RIGA TECHNICAL UNIVERSITY

Edgars VĪGANTS

A STUDY OF A CONDENSATION SYSTEM FOR COOLING FLUE GASES

Summary of thesis

Riga 2012

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

Edgars VĪGANTS
Environmental Science Doctoral Program

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Summary of thesis

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DISSERTATION PROPOSED FOR DR.SC.ING.
DEGREE IN ENVIRONMENTAL ENGINEERING
AT RIGA TECHNICAL UNIVERSITY

This study is proposed for attaining the degree of Dr.Sc.Ing. in Environmental Engineering and will be defended on November 30, 2012, at the Riga Technical University, faculty of Power and Electrical Engineering, Kronvalda Blvd. 1, room 21.

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CONFIRMATION STATEMENT

I, the undersigning, hereby confirm that I have developed this dissertation, which is submitted for consideration at Riga Technical University for attaining the degree of Dr.sc.ing. in Environmental Engineering. This dissertation has not been submitted to any other university for the purpose of attaining a scientific degree.

Edgars Vīgants ______________________

Date ________________________

The dissertation is written in Latvian and contains: introduction, four chapters, conclusions, bibliography, 60 figures, 3 tables and 105 pages. The bibliography contains 92 references.

SIGNIFICANCE OF THE TOPIC

The conditions for sustainable development of the energy sector in any country involve a continual process of improving energy efficiency and diverse use of renewable energy resources. These issues are also necessary for green growth and development in Latvia.

The efficient use of renewable energy resources is important for a number of reasons. First, it is very important in the move to replace fossil fuels, which allows the consumption of imported fuel to be decreased on a national level, thereby ensuring national energy independence and increased security of the country's energy supply. Second, it positively influences the national economy and economic development in general because it generates new jobs in the preparation and supply of wood fuel and in the full acquisition of local resources. At the same time, the use of renewable energy resources also works towards decreasing climate change on a global and regional scale.

Wood fuel in the form of logs, chips, and pellets is one of the well - grounded renewable energy resources use of whatis technologically and economically stated asenergy source inthe Baltic States. Wood chip boiler houses are playing an increasingly larger role within urban and ruralcentral heat supply systems. Before long, wood chips will replace fossil fuels in the majority of natural gas boiler houses. Various preconditions are necessary for this to take place:

- wood chips are two to three times cheaper than fossil fuels;
- diversification of fuel suppliers is possible by selecting for adifferentwood chip quality;
- efficient wood chip combustion technologies are available;
- automated management of boiler house operations is possible;
- possibility to increase the energy efficiency of wood chip boiler houses.

In order to fulfil this last precondition, technologies that improve the efficiency of boiler house systems must be developed. This system could be a technology that condenses the existing vapour in flue gases, which allows the burning of lower quality wood chips with higher moisture content, because the heat from the vapour condensation is recovered in the gas condenser. The term “gas condenser” is used to emphasize the fact that the most important processes in the gas condensing unit are the phase transition processes.

Research and development at the gas condensing unit construction school of the Institute of Energy Systems and Environment at Riga Technical University has resulted in the development of a gas condenser. The school was established in the 1980s within the Department of Thermal Engineering when development of a line of new contact type gas condensing units took place. The first doctoral dissertation was defended in 1988, and research of vaporization and condensation processes has been continued to the present day.

GOAL OF THE THESIS

The goal of the dissertation is to develop an industrial model of a flue gas condenser, perform modelling of the heat and mass transfer processes in the gas condensing units, and to study its effectiveness in the use of biomass.

The following tasks for scientific study have been put forth in order to fulfil the goal of the dissertation:

1. prepare a mathematical description of heat and mass transfer processes in the vaporization and condensation sections of the gas condenser;
2. develop a mathematical model for the gas condenser and develop a computer program based on it for the modelling of operations;
3. carry out an industrial experiment in order to obtain an empirical model for the interaction of parameters for gas condenser operations;
4. analyze the results of the data obtained from the modelling and the industrial experiment and propose suggestions for improving the efficiency of gas condenser operations.

SCIENTIFIC ORIGINALITY OF THE THESIS

The dissertation has developed a method for the planning of an industrial experiment of a direct contact gas condenser and the processing of data obtained it; it had also developed a model for the heat and mass transfer processes in this system.

The development of the dissertation began with a constructive calculation of the gas condenser and sketches, design, manufacture, and set up of the system. The methodology for the development of the experimental system includes the algorithm of the constructive calculation model.

The dissertation presents the methodology for an experimental study, which includes a regression analysis of the obtained experimental data and an empirical model created with the help of the STATGRAPHICS Plus computer program for defining the parameters of the gas condenser operations.

The modelling of the heat and mass transfer processes in the gas condenser is performed separately for the vaporization and condensation sections, taking into account the gradualness of the processes. The model consists of an equation system: the calculations are based on the mathematical description of the heat and mass transfer processes and the solution to this equation system. As a result, a computer model is created which can help to determine the parameters of the heat and mass transfer process for an empty direct contact gas condenser.

A method has been created for the comparison of results from the empirical model and the computer model obtained and created from the industrial experiment.

SCIENTIFIC SIGNIFICANCE OF THE THESIS

The dissertation offers the results of the experimental study of an industrial gas condenser system, and the empirical equation obtained during the study shows the mutual links between the parameters of the system's operations. An empirical model has been obtained which can help to model the definition of gas condenser capacity at variable loads.

The dissertation has developed and approbated a computer model for heat and mass transfer processes that can help to perform modelling of various processes taking place in a gas condenser and evaluate the influence of the parameters of the system's operations on these processes. The calculation model is created with *Microsoft Office Excel*.

The dissertation has developed a methodology for the integration into the mathematical model of the results obtained from the empirical model and has also developed a methodology for the comparison of the obtained experimental and calculated results.

PRACTICAL USE OF THE THESIS

A gas condenser system has been developed and patented, and the company “Komforts” has begun to commercially manufacture this system.

The developed system is an important step in the efficient use of renewable energy resources in the Latvian and European energy sectors. The results of the dissertation are practically applicable on a national level as well as at the regional and local municipality level. Any boiler house that burns wood chips can set up this gas condenser for the purpose of improving energy efficiency and obtain an up to 20% decrease in the consumption of energy resources.

The results of the dissertation are also important for the continuation of scientific study and the implementation of results. The methodology and computer model can be used by gas condenser operation regulators and users, designers, and researchers of such systems, as well as engineering students.

APPROBATION

The results of the dissertation have been reported and discussed in 21 local and international conferences. The results of the dissertation have been described and analyzed in ten publications, of which four are internationally respected publications. The gas condenser system has been patented during the work on the dissertation, and a patent has been obtained.

The results of the dissertation have been reported and discussed:

1. International Conference„World Scientific and Engineering Academy and Society 1st International Conference on Energy and Environment Technologies and Equipment” (EEETE`12), Tomas Bata University in Zlin, Czech Republic, September 20 - 22, 2012.
2. International Symposium“13th International Symposium on District Heating and Cooling”, Copenhagen, Denmark, September 3-4, 2012.

