RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Heat, Gas and Water technology

Deniss PILSCIKOVS
PhD of Doctoral study program „Heat, gas and water technology”

ENERGY EFFICIENCY ANALYSIS FOR OPTIMISATION OF VARIABLE SPEED PUMP OPERATION

Summary of Promotion Thesis

Scientific supervisor
Dr. habil. sc. ing., professor
E.DZELZITIS

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THE PROMOTION THESIS IS NOMINATED FOR SCIENTIFIC DEGREE OF THE DOCTOR OF ENGINEERING SCIENCES IN RIGA TECHNICAL UNIVERSITY

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OFFICIAL OPPONENTS:

Prof., Dr.sc.ing. Boriss Gjunsburgs
Riga Technical University

Prof., Dr.habil.phys. Juris Ekmanis
Latvian Academy of Sciences / Institute of the Physical Energetics

Prof., Dr.habil.sc.ing. Andris Šnīders
Latvia University of Agriculture

CONFIRMATION

I confirm that the given doctoral thesis has been worked out by myself and submitted for nomination for scientific degree of the doctor of engineering sciences in Riga Technical University. The doctoral thesis has not been submitted in any other university for obtaining the scientific degree.

Deniss Pilscikovs…………………………….(Signature)
Date: ………………………

The Promotional Work is written in Latvian with 115 pages, it contains Introduction, 4 Sections, Conclusions, Appendix, and References with 126 units.

ANNOTATION

Pilscikovs D. Energy efficiency analysis for optimization of variable speed pump operation: Ph.D. thesis in engineering science, Riga, RTU, 2014. The paper contains 4 chapters, 115 pp., 25 tables and 74 pictures. References in the paper – overall number are 126.

About 10% of the total electrical energy produced in the world has been consumed by centrifugal pumps and close to 60% of that can be saved up. Depending on the type of hydraulic system and centrifugal pump application, it is possible to define a number of criteria to be taken into account during the optimization activities of variable speed pump operation.

The objective of the thesis is to develop the criteria of the energy efficiency analysis for further optimization of operation of variable speed centrifugal pumps in public water supply and district heating systems.

The main tasks of the research are:

- To study aspects of operation and design of variable speed centrifugal pumps.
- To determine statistically and experimentally check the energy efficiency improvement potential of variable speed pump operation, if the proportional pressure control mode is applied instead of the constant (differential) pressure control mode.
- To calculate statistically the reduction potential of water leakage in network, if the proportional pressure control is applied instead of the constant (dif.) pressure control.
- To determine statistically and experimentally check the efficiency change of variable speed pumps according the duty point deviation from pump nominal head.
- To define statistically and experimentally check pump efficiency at the best efficiency point of inline single-stage and multi-stage centrifugal pumps as well as end-suction single-stage centrifugal pumps according to flow and head values.

Developed criteria of the energy efficiency analysis can be used for water supply and heating systems as:

- Recommendations for designers selecting centrifugal pump technology for calculated duty points.
- Initial assessment planning the energy efficiency improvement activities: pump audit, reconstruction of pumping system, reduction of water leakage.
- Educational tool for technical schools studying centrifugal pumps' and/or the overall system energy efficiency issues.

The research results regarding the promotion thesis have been reported in 7 scientific conferences, and they are represented in 10 international publications.

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INTRODUCTION

Topicality

With the increase of energy costs worldwide, more attention is paid to energy efficiency measures. More than 10% of the world's total production of the electric energy is consumed in centrifugal pump systems, and 60% of them can be saved. Around 16.8 PWh of electricity has been consumed in the world in 2009, and about 6 % of it can be saved using a variable speed pump technology with the right pump control mode.

Along with saving energy, the water leakage can also be reduced in the existing networks. Public water supply systems are described with the water leakage rate of 45 million m^3/day in developing countries around the world, which would be enough to provide water to about 200 million people.

Latvian scientists: E. Dzelzitis, B. Gjunsburgs, E. Tilgalis, V. Ledins, R. Neilands, D. Turlajs, A. Sniders, D. Rusovs, K. Silke, V. Skards, R. Trops, A. Mezs etc. previously studied issues related to the pump types, its selection and use, as well as theoretical control modes. Foreign scholars: B. Leznovs, A. Marchi, D. Kaya, K. Yigit, N. Mehzad, Khin Cho Thin, De Paola, A. Moreno, P. Planells, Zhenjun Ma etc. thoroughly studied variable-speed pump performance optimization issues as well as pressure and leakage interactions.

Depending on the hydraulic system type and centrifugal pump application, it is possible to define a range of engineering criteria, which should be taken into account during the optimization of variable speed pumps’ operation.

Among these criteria are as follows: use of the proportional pressure control mode instead of the constant (differential) pressure control mode for variable speed centrifugal pumps, the duty point position and its deviation from the head value of the best efficiency point (BEP) of variable-speed centrifugal pumps, centrifugal pump design types.

It is important to select a pump technology solution with the highest possible efficiency and energy efficient pump control mode as well. All these criteria should be focused on the improvement of the energy efficiency of water supply and heating systems.

Objective and tasks

The objective of the thesis is to develop the criteria of the energy efficiency analysis for further optimization of operation of variable speed centrifugal pumps in public water supply and district heating systems.

The main tasks of the research are:

- To study aspects of operation and design of variable speed centrifugal pumps.
- To determine statistically and experimentally check the energy efficiency improvement potential of variable speed pump operation, if the proportional pressure control mode is applied instead of the constant (differential) pressure control mode.
- To calculate statistically the reduction potential of water leakage in network, if the proportional pressure control is applied instead of the constant (differential) pressure control.
- To determine statistically and experimentally check the efficiency change of variable speed pumps according the duty point deviation from pump nominal head.
- To define statistically and experimentally check the efficiency ratio at the best efficiency point of inline single-stage and multi-stage centrifugal pumps as well as end-suction single-stage centrifugal pumps according to flow and head value.

Scientific novelty

The criteria of the energy efficiency analysis have been developed for optimization of variable speed pump operation in centralized water supply and heating systems.

