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GAS TURBINE INTAKE AIR COOLING SYSTEMS OF COMBINED TYPE AND THEIR OPTIMUM DESIGNING

Abstract: *Turbine intake air cooling (TIAC) by absorption lithium-bromide chillers (ACh) utilizing the exhaust heat is considered as the most effective fuel saving technology for temperate climatic conditions. But the cooling potential of TIAC systems based on ACh of a simple cycle is limited by a comparatively increased chilled water temperature of about 7°C excluding cooling intake air lower than 15°C. The application of a refrigerant as a coolant enables deeper cooling intake air to 10°C and lower. The application of two-stage hybrid absorption-ejector chillers (AECh) with a refrigerant ejector chiller (ECh) as a low temperature stage makes it possible to increase the annual fuel saving approximately twice in temperate climate due to deeper cooling air as compared with ACh. Furthermore, this effect can be achieved with the sizes of TIAC system reduced by about 20% due to determining the rational refrigeration capacity of AECh providing practically maximum annual fuel saving increment and the use of the current excessive refrigeration capacities to cover peaked loads.*

Keywords: *turbine, intake air, two-stage cooling, combined chiller, fuel efficiency.*

Introduction

The ambient air temperature makes a considerable influence on the efficiency of gas turbines (GT) [1, 2]. The absorption lithium-bromide chillers (ACh) [3, 4] are the most widespread for turbine intake air cooling (TIAC) by using the exhaust heat [5, 6]. But their application is limited by the values of ambient air temperature of about 15°C because of comparatively raised temperature of chilled water from them of about 15°C for ACh of a simple cycle [7, 8]. Therefore, their application in temperate climatic conditions is not so prosperous [9, 10]. But they can be applied as a stabilizing boost high temperature stage to minimize the fluctuations of current loading at increased ambient air temperatures above 15°C [11, 12]. In order to enhance the effect in fuel saving due to TIAC the further subcooling the air, precooled in ACh, might be conducted by the chillers which efficiency is effected by changing thermal loads [13, 14]. Thus, the ejector chillers (ECh) could be applied [15, 16] as a low temperature stage and the most simple in design and cheapest [17, 18]. The application of combined absorption-ejector chillers (AECh) can be prosperous for TIAC in temperate climatic conditions [19, 20].

The efficiency of exhaust heat utilization [21, 22] and cooling systems [23, 24] can be improved due to application of low temperature condensing surfaces [25, 26], providing deep engine exhaust heat utilization [27, 28], and low temperature air coolers-refrigerant evaporators [29, 30]. The energetic efficiency of the chillers [31, 32] and heat exchangers [33, 34] can be improved due to intensification of heat transfer in evaporators [35, 36] and condensers [37, 38], hydrodynamic in minichannels [39, 40], advanced system scheme decisions [41, 42], utilization of exhaust heat by jet technics [43, 44] to enhance the heat for conversion into refrigeration [45, 46]. The additional refrigeration capacity, generated by deep recovering the heat exhausted from the engine, can be used for engine cyclic air cooling: intake air at the suction of turbocharger and scavenge air.

Many publications focused for improving ambient air processing in waste heat recovery technics for combined heat and power (CHP), combined cooling, heating and power (CCHP) [47, 48], i.e. trigeneration or integrated energy systems [49, 50].

Such engine in-cycle trigeneration provides enhancing engine fuel efficiency and prolong the time of efficient operation of trigeneration plant, since cooling demands for technological needs have, as a rule, periodic character.

Some of principal technical innovations and methodological approaches in heat recovery: jet technologies, deep exhaust heat use for increasing the available waste heat potential to be converted into refrigeration and others were developed for TIAC or might be successfully applied in TIAC to match current cooling demands.

Practically all the methods of analyses are aimed to increase the effect gained due to ambient air processing through rational loading [51, 52] to reduce energy and fuel consumption [53, 54]. Many of such methods include calculation of cooling degree-hours (CDH) [55, 56] and modified versions [57] to match current cooling duties according to actual climatic conditions as well as thermal demand management (TDM) [58, 59] based on different criteria [60, 61] to save energy.

So as the performance efficiency of TIAC systems needs to be analyzed across the full range of operating conditions, the CDH number is used to determine the total amount ΣCDHs in a particular climate over a considered period. The use of TIAC potential in terms of CDH provides easy calculation of fuel reduction and engine power output augmentation for any considered period.

The ambient air temperature and relative humidity distribution during year or any cooling period is very important input data for energy analyses and a design cooling load determination. The studies on the input ambient data when evaluating gas turbine inlet cooling are presented in [62].

Although many researchers consider the cumulative CDH profile along with time elapsed, only a few studies focus on analyzing the behavior of yearly cumulative cooling profiles in dependence on loading to determine a design cooling load [62, 63].

Practically all the generally accepted methods for TIAC system designing issue from the assumption to cover the maximum cooling needs over the full range of yearly operating conditions [62, 63]. Such approach inevitable leads to considerable overestimation of cooling capacities and TIAC systems oversizing, that requires to define a correct design cooling load without overestimation.

A reduction of the chiller sizes with maximum annual fuel saving is possible due to defining the rational and optimum design cooling capacities providing maximum annual fuel saving and maximum rate of annual fuel saving increment and through their rational distribution providing small deviation of current loads from a design value.

The purpose of the study is to develop the advanced combined AECh TIAC systems and the advanced methodology of their designing with rational distribution of the overall design cooling capacity between ACh to cover the unstable thermal load range for ambient air precooling and ECh operating in a comparatively stable load range of further air subcooling, that provides practically twice reduction of a design boost cooling capacity and about 20% of the overall cooling capacity and about twice annual fuel saving in temperate climatic conditions as compared with ACh.

Methodology

A reduction of the chillers design cooling capacity is possible by determining its rational value to provide closed to maximum annual fuel saving as the first step of the methodology for designing the

TIAC system and further distribution of the available cooling capacity in response to the current demands as the second step.

The annual fuel saving ΣB_e of the GT due to inlet air cooling is assumed as a criterion to determine a rational design cooling capacity Q_0 of the TIAC system. With this the current fuel reduction B_e have been summarized over the year:

$$\sum B_e = \sum (\Delta t_a \cdot \tau) \cdot b_{et} \cdot N_e \cdot 10^{-3}, \text{ t} \quad (1)$$

where:

- Δt_a – current intake air temperature drop; $\Delta t_a = t_{amb} - t_{a2}$, K or °C;
- t_{amb}, t_{a2} – ambient air and air temperature at the air cooler outlet, K or °C;
- N_e – turbine power output, kW;
- τ – time interval, h;
- b_{et} – specific fuel reduction for 1 K (1°C) air temperature drop, assumed 0.7 g/(kWh·K) for UGT10000 [64].

A total cooling capacity Q_0 for air mass flow rate G_a, kg/s:

$$Q_0 = G_a \Delta t_a \ \xi \cdot c_{ma}, \text{ KW} \quad (2)$$

where:

- ξ – specific heat ratio;
- c_{ma} – specific heat of wet air, kJ/(kg·K).

Specific cooling capacity q_0 as the total its value Q_0 referred to air mass flow rate G_a = 1 kg/s:

$$q_0 = Q_0 \ / G_a, \text{ kW/(kg/s) or kJ/kg} \quad (3)$$

According to the developed method the fluctuations of the current GT fuel reduction B_e due to cooling intake air are considered by the rate of their annual increment ΣB_e as relative annual fuel saving increment $\Sigma B_e / Q_0$ referred to needed cooling capacity Q_0.

Such a methodological approach makes it possible to increase the accuracy of the calculation results by excluding the approximation of the current changeable values of B_e.

The optimum design cooling capacity of the chiller $Q_{0.opt}$ provides a maximum rate of annual fuel saving increment $\Sigma B_e / Q_0$ and minimum sizes of the chiller and TIAC system.

Thus, a relative annual fuel saving increment $\Sigma B_e / Q_0$ is used as indicator to choose a maximum rate of annual fuel saving increment as a maximum value of $\Sigma B_e / Q_0$ and corresponding cooling capacity is considered as optimum $Q_{0.opt}$.

Results

A developed combined two-stage TIAC system with AECh is presented in Figure 1.

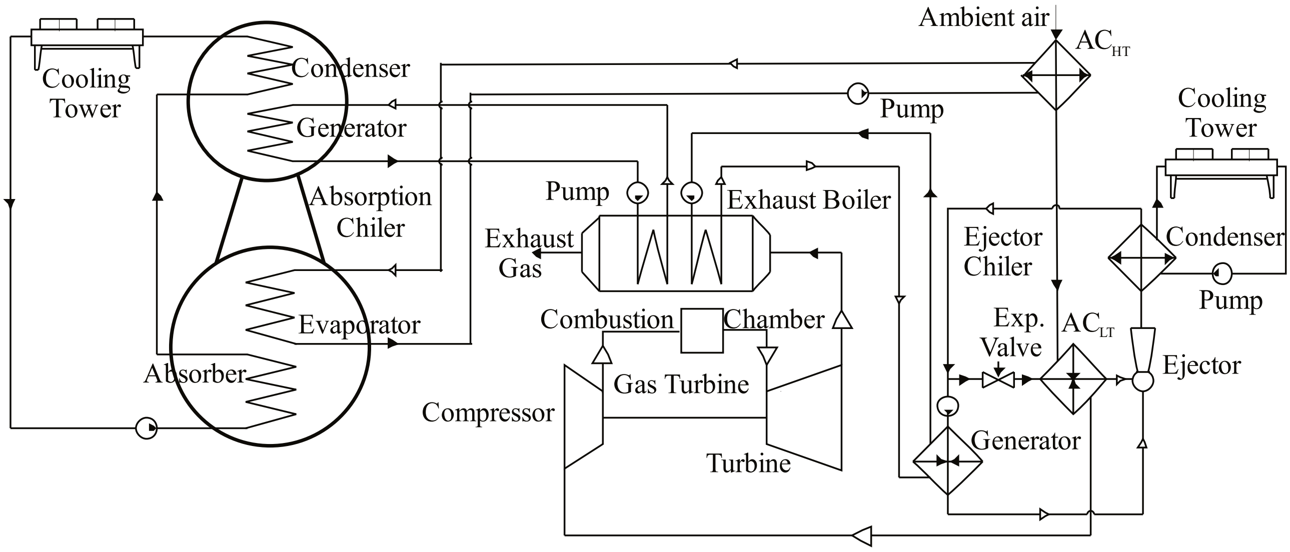

FIGURE 1. *A combined two-stage TIAC system with AECh: AC$_{HT}$ – high-temperature air cooler stage; AC$_{LT}$ – low-temperature air cooler stage; Exp. Valve – expansion valve*

Current values of ambient air temperatures t_{amb} and relative humidities φ_{amb}, specific cooling capacities $q_{0.10}$ and $q_{0.15}$ needed for cooling ambient air at the inlet of GT to t_{a2} = 10°C and 15°C during 2017 in Nikolaev region, southern Ukraine, are presented in Figure 2.

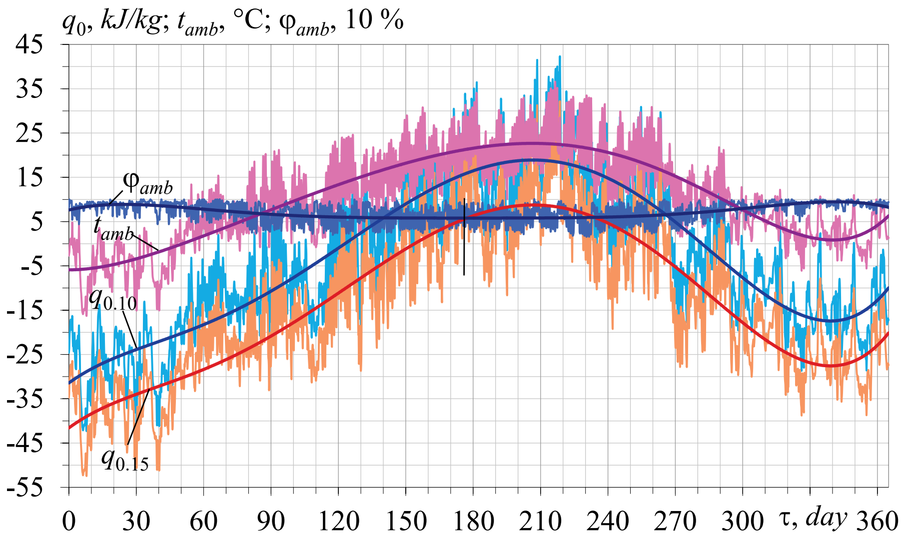

FIGURE 2. *Current ambient air temperatures t_{amb} and relative humidities φ_{amb}, specific cooling capacities $q_{0.10}$ and $q_{0.15}$ needed for cooling ambient air at the inlet of GT to t_{a2} = 10°C and 15°C during 2017 in Nikolaev region, southern Ukraine*

Because of considerable fluctuation of current specific cooling capacities q_0 and their total values Q_0 needed for cooling ambient air at the inlet of GT it is practically impossible to determine its rational value that would provide closed to maximum annual fuel saving ΣB without TIAC system oversizing.

Following the method developed the fluctuations of the current cooling capacities Q_0 and corresponding fuel saving B_e are considered by the rate of annual fuel saving increment ΣB_e as relative annual fuel saving increment $\Sigma B_e / Q_0$ referred to needed cooling capacity Q_0. A such methodological approach makes it possible to increase the accuracy of the calculation results by excluding the approximation of the current changeable values of Q_0 and B_e.

The optimum design cooling capacity of the chiller $Q_{0.opt}$ provides a maximum rate of annual fuel saving increment $\Sigma B_e / Q_0$ and minimum sizes of the chiller and TIAC system (Fig. 3a). The calculations are performed for gas turbine UGT 10000.

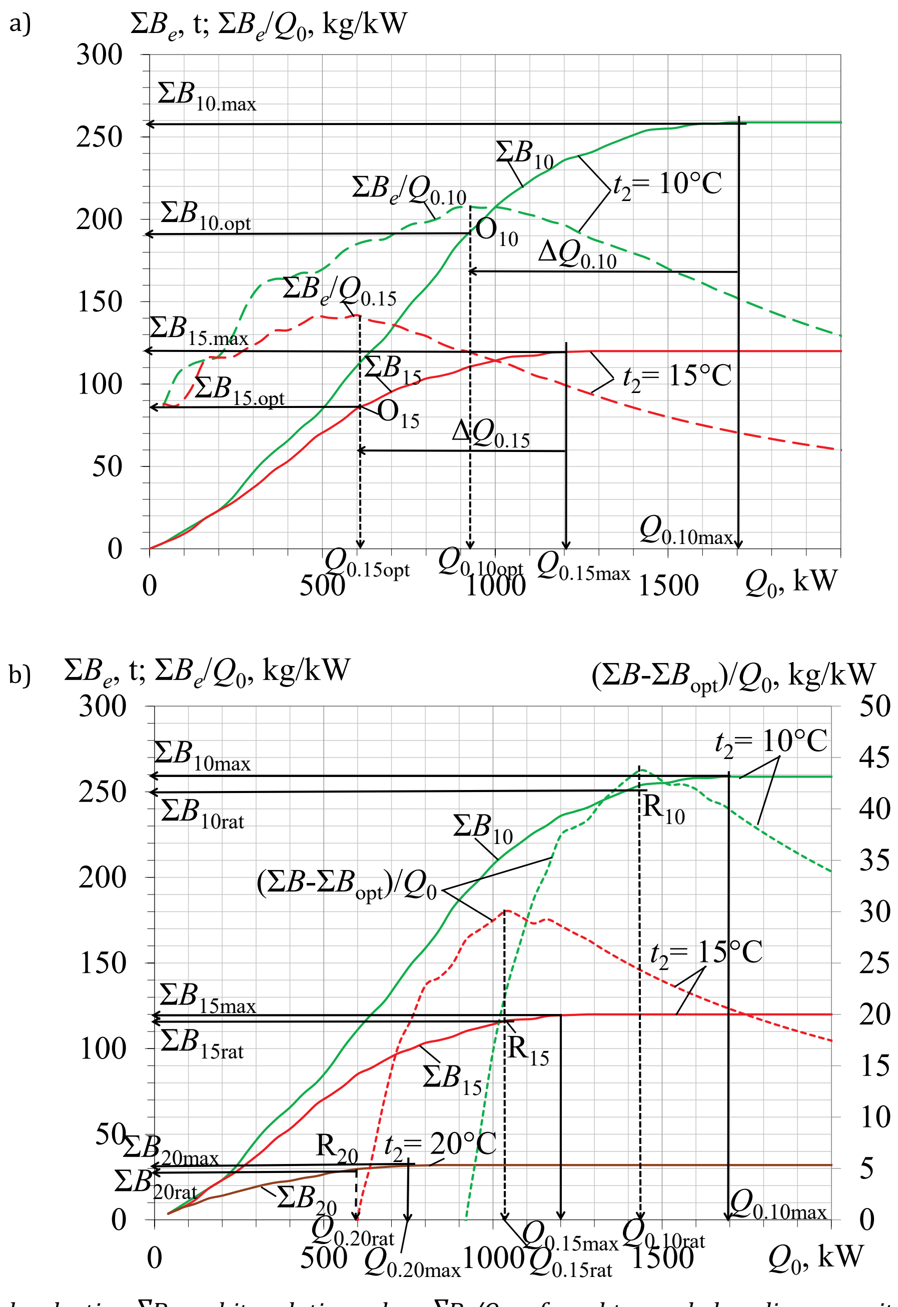

FIGURE 3. *Annual fuel reduction ΣB_e and its relative values $\Sigma B_e/Q_0$ referred to needed cooling capacity Q_0 (a); annual fuel reduction ΣB_e and relative values $\Sigma(B_e - B_{e.opt})/Q_0$ beyond the optimum values $\Sigma B_{e.opt}$ and $Q_{0.opt}$ (b); versus cooling capacities Q_0 needed for cooling ambient air at GT inlet for cooling ambient air to t_{a2} = 10°C, 15°C and 20°C ΣB_e*

A maximum rate of annual fuel reduction increment $\Sigma B_e / Q_0$ for t_{a2} = 10°C takes place at the optimum design cooling capacity $Q_{0.10opt}$ of about 1050 kW and corresponding ΣB_{10opt} of about 140 t (Fig. 3a).

In order to determine a rational value of design cooling capacity $Q_{0.rat}$, providing a closed to maximum annual fuel reduction ΣB_e it is necessary to define the second maximum of annual fuel reduction ΣB_e increment beyond the first maximum rate: $Q_0 > Q_{0.opt}$ and $\Sigma B_e > \Sigma B_{e.opt}$ accordingly. With this a relative value $\Sigma(B_e - B_{e.opt}) / Q_0$ is used as indicator to choose a rational value $Q_{0.rat}$ (Fig. 3b).