3. RTU seminar "Woodchip Boiler Gas Condenser. From idea to Ludza Boiler House", Riga, February 7, 2012.
4. Freedom and Solidarity Foundation, the Nordic Council of Ministers and NORDEN forum, "Latvian Green National Economy Potential - Northern Practice the Possibilities and Obstacles", Riga, September 14, 2012.
5. Training workshop on "Technical Options for Reducing CO2 Emissions at Municipalities", Salaspils, January 20, 2012.
6. International Conference on „Energy Politics and Climate Protection. Where We Stand 20 Years After Rio?”, Riga, February 23, 2012.
7. The seminar "The Role of Municipalities in Planning a Sustainable Energy", Riga, March 9, 2012.
8. An expert meeting "Latvian Biogas Market's Future Development Directions", Riga, June 29, 2012.
9. The seminar „Green Energy Roads in Latvia: from Technical Solutions to Policy”, Riga, December 14, 2011.
10. 52nd RTU International Scientific Conference "Energy Resources 2011” Riga, October 12 –13, 2011.
11. 3rd World *Congress* of *Latvian Scientists,* section"Power and Electrical Engineering", Riga, October 25, 2011.
12. The conference "The multi-sector regulation - Today and Future Challenges", Riga, June 10th, 2011.
13. Training course „Technology Solutions of Renewable Cogeneration”, Riga, May 13, 2011.
14. The workshop "Bioenergy Technology", Riga, April 20, 2011.
15. EEA Grants Program „Environmental policy integration programs in Latvia” final conference, Riga, April 14, 2011.
16. Project seminar of Institute of Physical Energetics, Latvian Academy of Sciences and the RES-H Policy on „Improvement of Framework of Policy for use of Renewable Energy in Latvian Heat Supply”, Riga, March 30, 2011.
17. The seminar "The Sun and Biofuels from A to Z", Riga, December 7, 2010.
18. LATO public discussion on „Power Solutions in Latvia: Baltic Sea Region Perspectives”, December 21, 2010.

19. The report "National Action Plan for renewable energy and environmental projects and opportunities for the Latgale region " seminar, Livani, July 8, 2010.
20. The conference „Multi-Sectoral Regulation – Present and Future Challenges", June 10, 2010.
21. Workshop „Renewable energy for heating of the buildings", February 24, 2010.

AUTHOR'S PUBLICATIONS

1. Vīgants E., Blumberga D., Veidenbergs I. Climate Technology in a Wood Chips Boiler House // RTU zinātniskie raksti. 13. sēr., Vides un klimata tehnoloģijas. - 6. sēj. (2011), pages 127-131.
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4. Vīgants E., Blumberga D., Veidenbergs I., Vīgants Ģ., Rochas C. Experimental Research of Flue Gas Condensing Unit // Advances in Environment, Biotechnology and Biomedicine, Czech Republic, Tomas Bata University in Zlin, September 20-22, 2012. – pages 179-189.
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10. Blumberga D., Kuplais Ģ., Romagnoli F., Vīgants E. CHP or Power Station: Question for Latvia // District Heating and Cooling: Conference Proceedings, Estonia, Tallin, September 5-7, 2010, – pages 30-36.

STRUCTURE OF THE THESIS

The work consists of the introduction, four sections and conclusions. It includes 105 pages, including 60 figures, 3 tables and a bibliography with 92 literature sources. The bibliography is not included in this summary.

1. CALCULATION MODEL OF THE CONDENSER AND ANALYSIS OF THE MODELLING RESULTS

1.1. Calculation model of the condenser

Modelling of the heat and mass transfer processes in a direct contact gas condenser takes place based on the principle of gradualness: step by step from the raw data to the mathematical description of the processes, the determination of the relevance of the processes, and the selection of assumptions, to the definition of changes in the parameters and calculations of efficiency and capacity. The algorithm of the calculation model of the heat and mass transfer processes is illustrated in Figure 1.1.

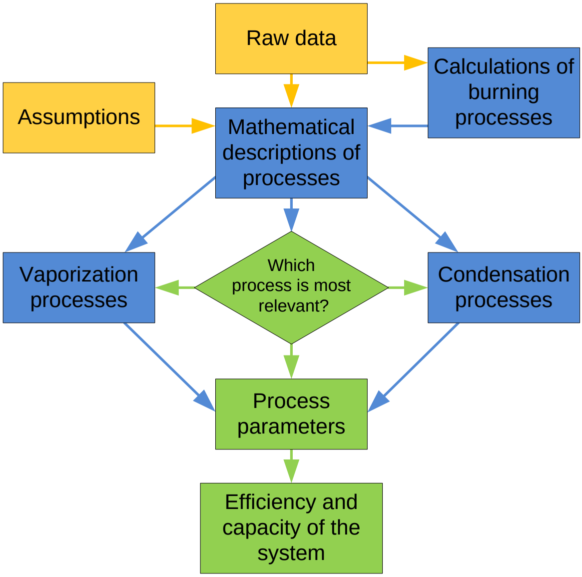

Fig.1.1. Algorithm of the calculation model of the heat and mass transfer processes

The *Raw data block* includes data about the wood chip boiler operations, the composition of the wood chips, their moisture and ash content, the water temperature at the boiler entry and exit, parameters for burning processes, and other data.

The *Assumption data block* includes the quantities necessary for further calculations, but these quantities are not known, for example, the air consumption coefficient in the boiler.

The *Calculations of burning processes block* includes calculations of the burning process, which help to define the content of the flue gases and the enthalpy of flue gases and air in the gas condenser entry under conditions of stoichiometric burning and during actual burning processes.

The *Mathematical equation processes block* includes equation systems that mathematically describe the heat and mass transfer processes in a direct contact gas condenser.

The *Vaporization processes block* includes a chain of linked elements of the solutions of the equation system of the mathematical description of the vaporization processes, the height of which is defined in the Assumptions block.

The *Condensation processes block* includes a chain of linked elements of the solutions of the equation system of the mathematical description of the condensation processes, the height of which is defined in the Assumptions block.

The *Definition of process parameters block* includes the definition of parameter values for heat and mass transfer processes throughout the path of the gas-vapour mixture from its entry into the gas condenser to its exit and a graphic illustration of the changes in parameters.

The *Definition of efficiency and capacity block* includes a definition of the efficiency of the boiler system and gas condenser and an evaluation of the specific capacity in a direct contact gas condenser depending on the heat and mass transfer parameters previously defined in the model.

The condenser calculations model consists of three parts. The first part calculates the fuel burning processes for variable fuel composition and boiler capacities. As a result, raw data for the calculations of gas condenser processes is obtained. The second part models the processes in the gas condensing unit vaporizer, where the flue gases exiting the boiler are processed by cleaning, cooling, and humidifying them. The third part performs modelling of the gas condensing unit condenser processes and defines the flue gas heat condenser capacity and exit parameters after the flue gas condenser. The processes in the second and third parts of the calculation are further divided into several stages according to the assumed stage of changes in flue gas temperature. The calculation model was created using *Microsoft Office Excel*. The calculation is performed in real time, that is, the output of results takes place immediately after the input of raw data. It is possible to change the raw data in the model, and it is also possible to correct the calculation formulas if necessary.

