VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Giedrė STRECKIENĖ

RESEARCH OF HEAT STORAGE TANK OPERATION MODES IN COGENERATION PLANT

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
ENERGETICS AND POWER ENGINEERING (06T)

VGTU LEIDYKLA

Vilnius TECHNIKA 2011

Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2006–2011.

Scientific Supervisor

Prof Dr Habil Vytautas MARTINAITIS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T).

Consultant

Prof Dr Habil Petras VAITIEKŪNAS (Vilnius Gediminas Technical University, Technological Sciences, Environmental Engineering – 04T).

The dissertation is being defended at the Council of Scientific Field of Energetics and Power Engineering at Vilnius Gediminas Technical University:

Chairman

Prof Dr Habil Rimantas KAČIANAUSKAS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T).

Members:

Prof Dr Egidijus Saulius JUODIS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T),

Assoc Prof Dr Arnas KAČENIAUSKAS (Vilnius Gediminas Technical University, Technological Sciences, Mechanical Engineering – 09T),

Dr Robertas POŠKAS (Lithuanian Energy Institute, Technological Sciences, Energetics and Power Engineering – 06T),

Prof Dr Habil Stasys ŠINKŪNAS (Kaunas University of Technology, Technological Sciences, Energetics and Power Engineering – 06T).

Opponents:

Prof Dr Habil Benediktas ČĖSNA (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T),

Prof Dr Habil Gintautas MILIAUSKAS (Kaunas University of Technology, Technological Sciences, Energetics and Power Engineering – 06T).

The dissertation will be defended at the public meeting of the Council of Scientific Field of Energetics and Power Engineering in the Senate Hall of Vilnius Gediminas Technical University at 2 p. m. on 9 June 2011.

Address: Saulėtekio al. 11, LT-10223 Vilnius, Lithuania.
Tel.: +370 5 274 4952, +370 5 274 4956; fax +370 5 270 0112;
e-mail: doktor@vgtu.lt

The summary of the doctoral dissertation was distributed on 6 May 2011.

A copy of the doctoral dissertation is available for review at the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223 Vilnius, Lithuania).

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Giedrė STRECKIENĖ

KOGENERACINĖS JĖGAINĖS ŠILUMOS AKUMULIACINĖS TALPOS VEIKIMO REŽIMŲ TYRIMAI

DAKTARO DISERTACIJOS SANTRAUKA

TECHNOLOGIJOS MOKSLAI,
ENERGETIKA IR TERMOINŽINERIJA (06T)

LEIDYKLA
Vilnius TECHNIKA 2011

Disertacija rengta 2006–2011 metais Vilniaus Gedimino technikos universitete.
Mokslinis vadovas

prof. habil. dr. Vytautas MARTINAITIS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T).

Konsultantas

prof. habil. dr. Petras VAITIEKŪNAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, aplinkos inžinerija ir kraštotvarka – 04T).

Disertacija ginama Vilniaus Gedimino technikos universiteto Energetikos ir termoinžinerijos mokslo krypties taryboje:

Pirmininkas

prof. habil. dr. Rimantas KAČIANAUSKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T).

Nariai:

prof. dr. Egidijus Saulius JUODIS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T),
doc. dr. Arnas KAČENIAUSKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, mechanikos inžinerija – 09T),
dr. Robertas POŠKAS (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija – 06T),
prof. habil. dr. Stasys ŠINKŪNAS (Kauno technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T).

Oponentai:

prof. habil. dr. Benediktas ČĖSNA (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T),
prof. habil. dr. Gintautas MILIAUSKAS (Kauno technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T).

Disertacija bus ginama viešame Energetikos ir termoinžinerijos mokslo krypties tarybos posėdyje 2011 m. birželio 9 d. 14 val. Vilniaus Gedimino technikos universiteto senato posėdžių salėje.
Adresas: Saulėtekio al. 11, LT-10223 Vilnius, Lietuva.
Tel.: (8 5) 274 4952, (8 5) 274 4956; faksas (8 5) 270 0112;
el. paštas doktor@vgtu.lt
Disertacijos santrauka išsiuntinėta 2011 m. gegužės 6 d.
Disertaciją galima peržiūrėti Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).
VGTU leidyklos „Technika“ 1875-M mokslo literatūros knyga.

Introduction

Topicality of the problem. Solution of heat accumulation is a wide field for scientific research, bridging both theoretical scientific issues of heat and mass transfer and practical applications. Since 1970 the research on heat and mass transfer in the heat storage tanks was intensively undertaken in order to maintain and regain the high quality heat from the storage tank. However, the developing modern technologies allow analysing processes in the storage tank in a more rapid, cheaper and more accurate way.

Combination of heat accumulation and cogeneration (CHP) technologies assists in achievement of goals of energy production efficiency and environmental pollution reduction. However, the potential of optimisation possibilities of small-scale CHP plants has not availed, and recent studies of CHP plants with heat storage and the created optimisation methods are usually narrowed by only economical selection of the equipment size. The main problem of these studies to be solved converges to a finding of minimal maintenance and operation expenses of the CHP plant under certain economic conditions. In these cases the thermal processes inside the storage tank are not examined, and this equipment in the system may be referred as "a black box". Research of operation modes of heat storage tank in the CHP plant would enable to use the theoretical knowledge in practice, contributing to a more precise selection of storage tank volume and results of modelling of the entire energy production system. It should be noted, that selection problem of CHP plant with heat storage is topical not only in Lithuania, but also in other countries.

Object of research – operation modes of heat storage tank of small-scale CHP plant and thermal stratification that formed during its operation.

Aim and tasks of the work. The aim of this work is to investigate peculiarities of operation modes of heat storage tank in small-scale CHP plant, develop an algorithm allowing to choose the tank volume and present a model allowing determination of thermal stratification in the storage tank at any time of its operation.

The tasks of the work are:

1. To investigate the characteristic operation modes of heat storage tank in small-scale CHP plant. To evaluate the impact of consumers' demands changes and electricity tariffs on the operation of the CHP plant with heat storage tank.

2. Having determined the key factors having impact on the heat storage tank size and operation, to develop the algorithm for selection of economically optimal tank volume for small-scale CHP plant.
3. Having assessed the heat and mass transfer processes, taking process in the heat storage tank, to form the semi-analytical and numerical models, which allow determining thermal stratification at any moment of operation of the heat storage tank.
4. To compare the results of numerical and semi-analytical modelling with the actual data of the heat storage tank.
5. To present the recommendations for engineering calculations in selecting of heat storage tank for the CHP plant and determining thermal stratification in the storage tank.