A maximum rate of annual fuel reduction increment $\Sigma(B_e - B_{e.\mathrm{opt}})/Q_0$ beyond the value $\Sigma B_{f.\mathrm{opt}}$ = 140 t corresponding to $Q_{0.\mathrm{opt}}$ = 900 kW takes place at the rational design cooling capacity $Q_{0.\mathrm{rat}}$ about 1400 kW and provides annual fuel reduction $\Sigma B_{e.\mathrm{rat}}$ = 150 t that is very closed to its maximum value 160 t but at a reduced design cooling capacity $Q_{0.\mathrm{rat}}$ = 1400 kW less than $Q_{0.\max}$ = 1800 kW by 15%.

As Figure 3b shows, optimum designing of TIAC systems provides decrease of installed cooling capacities of the chillers and TIAC systems in the whole by the values of $\Delta Q_{0.10,15,20}$, i.e. by 15% to 20% compared with their maximum magnitudes $Q_{0.10,15,20\max}$, calculated according to conventional practice of designing.

Deeper turbine intake air cooling to t_{a2} = 10°C in AECh instead of typical cooling air to t_{a2} = 15°C in ACh provides practically twice increase in annual fuel saving $\Sigma B_{10\max}$ as compared with $\Sigma B_{15\max}$ for ACh in temperate climatic conditions (Fig. 3b).

Furthermore, this effect can be also achieved with the sizes of TIAC system reduced by about 20% due to operation at the optimum refrigeration capacity of AECh providing a maximum rate of annual fuel saving increment. With this the problem of using the current excessive refrigeration capacities to cover peaked loads is to be solved by rational distribution of the overall design cooling capacity between ACh and ECh.

Therefore the further development of the methodology of TIAC system designing focuses to reveal the addition reserves of their enhancing due to matching current loading through rational distribution of the overall design cooling capacity between ACh to cover the unstable thermal load range for ambient air precooling and ECh operating in a comparatively stable load range of further air subcooling.

The values of cooling capacities $Q_{0.15}$ needed for cooling ambient air to t_{a2} = 15°C, rational cooling capacities $Q_{0.10\mathrm{rat}}$ and $Q_{0.15\mathrm{rat}}$ and $Q_{0.20\mathrm{rat}}$ for cooling ambient air to t_{a2} = 10°C, 15°C and 20°C accordingly, the basic cooling capacity as difference $Q_{0.10-15} = Q_{0.10} - Q_{0.15}$, needed for cooling air from t_{a2} = 15°C to t_{a2} = 10°C, available residual boost cooling capacities $Q_{0.b10-15}$ and $Q_{0.b10-20}$ are calculated for climatic conditions in Nikolaev region, southern Ukraine, July 2017 (Fig. 4).

The considerable fluctuations of the current thermal loads $Q_{0.15}$ during cooling the ambient air to t_{a2} = 15°C indicates to significant excessive cooling capacities in the temperate daily hours. Meantime, when air is cooled from t_{a2} = 15°C to t_{a2} = 10°C, the fluctuations in the thermal load $\Delta Q_{0.10-15} = Q_{0.10} - Q_{0.15}$ are relatively small. Proceeding from this, the temperature of cooled air t_{a2} = 15°C is considered as the threshold temperature to shear the overall design thermal load on the TIAC system $Q_{0.10\mathrm{rat}}$ into a comparably stable load range $\Delta Q_{0.10-15}$ and the boost unstable range of ambient air precooling. The stable load value $\Delta Q_{0.10-15}$ is considered as a basic stable part $\Delta Q_{0.10-15} = Q_{0.10} - Q_{0.15}$ of a design cooling capacity $Q_{0.10\mathrm{rat}}$ = 1400 kW (Fig. 3).

Accordingly, the remaining part of $Q_{0.10\mathrm{rat}}$ is used for precooling the ambient air to the threshold temperature t_{a2} = 15°C and determined as $Q_{0.b10-15} = Q_{0.10} - \Delta Q_{0.10-15}$ (Fig. 4b). The unstable $Q_{0.15}$ thermal load range can be covered by ACh as well as the stable $Q_{0.10-15}$ thermal load range – by ECh (Fig. 1).

As Figure 4a shows, the available boost cooling capacity $Q_{0.b10-15}$ generally covers current thermal loads $q_{0.15}$ for precooling ambient air to t_{a2} = 15°C.

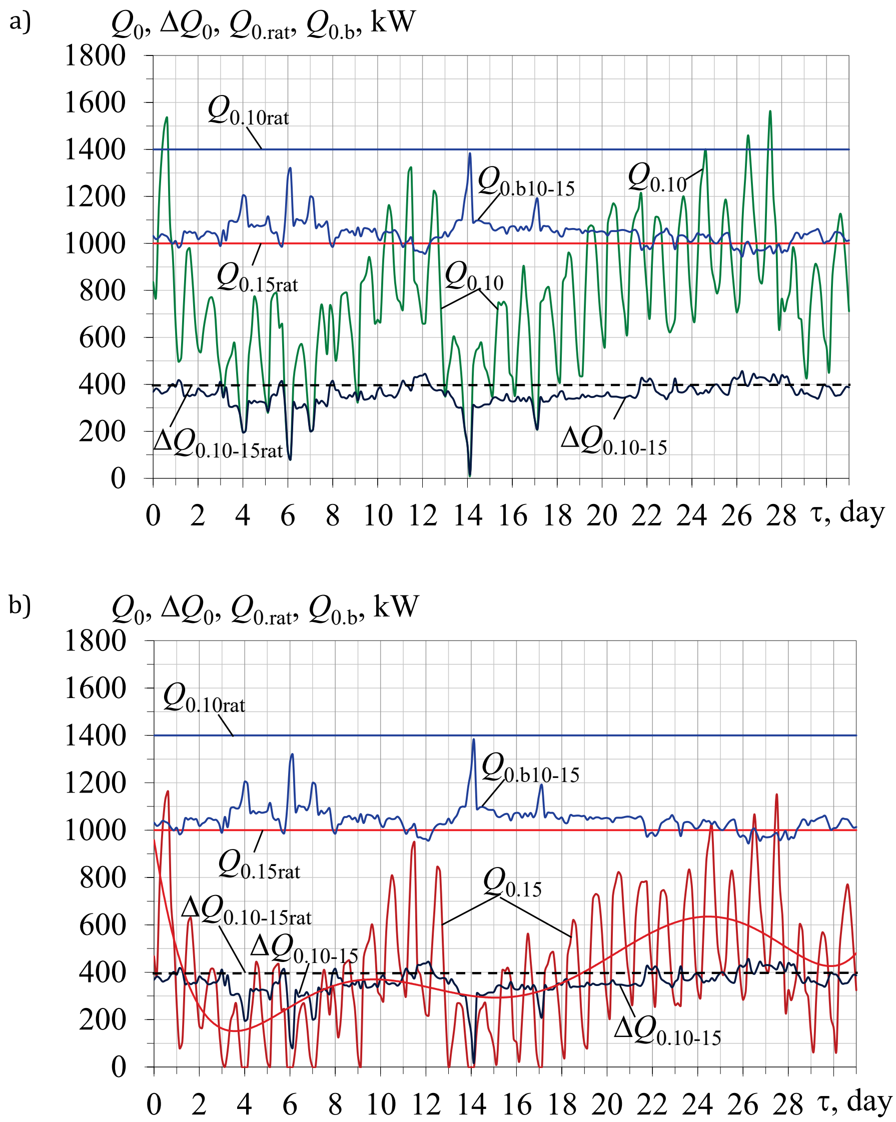

Figure 4. *The values of cooling capacities $Q_{0.10}$ and $Q_{0.15}$ needed for cooling ambient air to t_{a2} = 10°C and 15°C, rational cooling capacities $Q_{0.10rat}$ and $Q_{0.15rat}$ for cooling ambient air to t_{a2} = 10°C and 15°C, cooling capacities $\Delta Q_{0.10\text{-}15}$, needed for subcooling air from t_{a2} = 15°C to t_{a2} = 10°C, available remained boost cooling capacity $Q_{0.b10\text{-}15}$ for ambient air precooling to t_{a2} = 15°C in climatic conditions in Nikolaev region, southern Ukraine, July 2017: a) $Q_{0.10}$; b) $Q_{0.15}$; $\Delta Q_{0.10\text{-}15} = Q_{0.10} - Q_{0.15}$; $Q_{0.b10\text{-}15} = Q_{0.10rat} - \Delta Q_{0.10\text{-}15}$*

The further enhancing the efficiency of TIAC systems and development of their design methodology is followed from daily boost thermal load fluctuations. Proceeding from this, a design unstable boost range of cooling capacity $Q_{0.b10-15}$ is divide in two parts as $Q_{0.b10-15} = Q_{0.b10-20} + \Delta Q_{0.15-20}$ or $Q_{0.15\text{rat}} = Q_{0.20\text{rat}} + \Delta Q_{0.15-20}$ (Fig. 5).

Issuing from the comparison of the available boost cooling capacity $Q_{0.b10-20}$ designed for cooling air to t_{a2} = 20°C with current loads $Q_{0.15}$ it is quite reasonable to make a conclusion that the available boost cooling capacity $Q_{0.b10-20}$ covers the current loads $Q_{0.15}$ except quite short periods of daylight hours (Fig. 5b). The current deficit of design cooling capacity $q_{0.20\text{def}} = q_{0.15} - q_{0.b10-20}$ can be covered through using the daily accumulated excessive refrigeration energy at decreased current loads.

Thus, the hypothesis to reduce a design boost thermal load range $Q_{0.b10-15}$ or $Q_{0.15\text{rat}}$ through using $Q_{0.20\text{rat}}$ to cover current cooling loads $Q_{0.15}$, i.e. practically twice as compared with a design rational value $Q_{0.15\text{rat}}$ has been approved (Fig. 5b).

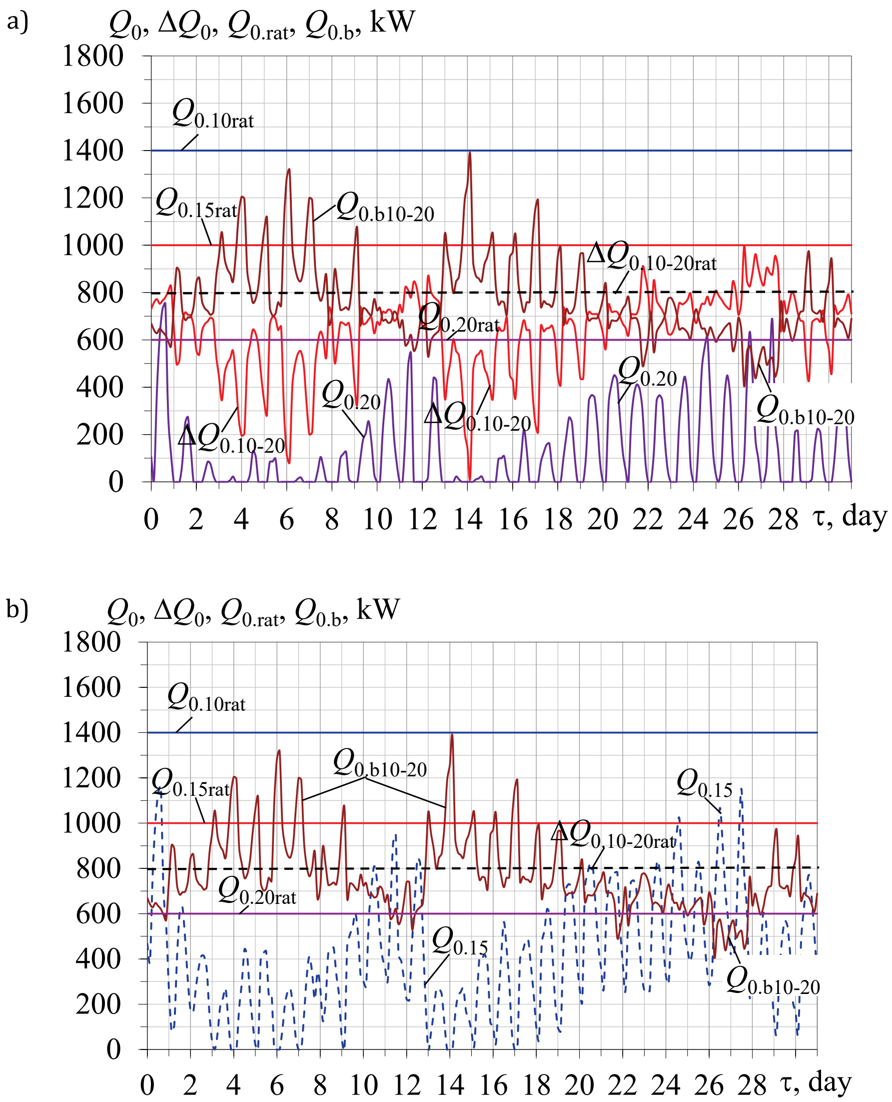

FIGURE 5. *The values of cooling capacities $Q_{0.15}$ and $Q_{0.20}$ needed for cooling ambient air to t_{a2} = 15°C and 20°C, rational design cooling capacities $Q_{0.10rat}$, $Q_{0.15rat}$ and $Q_{0.20rat}$ for cooling ambient air to t_{a2} = 10°C, 15°C and 20°C, rational design cooling capacity $\Delta Q_{0.10\text{-}20rat}$ for subcooling air from t_{a2} = 20°C to t_{a2} = 10°C, cooling capacities $\Delta Q_{0.10\text{-}20}$, needed for subcooling air from t_{a2} = 20°C to t_{a2} = 10°C, available remained boost cooling capacity $Q_{0.b10\text{-}20}$ for air precooling to t_{a2} = 20°C: a) $Q_{0.20}$; b) $Q_{0.15}$; $\Delta Q_{0.10\text{-}15} = Q_{0.10} - Q_{0.15}$; $Q_{0.b10\text{-}15} = Q_{0.10rat} - \Delta Q_{0.10\text{-}15}$; $\Delta Q_{0.10\text{-}20rat} = Q_{0.10rat} - Q_{0.20rat}$*

In the case of optimally designing, the optimum design cooling capacities $Q_{0.10opt}$ and $Q_{0.15opt}$ do not cover the current cooling capacities $Q_{0.10}$ and $Q_{0.15}$ needed for cooling ambient air to t_{a2} = 10°C and 15°C over the whole moth (Fig. 6).

However, the large fluctuations of actual loads $Q_{0.10}$ and $Q_{0.15}$ with their falling much more lower than optimum design cooling capacity values $Q_{0.10opt}$ and $Q_{0.15opt}$ point to considerable reserves of the using the excessive refrigeration energy accumulated at decreased current loads to cover increased loads even within daily variation (Fig. 6).

The rational distribution of the installed cooling capacity of ACh enables to reduce a design boost load by the value $\Delta Q_{0.15\text{–}20rat} = Q_{0.15rat} - Q_{0.20rat}$ (Fig. 5b and Fig. 7), i.e. practically twice as compared with $Q_{0.15rat}$.

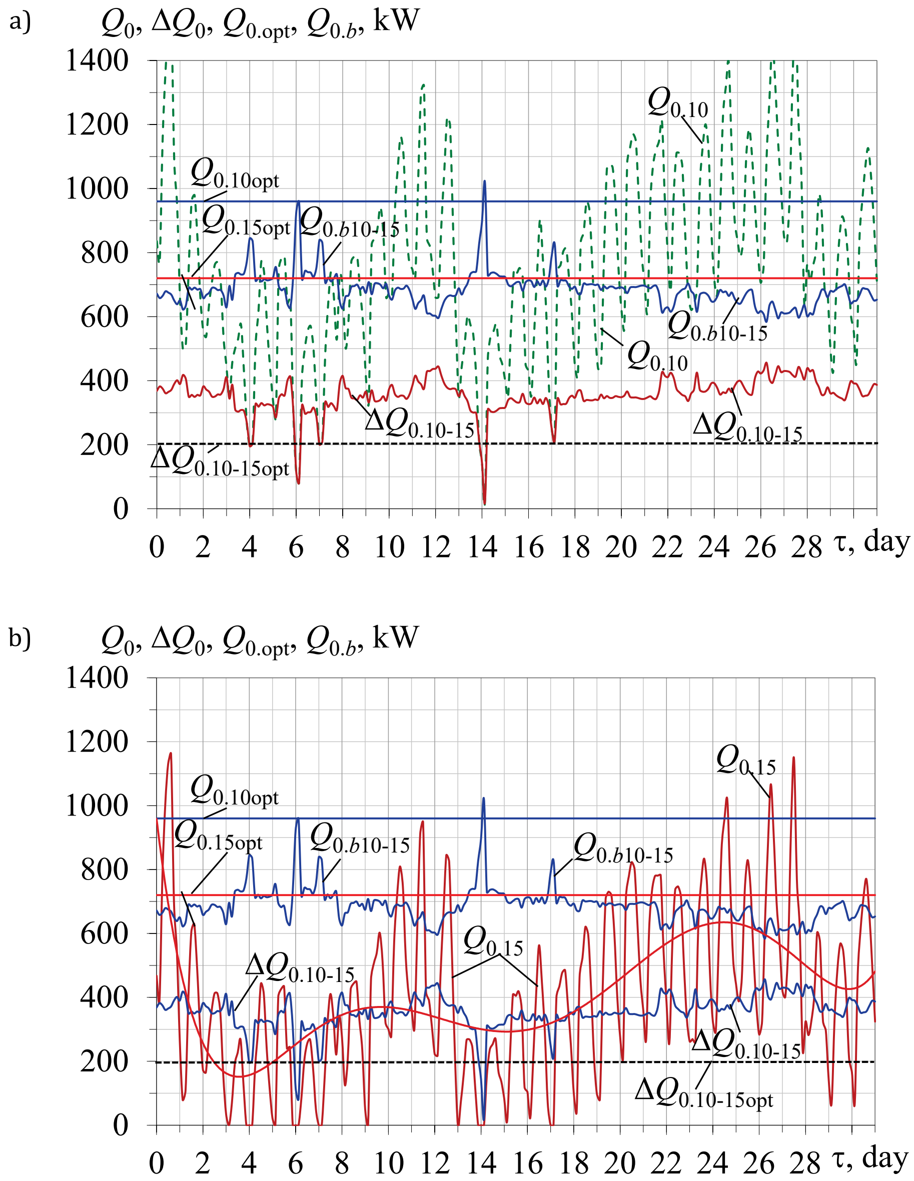

FIGURE 6. *The values of cooling capacities $Q_{0.10}$ and $Q_{0.15}$ needed for cooling ambient air to t_{a2} = 15°C and 20°C, optimum design cooling capacities $Q_{0.10opt}$ and $Q_{0.15opt}$ for t_{a2} = 10°C and 15°C, optimum design cooling capacity $\Delta Q_{0.10\text{-}15opt}$ for subcooling air from t_{a2} = 15°C to t_{a2} = 10°C, cooling capacities $\Delta Q_{0.10\text{-}15}$, needed for subcooling air from t_{a2} = 15°C to t_{a2} = 10°C, available remained optimum boost cooling capacity $Q_{0.b10\text{-}15}$ for air precooling to t_{a2} = 15°C: a) $Q_{0.10}$; b) $Q_{0.15}$; $\Delta Q_{0.10\text{-}15} = Q_{0.10} - Q_{0.15}$; $Q_{0.b10\text{-}15} = Q_{0.10opt} - \Delta Q_{0.10\text{-}15}$; $\Delta Q_{0.10\text{-}20opt} = Q_{0.10opt} - Q_{0.15opt}$*

As Figure 7 shows, rational designing of TIAC systems provides decrease of installed cooling capacities of the chillers and TIAC systems in the whole by the values of $\Delta Q_{0.10,15,20\max-\mathrm{rat}}$, i.e. by 15% to 20% compared with their maximum magnitudes $\Delta Q_{0.10,15,20\max}$, calculated according to conventional practice of designing.