- The mathematical relationship has been acquired between the proportional pressure control use instead of the constant pressure control for variable speed pumps and the improvement of the energy efficiency (energy / water leakage reduction).
- The mathematical relationship has been derived between the efficiency change of variable speed pumps and duty point deviation from the nominal pump head.
- The comparison of the highest efficiency levels has been acquired for in-line multistage and end-suction single-stage centrifugal pumps in public water supply systems (Q_{nom}=10÷140 m3/h at H_{nom}=30÷55 m), and for in-line and end-suction

single-stage centrifugal pumps in district heating systems (Qnom=50÷770 m3/h at Hnom=10÷60 m).

Practical application

These energy analysis criteria can be used as follows:

- Recommendations for designers selecting centrifugal pump technology for calculated duty point in public water supply and district heating systems.
- Recommendations of the energy efficiency improvement for pump operation in public water supply and district heating systems by realizing designing or reconstruction works.
- Study materials in technical schools studying energy issues of centrifugal pump and / or complete hydraulic system.

Each criterion can be applied to a particular engineering system.

- The proportional pressure control mode instead of the constant pressure control:
  - First / second / third stage pressure boosting pumps in water supply systems.
  - Network pumps in heating systems.
- The efficiency change of variable speed pumps according to duty point deviation from the head value of the best efficiency point (BEP):
  - Flow filter pump in heating systems.
- Efficiency comparison in the best efficiency points (BEP) of various pump designs:
  - First / second stage pressure boosting pump for operation with water tower in water supply systems.
  - Filter flushing pumps in water supply systems.

1. SELECTION OF VARIABLE SPEED CENTRIFUGAL PUMP TECHNOLOGY AND CONTROL MODE FOR PUBLIC WATER SUPPLY AND DISTRICT HEATING SYSTEMS

There are a number of variable speed centrifugal pump control modes:

- the constant pressure control,
- the constant differential pressure control,
- the measured proportional pressure control,
- the calculated proportional pressure control,
- the constant curve control etc.

It is not always used the most energy efficient pump control mode in water supply and heating system. Therefore, it is very important to make an evaluation of the potential energy savings in engineering systems where the pump control modes are used.

There are a lot of centrifugal pump designs, which are used in public water supply and district heating systems:

- end-suction pumps,
- in-line pumps,
- horizontal pumps,
- vertical pumps,
- single-stage pump,
- multistage pumps etc.

Centrifugal pumps are available in various design performance for installation in water supply and heating systems. Each pump design is characterized by its own characteristics, advantages and disadvantages, so it is very important to select the right centrifugal pump design for corresponding engineering system.

A number of studies have been performed on a constant-speed and variable-speed centrifugal pumps and its operation in engineering systems. Among the researches of centrifugal pump technology the main directions are as follows:

- Efficiency evaluation of variable speed pump operation in water supply systems with a focus on the efficiency values at partial loads and reduced speed.
- Multi-parameter real measurements of pump systems and optimization proposals for a given pumping system.
- Energy efficiency and system reliability analysis using variable and constant speed pumping comparison.
- Performance analysis of single-stage end-suction centrifugal pump.
- Pressure and water leakage interaction analysis.
- Theoretical overview of variable speed pumps control modes.
- Different types of pumps, its application and calculations.

This study combines the calculation model based on the theoretical load profiles with real experimental tests, resulting in proposed criteria of the energy efficiency analysis. These criteria may be suitable for optimization of variable speed centrifugal pumps operation in water supply and heating systems.

Constant (differential) pressure control mode is characterized by high energy consumption in public water supply and district heating systems.

Proportional pressure control method is closely related to consumed energy and overall water leakage reduction in centralized systems. The higher deviation of the proportional pressure control curve is the greater energy savings and lower water leakage rate is in centralized water supply and heating systems. (Table 1.1).

Table 1.1

Energy consumption of control modes of variable speed centrifugal pumps

($\Delta Z_{11}<\Delta Z_{21}<\Delta Z_{31}<\Delta Z_{41}$, $\Delta Z_{12}<\Delta Z_{22}<\Delta Z_{32}<\Delta Z_{42}$, $\Delta Z_{13}<\Delta Z_{23}<\Delta Z_{33}<\Delta Z_{43}$), kWh/year

Flow component (Q_x/Q_n), % / Pump control mode	100	75	50	25
Constant (differential) pressure control mode	Z	Z-ΔZ_{11}	Z-ΔZ_{12}	Z-ΔZ_{13}
Proportional pressure control mode: linear deviation	Z	Z-ΔZ_{21}	Z-ΔZ_{22}	Z-ΔZ_{23}
Proportional pressure control mode: square deviation	Z	Z-ΔZ_{31}	Z-ΔZ_{32}	Z-ΔZ_{33}
Temperature control mode	Z	Z-ΔZ_{41}	Z-ΔZ_{42}	Z-ΔZ_{43}

There are two variable speed pump control modes for network pumps: the constant pressure control mode and the proportional pressure control mode (Fig. 1.1), which is used in public water supply and district heating systems.

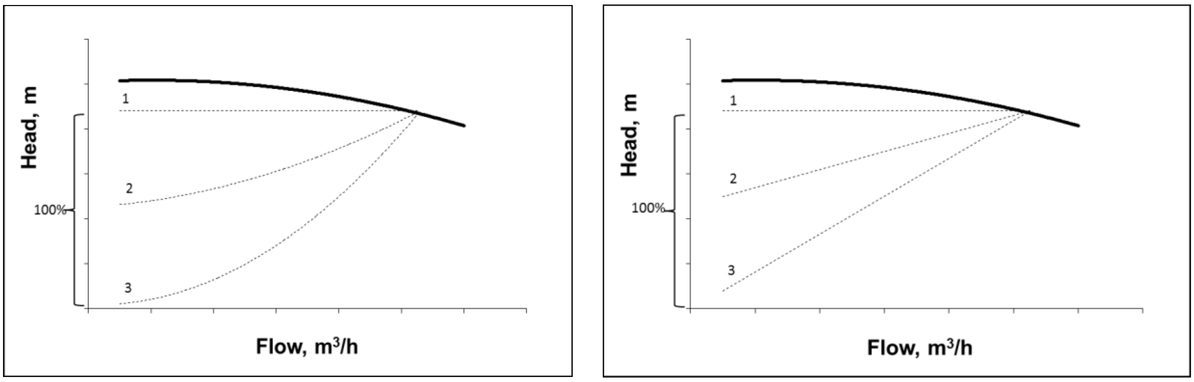


Fig. 1.1 Variable speed pump control modes

From left: square deviation, from right: linear deviation, 1 – constant pressure control, 2-3 – proportional pressure control

Up to 5% of the public water supply systems in Latvian towns (up to 10,000 inhabitants) are characterized by using the proportional pressure control with an average head deviation of ~ 15% (Fig. 1.2). Around 31% of district heating systems are characterized by using proportional pressure control with an average head deviation of ~ 37% (Fig. 1.2). This was stated by statistically analyzing the public water supply and district heating systems.