1.2. Modelling results

The study has developed a calculation model in *Microsoft Office Excel* describing the heat and mass transfer processes. The modelling was performed for a condenser that was set up following a 6 MW wood chip boiler, if the flue gas temperature in the vertical condensing unit of the condenser is 90ºC, the temperature of the sprayed water t_{2k} is 55ºC, and the spray densities are 12 $kg/m^2 \cdot s$ and 16 $kg/m^2 \cdot s$.

The prepared calculation model consists of three parts:

- calculation of fuel burning processes for variable fuel composition and boiler capacities;
- calculation of vaporization processes in the gas condensing unit without filler elements;
- calculation of condensation processes in the gas condensing unit with filler elements.

Overall, the created calculation model provides an opportunity to model the heat and mass transfer processes in a flue gas condenser by determining its heat capacity at various parameters for fuel quality, boiler capacity, and heat carriers.

An analysis of the modelling results from the processes within the first part of the flue gas condenser (gas condensing unit vaporizer) clarifies that the maximum possible moisture content values for flue gases entering the second part can be achieved if:

- the temperature of the sprayed water increases (see Figure 1.2.);By increasing the temperature of the sprayed water from t_{iesm}=60ºC to

t_{iesm}=64ºC, the moisture content increases by 21%, from d=0.17 kg/kg dry gas to d=0.205 kg/kg dry gas.

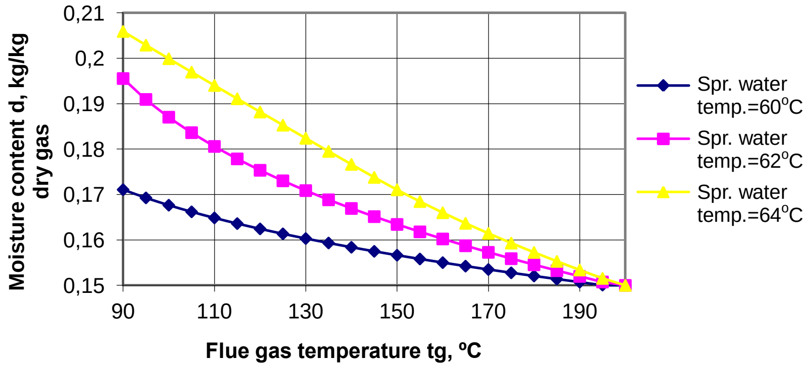

Fig.1.2. Changes in moisture content depending on flue gas temperature at various sprayed water temperatures

- the amount of sprayed water decreases (see Figure 1.3.);By decreasing the amount of sprayed water from $G_{\bar{u}}$=8 kg/s to $G_{\bar{u}}$=4 kg/s, the moisture content increases by 11% and changes from d=0.185 kg/kg dry gas to d=0.205 kg/kg dry gas.

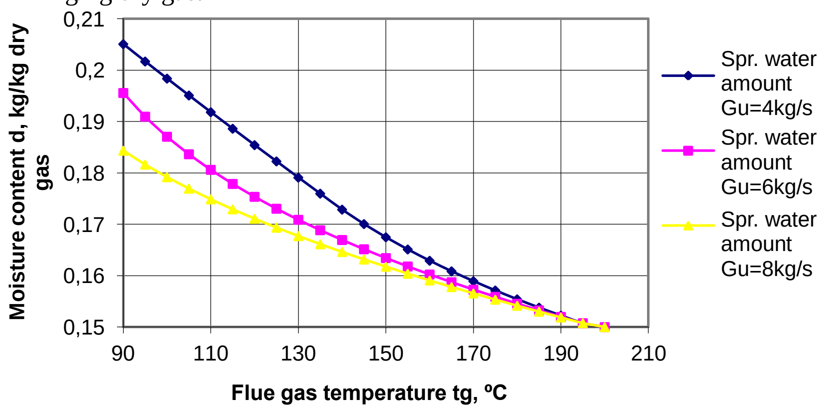

Fig.1.3. Changes in gas moisture content depending on flue gas temperature at various amounts of sprayed water

- the flow of dry gases increases (see Figure 1.4.);By increasing the flow of dry flue gases from L_{sg}=3.29 kg/s (50% of boiler capacity) to L_{sg}=6.58 kg/s (100% of boiler capacity), the moisture content increases by 3%.

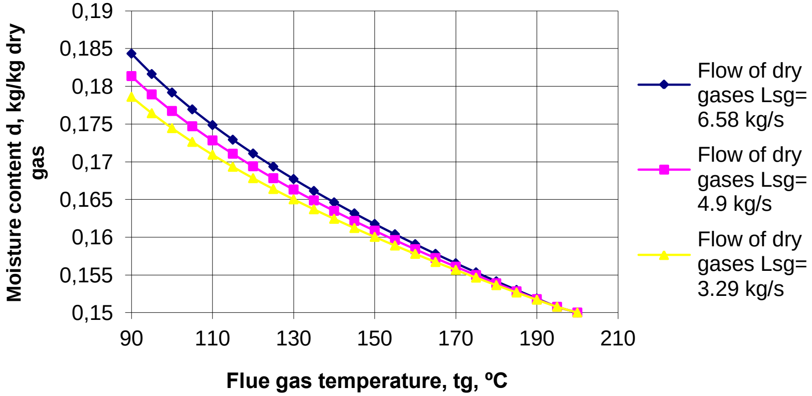

Fig.1.4. Changes in moisture content depending on flue gas temperature at various flows of dry gases

An analysis of the results of the modeling of the processes within the second part of the gas condensing unit (gas condensing unit condenser) shows that:

- a more complete cooling of flue gases and greater heat capacity for the system is obtained by spraying water of as low a temperature as possible. The analysis shows that by decreasing the water temperature from t_{iesm}=56°C to t_{iesm}=52°C the heat capacity increases from Q=1100 kW to Q=1580 kW, or by 44%;

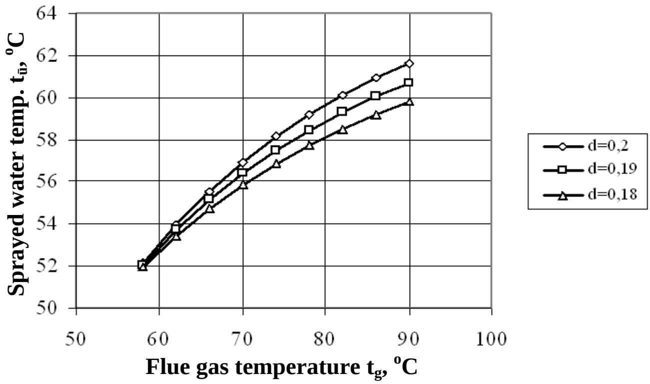

Fig.1.5. Changes in sprayed water temperature depending on gas temperature at various initial moisture contents

- by increasing the moisture content of the introduced gases, the amount of condensed vapour increases as does the heat capacity of the condenser. An analysis of the changes in the condenser's heat capacity depending on the moisture content of the gases at the entry finds that at an entry moisture content of *d*=0.18 kg/kg dry gas the heat capacity of the condenser is

Q=1350 kW, but if the moisture content at the entry of the condenser is *d*=0.2 kg/kg dry gas, the heat capacity of the gas condensing unit is Q=1620 kW, which is 20% greater;

- the exit temperature of the sprayed water must not exceed the dew point temperature of the flue gases at the entry (see Figure 1.6.), otherwise circulation heat from the process is created, which increases the measurements for the system.

