05	11916	0,070	0,44	0,01	4,4	507	0,2	1,1	0,05
Võru											
old network	4,7	0,20	20083	0,166	1,04	0,05	3,8	76	0,7	1,5	0,13
new optimized network	4,7	0,09	20083	0,123	0,78	0,03	3,4	109	0,3	0,9	0,11
Kiviõli											
old network	4,9	0,26	11004	0,179	1,12	0,07	5,1	75	1,3	2,4	0,11
new optimized network	4,9	0,08	11004	0,085	0,54	0,01	4,3	321	0,3	1,3	0,06
f). Supplyed heat over 100000 MWh/year											
Tallinn, Kesklinna SVR											
old network	4,9	0,18	84366	0,206	1,29	0,12	5,4	45	1,0	1,5	0,12
new optimized network	5,0	0,06	82902	0,104	0,65	0,03	4,8	156	0,3	0,9	0,07
Tallinn, Lasnamäe SVR											
old network	5,1	0,21	146002	0,335	2,11	0,38	5,6	15	1,2	1,1	0,19
new optimized network	5,1	0,08	138794	0,204	1,28	0,07	5,0	77	0,4	0,6	0,13
Tallinn, Mustamäe SVR											
old network	4,8	0,16	143299	0,202	1,27	0,11	6,0	54	1,0	1,6	0,10
new optimized network	4,8	0,05	144036	0,109	0,69	0,03	5,3	159	0,3	0,9	0,06
Narva											
old network	4,9	0,18	68569	0,249	1,56	0,15	8,4	58	1,5	2,0	0,09
new optimized network	4,9	0,07	68569	0,198	1,24	0,06	7,4	121	0,5	0,7	0,08

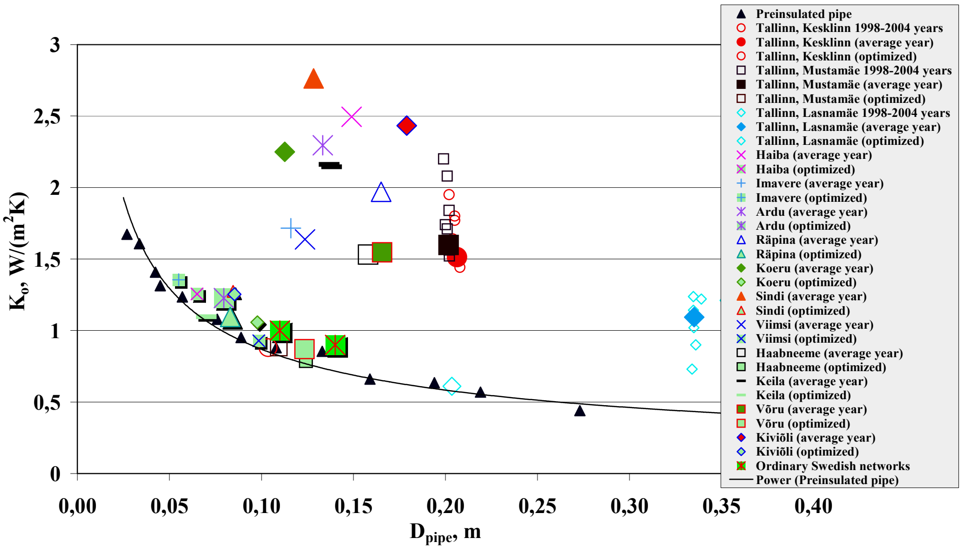


Figure 5.3 Total overall heat transfer coefficient for old and new optimized Estonian district heating systems, depending on the average diameter of the pipes (1998-2009 years)

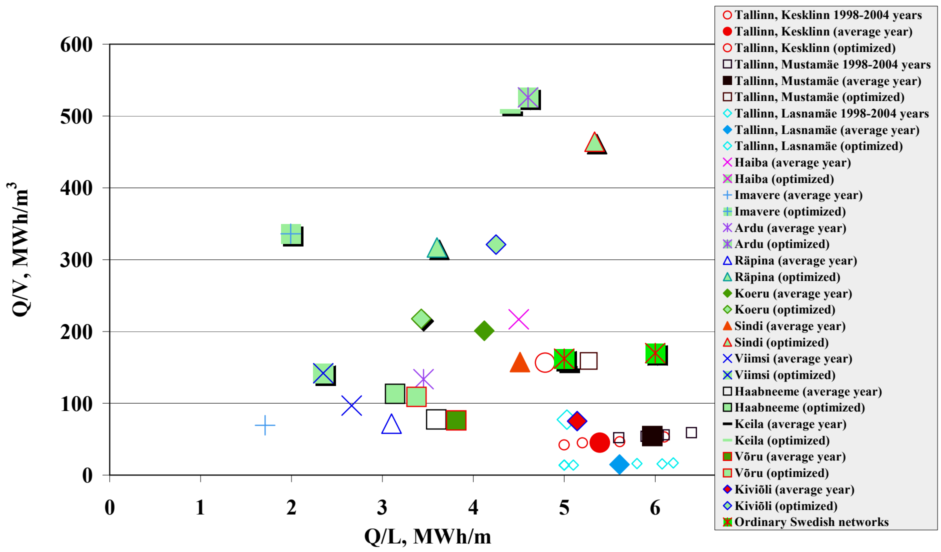


Figure 5.4 The specific volume heat supply for old and new optimized Estonian district heating networks depending on the specific length heat supply (1998-2009 years)

5.2 Conclusions of the chapter

Main characteristic parameters of the Estonian district heating networks are estimated for the first time according to presented methodology and compared one to another and with the typical modern networks.

The relative heat losses in the typical Estonian small towns old networks are about 15 – 25%. Extremely high relative heat losses for example are in the Türi towns Terme network, there are about 30 – 40%, due to low heat demand density and high heat transfer coefficient of pipes. In the Tallinn networks relative heat losses are lower than in the small towns networks due to higher concentration of the district heating demand, and are 16 – 23%. In Swedish typical networks relative heat losses are 7 – 9%, and there are have the similar heat demand concentration than in Tallinn: 5 – 6 MWh/m, but much better heat insulation of pipes: overall heat transfer coefficient is 0,9 – 1,1 W/(m^{2}K), more than two times less than in Tallinn networks.

Efficiency of heat insulation for typical Estonian networks, which is estimated by the overall heat transfer coefficient, is 2-3 times less than same value for the ordinary Swedish networks. For example in the Võru network, overall heat transfer coefficient during last years was in the range of 1,6 – 1,9 W/(m^{2}K), and this value is 1,6 – 1,9 times higher than in Swedish networks. In Orissares totally renovated network, overall heat transfer coefficient is about 0,9 – 1,0 W/(m^{2}K), and it is in the same range that in modern networks.

As investigations shows, heat transfer coefficient for pipes in old underground concrete ducts may significantly increase rainy season up-to 2 – 3 times compares with dray season.

Variation of the heat transfer coefficients values are depended on the climate condition differences. Old pipelines, which are located in the underground concrete ducts, are very sensitive to the rainfall. Moisture from rain and melted snow, which infiltrated to the duct, significantly increases heat transfer coefficient (figure 5.5). Also in figure 5.6 is presented heat transfer coefficient for totally renovated Orissaare network, and we can see that moisture from rain and melted snow did not increase so much heat transfer coefficient of pipes.

Total overall heat transfer coefficients before and after prospective optimization for Estonian district heating networks are presented on the figure 5.3.

The network pipelines are over-dimensioned. The pumping energy consumption for the over–dimensioned pipes can be less than for the optimal designed pipelines due to smaller hydraulic resistance, but heat losses are much bigger compare with optimal designed and well insulated pipelines.

On the figure 5.7 the pipes optimal diameter depending to the heat load is presented. Next figures 5.8 and 5.9 presents real and optimized values of water velocity and friction loss depending to pipe diameter. The example is given for typical Estonian old district heating network witch situated in Võru town. Calculations results for water velocity and friction losses are presented for the full heat load if outdoor temperature is –22^{o}C and also for summer load. Received results are practically useable in DH pipelines design and in renovation of old district heating networks.

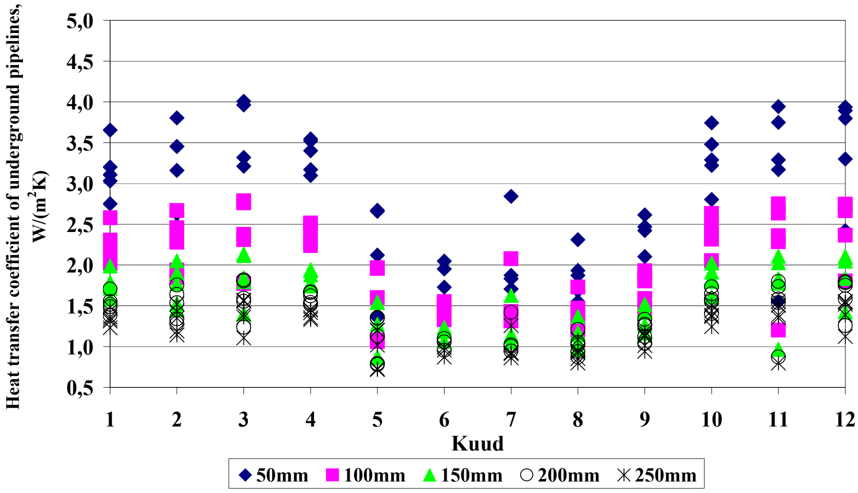


Figure 5.5. Heat transfer coefficient for Võru town Võrusoo network pipes depending on the climate condition differences (rainwater) during the year

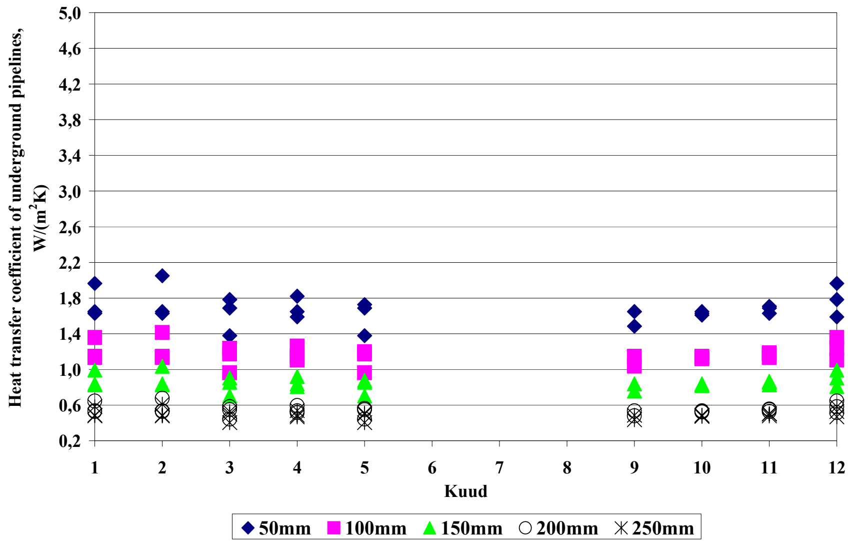


Figure 5.6. Heat transfer coefficient for Orissare town network pipes depending on the climate condition differences (rainwater) during the year

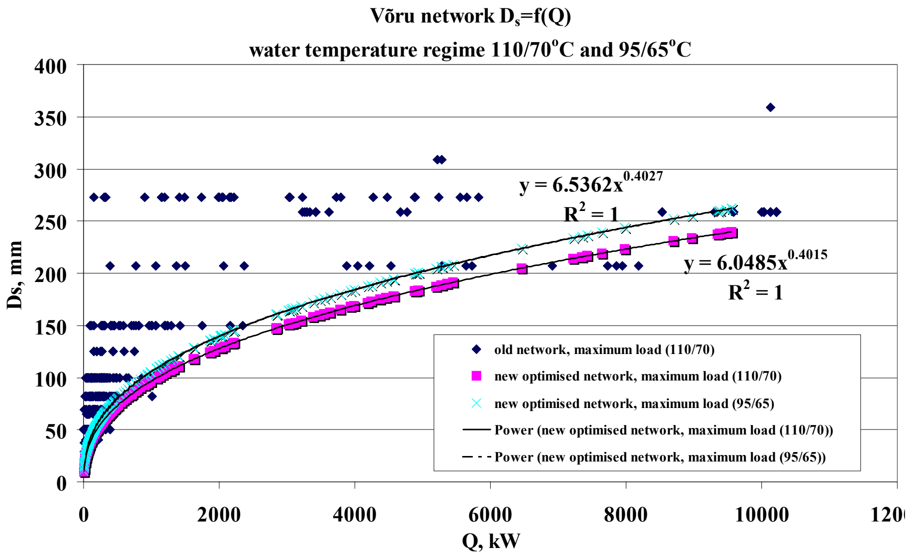


Figure 5.7 Optimal diameter depending to heat load $D_s = f(Q)$ *in Võru town DH network*

The water velocities and friction losses in pipes of Estonian old district heating networks as rule are much lower than optimum values (~0,6–1,2 m/s and ~100–70 Pa/m for 50–250 mm pipes) (figures 5.8 and 5.9).

This situation exists because old networks where designed for much bigger load and take into account growing potential.

As figure 5.9 shows, the 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. The optimal friction losses decreases slowly with diameter growing, for example from 150 Pa/m (DN 25) to 75 Pa/m (DN200), and water temperature regime is 110/70°C. The optimal value of friction losses for the lower temperature difference – temperature regime 95/65°C, will be little beat higher.