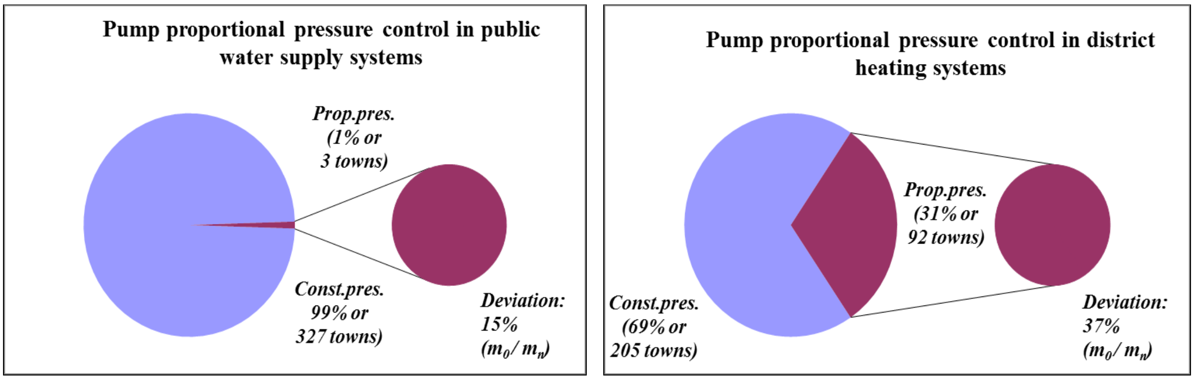


Fig. 1.2 Usage of pump proportional / constant pressure control mode in public water supply and district heating systems

It is important to select a pump technology solution with the highest possible efficiency. Pump efficiency indicates the ratio between the supplied and usefully consumed power. In fact, by reducing the pump rotation speed, the efficiency is slightly being decreased.

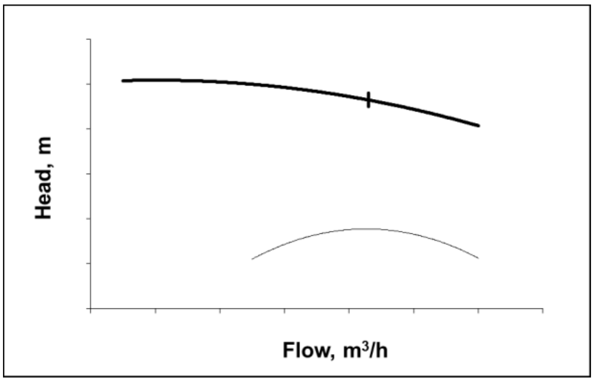


Fig. 1.3 Best efficiency point (BEP) of centrifugal pump

Normally, the efficiency in the best efficiency point (Fig. 1.3) is higher than the efficiency that is achieved in the actual duty point. In this way, the pump selection process should focus not only on the required head and flow values, but also on the required hydraulic parameters are achieved at the maximum pump efficiency.

Two centrifugal pump designs are used in public water supply systems in Latvian towns:

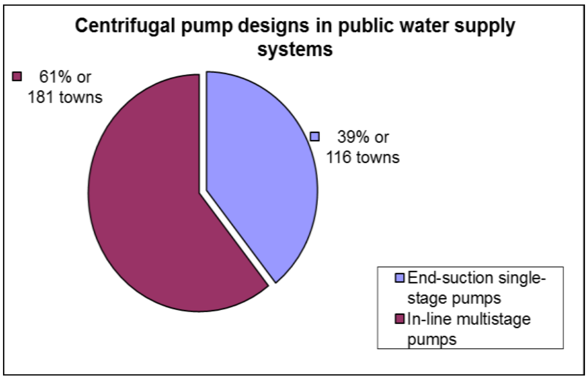
- single-stage end-suction centrifugal pumps,

- multistage in-line centrifugal pumps.

At the same time, two centrifugal pump designs are used in district heating systems in Latvian towns:

- single-stage end-suction centrifugal pumps,
- single-stage in-line centrifugal pumps.

The percentage breakdown of pump design in public water supply and district heating systems in Latvian towns (up to 10,000 inhabitants) is shown in Fig. 1.4. This was stated by statistically analyzing the water and heating systems.



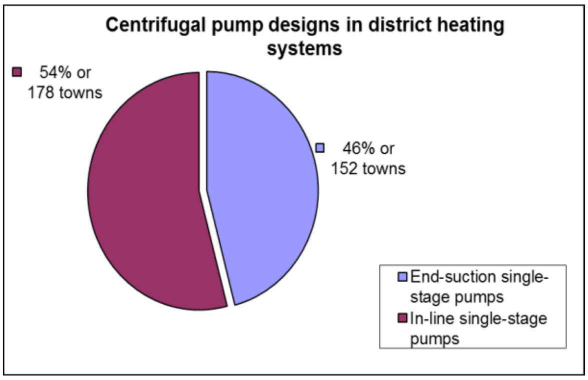


Fig. 1.4 Usage of pump designs in public water supply and district heating systems in Latvian towns (up to 10,000 inhabitants)

Therefore, it is important to know which of centrifugal pump design is the most efficient for a given flow and head range in water supply and heating systems.