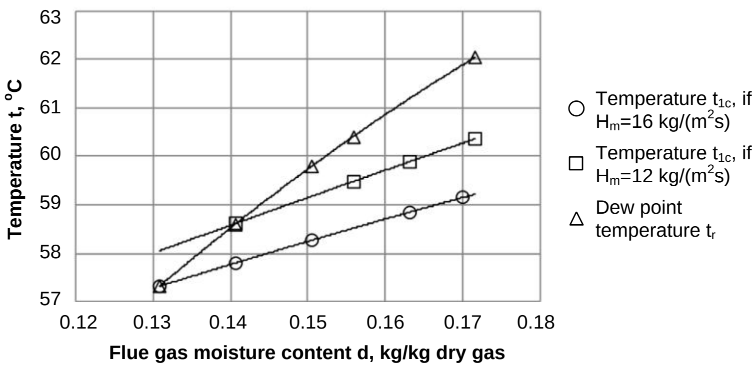

Fig.1.6. Water temperatures after changes in the condenser depending on the moisture content of flue gases at the entry to the vertical gas condensing unit

The prepared methodology for gas condensing unit calculations provides the opportunity to quantitatively evaluate the processes taking place in the condensing units and their specific character as well as to search for ways in which to improve the technical and economic parameters for the operation of such systems. Optimization of systems using flue gas heat and optimizing operating modes results in a decrease in fuel consumption, which lowers manufacturing costs and allows a business to become more competitive. In addition, the flue gases are more effectively cleaned of dust, sulphur, nitric oxide, and other harmful compounds, which results in fewer harmful emissions in the environment.

2. EXPERIMENTAL STUDY OF A FLUE GAS CONDENSER AND ANALYSIS OF RESULTS

The condenser system is built into the chimney and set up on the outside of the boiler house. A part of the measuring devices are built into the condenser, while others are distributed throughout the boiler house. The measuring meters are located on the control board, where measurements can be read. The arrangement of measuring devices within the system is shown in Figure 2.1.

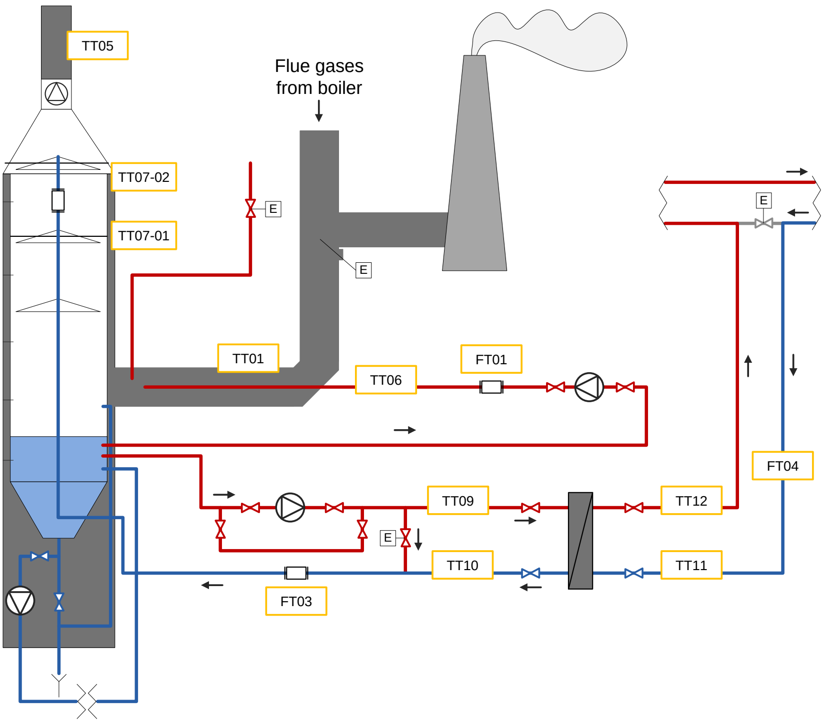

Fig.2.1. Basic diagram of the experiment

The empirical data are processed using statistical processing of data: correlation and regression analyses. Correlation analysis determines the connection between two quantities and their closeness. Regression analysis is used to determine the multifactor regression model and the statistical significance of its coefficients.

In this study the statistical processing of data and the creation of the multifactor empirical model were performed using the computer program *STATGRAPHICS Plus*.

The goal of the regression analysis is to obtain a multifactor empirical equation that quantitatively describes the condenser capacity according to the characteristic and statistically significant indicators of the boiler system operations and serve as a foundation for prognoses and evaluations of the system's operating mode results.

The regression analysis determines precise quantitative parameters for changing quantities, that is, it expresses the significance of the stochastic link in functional connections.

The regression analysis in the study is performed in the following order:

- the law of distribution for the dependent variable quantity for condenser capacity N_{ko} is verified;
- the regression equation is determined using the squares method;
- a statistical analysis of the obtained results is performed.

The regression analysis begins with defining the dependent variable quantity distribution, and the analysis can be continued if the distribution corresponds with the normal law of distribution. The results of the law of distribution verification are shown in Figure 2.2.

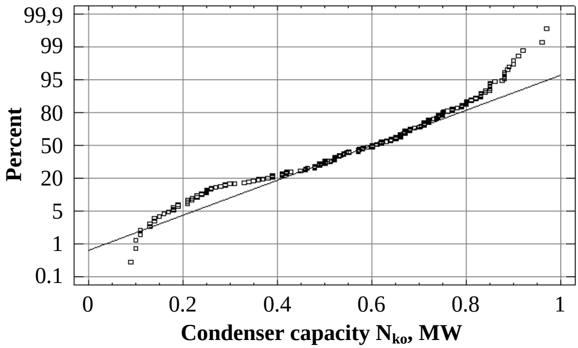

Fig.2.2. Distribution of condenser capacity values

The study results in a regression equation that establishes condenser capacity depending on the moisture content of flue gases d, the density of spray H_m, boiler capacity N_k, flue gas temperature before the condenser t_{1g}, water temperature after the condenser t_{1k}, return temperature of network water t_{1t}, and temperature of water to be sprayed into the condenser t_{2k}.

$$N_{ko} = -0,763 + 1,126 \cdot d + 0,0423 \cdot H_m + 0,02 \cdot N_k + 0,00051 \cdot t_{1g} + 0,0183 \cdot t_{1k} - 0,0213 \cdot t_{1t} + 0,0092 \cdot t_{2k} \quad (2.1)$$

The statistical processing of the data from the prepared empirical model results in an R^2 value of 0.96. This means that the prepared model (2.1) can explain 96% of the changes in the analyzed data. The remaining 4% can be attributed to the variables not included in the equation or the independent variables not defined in the study or due to the effect of their mutual influence.

The equation (2.1) is adequate and can be used to describe the analyzed data within the following boundaries:

- boiler capacity N_k from 1 to 6.5 MW;
- flue gas temperature before the condenser t_{1g} from 140 to 230ºC;
- sprayed water temperature t_{2k} from 50 to 60ºC;
- water temperature after the condenser t_{1k} from 50 to 65ºC;
- return temperature of network water t_{1t} from 45 to 56 ºC;
- density of condenser spray H_m from 11 to 16 kg/m^2·s;
- flue gas moisture content d from 0.042 to 0.16 kg/kg dry gas.

