KAUNAS UNIVERSITY OF TECHNOLOGY

JURGITA ČERNECKIENĖ

INVESTIGATION OF WIND ENERGY USAGE FOR HEATING BUILDINGS BY APPLYING A HYDRAULIC SYSTEM

Summary of Doctoral Dissertation
Technological Sciences, Civil Engineering (02T)

2017, Kaunas

Doctoral dissertation was prepared at Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Department of Building Energy Systems in 2012–2017.

Scientific Supervisor:
Prof. dr. Tadas ŽDANKUS (Kaunas University of Technology, Technological Sciences, Civil Engineering (02T).

Editor: Dovilė Dumbrauskaitė (Publishing Office "Technologija")

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The official defence of the dissertation will be held at 10 a.m. on 15th of September, 2017 at the public meeting of Dissertation Defence Board of Civil Engineering Science Field in Dissertation Defence Hall at Kaunas University of Technology.

Address: K. Donelaičio St. 73-(403), 44249 Kaunas, Lithuania.
Tel. no. (+370) 37 300 042; fax. (+370) 37 324 144; e-mail doktorantura@ktu.lt.

Summary of doctoral dissertation was sent on 14th of August, 2017.
The doctoral dissertation is available on the internet http://ktu.edu and at the library of Kaunas University of Technology (K. Donelaičio St. 20, 44239 Kaunas, Lithuania).

KAUNO TECHNOLOGIJOS UNIVERSITETAS

JURGITA ČERNECKIENĖ

VĖJO ENERGIJOS NAUDOJIMO PASTATUI ŠILDYTI TAIKANT HIDRAULINĘ SISTEMĄ TYRIMAS

Daktaro disertacijos santrauka
Technologijos mokslai, statybos inžinerija (02T)

2017, Kaunas

Disertacija rengta 2012–2017 metais Kauno technologijos universiteto Statybos ir architektūros fakulteto Pastatų energinių sistemų katedroje. Disertacija ginama 2017 metais.

Mokslinis vadovas:
Prof. dr. Tadas ŽDANKUS (Kauno technologijos universitetas, technologijos mokslai, statybos inžinerija – 02T).

Redagavo: Dovilė Dumbrauskaitė (Leidykla "Technologija")

Statybos inžinerijos mokslo krypties disertacijos gynimo taryba:
Prof. dr. Raimondas BLIŪDŽIUS (Kauno technologijos universitetas, technologijos mokslai, statybos inžinerija, 02T) – **pirmininkas**;
Dr. Karolis BANIONIS (Kauno technologijos universitetas, technologijos mokslai, statybos inžinerija, 02T);
Dr. Demetri BOURIS (Nacionalinis Atėnų technikos universitetas, technologijos mokslai, statybos inžinerija, 02T);
Dr. Eugenijus PEREDNIS (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija, 06T);
Prof. dr. Petras PUNYS (Aleksandro Stulginskio universitetas, technologijos mokslai, aplinkos inžinerija, 04T).

Disertacija bus ginama viešame Statybos inžinerijos mokslo krypties disertacijos gynimo tarybos posėdyje 2017 m. rugsėjo 15 d. 10 val. Kauno technologijos universiteto disertacijų gynimo salėje.

Adresas: K. Donelaičio g. 73-(403), 44249 Kaunas, Lietuva.
Tel. (370) 37 300 042; faks. (370) 37 324 144; el. paštas doktorantura@ktu.lt.

Disertacijos santrauka išsiųsta 2017 m. rugpjūčio 14 d.
Su disertacija galima susipažinti internetinėje svetainėje http://ktu.edu ir Kauno technologijos universiteto bibliotekoje (K. Donelaičio g. 20, 44239 Kaunas).

INTRODUCTION

Climate change caused by increasing greenhouse gas emissions became a focus of concern for the global community since the Kyoto Protocol to the United Nations Framework Convention on Climate Change was adopted at the third conference on the Climate Change of the United Nations in 1991. The third world and industrialized countries committed to take all responsibility to mitigate the emissions of greenhouse gases around the world which emerge when the demands of development of the countries are fulfilled. The overall increase of greenhouse gas emissions causes the warming of the Earth's surface and atmosphere which may negatively affect the ecosystems (United Nations, 1992). At the 21st Conference of the Parties (COP21) to the United Nations Framework on Climate Change held in Paris in 2015, the action plan for climate change control and reduction was established with a goal of keeping the average temperature of the Earth to 2°C by 2020, comparing with pre-industrial levels.

A stronger focus has to be paid to the civil engineering sector as, with regards to the data of 2014, 43% of the entire European Union energy was consumed by the building of hospitality and service sector. 11% of the energy for general demands was consumed as thermal energy, according to Eurostat (2015, 2016). A wider-range usage of various renewable energy sources would allow implementing the commitment to reduce collective greenhouse gas emissions by 20% by 2020. It would also help to control climate warming (European Parliament and European Commission, 2010), since considering the data of 2014, 92% of thermal energy was released from burning of fuel (Eurostat, 2016). The primal alternative for the fuel combustion is the direct solar energy. However, the peaks of solar energy potential in cool climate zones are inversely proportionate to the demand of thermal energy; therefore, the issues of engineering cause difficulties in the preservation of the energy.

Relevance of the research

Wind energy can provide a part of thermal energy demand of buildings. Wind energy distribution throughout the year correlates with the needs of thermal energy of the cool temperate zone (Černeckienė and Ždankus 2015). Thermal energy needs of buildings from renewable energy sources contributes to the development of zero carbon emission as well as a solution to climate change.

Research object

The process of wind energy conversion into thermal energy with a hydraulic unit and its use for heating buildings.

The aim of the research

To analyse the possibility of converting wind energy into thermal energy and applying it to satisfy the demand of thermal energy in energy-efficient buildings which convert mechanical wind energy into thermal energy by using a hydraulic device.

Tasks of the research

1. To evaluate the demands of heating and ventilation energy as well as the demands of installation power for energy-efficient buildings.
2. To analyse the dynamics of annual wind energy potential in a few typical districts according to wind energy in Lithuania and its correspondence to the demand of thermal energy for the building.
3. To create the working curves of a hydraulic device for different operating modes of the hydraulic system by simulating the wind effect experimentally with an electric motor.
4. To analyse the possibilities of automatic control of the hydraulic system by evaluating the specifications of energy conversion with the hydraulic system.
5. To create an algorithm, according to which the wind energy converted to thermal energy can be integrated into the building heating system.

Methods of research

An analytical assessment of the heating demand for a private residential building.

An analytical assessment of climatological conditions.

An experimental study of the operating regimes of the hydraulic device.

Scientific novelty of the research

The processes of converting mechanical energy into thermal energy in hydraulic systems have already been analysed as an adverse side effect, but there is no work so far which has dealt with the thermal power generation process as the main task of the system. In order to use wind as a renewable energy source for building heating, an experimental heat-generating hydraulic system was designed and the optimal system performance regimes were determined. The performance of the hydraulic system was evaluated including low wind speed range performance which is relevant for the Lithuanian climate conditions. The results of research and the algorithm for the integration of wind energy into the building heating system extend the scopes of civil engineering science branch.

Applicability of the research

1. The results of this experimental research may be applied for assessing the financial costs of a hydraulic system which converts wind energy to heat.
2. The method of this research may be applied to various types research regarding the hydraulic systems converting mechanical energy to heat.
3. The studies and experimental results of this research may be beneficial for the development and installation of a prototype of such energy conversion device in buildings.

The defended statements

Direct mechanical wind energy conversion into thermal with the hydraulic system enables to expand the range of wind energy application which helps to mitigate the greenhouse gas emissions.

The efficiency of wind energy conversion into thermal energy with a hydraulic system may reach more than 90% and the utilization of wind energy potential may increase as well.

1. LITERATURE REVIEW

According to the newest reports of one of the most prestigious organizations in the world, the International Panel on Climate Change (IPCC), the increasing amount of carbon dioxide (CO_2) emissions caused by the increasing combustion of fossil fuel is the major reason causing the majority of negative changes in the nature (Pachauri and Meyer, 2014; Stocker, Qin et al., 2013). Climate change today receives considerable attention from scientists, as it has already been recognized that questions on the mitigation of energy demand and research for sustained production of energy must be discussed in an interdisciplinary and collaborative way.

According to the data of the European Union, the construction and service industries consume 40% of all energy. Therefore, certain actions within these sectors may significantly help to reduce the emissions of CO_2 (The Council of the European Communities, 1993). The USA is in an analogical situation of pollution, where CO_2 emissions caused by the construction industry account for 40% of all pollution of the country (United States Department of Energy, 2016).

If the global community is to solve the problems of global warming by seeking for ways to reduce greenhouse gas emissions, countries, including Lithuania, which have limited fossil fuel resources and do not meet energy demands of the country, have to solve their geopolitical and development problems (Valodka and Valodkienė, 2015, Blazev, 2015).

The encouragement to use energy-efficient and cleaner technologies in the EU is regulated under certain directives; the 2002/91/EC Directive of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings as well as its recast 2010/31/EU of 19 May 2010 are the most important for the construction industry.

The implementation of directives on building energy efficiency ensure a decrease of heat loss in new and renovated buildings which leads to changing technical specifications of building heating systems. These changes firstly can be noticed in the general power of the heating system, measurements of heating devices and the temperatures of heat-transfer media. Compared with the less efficient buildings, devices of certain power which generate thermal energy may ensure a larger amount of thermal energy required for a building (Černeckienė and Ždankus, 2015). Carvalho et al (2017) predicts that Eastern Europe, especially the Baltic countries, has great potential for the growth of wind energy (about + 30%), and also notes that the wind energy potential is higher during the cold season compared with the warm season in the eastern part of Europe.