2. DEVELOPMENT OF CRITERIA OF ENERGY EFFICIENCY ANALYSIS FOR PUMP OPERATION

The criteria of the energy efficiency analysis have been derived in order to perform the energy efficiency analysis of variable speed pump operation in public water supply and district heating systems, as well as to realize further optimization using the certain design of variable speed centrifugal pumps (Fig. 2.1). These criteria can be used for operation analysis of variable speed centrifugal pumps in water supply and heating systems in Latvian towns (up to 10,000 inhabitants).

Fig. 2.1 Algorithm of energy efficiency evaluation of centrifugal pumps operation (by criteria)

During the energy efficiency analysis of operation of variable speed centrifugal pumps, the concept of pressure drop (2.1), relationship between pump power and rotation speed (2.2.), pump efficiency (2.3) and water leakage reduction has been considered (2.4).

$$\Delta p = f * \frac{L}{D} * \rho * \frac{V^2}{2}, \tag{2.1}$$

where Δp - pressure drop, Pa;

f - friction factor;

L - pipe length, m;

D - pipe inner diameter, m;

ρ - fluid density, kg/m^3;

V - average fluid velocity, m/s.

$$\frac{P_n}{P_x} = \left(\frac{n_n}{n_x}\right)^3, \tag{2.2}$$

where P_n - pump initial power, kW;

P_x - pump reduced power, kW;

n_n - pump initial rotation speed, RPM;

n_x - pump reduced rotation speed, RPM.

$$\eta_P = \frac{\rho * g * Q * H}{P_2}, \tag{2.3}$$

where η_P - pump efficiency, $\%$;

P_2 - pump shaft power, W;

ρ - pumped liquid density, kg/m^3;

g - gravity acceleration, m/s^2;

Q - pump flow, m^3/s;

H - pump head, m.

$$C = \sqrt{2 * g * H} * 0.6 \tag{2.4}$$

where C - flow velocity in pipe rupture, m/s;

g - gravity acceleration (constant: $9{,}80665$), m/s^2;

H - pump head, m.

Proportional pressure control mode (reduction of consumed electric energy)

The proportional pressure pump control mode has been anayzed for public water supply and district heating systems. The pump control mode was compared with the constant (differential) pressure control mode.

Table 2.1

Energy calculation of variable speed centrifugal pumps by using theoretical load profile of water supply systems (proportional pressure control mode)

Flow component (Q_x/Q_n), %	100	75	55	35	12
Head component (m_x/m_n), %	100	100-ΔX_1	100-ΔX_2	100-ΔX_3	100-ΔX_4
Operational time, h/year	164	296	460	887	1478
Motor power (P_1), kW	Y_1	Y_2	Y_3	Y_4	Y_5
Energy consumption, kWh/year	Z_1	Z_2	Z_3	Z_4	Z_5
Energy consumption, kWh/year	ΣZ_n				

Table 2.2

Energy calculation of variable speed centrifugal pumps by using theoretical load profile of heating systems (proportional pressure control mode)

Flow component (Q_x/Q_n), %	100	75	50	25
Head component (m_x/m_n), %	100	100-ΔX_1	100-ΔX_2	100-ΔX_3
Operational time, h/year	410	1026	2394	3010
Motor power (P_1), kW	Y_1	Y_2	Y_3	Y_4
Energy consumption, kWh/year	Z_1	Z_2	Z_3	Z_4
Energy consumption, kWh/year	ΣZ_n			

The comparison of the consumed electric energy by pumps has been performed by realizing energy calculations of variable speed centrifugal pumps using the theoretical load profiles of water and heating systems (Table 2.1 / 2.2). Amount of energy consumed at different proportional pressure deviations has been compared with the energy amount consumed at constant pressure control mode application (Table 2.3).

Table 2.3

Comparison of consumed energy by variable speed centrifugal pumps

Deviations of proportional pressure control curve (m_0/m_n), %	Comparison of consumed energy: proportional pressure / constant pressure (kWh_p/kWh_k), %
0	$1-\Sigma Z_0/\Sigma Z_0$
20	$1-\Sigma Z_{20}/\Sigma Z_0$
40	$1-\Sigma Z_{40}/\Sigma Z_0$
60	$1-\Sigma Z_{60}/\Sigma Z_0$
80	$1-\Sigma Z_{80}/\Sigma Z_0$
100	$1-\Sigma Z_{100}/\Sigma Z_0$

The actual load profile has to be similar to the theoretical load profile in order to ensure an accurate energy efficiency evaluation of variable speed pump operation. If the actual load profile is totally different from the theoretical load profile, then the calculation adjustments focused on the load profile data changes have to be performed.

Amount of energy consumption if the constant pressure control mode is applied has been compared with the amount if the proportional pressure control mode is applied with different linear and square deviations of control curve (Table 2.3). Then, the regression equations of the polynomial trend type ($y = a_0 + a_1 * x + a_2 * x^2 + \varepsilon$) and the coefficients of determination have been derived. By using the equations, it is possible to evaluate the reduction potential of energy consumption at various deviations of the proportional pressure control curve (Fig. 2.2).

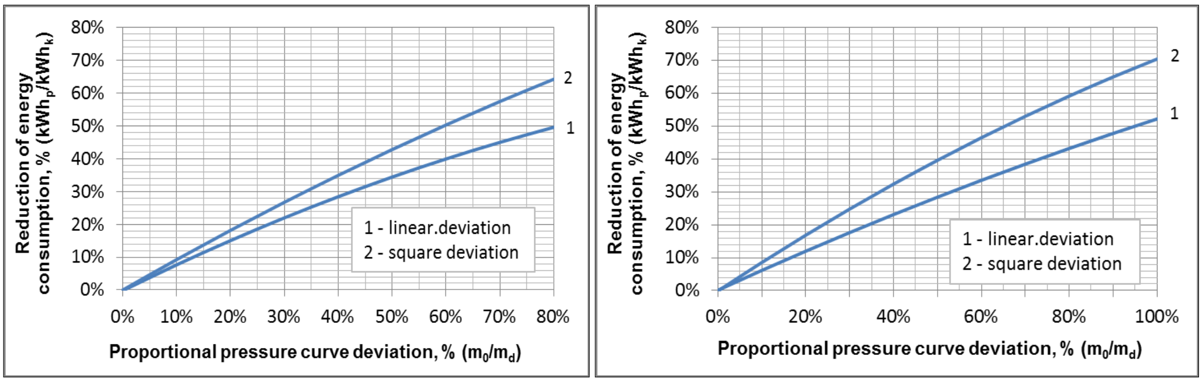


Fig. 2.2 Reduction of electrical energy consumption by pumps

Proportional pressure control vs. constant pressure control

From left - public water supply system; from right – district heating system

16 variable speed centrifugal pumps of various designs have been analyzed during the research:

- in-line multistage centrifugal pumps,
- end-suction single stage centrifugal pumps,
- in-line single stage centrifugal pumps.