Methodology of research. In order to perform the defined tasks, the combination of various methods and models is applied in the work. A case study method, implemented on the base of simulation model *energyPRO*, and economical research methodology are chosen for technical and economical evaluation of the heat storage tank in the CHP plant. Sensitivity analysis is employed for risk assessment. The semi-analytical and numerical research, which uses the package *PHOENICS* incorporating the finite volume method, is applied in the analysis of thermal processes in the storage tank.

Scientific novelty

1. Analysis of selection of the storage tank volume for small-scale CHP plant is performed with a reference to consumers' demand, electricity tariffs and CHP plant operation strategy. Investigated cases of CHP plant installation are:
   – when this system satisfies a part of consumer's electricity demand and
   – when all electricity produced by CHP unit is sold in spot market.
2. Numerical models (two-dimensional and three-dimensional) are created and two semi-analytical models are adapted for simulating the thermal stratification in heat storage tanks installed both in CHP plants and other energy production systems.

Practical value. Assessment of heat storage tank, as presented in this work, can serve a versatile analysis of CHP plants. The research results may be used during planning and engineering design of CHP plants, when the optimal storage tank volume is determined in the system adequately to the consumption. The created semi-analytical models may be easily integrated to optimisation and simulation models enabling selection and analysis of the energy production systems with heat storages. This would allow estimating thermal processes and thermal stratification in the storage tank. Meanwhile, numerical model can be applied for more specific research of stratified storage tanks.

Defended propositions

1. When the CHP unit in the CHP plant operates at nominal power, only two characteristic operation regimes are formed in heat storage tank.
2. When the curves of consumers' energy demand are more complicated, more potential alternatives occur for operation strategy of CHP unit and heat storage tank.
3. Greater fluctuation in electricity prices in spot market promotes the use of CHP plants with heat storage.
4. The created numerical model, the prepared semi-analytical energy balance and "plug flow" models are proper to be used in research of heat storage tanks of different volume and purpose.
5. Application possibilities of the created numerical model are more flexible and more diverse than of semi-analytical models, however, this model is more computationally expensive and requires investigator's specific technical skills.

The scope of the scientific work. The scientific work consists of the general characteristic of the dissertation, 4 chapters, general conclusions, list of literature, list of publications and addenda. The total scope of the dissertation is 136 pages, 65 pictures, 11 tables and 2 addenda.

1. Analysis of heat accumulation in storage tanks

In this chapter the possibility of heat accumulation in the stratified thermal energy storage tanks is analysed. The literature review has showed that the formation of the thermal stratification is determined by the geometry of the storage tank, the inlet, the hydrodynamics and thermal characteristics of the water flow in the tank. With advancement of computer technologies, more two-dimensional and three-dimensional simulations are performed in thermal stratification field. However, there is still noticed the demand of numerical and analytical models that can furnish the results in an accurate and rapid way.

One of the fields of thermal energy storage application is the installation of heat storage tank in CHP plant. In this system the heat storage tank provides flexibility for CHP plant, as plant operation becomes less dependent on consumers' heat demand that is alternating in time. With storage tank installed, the production of electricity and heat can be uncoupled for a period of time. Such uncoupling can be very beneficial for enabling maximum electricity production during the hours where electricity is being paid the best. Studies that were performed in CHP with heat storage usually approach only economical aspects of the CHP plant. In the accomplished engineering calculations and optimisation models the heat storage tanks are examined as non-stratified tanks. Considering this, there appear a need to integrate into the available software the unsophisticated engineering calculations and analytical methods that are designed to determine the thermal stratification in the heat storage tank.

2. Methods for selecting storage tank size and determining thermal stratification

In this chapter an economical model of selection of storage tank volume is described. The model consists of consumers' demand segregation, evaluation of economic and technological circumstances, composition of cases to be analysed, introduction of principal scheme of the analysed system, finding of an algorithm of economically optimal storage tank volume. A simple CHP system is investigated. The system contains a CHP unit (gas engine), a peak boiler and a hot water storage tank. *energyPRO* software has been chosen for the economic analysis because it allows the user to carry out a comprehensive, integrated and detailed technical analysis. The economic feasibility analysis of the chosen CHP plant configuration is based on the net present value (NPV) and simple payback time. The NPV is selected as the preferred criteria for the optimality of the CHP plant configuration.

Two models are prepared in order to carry out the semi-analytical determination of thermal stratification in the heat storage tank: energy balance model and "plug flow" model. During analytical investigation of temperature distribution in the heat storage tank at any time of its operation, the entire tank is divided into *N* equal layers. In energy balance model an every layer of this storage tank is described by following equation:

$$(m_i c_p)\frac{dT_i}{d\tau} = \psi_i^p \left(\dot{m} c_p\right)_p \left(T_p - T_i\right) - \psi_i^d \left(\dot{m} c_p\right)_d \left(T_i - T_d\right) - kA_{pav}\left(T_i - T_a\right)$$
$$+ \psi_i^+ \dot{m}_i c_p \left(T_{i-1} - T_i\right) + \psi_i^- \dot{m}_{i+1} c_p \left(T_i - T_{i+1}\right) + A_i \frac{\lambda_{eff}}{z_i}\left(T_{i+1} - 2T_i + T_{i-1}\right), \quad (1)$$

where m – mass; c_p – specific heat capacity at constant pressure; T – temperature; τ – time; k – overall heat transfer coefficient; A_{pav} – exterior surface of the layer; A_i – cross-section are of the layer; λ_{eff} – effective vertical heat conductivity; z_i – height of the layer; ψ – parameter which indicates if flow exist or not; subscripts: p – production; d – demand.

In "plug flow" model the volume of inflow during the particular period is inserted in to the model of the tank, and correspondingly the same fluid volume is removed. Layers in the tank are changed from above downwards or from bottom upwards with reference to the nature of the process, i.e. charging or discharging. Implementing this model every layer of this tank is described by following equation:

$$T_{i,\tau} = T_a + (T_i - T_a)\exp\left(\frac{-kA_{pav}\Delta\tau}{m_i c_{p,i}}\right), \quad (2)$$

where $T_{i,\tau}$ – temperature of the respective layer after time $\Delta\tau$.

In semi-analytical calculations the mass of layer i is assessed to be product of water density and volume. As the water density and specific heat depends on temperature, so these values are assessed to be functions subordinate to temperature.

Numerical modelling of thermal stratification in heat storage tank is performed using *PHOENICS* software, based on a finite volume method. Transient heat and mass transfer processes bound in the storage tank are described by continuity, momentum and energy equations.