Renewable energy is defined as the energy extracted from sun, wind, rivers, ground, household waste and biofuel. During the conversion of solar and wind energy to the energy suitable for consumption, the greenhouse gases are not emitted; therefore, such energy sources are unquestionably considered clean. Thermal and electric energy produced by photovoltaic or solar thermal collectors as well as electric energy produced by a wind power station is described by a zero CO_2 emission factor M_{CO2}=0 kgCO_2/kWh (Ministry of Environment of the Republic of Lithuania, 2015). However, a wide-range usage of biofuel is considered differently (Haberl et al., 2010; Popp et al., 2014); therefore, the creation of other technologically rational renewable energy sources should be spread as widely as possible.

The dynamics of wind energy potential correlate with the heating demand of buildings. Therefore, the development of mechanical wind energy conversion into thermal energy in Lithuania and other countries of similar climate is very promising.

As there are no statistics or data on other forms of energy generated from wind, almost all wind energy in the EU today is converted into electric, according to Eurostat. However, since a large amount of energy is consumed as thermal energy in cool climate zones, additional energy conversion is not reasonable from a technological point of view; therefore, thermal energy generation from wind becomes a very interesting subject for the scientists. Another reason, which shows a positive effect of direct wind energy conversion into thermal energy is the ability to accumulate it. The biggest issue of such renewable energy sources is to ensure their long-term consumption; therefore, an energy accumulation system is one of the most important parts of the system of renewable energy sources. The implementation of an energy accumulation system allows stabilizing the overall centralized energy supply network as well as to increase the reliability of energy supply.

Principles of heat generation directly from mechanic wind energy have been already presented in previous works of various engineers and scientists. Such devices are mostly based on the use of volume hydraulic machines (pumps) where kinetic energy of a wind rotor shaft is transferred into potential fluid energy, and due to the artificial obstacle and friction to it, the fluid potential energy is transferred into thermal energy (Maegaard et al., 2013). The original device that used fluid potential energy was first described and patented in 1950 in the USA by Raymon E. Thompson in his work “Fluid pressure energy translating device” (Raymond, 1950) and by Grenier in 1979 in “Fluid operated heating system” (Grenier, 1979). In 1973–1974 Ashiklan (Wind operated heating system) (Ashiklan, 1973, 1974) and Knecht (Wind driven heating system) in 1983 (Knecht, 1978) patented an analogous device and suggested using heat generated by fluid friction as well as a wind rotor as the source of primary energy. In 1973, engineers Kofoed and Matzen from the Institute of the Agriculture Engineering (Taastrup, Denmark) designed, tested and developed a wind power plant “Mark” (versions “Mark I” and “Mark II”) which produced thermal energy from mechanical wind energy (Maegaard et al., 2013). Soon after that, Ekner designed a wind power plant “Calorius” which gained the attention of other scientists. Capacity and noise level tests were performed with this power plant and in 1993–2000 the Westrup company from Denmark installed and launched another 34 “Calorius” power plants. According to data from 2010, 17 of these power plants are still in use. Although many scientists and engineers see a lot of benefits of wind power plants, heat production by such power plants have not been used widely yet.

In Lithuania, the possibilities of using wind energy have been explored in more detail and various publications in A. Stulginskis University (former University of Agriculture of Lithuania). In 2001, at the Institute of the Agriculture Engineering of the Lithuanian Agriculture University, Gulbinas has defended a doctoral dissertation titled “Investigation of the Effective Usage of the Wind Energy Equipment in the Agriculture”. This study explores the hydrodynamic load device the operating principle of which is based on thermal energy produced by the friction between a rotary connected to a wind rotor and an operating fluid. In 2011, Kavolynas defended a doctoral dissertation “Solar and Wind Energy Usage for Meeting the Demand of the Buildings in the Rural Localities” at A. Stulginskis University as well. However, the author focused on researching the use and accumulation of solar energy. Wind energy was explored in the studies of other authors (Kavolynas, 2011).

The conceptual study of Okazaki, Shirai and Nakamura (2015) presented a method of electromagnetic induction that allowed converting wind energy into heat, accumulate wind energy as thermal energy and to convert it into electric energy depending on the needs of consumers. In his paper, the author notes that such application of wind energy enables to use wind source potential of the locality more effectively and that it is more effective than directly generating electric energy (Okazaki et al, 2015).

Today, buildings may be heated by using wind energy and electric devices. The electric energy can be generated by wind power plants by using the following scheme: wind rotor (mechanical wind energy) –electricity generator (mechanical energy conversion to electric energy) – electric energy accumulation – heating system of the building (heating devices using electric power, such as air, oil, or radiant heater, etc.).

Wind energy may be transformed into thermal energy with a hydraulic system instead of an electric one. The following scheme can be applied: wind rotor – heat generator (hydraulic system) – the accumulator of thermal energy – heating system of the building. According to Žiedelis (2009), the temperature of the fluid may significantly increase when it passes through various valves, throttles and distributors in the hydraulic gears. In a hydraulic system, the mechanical energy of a hydraulic pump is transferred into the fluid mechanical energy which may be transported to any place over the pipes allowing it to pass through gaps, diaphragms or chokes, thus generating heat. However, some of this heat is transferred to the surroundings and some starts to heat the fluid; therefore, heat is already generated at the second grid. If a hydraulic pump is submerged into a fluid, all heat inside a pump is delivered to a fluid or a heat-transfer media.

Heat generated from wind energy may be used for heating buildings by means of a heat pump – a transitional device that transforms thermal energy. Heat may be directed to the ground, thus thermal energy may be accumulated by placing pipes of a hydraulic system into the ground close to a building where a ground source collector is installed (Ozgener, 2010).

Although hydraulic systems for wind energy conversion into heat have many benefits it is still argued that a sufficient amount of energy is not produced by using this method and that the production of electric energy by using powerful wind power plants is more efficient, as such energy may be used to produce heat. The use of hydraulic systems transferring wind energy into heat is very rare in practice.

2. AN EXPERIMENTAL STUDY OF MECHANICAL WIND ENERGY CONVERSION INTO HEAT BY USING A HYDRAULIC DEVICE

An experimental hydraulic system has been designed for researching the conversion of mechanical wind energy into thermal energy. The image and schematic view of the system is presented in Figure 2.1.

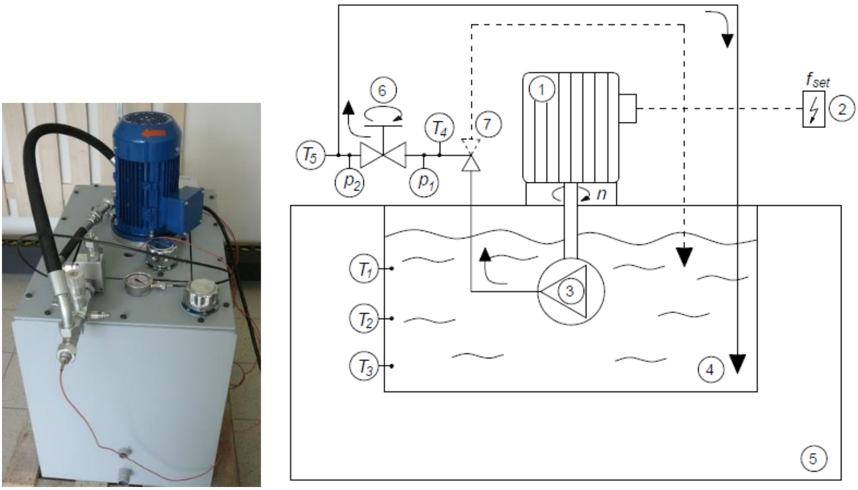

Figure 2.1. The experimental hydraulic system for the research of mechanical wind energy conversion into thermal energy (image and principle scheme): 1 – electric motor; 2 – electric power frequency converter; 3 – hydraulic pump; 4 – internal oil tank; 5 – external tank; 6 – load control valve; 7 –overpressure protecting valve

In order to change the performance characteristics of the wind rotor in the laboratory, an electric motor was used to simulate mechanical wind energy. The experimental hydraulic system consists of an oil tank, a hydraulic pump, a pipe system and an oil flow control valve.

A three-phase asynchronous four-pole electric motor 4AK2 90L-4B14 (Bevi, Blomstemåla, Sweden) with a power of 1.5 kW was used to simulate the performance of the wind rotor. The electric motor imitates the torque of the wind rotor shaft behind the transmission system that changes the torque. The shaft of the electric motor was connected to a gear pump shaft via rigid coupling.

The rotation frequency of the shaft of the electric motor was changed with a three-phase electric frequency converter FR-D740-036SC-EC (Mitsubishi Electric, Tokyo, Japan) with a power of 1.5 kW with the electric current flow frequency control range of 0.2–400 Hz.

The hydraulic pump X2P5702 (Vivolo, Budrio, Italy) was used for the research. The relative displacement of the pump was V_p=26.2 cm^3/rot.

The system was filled with 20 l of hydraulic oil Tellus S2 M 46 (Shell, The Hague, the Netherlands) – viscosity degree of ISO 3448 was 46, density $\rho_{15\ ^\circ C}$ = 879 kg/m^3, kinematic viscosity $\nu_{20\ ^\circ C}$ = 104 cSt, specific heat capacity of the oil c = 1.67 kJ/(kg·K).

The loading of the hydraulic system was changed by decreasing the permeability of the load control valve VRFB 90° ¾ (Contarini, Lugo, Italy) which was installed in the system. Parameter γ which describes the proportion of valve position φ and a fully opened valve position φ_{max}: $\gamma=\varphi/\varphi_{max}$ was used to describe of the valve opening position.