Proportional pressure control mode (reduction of existing water leakage)

General water leakage has been analyzed at the certain values of deviation of the proportional pressure control curve in public water supply and district heating systems. This has been done by making a comparison between the proportional pressure control mode and the constant pressure control mode for variable speed pumps.

By implementing water leakage index calculations based on the theoretical load profiles for water supply and heating systems, there has been determined the reduction of general water leakage in networks at different deviations of the proportional pressure control curve (Table 2.4 and 2.5).

Table 2.4

Calculation of water leakage index by using theoretical load profile of water supply systems (proportional pressure control mode)

Flow component (Q_x/Q_n), %	100	75	55	35	12
Head component (m_x/m_n), %	100	100-ΔX_1	100-ΔX_2	100-ΔX_3	100-ΔX_4
Operational time, h/year	164	296	460	887	1478
Water leakage index	C_{100}/C_{100}	C_1/C_{100}	C_2/C_{100}	C_3/C_{100}	C_4/C_{100}
Water leakage index with influence of flow and operational time components	C_{Qt1}	C_{Qt2}	C_{Qt3}	C_{Qt4}	C_{Qt5}
Water leakage index with influence of flow and operational time components	ΣC_{Qtn}				

Table 2.5

Calculation of water leakage index by using theoretical load profile of heating systems (proportional pressure control mode)

Flow component (Qx/Qn), %	100	75	50	25
Head component (mx/mn), %	100	100-ΔX_1	100-ΔX_2	100-ΔX_3
Operational time, h/year	410	1026	2394	3010
Water leakage index	C_{100}/C_{100}	C_1/C_{100}	C_2/C_{100}	C_3/C_{100}
Water leakage index with influence of flow and operational time components	C_{Qt1}	C_{Qt2}	C_{Qt3}	C_{Qt4}
Water leakage index with influence of flow and operational time components	ΣC_{Qtn}			

The actual load profile has to be similar to the theoretical load profile in order to ensure an accurate energy efficiency evaluation of variable speed pump operation. If the actual load profile is totally different from the theoretical load profile, then the calculation adjustments focused on the load profile data changes have to be performed.

Water leakage rate in networks if the constant pressure control mode is applied has been compared with the existing water leakage rate if the proportional pressure control mode is applied with different linear and square deviations of control curve (Table 2.6).

Table 2.6

Comparison of water leakage

Deviations of proportional pressure control curve (m_0/m_n), %	Comparison of water leakage: prop. pressure / constant pressure (m^3_p/m^3_k), %
0	$1-\Sigma C_{Qt0}/\Sigma C_{Qt0}$
20	$1-\Sigma C_{Qt20}/\Sigma C_{Qt0}$
40	$1-\Sigma C_{Qt40}/\Sigma C_{Qt0}$
60	$1-\Sigma C_{Qt60}/\Sigma C_{Qt0}$
80	$1-\Sigma C_{Qt80}/\Sigma C_{Qt0}$
100	$1-\Sigma C_{Qt100}/\Sigma C_{Qt0}$

Then, the regression equations of the polynomial trend type ($y = a_0 + a_1 * x + a_2 * x^2 + \varepsilon$) and the coefficients of determination have been derived. By using the equations, it is possible to evaluate the reduction potential of water leakage at various deviations of the proportional pressure control curve (Fig. 2.3).

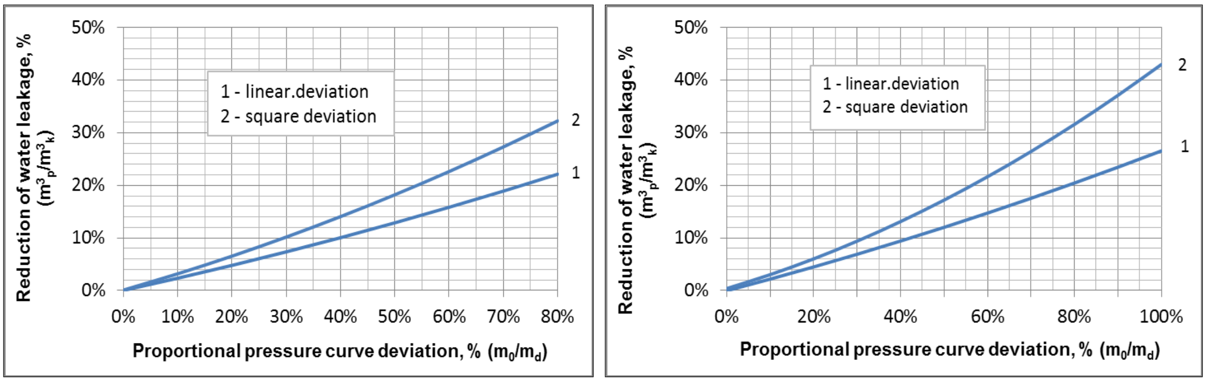


Fig. 2.3 Reduction of annual water leakage

Proportional pressure control vs. constant pressure control

From left - public water supply system; from right – district heating system

Knowing the deviation value of the proportional pressure control curve and the existing water leakage rate, it is possible to determine the annual reduction in water flow by using the proportional pressure control mode for variable speed centrifugal pumps (compared to the constant pressure control mode).

Pump efficiency change according the duty point deviation from the nominal head value

According the duty point deviation from the nominal head value at the constant flow, the trend of pump efficiency change has been determined during the analysis of variable speed centrifugal pump efficiency.

Pump efficiency value drops if centrifugal pumps operate with decreased rotational frequency. Duty point deviations from the nominal head value of variable speed pump may be seen in Fig. 2.4.