In order to check the accuracy of results received using different models, the data of the real heat storage tank in *Hvide Sande* CHP plant are used. This storage tank is 14.99 m height, 12.9 m in diameter; it has 0.3 m of thermal insulation. During operation of CHP plant, temperature of hot water fed to the top of the tank reaches about 94–95 ºC, temperature of cold water fed from the bottom of the tank is less, about 42–45 ºC. Temperature data of the tank are obtained from 15 PT100 temperature sensors. Lowest temperature sensor is installed in height of 0.5 m above the bottom of the tank; the highest sensor is located 0.5 m below upper diffuser, which is fitted in height of 14.49 m. Error of the used temperature sensors ranges from ±0.50 ºC to ±0.78 ºC when the temperature of stored water is in range 40 ºC to 95 ºC.

3. Economic analysis of storage tank volume selection

Performing search and analysis of economically optimal tank volume in CHP plant, several different consumers' demands were analysed. Type *A* consumer is characterised by the scenario, when there is only one increase in demand of domestic hot water (DHW) and electricity during one day, and type

B – when there are two increases in demand of DHW and electricity. The examined annual consumers' demands varied in the following ranges: demand of electricity 500–5000 MWh; heat for heating of premises – 1200–14500 MWh and heat for DHW preparation – 300–3500 MWh.

During analysis it was determined that when CHP unit has priority to operate all day, and the generated electricity is possible to use not only for the own needs, but also for sale, then in cases of type *A* consumer it is most economically beneficial to install the CHP unit satisfying the greatest consumer's demand for electricity. Such a CHP unit provides 32–44 % of necessary annual heat. Economically optimal relative tank volume of 10–17 m^3/1000 MWh of annual heat delivered from CHP unit is required.

In cases of type *B* consumers it is received that CHP unit of optimal power with optimal tank volume provides about 33–46 % of required annual heat. After calculations it is determined that optimal relative tank volume of 7–9 m^3/1000 MWh of delivered annual heat is required in CHP plants, when the tank is charged twice per day, and CHP unit operates only at peak periods. If it is supposed that CHP unit would have only one start-up per day, then the relative tank volume of 14–19 m^3/1000 MWh of delivered annual heat is required. After study of consumer, whose annual demands are following: 2000 MWh for electricity, 1800 MWh for DHW and 5500 MWh for heating, it is determined that at single time interval electricity tariff the economically optimal storage tank in 320 kW_e CHP plant is 35 m^3, as it is depicted in Fig. 1. Such CHP plant configuration allows achieving the highest NPV.

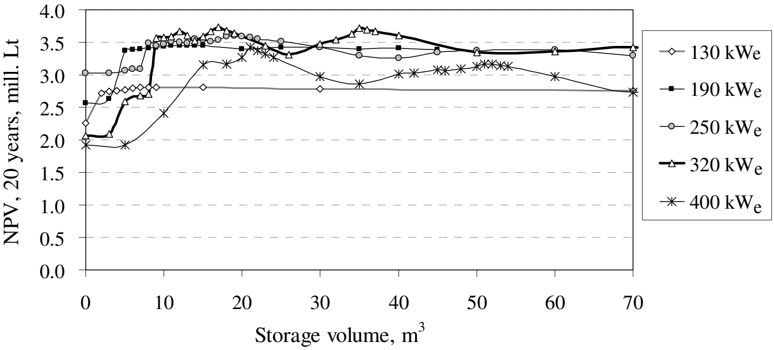

Fig. 1. NPV dependency given a different combination of CHP plant equipment, type *B*

Operation of tanks of different size in the CHP of 320 kW_e during non-heating period, in case of type *B* consumer, is represented in Fig. 2. As it can be seen, the tank, which volume is small (5 m^3 and 15 m^3), often is charged and discharged during one day, and simultaneously it interferes the operation of CHP unit, which is to be additionally stopped and again re-started. At the same time, the tank of too big volume can transpose the production of CHP unit in time, if in the strategy of CHP plant operation it is intended that CHP unit operates until the time when the tank is fully charged and it does not operate at those periods when the storage tank satisfies all the demands of consumers for DHW. Thus, the highest economic impact is achieved not in all cases of increasing the volume of heat storage tank.

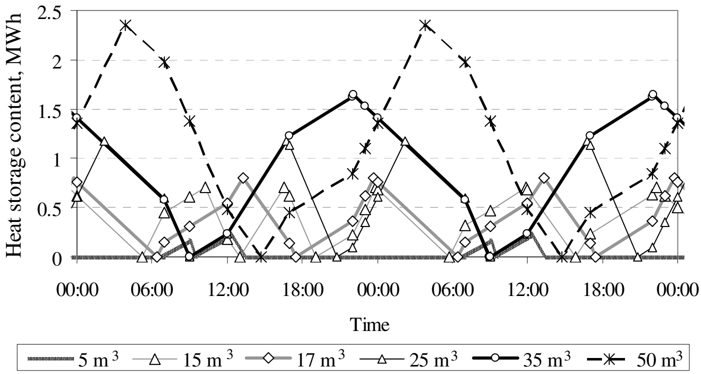

Fig. 2. Operation of tanks of different size in the CHP of 320 kW_e, when CHP unit has priority to operate all day, type *B*

Investigating the strategy of CHP plant operation, when the CHP unit has priority to operate only at the day-time tariff, it was determined that in cases of type *A* consumers, given a possibility to sell the electricity, the CHP unit of optimal power provides about 20–25 % of required annual heat, and optimal relative tank volume of 40–47 m^3/1000 MWh of annual heat delivered from CHP unit is required. In cases of no possibility to sell the electricity, it was obtained that optimal relative volume decreased and formed 18–30 m^3/1000 MWh annual heat delivered from CHP unit.

In cases of type *B* consumers, given a possibility to sell the electricity, it was obtained that it was most economically beneficial to install the CHP unit that would assist to satisfy the maximum electricity demands. In case of this selection of CHP unit, it provides 21–29 % of required annual heat. Under these conditions, in various alternatives the optimal relative size of storage tank was 41–48 m^3/1000 MWh of annual heat produced in CHP unit. In cases of no possibility to sell the electricity, it was obtained that the economically optimal power of CHP unit was of such value that would allow operating the CHP unit during electricity peak demands and between them. These CHP units provided about 12–15 % of required heat per year. In this situation optimal relative volume of the storage tank was 6–21 m^3/1000 MWh of annual heat production generated in the CHP unit.

In the case of type *B* consumer as detailed above, it was received that the economically optimal combination of equipment was CHP unit of 190 kW_e and heat storage tank of 5 m^3 when it is not planned to sell electricity and CHP unit has priority to operate only during valid electricity day-time tariff. Operation of heat storage tanks of different volumes in CHP plant of 190 kW_e capacity is depicted in Fig. 3.