Speed, torque, pressure, flow, and temperature were measured during the experiment at different conditions. The specifications of the experimental measuring system are presented in the Table 2.1. At the beginning of each experiment, the room and oil temperature was equal to 20–21°C.

Table 2.1. Technical specifications of the measuring system used for the experiment with the hydraulic system

Pressure sensor	Producer	Trafag, Bubikon, Switzerland
	Type	8253.83.2317 25.0 A
	Measurement range	0–25 bar
	Maximum operating pressure	50 bar
	Measurement accuracy	± 0.3%

table continued on next page

Pressure sensor	Producer	Trafag, Bubikon, Switzerland
	Type	8253.75.2317 2.5 A.
	Measurement range	0–2,5 bar
	Maximum operating pressure	5 bar
	Measurement accuracy	± 0.3%
Pressure indicators	Producer	Lumel, Zielona Góra, Poland
	Type	N20–6112008
	Measurement range	0–20 mA
	Measurement accuracy	± 0.2% from maximum value
Tachometer	Producer	Testo, Lenzkirch, Germany
	Type	465
	Measurement range	1–99999 rpm
	Measurement accuracy	±0.02%
	Resolution	0,01 rpm (range 1–99.99 rpm) 0,1 rpm (range 100–999.9 rpm) 1 rpm (range 1000–99999 rpm)
Temperature sensors	Producer	Auregis, Kaunas, Lithuania
	Type	TJ-Pt100
	Measurement range	-50°C–400°C
	Measurement accuracy class	1/3B
	Measurement accuracy	±0,1–0,26°C (±0,04÷0.1 Ω), when the temperature is 0–100°C
Temperature indicators and data logger	Producer	Pico Technology, Cambridgeshire, United Kingdom
	Type	PT-104
	Measurement range	0–375 Ω
	Measurement accuracy	±0.015°C
	Resolution	0.001°C

The hydraulic system was tested while operating under different characteristics. The electric frequency f_{set} of the electric motor was changed from 1 to 50 Hz during the test. The opening position of the valve was changed from a fully opened position φ_{max}=9 rev. (γ=1) to a fully closed φ=0 rev. (γ=0). The simulated wind velocity v^* which corresponded to the operating regime of the electric motor was calculated for different electric motor operating regimes where the area of wind rotor was 10 m^2, the efficiency of wind energy conversion at wind rotor and gear mechanism was 0.45 and air density was 1.293 kg/m^3. The operating conditions of the experiment are presented in Table 2.2.

The experimental measurements were performed to calculate the efficiency of the mechanical energy conversion into thermal energy. The conversion efficiency is calculated according to the proportion of mechanical and the produced thermal energy.

Table 2.2. Operating conditions of the experiment

f_{set}, Hz	1	2	3	4	5	6	7	8
v *, m/s	1.18	1.79	2.16	2.50	2.76	2.97	3.10	3.29

f_{set}, Hz	10	12	14	16	20	30	40	50
v *, m/s	3.51	3.83	4.09	4.35	4.76	5.67	6.36	6.97

Mechanical characteristics of the electric motor at different operating regimes were calibrated in the Laboratory of the Electromechanical Converters (The Faculty of Electrical and Electronics Engineering of Kaunas University of Technology). The purpose of calibration was to determine the highest possible output power P_{m_out} of the tested electric motor at different electric frequencies f_{set}. The highest output power of the motor may be calculated by using the following equation:

$$P_{m\_out} = \omega_{el.motor} M_{el.motor} = 2\pi n M_{el.motor} \quad (1)$$

where: $M_{el.motor}$ – torque of electric motor shaft, N·m; $\omega_{el.motor}$ – angular velocity of the electric motor shaft rotation, rad/s; n – electric motor shaft rotation frequency, rps.

The torque of the electric motor $M_{el.motor}$ was measured with the DR-2512 torque sensor (Lorenz Messtechnik, Alfdorf, Germany) with an electric motor calibration model (Fig. 2.2.). The rotation frequency n_{set} of the electric motor shaft was measured with a contactless tachometer Testo 465 (Testo, Lenzkirch, Germany).

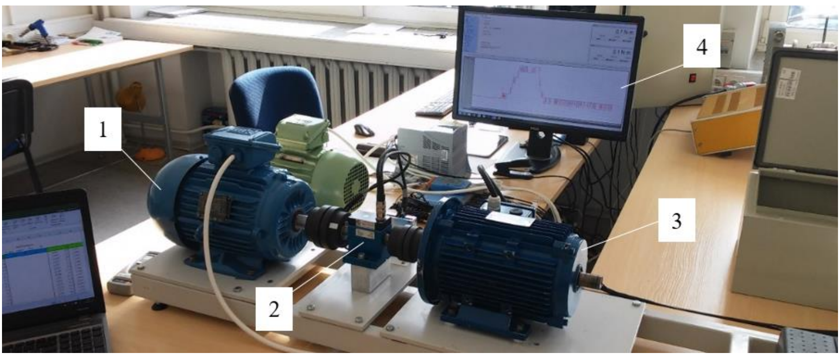

Figure 2.2. The electric motor calibration model at the laboratory of electromechanical converters: 1 – load creating motor; 2 – torque sensor; 3 – the investigated motor; 4 – monitor

A four-pole motor was used for the experiment. Its shaft rotation frequency n_{set} dependence is determined with $n_{set} = f_{set}/2$.

The results of the highest output values $P_{m\_out}=f(n_{opt})$ of the calibration of different rotation frequency n_{set} are presented in the Table 2.3.

Table 2.3. The mechanical specifications of the electric motor

f_{set}, Hz	1	2	3	4	5	6	7	8
n_{set}, rps	0.5	1	1.5	2	2.5	3	3.5	4
n_{opt}, rps	0.27	0.52	0.90	1.34	1.79	1.97	2.34	2.60
P_{m_out}, W	4.7	16.3	28.4	44.5	59.4	74.2	84.6	100.7

f_{set}, Hz	10	12	14	16	20	30	40	50
n_{set}, rps	5	6	7	8	10	15	20	25
n_{opt}, rps	3.75	4.26	5.32	6.08	8.05	12.50	16.82	21.83
P_{m_out}, W	122.5	159.9	193.8	233.0	305.9	518.1	728.7	959.8

Electric current parameters analogous to the mechanical characteristics of the experimental electric motor were used to estimate the thermal performance efficiency of the system (Table 2.2.). Each series of experiments started with a fully opened load control valve (γ=1) and continued until the valve was fully closed ($\gamma \longrightarrow 0$). The rotation frequency n of the hydraulic pump shaft and oil pressure in the system before and after the load control valve was calculated for each experiment. The readings of the pressure sensors indicate a pressure drop in the load control valve. The characteristics of the hydraulic system during the experimental series when $f_{set}=const$ are presented in Table 2.4.

Table 2.4. The operating regimes of the hydraulic system

No.	Operating regime of the system	Degree of the control valve opening, γ	Rotation frequency, n and torque, M	Pressure drop, Δp	Flow rate of heat-transfer media, Q
1	Unloaded system	$\gamma = 1$	$n = n_{max}$ $M \approx 0$	$\Delta p \approx 0$	$Q = Q_{max}$
2	System loading	$\gamma \longrightarrow \gamma_{opt}$ $(0 < \gamma < 1)$	$n \longrightarrow n_{opt}$ $M \longrightarrow M_{opt}$	$\Delta p \longrightarrow \Delta p_{opt}$	$Q \longrightarrow Q_{opt}$
3	Optimal performance regime	$\gamma = \gamma_{opt}$	$n = n_{opt}$ $M = M_{opt}$	$\Delta p = \Delta p_{opt}$	$Q = Q_{opt}$
4	System overloading	$\gamma \longrightarrow 0$ $(0 < \gamma < 1)$	$n \longrightarrow 0$ $M \longrightarrow M_{max}$	$\Delta p \longrightarrow \Delta p_{max}$	$Q \longrightarrow 0$
5	Overloaded system	$\gamma \approx 0$	$n \approx 0$ $M = M_{max}$	$\Delta p\downarrow$	$Q \approx 0$

During the test, the rotation frequency n of the hydraulic pump shaft as well as the flow rate Q decreased and the system was overloaded when the peak point was reached. Such overloading of the hydraulic system may be used as a hydraulic break to stop a wind rotor in case of extreme wind conditions when the marginal operating conditions of a power plant are outreached. In some scientific literature, hydraulic systems that generate heat are considered as hydraulic break systems. The load control valve is the most important device in thermal energy production at wind power plants as the control of its parameters opens a wide range of possibilities to control a power plant, thus allows adapting to low wind conditions.

The dependence of rotation frequency of the hydraulic pump on the opening degree of the valve is presented in Figure 2.3.