The empirical and calculated data are compared to verify the adequacy of the empirical equation. This comparison of data is shown in the graph in Figure 2.3.

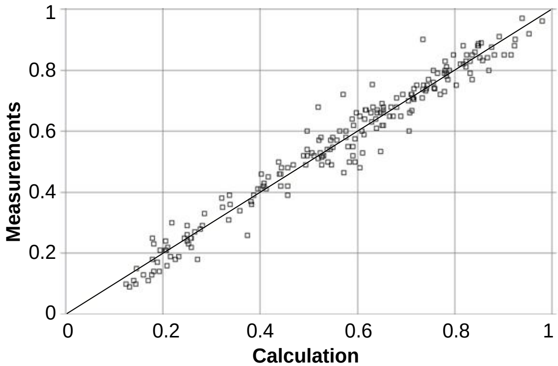

Fig.2.3. Comparison of empirical and calculated data for capacity

As seen in Figure 2.3., a good correlation between the two groups of data can be seen. If the calculated value were to precisely correspond to the measurement results, the points on the graph would be located in straight lines. But an increased dispersion around the average values for condenser capacity can be observed.

The statistical processing of data from the industrial experiment of the condenser, using methods of regression analysis, determines the most essential characteristic factors of the system operations, or, the independent parameters. The connection between condenser capacity and the parameters that influence it are determined by the regression equation obtained during the processing. Testing for the accuracy of each step and readiness to continue to the next step of the analysis is performed at each point of the regression analysis. The analysis shows that:

- the use of the regression data analysis is correct, because the dependent variable values conform to the law of normal distribution;
- the use of the square method in determining quantities is justified, and these quantity values are not distorted, because the defined DW criteria values are greater than the permissible border values;
- the evaluation of the regressions equation coefficients is correct, because a correlation between them cannot be seen;
- the data evaluation standard error is assessed as correct, because the distribution of the remainder corresponding to the specified dependent and the independent variable is regular.

The deep cooling of flue gases and heat retrieval has a specific character. An analysis of the operation of only the boiler and the condenser itself (where the deep cooling of flue gases takes place) is not enough. The recovered thermal energy has a low potential (temperature) and a consumer for it must be found. Such consumers could be heat supply systems in which the recovered heat is used for primary heating of network water. The heat supply system influence on the use of heat is linked to the temperature level in the heating network. The return temperature is significant. The changes in condenser capacity depending on the return temperature of network water can be seen in Figure 2.4.

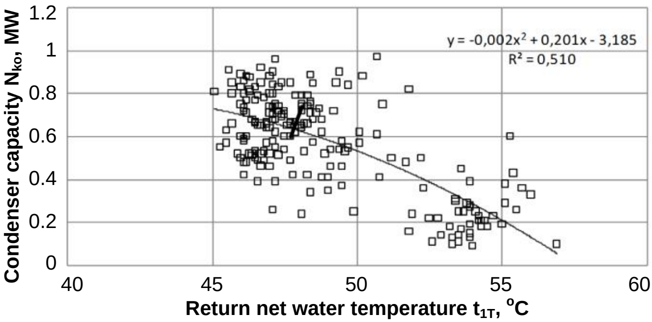

Fig.2.4. Changes in condenser capacity depending on the return temperature of network water

As the return temperature of the network water increases, the heat capacity of the condenser decreases, because the heat exchange between the heating network and the water circuits of the condenser in the network water heat exchanger deteriorates. The water heated in the condenser is cooled less well in the network water heat exchanger and is therefore sprayed through the nozzles into the condenser at a higher temperature. Both the dry heat transfer between droplets and flue gases as well as the mass transfer deteriorate at a higher sprayed water temperature. In the case of condensation, the partial pressure of the vapour on the surface of the water droplet is lower than the partial pressure in the flue gases. As the temperature of the water droplet increases, the partial pressure of the vapour on the droplet surface also increases and the difference in partial pressures decreases. As a result, the condensation process no longer works as well and the flue gases leave the condenser with higher moisture content. Poorer dry heat transfer is connected to higher temperatures in the exiting flue gases. Overall, less intensive heat and mass transfer results in poorer use of flue gas heat and lower boiler house efficiency.

Water that is heated in a direct contact heat exchanger is sprayed through nozzles into the upper part of the condensing unit. The flue gases and sprayed water move in counterflow, and heat and mass transfer between the two environments takes place throughout the whole condenser. The amount of sprayed water is defined by the density of spray. Figure 2.5.shows the experimentally defined changes in condenser capacity depending on the density of spray.

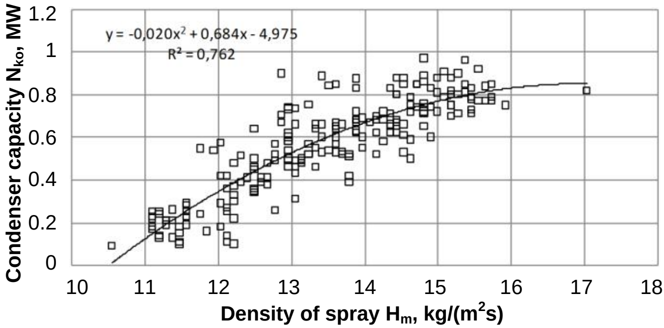

Fig.2.5. Changes in condenser capacity depending on the density of spray

As the spray density increases, the condenser capacity increases non-linearly. The capacity increases more quickly at lower spray densities; it decreases and becomes more saturated at higher density values. As the volume of sprayed water increases, its end heating temperature t_{1K} and spray temperature t_{2K} decrease. At lower spray water temperatures the flue gases are more deeply cooled and their temperature after the condenser is lower. A deeper cooling of flue gases ensures a more intensive dry heat transfer. At lower droplet surface temperatures the partial pressure of vapour on the surface is lower, and the difference in partial pressure on the droplet surface and in the flue gases increases and the mass transfer intensifies. The dry heat transfer and mass transfer processes are such that the flue gases are more deeply cooled and the recovering of heat in the condenser increases.

The wood chip boiler capacity changed from 1 to 6.5 MW during the industrial experiment. The changes in condenser capacity depending on boiler capacity are shown in Figure 2.6.

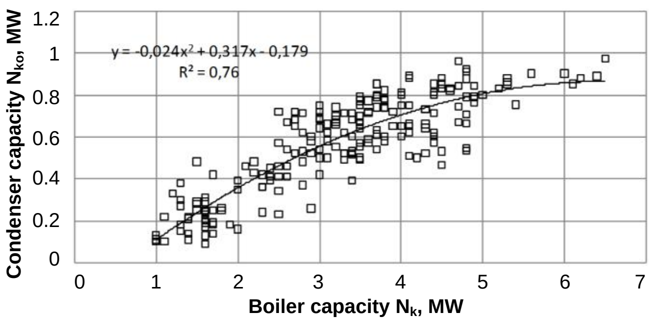

Fig.2.6. Changes in condenser capacity depending on boiler capacity

Changes in condenser capacity depending on boiler capacity are mainly influenced by two factors: the volume of exiting flue gases and changes in the temperature of the flue gases. The heat and mass transfer between flue gases and the sprayed water also intensifies, which likewise increases the condenser capacity. As the boiler capacity increases, fuel consumption also increases. When constant quantities of oxygen in the flue gases and fuel moisture content are maintained, the volume of flue gases is directly proportional to fuel consumption, which is in turn inversely proportional to boiler efficiency.