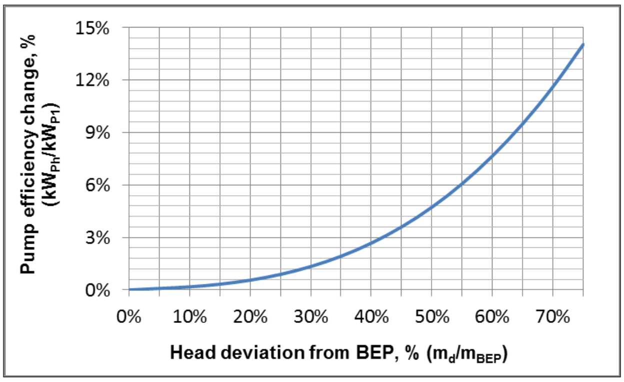


Fig. 2.4 Centrifugal pump efficiency reduction at different changes of head value from the nominal head

During the analysis of centrifugal pumps efficiency change, the regression equations of the polynomial trend type ($y = a_0 + a_1 * x + a_2 * x^2 + a_3 * x^3 + \varepsilon$) and the coefficients of determination have been derived. By using the equation, it is possible to evaluate the efficiency reduction of variable speed centrifugal pumps at different head deviations from the nominal head value (Fig. 2.5).

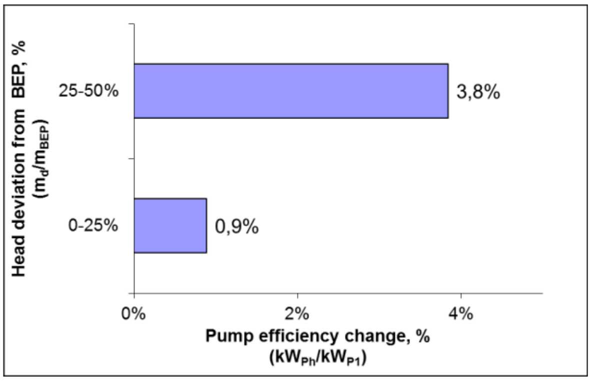


Fig. 2.5 Centrifugal pump efficiency reduction at different changes of head value from the nominal head

15 centrifugal pumps of various designs have been analyzed during the research:

- in-line single stage centrifugal pumps,
- in-line multistage centrifugal pumps,

- end-suction single stage centrifugal pumps.

Comparison of BEP efficiency of centrifugal pumps of various designs

Two dry rotor centrifugal pumps designs have been investigated during the analysis of the energy efficiency of centrifugal pumps operation in public water supply systems in Latvian towns (up to 10,000 inhabitants):

- in-line multistage centrifugal pumps,
- end-suction single stage centrifugal pumps.

Realizing the efficiency analysis of centrifugal pumps operation, it was found that in-line multistage pumps are more energy efficient than end-suction single stage pumps (up to 21%), if the flow is less than 72 m^3/ h (Fig. 2.6). During the research, the flow and the head values varied in the range of Q = 10 ÷ 140 m^3/h at H = 30 ÷ 55 m.

Two dry rotor centrifugal pumps designs have been investigated during the analysis of the energy efficiency of centrifugal pumps operation in district heating systems in Latvian towns (up to 10,000 inhabitants):

- in-line single stage centrifugal pumps,
- end-suction single stage centrifugal pumps.

Realizing the efficiency analysis of centrifugal pumps operation, it was found that end-suction single stage pumps are more energy efficient than in-line single stage pumps (~4-6%). It can be seen from Fig. 2.6. During the research, the flow and the head values varied in the range of Q = 50 ÷ 770 m^3/h at H = 10 ÷ 60 m.

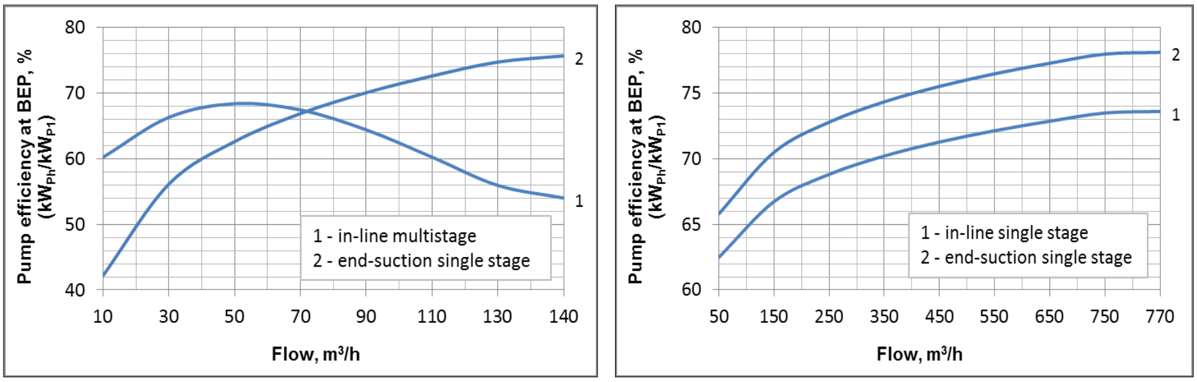


Fig. 2.6 Pump efficiency

From left – public water supply system, if H=30÷55 m; from right – district heating system, if H=10÷60 m

During the analysis, the regression equations of the following trend type and the coefficients of determination have been derived:

- the polynomial trend type ($y = a_0 + a_1 * x + a_2 * x^2 + a_3 * x^3 + \varepsilon$),
- the logarithmic trend type ($y = a_0 + a_1 * ln(x) + \varepsilon$),
- the power trend type ($y = a * x^b$).

By using the equations, it is possible to evaluate the highest possible pump efficiency levels at BEP for in-line multistage and end-suction single stage pumps in public water supply, and for in-line and end-suction single stage pumps in district heating (Fig. 2.6).

368 centrifugal pumps of various designs have been analyzed during the research:

- in-line multistage centrifugal pumps,
- end-suction single stage centrifugal pumps,
- in-line single stage centrifugal pumps.