After optimal selection of network pipes diameters, according to consumers real heat demand and total renovation of pipes (replacing by the preinsulated pipes), relative heat losses drastically decreases.

Relative heat losses, for example in Tallinn city networks Mustamäe-Õismäe and Kesklinn region decrease from 16–18% to 6–7%, in Lasnamäe region – from 20–22% to 8%, in Võru town network – from 20% to 9%, in Keila town network – from 18–19% to 5%, in Kiviõli town network from 26% to 8%, and in Viimsi and Haabnmeeme settlements networks decrease from 21–22% to 10–11%.

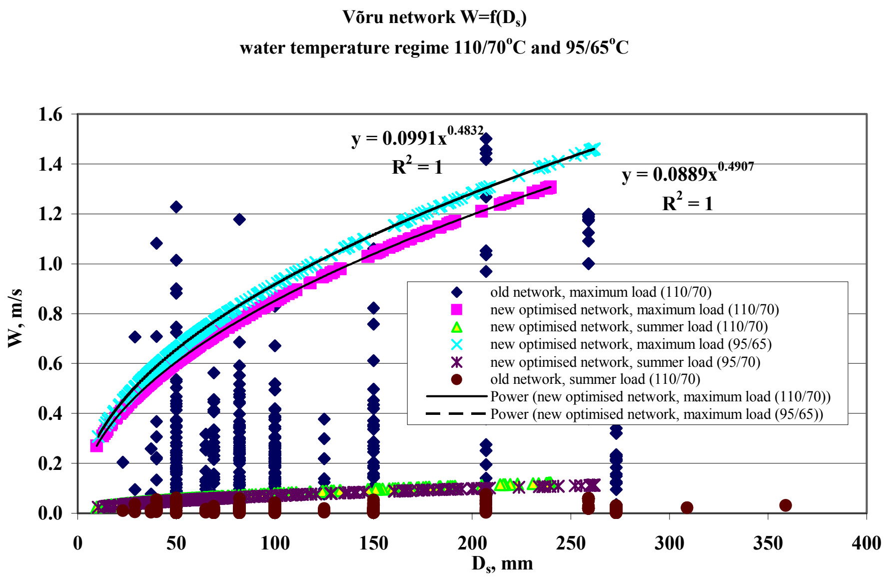


Figure 5.8 Water velocity depending to pipe diameter $W = f(D_s)$ in Võru town DH network

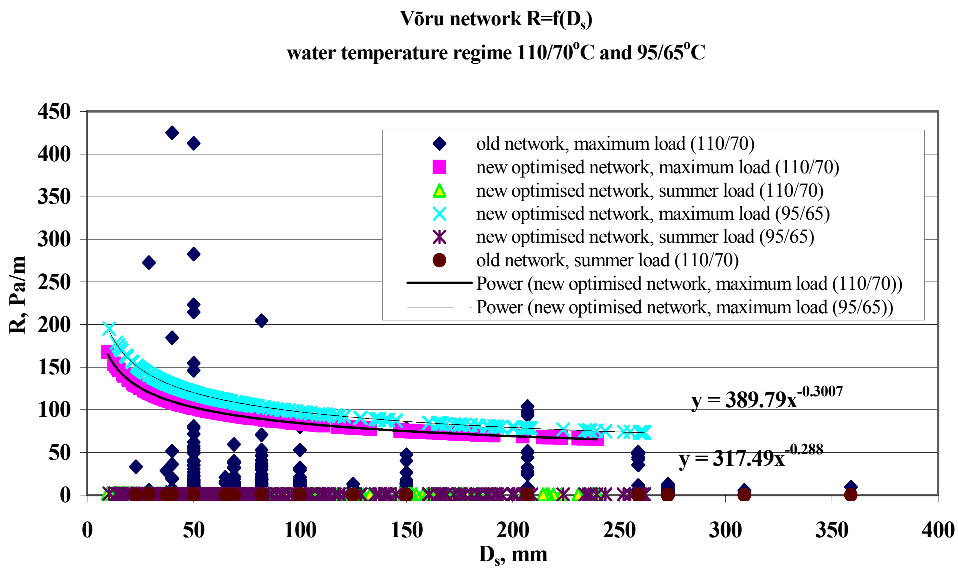


Figure 5.9 Friction losses in Võru town DH network depending to pipe diameter

Especially big decreasing of heat losses can be in those networks where old 4 pipes system will be replaced by the new optimized 2 pipes system. For example Haiba settlement network heat losses decreases from 26% to 5%.

As we can see, heat losses decreasing potential is very big. After optimization and total renovation of old networks, heat losses can decrease up to 2–4 times and especially big decreasing, up to 5–6 times, will be observe after old 4 pipes system replacement by the 2 pipes optimized and well insulated system.

Recently, considerable tendency of the overall heat transfer coefficient reduction in the district heating networks in Tallinn and Narva was observed. This reduction is caused by replacement of district heating network old sections with new pre-insulated pipes. Several "wet" sections of the network can significantly increase the value of the heat transfer coefficient. Replacement of these sections will significantly decrease the overall heat transfer coefficient. As a result of reconstruction the overall heat transfer coefficient considerably decreases also reliability of a district heating system work considerably increases. Detailed research of damages statistics and its changes is resulted in the following chapter.

Further figures (figures 5.10 and 5.11) showing the reduction tendency of the overall heat transfer coefficient in district heating networks of Tallinn and Narva cities.

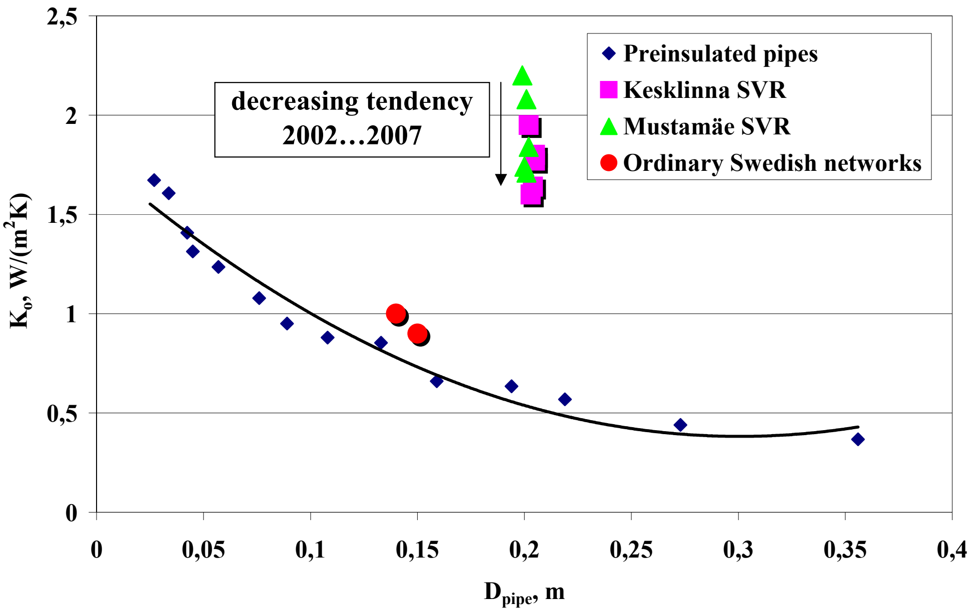


Figure 5.10 The overall heat transfer coefficient reduction tendency in Tallinn DH networks (2002-2007 years)

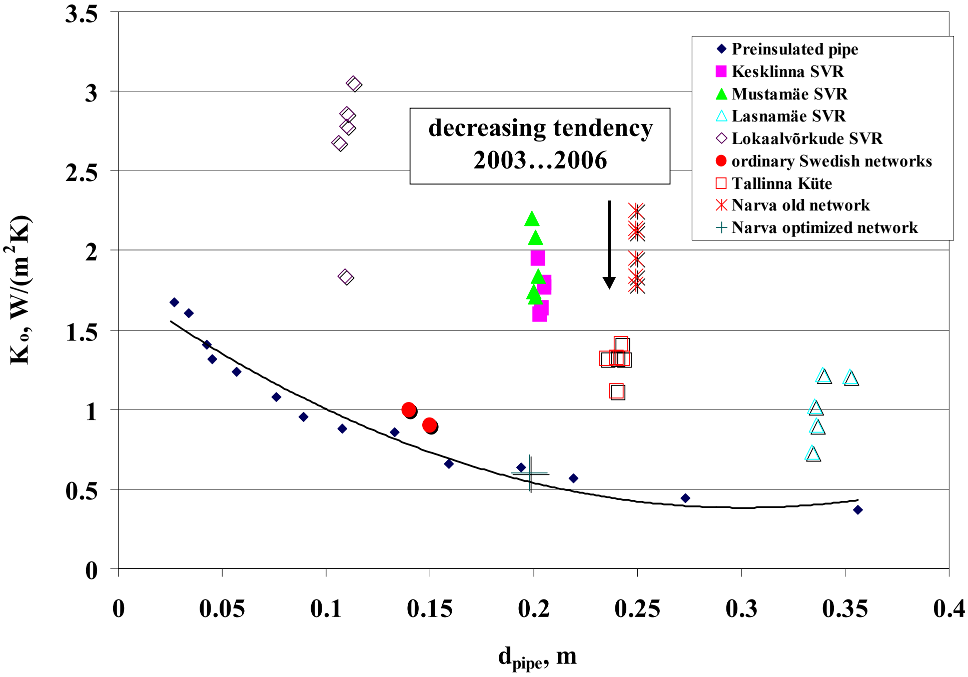


Figure 5.11 The overall heat transfer coefficient reduction tendency in Narva DH network (2003-2006 years)

6 STATISTICS OF DH NETWORKS DAMAGES AND INDICATIVE PARAMETERS FOR AN ESTIMATION OF THE NETWORKS GENERAL CONDITION

The purpose of the given research was to define on the basis of operational data the valid condition of typical old networks in Estonia and the reasons of damages occurrence. Networks of Tallinn city have been investigated.

6.1 The description of the considered district heating systems

The AS Tallinna Küte enterprise makes operation of a bigger part of district heating networks and boiler-houses of Tallinn.

District heating systems of Tallinn consist of five districts of the central heat supply:

- Kesklinna district (all length ~92 km, length on balance of AS Tallinna Küte ~76 km),
- Lääne district (all length ~162 km, length on balance of AS Tallinna Küte ~141 km),
- Lääne district local networks (all length ~12 km, length on balance of AS Tallinna Küte ~11 km),
- Lasnamäe district (all length ~114 km, length on balance of AS Tallinna Küte ~106 km),
- Maardu district (all length ~25 km, length on balance of AS Tallinna Küte ~14 km).

District heating systems of areas Kesklinna and Lasnamäe are connected through pump station Laagna. The total length of heating networks makes 407 km from which on balance of AS Tallinna Küte there are 348 km or 85,7 %.

The following CHP station and boiler-houses supply heat to the Kesklinn and Lasnamäe areas:

1). CHP Iru working on natural gas: electric capacity makes 190 MW, total thermal capacity – 748 MW, in a CHP mode – 398 MW, produced heat in 2008 was 1048 GWh and electricity – 414 GWh.

2). Boiler-house Ülemiste working on natural gas: is the most part of time in a reserve, thermal capacity makes 180 MW, produced heat in 2008 was 12 GWh.

3). Since 2009 the CHP Väo start to operate. It working on woodchips and peat: thermal capacity makes ~65 MW, electric – ~25 MW, planned annual heat production will make ~450 GWh.

Two boiler-houses supply heat in the area Lääne:

1). Boiler-house Mustamäe: thermal capacity makes 390 MW, annual heat production in 2008 was 401 GWh.

2). Boiler-house Kadaka: thermal capacity makes 290 MW annual heat production in 2008 was 353 GWh.

Except for these big areas of the central heat supply, exist still a number of local areas of the central heat supply and small boiler-houses.

District heating systems of Tallinn are constructed basically in 1960...1980 years and their average age makes more than 20 years. In following figure 6.1 the basic scheme of a heat supply of Tallinn is given.

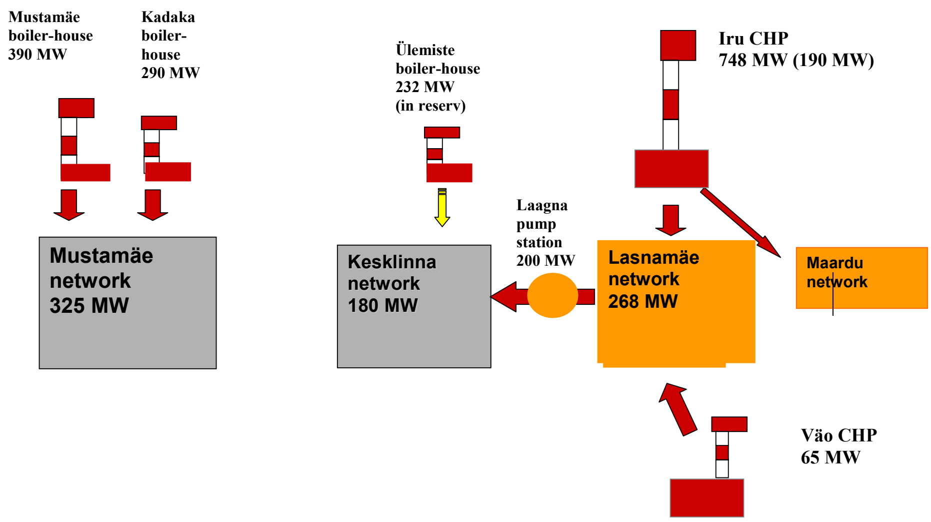


Figure 6.1 The basic scheme of a heat supply in Tallinn and Maardu

6.2 The analysis of a district heating systems condition

6.2.1 Lasnamäe district heating area

The present condition

In Lasnamäe area construction of district heating systems has begun in 1970. Middle age of networks makes 22 years for today.