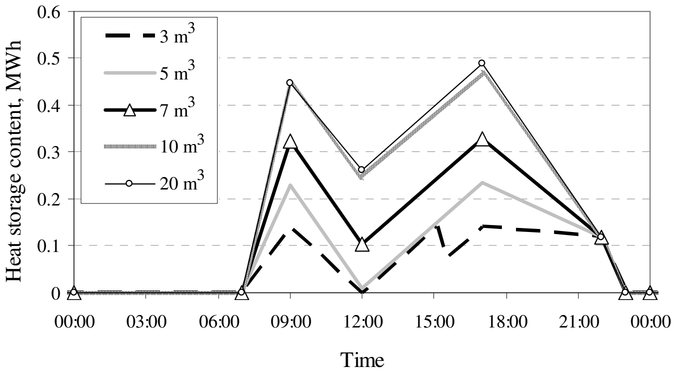

Fig. 3. Operation of tanks of different size in the CHP of 190 kW_e CHP plant, when CHP unit has priority to operate during day-time tariff, type *B*

Where it is seen that initially after the beginning of peak of DHW demand, the tank is suddenly charged to the highest thermal input, and in a follow-up of this peak demand it is discharged, later when the heat demand is decreasing, the tank again is charged, only in slower speed. In this case the charging and discharging of heat accumulator allows prolonging the period of CHP unit operation, besides, all the necessary DHW demand during day time is delivered from the CHP unit and the storage tank.

Operation of heat storage tanks of volumes 10 m^3 and 20 m^3 during non-heating season is similar, thus an increase of tank volume over 10 m^3 is inexpedient. In case of the heat storage tank of too small volume (3 m^3), it is charged more often per day, and simultaneously the CHP unit must be additionally stopped and again re-started. Meanwhile, the heat storage tank, which volume is too great for the system, is not fully used during non-heating season, as it is not charged until its maximum thermal power. Taking into our account that in the CHP plant of 190 kW_e the heat storage tank of volume of 10 m^3 is also efficiently used, it is suggested to install this greater tank.

Spot market. While in Lithuania there are no additional CHP support mechanisms, installation of small-scale gas-fired CHP plant, when all the generated electricity is sold in spot market, is not beneficial for electricity producer from the economical point of view. On purpose to enhance the economical attractiveness of these plants, the support schemes would be in need of introduction, e.g. privileged tax treatment, grants, bonuses and etc. In the analysis of German EEX market it was identified that under the heat demand of 30 000 MWh, it was economically beneficial to install CHP unit of 4 MW_e with heat storage tank of 650 m^3 volume. The sensitivity analysis of this plant showed that high variations in spot prices provided a significant incentive for the use of heat storage tanks at CHP plants.

4. Analysis of numerical and semi-analytical simulation results

The research of reliability of temperature distribution modelling of the prepared semi-analytical and numerical models in the heat storage tank is performed using data of heat storage tank of *Hvide Sande* CHP plant. For modelling there were selected 5 processes of charging and discharging of heat storage tank of this CHP plant, taking from 15 min to 6 h and having different ambient air temperatures and inflow rates. In cases of semi-analytical models it was investigated the entire area of heat storage tank, and in case of numerical model – a half of vertical section through axis z.

In case of numerical model there were analysed three sizes of grids in two-dimensional (2D) cylindrical polar coordinates: 17×43, 40×58 and 104×104. In cases of the first and second grids the compression of cells was performed at inflow and outflow positions and at the storage tank walls. Meanwhile, the third grid consisted of all the cells of the same size. The most accurate results were achieved by using the grid of equal cells, but considering that grid of cells of 40×58 enabled to obtain sufficiently precise results and was not computationally expensive; namely it was selected to carry out the farther calculations.

In order to check the possibilities of transformation of the created 2D model to 3D coordinates, the space around central axis was divided into ten parts. On the example of the pending task it was determined that there is no great difference between results of 2D and 3D models when the inflow and outflow openings or diffusers are located symmetrically around vertical axis, because similar average temperature discrepancies are received.

In formation of numerical models of charging and discharging processes, the best modelling results of the charging process were achieved by assessment of density as a function of temperature in all the heat and mass transfer equations. Meanwhile, the actual values of discharging process was fulfilled at best by a model when *Boussinesq*'s assumption was adopted in calculations.

The performed analysis of the time step size of the modelled processes showed that the most accurate results of numerical model were achieved when the time was divided into 50 equal time steps. In analysis of energy balance model it was determined that a time step size is an important parameter having impact on accuracy of modelling results. There were investigated the time steps from 2 s to 45 s, which in the research were expressed by non-dimensional *Fourier* number (Fo). During the research it was identified that the most accurate results of modelling of charging processes were obtained when $\Delta\tau = 5$ s (Fo = 1/128), and in case of discharging processes – $\Delta\tau = 2$ s (Fo = 1/320). Meantime, in the formed "plug flow" model the time step size was not investigated, as the final process temperature distribution was received at once, if the conditions describing the process were maintained unchanged.

After determination of necessary parameters of space and time division, there were modelled the selected charging and discharging processes of *Hvide Sande* storage tank. Fig. 4 presents the modelling results of two processes (charging – ID 176 and discharging – ID 231), taking 6 h, and using different models. As it is seen the obtained temperature distributions using different models correspond well the actual temperature distributions that are formed in the heat storage tank. The greatest temperature discrepancies are obtained in height of 6.8 m at the 8th sensor, because no readings of the 9th sensor located above were obtained. The lacking temperature values in the relevant height in the models were calculated as the average values. Besides, the 8th sensor falls into intermediate temperature zone where the greatest temperature gradient changes are present.

In assessment of simulation accuracy of charging and discharging processes lasting for 15 min–6 h, which were obtained using different models, the average relative temperature discrepancies (δT) were calculated. These discrepancies are depicted in Fig. 5. It is observable, that given a short period of the modeled process the average relative temperature discrepancies are small, and these discrepancies are even greater when the process gets longer.