3. EXPERIMENTAL TEST OF CRITERIA OF ENERGY EFFICIENCY ANALYSIS

By implementing a number of different measurements in various public water supply and district heating systems, the experimental test of criteria of the energy efficiency analysis has been performed for centrifugal pumps operation.

There are the following criteria of the energy efficiency analysis of variable speed centrifugal pumps operation in public water supply and district heating systems, which are described by regression equations and experimentally verified by measurements: 1) the energy efficiency analysis of the proportional pressure control mode in comparison with the constant (differential) pressure control mode, 2) the analysis of the efficiency change value of variable speed centrifugal pumps according the duty point deviation from pump nominal head, 3) the efficiency value of the best efficiency points of centrifugal pumps of various designs according to flow and head value.

Energy efficiency analysis of pump operation in public water supply (proportional pressure control vs. constant pressure control)

The measurements have been done for the second booster system in the public water supply of Jaunolaine town in Latvia. The booster system supplies drinking water to ~2000 inhabitants.

Public water supply system is characterized with the following parameters:

- Max water consumption: 36 m^3/h.
- Pressure after the second stage booster system: 3.5 bar ≈ 35 m.
- Water leakage in network: ~23%.

Pressure booster system is characterized with the following parameters:

- Pressure booster station consists of 5 pumps: 2 – stand-by pumps, 2 – fire fighting pumps and 1 – duty pump.
- Pumps are equipped with frequency drives.
- Nominal flow/head values of each pump: 45 m^3/h/60 m.
- Pump shaft power: P_2=11 kW.
- BEP of each pump: 64.8 %.

15% deviation of the proportional pressure control curve has been chosen (Fig. 3.1). This has been done so to ensure the constant pressure value at critical end-users during the daytime both at the minimal and maximal flow rate.

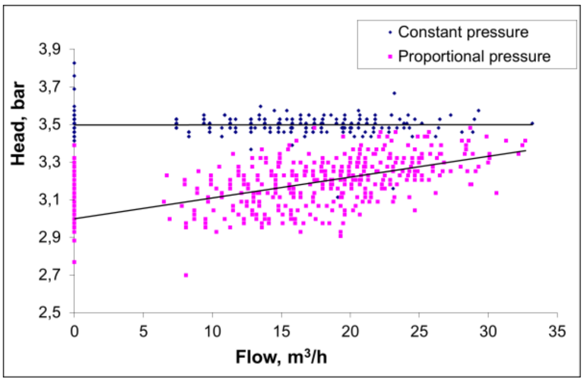


Fig. 3.1 Pump head and flow values of second stage booster system

Constant pressure and proportional pressure (15% deviation) control modes

Analyzing the electrical energy consumption of the constant pressure control and the proportional pressure control (with linear deviation), it has been determined that the actual energy savings are 11.7%. Analysing of the electrical energy consumption with the criteria of the energy efficiency analysis has been resulted in energy savings expressed by ~ 12%.

When comparing the results made by the energy efficiency criteria of centrifugal pump operation with the actual measurements obtained in the real object (iron removal plant), it is evident that the results are similar. The absolute error is below 1%.

Energy efficiency analysis of pump operation in district heating system (proportional pressure control vs. constant pressure control)

The measurements based on pump energy audit have been implemented for main network pumps in district heating system of Haapsalu city in Estonia. The main network pumps of the boiler house supply heat energy to more than 11,000 inhabitants.

The main network pumps are characterized with the following parameters:

- 2 network pumps (1 – stand-by pump, 1 – duty pump).
- Each pump has an external frequency drive for variable speed operation.
- Nominal flow/head values of each pump: 750 m^3/h/28 m.
- Pump shaft power: P_2=90 kW.
- BEP of each pump: 77 %.
- Centrifugal pumps are controlled via the proportional pressure control (the constant differential pressure of 18 m was measured after the boiler house).

The constant differential pressure of 18 m measured after the boiler house has been changed to 10 m. Then the proportional pressure control mode has been realized with the change of the control curve square deviation from 35.7% to 64.3% (Fig. 3.2).

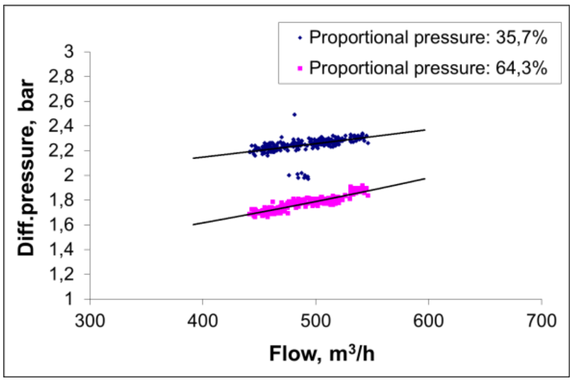


Fig. 3.2 Pump differential pressure and flow values of main network pumps

Proportional pressure control modes with different control curve deviations (35.7% to 64.3%)

It has been determined during the experimental measurements that the actual energy savings are 24.4%. Analysing of the electrical energy consumption with the criteria of the energy efficiency analysis has been resulted in energy savings expressed by ~29%.

When comparing the results made by the energy efficiency criteria of centrifugal pump operation with the actual measurements obtained in the real object (boiler house), it is evident that the results are similar. The absolute error is about 4%.

Efficiency value of the best efficiency points of centrifugal pumps of various designs

Experimental measurements have been made for six public water supply and district heating systems to determine the efficiency change value of variable speed pumps according to the actual duty point location regarding the best efficiency point (Table 3.1).

Analysing the difference among the actual measured values and the theoretical calculation values of centrifugal pumps' efficiency change, the mean squared error is ~1%.

Table 3.1

Absolute errors among actual and theoretical calculations of pumps' efficiency change

	System type	City	Head deviation from BEP, %	Power (P_1), kW	Absolute error, %
1	Water supply	Dobele	50.0	3.9	0.6
2	Water supply	Jaunolaine	33.2	7.9	0.6
3	Water supply	Lubana	41.3	2.6	0.5
4	Heating	Liepaja	16.1	67.2	0.1
5	Heating	Tukums	20.1	14.8	0.1
6	Heating	Broceni	33.3	6.1	0.3

Efficiency analysis of pump BEP

Experimental measurements have been made for eight public water supply and district heating systems to determine the highest efficiency of in-line single stage, in-line multistage, and end-suction single stage centrifugal pumps (Table 3.2).