In Lasnamae area the length of a network makes ~106 km that makes ~26% from the total length of the Tallinn DH networks. The volume of main pipes DN1200 in Lasnamäe network is equalled ~49000 m^3, that makes ~59 % from volume of all networks of Tallinn. Heating systems of Lasnamäe area with their today's loading are most over dimensioned networks in city.

As a lining of a network in Lasnamäe area are subdivided as follows: the length of underground networks placed in the concrete channel makes ~56,5 km (~53%), length of networks lining on cellars - ~30,0 km (28%), the length of underground networks made from the preinsulated pipes makes ~16,9 km (~16%), an air lining - ~2,8 km (2%).

Very old underground networks with bitumenperlit thermal insulation basically are liquidated, there were only ~390 m.

The length of main pipelines DN1000-1200 makes ~19 km, the length of pipes DN400-800 makes ~4,4 km. The share of the main networks is enough big and makes ~22 % of total length. Thermal insulation is made of glass wool according to old soviet building norms and it is the reason of big heat losses in a network. Heat losses in Lasnamäe network in 2008 have made 115 578 MWh, or 21% from produced heat.

In Lasnamäe network there are 180 section latches and 476 latches on branches, totally 656 latches. More than half from them it is old latches still soviet times in quantity of 361 pieces (~55 %).

The quantity of thermal lengthening compensators makes 450 pieces from which 322 pieces (~72 %) these are old axial compensators which resource by today's time is already settled.

Investments

In figure 6.2 the length of the repaired sites of a network on years is resulted. In Lasnamäe network growth of the repaired sites quantity is observed since 1998. Basically investments are directed on increase in reliability of a network.

For last 10 years replacement of ~4 kilometres of networks is made that makes ~3,5% from all length of Lasnamäe district heating network.

The district heating system of Lasnamäe area is newest from the Tallinn networks, but by the today's moment has already reached such age that significant growth of malfunctions is observed.

The criterion of a network repair basically is not age, and first of all is valid reliability of a network a basis for which estimation are the damages quantity and data received at routine inspection.

In the nearest five years the most part of investments will be made with replacement of thermal lengthening compensators and locking armature by the main networks DN1200. The above-stated measures substantially will help to increase reliability of main pipelines on which is supplied with heat of 2/3 Tallinn consumers, outflow of water and faults in a heat supply will decrease. However these measures will not considerably reduce heat losses and will not reduce increase of networks age.

In the future it will be necessary to invest more in drainage systems, channels, in moving and dead supports, compensators of thermal lengthening. Badly working compensators of thermal lengthening and moving supports can cause too big forces in metal structure.

As a priority at planning repair of networks was reliability of a heat supply, till today's time it was not given attention to replacement and improvement of pipes thermal insulation.

Heat losses through old thermal insulation of pipes are very big. In table 6.2 comparison of heat transfer coefficients of old pipes and the new preinsulated pipes of an underground lining is resulted.

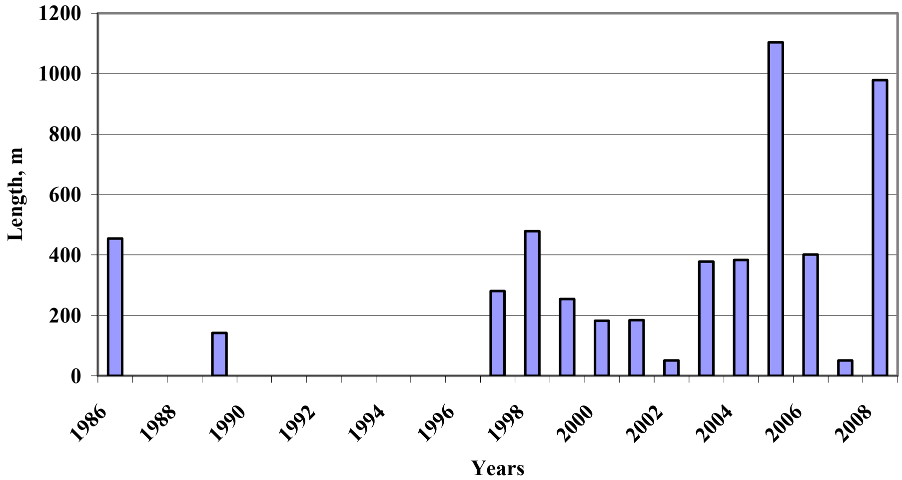


Figure 6.2 Length of the replaced pipelines on years in Lasnamäe network

At the moment the length of constantly flooded networks makes 704 m and 517 m of networks are periodically flooded, and totally is flooded 1221 m.

The analysis of damages

On the basis of the valid data received for last 12 years the analysis of networks damages statistics is made.

In figure 6.3 distribution of damages of Lasnamäe district heating network on middle age of a networks sites is resulted and it is visible that the most critical age is 18–28 years or sites constructed in 1980–90 years. On sites of a network constructed in 1980–85 years were 123 damages and on sites constructed in 1985-90 years were 77 damages. It can be explained by bad quality of construction and materials. During this period the networks were under construction with haste and with insufficient supervision of construction.

In figure 6.4 the statistics of damages quantity on one kilometre of a network is resulted.

Most of all damages have occurred during the 1999-2001 years: 0,34 of damage on 1 km was in 1999 and these sites have been constructed during 1980-85 years. After that period the quantity of damages has gone on recession. It speaks most likely that that problems of pipelines constructed in 1980–90 have come to light.

In figure 6.5 the place of damages on networks elements is shown: armature, compensators of thermal lengthening, a design, and pipes.

Most of all damages were on pipes. Damages of compensators and locking armature were very little.

Most of all damages on compensators were in 1999–2001 years. However the part of old compensators installed during 1978–80 years still works: on two main pipelines I and II with diameter DN1200 in Lasnamäe network works 175 old axial compensators.

Lifetime of axial compensators of thermal lengthening makes 30 years and has already come to an end.

Danger of damages occurrence and water outflow sharply increases in the end of service life of axial compensators.

In figure 6.6 characters of damages is resulted. In Lasnamäe network a significant part of damages is caused by external corrosion of pipes. Principal cause of external corrosion is the bad waterproofing of underground channels and chambers and the collapsed drainage. Also defects of pipes supports and destruction of channels concrete are observed.

As during the basis of Lasnamäe area in 1980–87 years and during last building boom in 2000–08 years there was an active construction of buildings and expansion of an infrastructure. As a result of use the heavy technical equipment during construction there was a strong vibration and dynamic loading which has destroyed a waterproofing on a part of old underground channels. It causes hit of moisture in channels, thermal insulation is humidified and heat losses increase.

One reason of pipes external corrosion are idle drainages and because that there is a constant or periodic flooding of channels by subsoil waters. As a result of it thermal insulation is humidified, also heat losses grow.

The share of internal corrosion in comparison with external in Lasnamäe network was very insignificant as quality of water in network was good, the open system of hot water supply did not exist. Rigidity of network water is given in table 6.1.

Other reasons of a network damages were defects of installation and factory defects.

Hence it is possible to note that in Lasnamäe area besides factors influencing normal ageing of a network additional influence is rendered with external local corrosion of pipes. External corrosion is caused basically by hit of moisture in channels from for an idle drainage and the damaged waterproofing of channels.

Table 6.1 *Rigidity of water in Lasnamäe network*

Year	Lasnamäe water rigidity, mg-ekv/l
2001	0,029
2002	0,025
2003	0,021
2004	0,018
2005	0,012
2006	0,013
2007	0,015
2008	0,018

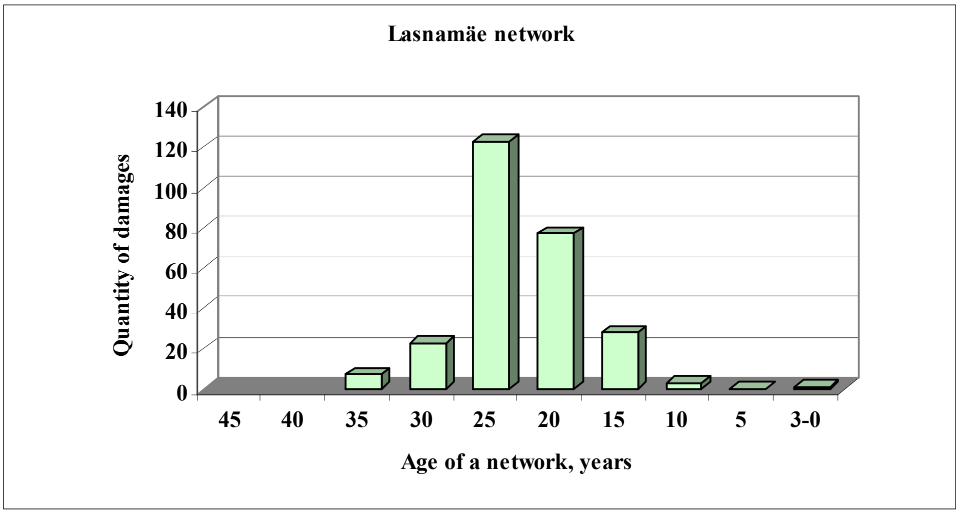


Figure 6.3 Distribution of damages in Lasnamäe district heating network on middle age of a networks sites

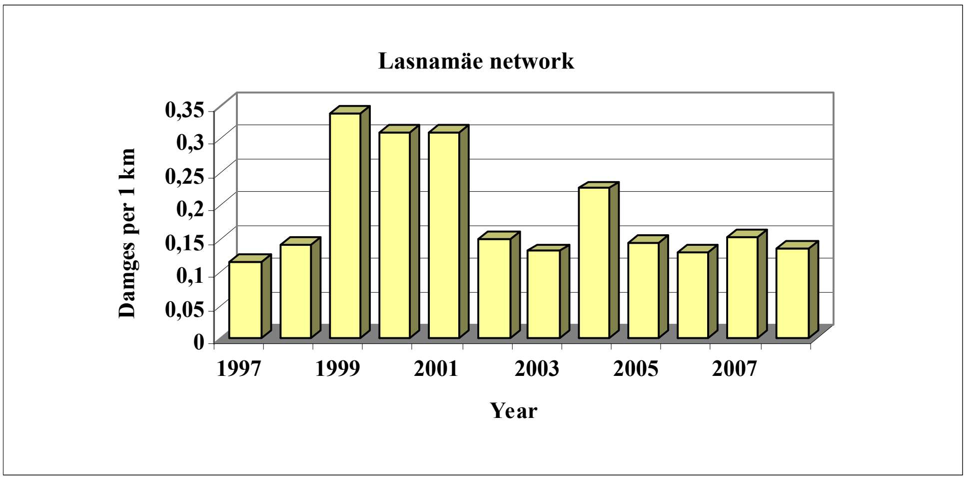


Figure 6.4 Statistics of damages quantity on one kilometre in Lasnamäe network

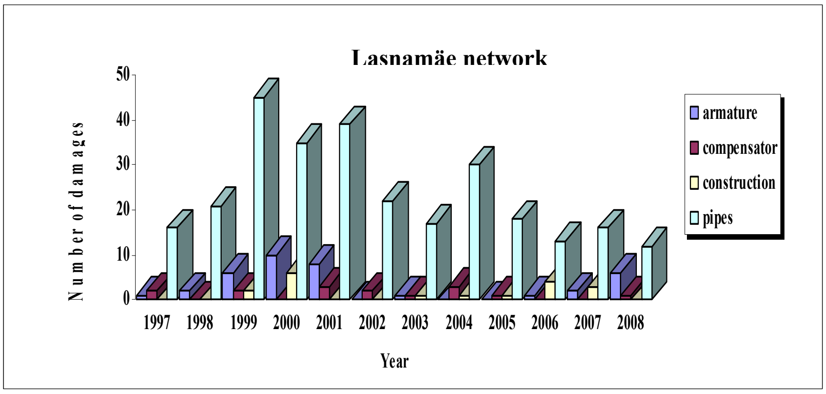


Figure 6.5 The place of damages on elements in a Lasnamäe network

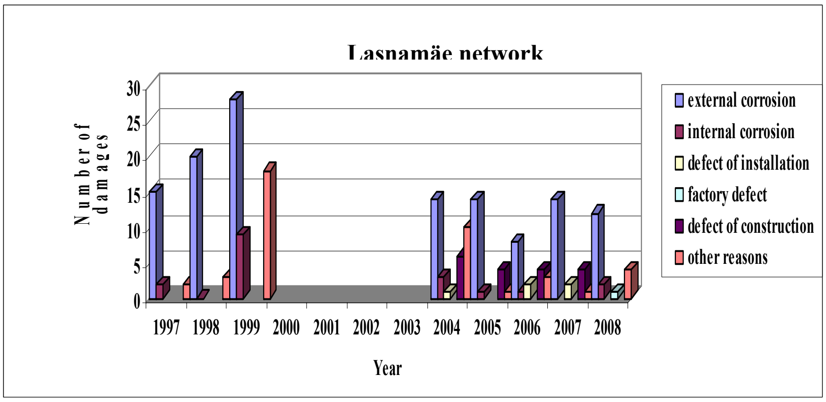


Figure 6.6 The character of damages in Lasnamäe network

6.2.2 Lääne (Mustamäe-Õismäe) district heating area

The present condition

Connected among themselves district heating systems of Mustamäe, Kadaka and Karjamaa (not in operation now) boiler-houses concern to area Lääne (Mustamäe-Õismäe). In the beginning it there were two separate networks which later after growing were connected among themselves.