In temperate climatic conditions the application of hybride two-stage TIAC systems with combined AECh rationally as well as optimally designed enables to provide about twice higher annual fuel saving ΣB_{10} at $Q_{0.10}$ as compared with ΣB_{15} at $Q_{0.15}$ for ACh (Fig. 7) and can be considered as a novel prosperous trend in TIAC.

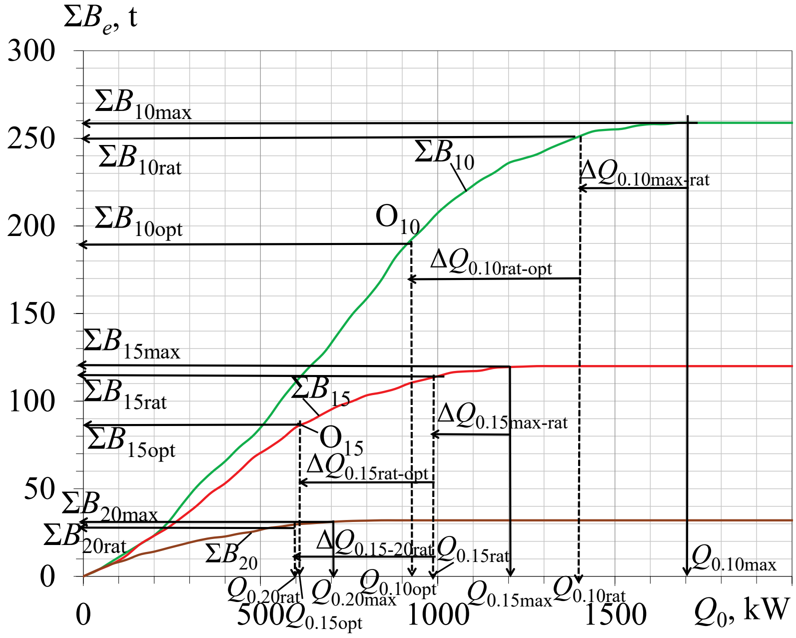

FIGURE 7. Annual fuel reduction ΣB_e versus cooling capacities Q_0 needed for cooling ambient air at GT inlet for cooling ambient air to t_{a2} = 10°C, 15°C and 20°C: $\Delta Q_{0.max\text{-}rat} = Q_{0.max} - Q_{0.rat}$; $\Delta Q_{0.rat\text{-}opt} = Q_{0.rat} - Q_{0.opt}$; $\Delta Q_{0.15\text{-}20rat} = Q_{0.15rat} - Q_{0.20rat}$

Conclusions

A novel trend in TIAC by two-stage air cooling in combined AECh is proposed for temperate climatic conditions to provide about twice higher annual fuel saving as compared with typical TIAC by ACh.

An advanced methodology of rational designing of TIAC systems is developed to provide closed to maximum annual fuel saving at the installed cooling capacities of the chillers and TIAC systems in the whole decreased by 15% to 20% compared with their maximum magnitudes, calculated according to conventional practice of designing.

The methodology of TIAC system designing is based on the novel approach of rational distribution of the overall design cooling capacity between ACh to cover the unstable thermal load range for ambient air precooling and ECh operating in a comparatively stable load range of further air subcooling.

According to the developed method the fluctuations of the current GT fuel reduction B_e due to cooling intake air are considered by the rate of their annual increment ΣB_e as relative annual fuel saving increment $\Sigma B_e / Q_0$ referred to needed cooling capacity Q_0.

Such a methodological approach makes it possible to increase the accuracy of the calculation results by excluding the approximation of the current changeable values of fuel reduction B_e.

The optimum design cooling capacity of the chiller $Q_{0.\text{opt}}$ provides a maximum rate of annual fuel saving increment $\Sigma B_e / Q_0$ and minimum sizes of the chiller and TIAC system.

With this a relative annual fuel saving increment $\Sigma B_e / Q_0$ is used as indicator to choose a maximum rate of annual fuel saving increment as a maximum value of $\Sigma B_e / Q_0$ and corresponding cooling capacity is considered as optimum $Q_{0.\text{opt}}$.

The hypothesis to reduce the boost unstable thermal load practically twice as compared with a design rational value has been approved.

Conflicts of Interest: The author declares no conflict of interest.

References

[1] Farouk N., Sheng L., Hayat Q., *Effect of Ambient Temperature on the Performance of Gas Turbines Power Plant*. International Journal of Computer Science Issues, Vol. 10, Issue 1, No. 3, 2013, pp. 439-442.

[2] Ameri M., Hejazi S.H., *The study of capacity enhancement of the Chabahar gas turbine installation using an absorption chiller*. Applied Thermal Engineering, Vol. 24, 2004, pp. 59-68.

[3] Forduy S., Radchenko A., Kuczynski W., Zubarev A., Konovalov D., *Enhancing the fuel efficiency of gas engines in integrated energy system by chilling cyclic air* [in:] Tonkonogyi V. et al. (eds.), *Grabchenko's ICAMP*. InterPartner-2019. LNME. Springer, Cham, 2020, pp. 500-509, https://doi.org/10.1007/978-3-030-40724-7_51.

[4] Popli S., Rodgers P., Eveloy V., *Gas turbine efficiency enhancement using waste heat powered absorption chillers in the oil and gas industry*. Applied Thermal Engineering, Vol. 50, 2013, pp. 918-931.

[5] Trushliakov E., Radchenko A., Forduy S., Zubarev A., Hrych A., *Increasing the Operation Efficiency of Air Conditioning System for Integrated Power Plant on the Base of Its Monitoring* [in:] Nechyporuk M. et al. (eds.), (ICTM 2019). AISC, Springer, Cham, Vol. 1113, 2020, pp. 351-360, https://doi.org/10.1007/978-3-030-37618-5_30.

[6] Elberry M., Elsayed A., Teamah M., Abdel-Rahman A., Elsafty A., *Performance improvement of power plants using absorption cooling system*. Alex. Eng. J., Vol. 57, 2018, pp. 2679-2686, doi:10.1016/j.aej.2017.10.004.

[7] Ehyaei M.A., Hakimzadeh S., Enadi N., Ahmadi P., *Exergy, economic and environment (3E) analysis of absorption chiller inlet air cooler used in gas turbine power plants*. Int. J. Energy Res., Vol. 36, 2011, pp. 486-498, doi:10.1002/er.1814.

[8] Andi B., Venkatesan J., Suresh S., Mariappan V., *Experimental Analysis of Triple Fluid Vapour Absorption Refrigeration System Driven by Electrical Energy and Engine Waste Heat*. Therm. Sci., Vol. 23, 2019, pp. 2995-3001.

[9] Radchenko A., Scurtu I.-C., Radchenko M., Forduy S., Zubarev A., *Monitoring the efficiency of cooling air at the inlet of gas engine in integrated energy system*. Thermal Science, OnLine-First Issue 00, 2020, pp. 344-344, https://doi.org/10.2298/TSCI200711344R.

[10] Radchenko A., Mikielewicz D., Forduy S., Radchenko M., Zubarev A., *Monitoring the fuel efficiency of gas engine in integrated energy system* [in:] Nechyporuk M. et al. (eds.), *ICTM 2019*, AISC, Springer, Cham, Vol. 1113, 2020, pp. 361-370.

[11] Radchenko A., Stachel A., Forduy S., Portnoi B., Rizun O., *Analysis of the efficiency of engine inlet air chilling unit with cooling towers* [in:] Ivanov V. et al. (eds.), *Advances in Design, Simulation and Manufacturing III (DSMIE 2020)*. Lecture Notes in Mechanical Engineering, Springer, Cham, 2020, pp. 322-331.

[12] Radchenko A., Trushliakov E., Tkachenko V., Portnoi B., Prjadko O., *Improvement of the* refrigeration *capacity utilizing for the ambient air conditioning system* [in:] Tonkonogyi V. et al. (eds.), *Advanced Manufacturing Processes II. InterPartner 2020*. Lecture Notes in Mechanical Engineering, Springer, Cham, 2021, pp. 714-723.

[13] Radchenko R., Kornienko V., Pyrysunko M., Bogdanov M., Andreev A., *Enhancing the efficiency of marine diesel engine by deep waste heat recovery on the base of its simulation along the route line* [in:] Nechyporuk M. et al. (eds.), *ICTME. AISC*, Springer, Cham, Vol. 1113, 2020, pp. 337-350.

[14] Radchenko R., Pyrysunko M., Radchenko A., Andreev A., Kornienko V., *Ship engine intake air cooling by ejector chiller using recirculation gas heat* [in:] Tonkonogyi V. et al. (eds.), *AMP. InterPartner-2020*. LNME, Springer, Cham, 2021, pp. 734-743.

[15] Konovalov D., Trushliakov E., Radchenko M., Kobalava G., Maksymov V., *Research of the aerothermopresor cooling system of charge air of a marine internal combustion engine under variable climatic conditions of operation* [in:] Tonkonogyi V. et al. (eds.), *ICAMP, InterPartner-2019*. LNME, Springer, Cham, 2020, pp. 520-529.

[16] Konovalov D., Kobalava H., Maksymov V., Radchenko R., Avdeev M., *Experimental Research of the Excessive Water Injection Effect on Resistances in the Flow Part of a Low-Flow Aerothermopressor* [in:] Ivanov V. et al. (eds.), *Advances in Design*, Simulation and Manufacturing III (DSMIE 2020). Lecture Notes in Mechanical Engineering, Springer, Cham, 2020, pp. 292-301.

[17] Konovalov D., Kobalava H., Radchenko M., Scurtu I.C., Radchenko R., *Determination of hydraulic resistance of the aerothermopressor for gas turbine cyclic air cooling* [in:] *TE-RE-RD 2020*, p. 14, E3S Web of Conferences 180, 2020, No. 01012.

[18] Radchenko R., Pyrysunko M., Kornienko V., I.C. Scurtu, Patyk R., *Improving the ecological and energy efficiency of internal combustion engines by ejector chiller using recirculation gas heat* [in:] Nechyporuk M., Pavlikov V., Kritskiy D. (eds.), *Integrated Computer Technologies in Mechanical Engineering – 2020*. ICTM 2020. Lecture Notes in Networks and Systems, Springer, Cham, Vol. 188, 2021, pp. 531-544.

[19] Radchenko A., Trushliakov, E., Kosowski, K., Mikielewicz, D., Radchenko, M.: *Innovative turbine intake air cooling systems and their rational designing*, Energies, Vol. 13, Issue 23, 2020, No. 6201, doi:10.3390/en13236201.

[20] Radchenko R., Radchenko N., Tsoy A., Forduy S., Zybarev A., Kalinichenko I., *Utilizing the heat of gas module by an absorption lithium-bromide chiller with an ejector booster stage*. AIP Conference Proceedings, Vol. 2285, 2020, No. 030084, https://doi.org/10.1063/5.0026788.

[21] Kornienko V., Radchenko R., Konovalov D., Andreev A., Pyrysunko M., *Characteristics of the rotary cup atomizer used as afterburning installation in exhaust gas boiler flue* [in:] Ivanov V. et al. (eds.), *Advances in Design*, Simulation and Manufacturing III (DSMIE 2020). Lecture Notes in Mechanical Engineering, Springer, Cham, 2020, pp. 302-311.

[22] Kornienko V., Radchenko R., Mikielewicz D., Pyrysunko M., Andreev A., *Improvement of characteristics of water-fuel rotary cup atomizer in a boiler* [in:] Tonkonogyi V. et al. (eds.), *Advanced Manufacturing Processes*. InterPartner-2020. Lecture Notes in Mechanical Engineering, Springer, Cham, 2021, pp. 664-674.

[23] Radchenko A., Andreev A., Konovalov D., Zhang Qiang Z., Zewei L., *Analysis of ship main engine intake air cooling by ejector and turbocompressor chillers on equatorial voyages* [in:] Nechyporuk M., Pavlikov V., Kritskiy D. (eds.), *Integrated Computer Technologies in Mechanical Engineering – 2020*. ICTM 2020. Lecture Notes in Networks and Systems, Springer, Cham, Vol. 188, 2021, pp. 487-497.

[24] Radchenko M., Mikielewicz D., Andreev A., Vanyeyev S., Savenkov O., *Efficient ship engine cyclic air cooling by turboexpander chiller for tropical climatic conditions* [in:] Nechyporuk M., Pavlikov V., Kritskiy D. (eds.), *Integrated Computer Technologies in Mechanical Engineering – 2020*. ICTM 2020. Lecture Notes in Networks and Systems, Springer, Cham, Vol. 188, 2021, pp. 498-507.

[25] Kornienko V., Radchenko M., Radchenko R., Konovalov D., Andreev, A., Pyrysunko M., *Improving the efficiency of heat recovery circuits of cogeneration plants with combustion of water-fuel emulsions*. Thermal Science, Vol. 25, Issue 1, Part B, 2021, pp. 791-800, https://doi.org/10.2298/TSCI200116154K.

[26] Kornienko V., Radchenko R., Stachel A., Andreev A., Pyrysunko M., *Correlations for pollution on condensing surfaces of exhaust gas boilers with water-fuel emulsion combustion* [in:] Tonkonogyi V. et al. (eds.), *AMP. InterPartner-2019*. LNME, Springer, Cham, 2020, pp. 530-539.

[27] Kornienko V., Radchenko R., Bohdal Ł., Kukiełka L., Legutko S., *Investigation of condensing heating surfaces with reduced corrosion of boilers with water-fuel emulsion combustion* [in:] Nechyporuk M. et al. (eds.), *ICTM 2020*. LNNS, Springer, Cham, Vol. 188, 2021, pp. 300-309.

[28] Kornienko V., Radchenko M., Radchenko R., Bohdal Ł., Andreev A., *Thermal characteristics of the wet pollution layer on condensing heating surfaces of exhaust gas boilers* [in:] Ivanov V., et al. (eds.), *Advances in Design, Simulation and Manufacturing IV (DSMIE 2021).* Lecture Notes in Mechanical Engineering. Springer, Cham, 2021.

[29] Radchenko R., Pyrysunko M., Kornienko V., Konovalov D., Girzheva O., *Enhancing energy efficiency of ship diesel engine with gas ecological recirculation* [in:] Ivanov V., et al. (eds.), *Advances in Design, Simulation and Manufacturing IV (DSMIE 2021)*. Lecture Notes in Mechanical Engineering. Springer, Cham, 2021.

[30] Trushliakov E., Radchenko M., Portnoi B., Tkachenko V., Hrych A., *Analysis of operation of ambient air conditioning systems with refrigeration machines of different types* [in:] Nechyporuk M., Pavlikov V., Kritskiy D. (eds.), *Integrated Computer Technologies in Mechanical Engineering – 2020*. ICTM 2020. Lecture Notes in Networks and Systems, Springer, Cham, Vol. 188, 2021, pp. 545-555.

[31] Dąbrowski P., Klugmann M., Mikielewicz D., *Selected studies of flow maldistribution in a minichannel plate heat exchanger*. Archives of Thermodynamics, Vol. 38, 2017, pp. 135-148.

[32] Kumar R., Singh G., Mikielewicz D., *A new approach for the mitigating of Flow Maldistribution in Parallel Microchannel Heat Sink*. Journal of Heat Transfer, Vol. 140, 2018, pp. 72401-72410.

[33] Kumar R., Singh G., Mikielewicz D., *Numerical study on mitigation of flow maldistribution in parallel microchannel heat sink: channels variable width versus variable height approach*. Journal of Electronic Packaging, Vol. 141, 2019, pp. 21009-21011.

[34] Dąbrowski P., Klugmann M., Mikielewicz D., *Channel blockage and flow maldistribution during unsteady flow in a model microchannel plate heat exchanger*. Journal of Applied Fluid Mechanics, Vol. 12, 2019, pp. 1023-1035.

[35] Kobalava H., Konovalov D., Radchenko R., Forduy S., Maksymov V., *Numerical simulation of an aerothermopressor with incomplete evaporation for intercooling of the gas turbine engine* [in:] Nechyporuk M., Pavlikov V., Kritskiy D. (eds.), *Integrated Computer Technologies in Mechanical Engineering – 2020.* ICTM 2020. Lecture Notes in Networks and Systems, Springer, Cham, Vol. 188, 2021, pp. 519-530.

[36] Trushliakov E., Radchenko M., Bohdal T., Radchenko R., Kantor S., *An innovative air conditioning system for changeable heat loads*. ICAMP, InterPartner-2019. LNME, Springer, Cham, 2020, pp. 616-625.

[37] Kuczyński W., Charun H., *Experimental investigations into the impact of the void fraction on the condensation characteristics of R134a refrigerant in minichannels under conditions of periodic instability*. Arch. Thermodyn., Vol. 32, 2011, pp. 21-37, doi:10.2478/v10173.

[38] Bohdal T., Sikora M., Widomska K., Radchenko A.M., *Investigation of flow structures during HFE-7100 refrigerant condensation*. Arch. Thermodyn., Vol. 36, 2015, pp. 25-34, doi:10.1515/aoter-2015-0030.

[39] Kuczyski W., Charun H., Bohdal T., Kuczynski W., *Influence of hydrodynamic instability on the heat transfer coefficient during condensation of R134a and R404A refrigerants in pipe minichannels*. Int. J. Heat Mass Transf., Vol. 55, 2012, pp. 1083-1094, doi:10.1016/j.ijheatmasstransfer.2011.10.002.

[40] Bohdal T., Kuczynski W., *Boiling of R404A refrigeration medium under the conditions of periodically generated disturbances*. Heat Transf. Eng., Vol. 32, 2011, pp. 359-368, doi:10.1080/01457632.2010.483851.

[41] Radchenko N., Radchenko A., Tsoy A., Mikielewicz D., Kantor S., Tkachenko V., *Improving the efficiency of railway conditioners in actual climatic conditions of operation*. AIP Conference Proceedings, Vol. 2285, 2020, No. 030072, https://doi.org/10.1063/5.0026789.

[42] Radchenko N.I., *On reducing the size of liquid separators for injector circulation plate freezers*. International Journal of Refrigeration, Vol. 8, No. 5, 1985, pp. 267-269.

[43] Radchenko M., Radchenko R., Tkachenko V., Kantor S., Smolyanoy E., *Increasing the Operation Efficiency of Railway Air Conditioning System on the Base of Its Simulation Along the Route Line* [in:] Nechyporuk M. et al. (eds.), *ICTME (ICTM 2019)*. AISC (2020), Springer, Cham, Vol. 1113, 2020, pp. 461-467, https://doi.org/10.1007/978-3-030-37618-5_39.