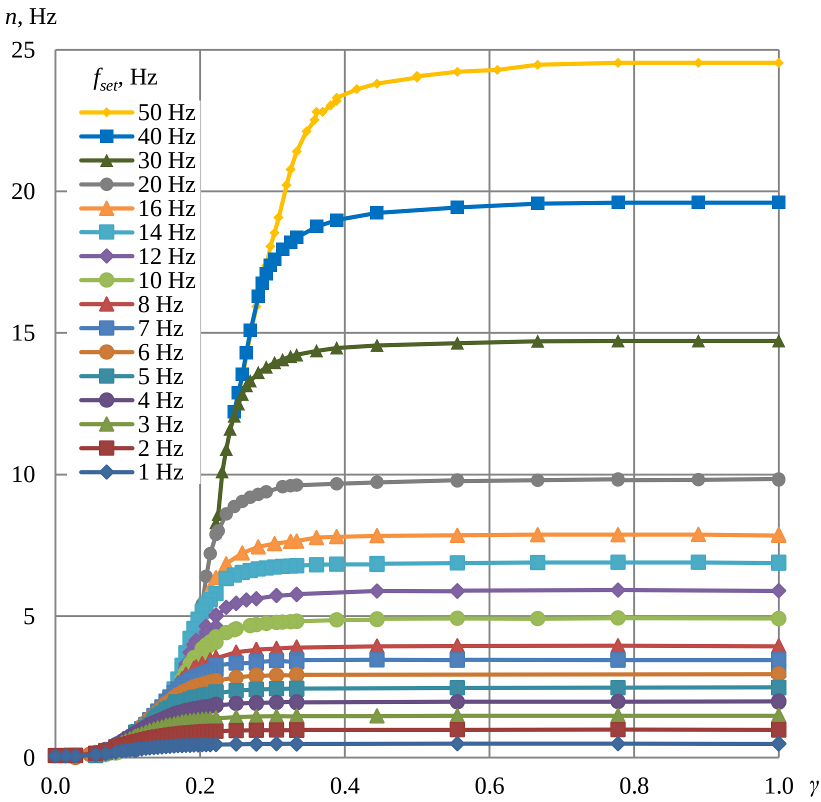

Figure 2.3. The dependence of rotation frequency n of the hydraulic pump on the degree γ of the valve opening

When a wind rotor operates with a hydraulic pump that has no gear mechanism, an opening degree γ of the load control valve directly changes the coefficient of relative linear velocity of a wind rotor. The coefficient also depends on wind velocity and it influences the power coefficient c_p of the wind rotor.

In order to achieve the maximum wind rotor power coefficient $c_p \rightarrow max$, a certain load condition γ of a hydraulic system has to bet set so that the wind rotor would operate in a coefficient zone λ of the optimal relative linear velocity. The overall energy conversion efficiency of the wind rotor and the hydraulic system is the highest when $c_p \cdot \eta_{hs} \rightarrow max$.

When converting energy, if a wind rotor operates with a hydraulic pump with a gear mechanism, energy losses occur in the reducer. The overall energy conversion efficiency of a wind rotor, reduction and a hydraulic system is maximum when $c_p \cdot \eta_{red} \cdot \eta_{hs} \rightarrow max$ (η_{red} – efficiency coefficient of the reducer).

The present study estimates the amount of thermal energy which is produced at certain valve control conditions. The thermal power of the valve is calculated with the following equation:

$$P_{Tl} = \Delta p Q = 8 \rho \zeta \frac{\eta_{pV}^3 V_p^3}{\pi^2 d^4} n^3 \quad (2)$$

where: Δp – pressure drop at valve, Pa; Q – volumetric flow rate of the oil, m³/s; ρ – oil density, kg/m³; η_{pV} – pump volumetric efficiency coefficient (1.0 is suitable for an unused pump); V_p – relative displacement of the hydraulic pump, cm³/r; d – orifice diameter, m.

Figure 2.4 presents the results of measurements and calculations.

When the rotation frequency of the pump and the load of the system increases the influence of valve control position on the load changes as well: when f_{set}=1 Hz and n_{set}=0.5 rps, a significant influence on the load is noticed at γ=0.23, when f_{set}=50 Hz and n_{set}=25 rps, a significant influence on the load is noticed at γ=0.77. Such results show that a changing hydraulic load may be influenced by the changes of energy supply in a wide range from P_{Tl}=3.7 W to P_{Tl}=767.6 W, while other technical parameters of the system remain unchanged. This indicates low inertia of the hydraulic system which generates thermal energy and allows us to utilize wind energy effectively in case of low wind velocity.

The rotation frequency of a hydraulic pump must be determined to synchronize the performance of the wind rotor with the hydraulic system for an optimal and efficient operation of the system. The experimental hydraulic system has a fixed relative displacement of the hydraulic pump V_p, therefore, $P_{Tl}=f(Q)$ (2) is implemented by $P_{Tl}=f(n)$ (2). More accurate optimal conditions of a hydraulic system would be available if a variable displacement pump were designed for the hydraulic system; however, such systems would be more complicated and expensive.

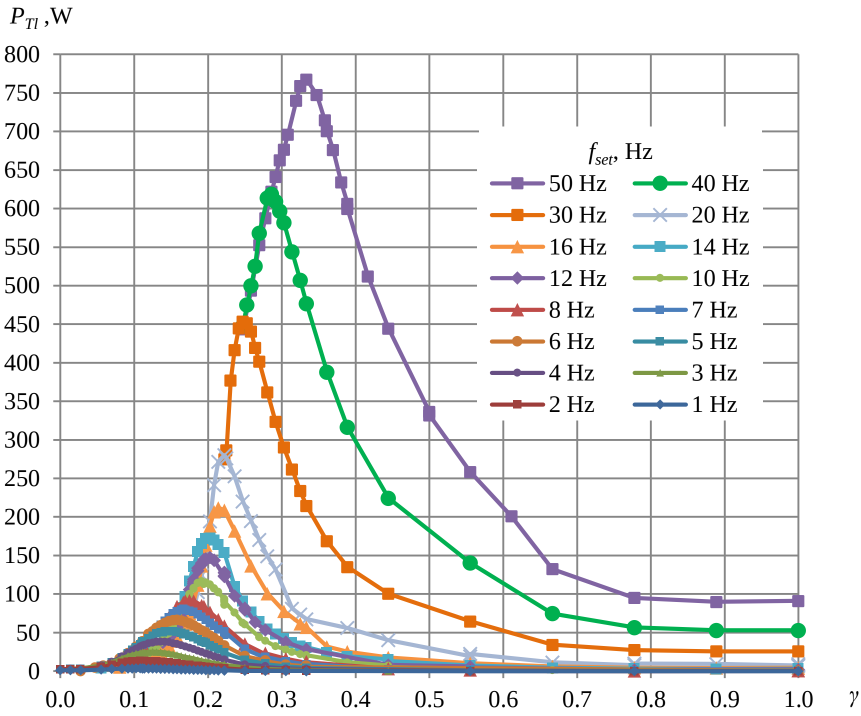

Figure 2.4. The dependence of thermal energy P_{Tl} generated by the hydraulic system on the opening degree γ of the load control valve

Figure 2.5 presents the influence of the rotation frequency of the pump n on the generated thermal power P_{Tl}.

According to $P_{Tl}=f(n)$ presented in Figure 2.5, if the optimal frequency is not suitable to achieve the highest efficiency of a wind rotor-hydraulic system due to specifications of a gear mechanism or wind rotor operating regimes, lower thermal power may be generated when the system operates at two other operating frequencies which are similar to the optimal hydraulic system $n_{-opt}<n_{opt}<n_{+opt}$. In this case, n_{+opt} is the operating frequency of the overloaded system and n_{-opt} is the operating frequency of the loaded system.

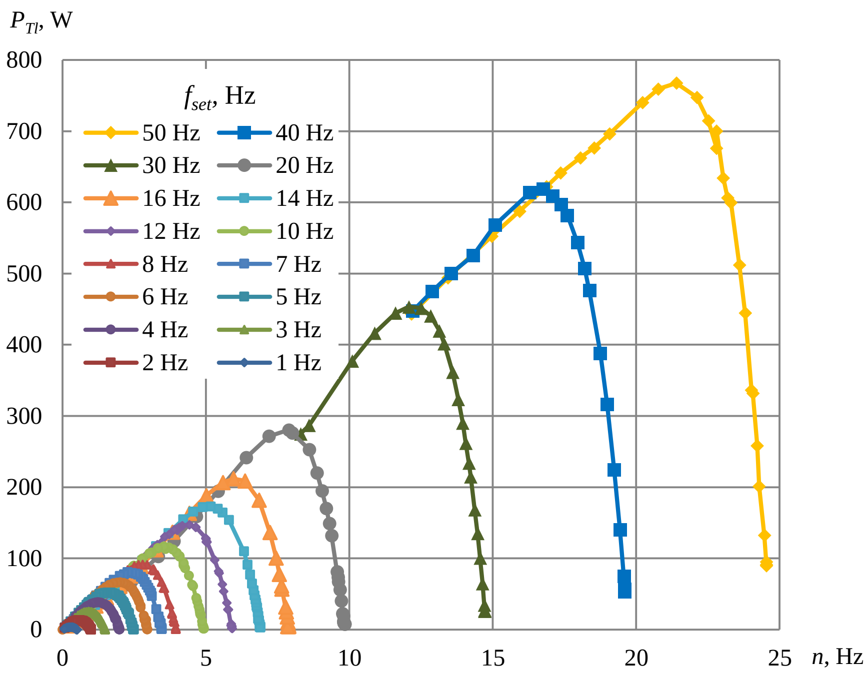

Figure 2.5. The dependence of thermal power P_{Tl} generated with the hydraulic system on the rotation frequency of the pump when f_{set}=1–50 Hz.

The direct thermal power P_T of the hydraulic system was calculated according to the readings of the temperature sensor T_5 (T_{out}), the difference of readings of the temperature sensors T_1, T_2, T_3 (T_r) and the rotation frequency n measurements of the hydraulic pumps. Calculations were carried out according to the following equation:

$$P_T = \eta_{pV} n\, V_p \rho\, c\, (T_{out} - T_r). \qquad (3)$$

where η_{pV}=1.0; V_p=2.62 cm³/rot; c=1.67 J/(kg·K); ρ=867 kg/m³ (when the oil temperature was +20°C). Complete temperature measurements were taken for not loaded to overloaded systems operating at the conditions when f_{set}=20 Hz and f_{set}=40 Hz (according to the operating regimes presented in Table 2.4). The calculations and measurements are presented in Figure 2.6 and Figure 2.7.

