https://doi.org/10.33271/nvngu/2022-2/048

V. Nikolsky[1],
orcid.org/0000-0001-6069-169X,
R. Dychkovskyi[2],
orcid.org/0000-0002-3143-8940,
A. Lobodenko[1],
orcid.org/0000-0003-4255-7272,
H. Ivanova[2],
orcid.org/0000-0003-4219-7916,
E. C. Cabana[3],
orcid.org/0000-0002-0066-1349,
Ja. Shavarskyi[4],
orcid.org/0000-0002-9258-575X

1 – Ukrainian State Chemical Technology University, Dnipro, Ukraine
2 – Dnipro University of Technology, Dnipro, Ukraine, e-mail: Dychkovskyi.r.o@nmu.one
3 – Universidad Nacional de San Agustin de Arequipa, Arequipa, Peru
4 – JARAD Recycling Technology Sp. z. o.o, Smolnica, the Republic of Poland

THERMODYNAMICS OF THE DEVELOPING CONTACT HEATING OF A PROCESS LIQUID

Purpose. To study development of contact heating of a process liquid basing on the main principles of thermodynamics in terms of specially developed equipment.

Methodology. The research of efficient operation of plants for contact heating of process liquids was based on analytical and laboratory studies. The analytical studies relied on determining heat and material balance of the process on the basis of quantitative parameters of the obtained heat, basing on contact heating of water (process liquid) as the end (intermediate) heat carrier. Test studies were carried out in terms of special plants for modelling thermodynamic processes of contact liquid heating.

Findings. The efficiency of operation of the special equipment was substantiated by improving its design that makes it possible to preserve the balance between temperatures of liquids on the inlet and outlet of a special heating plant. Basing on the averaged value of the parameters characterizing thermodynamic transformations, time periods of the process liquid heating were identified.

Originality. Dependences and numerical values of changes in maximum equilibrium temperature (boiling temperature) and relative amount of the evaporated water on the specified excess-air coefficient during the natural gas combustion in the submerged combustion devices were obtained. Parameters of the temperature field distribution in the heating system were obtained basing on the design features of a heating plant. The research data were aimed at identifying the efficiency of system operation depending on water consumption at the device inlet. The research was carried out in terms of one-stage and two-stage heating of a process liquid.

Practical value. Design of a test plant for thermochemical water heating was improved; that helped simplify a process of the heating plant control to get maximum amount of heat energy. The efficiency of its operation was substantiated by controlling the temperature field distribution in the heating devices.

Keywords: *contact heating, thermal field, process liquid, heating plant, liquid circulation*

Introduction. Current realias are dictating the necessity of searching for new alternative technologies of thermal energy generation. This problem is of special topicality while providing communal and private enterprises with heating systems. Growing gas prices as well as changing infrastructure in the coal market is making us find new alternative energy source and improve the existing heat supply systems. Moreover, there is the situation when the available natural reserves of energy resources (oil, natural gas) do not guarantee energy security and economic growth of the country. Real wars can take place in the raw material markets, resulting in the problems not only in the third-world countries but also in the ones with developed economies [1].

In terms of our country, a problem of searching for new energy sources to have possibility of short-term maximum reduction of oil and gas export needs is especially acute. The authors have paid much attention to the studies of alternative and traditional technologies of mineral mining [2], processing and transformation of raw materials into different energy types [3]. Special attention is paid to underground, ground coal gasification and integrated use of end products in a unified energy-chemical complex [4]. Technologies of mining, processing of hydrocarbon-bearing raw materials, generation of different types of energy with its further use for national economy of Ukraine are rather important. Development of the technologies for using low-potential heat and energy transformation with the help of cavitation methods of the formation of heat flows for their further use for heating communal and industrial objects are rather promising trends [5]. One of the areas for increasing energy efficiency of the national economy objects is the use of heat supply systems, which are based on submerged combustion of natural gas. This technology is analyzed quite well in technical studies by both national and foreign researchers [6]. In this context, a problem of thermodynamic analysis of the efficiency of heating systems with different heat recovery schemes for exhaust gases requires additional examination, i.e. it concerns their technical and technological improvement.

Literature review. Recently, numerous papers have been devoted to reduction of energy consumption. It especially concerns energy generation from nonrenewable sources. Use of a method of thermodynamic analysis, resulting in minimum costs for obtaining end products and maximum coefficient of efficiency from the whole system operation is an important element while studying the processes of raw material transformation as a result of thermal destruction with heat exchange.