[44] Radchenko A., Radchenko N., Tsoy A., Portnoi B., Kantor S., *Increasing the efficiency of gas turbine inlet air cooling in actual climatic conditions of Kazakhstan and Ukraine*. AIP Conference Proceedings, Vol. 2285, 2020, No. 030071, https://doi.org/10.1063/5.0026787.

[45] Radchenko M., Portnoi B., Kantor S., Forduy S., Konovalov D., *Rational thermal loading the engine inlet air chilling complex with cooling towers* [in:] Tonkonogyi V. et al. (eds.), *Advanced Manufacturing Processes II*. InterPartner 2020. Lecture Notes in Mechanical Engineering, Springer, Cham, 2021, pp. 724-733.

[46] Radchenko N., Trushliakov E., Radchenko A., Tsoy A., Shchesiuk O., *Methods to determine a design cooling capacity of ambient air conditioning systems in climatic conditions of Ukraine and Kazakhstan*. AIP Conference Proceedings, Vol. 2285, 2020, No. 030074, https://doi.org/10.1063/5.0026790.

[47] Mikielewicz, D., Mikielewicz, J., *A thermodynamic criterion for selection of working fluid for subcritical and supercritical domestic micro CHP*. Applied Thermal Engineering, Vol. 30, 2010, pp. 2357-2362.

[48] Ortiga J., Bruno J.C., Coronas A., *Operational optimization of a complex trigeneration system connected to a district heating and cooling network*. Applied Thermal Engineering, Vol. 50, 2013, pp. 1536-1542.

[49] Khaliq A., Dincer I., Sharma P.B., *Development and analysis of industrial waste heat based trigeneration for combined production of power heat and cold*. Journal of Energy Institute, Vol. 83, Issue 2, 2010, pp. 79-85.

[50] Rodriguez-Aumente P.A., Rodriguez-Hidalgo M.C., Nogueira J.I., Lecuona A., Venegas M.C., *District heating and cooling for business buildings in Madrid*. Applied Thermal Engineering, Vol. 50, 2013, pp. 1496-1503.

[51] Radchenko A., Radchenko M., Trushliakov E., Kantor S., Tkachenko V., *Statistical method to define rational heat loads on railway air conditioning system for changeable climatic conditions. 5th International Conference on Systems and Informatics*, ICSAI 2018, Jiangsu, Nanjing, China, 2019, pp. 1294-1298, https://doi.org/10.1109/ICSAI.2018.8599355.

[52] Radchenko M., Trushliakov E., Tkachenko V., Rizun O., Tsaran F., *Rational refrigeration loading of ambient air conditioning system* [in:] Ivanov V., et al. (eds.), *Advances in Design, Simulation and Manufacturing IV (DSMIE 2021)*. Lecture Notes in Mechanical Engineering. Springer, Cham, 2021.

[53] Cardona E., Piacentino A., *A methodology for sizing a trigeneration plant in mediterranean areas*. Applied Thermal Engineering, Vol. 23, 2003, p. 15.

[54] Trushliakov E., Radchenko M., Radchenko A., Kantor S., Zongming Y., *Statistical approach to improve the efficiency of air conditioning system performance in changeable climatic conditions*. 5th International Conference on Systems and Informatics, ICSAI 2018, Jiangsu, Nanjing, China, 2019, pp. 256-260, https://doi.org/10.1109/ICSAI.2018.8599434.

[55] Chaker M., Meher-Homji C.B., Mee T., Nicholson A., *Inlet fogging of gas turbine engines detailed climatic analysis of gas turbine evaporation cooling potential in the USA*. J. Eng. Gas Turbines Power, Vol. 125, 2002, pp. 300-309, doi:10.1115/1.1519266.

[56] Chaker M., Meher-Homji C.B., *Inlet fogging of gas turbine engines: climatic analysis of gas turbine evaporative cooling potential of international locations*. J. Eng. Gas Turbines Power, Vol. 128, 2006, pp. 815-825, doi:10.1115/1.1707034.

[57] Oktay Z., Coskun C., Dincer I., *A new approach for predicting cooling degree-hours and energy requirements in buildings*. Energy, Vol. 36, Issue 8, 2011, pp. 4855-4863.

[58] Canova A., Cavallero C., Freschi F., Giaccone L., Repetto M., Tartaglia M., *Optimal energy management*. IEEE Industry Applications Magazine, Vol. 15, 2009, pp. 62-65.

[59] Rodriguez-Aumente P.A., Rodriguez-Hidalgo M.D.C., Nogueira J.I., Lecuona A., Venegas M.D.C., *District heating and cooling for business buildings in Madrid*. Appl. Therm. Eng., Vol. 50, 2013, pp. 1496-1503, doi:10.1016/j.applthermaleng.2011.11.036.

[60] Kavvadias K., Maroulis Z., *Multi-objective optimization of a trigeneration plant*. Energy Policy, Vol. 38, 2010, pp. 945-954, doi:10.1016/j.enpol.2009.10.046.

[61] Lozano M.A., Ramos J.C., Serra L.M., *Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints*. Energy, Vol. 35, 2010, pp. 794-805, doi:10.1016/j.energy.2009.08.022.

[62] Forsyth J.L., *Gas turbine inlet air chilling for LNG, 2013: IGT International Liquefied Natural Gas Conference Proceedings*, 3, pp. 1763-1778, https://www.scopus.com/record/display.uri?eid=2-s2.0-84904725071&origin=nward&txGid=b9d07662f250f4a4511cbfc9c242297a.

[63] Kalhori S.B., Rabiei H., Mansoori Z., *Mashad trigeneration potential – An opportunity for CO_2 abatement in Iran*. Energy Conv. Manag. 2012, 60, pp. 106-114.

[64] *Gas turbine electrical stations*. Nikolaev: "Zorya-Mashproject", 2007, p. 16, http://www.zmturbines.com.

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A RESULT-ORIENTED FRAMEWORK TO SUPPORT THE LOW-CARBON TRANSFORMATION OF ENERGY SERVICES MARKETS

Abstract: *Today, the scope of energy services markets (ESMs) has expanded worldwide and covered almost all areas of production and consumption of goods and services for both industrial and public appointments, as well as households, mainly due to energy efficiency and renewable energy sources. At the same time, the incompleteness of theoretically grounded bases significantly reduces the pace of these markets development. The purpose of this study is to present the framework for the determination of directions and construct a model of structural organization and functional interaction of the ESMs participants. Such approach allows, by combining resources, capabilities and information, to expand the scope and improve the efficiency and productivity of energy services. A new structure-function model of ESMs participants' interaction has been developed. In addition, a new organizational mechanism is proposed to support the efficient functioning of the ESMs in the form of a cycle of continuous improvement of the energy services results. The practical significance of the study is to create a conceptual framework for the organization and functioning of ESMs, which allows to systemically assess the new opportunities for such markets in both developed and developing countries.*

Keywords: *energy services, market structure, continuous improvements.*

Introduction

Pollutions from the burning of fossil fuels-and-energy resources are largely responsible for the dramatic changes in the behavior of the global ecosystem. They are increasingly affecting the socio-economic situation and human health. These, and especially recent events Covid-19 coronavirus pandemic, point to the urgent need to create and without delay to implement of a new methodological framework for large-scale realization of measures to improve energy efficiency (EE) and the use of renewable energy sources (RES). This study considers the implementation of such a framework based on the methodological provisions of the business concept of "energy services market", the principles of the formation and functioning of which we determine by comparison with similar principles of an ecosystem, where stable equilibrium is achieved due to the balanced interaction of its components (elements) with environment. Therefore, when choosing a solution to the problem of pollutions from business activities, we should clearly understand that the natural reserves required for the functioning of business would be short-lived if these reserves were not renewed through a balanced exchange of energy and resources between the elements of eco- and business systems.

Business systems are complex; therefore, within the proposed framework we will consider them in a generalized form, which, however, should cover all the main market participants. Among them are manufacturers, suppliers, distributors and consumers, state and local authorities, regulators, etc., which are directly or indirectly involved in the creation (production, supply, use) and disposal of the products, goods or services.

The field of energy services covers all major branches of the global economy, where fuel and energy resources are used intensively. Primarily, these are energy, industry, transport, housing and communal sectors, agriculture etc. Since the beginning of the third millennium, global energy services markets are rapidly developing in two priority fields. These are EE and RES, where energy efficiency is considered as “a special type of fuel”. According to the International Renewable Energy Agency, the cumulative investment in EE and RES in the world for 2016-2050 under different scenarios will be $ (29.0-37.0) trillion and $ (13.0-27.0) trillion, respectively.

Energy service companies (ESCOs) are some of the most efficient and most commonly used energy service providers that meet these challenges in practice around the world. Thanks to their joint efforts with national and local authorities, energy services markets are actively developing in the vast majority of countries, demonstrating high growth rates. However, despite their significant efforts, including those associated with the public and business, the volume of environmental pollution is constantly increasing in the world, and this is a global problem for our planet.

Our study shows a huge number of publications, including scientific ones, devoted to the formation and development of energy services markets at the national and local levels, but the structural and organization schemes of these markets are still unresolved and, no less important, there are still no formalized models and mechanisms of their operation.

In general, this requires a comprehensive development of theoretical and methodological foundations to support the low-carbon transition and improve the efficiency of energy services markets, and, as an initial step, it is necessary to develop a conceptual result-oriented framework for realization such support.

Literature analysis

Legal framework

The availability of an appropriate legal framework is a determining factor in the success of the transition to a low-carbon economy, the main strategic goals of which are determined as EE and RES. To succeed in this, a branched network of federal and local energy-saving agencies, as well as the programs for financing and promoting EE and RES technologies have been developed and implemented in all developed and in most developing countries. Among the major achievements in the USA, we have selected a special fund for investing in energy services activities in accordance with the Federal Energy Policy Act of 1992, the Energy Policy Act of 2005, Energy Independence and Security Act of 2007. The National Action Plan for Energy Efficiency of 2005 represents a private-public initiative to create a sustainable, aggressive national commitment to EE, the American Recovery and Reinvestment Act, designed for 10 years. In total, 34 new or updated standards concerning EE and RES have been introduced in the USA since 2009. As for European Union, EE and RES services are the key driver in attracting investment in energy infrastructure transformation in order to achieve the Union’s headline targets on EE of at least 32.5%. In total, EU framework in regulating EE and RES sphere covers tens binding directives for EU member states, over 340 standards of International Electrotechnical Commission, more than 110 standards of International Organization for Standardization (ISO) and 300 European Standards EN [1-3]. Among the major achievements in the Poland, we chose National Fund for Environmental Protection and Water Management, established in 1989, the Polish National Energy Conservation Agency (KAPE), which operates since 1994, the Energy Law of 1997, National Energy Efficiency Action Plan of 2007, Act on Renewable Energy Sources of 2015, and the Energy Efficiency Law of 2016.

With regard to the development of the energy services markets in developing countries, Ukraine is a typical example [3]. The Law of Ukraine About Energy Saving of 1994 can be identified as a key starting point, the State Committee of Ukraine On Energy Saving of 1995 (State Agency for Energy Efficiency and Energy Saving of Ukraine since 2014). The decisive points are the National Action Plan for Renewable Energy for the Period Until 2020 of 2014, Law of Ukraine On Introduction of New Investment Opportunities, Guaranteeing the Rights and Legal Interests of Entrepreneurs for Large-Scale Energy Modernization of 2015, the Law of On Energy Efficiency Fund of 2017. The Energy Strategy of Ukraine till 2035: Safety, Energy Efficiency, Competitiveness of 2017 as a most comprehensive act.

A comparative analysis of legal and regulatory frameworks in other developed countries aimed at stimulating energy services improvement can be found in [4, 5].

Energy services

Over past few decades, the global economy is increasingly transforming from a manufacturing (product) economy to a service economy [6-8]. Among the models (mechanisms) of transformation, the most common are models based on the concepts of Service-Dominant Logic [9] and Product-Service Systems [10, 11]. The activity of economic entities of all forms of ownership and functional purpose has significantly intensified in the energy services markets due to the significant growth of the role of energy efficiency and renewable energy sources in the low-carbon restructuring of the modern economy [12-15]. It is important that in addition to energy service companies (ESCOs), other economic entities are actively involved in this activity, first of all, manufacturers of EE and RES equipment and materials, suppliers of primary fuel and energy resources, utilities, investors, representatives of trading platforms, state and local authorities and regulators [5, 16].

Up-to-date energy services consist of professional business (commercial) activities, including scientific and technical, as well as management and consulting services. The specifics of energy services are defined in EU legislation as “the physical benefit, utility or good derived from a combination of energy with energy efficient technology and/or with action, which may include the operations, maintenance and control necessary to deliver the service, which is delivered on the basis of a contract, and in normal circumstances has proven to lead to verifiable and measurable or estimable energy efficiency improvement and/or primary energy savings” [17-19].

The category of energy services by its purpose covers the activities, mechanisms and resources needed to improve the efficiency (productivity, quality, etc.) of production, transmission, distribution, supply and final consumption of energy. So, when we talk about efficiency, we have to classify this type of service as energy performance services or energy-related services [19-20]. These services provide additional added value (profitability, benefit, usefulness, etc.) by combining energy with energy efficient technology and/or operation, including maintenance and control procedures required to provide services [18, 21-23]. More detailed information on energy services can be found in [24-26].

A significant impetus for the implementation of energy services is the use of smart technologies that allow on a fundamentally new platform to integrate the capabilities of products, goods and services for further use to meet the end needs of consumers. Such integration of smart goods and services allows implementing their new properties when using services by consumers through, for example, smart measurement, verification and adjustment in real time [27].

Energy services companies

Energy Services Companies (ESCOs) are one of the most efficient and widespread types of commercial organizations that provide energy-oriented services, including the implementation of measures (investment projects) for energy efficiency and renewable energy. Therefore, the task of combining and strengthening the efforts of ESCOs aimed at overcoming the problems of environmental pollution and improving the efficiency of natural resources use is more relevant today than ever before [7, 28-30].

ESCOs operate based on energy service contracts, providing a wide range of energy services that cover technical, economic, financial and legal aspects of design, engineering, installation, commissioning, monitoring and verification of the results achieved from the implementation of innovative projects in the areas of EE, RES and energy infrastructure improvement [29-33].

The energy services provided by ESCOs have the following fundamental differences:

1. The energy service contractor (ESCO) shall guarantee that the savings of fuel, energy and other material and technical resources, stipulated in energy service contract and received as a result of implementation of turnkey energy service project, will exceed the payments to cover all project costs for the payback period.
2. The energy service contractor invests its own funds (in whole or in part) in the implementation of energy service projects. If the savings guaranteed by him do not materialize, the difference is compensated at the expense of the contractor.

Different types of funding for ESCO projects may also include such as "funds, subsidies, tax rebates, loans, third-party financing, energy performance contracting, guarantee of energy savings contracts, energy outsourcing and other related contracts that are made available to the market place by public or private bodies in order to cover partly or totally the initial project cost for implementing energy efficiency improvement measures" [17, 18].

Varieties of ESCO energy service contracts are discussed in detail in numerous publications, for example in [33-37], where the following main models are among the most common: Energy Performance Contracting (EPC), Energy Supply Contracting (ESC), Chauffage, and Full Management Contracting (FMC). It is noted that most of these contracts used in practice are mixed. The most widespread is the EPC, which sets out the ESCO's obligations to increase the productivity (efficiency) of energy service outcomes, which under this contract may cover both the supply side and the final energy consumption side. The customer in accordance with the achieved level of energy efficiency pays ESCO costs agreed under the contract [8].

The main components of energy service contracts in conjunction with the scheme of causal chains of ESCO interaction with the customer and other project participants (subcontractors, financial institutions and support funds, etc.) are presented in detail in [19]. It should be added here that the complexity of implementing ESCO projects significantly slows down their financing, mainly due to the need to ensure a guaranteed level of energy saving in an uncertain business environment.

The results of a comparative analysis of the properties of energy services projects under ESCO contracts with other type of services considered within the framework of the service-dominant logic and product-service systems show that they have many common features [25, 26, 38, 39]. Their integrated use allows realizing the synergy of system interaction of these services, aimed at expanding the scope of their use and increasing the amount of systemically created benefits. This, of course, requires the improvement of the conceptual provisions of energy services, which will provide more favorable conditions for result-oriented framework to support the low-carbon transition by the way of ensuring mutually beneficial interaction between ESCOs and other market participants, in particular with customers and final consumers of goods and services.

Estimation of energy services markets sizes

Potential and development trends of energy services markets is largely determined by the size and growth rate of energy markets, as well as investments involved in their development. Analysis shows that, the consumption of fuel and energy resources in the world is constantly growing and is projected to grow until 2050. Thus, in 2040, compared to 2016, world oil consumption may increase by 10.3%, natural gas – by 31.9%, coal consumption will not change, nuclear energy production will increase by 35.1%, hydropower – by 26.7% and energy from other RES – by 80.1% [40]. The global crises certainly have a significant impact on the growth rates. So, the IEA expects global consumption and CO_2 emissions to decline by 8% in 2020 compared to 2019 through Covid-19 pandemic [41].

It is important for us that the proportions of the growth rates of the markets generally remain unchanged until 2050, demonstrating the outstripping growth of RES. In this vein, the transition to low carbon technologies opens up many new investment opportunities that can support the development of energy services market, such as investments in energy efficiency, smart grids, building retrofits, and so on, as the cost of renewables and other green technologies has dropped sharply. For example, solar photovoltaics (PV) prices fell 90% between 2009 and 2018 and battery prices by 85% between 2010 and 2018 [42]. At the same time, global investments in clean energy increased 1.33 times over this period – to USD 322.5 billion in 2018.

The significantly faster development of energy services markets is driven by a number of additional factors, primarily significant changes in the complexity of EE and RES technologies, which require special techniques, equipment and knowledge from energy service providers to solve problems of both clean energy project development and commissioning. Among the main ones, they need to overcome the following obstacles: unsupported legal framework, incentive sharing dilemma, lack of best practices as well as standards, complex and lengthy procurement and time frames, resistance to outsourcing, etc. [4, 43, 44].

For example, the analysis of the activities of Ukrainian ESCOs in the energy services market shows that the percentage of able to fulfill energy service contracts in 2018-2022 at lending rates 20-25%, 15-20%, 10-15% and 5-10% per annum in the national currency amount to 0%, 7%, 36% and 57%, respectively [45-47]. For comparison, the dominant form of financing energy service projects for EU countries is customers' own funds (52%), 26% of respondents use the services of banks and other borrowers, and by ESCO services – an average of 5% [4, 43].

Object, subject, and methods of research

The object of research is the processes of organizing the energy services market as a complex technological system aimed at improving EE, attracting RES and reducing CO_2 emissions.

The subject of research is the methods and models of structural organization and functional interaction of elements (participants) of energy services markets.

Methods of research. The methods of complex analysis of large systems, conceptual logic and black box that are used in determining the directions of development and construction of the model of structural organization of the energy services markets, as well as elements of set theory and energy management method – to formalize the functional interaction of elements (participants) the market.