As the amount of flue gases increases, the speed of gases in the condenser also increases. Due to the counterflow between the sprayed water and the flue gases, an intensive turbulization of the gas-water mixture is observed when the speed of the gases increases. As a result, the heat and mass transfer between the two environments intensifies and more heat is recovered in the condenser.

Figure 2.6.shows that the changes in condenser capacity are non-linear. This is explained by the character of changes in boiler efficiency and flue gas temperature depending on boiler capacity. Figure 2.7.shows the flue gas temperatures after changes in boiler capacity, as determined in the experiment.

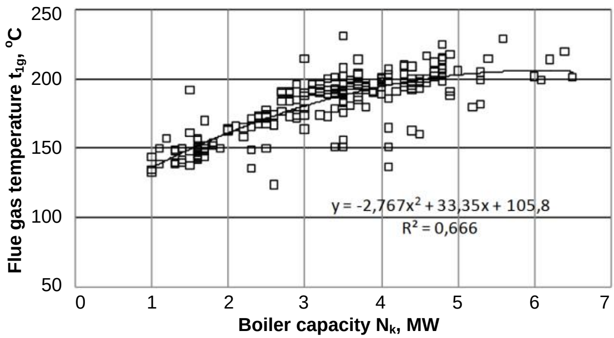

Fig.2.7. Changes in flue gas temperature depending on boiler capacity

In the case of greater boiler capacity, the furnace simultaneously burns a greater amount of fuel, more heat is discharged, the combustion temperature increases, and as a result the temperature of the exiting flue gases also increases.

Overall, it can be said that as the boiler capacity increases, the potential of the usable heat also increases – the amount of heat in the flue gases and the temperature increase, resulting in a non-linear increase in condenser capacity. The condenser capacity is 17% of the boiler capacity if the boiler capacity is relatively small and 14% if the boiler capacity is 6 MW.

Condenser operation is linked to the cooling of the flue gases to lower than the dew point temperature. When flue gases are cooled this deeply, moisture condenses and phase transition (vaporization) heat is obtained. The amount of heat that can be recovered as the result of condensation depends on the moisture content of the flue gases, the temperature of the sprayed water, the spray density, the amount of time the flue gases have spent in the condenser, and other conditions. The data obtained during the industrial experiment about changes in condenser capacity as the moisture content of the flue gases changes after leaving the boiler (at the entry to the condenser) are shown in Figure 2.8.

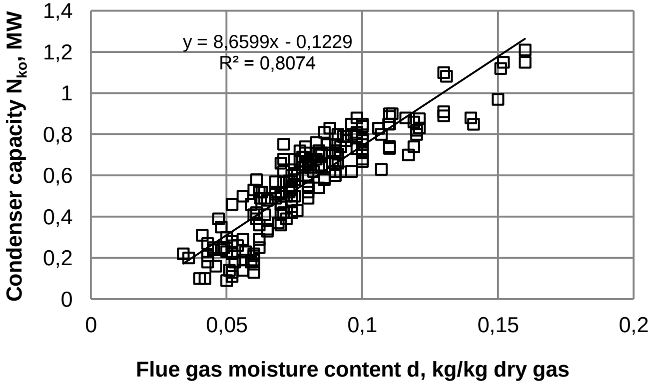

Fig.2.8. Changes in condenser capacity depending on the moisture content of flue gases

An increasing trend in capacity is noticed as the moisture content of the flue gases increases. A dispersion of data is also observed, which can be explained by the simultaneous influence of other above-mentioned parameters. The regression equation obtained from the processing of the experimental data is used to isolate the influence of other parameters. Other parameters are considered constant in the calculations.

The assessment of the influence of flue gas moisture content on the heat capacity of the condenser is calculated with the help of the regression equation and shown in Figure 2.9.

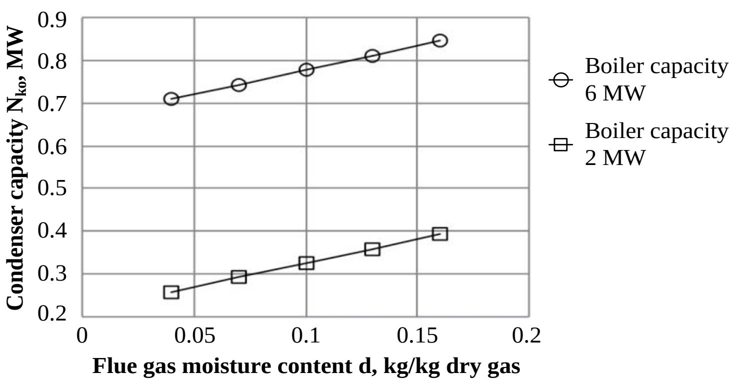

Fig.2.9. Changes in condenser capacity depending on flue gas moisture content after exiting the boiler

An assessment of the influence of moisture content is performed for two boiler capacities: 2 MW and 6 MW. The spray water temperature t_{2k} in both cases is 55ºC. The flue gas temperature in the entry to the condenser is assumed to correspond to the boiler capacities from Figure 2.4. The spray water density is 12 $kg/m^2 \cdot s$ for a boiler capacity of 2 MW and 16 $kg/m^2 \cdot s$ for a boiler capacity of 6 MW.

The figure shows that as the flue gas moisture content increases, so too does the condenser capacity, because the flue gases contain a larger amount of vapour, which when condensed recovers a larger amount of phase transition heat. But, in order for vapour condensation to take place, appropriate conditions must be created. The temperature of the sprayed water must be such that the partial pressure of the vapour on the surface of the sprayed water droplet is less than the partial pressure of saturated vapour in the gases. Water is sprayed into the upper section of the condenser, where the cooled flue gases are led out (see Figure 2.1.). The temperature of the sprayed water t_{2k} is approximately 55ºC, and this is influenced by the heat transfer in the network water heater. The lower the return temperature of the network water, the better the sprayed water is cooled and the lower the t_{2k} temperature value. The lowest t_{2k} temperature value is determined by the sum of the return temperature of the network water t_{1T} and the difference between the temperatures necessary for heat transfer in the heat exchanger. In order for condensation to take place, the temperature of the sprayed water must be lower than the flue gas dew point t_r at the site of water spray. The flue gas dew point temperature is determined by the temperature and moisture content of the flue gases. In the case of counterflow between water and flue gases, the flue gas temperature in direct contact heat exchangers is 5–10ºC higher than the water temperature. The lowest temperature difference is observed in condensers with filler elements.

In the case at hand, the relative expanded uncertainty for determining condenser capacity is 3.2%.