Table 3.2

Absolute errors among actual and theoretical calculations of pumps' efficiency change

	System type	City	Pump design	Power (P_1), kW	Absolute error, %
1	Water supply	Jaunolaine	In-line multistage	10.7	4.7
2	Water supply	Lubana	In-line multistage	4.3	4.8
3	Water supply	Dobele	End-suction single stage	7.8	1.9
4	Water supply	Carnikava	End-suction single stage	5.3	5.1
5	Heating	Tukums	End-suction single stage	17.9	0.7
6	Heating	Liepaja	End-suction single stage	79.1	4.5
7	Heating	Broceni	In-line single stage	8.7	3.0
8	Heating	Jekabpils	In-line single stage	54.3	3.6

Analysing the difference among the actual measured values and the theoretical calculation values of the efficiency at the best efficiency points, the mean squared error is around 1%.

4. ECONOMIC ANALYSIS OF PROPORTIONAL PRESSURE CONTROL USE

Economic analysis of operation of the second stage booster station of water supply

The economic analysis has been carried out for the second stage booster station in the public water supply system which supplies drinking water for 2000 inhabitants. The savings associated with the decreased water flow rate through the iron removal plant due to the reduction of water leakage in network has not been taken into consideration.

- Max water consumption: 36 m^3/h.
- Pressure after the second stage booster system: 3.5 bar ≈ 35 m.
- Water leakage in network: ~23%.

Electric energy savings are 2544 kWh/year, if the proportional pressure control mode is used instead of the constant pressure control mode (linear deviation of 15%).

The following data has been adopted: 1) the electricity tariff: 0.08126 Ls/kWh, 2) the investment for an additional control panel installation ensuring the proportional pressure control: 870 Ls w/o VAT, 3) the discount rate: 10%/year, 4) operational period: 10 years.

The results of the economic analysis of the second stage booster station (the proportional pressure control vs. the constant pressure control) are as follows:

- NPV Net present value: 97.53 Ls.
- IRR internal rate of return: ~13%.
- Discounted payback period: 8.45 years.

Economic analysis of operation of the main network pumps in district heating system

The economic analysis has been carried out for the main network pumps in the district heating system which supplies heating energy for ~11000 inhabitants. The savings associated with the decreased water flow rate through the water treatment plant due to the reduction of water leakage in network has not been taken into consideration.

- Max flow rate: 750 m^3/h.
- Friction losses across the system: 28 m.

Electric energy savings are ~54000 kWh/year, if the square deviation of the proportional pressure control mode has been changed from 35.7% to 64.3%.

The following data has been adopted: 1) the electricity tariff: 0.08126 Ls/kWh, 2) the investment for an additional control panel installation ensuring the different deviation of the proportional pressure control: 1250 Ls w/o VAT, 3) the discount rate: 10%/year, 4) operational period: 10 years.

The results of the economic analysis of the main network pumps (deviation change of the proportional pressure control) are as follows:

- NPV Net present value: 21505 Ls.
- IRR internal rate of return: 296%.
- Discounted payback period: 0.37 years.

CONCLUSIONS

1. The constant pressure control is used for the first/second stage booster pumps in 99% of public water supply systems (327 towns). The constant differential pressure control is used for network pumps in 69% of district heating systems (205 towns). The proportional pressure control can be used in all these systems in such way: 15% curve deviation - for heating systems, and at least 50% - for water systems (the criteria of the energy efficiency analysis). The towns are described with up to 10000 inhabitants.
2. Overal water leakage rate is around 24% in public water supply systems in Latvia. That is similar with water leakage rate in EU countries such as Spain, France and Slovakia, but is still far away from the best performers like Denmark and Germany (the water leakage rate is below 10%). By using the proportional pressure control mode as a criterion of the energy efficiency analysis, it is possible to determine the reduction potential of water leakage.
3. By applying the proportional pressure control mode with 15% deviation as the criterion of energy efficiency analysis for the first/second stage booster pumps in water supply systems, the annual energy consumption may be reduced by ~14%, and the water leakage – by ~5% (from existing water leakage rate). In fact, the total electric energy consumption can be reduced by at least 1 GWh.
4. By using the proportional pressure control mode with 50% deviation as the criterion of energy efficiency analysis for network pumps in heating systems, the annual energy consumption may be reduced by ~40%, and the water leakage – by ~17% (from

existing water leakage rate). In fact, the total electric energy consumption can be reduced by at least 7.6 GWh.

5. Increase of head deviation from the highest efficiency point of flow filter pumps at the constant flow result in uneven reduction of pump efficiency. The criterion of the energy efficiency analysis shows that the deviation increase of 25% results in the pump efficiency drop of ~1%. The pump efficiency drops up to 4%, if the deviation increases from 25% to 50%.
6. The criterion of the energy efficiency analysis shows that the pump efficiency at BEP is equil for in-line multistage and end-suction single stage pumps, if flow is 72 m^3/h in water supply system (Q_{nom}=10÷140 m^3/h at H_{nom}=30÷55 m). The smaller flow is, the higher efficiency at BEP is for in-line multistage pumps in comparison with end-suction single stage pumps (up to 21%). The pump efficiency at BEP is higher for end-suction single stage pumps in comparison with in-line single stage pumps in heating systems (Q_{nom}=50÷770 m^3/h at H_{nom}=10÷60 m). The difference is about 4-5%.
7. When comparing the results made by the energy efficiency criteria of centrifugal pump operation with the actual measurements obtained in the real objects, it is evident that the results are similar. The absolute errors are less than 5%.
8. The greater pump motor power and/or the deviation of the proportional pressure curve is, the shorter payback period is. If the control curve deviation is increased from 15% up to 20% for the second stage booster pumps in water supply system supplying drinking water to 2000 inhabitants, then the payback period of the implementation of the proportional pressure control is decreased from 5.53 up to 3.93 years, and the internal rate of return for 10 years' period is increased from 12.55% up to 21.92% (the initial investment is 870 Ls and the electricity tariff is ~0.08 Ls/kWh).

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