The goal of the research is to determine the directions of development and construct a model of structural organization and functional interaction of participants of the energy services markets, which determine (highlight) the main components (segments) of the markets and their interaction with other (complementary) markets, primarily organized by energy and manufacturing companies.

Realization of the set purpose demands the solution of the following tasks.

Carrying out a systemically coordinated analysis of literature sources, covering:
- the legal framework for the organizing the energy services markets,
- clarifying the terminology of energy and energy-related services,
- analyzing the activities of energy service companies (ESCOs), and
- assessing the development of the markets in the world and in Ukraine.

Conducting research on:
- identifying the stages that form the cycle of continuous improvement of energy services results,
- developing a structural and functional model of the energy services market,
- formulating conceptual provisions for the development of the energy services market,
- conducting a comparative analysis of ESCOs in developed and developing markets.

Results

The cycle of continuous improvement of energy services results

To succeed in the implementation of energy services, everyone needs to organize the energy services management cycle based on the Deming closed-loop model: a plan-do-check-act, which activates the process of continuous improvement of results [48, 49]. The proposed energy services cycle includes the following main components, represented in Figure 1. Among them the key are: conducting marketing for the selection and evaluation of clients, providing the preliminary and investment audits, as well as comprehensive financial and legal expertise of clients, necessary for fulfillment of guarantee and post-guarantee ESCOs obligations.

It should also be noted that the implementation of energy services projects today requires the involvement of cloud (virtual) technologies for monitoring, control and optimization of parameters and modes of operation of technological equipment [50]. The use of virtual technologies for providing services allows participants of energy services projects to use hardware and software, tools and methodologies that are not available for the technical possibilities of their own technological and computing base, not to spend significant funds on licensed software and not to monitor updates. However, of course, there are disadvantages to using virtual technology services. Thus, the storage of user data and their cybersecurity is usually provided by a third-party organization – a cloud technology provider, the user does not have the actual ability to upgrade software, and access to "cloud" services requires a constant connection to the Internet.

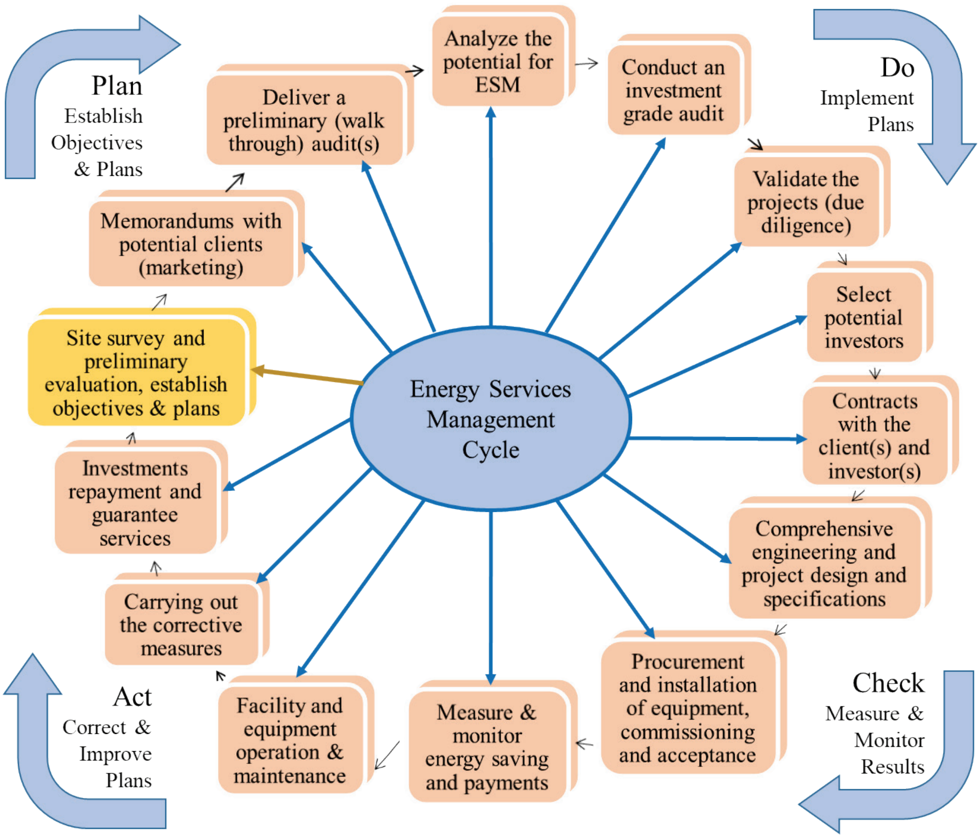

FIGURE 1. *Deming closed-loop for the implementation of energy services projects*

Structure-function model of the energy services market

The specifics of energy services market in this manuscript is reflected in the form of a conceptual model, the structural and functional elements of which are linked by the flows of energy, information, other resources (materials, equipment, etc.) used or affect the effectiveness of each element and the market as a whole. Such vision allows us break down the difficult to analyze problem into workable sub-blocks (elements).

The proposed structure-function model, where the main participants in the energy services market and their relationships, formalized based on set theory, is presented in Figure 2.

Among the participants of the energy services market are representatives of [3]:

- state and local governments and regulators, investors, trading platforms, etc.;
- primary energy resources markets (natural gas, coal, biomass, portable water, wind, and solar radiation, etc.). And secondary energy resources markets (which operate with resources that have been converted or stored, for example electricity, heating and cooling);
- providers of energy services (ESCOs);
- manufacturers of energy-efficient and RES equipment and materials; and
- consumers of services from different sphere of their business activity, which are the principal participants of the low-carbon transition under the proposed framework.

ESCOs play a leading role in organizing the interaction of participants by implementing the energy services projects (see details in [3, 50]).

To formalize the interactions in such multipart system of the market participants, we use the theory of set, which allows reflecting correctly the scale and complexity of such interactions. In such a way, the ordered sets of notations $\cap_M^R$,$\cap_M^G$,$\cap_M^C$,$\cap_M^E$,$\cap_M^H$,$\cap_M^{ES}$,$\cap_M^{SC}$,$\cap_M^{CN}$, which correspond considered markets of RES, natural gas, coal, electricity, heat and cooling, ESCOs, subcontractors and consumers, shown in Figure 2 based on the Sankey diagram. To do this, we calculate the areas of intersections of sets in families represented here by mathematical signs (∩). Likewise, the use of the "U" forms with indices allows us to denote direct and feedback links between different participants of the markets.

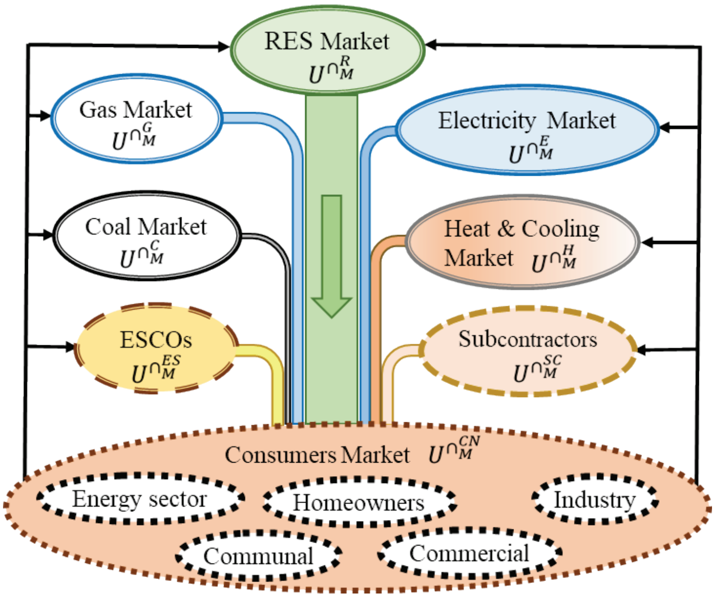

***FIGURE 2.** Structure-function model of the energy services market organization*

For example, $U^{\cap_M^R/\cap_M^E}$ will be denote direct links between RES and electricity markets in the form of mappings of ordered sets of input variables into sets of output variables. In our case these are $\cap_M^R$ and $\cap_M^E$ (see details in [3, 19]).

Conceptual provisions of energy services market development

Among the main measures to ensure the result-oriented development of the energy services market, first of all, should be:

- strengthen the legislative and regulatory framework through gradual harmonization with the EU's energy acquis;
- implement an integrated approach to the national and local energy security through diversification of resources;

- increase the share of renewable energy, cogeneration, low-potential sources and waste energy potential;
- ensure the quality and availability of energy services, making them reliable, secure and affordable for consumers;
- reduce the ecological impact on the environment;
- attract investments from international financial institutions and private investors;
- strengthen and maintain the financial viability of energy services providers;
- implement information and measurement systems for energy management.

Particular attention needs to be paid to solving the problem of attracting investment in energy service projects, the successful solution of which mainly depends on the coordinated efforts of the government, regulators and businesses.

Specifics of energy services market in developing countries

The existing experience of building energy services markets in developed countries can be used in developing ones only partially and only to select strategic directions for their development, while the practical content of their implementation mechanisms requires restructuring of existing mechanisms taking into account fundamentally different economic and social conditions in these countries.

Among the main risks of formation and functioning of the energy services markets in developing countries, it is necessary to note the following:

Policy. There is a lack of policy measures to provide a favorable basis, requirements or incentives for energy service market participants to provide and/or purchase energy services, as well as to take other measures to improve EE and implement RES.

Institutional. High dependence on state and local governments support, fears of customers and contractors of energy services that state programs to support EE will not be implemented (dependence on subsidies).

Financial. Medium- and long-term cost planning remains in short supply and is exacerbated by weak discipline in the private and, in particular, the public sector in return on EE and RES investments.

Investment. Weak demand for investment in energy services due to the instability of the economic situation, high interest rates of local banks and low energy prices compared to prices for energy efficient equipment and materials.

Executive. The tendency to reduce outsourcing and increase customers' own capabilities due to high operating costs of energy service providers.

Environmental. Lack of an integrated approach to EE and RES, which leads to systematic violations of sanitary norms and environmental requirements.

Information. Lack of information and awareness of officials and business representatives about the real benefits of energy service, lack of trust in its performers and their level of qualification.

Conclusions

1. Energy service is a fundamental instrument for putting energy efficiency and renewable energy technologies into practice the worldwide. Energy services are particularly important for the well-being of any entity and community, as adequate heating, cooling, lighting and other energy and non-energy uses are essential services that guarantee a decent standard of living and health for people.
2. The proposed result-oriented framework for identifying the main components and stages of sustainable development of the energy services market is aimed at solving the complex tasks of low-carbon transition by systemically overcoming political, institutional, financial, economic, environmental and information barriers based on the synergy of energy services market incentives and management.

3. The main strategic direction of the market development becomes the creation of a smart network of coordinated actions of energy services market participants, which is focused not on the procedures of purchase and sale of goods (products), but on the provision of energy-related services to meet the needs of consumers. Such services, when based on the systemic implementation of EE and RES measures and the closed cycle of energy management, as a powerful tool to manage this process, are becoming a fundamental unifying factor in realizing the benefits of energy services.
4. The transition to low-carbon production requires adapting existing energy services market legislation and regulations and changing the existing roles of market participants, making them transparent and fair, and unlocking many new opportunities for all customer groups – industrial, commercial, households, etc. Active involvement of state and local authorities and regulators creates new opportunities to increase using the EE and RES technologies.
5. The fundamentally different economic and social conditions for the functioning of energy services markets in developed and developing countries require special research when someone is going to transfer their rules and technologies from one country to another.
6. In general, the analysis conducted in this manuscript indicates the urgent need to develop mathematical models and perform numerical calculations to determine the optimal structure and parameters of the energy-related services market, which is a priority for further research.

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References

[1] Directive EU 2018/2002 amending Directive 2012/27/EU on energy efficiency, Official Journal of the European Union, 2018, No. L 328, pp. 210-230, ISSN 1977-0677.

[2] Energy Efficiency Progress Report: 2018 assessment of the progress made by Members States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive as required by Art. 24(3) of the Energy Efficiency Directive 2012/27/EU, EU Commission, Brussels 2019.

[3] Deshko V.I., Kovalko O.M., Novoseltsev O.V., Yevtukhova M.Y., *Energy Services Market: Conceptual Framework and Mechanism of Forming*, International Journal of Civil, Mechanical and Energy Science, 2020, Vol. 6, Issue 6, pp. 48-55, ISSN 2455-5304, https://dx.doi.org/10.22161/ijcmes.66.4.

[4] Report on the European EPC Market, Graz: Grazer Energieagentur GmbH, Grazer Energy Agency, 2016, http://www.grazer-ea.at.

[5] Szomolanyiova J., Keegan N., *European Report on the Energy Efficiency Services Market and Quality*, QualitEE, Vienna 2018.

[6] Alatorre Frenk C., Backhaus M., Bauer N., et al., *Perspectives for the energy transition: Investment needs for a low-carbon energy system*, IEA & IRENA Publications, Berlin 2017.

[7] Ritchie J., Lane K., Sung J., et al., *Energy efficiency 2018: Analysis and outlooks to 2040*, IEA Publications, Paris 2019.

[8] Novoseltsev O., Kovalko O., Evtukhova T., *Cross-border cooperation of energy service companies as a factor enhancing energy and economic safety* [in:] *Energy Efficiency Improvement of Geotechnical Systems*, Taylor & Francis Group, CRC Press, London 2013.

[9] Lusch R.F., Nambisan S., *Service Innovation: A Service-Dominant Logic Perspective*, MIS Quarterly, 2015, Vol. 39, No. 1, pp. 155-175.

[10] Tukker A., *Product services for a resource-efficient and circular economy – a review*, Journal of Cleaner Production, 2015, Vol. 97, pp. 76-91.

[11] Haase R.P., Pigosso D.C.A., McAloone T.C., *Product/Service-System Origins and Trajectories: A Systematic Literature Review of PSS Definitions and their Characteristics*, Procedia CIRP 64, 2017, pp. 157-162.

[12] *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*, IEA & IRENA Publications, Berlin 2017, www.irena.org/remap.

[13] Energy Efficiency 2018: Analysis and Outlooks to 2040, IEA Publications, Paris 2019, https://www.iea.org/reports/energy-efficiency-2018.

[14] Global energy transformation: A roadmap to 2050, IRENA, Abu Dhabi 2019, www.irena.org/remap.

[15] Energy Efficiency China 2018. Beijing: China Council for an Energy Efficient Economy, China Council, 2019, https://www.energycharter.org/fileadmin/DocumentsMedia/EERR/EER-China_ENG.pdf.

[16] Report on the European EPC Market. Graz: Grazer Energieagentur GmbH, 2016, www.guarantee-project.eu.

[17] Directive 2006/32/EU of the European Parliament and of the Council of 5 April 2006 on Energy end-use efficiency and energy services, Official Journal of the European Union, L 114, pp. 64-85.

[18] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy efficiency, Official Journal of the European Union, L 315, pp. 1-56.

[19] Eutukhova T., Kovalko O., Novoseltsev O., Woodroof E., *Energy Services: A Proposed Framework to Improve Results*, Energy Engineering, 2020, Vol. 117, No. 3, pp. 99-110.

[20] Energy Services. Background note by the Secretariat, World Trade Organization, No. S/C/W/52, Geneva 1998, www.wto.org.

[21] Energy services – Guidelines for the assessment and improvement of the energy service to users, ISO 50007:2017, ISO/TC 301, International Organization for Standardization, 2017.

[22] Energy efficiency services – Definitions and requirements, EN 15900:2010, European Committee for Standardization, Beuth Verlag GmbH, 2010.

[23] Larsen P.H., Goldman C.A., Satchwell A., *Evolution of the U.S. energy service company industry: market size and project performance from 1990-2008*, Energy Policy, 2012, Vol. 50, pp. 802-820.

[24] Sorrell S., *The economics of energy service contracts*, Energy Policy, 2007, 35(10), pp. 507-521.

[25] Benedetti M., Cesarotti V., Holgado M., Introna V., Macchi M., *A proposal for Energy Services' classification including a Product Service Systems perspective*, Procedia CIRP, 30, 2015, pp. 251-256.

[26] Nolden C., Sorrell S., Polzin F., *Catalysing the energy service market: The role of intermediaries*, Energy Policy, 2016, 98, pp. 420-430.

[27] Valencia A., Mugge R., Schoormans J.P.L., Schifferstein H.N.J., *The Design of Smart Product-Service Systems (PSSs): An Exploration of Design Characteristics*, International Journal of Design, 2015, Vol. 9(1), pp. 13-28.

[28] Yan L., Keay-Bright S., Antonenko O., *Energy efficiency China*, Energy Charter Secretariat, Brussels 2019.

[29] Stuart E., Larsen P.H., Carvallo J.P., Goldman C.A., Gilligan D., *U.S. energy service company (ESCO) industry: Recent market trends*, Orlando Lawrence Berkeley National Laboratory, Ernest 2016.

[30] Boza-Kiss B., Bertoldi P., Economidou M., *Energy service companies in the EU – Status review and recommendations for further market development with a focus on energy performance contracting*, Publications Office of the European Union, Luxembourg 2017.

[31] Hansen S.J., Bertoldi P., Langlois P., *ESCOs around the world: Lessons learned in 49 countries*, The Fairmont Press, Washington 2009.

[32] Woodroof E.A., Thumann A., *How to finance energy management projects: Solving the "Lack of capital problem"*, Fairmont Press, Washington 2012.

[33] Hofer K., Limaye D., Singh J., *Fostering the Development of ESCO Markets for Energy Efficiency*, World Bank, Washington 2016.

[34] Kim J.-I., Jain N., Lee H., Nieto M.T., Husband D., et al., *Business models to realize the potential of renewable energy and energy efficiency in the Greater Mekong Subregion*, Asian Development Bank, Manila 2015.

[35] IFC energy service company market analysis, International Finance Corporation, Econoler, Quebec 2011, https://www.yumpu.com/en/document/read/4636985/ifc-energy-service-company-market-analysis.

[36] Carbonara N., Pellegrino R., *Public-private partnerships for energy efficiency projects: A win-win model to choose the energy performance contracting structure*, Journal of Cleaner Production, 2018, Vol. 170, pp. 1064-1075.

[37] Il'chuk M., Reminska O., Shapovalenko V., Kyrychok O., *Energy Service Contracts: opportunities and prospects in Ukraine*, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn 2015.

[38] Mourtzis D., Boli N., Alexopoulos K., Rozycki D., *A framework of Energy Services: from traditional contracts to Product-Service System (PSS)*, Procedia CIRP, 2018, 69, pp. 746-751.

[39] Nolden C., Sorrell S., *The UK market for energy service contracts in 2014-2015*, Energy Efficiency, 2016, 9, pp. 1405-1420.

[40] BP Energy Outlook, London 2018, British Petroleum, http://www.bp.com/energyoutlook.

[41] Global Energy Review 2020. The impacts of the Covid-19 crisis on global energy demand and CO_2 emissions, IEA, Paris 2020, https://www.iea.org/reports/global-energy-review-2020.