Thermodynamic analysis is the main instrument of preliminary evaluation of any energy or thermal technological device including heating systems. As far back as in late 1980s, A. N. Alabovskyi guided the studies on thermodynamic analysis of concentration of process solutions by evaporation in the submerged combustion devices without additional utilizers [7] and while using surface devices-utilizers and contact heat and mass exchangers for preliminary concentration of the dissolved substance [8]. Those studies were based on the heat and material balance of the devices represented not from the unified viewpoint in terms of complete enthalpies but in terms of properties of the substance changing the liquid concentration at each of the control stages.

Papers [6, 9] represent calculations of the efficiency of submerged fluid (water) heating during the natural gas combustion without using special heat recovery devices. The pa-

---

rameters to be determined in these papers include the following: dew point, equilibrium heating temperature (temperature of a wet-bulb thermometer), specific amount of evaporated moisture per fuel unit, coefficient of the system efficiency. Original calculated values of the enumerated parameters are compared with the data by other studies as well as with the values obtained by the company "Gaz de France" and as a result of their own experimental works. It is shown that there is satisfactory coincidence of the determined values according to different methodologies and measurements.

In the earliest 1990s, R. Guillet calculated the energy coefficient of efficiency related to the highest combustion heat depending on the "temperature of a wet-bulb thermometer" of the combustion products. The analogical results were fulfilled at work [10]. In this context, consideration of possibilities for different ways of heat recovery for combustion products is imposed upon a standard dependence for the main process (low, medium-, and high-temperature). The devices for those heat recovery ways include boilers, vapour pumps, and recuperators. In their studies, "Gaz de France" pays special attention to the vapour pump systems with the efficiency up to 75 % that makes it possible to increase the system operating efficiency (η_h) up to 95 %. Thus, it is possible to bring the high-temperature processes up to the level of efficiency characteristic for the low-temperature devices: t_{wb} of the outgoing combustion products at the vapour pump outlet is lower than the one at the outlet of the main fuel-consuming device by 15–20 K.

Unsolved aspects of the problem. Currently there are quite many studies on heat exchange parameters and mathematical mechanisms on thermodynamics of contact liquid heating and other complex processes of energy exchange physics during submerged or other autonomous systems of energy source combustions. They are based on the developments with the analysis of stress-strain state of the surrounding medium by analytical and experimental methods [11], geofiltration processes and liquid viscosity during their cavitation heating [12], volumes and qualitative characteristics of temperatures depending on equipment design [13] particularly at the expense of analysis of heat and material balance of heat exchange [14], distribution of a temperature field [15] and practical implementation under conditions of communal and industrial enterprises [4].

At the same time, a difference between pressure at the inlet and all stages of the devices while determining thermodynamics of the heat exchange process development has not been completely considered yet. Consequently, there arises a necessity in carrying out additional studies to substantiate parameters of temperature fields in the devices of submerged combustion of natural gas as well as to focus on the development of new equipment design features that will make it possible to use submerged combustion devices (SCD) at new level with the increased coefficient of their operating efficiency.

Purpose of the paper is to study activation of the heat exchange processes in the devices of deep submersion basing on the balanced process liquid supply and peculiarities of design improvement of the equipment.

Methods. To evaluate energy efficiency of the heating system based on submerged natural gas combustion, the research involves special equipment represented in Fig. 1. To analyze the influence of different factors on the system operation (excess-air coefficient, pressure in the device, consumption and temperature of energy carriers etc.) a system of equations of heat and material balances of SCD and recovery heat exchangers is used to be solved by the method of successive approximations.

The mathematical apparatus is based on the following ideas and assumptions. The key ones are given below:

- a steady process is considered in terms of temperature of media involved in the heat and mass exchange;
- equation of combustion reaction is taken as follows [9]

$$CH_4 + 2\lambda O_2 + 7.52\,\lambda N_2 + 15.25d\lambda H_2O =$$
$$= CO_2 + 2(\lambda - 1)O_2 + 7.52\lambda N_2 + (15.25d\lambda + 2)H_2O$$

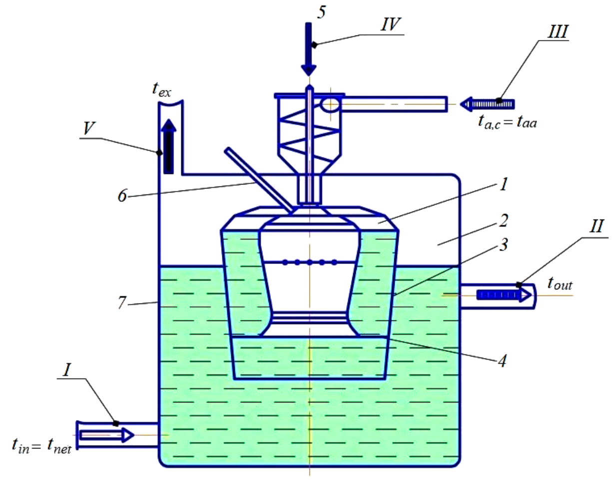

Fig. 1. Scheme of a heating plant based on SCD:

1 – combustion chamber; 2 – vapour and gas space; 3 – circulation cap; 4 – gas-distributing grate; 5 – burner; 6 – igniter; 7 – water bath; I – water at the heating device inlet; II – water at the heating device outlet; III – air; IV – natural gas; V – outgoing combustion products

i.e. air is represented by the mixture of nitrogen, oxygen, and water vapour while natural gas is represented in the form of methane; chemical underburning, formation of NO_x are neglected as for their effect on the balance of heat energy and mass;

- energy balance is formed in terms of complete enthalpies of the substances formed in the systems of C, H, O, N elements as the latter covers both fuel, oxidizer, combustion products and thermally processed medium (water) $I^{\circ}i(T) =$ $= (\Delta H^{\circ}to)i + (H^{\circ}t - H^{\circ}to)I$ that is a specific feature compared to the calculation methods proposed in [7, 8]. The expressions approximating complete enthalpy of substances including vapour and condensate (water) are obtained, depending on the temperatures, on the basis of reference data used in paper [9]; that gives similar results;
- it is suggested that temperature potential of the combustion products, bubblering a water bath, is worked out completely up to the reaching the final water heating temperature;
- complete enthalpy of the combustion products at the SCD inlet is equal to the complete enthalpy of the initial mixture of fuel and oxidizer supplied into the combustion chamber, i.e. there are no heat losses while combusting, and heat removal from the combustion chamber (e.g. heat losses by radiation) is used in the SCD chamber (absorbed in the water bath);
- it is supposed that the vapour and gas mixture above the bath surface obeys the equation of ideal gas and Dalton law;
- it is supposed that the vapour above the bath surface in SCD is saturated and its partial pressure is a single-valued function of the vapour temperature, which in its turn does not differ from the equilibrium temperature of water heating in the bath;
- it is assumed that above the water bath surface the dynamic temperature balance is established with the vapour-gas mixture being removed from the bath. Thus, the latter has the temperature of a "wet-bulb thermometer" corresponding to the moisture and heat content of the combustion products;
- it is assumed that the heat recovery devices are represented by the heat and mass exchangers of a contact type;
- while calculating, it is supposed that the heat exchange processes in the recovery devices continue without any heat losses into the environment.

As a result of extended set of calculations, it is necessary to represent a thermodynamic analysis of the operation of heating plants based on SCD without heat recovery and with its different design schemes.

Thermodynamic analysis of the heating system efficiency in terms of submerged combustion. The effect of pressure in a device and excess-air coefficient on the temperature amount of evaporating water is analyzed (Figs. 2, *a, b*). To do this, a bubblering process of large volume of water with the combustion products in SCD (Fig. 1) is considered after establishment of a balance if there is no liquid supply and removal. An interesting fact is recorded: if $\lambda \approx 2.4$, then the value of m_w, n_g does not depend on pressure, being 20.31 kg/kg of gas.

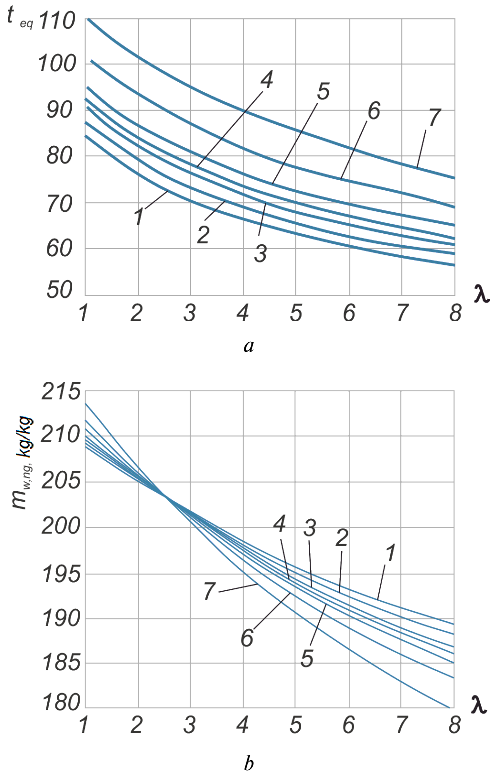

Fig. 2. Dependence of maximum equilibrium temperature (boiling temperature) t_{eq} (a) and relative amount of the evaporated water m_w,n_g (b) on the excess-air coefficient during natural gas combustion in the submerged combustion device. Pressure above the water bath P, MPa is:

1 – 0.08; 2 – 0.09; 3 – 0.101; 4 – 0.11; 5 – 0.12; 6 – 0.15; 7 – 0.20

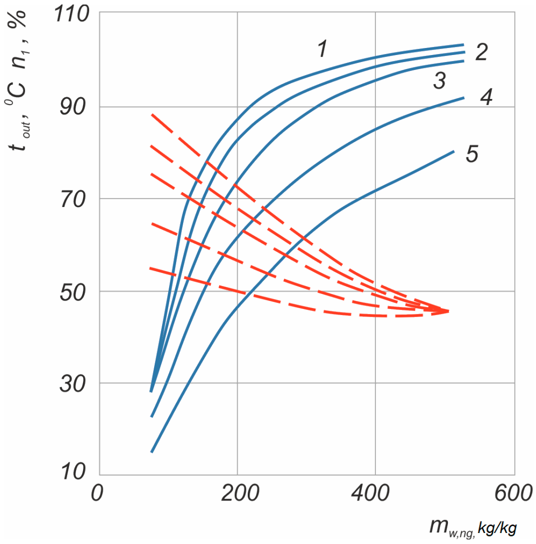

Fig. 3. Temperature of water heating t_{out} (dotted lines) and the coefficient of efficiency of a heating device η_1 (solid lines) depending on relative water consumption at the heating device inlet. Excess-air coefficient λ is:

1 – 1.1; 2 – 1.4; 3 – 2.0; 4 – 4.0; 5 – 8.0

To determine water heating in SCD (Fig. 2) in case of its continuous-flow system of supply and removal, dependence of water heating temperature and relative amount of evaporated moisture on the excess-air coefficient is calculated as well as the coefficient of efficiency of plant h_1 determined according to the lowest fuel specific energy (Fig. 3). The calculations are performed in terms of pressure $P = 0.101$ MPa, moisture content and air temperature $d_{a,a} = 0.004$ kg/kg and $t_{a,a} = 25$ °C, respectively, water temperature at the system inlet $t_{net} = 20$ °C; further, if it is not specified with a difference, these conditions are remained with the additional adoption of $\lambda = 1.15$.

The graphs show that while implementing such systems and in case of nonavailability of heat recovery devices, the appropriate efficiency can be obtained only in terms of comparatively low heating temperatures when there is not moisture evaporation from the heated water but there is condensation of vapour combustion products, i.e. at the temperatures of dew point heating t_d. For instance, $t_d = 53$ °C at $\lambda = 1.15$, under conditions of the continuous-flow system the equilibrium temperature $t_{eq} = t_d = 53$ °C is reached at specific water consumption at the system inlet m_w, $n_g = 360$ kg/kg of gas; at the growing water supply m_w, $n_g > 360$ kg/kg, t_{eq} increases and a condensation process prevails; if m_w, $n_g < 360$ kg/kg, water evaporation from the bath prevails. If heating temperatures close to the maximum possible one (Fig. 2, *a*), the main heat consumption is used not

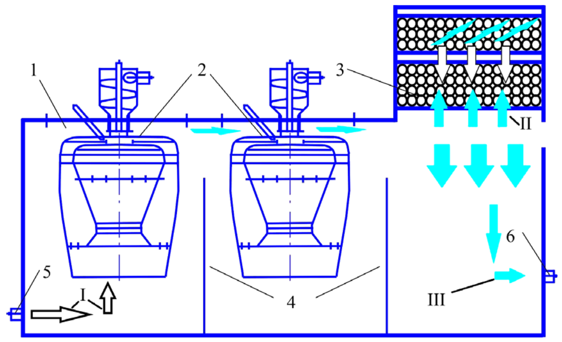

Fig. 4. Heating plant:

1 – SCD tank; 2 – submerged heater; 3 – contact-type wasteheat exchanger; 4 – plates-partitions; 5 – branch pipe of the return water supply; 6 – branch pipe of water supply into the heating system; I – water from the heating system; II – flue gases; III – hot water into the heating system

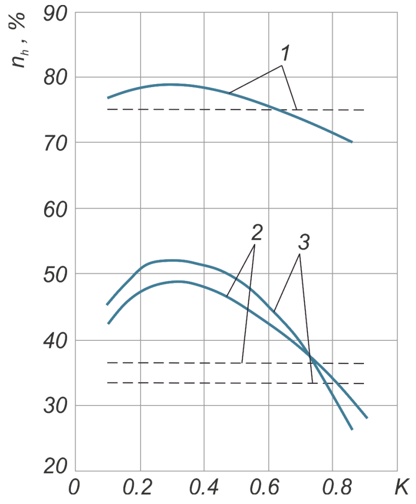

Fig. 5. Dependence of the efficiency of two-stage (two-chamber) water heating η_h on power distribution throughout the stage chambers. Dotted lines show the coefficient of efficiency of one-stage water heating. Temperature tour and $t_{in} = t_{net}$ °C are:

1 – 70 and 45; 2 – 85 and 45; 3 – 85 and 20, respectively for heating but for evaporation of the heated liquid. For instance, if $\lambda = 1.4$ and $t_{out} = 84$ °C, which m_w, $n_g = 60$ kg/kg of gas corresponds to, the ratio of mass flows of the vapour evaporated from the water and the water at the inlet is $m_{v,w} = 0.23$.