In area Lääne construction of district heating systems has begun with 1960. Middle age of heating systems in this area makes 23 years.

The length of a Lääne area network is equalled ~141 km that makes ~35 % from the total length of Tallinn district heating systems. As a lining type of a network in Lääne area are subdivided as follows: the length of underground networks placed in the concrete channel makes ~ 67,8 km (~48%), length of networks lining on cellars – ~29,5 km (21%) the length of underground networks made from the preinsulated pipes makes ~34,5 km, (~24%), an air lining – ~9,1 km (6%).

Diameters of the main pipelines is less than in area Lasnamäe. The volume of Lääne network makes (~16 682 m^3) or ~20 % from total volume of all networks in Tallinn. The length of the main pipelines with diameters DN400–900 makes ~27,8 km. Heat losses of a network in 2008 were 113643 MWh or 16 %.

In Lääne network there are 158 section latches and 651 latches on branches, totally 809 latches and 138 pieces (~17 %) of them is old latches still soviet times, also require replacement.

The quantity of thermal lengthening compensators makes 572 pieces from which 464 pieces (~81 %) these are old axial compensators which resource by today's time is already settled.

Feature of a heating system of area Lääne is that earlier in networks of boiler-houses Mustamäe and Kadaka there was an open system of hot water supply and water added in a network had not time to clear sufficiently in water there was an oxygen and rigidity (figures 6.8 and 6.9) that has led to intensive internal corrosion of pipes.

Since 1966 in boiler-house Mustamäe and later in boiler-houses Kadaka and Karjamaa (not in operation now), experiences with samples of metal on speed of corrosion were periodically done.

In figure 6.10 results of experiments on speed of internal corrosion are resulted, mid-annual speeds of corrosion are specified.

Investments

In figure 6.7 the length of all repaired sites separately on years is shown. Since 1980 till today serial repair of Lääne district heating system was carried out.

Basically investments have been directed on increase in reliability and reduction of quantity and duration of faults in a heat supply. It has been much invested in locking armature. For last 10 years ~18 km of district heating pipelines have been replaced that makes 11 % from all length of district heating systems of Lääne area.

In the nearest five years the most part of investments it is planned in replacement of old axial thermal lengthening compensators.

Also in a greater degree it will be necessary to invest in repair of drainage system, a waterproofing and supports of the main pipelines.

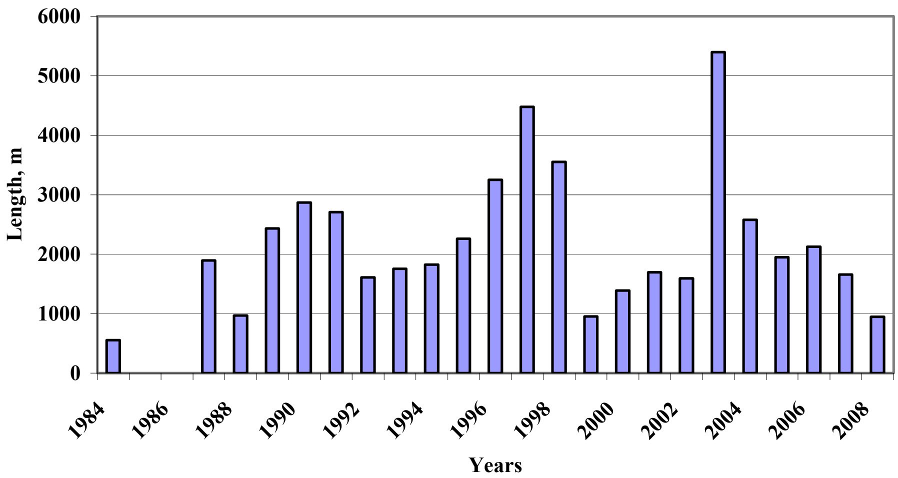


Figure 6.7 Length of the replaced pipelines on years in Lääne area network
The mark: In 2003 there was a connection of Pelguranna local boiler-houses networks area to the central network.

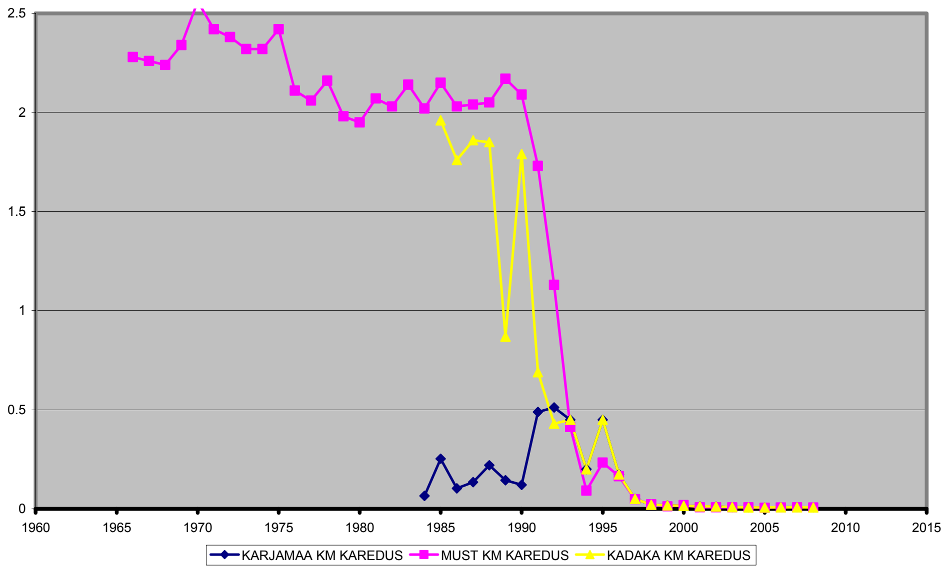


Figure 6.8 Average indices of water rigidity [mg-ekv/l] in Mustamäe, Kadaka and Karjamaa networks

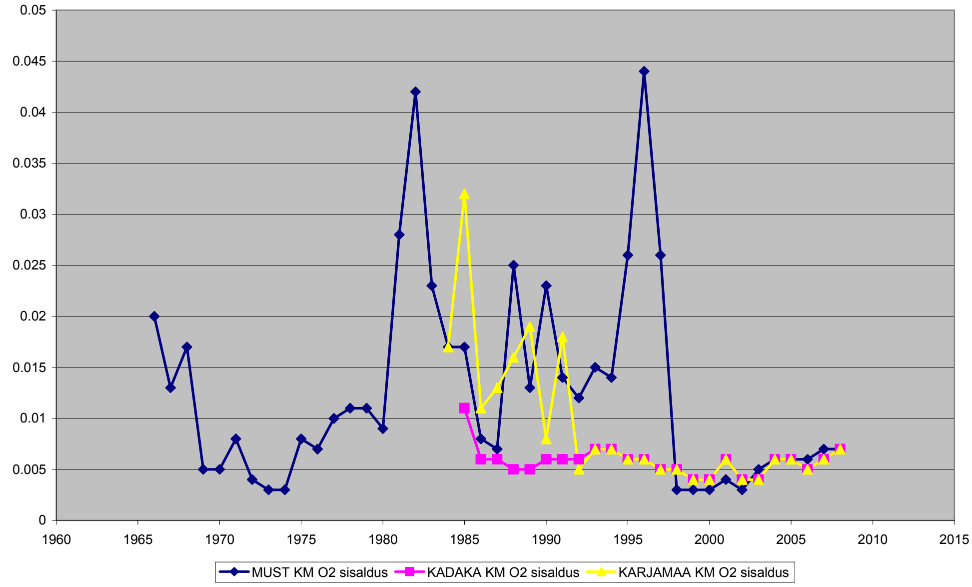


Figure 6.9 The average contents of oxygen in water [mg/l] in Mustamäe, Kadaka and Karjamaa networks

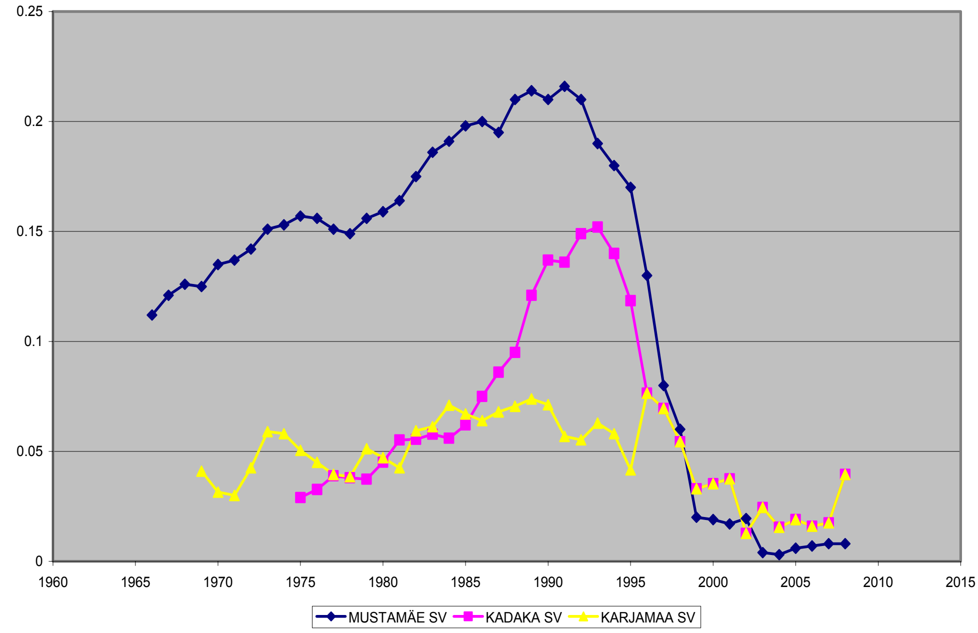


Figure 6.10 Depth of pipes internal corrosion [mm/year] in Mustamäe, Kadaka and Karjamaa networks

At the moment the length of constantly flooded sites makes 2277 m and periodically flooded sites – 2780 m that together makes 5057 m.

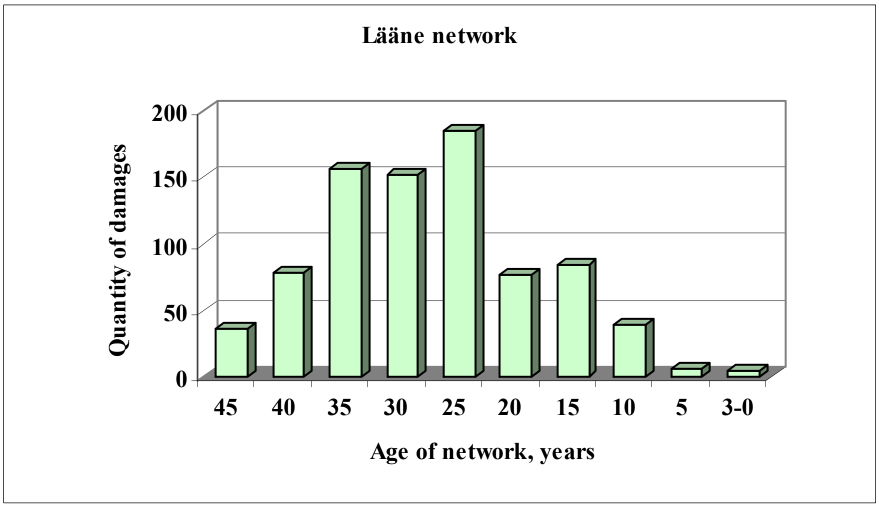


Figure 6.11 Distribution of damages in Lääne district heating network on middle age of a networks sites

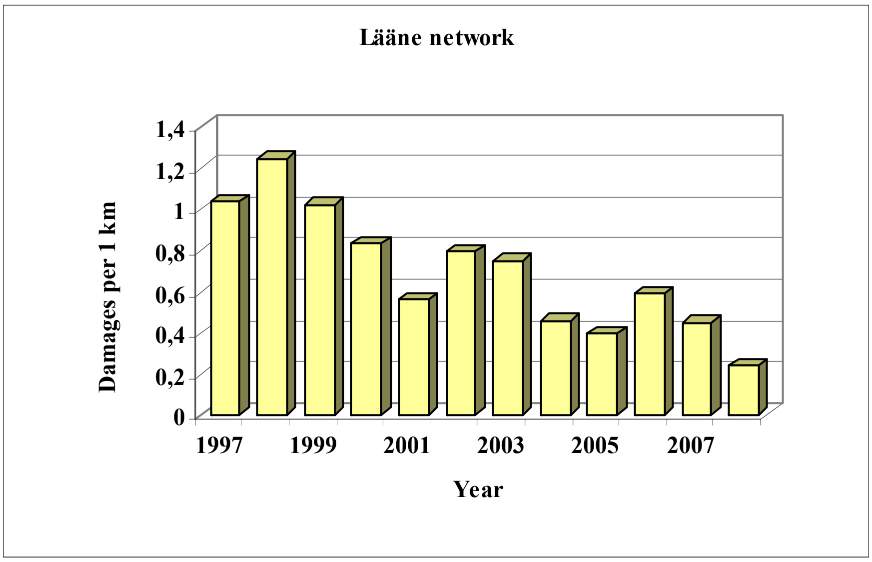


Figure 6.12 Statistics of damages quantity on one kilometre in Lääne network

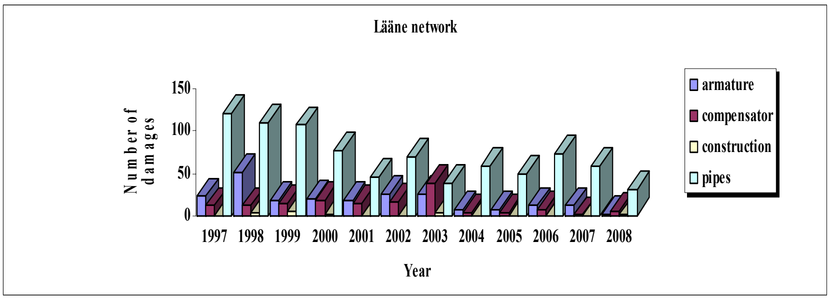


Figure 6.13 The place of damages on elements of a Lääne network

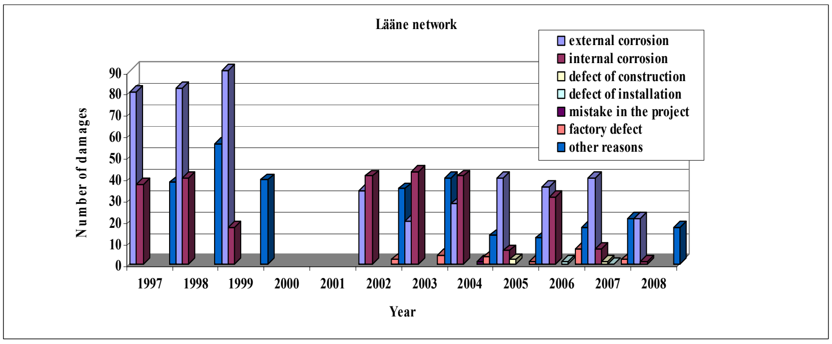


Figure 6.14 The character of damages in Lääne network

The analysis of damages

In figure 6.11 the statistics of a network damages distribution on middle age is given. The most critical is the age of 25–40 years (are constructed in 1970–85). Most of all damages were in networks constructed in 1980–85 years.