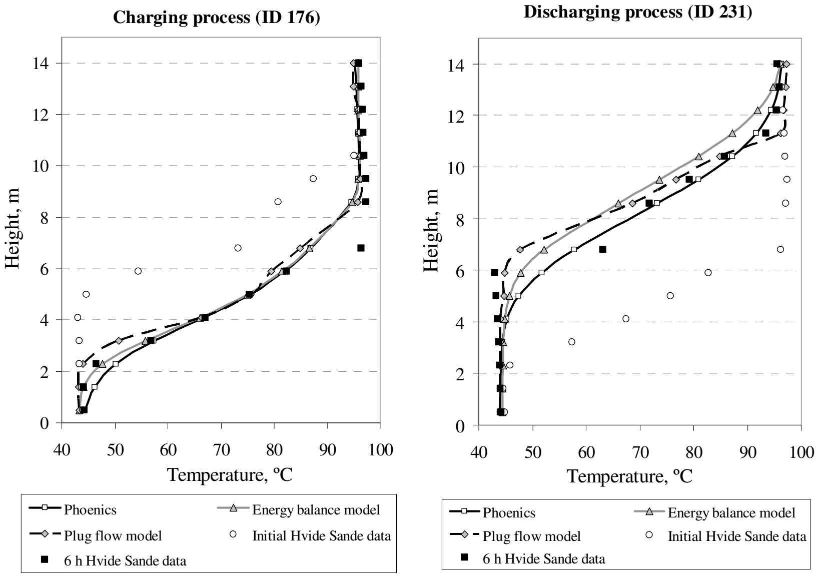

Fig. 4. Comparison of modelling results of charging and discharging processes of 6 h using the different models

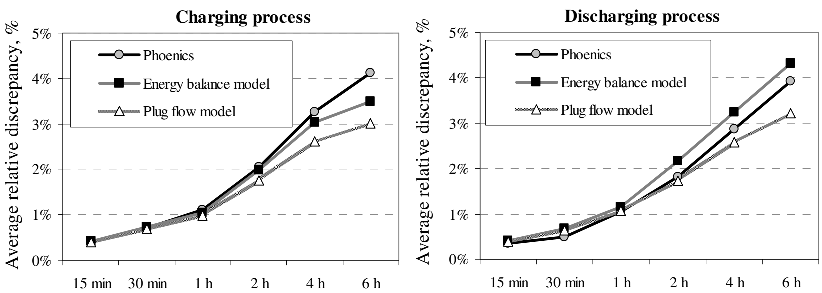

Fig. 5. Average relative temperature discrepancies of charging and discharging processes

Analysis of charging processes, having different inflow rate, shows that while the flow rate is increasing, the accuracy of models is decreasing. The calculated average δT varies in range of 0.42–4.13 %, using numerical model, and in range of 0.42–3.48 % using energy balance model, and in range of 0.40–

3.02 %, using “plug flow” model, when the charging processes of 15 min–6 h duration are modelled, where the inflow rate varies in range of 38.1–107.6 m^3/h.

In cases of discharging processes modelling the inflow cold water flow rate value has no great influence on accuracy of models representation. The average relative temperature discrepancies of theses processes formed in following values: 0.35–3.93 % δT using numerical model, 0.41–4.32 % δT using energy balance model and 0.39–3.23 % δT using “plug flow” model, when in average the flow rate varied in range of 44.4–96.6 m^3/h.

In order to investigate the creation of intermediate temperature zone in the heat storage tank using different models it was analysed the theoretical possibility that all the tank of the *Hvide Sande* CHP plant was filled with water of equal temperature. During research it was determined that “plug flow” model did not create the intermediate temperature zone in the tank, and the temperature distribution obtained by this model may be used only for ideal case of thermal stratification. Meanwhile, the energy balance model and numerical model created intermediate temperature zone.

Comparison of the results with other researchers’ results. The comparison of the results by used numerical model in this dissertation and numerical and experimental results of Zachar *et al.* (2003) showed a very good agreement. This shows that the created *PHOENICS* numerical model is universal and it could be applied not only for research of heat storage tanks of great volumes, but also of small volumes, which are especially popular in solar heating systems.

Assessment of thermal stratification. Basing on the analysis of data of heat storage tank in *Hvide Sande* CHP plant it was determined that while increasing the part in the tank occupied by the intermediate temperature zone the stratification number decreased according to the linear dependence.

General conclusions

1. The prepared strategy for selecting the heat storage tank of the CHP plant allowed performing determination and analysis of economically optimal storage tank volume. The analysis showed that if the selected storage tank size is too small in the system, the tank is fully charged and discharged several times a day. Choosing an oversized storage tank volume increases initial investment and the tank size can not be used when CHP unit operates determined number of hours every day, e. g. at day-time tariff.
2. With presented storage tank volume determination algorithm it was determined that for the consumer with residential electricity and domestic hot water demand economically the most profitable CHP unit is that satisfies the

maximum electricity power demand, when CHP unit has priority to operate all day. For this analysed case, the chosen volume of the heat storage tank should ensure that CHP unit has only one start-stop during the non-heating season day.

3. The performed economic analysis of small-scale gas-fired CHP plants shows that the optimal relative storage tank volume should be 10–19 m^3/1000 MWh of annual heat delivered by CHP unit for such systems, when the CHP unit has the priority to operate all the day and there is possibility to sell electricity.

4. When the CHP unit has priority to operate only during day-time tariff and there is a possibility to sell electricity, the optimal relative storage tank size should be 40–48 m^3/1000 MWh of annual heat delivered by the CHP unit. When it is not planned to sell electricity, the relative storage tank volume can be designed smaller (6–30 m^3/1000 MWh of annual heat delivered from the CHP unit).

5. Higher variation in electricity prices may support the use of CHP plants with heat storage tanks. When all produced electricity is sold in the spot market, the installation of the small-scale gas-fired CHP plant without an additional support policy is economically unprofitable for the electricity producer. In order to increase the economic attractiveness of these plants, political and economical promotion is required for small-scale cogeneration.

6. The analysis of prepared semi-analytical (energy balance and "plug flow") and created numerical models which allow determining thermal stratification in the storage tank showed that only models which assess conductivity of water between the water layers can present the formation of thermal stratification.

7. Making numerical model with *PHOENICS*, it is determined that water density as variable should be solved in all heat and mass transfer equations when charging process is modelled. For the modelling of discharging process, *Boussinesq's* assumption should be used.

8. Comparison of the two-dimensional (2D) and three-dimensional (3D) models showed that there is no big difference between the accuracy of results of these models when the inflow/outflow openings and storage tank geometry is symmetrical around vertical centre axis. However, the calculation time of 3D model is 5 times longer when the computation domain is 10 times greater.

9. Temperature distributions determined using the created numerical and applied semi-analytical models matched the actual temperature data of the heat storage tank in *Hvide Sande* CHP plant well. After the simulation of processes lasting for 15 min–6 h, the average accuracy of the prediction of charging processes expressed as an average relative temperature discrepancy did not exceed 4.3 %, when using different models.