It is possible to increase the efficiency without using special wasteheat exchangers but by applying two-stage water heating (Fig. 4). In terms of its design, a device has two water chambers switched on successively along with the water heating process. Each chamber is heated by its own SCD.

Fig. 5 represents a dependence of the efficiency of η_h plant calculated according to the highest combustion value from the stage loads ($\lambda = 1.15$ for each stage) using the coefficient of gas distribution between SCD.

In the graph, dotted straight lines correspond to a one-stage heating scheme. It is determined that the higher the water heating temperature and temperature differences at the inlet and outlet are, the more significant the advantage of two-stage heating is. In this context, there is an optimal value $K \approx 0.3$ that gives optimal efficiency gain irrespective of the inlet and outlet water temperature.

Analysis of the efficiency of a system with submerged combustion heating devices with different schemes of exhaust-gas heat recovery. Fig. 6 represents a scheme making it possible to increase considerably the efficiency of the SCD-based heating system by installing a contact wasteheat exchanger.

The latter is used for heating the water supplied into a device at the expense of heat of exhaust gases. Heat content (enthalpy) of the exhaust gases is defined mainly by the heat of vapour condensation, whose amount represents the total of flows of water vapour formed during the natural vapour combustion and the vapour generated from the water in the SCD bath.

In case of high water heating temperatures, the recovery helps increase considerably the coefficient of efficiency, which reaches 40 % at some t_{out} (Fig. 7). Within wide tem-

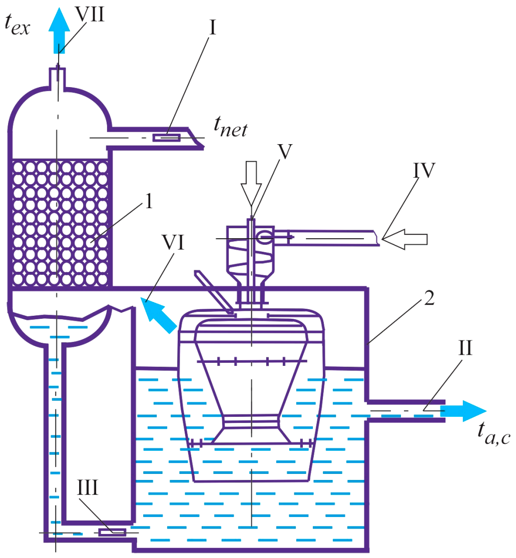

Fig. 6. Scheme of a heating plant based on SCD during the combustion-product heat recovery:

1 – contact heat-exchange unit; 2 – SCD; I – water at the heating plant inlet; II – water at the heating plant outlet; III – water at the SCD inlet; IV – air; V – natural gas; VI – combustion products at the SCD outlet; VII – outgoing combustion products

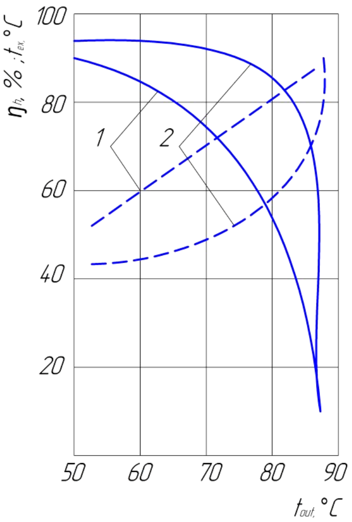

Fig. 7. Temperature of exhaust gases t_{ex} (dotted lines) and the coefficient of efficiency of a heating plant η_h (solid lines) depending on the water heating temperature:

1 – plant without heat exchange recovery (Fig. 1); 2 – plant with heat recovery based on the contact wasteheat exchanger

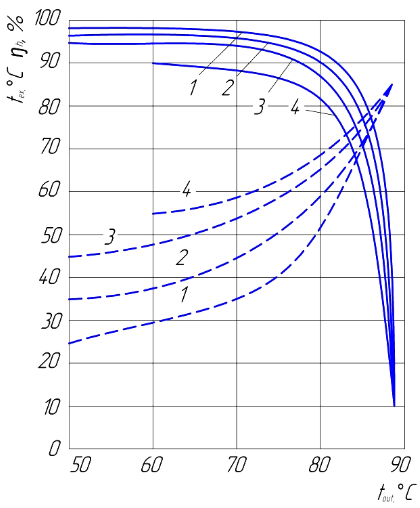

Fig. 8. Temperature of exhaust gases t_{ex} (dotted lines) and the coefficient of efficiency of a heating plant η_h (solid lines) depending on the water heating temperature at the system inlet t_{net}, °C:

1 – 25; 2 – 35; 3 – 45; 4 – 55

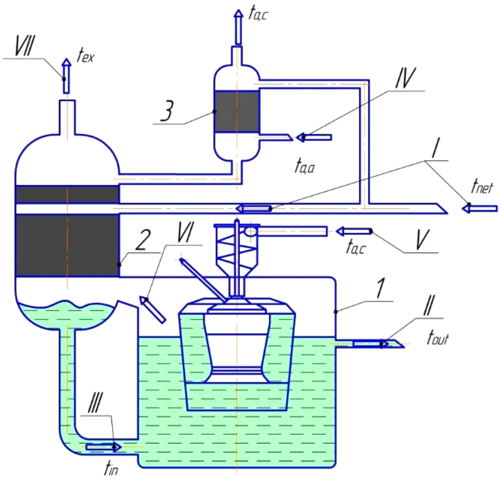

Fig. 9. Scheme of a heating plant with applied SCD and recovery of combustion-product heat, heating and moistening of the combustion air:

1 – SCD; 2 – contact heat exchanger; 3 – contact air heater; I – water at the heating device inlet; II – water at the heating device outlet; III – water at the SCD inlet; IV – air at the heating device inlet; V – combustion air; VI – combustion products at the SCD outlet; VII – outgoing combustion products

Table

Comparison of the main indices of heating systems: with the use of SCD and condensation boilers

Type of a heating device	t_{out}, °C	t_{net}, °C	t_{ex}, °C	η_l, %	Source
SCD and combined heat recovery system	70.0 80.0 85.0 88.0	45.0 50.0 55.0 70.0	29.0 31.9 35.4 50.9	108.9 108.3 107.5 102.1	Calculation
Condensation boilers UltraGas AM condens (500)	40.0 75.0	30.0 60.0	– –	109.4 106.1	[17]

perature ranges t_{net} and t_{out}, the efficiency reaches 90 % and more (Fig. 7).

The calculation is performed under condition that the temperature of outgoing combustion products is equal to the water temperature after utilizers t_{in} [16]. While implementing such a scheme and efficient heat exchange in a utilizer, it is possible to provide the equilibrium of water temperatures at the system inlet and combustion products leaving the utilizer, t_{net}, which will increase the efficiency by several percentage points. Disadvantage of such a plant is the necessity of obtaining the value of exhaust gas temperatures, which is crucial in determining the heating system efficiency, being lower than the temperature of liquid supply as well as strong dependence of the efficiency on t_{net} and t_{out} (Fig. 8). It is possible to eliminate the mentioned disadvantages with the help of a heating plant system represented in Fig. 9.

The latter is used for heating and moistening the air supplied for combustion, i. e. a principle of "vapour pump" is used. In the 1990s this principle was applied without creating additional water circuit. It was proposed by Aronov, I. Z. This scheme is presented in Fig. 9. The research studies based on "vapour pump" are strongly highlighted in specialised papers [10, 17]. Such a system allows using heat of condensation of the water vapour contained in the combustion products by its transfer to the combustion air at its heating and moistening to obtain a temperature of exhaust combustion products to be lower than the temperature of supply water at the system inlet [18].

Haep, J., & Nani, M. using of a heating device represented in Fig. 9 helps work with η_l, being close to 100 % (η_h is about 110 %), in the heating systems in terms of temperatures corresponding to the normal ones, which exceeds the values represented in for condensation boilers (η_h = 106.1 % at t_{net} = 60 and t_{out} = 75 °C). Characteristics of a plant with SCD and a combined scheme of heat recovery according to the scheme in Fig. 9 are given in Table 1 while operating with the following mode parameters: $\lambda = 1.15$, $d_{a,a} = 0.01$ kg/kg, $t_{a,a} = 25$ °C, relative humidity of the heated air is 70 %.

It is clear that the system efficiency decreases at rising t_{out}; moreover, the effect is more significant, the closer t_{out} is to t_{eq}. In its turn, at fixed t_{out} the efficiency of systems with deep recovery of outgoing combustion-product heat is higher, the greater is the difference between the temperatures at the heating device inlet and outlet (Fig. 8, Table), which coincides with the conclusions of paper [10]. Such regularity is confirmed practically for small condensation boilers.