[42] Clean Energy Investment Trends 2020, Bloomberg Finance L.P. Ltd., Stockholm 2020, https://webstore.iea.org.

[43] Boza-Kiss B., Toleikyté A., Bertoldi P., *Energy Service Market in the EU – Status review and recommendations 2019*, European Commission, Luxembourg 2019, ISBN 978-92-76-13093-2, doi:10.2760/768, JRC118815.

[44] Energy Efficiency Progress Report: 2017 assessment of the progress made by Members States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive as required by Art. 24(3) of the Energy Efficiency Directive 2012/27/EU, EU Commission, Brussels 2017.

[45] Removing Barriers to increase investment in Energy Efficiency in Public Buildings in Ukraine through the ESCO modality in Small and Medium Sized Cities, UNDP in Ukraine, UNDP-GEF Project, Kyiv 2017.

[46] Enhancing Competitiveness in Ukraine through a Sustainable Framework for Energy Service Companies (ESCOs), OECD, Kyiv 2018.

[47] Kovalko O., Novoseltsev O., *Analysis of the State and Development Trends of Energy Service Market in Ukraine*, Proc. of XIX International Scientific and Practical Conference "Renewable Energy and Energy Efficiency in the 21st Century", Kyiv, September 26-28, Interservice, Kyiv 2018, pp. 31-34.

[48] International Organization for Standardization, Energy Management Systems. Requirement with Guidance for Use (ISO 50001:2018), ISO Central Secretariat, Geneva 2018.

[49] Cosenza E., Devetta M., Rosa M., Zogla L., Barisa A., etc., *Energy Management System (EnMS) Guidebook for Local Authorities*, Local Governments for Sustainability, Freiburg 2018.

[50] Chupryna L., Kovalko O., Novoseltsev O., Woodroof E., *Virtual Organization of Energy Management: Service-Oriented Framework to Improve Results*, International Journal of Energy Management, 2020, Vol. 2, No. 6, pp. 47-63, ISSN 2643-6779 (print), ISSN 2643-6787 (on-line).

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A MODEL FOR THE COMBUSTION OF OIL/WATER EMULSION

Abstract: *The experimental data on the basis of which, there was studied the effect of various factors on the combustion temperature water-oil emulsion in the boiler units. By the method of experiment planning there was obtained mathematical model of the influence of these factors: the temperature of the emulsion, the water content in the emulsion viscosity, excess air ratio in the combustion temperature, which can be used to predict the operating parameters of the combustion process.*

Keywords*: modeling, fuel emulsion, burning.*

Introduction

Fuel savings in boilers basically achieved by reducing the air supply to the combustion chamber, the acceleration of the combustion process, increase the heat transfer from the gases to the heating surface, stopping supplying steam to the nozzles for spraying the fuel, increasing the flow of radiant energy, and thus enhance the flame temperature and a sharp reduce of carbon formation on the heating surfaces.

With the transfer of the boiler on the emulsified fuel [1-6], changes in the dynamics of combustion can be observed visually (Fig. 1).

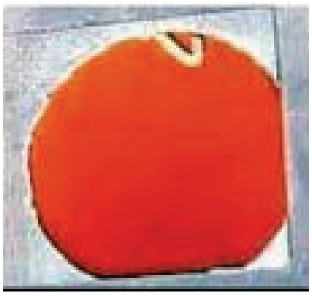
a)  b) 

Figure 1. *Combustion of fuel oil (a) and water-oil emulsions (b): a) combustion temperature 1350°C; b) combustion temperature 1890°C*

However, it should be noted that repeatability of results cannot be achieved. Therefore, it is necessary to examine all the factors affecting the combustion processes intensification water-oil emulsion and increasing combustion temperature.

The purpose of the work

The aim was to develop mathematical model that generalizes the influence of the main factors on the combustion rate of the emulsion.

Materials and research

The factors that determine the intensity and accordingly the combustion temperature selected temperature emulsion (X_1), the water content in the emulsion (X_2), viscosity (X_3), excess air ratio (X_4). Changing the values of these parameters in the range indicated in Table 1 according to plan experiments (Table 2), flame temperature pyrometer.

The data obtained in the course of the experiment is shown in Table 2. To construct the models used orthogonal central composite design of the second order with the kernel 24.

***TABLE 1.** Levels of varying factors*

X_i	–1.414	–1	0	1	1.414	Δ
X_1	1.76	3	6	9	10.24	3
X_2	2.73	5	10	15	17.27	5
X_3	11.7	20	40	60	68.3	20
X_4	73	100	150	200	227	50

***TABLE 2.** Values of indicators and factors*

No.	X_1	X_2	X_3	X_4	Y_i
1	1	1	1	1	1450
2	–1	1	1	1	1340
3	1	–1	1	1	1580
4	–1	–1	1	1	1430
5	1	1	–1	1	1450
6	–1	1	–1	1	1340
7	1	–1	–1	1	1600
8	–1	–1	–1	1	1540
9	1	1	1	–1	1560
10	–1	1	1	–1	1440
11	1	–1	1	–1	1630
12	–1	–1	1	–1	1550
13	1	1	–1	–1	1530
14	–1	1	–1	–1	1430
15	1	–1	–1	–1	1620
16	–1	–1	–1	–1	1560
17	–1.414	0	0	0	1550
18	1.414	0	0	0	1670
19	0	–1.414	0	0	1750
20	0	1.414	0	0	1590

Continuation of Table 2

No.	X_1	X_2	X_3	X_4	Y_i
21	0	0	–1.414	0	1610
22	0	0	1.414	0	1620
23	0	0	0	–1.414	1650
24	0	0	0	1.414	1570
25	0	0	0	0	1720

After the settlement of the simplex algorithm there were produced the following estimates of the coefficients in the models listed in Table 3.

Table 3. *Estimates of the coefficients in the models that characterize the degree of influence factors and their interactions on performance*

Factors and their interaction	Y_i	Factors and their interaction	Y_i
X_1	47.98	X_4^2	–66.75
X_2	–59.81	X_1X_2	5.63
X_3	–3.79	X_1X_3	8.13
X_4	–35.16	X_1X_4	4.38
X_1^2	–66.75	X_2X_3	10.63
X_2^2	–36.75	X_2X_4	–10.63
X_3^2	–64.25	X_3X_4	–10.63

To test the significance of the effect of factors and their interactions on the index, as well as the adequacy of the resulting model was found error observations indicator *U*. To do this, "zero" point $X_1 = X_2 = X_3 = X_4 = 0$ were four replicates. Their results are shown in Table 4.

Table 4. *Values of repeated experiments and error variances for the index Y*

Index	Value of the index in repeated experiments				The dispersion of the observational errors
	1	2	3	4	5
Y	1640	1670	1650	1640	200

As a result, for the formula variance estimation errors of observation:

$$S^2 = 0.33\sum_{i=1}^{4}\left(Y_i - \overline{Y}\right)^2 \tag{1}$$

where:

Y_1 – the observed value of the index in the Y *i*-th re-experience, and the average value of Y in "zero" point, got the error variance of observations (Table 4).

"Significance threshold" for the estimated coefficients characterizing the power to influence factors and their effects mutually interactions were like, where – the standard deviation of the observation error, $h_i = t_{kr}(\alpha;\ \varphi)^{-1} \cdot \sqrt{c_i}$; $t_{kr}(\alpha;\ \varphi)^{-1}$ – the critical value of the *t*-distribution for significance level and the number of degrees of freedom. In the studies $\varphi = 3$, $c_1 = 0.05$ for X_i, $c_2 = 0.125$ for X_i^2, $c_3 = 0.0625$ for $X_i X_j$, $i, j = 1, \ldots, 4$. As a result of the settlement of the above formula are obtained for the parameters Y "thresholds of significance" for the estimated coefficients are given in Table 5.

TABLE 5. *"Significance threshold" for factors and of their interactions*

Index	**Values for codes**		
	X_i	X_i^2	X_iX_j
Y	10.06	15.91	11.25

Excluded from the model factors and their interaction, the magnitude of the coefficients of which are less than the modulo "significance threshold" for the significance level obtained the following relationship:

$$Y = 1738.8 + 47.98 \cdot X_1 - 59.81 \cdot X_2 - 35.16 \cdot X_4 - 66.75 \cdot X_1^2 - 36.75 \cdot X_2^2 - \\ - 64.25 \cdot X_3^2 - 66.75 \cdot X_4^2; \quad R^2 = 0.967 \tag{2}$$

Verification of the adequacy of the obtained models was performed by the Fisher test. Estimated value of the *F* statistic is given by:

$$F_p = \frac{S_{rem}^2}{S^2} \tag{3}$$

To obtain the model residual variance was as:

$$S_{rem}^2 = \frac{1}{n-m} \sum_{i=1}^{n} \left(Y_i - \overline{Y} \right)^2$$

where:

$n = 25$ – the number of experiments, that – the number of coefficients in the model.

The resulting residual variance calculated and tabulated values of Fisher's statistics are given in Table 6.

Table 6. *Estimated and table value statistics Fisher*

Index	**Values S_{rem}^2, F_{cal}, F_{tabl}**		
	S_{rem}^2	F_{cal}	F_{tabl}
Y	513.12	2.566	8.703

Since the F_p model is less than F_{tabl}, the model is adequate with a confidence level of 0.95 and can be used to analyze technological processes and predict the values of Y indicators.

Conclusions

The resulting mathematical model analyzes the impact of the studied factors on the combustion temperature of the fuel emulsion.

The greatest influence on the combustion temperature of the emulsion has X_2 factor – the content of the dispersed water heating. The presence of water lowers the combustion temperature, of course, but it greatly intensifies. In the emulsion droplets come off the nozzle device contains several thousand microdroplets of water. Therefore, in the high temperature zone of the combustion chamber explodes emulsion droplet and there is a secondary fuel dispersion. The more fine droplets in an emulsion, the more pronounced this effect. As a result of these implosions occur in the furnace pockets of turbulent fluctuations and increases the number of elementary fuel droplets. Due to this increase in the volume of the torch to align the temperature field in the furnace combustor to decrease the local peak temperatures and an increase in average temperature in the furnace; increases the luminosity of the flame by increasing the surface radiation, which we saw in Figure 1. Thus, to obtain the desired temperature of the flame can provide a level of value factors: the amount of emulsified water; temperature of the emulsion and the excess air.

Conflicts of Interest: The author declares no conflict of interest.

References

[1] Pavlenko A.M., Koshlak H.V., Usenko B.O., *The processes of heat and mass exchange in the vortex devices*, Metallurgical and Mining Industry, 2014, No. 3, pp. 55-59.

[2] Pavlenko A.M., Koshlak H.V., Usenko B.O., *Thermal conductivity of the gas in small space*, Metallurgical and Mining Industry, 2014, No. 2, pp. 20-24.

[3] Pavlenko A.M., Koshlak H.V., Usenko B.O., *Peculiarities of controlled forming of propous structure*, Metallurgical and Mining Industry, 2014, No. 3, pp. 60-65.

[4] Pavlenko A.M., Basok B.I., *Kinetics of water evaporation from emulsions*, Heat Transfer Research, 2005, 36 (5), pp. 425-430.

[5] Pavlenko A.M., Basok B.I., *Regularities of boiling-up of emulsified liquids*, Heat Transfer Research, 2005, 36 (5).

[6] Pavlenko A.M., Koshlak H.V., Usenko B.O., *Basic principies of gas hydrate technologies*, Metallurgical and Mining Industry, 2014, No. 6, pp. 92-95.

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INVESTIGATION OF THE CHARACTERISTICS OF THE HYDROPHOBIC CEMENT SLURRY SILPAN-P FOR EFFECTIVE CEMENTING OF CASING PIPES OF OIL WELLS

Abstract: *In the laboratory conditions results on hydrophobic cement slurry are obtained that significantly improve the properties of existing materials in thermo corrosion stability cement rock, its mechanical properties, provide the estimated density of cement slurry, required rate strength gain.*

Keywords: *hydrophobic material, water-repellent, tamping mix.*

Relevance of work

The analysis of special literature and industrial and construction data shows that in various fields from 10% to 50% oil and to 60% gas wells have behind-the-casing water flow wherefore partly or completely are unsuitable for efficient operation. Success for wells cementing are defined by techniques and technology of cementation processes, the quality of the preparatory work, cement slurry and completeness of substitution of mud fluid by cement slurry.

Wells cementing, especially deep ones is the most important stage of construction. Value of cementing work is because they are the final process and failure in their implementation can minimize the successes of previous work. One of the main causes of these phenomena is poor completion of intermediate and producing casing of wells, particularly in the area of productive horizons.

The urgency of creation of new cements is the need to improve the quality of the insulation of productive layer at various stages of completion and well operations.

The purpose of work is to determine the laboratory and industrial characteristics of implementation of hydrophobic cement slurry Silpan-P (water-repellent admixture Ramsinks-2M, cement OWPC1-100 and NTPha) compared to not implemented solution Silpan-P concerning the quality of cementing the production casing.

Statement of main material

Previous experience with different cement materials allows to predict the possibility of creating a wide range of recipes with differentiated rate of strength gain. Scientists O.I. Bulatov, V.I. Vyakhirev, D.V. Oreshkin, O.O. Frolov, R.M. Pervushin, V.V. Kravchenko examined and positively solved a number of questions about the quality of cements, but hydrophobic cements were not investigated fully, suggesting the existence of this problem.

The use of cement OWPC1-100 is widely known. Let's have a more detailed look at hydrophobic material Ramsinks-2M [1, 8]. He successfully passed industry laboratory tests in the laboratory DD Ukrbugaz in Poltava and in the sector lito-physical research of research department of rock formation in UkrNDIgaz in Kharkiv, and then the experiment and industrial tests in the production fields of JSC Ukrnafta. Material performed insulating action on the surfaces of the pores of rock collectors, and this physical-chemical mechanism, according to the authors, with the composition of cement OWPC1-100should give the opportunity to improve the properties of cement materials that should prevent behind-the-casing water flow. The problem ofbehind-the-casing water flowcurrently exists on the wells of JSC Ukrnafta, PJSC UkrGasVydobuvannya, NJSC Naftogaz Ukraine. One of the newest cement slurry users is DD Ukrbugaz.

These advantages of modern cement slurry will allow to use these tamping mix for cementing oil and gas wells in areaswhich iseligible for industrial use. Application of new hydrophobiccement slurry should be implemented in the fields to behind-the-casing water flowof wells.

Technological properties of proposed materials are:

- NTPha – a nitrilotrymethylphosfonic acid, which is a white crystalline powder that is well dissolved in water at any temperature, as well as in acids and alkalis. It is widely used in well cementing to regulate the hardening of cement slurry.
- Ramsinks-2M – a water-repellent complex ofsilicium organic water repellentconjunction. The use of this repellent in the manufacture of cement mixture Silpan-P (water-repellent Ramsinks-2M + cement + OWPC1-100 + NTPha) increases elasticity of mixture, prevents uneven concentration of fillers and prevents stratification of the mixture and increases stability to corrosive factors and increases their durability. High water permability is achieved by a thin breakage of hydrophobic particles in the mixer SMN-20.

Test conditions:

- indoorair temperature 20°C,
- atmospheric pressure of 742 mmHg,
- humidity 78%,
- the pressure in the autoclave installation A-2.00.000.IE 450 atm.,
- the temperature in the autoclave installation A-2.00.000.IE 75°C.

The main indicators of quality and efficient use of repellent Ramsinks-2M are: water-repellent effect (degree); water absorption of cement and solutions; strength; water resistance; plasticity and others.

To form the cement stone of the cement mixture Silpan-P autoclave installation A-2.00.000.IE was used in combination with a special device to install metal forms with samples which function is to prevent the destruction of the samples.

In the autoclave installation were pre-formed in a specially made metal form cylindrical samples of stone cement mixture Silpan-P length 39.5 ~ 1.0 mm and diameter of 26 ~ 1.0 mm. For weighing samples with forms were used electronic scales VLK-500.

In the laboratory conditions the selection of balance OWPC1-100 and hydrophobic material Ramsinks-2M amounted to 1 : 0.001; 1 : 0.002; 1 : 0.003; 1 : 0.005; 1 : 0.008 provides the necessary density of cement slurry, rate of power ascension at high operating parameters of stone.

Conducted laboratory tests have shown that hydrophobic cements by mechanical interaction of hydrophobic material Ramsinks-2M with cement structure PTTS 1-100 will significantly improve the physical and mechanical and physical and chemical properties of standard cement slurry that ultimately will lead to a significant improvement of insulation of productive layers at the stage of well completion and their operations.

Determination of the hydrophobic effect was conducted by laboratory tests on the degree of water repellency of cement OWPC1-100 Ramsinks-2M. Cement samples in number of 200 g filled with water to obtain normal density paste, leaving in a space hold and marking time of water absorption of cement. Obtained data during the test with different amount of Ramsinks-2M in a percentage of the weight of cement (0.2%; 0.25%; 0.3%) are shown below in Table 1.

TABLE 1. Water repellent amount influence on cement properties

Cement mark and type	Mass of cement sample	Name of additive	Content of additive (% in cement mass)	Normal density paste (NDCP), ml	Degree of cement hydrophobicity, min
OWPC1-100	200 g	–	–	95 ml	8
OWPC1-100	200 g	Ramsinks-2M	0.02	95 ml	11
OWPC1-100	200 g	Ramsinks-2M	0.025	95 ml	14
OWPC1-100	200 g	Ramsinks-2M	0.03	95 ml	17

The optimal additive to cement slurry Ramsinks-2M depending on the temperature and pressure conditions of reservoir is 0.02-0.03% by weight of cementing. Further increase of additives leads to reducing the strength of cement rock that, in our opinion, clearly identified due to hydrophobic properties of Silpan-P. Laboratory experiments found that the degree of water repellency of cement OWPC1-100 with hydrophobic additive Ramsinks-2M depends on the amount of additive Ramsinks-2M in percentage (%) by weight of cement.

In the laboratory conditions are performed such works: implementation of selection of cement slurry composition with differentiated rate of power ascension for different temperature integrals. To study the physical and mechanical properties of plugging stone in the temperature range from 20°C to 80°C, to study the thermal stability of cement slurry at temperatures up to 80°C. It necessary to continue the study of thermal stability at temperatures up to 180°C.

Scheme selection of recipes with the required parameters and study of the physical and mechanical properties of the plugging rock is standard and accomplished at temperatures of 70°C, 100°C, 130°C, 160°C and pressures by appropriate leveling of cement ratio OWPC1-100 and hydrophobic material Ramsinks-2M for these conditions. When mixing occurs even in properties of cement slurry. Samples are stored in wet-dry pressure conditions for 1, 7 and 28 days. The use of additive Ramsinks-2M takes place directly during the cement works to prevent migration of reservoir fluids of behind the casing water flow.

Technology of intermediate column cementing

After run-in-hole operations it is necessary to make the transition to the mineralized solution. During drilling homogeneous GDS to determine the volume of the cavity they have important role in development to the completion of work on wells and are their integral part. The technical condition of wells is controlled through a set of geophysical methods: in clinometry; caliper measurement; double axis caliper logging of hole; control of cementing wells; double axis caliper logging of casing pipes; identifying the location of sleeve joints and casing thickness and behind the casing liquid circulation; installation depth water-absorbing horizons and monitor the effectiveness of some methods intensification of oil and gas.