In figure 6.12 the statistics of damages falling on one kilometre of a network is resulted. Most of all damages was in 1997–99 and after that there was a gradual reduction in quantity of damages (by 2007 quantity of damages has decreased in 6 times in comparison with 1998).

In figure 6.13 the statistics of damages places on elements of a network is resulted: armature, compensator, construction, and pipes. Most of all damages were on pipes. During 1997–2003 years were many problems with armature and compensators, after 2003 the quantity of damages to these elements has considerably decreased. The most part of armature is already replaced with today, but old axial compensators of thermal lengthening demand replacement. The most part of damages has fallen to 1997–99 years.

In figure 6.14 the reasons of damages are resulted. In Mustamäe area (part of Lääne area) the significant part of damages is caused by external corrosion of pipes. One of the reasons causing external corrosion is the damaged drainage that causes flooding of underground channels by subsoil waters. Thermal insulation of pipes becomes wet and heat losses increase. In Lääne area the length of flooded sites makes 5 km.

Quantity of damages caused by internal corrosion is also high. The reason of this is earlier used system with open hot water supply. The nearest years the share of damages caused by internal corrosion will increase even more. From table 6.4 received according to experiments carried out since 1960 it is visible that in Mustamäe networks thickness of metal eaten by internal corrosion makes ~5 mm and it means that a resource of the oldest pipes will be fast completely is exhausted.

6.2.3. Kesklinna district heating area

The present condition

In Kesklinn area construction of a network has begun in 1959 year. In the beginning the heat supply was carried out by Tallinna Soojuselektrijaam heat and power station and then from boiler-house Ülemiste.

The district heating system of Kesklinn area is the oldest in from all heating systems of Tallinn. Middle age of a network of Kesklinn area makes 25 years.

All length of a district heating network of Kesklinn area is equalled ~76 km that makes ~19 % from total length of all district heating networks of Tallinn.

Through Kesklinn area it runs two main pipelines with diameters DN400–900: Ülemiste and Gonsiori. The total volume of Kesklinn district heating system is equalled ~10362 m^3 that makes ~12 % from the total volume of all district heating networks of Tallinn.

As a lining type networks are distributed as follows: in the underground channel ~ 43,7 km (~57%), in houses cellars ~6,1 km, underground preinsulated pipes ~25,1 km, an air lining ~1,1 km (2%).

The length of the main pipelines with diameters DN400–900 makes ~13,8 km. The share of the main pipelines from the total length of Kesklinn area networks makes ~18,1%. Relative heat losses of Kesklinn network are within the limits of 15...18 % (in 2008 year were ~61 GWh, ~15%). In comparison with other areas relative heat losses is less, the reason for this are the bigger loading of a network, pipes are not oversized, enough big share of the preinsulated pipes.

In Kesklinna network there are 154 section latches and 1139 latches on branches, totally 1293 latches and 441 pieces (~34 %) of them is old latches still soviet times, also require replacement.

The quantity of thermal lengthening compensators makes 430 pieces from which 364 (~85%) pieces (~81 %) these are old axial compensators which resource by today's time is already settled.

Investments

In figure 6.15 lengths of the repaired sites on years are presented. Since the end of 1980 and till today stage-by-stage reconstruction of Kesklinn area networks was carried out.

Basically investments have been directed on increase in reliability and reduction of quantity and duration of faults in a heat supply. It has been much invested in section latches armature. For last 10 years ~15,7 km of district heating pipelines have been replaced that makes ~17 %.

In the nearest five years the most part of investments it is planned in replacement of old axial thermal lengthening compensators. Also it is necessary to pay the big attention to replacement of pipes which age already has stepped for 50 years. In the central part of cities network often lining in places with the limited access and emergency repair can be very complicated.

As a priority at planning repair of networks was reliability of a heat supply till today's time it was not given attention to replacement and improvement of thermal insulation of pipes. Heat losses through old thermal insulation of pipes are very big. In Kesklinn area there are many old pipelines isolated by asbestos. It is necessary to replace asbestoses insulation first of all at pipelines running in buildings cellars.

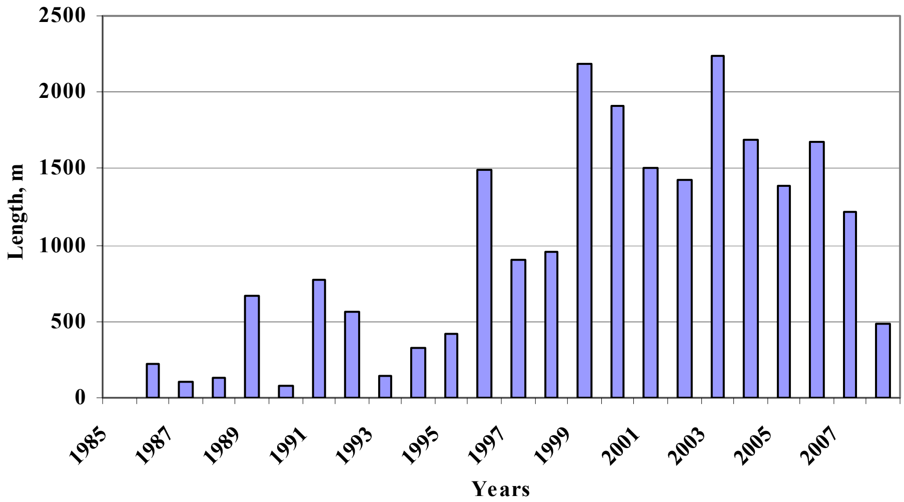


Figure 6.15 Length of the replaced pipelines on years in Kesklinn area network

At the moment the length of constantly flooded networks makes 1043 m and 1540 m of networks are periodically flooded, and totally is flooded 2583 m.

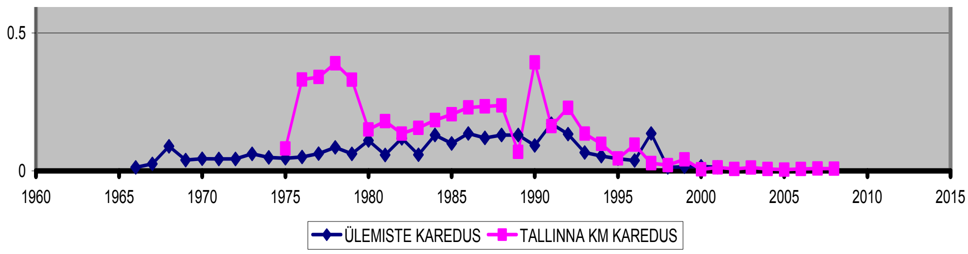


Figure 6.16 Average indices of water rigidity [mg-ekv/l] in Kesklinn network

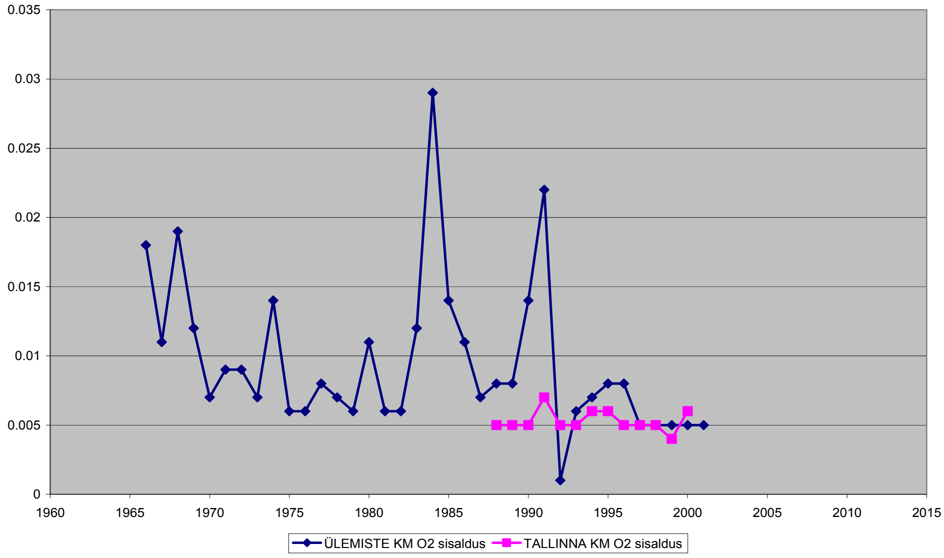


Figure 6.17 The average contents of oxygen in Kesklinn networks water [mg/l]

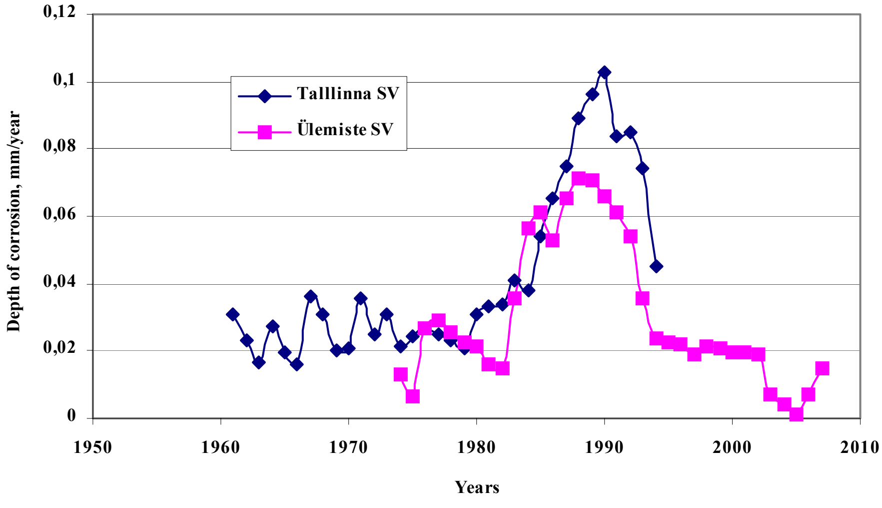


Figure 6.18 Depth of pipes internal corrosion [mm/year] in Tallinn and Ülemiste networks

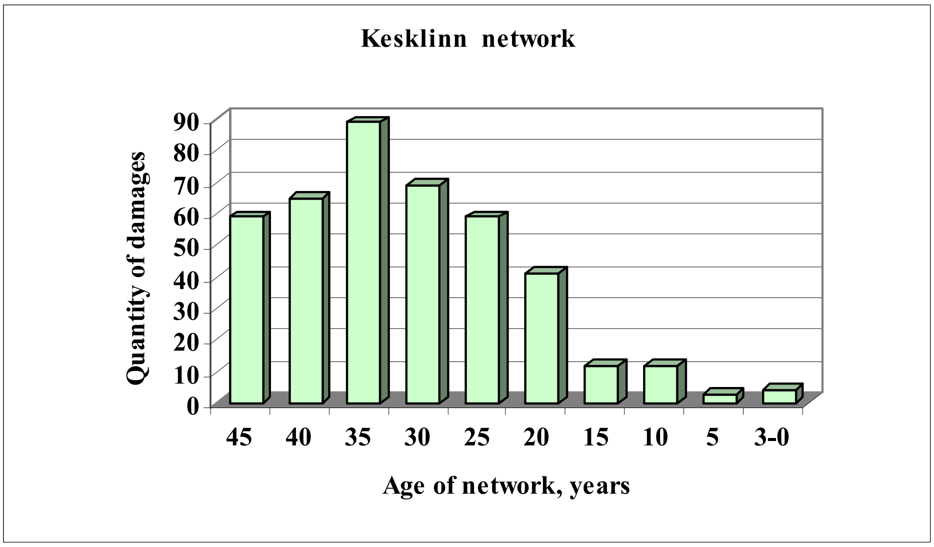


Figure 6.19 Distribution of damages in Lääne district heating network on middle age of a networks sites