Conclusions. Basing on the obtained results and comparing the data from the normative research results, one may conclude that it is possible to get high efficiency (energy efficiency) of the heat supply systems: on the basis of submerged heaters and contact utilizers, on the one hand, and condensation boilers, on the other hand. The represented equation of combustion reaction shows that the share of vapours in the combustion products can be increased either by using fuels with high oxygen content or by raising the combustion air moisture. In this context, natural gas is the best of all organic fuels including any hydrocarbons. On the other hand, it is possible to apply a recovery scheme "vapour pump" while using hydrogenless fuels as well. Apart from the increased efficiency, air moistening results in reduced NO_x concentration in the combustion products. That is also proved by the results of studies represented in [19] where possibility of obtaining heat energy in both considered boiler types is shown. Moreover, costs for combustion in the systems of submerged heaters are much lower than the ones in case of standard gas internal combustion boilers.

The obtained results make it possible to elaborate design documentation for manufacturing an industrial plant for heat energy generation to heat with the submerged combustion devices with different schemes of exhaust gas recovery. Development of this device meets the basic positions of declared policy of the Law of Ukraine "On energy saving" [20]. It demonstrates that the obtained results are of great significance for our national economy.

This work contains the research, which was conducted within the grant GP-503, Reg No. 0120U102084 (financed by the Ministry of Education and Science of Ukraine) Dubrovnik International ESEE Mining School and Training the trainers in East and Southeast Europe (projects within the framework of EIT Raw Materials).

References.

1. Dychkovskyi, R., Tabachenko, M., Zhadiaieva, K., Dyczko, A., & Cabana, E. (2021). Gas hydrates technologies in the joint concept of geoenergy usage. *E3S Web of Conferences*, *230*, 01023. https://doi.org/10.1051/e3sconf/202123001023.

2. Kicki, J., & Dyczko, A. (2010). The concept of automation and monitoring of the production process in an underground mine. *New Techniques and Technologies in Mining*, 245-253. https://doi.org/10.1201/b11329-41.

3. Beshta, O. S. (2012). Electric drives adjustment for improvement of energy efficiency of technological processes. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 98-107.

4. Cabana, E., Falshtynskyi, V., Saik, P., Lozynskyi, V. & Dychkovskyi, R. (2018). A concept to use energy of air flows of technogenic area of mining enterprises. *E3S Web of Conferences*, *60*, 00004. https://doi.org/10.1051/e3sconf/20186000004.

5. Pivnyak, G., Samusia, V., Oksen, Y., & Radiuk, M. (2014). Parameters optimization of heat pump units in mining enterprises. *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining*, 19-24. https://doi.org/10.1201/b17547.

6. Nikolsky, V. (2015). Development and study of contactmodular heating system using immersion combustion units. *Eastern-European Journal of Enterprise Technologies*, *4*(8), 31-35. https://doi.org/10.15587/1729-4061.2015.47459.

7. Hess, A. M., Kessler, D. A., Johnson, R. F., & Bojko, B. T. (2021). Towards a Simulation Method for Aluminum-Particle-Enhanced Solid Fuel Combustion Devices. *Solid Propellants*, 32-45. https://doi.org/10.2514/6.2021-3621.

8. Deshmukh, D., Siddique, M. H., & Samad, A. (2017). Surface Roughness Effect on Performance of an Electric Submersible Pump. *Compressors, Fans and Pumps; Turbines; Heat Transfer; Combustion, Fuels and Emissions*, *1*, 78-82. https://doi.org/10.1115/gtindia2017-4848.

9. Khojaev, I. K., & Hamdamov, M. M. (2020). Numerical Method for Calculating Axisymmetric Turbulent Jets of Reacting Gases During Diffusion Combustion. *Journal of Advanced Research in Dynamical and Control Systems*, *12*(SP7), 2061-2074. https://doi.org/10.5373/jardcs/v12sp7/20202324.

10. Wang, S., Wang, Q., Zhang, H., Wang, Y., Zhou, J., Zhao, P., & Liu, J. (2022). Performance analysis on parallel condensing air-source heat pump water heater system. *Energy Reports*, *8*, 398-414. https://doi.org/10.1016/j.egyr.2022.01.212.

11. Onishi, H., Yonekura, H., Tada, Y., & Takimoto, A. (2010). Heat Transfer Performance of Finless Flat Tube Heat Exchanger with Vortex Generator. *2010 14th International Heat Transfer Conference, 4.* https://doi.org/10.1115/ihtc14-23232.

12. Nikolsky, V., Kuzyayev, I., Dychkovskyi, R., Alieksandrov, O., Yaris, V., Ptitsyn, S., ..., & Smoliński, A. (2020). A study of heat exchange processes within the channels of disk pulse devices. *Energies*, *13*(13), 3492. https://doi.org/10.3390/en13133492.