3. ANALYSIS OF THE RESULTS OF THE STUDY OF CONDENSER OPERATION

3.1. Comparison of modelling and experimental data

This study uses two methods to study the changes in the parameters relating to the processes within the flue gas condenser, namely, an experimental study and modeling of the heat and mass transfer processes in the condenser. The downside to the experimental method is its inability to define the local parameters of the condenser along the horizontal and vertical gas condensing units. This is related to the measuring of the parameters of the water and flue gas mixture. In this study, the local parameters are determined with a model created in Microsoft Office Excel. The two methods supplement each other and lead to a more complete understanding of condenser processes. An important issue when analyzing the modeling results is how adequately they describe the actual processes. To answer this question, the parameters from the modelling and the parameters determined by the regression equation are compared. Changes in condenser capacity (as determined by both methods) depending on boiler capacity are compared, and the compared changes can be seen in Figure 3.1.

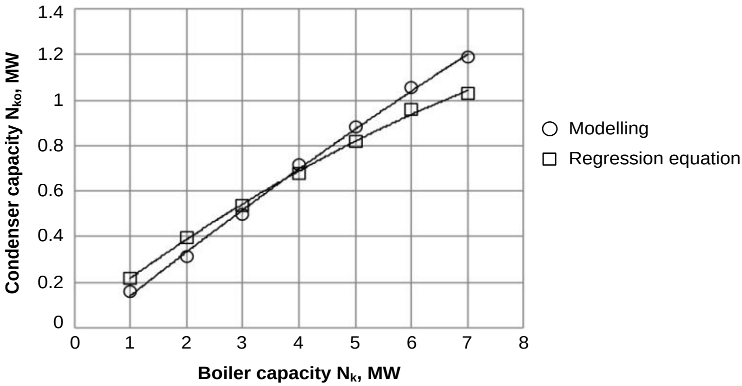

Fig.3.1. Comparison of results from condenser capacity modelling and calculations from the regression equation

Parameter values characteristic of boiler capacity observed in the experiment were used in the regression equation calculations and in the modeling. The figure shows a good correspondence of results in the capacity range of 3 MW to 5 MW. The condenser capacity values determined by the regression equation are higher for boilers with lesser capacity. In relation to the value determined by the regression equation, the difference in results for a boiler capacity of 1 MW is 15%. The difference for a boiler capacity of 7 MW is 18%. The comparison of results indicates that the correspondence is adequate and that the modeling results can be used to interpret changes in the local parameters of the condenser.

3.2. Analyzing the reduction in greenhouse gas emissions

The modelling of greenhouse gas (GHG) emissions reduction is necessary not only to evaluate the technological solutions, but also to predict how much climate technology co-financing is necessary in order to most efficiently implement the solutions.

The industrial experiment of the flue gas condenser was performed in the boiler house of the heat supply system in Ludza, Latvia. This boiler house has an 8 MW capacity wood chip boiler. A two-stage condenser is set up outside the boiler house, which has a spray nozzle in the centre the gas flow in the condenser's horizontal section. A group of nozzles is set up in the vertical section of the condenser, which also sprays fluid that comes in direct contact with the flue gases.

The reduction in GHG emissions is contingent upon the constructive and operational parameters of the gas condenser. In total, there are over 20 independent variables.

The results of the mathematical processing of the experimental data are used in the regression analysis of the GHG emission results, which is illustrated in Figure 3.2.

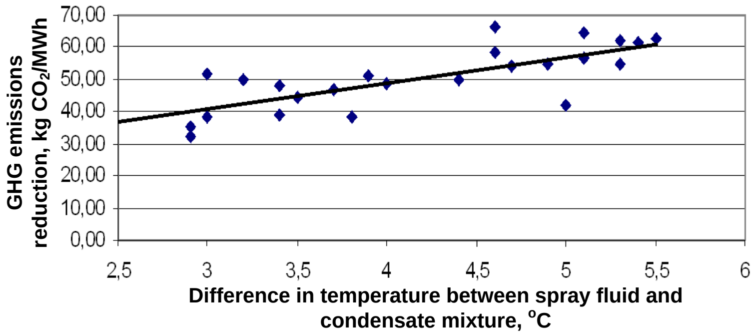

Fig.3.2. Specific reduction of GHG emissions depending on the difference in temperature between the spray fluid and the condensate mixture

The regression analysis of the experimental data results in an empirical relation that adequately correlates with the experimental data (correlation coefficientR^2=0.1316).

The obtained empirical model describes the relation between the specific reduction of GHG emissions and the difference in temperature between the sprayed fluid and condensate mixture. Its mathematical expression is:

$$\Delta CO_2 = 1{,}39 \cdot (t_1^k - t_2^k) + 51{,}69, \frac{tCO_2}{MWh} \qquad (3.1)$$

where

t_1^k–temperature of spray fluid and condensate mixture before nozzles, ºC;

t_2^k–temperature of spray fluid and condensate mixture after nozzles, ºC.

The reduction in GHG emissions depends on the difference in spray fluid and condensate mixture temperatures after and before the nozzles. The experimental data show that even a small difference in temperature (2–3ºC) can achieve a specific 25-30% reduction in GHG emissions if the flow of fluid remains constant.

The gain of the specific reduction in GHG emissions in relation to the produced unit of thermal energy in the boiler house depends on the price for GHG emissions quotas in the emissions market.

In 2010 and 2011 quota prices fluctuated between 12 to 15 EUR/tCO_2. European Union specialists predict that during the next emissions trading phase – from 2013 to 2020 – the GHG emissions price could range between 30 to 50 EUR/tCO_2. Based on these predictions, a distribution scheme for GHG emissions quotas for the third trading phase has been developed.

The specific gain from the reduction of GHG emissions is analyzed using the experimental measurement data from the gas condenser and the results of the mathematical processing. The example of the specific gain from the reduction of GHG emissions depending on the specific boiler load is shown in Figure 3.3., in which it is assumed that the price of emissions in the emissions market is 30 EUR/tCO2.

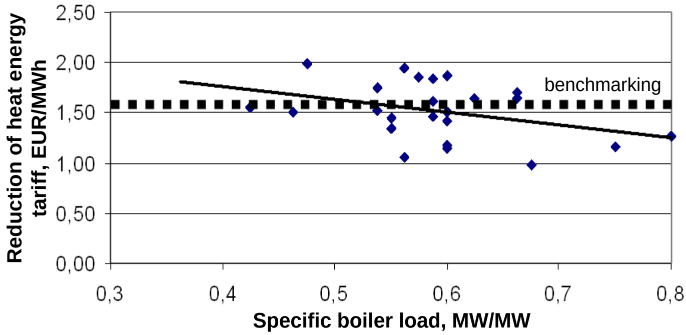

Fig.3.3. Specific gain from the reduction of GHG emissions depending on specific boiler load

The specific gain from the reduction of GHG emissions is determined by the mathematical processing of the experimental data for an empty gas condensing unit. The specific gain decreases as the boiler load increases. This trend is obtained as the result of a regression analysis of the data and can be explained with the increased speed of gasses in the gas condenser, which in turn causes the condensation process to weaken.

The modelling method for the specific gain from the reduction of GHG emissions includes the definition of a benchmark (dotted line), which can be used in this type of condenser and for the defined emission prices on the emissions market. This method is approbated if the emissions price on the emissions market is 30 EUR/tCO_2.

3.3. Gas condenser operations within the heat supply system

Any heat supply is a complex group of technological solutions of its separate parts, which must be examined as a unified system. The effective operation of this system depends on the creation of economically justified and environmentally friendly technological solutions.