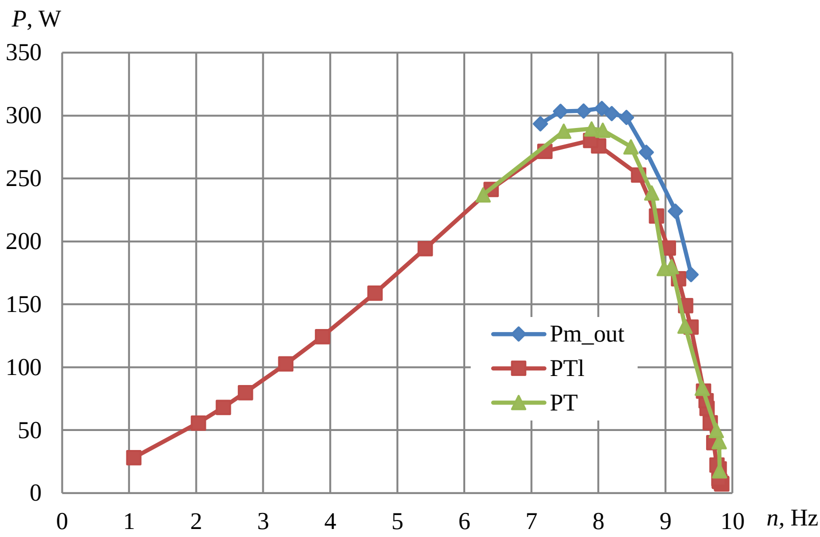

Figure 2.6. The dependence of thermal power *P* generated by the hydraulic system on the rotation frequency n of the pump when f_{set}=20 Hz

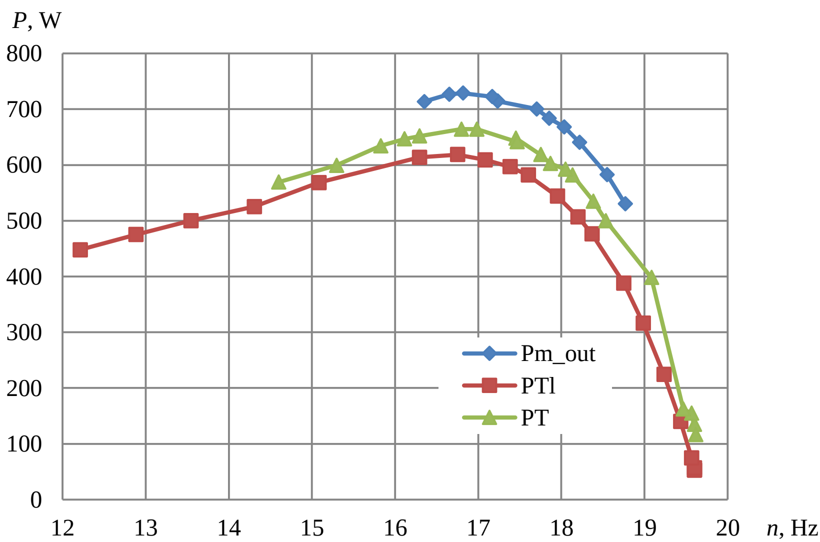

Figure 2.7. The dependence of thermal power *P* generated by the hydraulic system on the rotation frequency of the pump when f_{set}=40 Hz

According to Figures 2.6 and 2.7, optimal rotation frequencies of the hydraulic pump n_{opt} differ insignificantly when the performance of the hydraulic system is analysed according to the measurements of pressure and temperature; therefore, the measurements of other f_{set} variations are carried out when the system operates at the optimal regime frequency $n_{opt.}$

Table 2.5 presents the measurements of all temperatures in different experimental conditions.

Table 2.5. Technical parameters of the hydraulic system operating at the optimal working regime

f_{set}, Hz	1	2	3	4	5	6	7	8
n_{set}, Hz	0.5	1	1.5	2	2.5	3	3.5	4
v^*, m/s	1.18	1.79	2.16	2.50	2.76	2.97	3.10	3.29
$\gamma_{opt\_20\,°C}$	0.108	0.114	0.125	0.136	0.147	0.158	0.167	0.181
n_{opt}, Hz	0.28	0.57	0.90	1.23	1.56	2.01	2.27	2.79
P_{Tl_max}, W	3.7	13.3	25.4	38.5	52.2	66.3	80.8	91.2
P_{T_max}, W	4.4	15.4	26.5	41.9	56.1	69.1	79.8	95.1
η_{hs}	0.94	0.95	0.93	0.94	0.94	0.93	0.94	0.94

f_{set}, Hz	10	12	14	16	20	30	40	50
n_{set}, Hz	5	6	7	8	10	15	20	25
v^*, m/s	3.51	3.83	4.09	4.35	4.76	5.67	6.36	6.97
$\gamma_{opt\_20\,°C}$	0.192	0.203	0.203	0.214	0.222	0.247	0.286	0.333
n_{opt}, Hz	3.54	4.42	5.17	5.96	7.88	12.07	16.75	21.40
P_{Tl_max}, W	116.9	147.3	173.0	211.9	280.3	453.3	618.5	767.6
P_{T_max}, W	115.8	151.9	181.9	220.0	289.5	483.1	664.2	881.9
η_{hs}	0.95	0.95	0.94	0.94	0.95	0.93	0.91	0.92

Table 2.5 also presents the calculated energy conversion efficiency of different conditions at the range of 0.91–0.95.

The experimental hydraulic system which uses wind energy has to be automated and respondent to the constantly changing wind conditions. The dependence of the optimal rotation frequency n_{opt} of the hydraulic pump of the experimental system on the simulated wind velocity v^* is presented in Figure 2.8.

According to the measurements provided in Figure 2.8, $n_{opt}=f(v^*)$ of the experimental device is represented by the following equation:

$$n_{opt}=0{,}0296v^{*3}+0{,}3231v^{*2}-0{,}7158v^{*}+0{,}6014. \quad (4)$$

Equation (4) may be applied to develop an algorithm of the automated system.

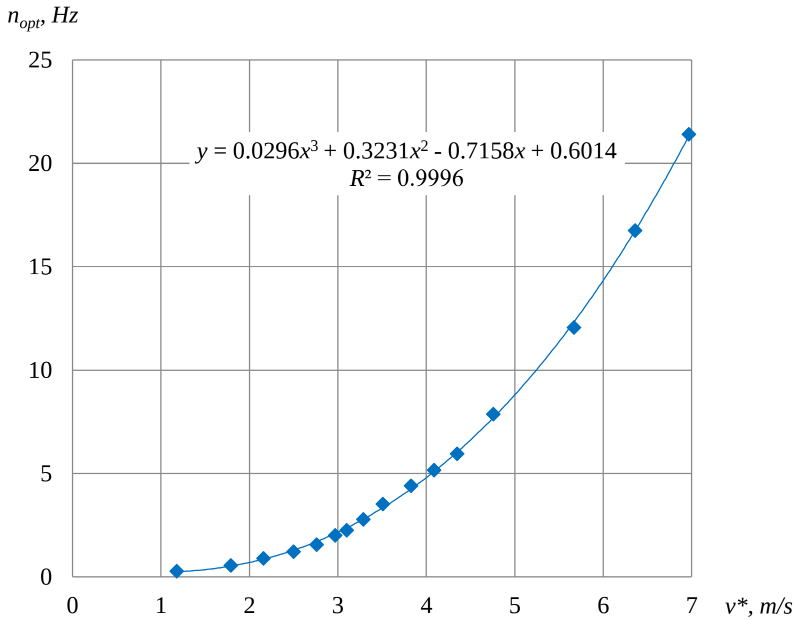

Figure 2.8. The dependence of thermal power P_T generated by the hydraulic system on the simulated wind velocity v*

3. APPLICATION OF CONVERTED MECHANICAL WIND ENERGY TO THE ENERGY DEMANDS OF A BUILDING

The object of the experimental research is a hydraulic system that converts mechanical energy into thermal as well as meets the needs of a residential building and wind conditions of a locality. Considering the requirements for newly constructed buildings, the analysis of heating demand for a 120 m² living building was carried out in order to determine the technical parameters of the hydraulic system.

The building has two floors with transparent partitions accounting for 19% of all vertical partitions. 64% of transparent partitions face the South (Fig. 3.1). The building was designed with regards to the principles of efficient use of energy in order to minimize heating expenditures during the cold season of the year and cooling expenditures during the warm season.

Fig. 3.1. A visualization of the building used for the analysis of heating demands (south-west orientation facades on the left and north-east facades on the right. Arch. Zaniauskas)

For the purpose of evaluating thermal energy demands for heating of the building, the calculations for four different variations of thermal specifications of the building's partitions were carried out: when the outside partitions meet the requirements of the energy-efficiency classes "B", "A", "A+" and "A++" which have to comply with the requirements for heating transition coefficients of the partitions which are used for the calculations of specific heat losses of the partitions (Construction Technical Regulations STR 2.01.09:2012 "Energy Performance of Building"). The calculation of thermal energy demands of the buildings was carried out according to the calculation method which is defined in STR 2.09.04:2008 in "The Power of the Heating System of the Building. Heat Demand for Heating". The estimated monthly heat demand of the building Q_h consists of monthly heat energy that covers heat loss through partitions Q_{en}, monthly heat energy that covers heat loss due to ventilation Q_v, and monthly heat gain Q_{hg}. The coefficient η_0 is used to evaluate the possibilities to absorb the gain of thermal energy through partitions. Heat demand of the building is calculated with the following equation:

$$Q_h = Q_{en} + Q_v - \eta_0 \cdot Q_{hg}. \qquad (5)$$

Heat demand with minus sign means a gain of heat (Table 3.1.).