13. Petlovanyi, M., Kuzmenko, O., Lozynskyi, V., Popovych, V., Sai, K., & Saik, P. (2019). Review of man-made mineral formations accumulation and prospects of their developing in mining industrial regions in Ukraine. *Mining of Mineral Deposits*, *13*(1), 24-38. https://doi.org/10.33271/mining13.01.024.

14. Petlovanyi, M., Lozynskyi, V., Saik, P., & Sai, K. (2019). Predicting the producing well stability in the place of its curving at the underground coal seams gasification. *E3S Web of Conferences*, (123), 01019. https://doi.org/10.1051/e3sconf/201912301019.

15. Pedchenko, M., Pedchenko, L., Nesterenko, T., & Dyczko, A. (2018). Technological Solutions for the Realization of NGH-Technology for Gas Transportation and Storage in Gas Hydrate Form. *Solid State Phenomena*, *277*, 123-136. https://doi.org/10.4028/www.scientific.net/ssp.277.123.

16. Tang, W., & Sarathy, M. (2020). Investigate Chemical Effects of Pre-Chamber Combustion Products on Main Chamber Ignition Performance under an Ultra-Lean Condition. *SAE Technical Paper Series*. https://doi.org/10.4271/2020-01-2001.

17. Butcher, T.A. (2018). Potential for Particulate Emission Reduction in Flue Gas Condensing Heat Exchangers in Biomass-Fired Boiler. https://doi.org/10.2172/1434002.

18. Jaya Sekhar, L. (2020). Automatic Temperature Monitoring and Controlling Water Supply System. *International Journal of Psychosocial Rehabilitation, 24*(5), 2781-2787. https://doi.org/10.37200/ijpr/v24i5/pr201981.

19. Tesser, R., & Santacesaria, E. (2020). Revisiting the Role of Mass and Heat Transfer in Gas–Solid Catalytic Reactions. *Processes, 8*(12), 1599. https://doi.org/10.3390/pr8121599.

20. Law of Ukraine No. 3260-IV (2019). About energy saving (with changes). *Supreme Soviet of Ukraine,* 12.

Термодинаміка процесу контактного нагрівання технологічної рідини

В. Є. Нікольський[1], *Р. О. Дичковський*[2], *А. А. Лободенко*[1], *А. П. Іванова*[2], *Є. К. Кабана*[3], *Я. Т. Шаварський*[4]

1 – Державний вищий навчальний заклад «Український державний хіміко-технологічний університет», м. Дніпро, Україна

2 – Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна, e-mail: Dychkovskyi.r.o@nmu.one

3 – Університет Святого Августина, м. Арекіпа, Перу

4 – ВАТ «JARAD рециклінгові технології», м. Смольніца, Республіка Польща

Мета. Дослідження активізації процесів контактного нагрівання технологічної рідини, виходячи з основних принципів термодинаміки, на спеціальному розробленому устаткуванні.

Методика. Дослідження ефективної роботи установок контактного нагрівання технологічних рідин ґрунтувалося на основі проведення аналітичних і лабораторних досліджень. Аналітичні дослідження ґрунтувались на встановленні матеріально-теплового балансу процесу на основі кількісних параметрів отриманого тепла, виходячи з контактного нагрівання води (технологічної рідини) як кінцевого (проміжного) теплоносія. Тестові дослідження проводились на спеціальних установках із моделювання термодинамічних процесів контактного нагрівання рідини.

Результати. Обґрунтована ефективність роботи спеціального обладнання шляхом покращення конструктивного його виконання, що дозволяє зберігати баланс між температурою рідини на вході та на виході спеціальної опалювальної установки. На основі усередненого значення параметрів, що характеризують термодинамічні перетворення, встановлені часові проміжки нагрівання технологічної рідини.

Наукова новизна. Отримані залежності та чисельні значення зміни максимальної рівноважної температури (температури кипіння) та відносної кількості випареної води від встановленого коефіцієнта надлишку повітря при спалюванні природного газу в апаратах зануреного горіння. Встановлені параметри розповсюдження температурного поля в системі теплонагрівання, виходячи з конструктивних особливостей опалювальної установки. Дані дослідження орієнтувалися на встановленні корисної дії роботи системи залежно від розходу води на вході апарату. Дослідження проведене при одно- та двоступеневому нагріванні технологічної рідини.

Практична значимість. Удосконалена конструкція тестової установки з термодинамічного нагрівання технологічної рідини, що спрощує процес управління нагрівальною установкою з метою максимального отримання теплової енергії. Обґрунтована ефективність її роботи шляхом контролю розповсюдження температурного поля в апаратах теплонагрівання.

Ключові слова: *контактне нагрівання, теплове поле, технологічна рідина, опалювальна установка, циркуляція рідини*

The manuscript was submitted 21.07.21.