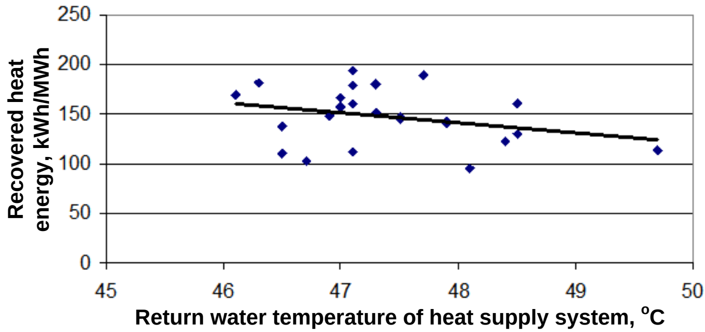

Fig.3.4. Eco-intensity of a gas condenser depending on the return water temperature of the heat supply system

As seen in Figure 3.4., the regression analysis indicates that the experimental data correlate poorly with the empirical model (straight line). However, a clear trend can be seen in which the recovered specific heat is greater if the return temperature of the heating network is lower and vice versa, namely, that the amount of recovered heat decreases as the temperature rises.

This confirms the view stated above that fuel savings depend on the operation of the entire system as a whole, of which the gas condenser is but one element. The condenser operation, in turn, depends on energy user efficiency, water speeds, and flow parameters in all the heat supply elements, including heat exchangers in the buildings' heating units. In order to increase the recovered thermal energy in the gas condenser, the return temperature of the heating network must be decreased, which is possible by modelling qualitative quantitative regulation modes in heat supply systems.

The increase in eco-intensity in boiler house operations using a gas condenser is also evaluated from the standpoint of reducing nitrogen emissions from the boiler house chimney. This happens for two reasons:

- fuel consumption decreases and the total amount of nitrogen emissions from the boiler house chimney also decreases;
- partial absorption of some nitrogen components takes place within the sprayed fluid: 10% of the total nitrogen is collected by the sprayed fluid.

CONCLUSIONS

1. Studies of the recovery of flue gas heat through the deep cooling of flue gases by direct and indirect contact of the heat carriers indicate that water introduced into the condenser through direct contact can be heated to a temperature that is 10-15°C higher than in indirect gas condensing units. Increased temperature is very important if the recovered heat is used for consumers' communal heat load.

2. Based on the results of the modelling of direct contact heat carrier heat and mass transfer processes, an innovative flue gas condenser construction has been developed and patented. This construction consists of two parts: a vaporizer and a condenser. This system has been set up in the boiler house in Ludza, and an experimental study has been undertaken for operating the system without filler elements. The results of the processing of the industrial experiment data indicate that the condenser capacity is 17% of the boiler capacity in cases of partial boiler load and 14% if the boiler capacity grows to 0.75 of the installed capacity.
3. In order to increase the temperature of the sprayed water and to clean the flue gases of particulate matter, heated water from the condenser's volume of water is sprayed into the vaporization section of the flue gas condenser, which then vaporizes and increases the moisture content of the flue gases. Modelling of the heat and mass transfer within the vaporizer indicates that the moisture content d increases by 0.03–0.05 kg/kg dry gas, and as a result the dew point temperature t_r and the wet-bulb temperature t_m increases by 3–5 ºC. The boundary value for the temperature of the sprayed water in the vaporizer is determined by the wet-bulb temperature, and the water may not exceed 66ºC. In order to promote the vaporization process, the spray density Hm is 6–8 $kg/m^2 \cdot s$, and this is lower than the spray density in the condensation section of the system.
4. Flues gases are cooled to lower than the dew point temperature in the condensation section of the system. The temperature after the condenser is mainly influenced by the temperature of sprayed water t_{2k}, the introduced flue gas temperature t_{1g}, and the spray density H_m. If the flue gases and water are in counterflow, the flue gases can be cooled to a temperature determined by the approximate relation $t_{2g} = t_{2k} + (5–10)$ºC. Higher flue gas temperature values correspond to a condenser without filler elements. The water sprayed into the condenser can be heated no higher than the dew point temperature t_r in the entry to the condenser. Under modelling conditions t_r is 60–64ºC, and this temperature is significantly influenced by the moisture content of the flue gases after the vaporizer.
5. The temperature of the water heated in the flue gas condenser is the temperature of the combination of sprayed water after the vaporizer and sprayed water after the condensation section. The highest water temperature obtained by the modelling is 65ºC, which is close to the highest temperature (63.8ºC) measured in the industrial experiment.
6. The regression analysis of the data from the industrial experiment resulted in a multifactor empirical equation that quantitatively determines condenser capacity depending on characteristic and statistically significant indicators of the boiler system and condenser operations and serves as a foundation for predictions and evaluations of the results of the system's operating modes. A verification of the significance of the regression equation

coefficients indicates that condenser capacity is significantly influenced by the following factors:

- moisture content of flue gases d;
- Spray density H_m;
- boiler capacity N_k;
- flue gas temperature before the condenser t_{1g};
- water temperature after the condenser t_{1k};
- return temperature of network water t_{1t};
- temperature of water sprayed into the condenser t_{2k}.

The experimental data values adequately correlate to the modelling results.

7. The analysis of experimental data from the boiler house in Ludza has resulted in an equation that describes the specific reduction in GHG emissions and the produced unit of energy depending on the difference in temperatures between the sprayed fluid and the condensate mixture. The experimental data indicate that even a small difference in temperature (2-3ºC) can result in a 25-30% specific reduction of GHG gas emissions if the fluid flow remains constant.
8. The economic evaluation of the specific reduction in emissions is performed using the gain from the specific reduction of GHG emissions per unit of produced thermal energy. The results of the mathematical processing of the experimental data indicate that the specific gain decreases as the boiler load increases. This can be explained by the greater speed of the gases in the gas condenser, which is in turn linked to a weaker condensation process. The method of evaluating the gain from the specific reduction in GHG emissions includes definition of the benchmark used for this type of condensers and for the established emissions prices on the emissions market. The benchmark value is 1.5 EUR/MWh, if the price of emissions on the emissions market is 30 EUR/tCO_2.
9. The operation of a boiler house with a gas condenser is significantly influenced by all the indicators of the whole heat supply system's operations. An evaluation of the effectiveness of the system's operation is performed using the eco-intensity indicator, which links the system operations indicators with fuel consumption and the reduction in produced emissions. The study provides a model for an analytical evaluation of the eco-intensity indicator of the heat supply system. The model consists of a system of four equations that describe the influence of the heat supply system's elements and the most significant parameters on the changes in the system's eco-intensity index. The equations describe:
   - changes in fuel quality;
   - changes in boiler operation indicators;
   - gas condenser operations;
   - heating network operations.

10. The study of the eco-intensity of the Ludza boiler house with the gas condenser was performed experimentally. Based on the results of the experimental study, it is evident that the eco-intensity indicator decreases as the outside temperature falls, the relative boiler load increases, and the return temperature of the heating network increases. As the relative boiler load increases from 0.4 to 0.8, the eco-intensity indicator falls by 5% from 1.17 to 1.11.

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A STUDY OF A CONDENSATION SYSTEM FOR COOLING FLUE GASES

Summary of thesis

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