According to the results shown in Table 3.1, heating is needed in May, June, July and September. However, there is no necessity of heating during these months in Lithuania; therefore, it is assumed that such calculation error may occur resulting in a surplus thermal energy assessment inaccuracies or multi-annual average monthly temperature inaccuracies. It is considered that the building demands no energy for heating in May and June for further calculations. The dynamics of thermal energy demand over the course of a year is presented in Figure 3.2.

Table 3.1. Calculation of heat demand for heating of the building Q_h, kWh

	Energy-Efficiency Class of the Building			
	B	A	A+	A++
January	3,520	2,178	1,843	1,547
February	2,997	1,783	1,481	1,220
March	2,317	1,224	1,002	759
April	1,203	536	459	306
May	335	313	333	323
June	195	135	105	60
July	-191	-105	-96	-111
August	-90	-24	-24	-46
September	436	280	335	329
October	1,459	814	684	586
November	2,639	1,650	1,402	1,178
December	3,424	2,156	1,837	1,553

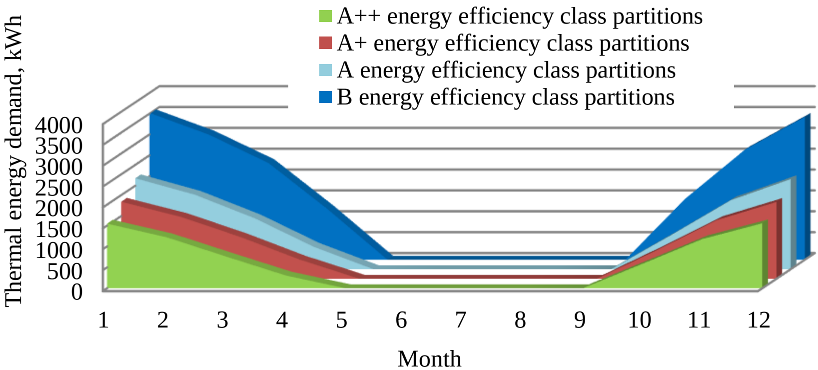

Figure 3.2. The dynamics of thermal energy demand of a private residential building over the year

In order to calculate monthly heat losses, the average monthly temperature of a locality is calculated. It is calculated according to meteorological observations of 1961–1990 considering contemporary building regulations (The Ministry of Construction and Urban Affairs of the Republic of Lithuania, 1995). However, the data of meteorological observations of Kaunas of

1981–2010 is used in this paper due to global climate warming (Galvonaitė, 2013).

The aim of this research is to determine the technical parameters of a heat producer operating at maximum load. Therefore, the heat demand of the building was estimated by calculating the average amplitude of the outdoor air temperature without considering the heat gain, assuming that such conditions may occur at night. The calculations are presented in Figure 3.3.

Although the building is not affected by the range of outdoor temperature due to its high inertia, it affects heat conductive partitions of the building, such as windows. Therefore, this was also taken into account when calculating the demands of heat.

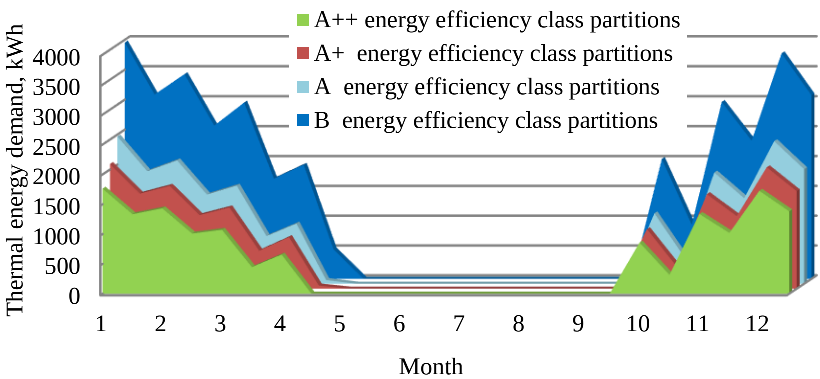

Figure 3.3. The dynamics of heat energy demand of a private residential building over the year considering the range amplitude of average monthly temperature

The power of a heating system of the building is also calculated according to STR 2.09.04:2008 "The Power of the Heating System of the Building. Heat Demand for Heating". The results of this calculation are presented in Table 3.2. The heat gain of the building was not estimated when calculating the heating energy of the building.

The power of a heat source using wind energy may be evaluated according to the demand of a heating system power. Since wind energy is variable, it cannot be the only source of energy for the building. Therefore, the power of an energy source and the percentage of annual heat demand which is covered after installation of the system has to be estimated. The monthly thermal energy demand of the building was evaluated considering the range amplitude of monthly average temperature. The power of wind energy using a heat generator of 4,0-2,0-1,5-1,0 kW was chosen and it accounted for 40–33% of the heating system power. The amount of thermal energy which can be covered by such power was calculated out of the overall heating demands for the building. Total annual energy demand for heating can be estimated by calculating the monthly demands. Calculations are presented in Table 3.2.

Table 3.2. The power of a heating system of the building, W

	Energy-Efficiency Class of a Building			
	B	A	A+	A++
Power of heating system of the building, W	9,975	5,041	3,919	3,054
Total thermal energy demand for heating per year , kWh	17,558	10,342	8,708	7,149
Comparative total thermal energy demand for heating per year , kWh/m^2	146	86	73	60
Alternative energy source power in the building, W	4,000	2,000	1,500	1,000
Output of wind energy using a heat generator out of the overall power of the heating system designed for the building, %	40%	40%	38%	33%
Total annual output of wind energy using a heat generator, kWh	16,157	8,252	6,340	4,333
Output of wind energy using a heat generator out of the overall annual heat demand for heating, %	92%	80%	73%	60%

Considering the demand of thermal energy for the building and the possible power of wind energy when using a heat generator, a 1.5 kW power energy source which covers a significant part of thermal energy demand (73%) of “A”, “A+” and “A++” class buildings was used for the experiment.

Wind energy systems for buildings as well as other renewable energy sources, such as sunlight or rain have some disadvantages related to their consumption and the potential disbalance. Although the annual dynamics of monthly average wind velocity correlates with the heat demand of a private residential building (see fig. 3.4), the velocity sometimes is very low; therefore, it cannot be processed technologically. The heating system of a building is inert and, depending on the energy efficiency of the building, it may take a few or a dozen hours to maintain the hygienic requirements corresponding with the temperature mode, but the building must be equipped with the guaranteed reserve of thermal energy source for lingering periods without wind. The reservoir may also be used for water heating, the consumption dynamics of which depend on individual needs rather than on climate conditions.

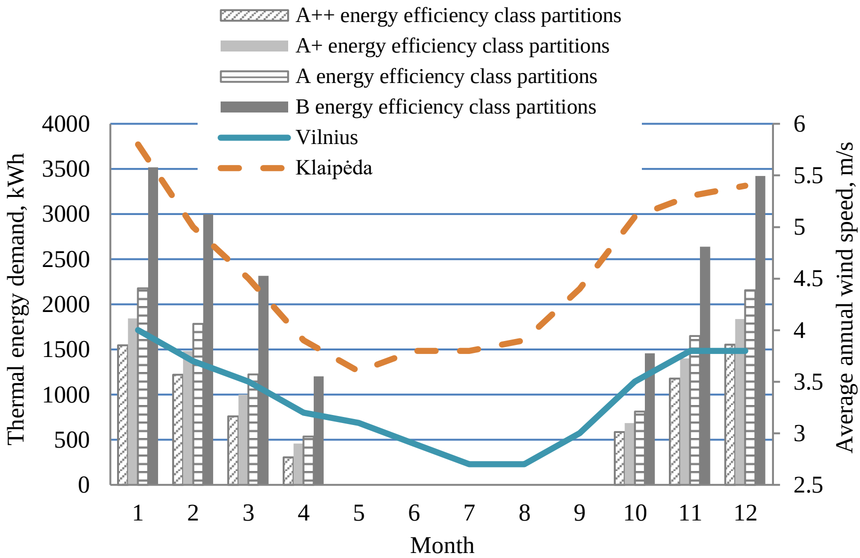

Figure 3.4. The dynamics of thermal energy demands for a private residential building and the dynamics of wind velocity of meteorological stations in Vilnius and Klaipėda over a year

Thermal energy may be delivered directly to the building when its thermal energy demand coincides with the generated energy. However, the temperature of heat-transfer media in such cases varies depending on the outdoor air temperature. When the temperature of heat-transfer media starts to change, the hydraulic friction coefficient λ, which is dependent on the fluid kinematic viscosity coefficient υ, and the temperature of the fluid starts to influence the production of thermal energy. In such case, hydraulic system automation is more complicated; therefore, the calculations with equation (3) and the measurements of wind velocity and rotation frequency are not sufficient to establish a signal for the gear of control valve. The analysis of the heat-transfer media under different temperatures (+20°C, +30°C, +40°C, +50°C) was carried out and the alteration of the position of the load control valve at f_{set}=20 Hz and f_{set}=40 Hz was estimated to justify the latter assumption. Hydraulic oil with the viscosity degree 46 (according to ISO 3448) was used for the experiment; its kinematic viscosity coefficient υ starts to change from 104 cSt when the temperature of oil is 20°C and from 30 cSt when the temperature is 50°C. The results are presented in Figures 3.5 and 3.6.