10. The created algorithm for selecting storage tank size in CHP plant, numerical and semi-analytical models can be used for determining optimal storage tank volume and estimating the stored heat amount during the design and operation of these systems. Semi-analytical models are recommended for designers and system planners to evaluate the temperature distribution formed in the storage tank at any time of its operation. These models can be also integrated into the simulation software, where heat storage tanks have been considered as non-stratified previously. Meanwhile, the numerical model can be applied when analysing the processes in various heat storage tanks in greater detail.

List of author's published works on the topic of the dissertation

In the reviewed scientific periodical publications

Streckienė, G.; Martinaitis, V.; Šiupšinskas, G. 2011. Economic assessment of selection of heat storage under different operation strategy of small scale CHP plant, *Energetika* 57(1): 1–10 (in Lithuanian). ISSN 0235-7208. (INSPEC).

Streckienė, G.; Martinaitis, V.; Andersen, A. N.; Katz, J. 2009. Feasibility of CHP-plants with thermal stores in the German spot market, *Applied Energy*, 86(11): 2308–2316. ISSN 0306-2619. (ISI Web of Science).

Pakulytė (Streckienė), G.; Martinaitis, V.; Milčius, D. 2006. Solid oxide fuel cells cost analysis, *Energetika*, No 4: 80–83 (in Lithuanian). ISSN 0235-7208. (INSPEC).

In the other editions

Streckienė, G.; Martinaitis, V. 2011. Determination of temperature distribution in the heat storage using two analytical models, in *Proceedings of the Conference "Heat Energy and Technology", held in Kaunas on 3–4 February, 2011* [Konferencijos „Šilumos energetika ir technologijos", įvykusios 2011 m. vasario 3–4 d., Mokslinių pranešimų medžiaga]. (in Lithuanian) (accepted for publishing).

Streckienė, G.; Martinaitis, V. 2009. Thermal stratification change in hot water storage tank, in *Proceedings of the Conference "Heat Energy and Technology", held in Kaunas on 5–6 February, 2009* [Konferencijos „Šilumos energetika ir technologijos", įvykusios 2009 m. vasario 5–6 d., Mokslinių pranešimų medžiaga]. Kaunas: Technologija, 291–296 (in Lithuanian). ISBN 978-9955-25-743-1 (CD).

Streckienė, G.; Martinaitis, V. 2008. Investigation of the impact of the heat storage size on its operation mode in small-scale cogeneration plants, in *Proceedings of the 5th Conference of Young Scientists on Energy Issues "CYSENI 2008", held in Kaunas on 29 May, 2008*. Lithuanian Energy Institute: 79–91. ISSN 1822-7554 (CD).

Streckienė, G.; Martinaitis, V. 2007a. Fuel cell or internal combustion engine in small-scale CHP plant? in *Proceedings of the Conference "Heat Energy and Technology", held in Kaunas on 1–2 February, 2007* [Konferencijos „Šilumos energetika ir technologijos", įvykusios 2007 m. vasario 1–2 d., Mokslinių pranešimų medžiaga]. Kaunas: Technologija, 237–240 (in Lithuanian). ISBN 978-9955-25-338-9.

Streckienė, G.; Martinaitis, V. 2007b. Heat storage methods and application – energetic and environmental aspects, in *Environmental Engineering Proceedings of the X Conference of Lithuanian Young Scientists "Lithuania without Science – Lithuania without Future", held in Vilnius on 29 March, 2007* [10-osios Lietuvos jaunųjų mokslininkų konferencijos „Lietuva be mokslo – Lietuva be ateities", įvykusios 2007 m. kovo 29 d. Vilniuje, Mokslinių pranešimų medžiaga]. Vilnius: Technika, 254–262 (in Lithuanian). ISBN 978-9955-28-162-7.

Streckienė, G.; Martinaitis, V. 2007c. Investigation of the operating modes of heat accumulator in hospital cogeneration plant with energyPRO model, in *Proceedings of the Respublican Conference "Buildings Engineering Systems", held in Vilnius on April 26–27, 2007* [Respublikinės konferencijos „Pastatų inžinerinės sistemos", įvykusios 2007 m. balandžio 26–27 d. Mokslinių pranešimų medžiaga]. Vilnius: Technika, 99–105 (in Lithuanian). ISBN 978-9955-28-119-1.

About the author

Giedrė Streckienė (Pakulytė) was born in Vilnius, on 12 November 1981.

First degree in Environmental Engineering, Faculty of Environmental Engineering, Vilnius Gediminas Technical University, 2004. Master of Science in Power Engineering, Faculty of Environmental Engineering, Vilnius Gediminas Technical University, 2006. In 2006–2011 – PhD student of Vilnius Gediminas Technical University. Giedrė Streckienė in 2008 was on internship at EMD International A/S company, in Denmark.

KOGENERACINĖS JĖGAINĖS ŠILUMOS AKUMULIACINĖS TALPOS VEIKIMO REŽIMŲ TYRIMAI

Mokslo problemos aktualumas. Šilumos akumuliavimo sprendimas – plati mokslinių tyrimų sritis, apimanti ir teorinius šilumos ir masės mainų mokslo klausimus, ir praktinį pritaikymą. Nuo 1970 m. intensyviai pradėti šilumos ir masės mainų, vykstančių akumuliacinėse talpose, tyrimai siekiant išlaikyti ir atgauti aukštos kokybės šilumą iš talpos. Tačiau besivystančios šiuolaikinės technologijos leidžia greičiau, pigiau ir tiksliau nagrinėti vykstančius procesus akumuliacinėje talpoje, o įvairių tyrimų rezultatai gali būti taikomi praktikoje.

Šilumos akumuliavimo ir kogeneracijos technologijų derinys padeda siekti energijos gamybos efektyvumo ir aplinkos užterštumo mažinimo tikslų. Tačiau nedidelės galios kogeneracinių jėgainių optimizavimo galimybių potencialas nėra išnaudotas, o esamos atliktos kogeneracinių jėgainių su šilumos akumuliavimu studijos ir sukurti optimizavimo metodai paprastai apsiriboja tik ekonominiu įrenginių dydžių parinkimu. Pagrindinė tokių studijų sprendžiama problema apsiriboja minimalių kogeneracinės jėgainės eksploatacijos išlaidų radimu tam tikromis ekonominėmis sąlygomis. Tokiais atvejais nėra nagrinėjami šiluminiai procesai, vykstantys talpos viduje, ir šis įrenginys sistemoje yra kaip „juodoji dėžė“. Akumuliacinės talpos veikimo režimų tyrimas kogeneracinėje jėgainėje leistų panaudoti teorines žinias praktikoje, kas turėtų įtaką tikslesniam talpos tūrio parinkimui ir visos energijos gamybos sistemos modeliavimui. Pažymėtina, kad kogeneracinės jėgainės su šilumos akumuliacine talpa parinkimo problema būdinga ne tik Lietuvai, bet aktuali ir kitose šalyse.