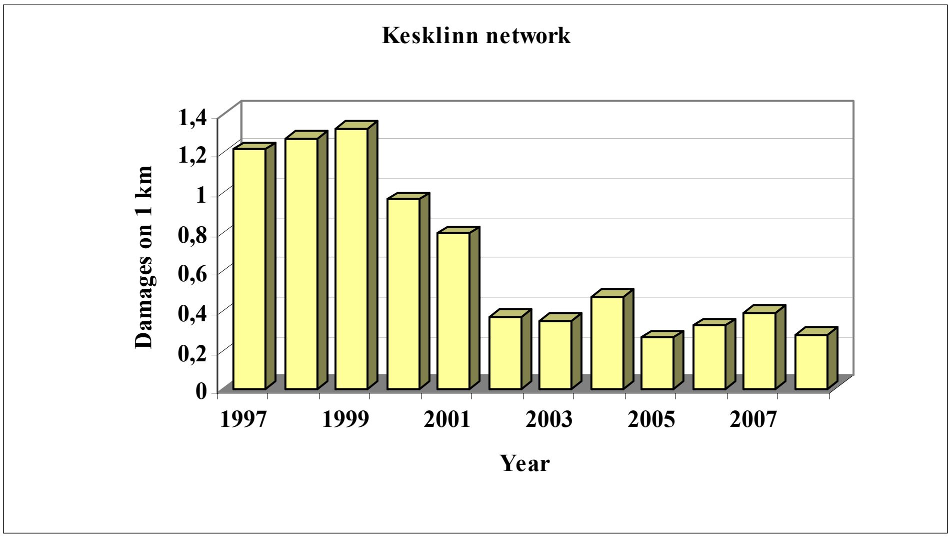


Figure 6.20 Statistics of damages quantity on one kilometre in Kesklinn network

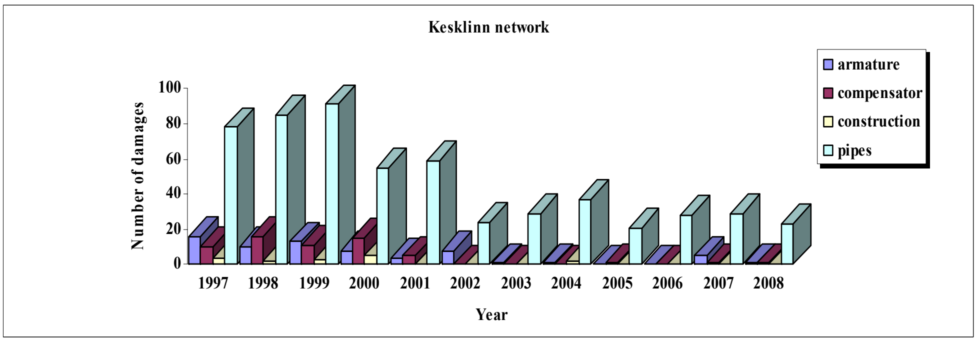


Figure 6.21 The place of damages on elements of a Kesklinn network

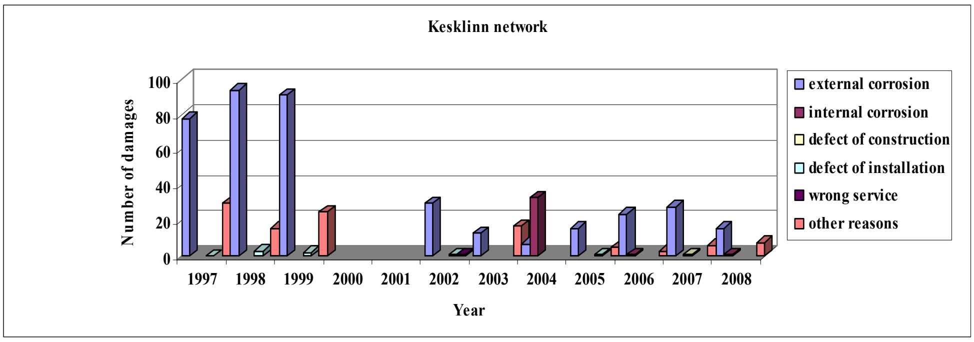


Figure 6.22 The character of damages in Kesklinn network

The analysis of damages

In figure 6.19 lengths of the repaired sites in Kesklinn network on years are presented. The most critical age is 25–50 years (are constructed in 1960–85). Most of all damages (89) were in pipelines constructed in 1970–75 years.

In figure 6.20 the statistics of damages falling on one kilometre of a network is resulted. Most of all damages was in 1997–99 and after that there was a strong reduction in quantity of damages (since 2002 quantity of damages has decreased more than 4 times).

In figure 6.21 the statistics of damages places on elements of a network is resulted: armature, compensators, construction, and pipes. Most of all damages were on pipes and then on armature and on compensators. Damages of armature and compensators basically are liquidated during 1997–2002 years. However the most part of compensators and locking armature still old and also require replacement.

In figure 6.22 the reasons of damages are resulted. In Kesklinn area the significant part of damages is caused by external corrosion of pipes. One of the reasons causing external corrosion is the damaged drainage that causes flooding of underground channels by subsoil waters. Thermal insulation of pipes becomes wet and heat losses increase. In Kesklinn area the length of flooded sites makes more than 1,5 km. Networks of area Kesklinn are much more close to a sea level in comparison with networks of other areas and subsoil waters can easily get in the channel. Old networks of an underground channel lining will expediently replace with completely tight preinsulated pipes.

The second principal cause of damages is internal corrosion. In 2004 many pipes damaged by internal corrosion were revealed. Damages of pipes caused by internal corrosion can come to light at any moment. At the same time in these networks was not big problems with quality of water preparation and theoretically big problems with internal corrosion should not be (figures 6.16 and 6.17 and table 6.3).

Except for this damages caused by defects of installation, defects of construction, factory defects, improper maintenance and other reasons have been registered.

6.3 Conclusions of the chapter

Further the basic supervision and conclusions according to damages of district heating systems in Tallinn are given:

1). From the analysis of damages statistics of the Tallinn district heating networks it is visible that in the most critical condition there are networks in the age of 20-25 years (are constructed in 1980–90 years). It speaks about poor quality of materials and constructions characteristic to this time.

Efficiency of thermal insulation of old networks leaves much to be desired. In table 6.2 normative heat transfer coefficients on one meter of a pipe for old and new pipelines are resulted. Apparently from table 6.2, even in an ideal case, efficiency of old thermal insulation considerably below what at the standard preinsulated pipes.

The basic quantity of damages happens with pipes, the locking armature, compensators and construction mistakes follows.

The oldest compensators of thermal lengthening work since 1959 year. The resource of axial compensators makes no more than 30 years and for today is already exhausted, the probability of failures sharply increases. For today 84 % of all compensators is a subject to replacement. As the part of old locking armature is a subject to replacement: in Lasnamäe area – 82%, in Kesklinn area – 39%, in Lääne area – 24%. Service life of armature has passed over 25 years.

2). The most part of pipes damages is caused by external corrosion. In Kesklinn and Lääne (Mustamäe area) networks often there are damages also caused by internal corrosion. Internal corrosion is the most serious problem in Lääne network where the open system of hot water supply earlier was used.

In figure 6.23 dynamics of pipes internal corrosion since 1960 is resulted Total corrosion depth from the moment of networks construction makes in Mustamäe (Lääne area) network – 5,42 mm, in Kadaka network (Lääne area) – 2,17 mm, in

Karjama network (Lääne area) – 1,46 mm, in Tallinn network (Kesklinn area) – 1,42 mm, in Ülemiste network (Kesklinn area) - 1,03 mm.

Quality of network and additional water in current of last 10 years is maintained at a good level. Since 2003 quality of network water watch according to the quality standard ISO 9001.

Defects of installation, mistake of designing and defects of elements produced at a factory cause damages to much smaller degree.

The reasons of occurrence of external corrosion are a subject to the further detailed studying. External corrosion can be caused both flooding of channels and electric vortical currents near to a cable.

For today it is precisely known that on a regular basis and periodically 8 km of underground networks in a channel lining are exposed to flooding.

Last years the quantity of damages in comparison with the end 1990-s years has considerably decreased, especially in Mustamäe (Lääne) and Kesklinn networks.

Hence it is possible to draw a conclusion that reliability in general has improved. One important reason of damages reduction is that in last years network have essentially reduced pressure. The network works on a stable temperature mode, reliability of heat sources is essentially improved, the quantity of the equipment emergency stops has decreased that is forces arising in networks pipes owing to sharp fluctuations of the heat-carrier temperature have decreased.

Not looking that recently the quantity of a network damages has considerably decreased for that middle age of a network remains high enough and process of ageing proceeds. Such tendency of damages reduction to long-term prospect can change and during the certain moment the quantity of damages can increase in steps:

a). From the analysis of damages statistics it is not visible that middle age of pipelines can be unique criterion at an estimation of a network reliability, however it is an essential parameter specifying that the resource of the pipeline and its elements comes to an end and it is possible to wait for growth of damages quantity.

b). Owing to the big age, the resource will be exhausted first of all at pipelines and their elements of smaller diameters due to smaller thickness of a wall. At pipelines of bigger diameter the resource under the same conditions of operation will be longer due to bigger wall thickness.

c). At increase in age of a network the probability of defects occurrence increases first of all in the weakest parts: sites working in adverse weather conditions (soil and rainwaters get in channels), compensators of thermal lengthening, armature.

d). For reduction of damages occurrence probability connected with the networks age, the volume of the repaired sites should be at least such that process of ageing was slowed down also middle age stabilized on the certain mark. For last 10 years rate of old pipelines replacement averaged 3.8 kilometres a year. For maintenance of a networks middle age at least at a former level, rate of old pipelines replacement should will increase at least in 3 times.

3). Places with the biggest quantity of damages are noted on a networks map by red colour and from there it is visible that there are certain problem areas with the increased concentration of damages.

4). For an estimation of networks reliability it is possible to consider as the basic indicator quantity of damages falling on 1 kilometre of a network.

Now full replacement of the pipelines damaged by corrosion carried out only on the preinsulated pipes. In Lasnamäe area the biggest quantity of damages falling on one kilometre of a network reached 0,34 and by 2008 has decreased up to 0,13. In Lääne (Mustamäe) area the biggest quantity of damages falling on one kilometre of a network reached 0,83 and by 2008 has decreased up to 0,24. In Kesklinn area the biggest quantity of damages falling on one kilometre of a network reached 0,96 and by 2008 has decreased up to 0,27. The biggest reduction in 72 % was in Kesklinn network area. The general reduction of damages on all networks of Tallinn for the period with 1999 for 2008 has made 68 %.

The second indicator can be a percentage part of the replaced sites of a network in relation to all networks length (table 6.3).

Data on replacement of old pipelines in Tallinn networks are resulted in table 6.3. Lengths of the replaced sites are resulted on all diameters. The length of district heating networks in Tallinn on years of construction is given on the figure 6.24.

Table 6.2 The normative heat transfer coefficients on one meter of a pipe for old and new underground pipelines

DN	Preinsulated pipes			Old pipes in channel	
	D_{pipe}/D_{isol}	Thickness of insulation, mm	K, W/(mK)	PV/TV thickness of insulation, mm	K, W/(mK)
1000	1016/1200 LR-1	92	1,0	80/40	4,932
800	813/1000 WTS 2P	93,5	0,828	80/50	3,551
600	610/900 LR-2	145	0,464	80/50	3,063
500	508/800 LR-2	146	0,398	80/40	2,672
400	406,4/630 LR-2	111,8	0,407	80/40	2,237

Table 6.3 Length of the pipes replaced sites in district heating networks of Tallinn.