According to the results presented in Figures 3.5 and 3.6, although the alteration of load control opening degree γ is insignificant $\Delta\gamma$=0,014, when the capacity of the energy source is higher - f_{set}=40 Hz, it increases to $\Delta\gamma$=0,039 at f_{set}=20 Hz and may become significant at lower capacity of the energy source. It shows that if the hydraulic system operated at more constant temperature regime it would be simpler to control it.

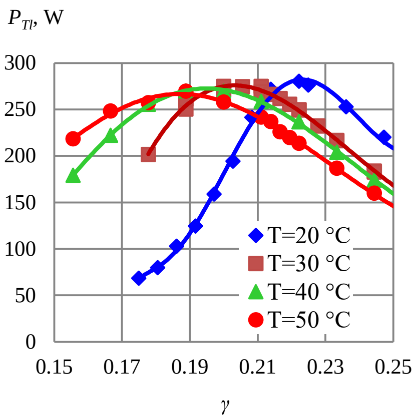

Fig. 3.5. The dependence of thermal power P_{Tl} of the hydraulic system on the load control valve degree γ at different temperatures of the heat-transfer media when f_{set}=20 Hz

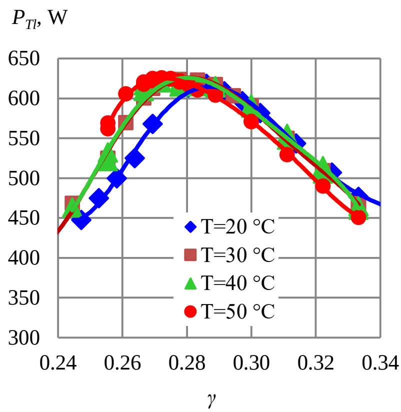

Fig. 3.6. The dependence of thermal power P_{Tl} of the hydraulic system on the load control valve degree γ at different temperatures of the heat-transfer media when f_{set}=40 Hz

More stable temperature regimes may be ensured by a larger thermal energy capacity accumulator. This may be achieved by the means of ground using such devices as heat pumps which transfer thermal energy. In such case, the heat pump operates as the guaranteed thermal energy reservoir and wind energy potential of warm season of the year is utilized. Figures 3.7 and 3.8 present the principle schemes of wind energy supply by integrating the heat pump.

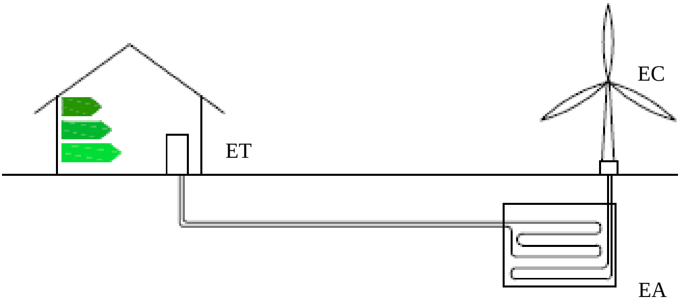

Figure 3.7. Wind energy conversion system for individual consumption: Wind rotor – Heat generator (energy conversion EC) – Heat accumulator (energy accumulation EA) – Heat network of the site – Heat pump (energy transformation ET) – Heating system of the building

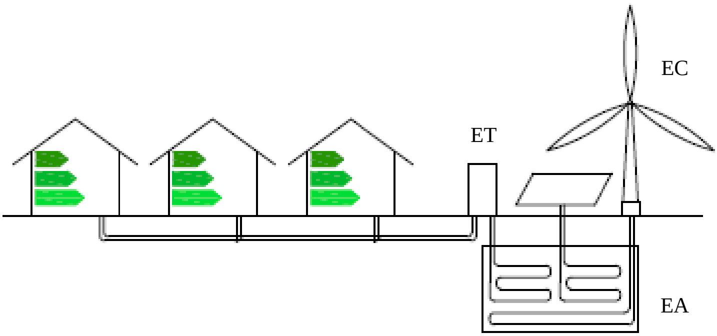

Figure 3.8. Wind energy conversion system for a group of consumers: Wind rotor – Heat generator (energy conversion EC) – Heat accumulator (energy accumulation EA) – Heat network of the locality – Heat pump (energy transformation ET) – Heating system of the building

The systems of these schemes may be divided into subsystems and analysed according to their function: the wind rotor and heat generator as the energy conversion subsystems (EC), heat networks as the energy transferring subsystems, heat pump as the energy transformation subsystem (ET). Each subsystem has its energy efficiency coefficient. It also reduces the primary energy and adjusts it to the consumers' needs. As energy transfer over time is one of the main issues of renewable energy sources, consumption energy accumulation (EA) is another significant subsystem for the consumption of renewable energy sources. Considering the future perspectives of renewable energy consumption, the use of such system including such subsystems as EC, EA and ET should be encouraged. Many of these subsystems can be evaluated by using analytical methods and statistics. They change under certain circumstances, while the process of mechanical energy conversion into heat depends on the same conditions but not on the building or on its locality. Sunlight and surplus thermal energy of various technological operations may also be accumulated and utilized as a thermal energy source at the wind energy conversion system for a group of consumers presented in Figure 3.8, thus expanding the use of sustained energy sources.

CONCLUSIONS

1. According to scientific literature, particular attention is paid to the construction sector with regards to the prevention of negative climate change due to a relatively low energy-efficiency of buildings leading to high energy costs. An integration of various renewable energy sources into energy systems in Lithuania is supported and encouraged by the government.
2. The statistics reflect wind power currently converted into electrical energy, even though, technically, wind energy conversion into heat is being implemented and remains a studied aspect of engineering. However, wind energy conversion into heat lacks an objective scientific assessment and this is, therefore, a big obstacle for a larger-scale usage of such systems.
3. The annual needs of thermal energy for heating and ventilation of an energy-efficient individual residential house were determined and consist of 17.558 MWh (146 kWh/m^2) for the building of energy performance class "B" and 7.149 MWh (60 kWh/m^2) for the building of “A++” energy performance class (2.46 times less). Respectively, the design heating power for the mentioned buildings is from 9.975 kW to 3.054 kW.
4. The research suggests that if a heat source corresponding to 33% of the power of designed heating system is installed in a nearly zero-energy building and the average monthly outdoor air temperature range amplitude is estimated, such energy source may cover up to 60% of the annual thermal energy demand for heating and ventilation of the building.
5. The calculations of correlation coefficient between the energy needs for heating of individual residential houses of different energy efficiencies and different areas of wind energy potential show that there is a strong correlation (ρ>0.70) between these parameters with a tendency to increase with increasing building energy performance class – from ρ=0.774 for energy efficiency class “B” of the building to ρ=0.858 for energy efficiency class “A++” of the building in Klaipeda and from ρ=0.907 for energy efficiency class “B” of the building to ρ=0.946 for energy efficiency class “A++” of the building in Vilnius.
6. The experimental hydraulic system that generates heat allows to analyse the process of mechanical energy conversion into thermal universally ($n=f(\gamma)$, $P_{Tl}=f(\gamma)$, $P_{Tl}=f(n)$) and in a wide range of options (when the power of energy source is from 5 W to 950 W). The range of energy conversion efficiency when

the energy was converted by the experimental hydraulic system was more than 91%.

7. The automation algorithm of performance of the experimental hydraulic system and the interaction of signals of the controller at the optimal performance of the energy conversion system were calculated and described by the following equation: n_{opt}=0,0296v^{*3}+0,3231v^{*2}−0,7158 v^{*}+0,6014.

8. The algorithm describing wind energy integration into the building heating system, consisting of the modules of wind rotor, hydraulic generator of the thermal energy, thermal energy accumulator and heat pump, was created.

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Information about the author

Jurgita Černeckienė was born on June 21, 1979 in Kaunas, Lithuania. Contact information: mob. phone +370 615 31533; e-mail: jurg.cerneckiene@gmail.com, jurgita.cerneckiene@ktu.lt,
1985-1997: Kaunas J. Urbšys Secondary School;
1997-2001: Bachelor studies and BA degree at Kaunas University of Technology, Faculty of Civil Engineering and Architecture;
2001-2003: Master studies and MA degree at Kaunas University of Technology, Faculty of Civil Engineering and Architecture;
2012-2016: Doctoral studies at Kaunas University of Technology, Faculty of Civil Engineering and Architecture;
2002-2007: Civil engineer, JSC "Gilius ir Ko";
2013-2017: Assistant at Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Department of Building Energy Systems;
Since 2007: Building energy efficiency certification expert, freelancer.
Since 2017: Lecture at Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Department of Building Energy Systems.

Scientific internships

From the 22nd to the 28th of March, 2015 – an internship at Technical University of Denmark (DTU).

Acknowledgements

I am very grateful to my scientific supervisor, head of the Department of Building Energy Systems, KTU, prof. PhD Tadas Ždankus for his sincere support during the PhD studies. I also would like to say many thanks to the entire personnel of the Department of Building Energy systems for their valuable comments, critics, help and inspiration.

The author is especially thankful to her husband Mindaugas, her mother, children and whole family for their patience, every kind of help and support during the years of studies.

REZIUMĖ

Tiesioginis mechaninės vėjo energijos konvertavimas į šiluminę energiją hidraulinėje sistemoje ir jos naudojimas pastatui šildyti leidžia praplėsti vėjo energijos, kurios naudojimo metu nesusidaro šiltnamio efektą sukeliančios dujos, taikymo ribas. Disertacijos tyrimo objektas yra šiluminės energijos generavimo hidrauliniame įrenginyje procesas, kaip energijos šaltinį naudojant simuliuojamą mechaninę vėjo energiją.