Upon completion of wells the greatest interest are the following options of layers: layer (or pore) pressure, pressure of well fracturing, void factor, ground pressure, as they, in turn, can provide such important technological parameters like density of drilling mud, permissible speed of the columns in the open hole, sizes of columns, construction of wells and so on. The main model of defining the layer (or pore) pressure is the ratio of:

$$grad\, p_n = grad\, p_{geo}\left(grad\, p_{geo} - grad\, p_{gidr}\right)\left(F_f / F_n\right)^A \tag{1}$$

where:

F_f, F_n – characteristic properties of rocks in the logging intervals, accordance actually observed and acceptable for normal (hydrostatic) conditions;

$grad\, p_n$, $grad\, p_{geo}$, $grad\, p_{gidr}$	–	according pore gradients (or layer) ground and hydrostatic pressure;
A	–	empirical factor depending on the physical meaning of the measured or calculated properties of rocks. So, for own potential, resistivity of rocks and d-exponent A = 1.2; for mechanical speed and drilling time of fixed intervals A = 3. The values for the various geological and physical conditions vary within very small measure.

For pressure of hydraulic fracturing of formation the most used is formula:

$$rad\, p_{gidr} = \left(grad\, p_{geo} - grad\, p_n\right)\mu + grad\, p_n \tag{2}$$

where μ is Poisson's ratio for rocks, which largely depends on the humidity and porosity of the material of the rocks.

When used as characteristics *d*-exponent, the adjusted value is calculated by the expression:

$$d_C = \frac{lg\left(\frac{v}{n}\right) grad\, p_{gidr}}{lg\left(\frac{G}{D_g}\right) grad\, p_{br}} \tag{3}$$

where:

v	–	mechanical drilling speed;
n	–	bit speed;
G	–	bit pressure;
$grad\, p_{gidr}$	–	pressure gradient of water;
$grad\, p_{br}$	–	mud pressure gradient;
p	–	factors that take into account wear and type of bits (p = 0.5 – 0.6) – for roller cone bits, p = 0.2 – for insert bits (p = 0.01 – for diamond bits).

All the methods discussed above have drawbacks, the main of which are: application mainly in argillaceous deposits, necessity to build a trend line and its subsequent use for regression area of significant intervals. All this leads to a rather large (10-20%) errors, especially in the transition areas, and large fluctuations in the evaluation of pore pressures for intermediate rocks. In addition, for physically correct data of great importance is the method by which the smoothing is occurred $grad\, p_n$ [3, 5].

In laboratory studies are made to determine the absolute gas permeability in samples of cement OWPC1-100 and hydrophobic additive Ramsinks-2M. Tests are performed according to GOST 26450.0-85-GOST 26450.2-85.

Table 2 shows the value of absolute gas permeability of portland cement OWPC1-100 and the hydrophobic additive Ramsinks-2M. This value is still irregular in Ukraine, but its definition of normalized by standard American Petroleum Institute API Recommended Practice 10B-2/ISO 10426-2. Indeed, to ensure reliable separation of layers the permeability of cement rock for layer fluid should be as short as possible.

TABLE 2. Results of the determination of absolute gas permeability by samples of cement OWPC1-100 and hydrophobic additive Ramsinks-2M

Lab. No. of sample	Formula of sample	Gas permeability $\times 10^{-15}$ m²
40443	Cement stone with OWPC1-100	0.15
40444	Cement stone with OWPC1-100, 0.2% additive Ramsinks-2M	0.15
40445	Cement stone with OWPC1-100, 0.25% additive Ramsinks-2M	0.10
40446	Cement stone with OWPC1-100, 0.3% additive Ramsinks-2M	0.05
40447	Cement stone with OWPC1-100, 0.35% additive Ramsinks-2M	0.04
40448	Cement stone with OWPC1-100, 0.4% additive Ramsinks-2M	0.04

Table 3 presents the results of tests samples of cement stone to bend.

TABLE 3. Results of tests samples of cement stone to bend

Test number	1	2	3	4	5	6	7	8	9	10
Destruction efforts of the sample in bending, MPa	5.9	7.08	5.9	6.49	7.67	4.13	4.13	3.54	2.95	4.13
Test number	11	12	13	14	15	16	17	18	19	20
Destruction efforts of the sample in bending, MPa	6.49	7.08	7.08	6.49	15.93	14.16	14.75	9.44	11.8	12.98

1-5 – OWPC-I-100 + 0.06% NTPha + 0.4% Ramsinks-2M + 2% SAS;
6-9 – OWP-I-100 + 0.06% NTPha + 0.2% Ramsinks-2M + 2% stinol;
10-14 – OWPC-I-100 + 0.06% NTPha;
15-20 – OWPC-I-100 + 0.06% NTPha + 0.2% Ramsinks-2M + 1.5% stinol

Figure 1 shows the dependence of the absolute gas permeability of cement slurry samples from per cent of additive Ramsinks-2M to the binding material. This graph represents the trend line (graphical representation of the direction change of data series) data series of per cent of additive Ramsinks-2M is the power function $y = 0.0049x^{-2.01045}$, magnitude of approximation probability at that (coefficient of determination) was $R^2 = 0.9321$. This function proves that gas permeability is reduced when using different formulations of hydrophobic additives, but the best data is achieved with 0.3% additive Ramsinks-2M in cement OWPC-I-100. Further increase per cent of amount of additive leads to deterioration of results.

In order to exclude the possibility of premature thickening of cement slurry before its wash at the performing the analysis to predict the mixer consistometer stops KC-3 in 3 hours to 0.5 hours with a consequent continuation of the analysis. Thickening time of cement slurry must meet calculated time plus 1 hour of spare time for the possibility of accelerating the sticking and thickening of the slurry in contact with bischofite. The required amount of hydrophobic cement slurry was prepared by mixing dry cement OWPC-I-100, hydrophobic material Ramsinks-2M and nitrilotrimethyl phosphonic acid (NTPha). In carrying out the cementing on the well No. 101 of Hadiach field was applied hydrophobic cement slurry Si1rap-R (modification Ramsinks-2M) in amount of 62.5 kg at cementing the 2nd section 245 mm (4580-3840 m) intermediate column (second portion of cement slurry 4580-4430) [6, 7].

Work is carried out as planned (updated calculation – see Table 4) carring out of cementing lower second section 245 mm intermediate columns in the well No. 101 Hadiach OGCF (oil-gas condendate field).

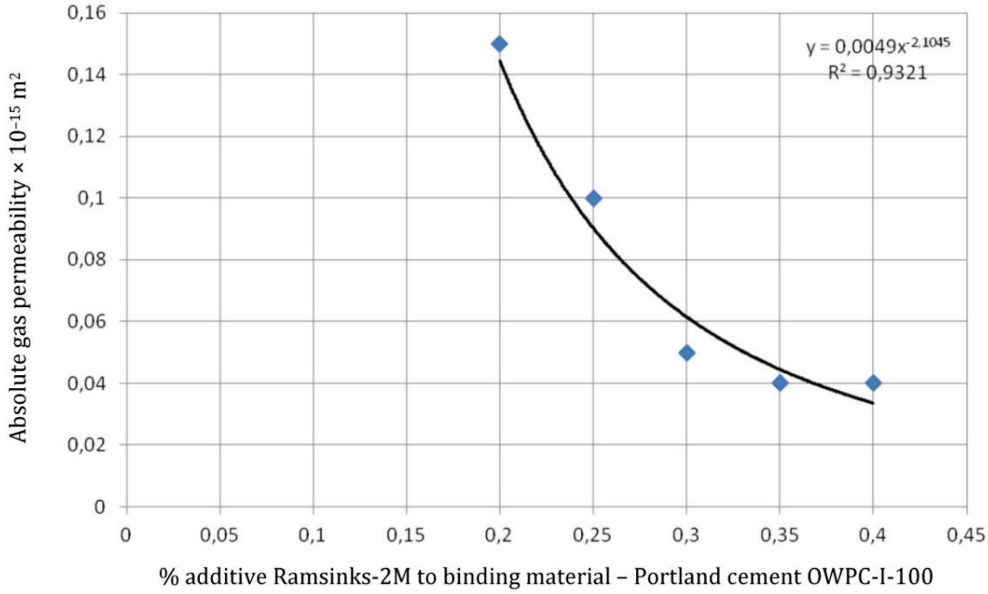

FIGURE 1. *Determination of absolute permeability by samples*

TABLE 4 . *Calculation of volume of cement slurry at caliper curve*

No.	Depth	Length	Diameter	Volume
1	3840-4580	740	K × 295.300	55.9

Clarifying calculation of cementation of second section 245 mm intermediate columns of well number 101 Hadiach OGCF.

Second section 4580-3840 m

The volume of cement slurry for flushing: V_m = 4 m³.

The total volume of cement slurry: 55.9 + 4 = 60 m³.

The required amount of dry cement: 60 × 1.05 × 1.244 = 79 m (OWPC-I-100).

Cement slurry is injected in two portions:

First portion 4430-3840 m

The volume of cement slurry for flushing V_m = 4 m³.

The total volume of cement slurry 37.5 + 4 = 41.5 m³.

Required amount of OWPC-I-100: 41.5 × 1.05 × 1.244 = 54 t.

Required amount of water for making cement slurry of first portion: 54 × 0.45 × 1.12 = 31 m³.

Second portion 4580-4430

Volume of cement slurry: 18.5 m³.

Required amount of OWPC-I-100: 18.5 × 1.05 × 1.244 = 25 t (out of them OWPC-I-100 – 25 t; hydrophobic additive Ramsinks-2M of modification Silpan-P in amount according to the analysis of BTP).

Required amount of water for making cement slurry of second portion: 25 × 0.45 × 1.25 = 14 m³.

Squeezing volume in drilling pipes: V_d = 33.78 m³.

Squeezing volume in casing pipe: V_{cp} = 29.03 m³.

Total volume of squeezing: 33.7 + 29.03 = 62.73 m³.

Volume of drill fluid for flushing cement slurry: V_{cp} = 231.49 m³ ; V_{cp} = 231.49 × 1.5 = 347 m³.

The expected pressure at the end of squeezing:
0.00001 × (1800 – 1280) × (4610 – 3840) + 0.001 × 4610 + 0.8 = 9.4 MPa.

Time of cement slurry pumping: 60/0.15/60 = 67 min.

Time of cement slurry squeezing: 62.73/0.018/60 = 59 min.

Time of cement slurry flushing: 231.49/0.025/60 = 155 min.

Total time of cementing operations: 67 + 15 + 155 + 10 = 291 min.

Required amount of cement slurry pumping of first portion: 18.5 × 1.05 × 1.244 = 25 t.

(Including OWPC-I-100- 25 t; hydrophobic additive Ramsinks-2M of modification Silpan-P – according to the number of analysis ITR).

The required amount of water to prepare cement slurry of the second portion: 25 × 0.45 × 1.25 = 14 m^3.

Squeezing volume in drilling pipes: V_d = 33.78 m^3.

Squeezing volume in casing pipe: V_{cp} = 29.03 m^3.

Total volume of squeezing: 33.7 + 29.03 = 62.73 m^3.

Volume of drill fluid for flushing cement slurry: V_{cp} = 231.49 m^3; V_{cp} = 231.49 × 1.5 = 347 m^3.

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Time of cement slurry pumping: 60/0.15/60 = 67 min.

Time of cement slurry squeezing: 62.73/0.018/60 = 59 min.

Time of cement slurry flushing: 231.49/0.025/60 = 155 min.

Total time of cementing operations: 67 + 15 + 155 + 10 = 291 min.

Required amount of cement slurry pumping of first portion: 291 × 1.25/60 = 6.1 hours.

Time of cement slurry pumping of second portion: 18.5/0.0015/60 = 21 min.

Time of cement slurry squeezing of first and second portion: 62.73/0.018/60 = 59 min.

Total time of cementing operations: 21 + 59 + 10 = 90 min.

Required amount of cement slurry pumping of second portion: 90 × 1.25/60 = 1.9 hours.

Required amount of cement-mixing machines: 79/15 = 6 pieces.

Required amount of cement equipment: 6 × 2 + 4 = 16 pieces.

General amount of slag-sand cement mixture (SSCM) – I–120 – 79 t, total volume of cement slurry – 60 m.

Layout and binding of equipment at cementing

Now in various areas of oil and gas areas are used slightly different from each other technological schemes of preparation and injection of cement slurry. This difference is caused by specific geological, technical, and sometimes climatic conditions of the area that determines the choice of well design, way of cementing and cement slurry for each area. The scheme in Figure 2 usually provides the same ratio between cement-mixing machines and cementing units, which ensured smooth uninterrupted preparation and injection of cement slurry Silpan-P into the well with a given rate.

Full lines show the movement of cement slurry, dash line–movement of squeezing liquid. The difference between this scheme is to use a different number of units for cementing and cement-mixing machines, as well as the use of special devices or mechanisms that improve the quality of cementing slurry and improve the working conditions of staff.

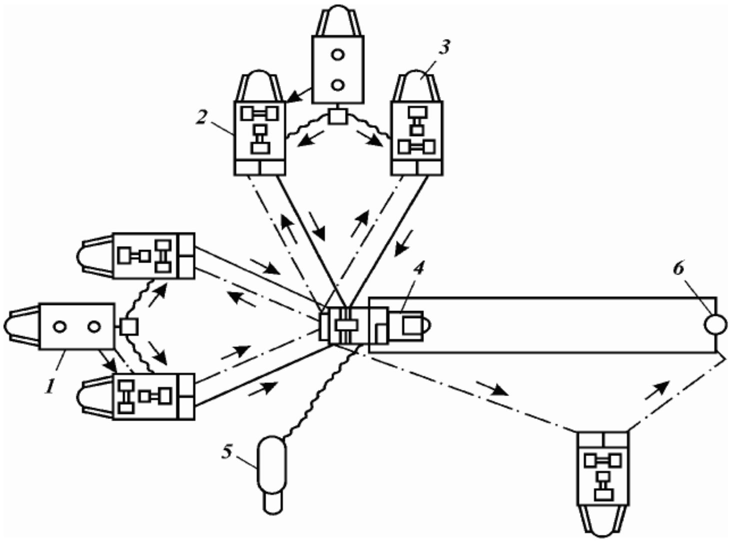

FIGURE 2. Scheme of binding units at well cementing using 20-40 tons of dry cement slurry: 1 – cement-mixing machine 2SMN-20; 2, 3 – cementing units CA-320M; ZCA-400A; 4 – manifold block 1BM-700, 5 – cementing control station; 6 – cementing head; dash line – squeezing fluid movement; full line – cement slurry movement

Usually, with one cement-mixing machine 2SMN-20 work two cementing units, one of which (having waterfalling pressure) delivers fluid to gauging hydrovacmixing device in cement mixing machines and the second (which does not have waterfalling presure) with the first one pump slurry into the well. Thus, the total supply of liquid (on passport data) by two units gives a bit more performance cement-mixing machine. As a rule, to push the upper knockout plug unit ZCA-400A is used, which is band with the cementing head. It is advisable to mix it for 15-20 minutes in the tank before applying the solution into the well, thus its homogeneity is improving, which significantly improves the quality of cementing [8].

Scientific novelty of the results is that the result of this research:

- proposed technical solution compared to the existing will provide hydrophobic cement slurry Silpan-P with lower density ranges cement slurry, high stability, good pumpability and high strength harden stone, ensures reliable isolation of productive horizons;
- determined that the use of formulations of hydrophobic cement slurry Silpan-P will significantly reduce the migration of reservoir fluids and use of different types of cement hydrophobic additive Ramsinks-2M will improve the success and efficiency of work units by DD Ukrburgaz.

By laboratory studies cement slurry and cement stone, which are conducted in the laboratory of cement slurry of Poltava plugging operations department found that hydrophobic cement slurry Silpan-P is prepared with additives NTPha for cements OWPC1-100 and Ramsinks-2M:

- does not reduce the technological parameters cement slurry and cement stone, which are determined by current standards of today, "Cements for plugging. Test methods. ISO BV-2.7-86-99 (GOST 26798.1-96)";
- increases the strength characteristics of cement stone, including the strength of binding, which increases durability and processability facilities – wells.

Conclusion

On the basis of the research in the laboratory of Poltava plugging operations department of drilling devision Ukrburgaz in Poltava and sector lithological and physical studies of research department of rocks and gas reserves calculating UkrNDIgaz proposed to implement in practice the new cement slurry Silpan-P in the structural units of DD Ukrburgaz. To improve the quality of cementing intermediate, casing pipes of oil wells cement slurry Silpan-P is recommended for:

- cementing oil and gas wells (for intermediate and operational casing) especially in the presence of closely spaced and productive aquifers horizons with different anomalous coefficient;

- the repair and insulation work in the process of construction and operation of oil and gas wells;
- creation of behind-the casingspace (open or lined borehole) blocking screens (Jumper) to prevent migration of reservoir fluids;
- installation of insulation cement bridges.

Technical parameters of new hydrophobic cement slurry (mobility, density, water trapping pumpability etc.) supported by the standard requirements for the instruments in the laboratory.

Conflicts of Interest: The author declares no conflict of interest.

Reference

[1] Nalivaiko A.I., *Advanced recovery methods and well capacity in the Ukrainian oilfield conditions*/A.I. Nalivaiko, M.I. Rudiy, Polevoi Yu. A., Scientific Bulletin of National Mining University, No. 12, Dnepropetrovsk 2015, pp. 15-21.

[2] Yurkov N.I., *Physical and chemical bases of oil production*, N.I. Yurkov, Volgograd 2004, p. 387.

[3] Iken H.W., *Handbuch der Betonprüfung: Anleitungen u. Beispiele*/Iken H.W., Lackner R.R., Zimmer U.P., 5. Auflage, Verlag Bau+Technik, Düsseldorf 2003, p. 380, ISBN 3-7640-0317-0.

[4] Russian Federation Patent No. 2188933 on 19.11.02, Nalivaiko A.I and others, *A method for increasing productivity of wells*.

[5] Pat. US 7658794 B2 United States of America, Classification C04B14/24.

[6] Muskat M., *Flowing of homogenous fluids in porous environment*, Izhevsk: Institute of Computer of Research, Moscow 2005, p. 628.

[7] Nalivaiko A.I., UDC 378.147:622 *Fundamentals of physics of petroleum later*/Nalivaiko A.I., Mangura A.M., Nalivaiko L.G., PoltNTU, Poltava 2011, p. 252.

[8] Panko D.A., Nalivaiko A.I., Rudyi M.I., Lapko C.V., Useful model patent of Ukraine No. 32045/*Solution for selective treatment of oil formation (Silpan-SV)/2008*, p. 12.