Diameter of a pipe	Lääne	Kesklinn	Lasnamäe	Totally
DN	Length, m			
32	292	39,5	49,0	302,6
40	1020	455,7	28	972,0
50	3942	1846,1	584	4669,1
65	5053	912,2	644,5	5583,6
80	6564	1967	616,8	7958,0
100	6822	1700,2	645,9	7994,4
125	4860	1299,2	662	5260,0
150	4804	2310,2	971,7	8455,4
200	3235	1736,7	415	5641,6
250	2346	1131,4	127,6	3752,4
300	2818	3304	137,7	6472,8
350	65	41,7	0	121,6
400	4240	2353,1	0	3507,1
500	1563	650	0	2637,5
600	2813	1265,2	0	5262,2
800	0	1237	0	15,0
900	0	236	0	220,0
1200	0	0	142,1	142,1
Totally, m	50 437	22 485	5 024	77 946
The replaced sites totally – 77 946 m				
Total length of pipelines, m	161 650	91 983	140 420	394 053
Share of the replaced pipes, %	31,2	24,4	3,6	19,8

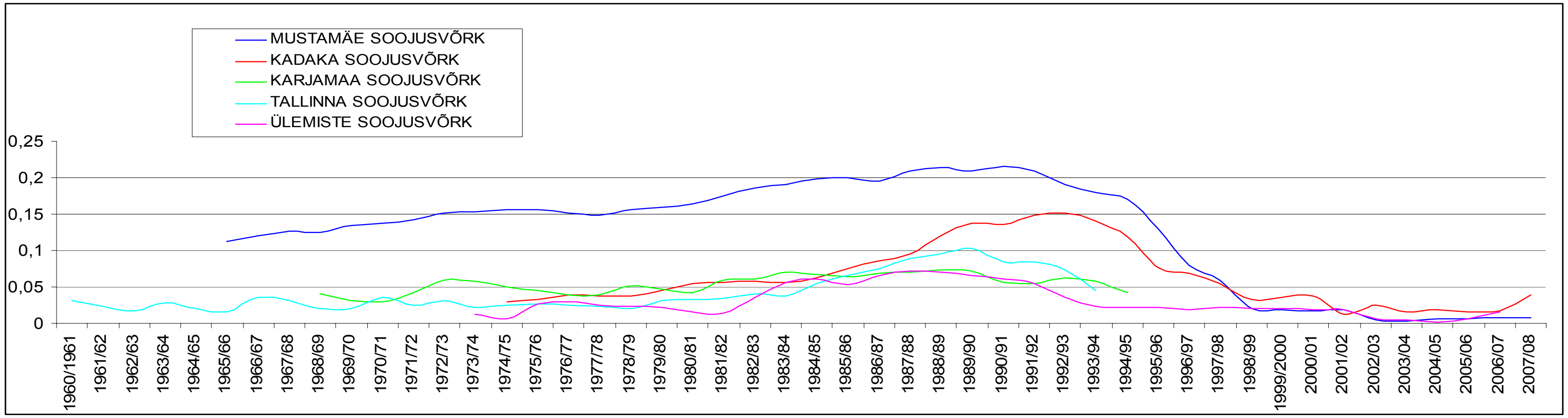


Figure 6.23 Internal corrosion in Mustamäe, Kadaka, Karjamaa, Tallinna and Ülemiste district heating networks in period 1961-2000 years, mm/year

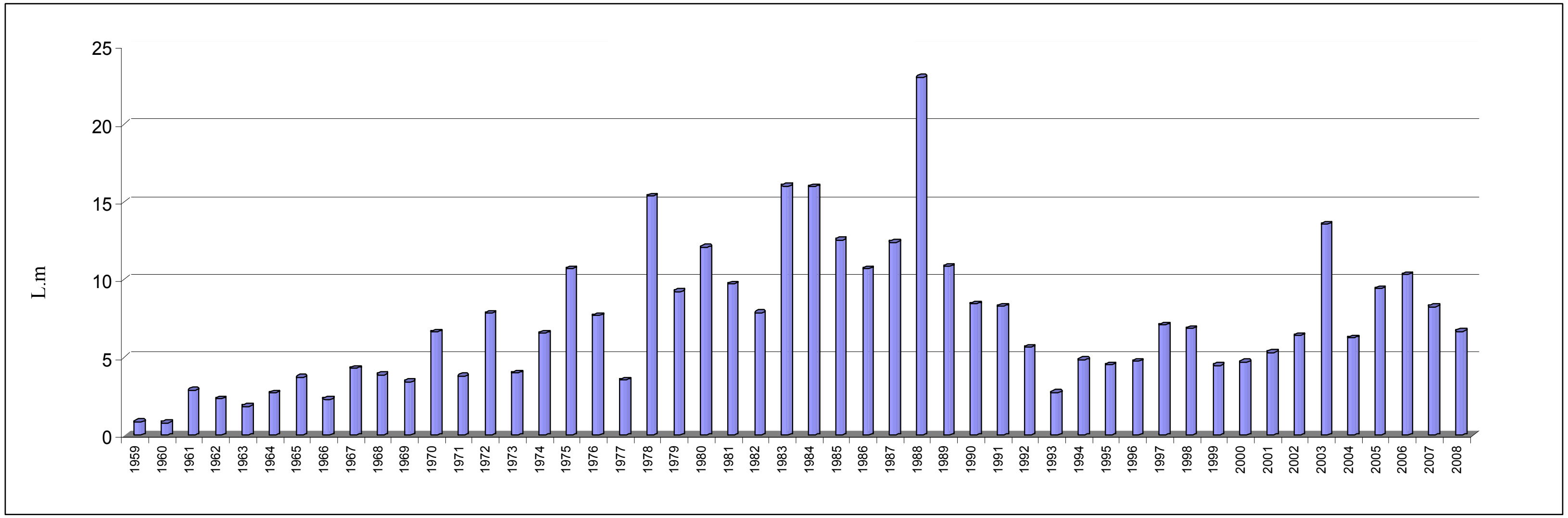


Figure 6.24 Length of district heating networks in Tallinn on years of construction

7 GENERAL CONCLUSIONS

1. The main characteristic parameters of the Estonian district heating networks and their difference from the optimal values was estimated. More than twenty Estonian district heating systems with small, average and big loading have been considered and analysed. District heating systems with annual thermal loading from less than 5000 MWh to over 100000 MWh have been considered.
2. The examples of new pipelines economic optimization have been presented in the given work. The Estonian old non-optimized district heating networks have been compared with new optimized networks. Old networks efficiency increasing potential has been found. The developed methodology on optimization of old district heating systems, in difference from optimization models developed in Denmark, Sweden, Finland and other western countries, allows to consider much more technical features peculiar to old Estonian district heating systems, such as various types of a network pipes lining (a underground network in the concrete channel, an air network), various heat insulation materials (old glass wool, stone wool, asbestos), change in properties of heat insulation materials during the time, various temperature modes of a network, various hydraulic modes of a network, various types of pipes, thermal expansion compensators, armature, changes in a pipes roughness.
3. The detailed estimation of efficiency of thermal insulation of several tens Estonian networks has been carried out by means of the networks thermal model developed in given work. The valid data on thermal insulation efficiency of old networks have been obtained and the heat losses of old networks where the actual data on heat losses are absent could be determined precisely enough on the basis of the obtained data.
4. During the research it has been found, that the value of the heat conductivity coefficient strongly depends on the season, to be more precise on the humidity. During the rainy spring and autumn periods, in the winter and in the spring at snow thawing the coefficient of heat conductivity of insulation strongly increases due to humidity increase. The results of the investigations have shown, that heat transfer coefficient of pipes in old underground concrete ducts may significantly increase in rainy season up to 1,7 – 3 times in comparison with dry season. The average increase in a heat transfer coefficient in old networks amounts two times. Efficiency of heat insulation for typical Estonian networks, which is estimated by the overall heat transfer coefficient, is 2 – 3 times less than the efficiency of the ordinary modern Nordic networks. For example the overall heat transfer coefficient of the totally renovated network in Orissare is about 0,9 – 1,0 $W/(m^2K)$, and it is in the same range that in modern Nordic networks.
5. The analysis of hydraulic modes of networks with different capacities has been performed in the given research. The hydraulic model has been made for each considered network. For calculations real thermal loadings have been used. Calculations have been carried out both for winter loading at temperature of

external air $-22^{o}C$ degree, and for summer loading when there is only a loading of hot water supply. As a result of hydraulic calculations the real velocities of the heat-carrier and specific hydraulic resistance for all sections of a network have been obtained. On the valid thermal loadings of sections, optimum internal diameters of pipes have been found. The results of calculations have shown that the diameters of pipes in Tallinn and also in the Estonian local district heating networks are over-dimensioned.

6. Pumping costs in old networks with over-dimensioned pipes are much lower than in new optimized networks. At the same time heat losses in old networks with over-dimensioned and badly insulated pipes are times higher. The reduction in heat losses leads to the great decreasing of total DH distribution cost. Despite of smaller cost of the heat-carrier pumping, the total cost of heat distribution in old networks is higher, than in new networks, due to over-dimensioned diameters and considerably poor thermal insulation.
7. At reconstruction of separate sections of old district heating systems it is necessary to choose pipes with optimum internal diameter taking into account the actual flow of the heat-carrier. Of course, the hydraulic mode of the old network should be considered, namely is it enough pressure head for required flow rate of the heat-carrier with reduced diameter of pipe and if it is not it is reasonable to install additional pump station.
8. On the basis of the data received during optimization, the equations and tables for determination of optimum diameter, specific pressure drop and velocity of the heat-carrier have been obtained for different temperature modes of a network.
9. The results of analysis have shown that heat losses decreasing potential is very big. After optimization and total renovation of old networks, heat losses could decrease up to 2–4 times and especially big decreasing, up to 5–6 times, could be observed after old 4 pipes system replacement by the 2 pipes optimized and well insulated system. After selection of optimal diameters of network pipes, according to consumers real heat demand and total renovation of pipes (replacing by the preinsulated pipes), relative heat losses drastically decreases. Relative heat losses, for example in Tallinn city networks Mustamäe-Õismäe and Kesklinn region decreases from 16–18% to 6%, in Lasnamäe region – from 20–22% to 8%, in Narva network – from 18% to 7–8%, in Võru town network – from 20% to 9%, in Keila town network – from 18–19% to 5%, in Kiviõli town network – from 26% to 8%, and in Viimsi and Haabneeme settlements networks decrease from 21–22% to 5–6% in that case if expansion will proceed, or 10–11% if expansion will not occur and only existing networks will be optimized. Especially big decreasing of heat losses can be in those networks where old 4 pipes system will be replaced by the new optimized 2 pipes system. For example in Haiba settlement network heat losses decreases from 26% to 5%.
10. Recent years a tendency of the overall heat transfer coefficient reduction in the district heating networks of Tallinn and Narva was observed. This reduction is

caused by replacement of old sections of district heating networks with new pre-insulated pipes. Several “wet” sections of the network can significantly increase the value of the heat transfer coefficient. Replacement of these sections could significantly decrease the overall heat transfer coefficient. Also the reliability of heating system increases considerably.

11. On the basis of the networks damages analysis results obtained on an example of Tallinn DH networks, several parameters for the estimation of a networks technical condition have been suggested. The basic parameters are the quantity of damages per 1 kilometre of the network and the relation of the replaced sections of the network to the total length. At present time the full replacement of the pipelines damaged by corrosion is carried out only on the preinsulated pipes. In Lasnamäe area the biggest quantity of damages per 1 kilometre of the network reached 0,34 and by 2008 year has decreased up to 0,13. In Lääne (Mustamäe) area the biggest quantity of damages per 1 kilometre of the network reached 0,83 and by 2008 year has decreased up to 0,24. In Kesklinn area the biggest quantity of damages per 1 kilometre of the network reached 0,96 and by 2008 year has decreased up to 0,27. The biggest reduction in 72 % was in Kesklinn network area. The general reduction of damages on all networks of Tallinn for the period with years 1999 for 2008 has made 68 %.
12. In spite of the considerable decrease of the quantity of a network damages the middle service time of the network remains high enough and process of ageing continues. The tendency of damages reduction to long-term prospect could change due to ageing of the network and as a result rapid increase of damages occurrence.
13. From the analysis of damages statistics it is not visible that middle age of pipelines can be unique criterion at an estimation of a network reliability, however it is an essential parameter specifying that the lifetime of the pipeline and its elements is close to the end and it is possible to wait for growth of damages quantity.
14. In order to reduce the probability of the damages occurrence due to ageing the share of the replaced sections should be at least such high, that allows the middle age of the whole network to remain at the same level. For example in Tallinn DH networks in recent 10 years the average rate of the pipelines replacement amounted 3,8 kilometres a year and in order to maintain the middle age of the network at the present level this rate should be increased at least in 3 times.
15. The received results allow to make proved and economically effective plans of district heating networks reconstruction, to increase the reliability and efficiency of the networks and to decrease the costs of heat distribution. Preservation of district heating systems in working order and their renovation are the basic preconditions for combined heat and power generation, and reduction of fuel consumption and environment pollution.

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KOKKUVÕTE

Kaugküttesüsteemide säilitamine ja korrastamine on põhiliseks eelduseks soojuse ja elektri koostootmiseks, seega ka kütuse kokkuhoiuks ja looduse säästmiseks. Põhisuunad selles küsimuses on toodud Euroopa Liidu valitsuse väljaandes "White Paper on District Heating and District Cooling Solutions in Environmental Perspective" [26]:

"Elektri ja soojuse koostootmine on ainus suurim lahendus, mis võimaldab täita EL-i eesmärki vähendada CO_2 heitmeid 20% võrra ja suurendada taastuvate energiaallikate osakaalu kuni 20%-ni."

Eelnevat arvestades on käesoleva uurimistöö eesmärk uurida põhjalikult ja objektiivselt Eesti suure, väikese ja keskmise soojusvõimsusega kaugküttevõrkude tegelikku seisundit ning leida, kui palju võib paraneda nende efektiivsus peale võrkude täielikku optimeerimist ja rekonstrueerimist ning kui suur on soojusvõrkude efektiivsuse tõstmise potentsiaal. Lisaks sellele on tehtud Tallinna soojusvõrkude vigastuste analüüs ja välja toodud indikatiivsed suurused, mis sobivad kaugküttevõrkude üldise seisukorra hindamiseks.

Töö uudsus seisneb selles, et esmakordselt on välja töötatud metoodika, mis võimaldab vanade soojusvõrkude tegeliku seisundi objektiivset hindamist, efektiivsuse tõstmise potentsiaali väljaselgitamist ja põhjendatud renoveerimisplaani koostamist. Kasutades väljatöötatud metoodikat, on tehtud üle kahekümne vana soojusvõrgu seisundi analüüs ja optimeerimine ning välja toodud nende efektiivsuse tõstmise potentsiaal ja rekonstrueerimistööde järjekord. Metoodika efektiivsust tõestab läbivaadatud ja rekonstrueeritavate soojusvõrkude efektiivsusnäitajate paranemine näiteks Narvas, Tallinnas ja Võrus.

Saadud tulemusi on esitatud ja heaks kiidetud paljudel konverentsidel, näiteks Peterburis – "The 5th Baltic Heat Transfer Conference 19–21 September, 2007 Saint Petersburg, Russia" ja Reykjavikis – "The 11th International Symposium on District Heating and Cooling, August 31 to September 2, 2008 in Reykjavik, ICELAND". Lisaks sellele on uuringute tulemused avaldatud nii Eesti kui ka Leedu Teaduste Akadeemia toimetistes.