Tyrimų objektas – nedidelės galios kogeneracinės jėgainės šilumos akumuliacinės talpos veikimo režimai ir jų metu susiformuojanti šiluminė stratifikacija.

Darbo tikslas ir uždaviniai. Darbo tikslas yra ištirti nedidelės galios kogeneracinės jėgainės šilumos akumuliacinės talpos veikimo režimų ypatumus, sudaryti algoritmą, padedantį parinkti tokios talpos tūrį ir pateikti modelį, leidžiantį nustatyti šiluminę stratifikaciją akumuliacinėje talpoje bet kuriuo jos veikimo metu.

Darbo uždaviniai:

1. Ištirti būdingus šilumos akumuliacinės talpos veikimo režimus nedidelės galios kogeneracinėje jėgainėje. Įvertinti, kokį poveikį turi

vartotojų poreikių kitimas ir elektros tarifai kogeneracinės jėgainės su šilumos akumuliacine talpa veikimui.

2. Nustačius pagrindinius veiksnius, turinčius poveikį akumuliacinės talpos dydžiui ir veikimui, sudaryti akumuliacinės talpos ekonomiškai optimalaus tūrio parinkimo algoritmą nedidelės galios kogeneracinei jėgainei.
3. Įvertinus šilumos ir masės mainų procesus, vykstančius akumuliacinėje talpoje, sudaryti pusiau analitinį ir skaitinį modelius, leidžiančius nustatyti šiluminę stratifikaciją bet kuriuo talpos veikimo metu.
4. Palyginti skaitinio ir pusiau analitinio modeliavimo rezultatus su realiai veikiančios akumuliacinės talpos duomenimis.
5. Pateikti rekomendacijas inžineriniams skaičiavimams, kaip parinkti šilumos akumuliacinę talpą kogeneracinėje jėgainėje ir kaip nustatyti šiluminę stratifikaciją šioje talpoje.

Tyrimų metodika. Siekiant atlikti užsibrėžtus uždavinius, darbe taikomas įvairių metodų derinys. Techninis ir ekonominis kogeneracinės jėgainės akumuliacinės talpos vertinimas atliekamas nagrinėjant kelis vartotojo poreikių atvejus. Šiems tyrimams naudojamas imitacinis modelis – *energyPRO* ir ekonominiai tyrimo metodai. Rizikos įvertinimui pasitelkiama jautrumo analizė. Vykstančių šiluminių procesų akumuliacinėje talpoje analizei taikomi pusiau analitiniai ir skaitiniai tyrimai, atliekami baigtinių tūrių metodo programų paketu *PHOENICS*.

Mokslinis naujumas

1. Atlikta šilumos akumuliacinės talpos tūrio parinkimo ir veikimo režimų analizė nedidelės galios kogeneracinėje jėgainėje atsižvelgiant į vartotojų poreikius, elektros tarifus ir jėgainės veikimo strategiją. Išnagrinėti kogeneracinės jėgainės įrengimo atvejai:
   - kai ši sistema užtikrina dalį vartotojo elektros poreikių ir
   - kai visa kogeneratoriaus pagaminta elektra parduodama realaus laiko rinkoje.
2. Sudaryti skaitiniai (dvimatis ir trimatis) ir pritaikyti du pusiau analitiniai modeliai šiluminei stratifikacijai modeliuoti akumuliacinėse talpose, įrengtose tiek kogeneracinėse jėgainėse, tiek ir kitose energijos gamybos sistemose.

Praktinė vertė. Darbe pateiktas šilumos akumuliacinės talpos įvertinimas gali pasitarnauti įvairiapusiškai kogeneracinių jėgainių analizei. Tyrimų rezultatai gali būti naudojami kogeneracinių jėgainių planavimo ir projektavimo metu, nustatant vartojimą atitinkantį optimalų akumuliacinės talpos tūrį sistemoje. Sudaryti pusiau analitiniai modeliai gali būti lengvai integruojami į optimizacinius ir imitacinius modelius, leidžiančius parinkti ir analizuoti energijos gamybos sistemas su šilumos akumuliacinėmis talpomis. Tai padėtų įvertinti vykstančius šiluminius procesus ir susidarančią šiluminę stratifikaciją talpoje. Tuo tarpu skaitinis modelis galėtų būti taikomas detalesniems įvairaus pobūdžio stratifikuotų akumuliacinių talpų tyrimams.

Ginamieji teiginiai

1. Kai kogeneracinėje jėgainėje kogeneratorius veikia nominalia galia, šilumos akumuliacinėje talpoje susiformuoja tik du būdingi veikimo režimai.
2. Kai vartotojo energijos poreikių kreivės sudėtingesnės, atsiranda daugiau galimų jėgainės kogeneratoriaus ir akumuliacinės talpos tūrio veikimo strategijos variantų.
3. Didesni elektros kainų svyravimai realaus laiko rinkoje skatina kogeneracinių jėgainių su šilumos akumuliavimu naudojimą.
4. Sukurtas skaitinis modelis ir pritaikyti pusiau analitiniai energijos balanso ir „sluoksnių išstūmimo“ modeliai tinkami naudoti įvairaus tūrio ir paskirties šilumos akumuliacinių talpų tyrimams.
5. Sudaryto skaitinio modelio taikymo galimybės yra lankstesnės ir įvairiapusiškesnės negu pusiau analitinių modelių, tačiau šis modelis imlesnis kompiuterio skaičiavimo laikui ir reikalauja specifinių techninių skaičiuotojo žinių.

Darbo apimtis. Darbą sudaro bendra darbo charakteristika, 4 skyriai, bendrosios išvados, literatūros sąrašas, publikacijų sąrašas ir priedai. Bendra disertacijos apimtis – 136 puslapiai, 65 iliustracijos, 11 lentelių ir 2 priedai.

Pirmame disertacijos skyriuje atlikta literatūros disertacijos tema apžvalga, susijusi su šiluminės stratifikacijos, susidarančios akumuliacinėse talpose, principais ir veikimu. Aptariami stratifikuotų akumuliacinių talpų modeliavimo metodai ir taikymas kogeneracinėse jėgainėse.

Antrame skyriuje aprašoma taikoma akumuliacinės talpos tūrio parinkimo metodika ir pateikiami pusiau analitinio bei skaitinio tyrimo modeliai.