Disertaciją sudaro įvadas, 3 skyriai, bendrosios išvados, naudotos literatūros sąrašas ir publikacijų disertacijos tema sąrašas.

Pirmas skyrius skirtas literatūros analizei, kurioje apžvelgiamos energetikos politikos gairės ir aktualijos, vėjo energijos naudojimo ypatumai bei vėjo energijos konvertavimo į šiluminę energiją patirtis moksliniu bei praktiniu aspektu.

Antrame skyriuje aprašoma tyrimui sukurtos hidraulinės sistemos konstrukcija, vėjo energijos simuliavimo sistema bei eksperimento metu naudota matavimų įranga. Taip pat šiame skyriuje aprašoma šiluminę energiją konvertuojančios hidraulinės sistemos tyrimo metodika, aptariami atlikto eksperimentinio tyrimo rezultatai bei pateikiami siūlymai hidraulinės sistemos darbo optimizavimui.

Trečiajame skyriuje analizuojama šiluminės energijos poreikių dinamika metų bėgyje skirtingų energinio naudingumo klasių individualiems gyvenamiesiems namas bei šiluminės energijos poreikių koreliacija su vėjo energijos potencialu dviejuose charakteringuose pagal vėjo energetiką Lietuvos miestuose – Vilniuje ir Klaipėdoje. Taip pat skyriuje pateikiamos galimos vėjo energijos integravimo į pastato šildymo sistemą schemos, aptariamos jų savybės, privalumai bei trūkumai.

Darbo uždaviniai

1. Įvertinti būdingų mažai energijos naudojančių pastatų šildymo ir vėdinimo energijos poreikius, nustatant pastato šildymo sistemos šiluminę galią.
2. Išanalizuoti vėjo energetikos aspektu būdingų Lietuvos vietovių metinio vėjo energijos potencialo dinamiką ir jos atitikimą pastato šiluminės energijos poreikiams.
3. Elektros varikliu imituojant vėjo jėgainės darbą eksperimentiškai ištirti hidraulinio įrenginio šilumos gamybos dėsningumus, sudaryti hidraulinio įrenginio darbo kreives esant skirtingiems darbo režimams.
4. Išanalizuoti eksperimentinės hidraulinės sistemos automatinio reguliavimo galimybes, įvertinant energijos konvertavimo hidraulinėje sistemoje specifiką.
5. Sudaryti algoritmą, kuriuo vadovaujantis iš vėjo energijos konvertuota šiluminė energija gali būti integruota į pastato šildymo sistemą.

Mokslinis naujumas

Mechaninės energijos konversija į šiluminę energiją nagrinėta hidraulinėse sistemose kaip nepageidaujamas šalutinis reiškinys, bet nėra darbų, kuriuose nagrinėjamas šiluminės energijos generavimo procesas kaip pagrindinis sistemos uždavinys. Siekiant panaudoti vėjo, kaip atsinaujinančio energijos šaltinio, energiją pastatų šildymo sistemose, buvo sukurta eksperimentinė šilumą generuojanti hidraulinė sistema ir nustatyta šilumą generuojančios hidraulinės sistemos optimalaus darbo režimo valdymo lygtis, leidžianti suderinti hidraulinės sistemos darbą su pirminiu energijos šaltiniu – vėju. Modeliuojant hidraulinės sistemos darbą buvo atliekamos vėjo energijos simuliacijos apimant mažų vėjo greičių intervalą. Gauti tyrimo rezultatai ir sudarytas vėjo energijos integravimo į pastato šildymo sistemą algoritmas praplečia statybos inžinerijos mokslo šaką.

Išvados

1. Atlikus literatūros analizę pastebima, kad klimato kaitos suvaldymo procese pastatų sektoriui skiriamas didelis dėmesys, dėl palyginti mažo pastatų energinio efektyvumo ir dėl jo susidarančių didelių energijos sąnaudų. Lietuvoje įvairių AEI integravimas į pastato energetines sistemas yra skatinamas ir reglamentuojamas valstybės.
2. Visa statistikoje atsispindinti vėjo energija šiuo metu konvertuojama į elektros energiją, nors techniškai vėjo energijos konvertavimas į šilumą yra įgyvendinamas ir inžineriniu aspektu nagrinėtas. Vėjo energijos konvertavimo į šilumą procesas stokoja objektyvaus mokslinio įvertinimo, o tai gali būti trikdis diegiant tokio tipo sistemas praktiškai.
3. Nustatyti metiniai mažai energijos naudojančio individualaus gyvenamojo namo šiluminės energijos poreikiai šildymui ir vėdinimui sudaro nuo 17,558 MWh (146 kWh/m^2) „B“ energinio naudingumo klasės pastatui iki 7,149 MWh (60 kWh/m^2) „A++“ energinio naudingumo klasės pastatui (t. y. 2,46 karto mažiau), o pastatui reikalinga šildymo sistemos galia sudaro atitinkamai nuo 9,975 kW iki 3,054 kW.
4. Nustatyta, kad energijos beveik nenaudojančiame pastate įdiegus 33 proc. projektinės šildymo sistemos galios atitinkantį šilumos šaltinį bei įvertinus vidutinę mėnesinę šildymo sezono lauko oro temperatūros svyravimo amplitudę, jis gali užtikrinti iki 60 proc. pastato metinių šiluminės energijos poreikių šildymui ir vėdinimui.
5. Lietuvos klimatinėmis sąlygomis atlikti koreliacijos koeficiento tarp skirtingų energinio naudingumo klasių individualaus gyvenamojo namo energijos poreikių šildymui ir skirtingų vietovių vėjo energijos potencialo skaičiavimai rodo, kad egzistuoja stiprus šių parametrų koreliacinis ryšys ρ>0,70 turintis tendenciją didėti, didėjant pastato energinio naudingumo klasei – nuo ρ=0,774 „B“ energinio naudingumo klasės pastatui iki ρ=0,858 „A++“ energinio naudingumo klasės pastatui Klaipėdoje ir nuo

ρ=0,907 „B“ energinio naudingumo klasės pastatui iki ρ=0,946 „A++“ energinio naudingumo klasės pastatui Vilniuje.

6. Sukurta eksperimentinė šilumą generuojanti hidraulinė sistema leidžia įvairiapusiškai ($n=f(\gamma)$, $P_{Tl}=f(\gamma)$, $P_{Tl}=f(n)$) ir plačiose ribose (kai energijos šaltinio galia yra nuo 5 W iki 950 W) analizuoti mechaninės energijos konvertavimo į šiluminę energiją procesus. Nustatytas eksperimentinės hidraulinės sistemos energijos konvertavimo proceso efektyvumas didesnis nei 91 proc.
7. Nustatytas tiriamos eksperimentinės hidraulinės sistemos darbo automatizavimo sistemos algoritmas ir valdiklio įėjimo signalų tarpusavio ryšys optimaliam energijos konvertavimo sistemos darbui, aprašomas lygtimi: $n_{opt}=0{,}0296v^{*3}+0{,}3231v^{*2}-0{,}7158v^{*}+0{,}6014$.
8. Sudarytas vėjo energijos integravimo į pastato šildymo sistemą algoritmas, kai sistemą sudaro vėjaratis, mechaninę vėjo energiją į šiluminę energiją konvertuojantis hidraulinis įrenginys, šiluminės energijos kaupykla ir šilumos siurblys.

Informacija apie autorę

Jurgita Černeckienė gimė 1979 m. birželio 21 d. Kaune. Kontaktinė informacija: mob. tel.+370 615 31533; el. paštas: jurg.cerneckiene@gmail.com, jurgita.cerneckiene@ktu.lt,

1985-1997: Kauno J. Urbšio vidurinė mokykla;

1997-2001: Statybos inžinerijos bakalauro studijos ir kvalifikacinis laipsnis Kauno technologijos universitete, Statybos ir architektūros fakultete;

2001-2003: Statybos inžinerijos magistro studijos ir kvalifikacinis laipsnis Kauno technologijos universitete, Statybos ir architektūros fakultete;

2012-2016: Statybos inžinerijos doktorantūros studijos Kauno technologijos universitete, Statybos ir architektūros fakultete;

2002-2007: projekto dalies vadovė, UAB “Gilius ir Ko”;

2013-2017: asistentė Kauno technologijos universitete, Statybos ir architektūros fakultete, Pastatų energinių sistemų katedroje;

Nuo 2007: pastatų energinio naudingumo sertifikavimo ekspertė.

Nuo 2017: lektorė Kauno technologijos universitete, Statybos ir architektūros fakultete, Pastatų energinių sistemų katedroje.

Mokslinės stažuotės

2015 m. kovo 22-28 d. – mokslinė stažuotė Danijos technikos universitete, Vėjo energetikos departamente (DTU).

Padėka

Dėkoju mokslinio darbo vadovui, KTU Pastatų energinių sistemų katedros vedėjui, prof. dr. Tadui Ždankui už nuoširdžią pagalbą ir konsultacijas rengiant disertaciją. Taip pat noriu padėkoti visiems Pastatų energinių sistemų katedros kolegoms už jų vertingus patarimus, kritiką bei įkvėpimą disertacijos rengimo metu.

Už kantrybę, visokeriopą paramą ir palaikymą esu ypač dėkinga vyrui Mindaugui, savo mamai, vaikams bei visiems artimiesiems.

UDK 697.1+621.22+697.7](043.3)

SL344. 2017-06-28, 2,5 leidyb. apsk. l. Tiražas 50 egz.

Išleido Kauno technologijos universitetas, K. Donelaičio g. 73, 44249 Kaunas

Spausdino leidyklos „Technologija“ spaustuvė, Studentų g. 54, 51424 Kaunas