Analüüside tegemiseks on uuritud kokku üle kahekümne Eesti suure, väikese ja keskmise soojusvõimsusega kaugkütte soojusvõrgu. Vaatluse all on soojusvõrgud aastase soojuse väljastusega alates <5000 MWh ja lõpetades üle 100000 MWh.

Uuringute käigus iga vaadeldud soojusvõrgu kohta on koostatud nii soojuslikud mudelid soojusisolatsiooni tegeliku seisundi hindamiseks kui ka hüdraulilised mudelid tegelike hüdrauliliste režiimide väljaselgitamiseks. Saadud tulemusi on võrreldud optimaalsetega. Vaadeldud soojusvõrkude torude sisediameetrid on optimeeritud soojuse minimaalse jaotuskulu tagamiseks. Kõik arvutused on tehtud praegustest tegelikest soojuskoormustest lähtuvalt ning hoogsasti arenevate võrkude korral on arvestatud ka soojuskoormuse võimalikku suurenemist.

Iga vaadeldud soojusvõrgu kohta on leitud põhilised suurused, mis iseloomustavad nende praegust efektiivsust, ning on analüüsitud soojusvõrkude efektiivsust mõjutavaid tegureid. Eesti soojusvõrkude efektiivsust on võrreldud kaasaegsete soojusvõrkude efektiivsusega. Suureks praktiliseks saavutuseks on see, et kindlaks on tehtud vanade võrkude korrastamisega saavutatav energia kokkuhoiu potentsiaal.

Saadud tulemused võimaldavad koostada vanadele soojusvõrkudele põhjendatuid ja majanduslikult efektiivseid rekonstrueerimise kavasid, mille rakendamisel vanade võrkude efektiivsus ja töökindlus oluliselt tõusevad ning säilib võimalus elektri ja soojuse koostootmiseks, seega ka kütuse kokkuhoiuks.

ABSTRACT

Preservation of district heating systems in working order is the basic precondition for combined heat and power generation, accordingly for fuel consumption and environment pollution reduction. The basic directions on this question are resulted in the edition of the European union "White Paper on District Heating and District Cooling Solutions in Environmental Perspective" [26]:

"Promoting combined heat and power generation (CHP) is the single biggest solution to the EU target of reducing CO_2 emissions by 20% and increasing the renewable share of energy to 20%."

Considering the aforesaid, the purpose of the given research work is detailed and objective estimation of the present condition of the Estonian district heating networks, and also determine how much can their efficiency increase after carrying out of full optimization and reconstruction and how big is efficiency increasing potential. Except for this, the analysis of damages statistics of district heating systems of Tallinn city is made and indicative parameters allowing to define a real condition of DH networks are developed.

Novelty of work consists in the creating of the methodology allowing objectively to estimate the valid condition of old district heating systems, estimate potential of their efficiency increasing and to develop the proved plan of reconstruction of a district heating system has been developed for the first time.

Using the developed methodology the analysis of a condition of more than twenty old district heating systems is made, their optimization is made and the order of their reconstruction is determined. Efficiency of the methodology was confirmed by improvement of parameters of the considered and reconstructed district heating systems, for example in Narva, Tallinn and Võru cities.

The received results are presented and approved at many international conferences and also are published in the scientific editions.

At carrying out of analyses it is considered more than twenty Estonian district heating systems with small, average and big loading. District heating systems with annual thermal loading from less than 5000 MWh to over 100000 MWh have been considered.

The thermal models, which are necessary for an estimation of the valid efficiency of thermal insulation, and the hydraulic models, which are necessary for definition of hydraulic regimes, have been made in the present work. The received results have been compared to optimum values. Diameters of pipes of the considered district heating systems have been optimized for minimization of heat distribution costs. All calculations have been made proceeding from the valid heat loadings and considering possible increase in loading at expansion of district heating networks.

For each considered district heating system key parameters defining their valid efficiency have been found, and also the analysis of factors influencing the district heating systems efficiency has been made. Efficiency of the Estonian district

heating systems has been compared to efficiency of modern Nordic district heating systems. The definition of the major characteristic parameters of district heating systems after full optimization and reconstruction has been performed. Greater practical achievement of the given work is that the possible potential of the energy savings received at reconstruction of old heating systems is certain, and also economically proved plans of reconstruction of district heating systems are developed.

The received results allow to make economically proved plans of district heating systems reconstruction and as a result of their introductions efficiency and reliability of old district heating systems will essentially increase, and also to be kept an opportunity of combined heat and power generation with lower fuel consumption. By results of researches plans on renovation of the district heating systems are made and successfully introduced, as one very successful example the plan of reconstruction of district heating system of the Narva city can serve, composed in 2002 and introduced till today, as a result efficiency and reliability of this district heating system has essentially raised.

APPENDIX 1

ELULOOKIRJELDUS

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Tallinna 6. Keskkool	1988	keskharidus

Teenistuskäik

Töötamise aeg	Organisatsiooni nimetus	Ametikoht
2000–käesoleva ajani	Tallinna Tehnikaülikool, Soojustehnika Instituut	lektor
1994–2000	Tallinna Tehnikaülikool, Soojustehnika Instituut	teadur

Keelteoskus

Keel	Tase
Inglise keel	hea
Eesti keel	väga hea
Vene keel	väga hea
Rootsi keel	algtase

Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
1993–1994	Magistriõpingud ja teadusalane tegevus Chalmers University of Technology's, Göteborg, Rootsi
1995	Royal Tehnikainstituudi (Stockholm) ja Riia Tehnikaülikooli organiseeritud täienduskursus "Energy Efficiency"

1995	Royal Tehnikainstituudi (Stockholm) ja Riia Tehnikaülikooli organiseeritud täienduskursus “Modern power system control and operation”
1998	“The Nordic Council of Minister`s Training Course for Energy Experts in the Baltik States Programme for Cooperation in Energy- efficient Economic Development” täienduskoolitus
2000	Technical University of Denmark, Department of Energy Engineering, Nordic Energy Research Programme Process Integration & Multi-source Heating Systems, Course in Control of Heating and Air Conditioning Systems in Buildings
2001	Nordic Energy Research program, Process Integration Course, Riia, Läti
2005	Eesti Jõujaamade ja Kaugkütte Ühingu pädevustunnistus eelisoleeritud kaugkütte torusüsteemide projekteerimise ja tehnilise järelevalve koolitusprogrammi eduka läbimise kohta

Teadustöö põhisuunad Kaugkütte ning soojuse ja elektri koostootmise efektiivsuse tõstmine

APPENDIX 2

CURRICULUM VITAE

First name	Aleksandr
Last name	Hlebnikov
Date and place of birth	23.06.1971, Estonia
Citizenship	Estonian
Contact	Kopli 116, 11712 Tallinn, Estonia Telephone: +372 620 39 08; E-mail: ahleb@staff.ttu.ee
Organization	Tallinn University of Technology (TUT), Thermal Engineering Department (TED)
Current position	Lecturer

Education

Educational institution	Year of graduation	Education
Tallinn University of Technology	2000	Master degree
Tallinn University of Technology	1993	Diploma of the engineer
Tallinn Secondary school No. 6	1988	Secondary education

Professional Employment

Period	Organisation	Position
2000–present	Tallinn University of Technology, Thermal Engineering Department	Lecturer
1994–2000	Tallinn University of Technology, Thermal Engineering Department	Researcher

Language skills

Language	Level
English	good
Estonian	very good
Russian	very good
Swedish	basic skills

Training courses

Period	Educational organisation
1993–1994	Postgraduate studies and advanced training at Chalmers University of Technology, Göteborg, Sweden.
1995	Royal Technical Institute (Stockholm) and Riga Technical University training course “Energy Efficiency”

1995	Royal Technical Institute (Stockholm) and Riga Technical University training course “Modern power system control and operation”
1998	“The Nordic Council of Minister`s Training Course for Energy Experts in the Baltik States Programme for Cooperation in Energy- efficient Economic Development” training course
2000	Technical University of Denmark, Department of Energy Engineering, Nordic Energy Research Programme Process Integration & Multi-source Heating Systems, Course in Control of Heating and Air Conditioning Systems in Buildings
2001	Nordic Energy Research program, Process Integration Course, Riga, Latvia
2005	Course of district heating pipelines systems design, Estonian Power and Heat Association

Research Interest Investigations of the efficiency improvement of district heating and combined heat and power generation

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *MECHANICAL AND INSTRUMENTAL ENGINEERING*

1. **Jakob Kübarsepp**. Steel-bonded hardmetals. 1992.
2. **Jakub Kõo**. Determination of residual stresses in coatings & coated parts. 1994.
3. **Mart Tamre**. Tribocharacteristics of journal bearings unlocated axis. 1995.
4. **Paul Kallas**. Abrasive erosion of powder materials. 1996.
5. **Jüri Pirso**. Titanium and chromium carbide based cermets. 1996.
6. **Heinrich Reshetnyak**. Hard metals serviceability in sheet metal forming operations. 1996.
7. **Arvi Kruusing**. Magnetic microdevices and their fabrication methods. 1997.
8. **Roberto Carmona Davila**. Some contributions to the quality control in motor car industry. 1999.
9. **Harri Annuka**. Characterization and application of TiC-based iron alloys bonded cermets. 1999.
10. **Irina Hussainova**. Investigation of particle-wall collision and erosion prediction. 1999.
11. **Edi Kulderknup**. Reliability and uncertainty of quality measurement. 2000.
12. **Vitali Podgurski**. Laser ablation and thermal evaporation of thin films and structures. 2001.
13. **Igor Penkov**. Strength investigation of threaded joints under static and dynamic loading. 2001.
14. **Martin Eerme**. Structural modelling of engineering products and realisation of computer-based environment for product development. 2001.
15. **Toivo Tähemaa**. Assurance of synergy and competitive dependability at non-safety-critical mechatronics systems design. 2002.
16. **Jüri Resev**. Virtual differential as torque distribution control unit in automotive propulsion systems. 2002.
17. **Toomas Pihl**. Powder coatings for abrasive wear. 2002.
18. **Sergei Letunovitš**. Tribology of fine-grained cermets. 2003.
19. **Tatyana Karaulova**. Development of the modelling tool for the analysis of the production process and its entities for the SME. 2004.
20. **Grigori Nekrassov**. Development of an intelligent integrated environment for computer. 2004.
21. **Sergei Zimakov**. Novel wear resistant WC-based thermal sprayed coatings. 2004.
22. **Irina Preis**. Fatigue performance and mechanical reliability of cemented carbides. 2004.
23. **Medhat Hussainov**. Effect of solid particles on turbulence of gas in two-phase flows. 2005.

24. **Frid Kaljas**. Synergy-based approach to design of the interdisciplinary systems. 2005.

25. **Dmitri Neshumayev**. Experimental and numerical investigation of combined heat transfer enhancement technique in gas-heated channels. 2005.

26. **Renno Veinthal**. Characterization and modelling of erosion wear of powder composite materials and coatings. 2005.

27. **Sergei Tisler**. Deposition of solid particles from aerosol flow in laminar flat-plate boundary layer. 2006.

28. **Tauno Otto**. Models for monitoring of technological processes and production systems. 2006.

29. **Maksim Antonov**. Assessment of cermets performance in aggressive media. 2006.

30. **Tatjana Barashkova**. Research of the effect of correlation at the measurement of alternating voltage. 2006.

31. **Jaan Kers**. Recycling of composite plastics. 2006.

32. **Raivo Sell**. Model based mechatronic systems modeling methodology in conceptual design stage. 2007.

33. **Hans Rämmal**. Experimental methods for sound propagation studies in automotive duct systems. 2007.

34. **Meelis Pohlak**. Rapid prototyping of sheet metal components with incremental sheet forming technology. 2007.

35. **Priidu Peetsalu**. Microstructural aspects of thermal sprayed WC-Co coatings and Ni-Cr coated steels. 2007.

36. **Lauri Kollo**. Sinter/HIP technology of TiC-based cermets. 2007.

37. **Andrei Dedov**. Assessment of metal condition and remaining life of in-service power plant components operating at high temperature. 2007.

38. **Fjodor Sergejev**. Investigation of the fatigue mechanics aspects of PM hardmetals and cermets. 2007.

39. **Eduard Ševtšenko**. Intelligent decision support system for the network of collaborative SME-s. 2007.

40. **Rünno Lumiste**. Networks and innovation in machinery and electronics industry and enterprises (Estonian case studies). 2008.

41. **Kristo Karjust**. Integrated product development and production technology of large composite plastic products. 2008.

42. **Mart Saarna**. Fatigue characteristics of PM steels. 2008.

43. **Eduard Kimmari**. Exothermically synthesized B_4C-Al composites for dry sliding. 2008.

44. **Indrek Abiline**. Calibration methods of coating thickness gauges. 2008.

45. **Tiit Hindreus**. Synergy-based approach to quality assurance. 2009.

46. **Karl Raba**. Uncertainty focused product improvement models. 2009.

47. **Riho Tarbe**. Abrasive impact wear: tester, wear and grindability studies. 2009.

48. **Kristjan Juhani**. Reactive sintered chromium and titanium carbide- based cermets. 2009.

49. **Nadežda Dementjeva**. Energy planning model analysis and their adaptability for Estonian energy sector. 2009.

50. **Igor Krupenski**. Numerical simulation of two-phase turbulent flows in ash circulating fluidized bed. 2010.