Trečiajame skyriuje pristatomi šilumos akumuliacinės talpos ekonomiškai optimalaus tūrio paieškos ir analizės rezultatai.

Ketvirtajame skyriuje aprašomi skaitinio ir pusiau analitinio šiluminės stratifikacijos modeliavimo rezultatai. Įvertinamas modelių rezultatų patikimumas.

Bendrosios išvados

1. Sudaryta kogeneracinės jėgainės šilumos akumuliacinės talpos parinkimo strategija leido atlikti akumuliacinės talpos ekonomiškai naudingiausio tūrio nustatymą ir analizę. Ši analizė parodė, kad sistemoje parinkus per mažo tūrio šilumos akumuliatorių, akumuliacinė talpa visiškai įkraunama ir iškraunama kelis kartus net per vieną parą. Per didelio tūrio akumuliacinės talpos pasirinkimas padidina visos sistemos pradines investicijas ir akumuliacinės talpos dydis gali būti neišnaudojamas, kai kogeneratorius veikia kiekvieną parą tik nustatytą valandų skaičių, pvz., dieninio tarifo metu.

2. Naudojant sudarytą šilumos akumuliacinės talpos tūrio parinkimo algoritmą, nustatyta, kad vartotojui, kuris pasižymi gyvenamojo sektoriaus elektros ir karšto vandens poreikių kitimo pobūdžiu, ekonominiu požiūriu naudingiausias kogeneratorius, kuris užtikrina didžiausią vartotojo elektros galios poreikį, kai kogeneratorius visą parą veikia pirmu prioritetu. Nagrinėjamu atveju tikslinga įrengti tokią šilumos akumuliacinę talpą, kuriai esant kogeneratorius turėtų tik vieną įjungimą ir išjungimą per nešildymo sezono parą.

3. Atlikta nedidelės galios dujinių kogeneracinių jėgainių ekonominė analizė rodo, kad tokioms sistemoms ekonomiškai naudingiausias santykinis akumuliacinės talpos tūris turėtų būti apie 10–19 m^3/1000 MWh patiekiamos metinės šilumos iš kogeneratoriaus, kai kogeneratorius visą parą veikia pirmu prioritetu ir galima elektrą parduoti.

4. Kai kogeneratorius veikia pirmu prioritetu tik dieninio tarifo metu ir yra galimybė elektrą parduoti, ekonomiškai optimalus santykinis akumuliacinės talpos tūris turėtų būti apie 40–48 m^3/1000 MWh patiekiamos metinės šilumos iš kogeneratoriaus. Kai elektros parduoti neplanuojama, šilumos akumuliacinės talpos tūrį galima projektuoti mažesnį – iki 6–30 m^3/1000 MWh patiekiamos metinės šilumos iš kogeneratoriaus.

5. Didesni elektros kainų svyravimai gali paskatinti kogeneracinių jėgainių su šilumos akumuliavimu naudojimą. Nesant papildomos rėmimo tvarkos, mažos galios dujinės kogeneracinės jėgainės įrengimas, kai visa pagaminta elektra parduodama realaus laiko rinkoje, elektros gamintojui ekonomiškai nenaudingas. Norint padidinti tokių jėgainių ekonominį patrauklumą, reikėtų politinių ir ekonominių mažos galios kogeneracijos skatinimo priemonių.

6. Pritaikytų pusiau analitinių (energijos balanso ir „sluoksnių išstūmimo“) ir sudarytų skaitinių modelių, leidžiančių nustatyti šiluminę stratifikaciją akumuliacinėje talpoje, analizė atskleidė, kad šiluminės

stratifikacijos formavimąsi parodo tik tie modeliai, kurie vertina vandens šilumos laidumą tarp atskirų vandens sluoksnių.

7. Sudarant skaitinį modelį PHOENICS programiniu paketu, nustatyta, kad modeliuojant įkrovimo procesą, vandens tankis, kaip kintamasis, turi būti ieškomas visose šilumos masės mainų lygtyse, o modeliuojant iškrovimo procesą, tikslinga taikyti Businesko prielaidą.

8. Dvimačio ir trimačio skaitinio modelio palyginimas atskleidė, kad, kai srauto įtekėjimo ir ištekėjimo angos bei akumuliacinės talpos geometrija yra simetriška apie vertikalią vidurio ašį, nėra didelio skirtumo tarp šių modelių rezultatų tikslumo. Tačiau trimačio uždavinio sprendimas užtrunka 5 kartus ilgiau negu dvimačio, kai skaičiuojamoji sritis padidėja 10 kartų.

9. Skaitinio ir pusiau analitinių modelių nustatyti temperatūros pasiskirstymai gerai sutapo su realios Hvide Sande kogeneracinės jėgainės akumuliacinės talpos temperatūros duomenimis. Modeliuojant 15 min–6 h procesus, įkrovimo ir iškrovimo procesų vidutinis perteikimo tikslumas išreiškiant jį vidutiniu santykiniu temperatūros nesutapimu neviršijo 4,3 %, kai naudojami skirtingi modeliai.

10. Sudarytas kogeneracinės jėgainės akumuliacinės talpos parinkimo algoritmas, skaitinis ir pusiau analitiniai modeliai gali būti naudojami šių sistemų projektavimo ir eksploatavimo metu, nustatant optimalų talpos tūrį ir įvertinant joje sukaupiamą šilumos kiekį. Projektuotojams ir sistemų planuotojams, aiškinantis susidarantį temperatūros pasiskirstymą talpoje bet kuriuo jos veikimo metu, rekomenduojami pusiau analitiniai modeliai. Šie modeliai taip pat gali būti integruojami į imitacines programas, kuriose akumuliacinės talpos anksčiau buvo nagrinėjamos kaip nestratifikuotos. Tuo tarpu skaitinis modelis gali būti taikomas detaliau analizuojant įvairiose talpose vykstančius procesus.

Trumpos žinios apie autorių

Giedrė Streckienė (Pakulytė) gimė 1981 m. lapkričio 12 d. Vilniuje.

2004 m. įgijo aplinkos inžinerijos bakalauro laipsnį Vilniaus Gedimino technikos universiteto Aplinkos inžinerijos fakultete. 2006 m. įgijo energetikos mokslo magistro laipsnį Vilniaus Gedimino technikos universiteto Aplinkos inžinerijos fakultete. 2006–2011 m. – Vilniaus Gedimino technikos universiteto doktorantė. Giedrė Streckienė 2008 m. stažavosi EMD International A/S įmonėje, Danijoje.