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REDUCING THE HARMFUL EMISSIONS AND POROUS POLLUTIONS WHILE COMBUSTION OF WATER-FUEL EMULSIONS

Abstract: *Based on the experimental and theoretical studies, a scheme of system for complex gas cleaning method of an internal combustion engine was developed. This system reduces the content of NOx in gases by 55%, SO_2 by 50%, and the content of solid particles by 3 times. The use of a complex system ensures that gases are purified from toxic ingredients and heat emissions to the level recommended by IMO.*

Keywords: *water-fuel emulsion, internal combustion engine, harmful emissions.*

Introduction

Receiving additional energy due to deep utilization of heat losses of an Internal Combustion Engine (ICE) saves fuel consumed for the operation of a ship's power plant. This, accordingly, leads to a decrease in emissions of harmful substances into the atmosphere, contributes to the satisfaction of the more stringent standards of the International Maritime Organization (IMO), which regulate the limits of these emissions.

According to the MAN specialists, the IMO requirements (III level from SO_2, NOx emissions) can be fulfilled using the following technologies: Water-Fuel Emulsion combustion (WFE) – WIF (Water in Fuel Emulsion); Scavenge Air Monistening (SAM); Exhaust Gas Recirculation (EGR); Selective Catalytic Reduction (SCR).

The use of a combined SAM & WIF scheme to reduce NOx emissions is promising: water vapor in the combustion chamber increases the heat output and reduces the O_2 content. According to MAN, an increase in thermal power and a reduction of O_2 in the charge air provides a decrease of the combustion temperature, which leads to a decrease in NOx emissions. In addition, it should be noted that with a decrease of the combustion temperature, the soot concentration increases, as well as the amount of CO.

The use of WIF technology leads to an increase of fuel consumption up to 1.2% (if the condensing surfaces of isn't used when gases cooling below the dew point temperature of H_2SO_4 and H_2O vapors), SAM technology – 2.3%, EGR technology – 4.6%, SCR technology – 7.5-15% (taking into account the price of urea). But WIF technology provides a reduction of NOx to 30%, SAM technology – 45%, the existing EGR system – 70%; SCR technology – by 80% (at the required level of IMO requirements (III level) – 80% reduction of NOx). In addition, the SCR system must be accompanied by scrubber technology for the removal of SO_2.

Literature Review

In [1] as consequence of deteriorated fuel quality, soot deposits on the EGB tubes, had increased and, in some cases, had resulted in soot fires. In extreme cases, the soot fire had developed into a high temperature iron fire in which the boiler itself burned. According to data of [2, 3], when water-fuel emulsion (WFE) is combustion, the deposits become loose, or fully absent due to decrease of soot and coke generation. During combustion of WFE drops micro-explosions are observed, which intensify burning process, which is also observed in combustion chambers of combustion engines [4]. However, in these literary sources there is no quantitative data of pollution intensity. In [5] the results of experimental studies on effect of standard diesel fuel (DF) combustion and environmental diesel fuel (EDF), with water content of 12%,…, 31% by mass on indicators of toxicity and smoke of exhaust gases are presented. According to [5], indisputable advantage of using EDF in diesel engine is its effect on exhaust gases smoking, which in maximum load is decreased in 1.3 times,..., 2.7 times. According to the data [5, 6] using of WFE does not require constructive alterations of diesel engine and can significantly improve environmental characteristics of engine.

Majority of the studies reported that soot and particulate matter (PM) were reduced with increase in water concentration [7, 8]. Numerical and experimental study showed reduction in the soot emission of 68% and 75% that when 10% and 15% respectively of water content by volume in the WFE were used [9, 10]. From the various experimental results reported, the majority of the studies confirmed that soot and PM are reduced by using the WFE emulsion fuel [11, 12]. WFE is used as alternative fuel and decreases the emissions of NOx and PM in diesel engines [13]. Based on the obtained results [14], it can be stated that an operation of the engine with diesel fuel and WFE reduces emissions of PM in 2.5 times,..., 3.5 times, that can be explained by the presence of water vapour in combustion chamber as a catalyst that helps burning carbon particles and other components difficult to oxidize. In [15] the influence of parameters of combustion process in existing low capacity boiler plants on the level of formation of nitrogen oxides, carbon monoxide and soot was studied.

Modern methods can be used for statistical treatment of experimental data [16, 17]. For estimating the efficiency of such greening and fuel saving technologies during the operation in actual climatic conditions various methods of modelling [18, 19] are applied.

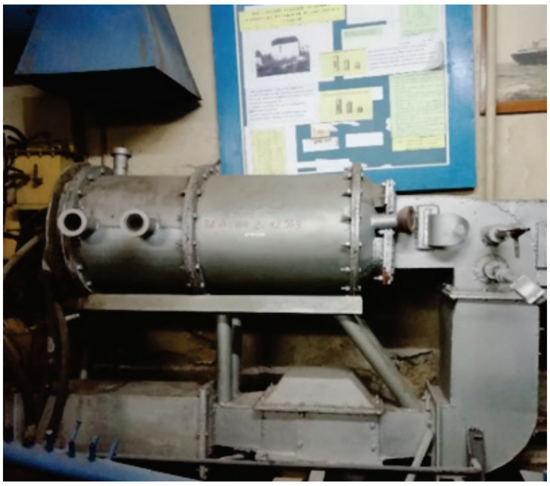
The aim of the research is to develop a system for the integrated purification of ICE exhaust gases. Research tasks: to carry out experimental research of pollution processes of EGB, that influence a heat transfer intensity, and EGB working reliability; to obtain dependences of pollution rate from wall temperature and values of wall temperature range with minimum pollution; to obtain emission rates of toxic ingredients before and after using system for the integrated purification of exhaust gases.

Methodology

Experimental researches of pollution intensity at wall temperature values below dew point temperature of sulfuric acid vapors were carried out in an experimental setup (Fig. 1a) with combustion of fuel oil and WFE based on them.

The experimental installation includes the following elements: combustion chamber, burner, fuel preparation system, gas duct. The form of combustion chamber provides a good filling of torch. The dimensions of the chamber: length – 800 mm, internal diameter – 300 mm. A rotary nozzle is used as a burner [20, 21]. Much attention during development and commissioning of experimental setup was paid to fuel system, which is designed to burn from 1 kg/h to 3 kg/h of fuel. Preparation of WFE for combustion in furnace of experimental setup was carried out in a separate installation. Air is supplied to the burner by a fan through the air heater. The temperature of hot air was 150°C,..., 180°C. The flue gases were removed from the installation by exhaust fan.

There were working areas (Fig. 1b) with sample tubes with an outer diameter of 25 mm provided in installation gas duct to study pollution process. Cooling of samples to study LTHS pollution was carried out with air from a receiver or from four thermostats with water and oil.


(a)

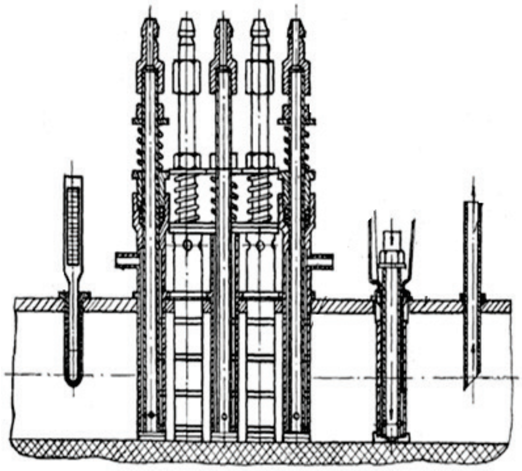

(b)

FIGURE 1. *General view of experimental setup (a) and tube-samples of low-temperature condensation economizer (b)*

The assemblies of three tube samples were installed in gas *duct* of experimental setup, where gas velocity was 7 m/s,..., 8 m/s and its temperature about 200°C.

Experiments were carried out measurements of the geometric characteristics of each tube-sample, which made it possible to determine the outer area of the sample *F* to the test. After that we weighed each sample (before the experiment) – mass m_1. At the end of experiment, packs of tube samples were pulled out from gas pipeline. Samples with corrosion products, acid and soot deposits were weighed against by analytical weights (mass of m_2).

The pollution speed of metal surface *K* at a certain temperature of the tube wall was determined by formula:

$$K_p = \frac{m_1 - m_2}{F \cdot \tau} \quad (1)$$

where:

K_p – pollution speed of metal surface, g/(m²·h);

m_1 – mass of sample before experiment, g;

m_2 – mass of sample after cleaning of soot deposits and corrosion products, g;

F – average surface of the outer surface of the sample to the experiment, m³;

τ – duration of experiment, h.

Results

Based on the experimental data, the equation of the pollution rate K_p depending on the wall temperature t_w during the fuel oils (W^r = 2%) combustion (1 mode) was obtained by the approximation method. In this case, the polynomial equation was selected:

$$K = 3082.92 - 117.228 \cdot t_w + 1.6613 \cdot t_w^2 - 1.0344 \cdot 10^{-2} \cdot t_w^3 + 2.3881 \cdot 10^{-5} \cdot t_w^4 \quad (2)$$

This equation (regression coefficient R = 98.3859; R^2 = 96.7718 is obtained for the following characteristics of the pollution intensity: t_w = 85°C,..., 130°C, W^r = 2%. Figure 2 shows the calculated (predicted) values for K_p using the fitted model. In addition to the best predictions, the figure shows:

95% prediction intervals for new observations and 95% confidence intervals for the mean of many observations. The prediction and confidence intervals correspond to the inner and outer bounds on the graph of the fitted model.

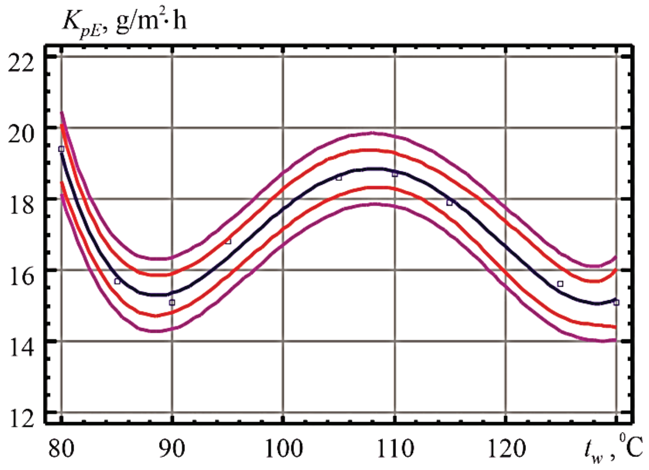


FIGURE 2. *Experimental dependences of pollution rate K_{pE} from wall temperature t_w with confidence and prediction curves during the fuel oils combustion*

Comparison of the calculated values of the pollution rate K_{pC} (equation (2)) from those obtained during the experimental study K_{pE} is δ_K = ±5% (Fig. 3).

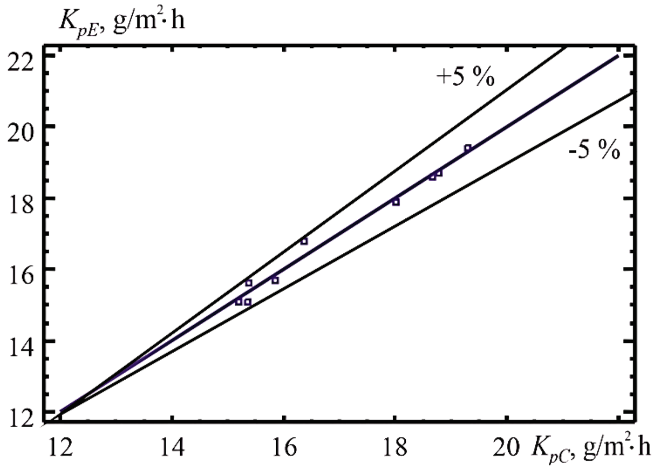


FIGURE 3. *Comparison of calculated pollution rate K_{pC} values with experimental K_{pE} during the fuel oils combustion*

The polynomial equation of the pollution rate K_p depending on the wall temperature t_w during the WFE (W^r = 30%) combustion (2 mode) based on the experimental data, was selected:

$$K = 624.931 - 23.3676 \cdot t_w + 0.3306 \cdot t_w^2 - 2.0583 \cdot 10^{-2} \cdot t_w^3 + 4.7526 \cdot 10^{-6} \cdot t_w^4 \quad (3)$$

This equation (regression coefficient R = 99.6865; R^2 = 99.373) is obtained for the following characteristics of the pollution intensity: t_w = 80°C,..., 130°C, W^r = 30%. Figure 4 shows the calculated (predicted) values for K_p with prediction and confidence intervals.

Comparison of the calculated values of the pollution rate K_{pC} (equation (2)) from those obtained during the experimental study K_{pE} is δ_K = ±5% (Fig. 5).

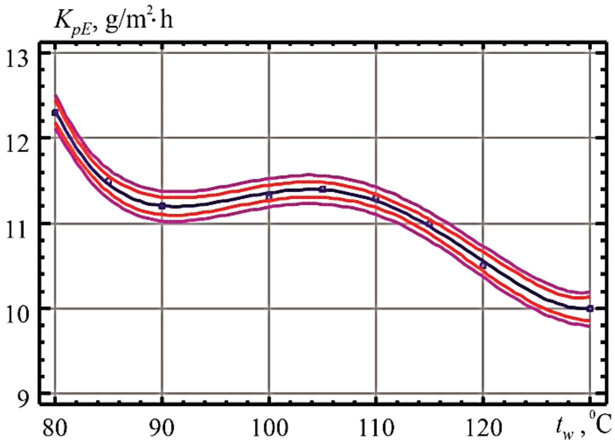


FIGURE 4. *Experimental dependences of pollution rate K_{pE} from wall temperature t_w with confidence and prediction curves during the WFE combustion*

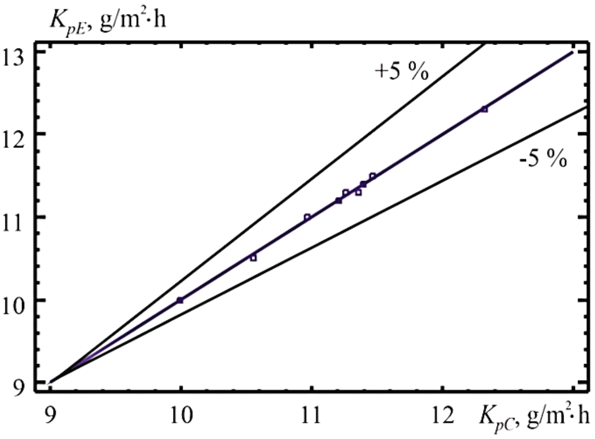


FIGURE 5. *Comparison of calculated pollution rate K_{pC} values with experimental K_{pE} during the WFE combustion*

System for complex gas cleaning method

Based on the experimental and theoretical studies (Fig. 1), a scheme of system for complex gas cleaning method of an ICE was developed (Fig. 6).

Possibility of solving complex problems in proposed technology is ensured by combustion of WFE with specifically recommended value of water content (W^r = 30%). Such WFE composition substantially affects not only running of thermal and physicochemical processes along the entire path of fuel combustion aggregates (starting from combustion zone and to cut of flue), but also directs them in the required direction. For performing tasks in technology of proposed method, providing solutions to problems of improving economic efficiency, improvement of environmental indicators and reliability, it is envisaged 4 stages of technological process:

1. WFE preparation with a water content of about 30%.
2. WFE combustion with a water content of about W^r = 30% leads to formation of equimolar ratio NO_2: NO in exhaust gases at outlet of combustion zone (as confirmed by patent and providing low-temperature corrosion (LTC) reduction), as well as reducing NOx, SO_2, PM emissions.
3. Installation of condensing surfaces, on which conditions are created for passivation of metal and a sharp decrease LTC intensity, as well as conditions from side of gases and in condensate to intensify NOx, SO_2, PM absorption.
4. Continuation of absorption intensification on condensing surfaces of gas flues (providing conditions for reliable operation of their metal) or maintaining temperature of metal of these gas flues above the dew point temperature of sulfuric acid vapour H_2SO_4 without NOx, SO_2 absorption, but ensuring reliability of work (at low LTC level).

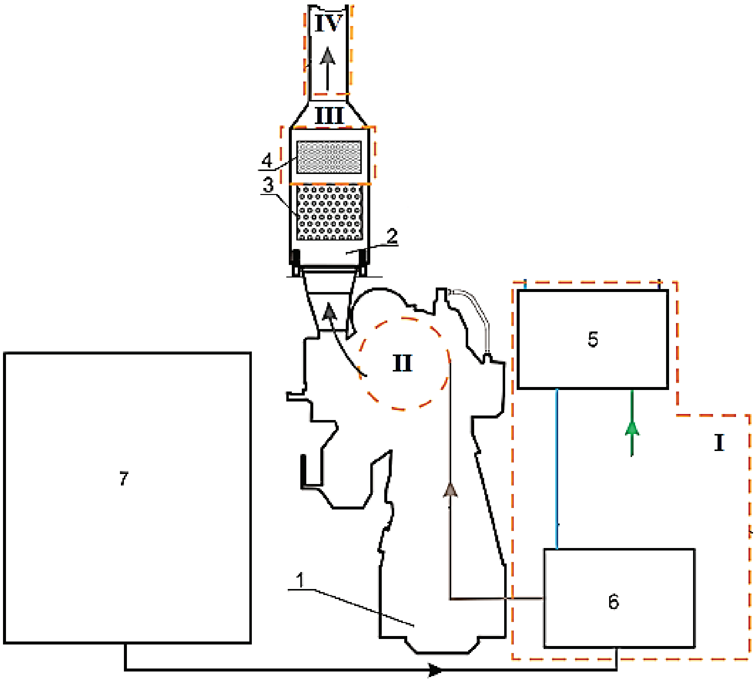


FIGURE 6. The scheme of system for complex gas cleaning method and stages of cleaning, where: I – WFE preparation with a water content of about 30%; II – reducing concentration of toxic substances and solids in gases when WFE is burnt with water content 30%; III – adsorption processes occurring on condensing surfaces of exhaust gas boilers; IV – processes occurring on condensing surfaces of gas flues; 1 – ICE: 2 – EGB; 3 – dry convective surface; 4 – condensing heating surface; 5 – water preparation unit; 6 – Water-Fuel Emulsion preparation unit; 7 – fuel tank

The main elements of the power plant, which provides for the combustion of specially prepared WFE with a water content of 30%, are the ICE and the EGB. A dry convective surface and a condensing surface must be installed. In the EGB to perform tasks. It is also mandatory to install a water treatment unit and WFE (the first stage of gas purification). Specially prepared WFE is supplied to the ICE injectors.

As a result of the combustion of activated WFE at the engine outlet we obtain exhaust gases of the corresponding composition with a reduced amount of toxic ingredients up to 35% or more, and most importantly, the equimolar ratio of NO_2 : NO in NOx (which is confirmed by our experimental and literature data). This is the second stage of exhaust gas cleaning, which allows to reduce, for example, the concentration of NOx by 30-50%.

Further, the exhaust gases enter to the EGB, in which a dry convective surface is installed at the inlet (superheater, vapor-generating surface), and a condensing convective surface in the form of an economizer and (or) a hot water supply section with a metal temperature of 70-130°C at the outlet, which leads to condensation of sulfuric acid vapors in the exhaust gases of ICE.

In the acid condensate under the indicated conditions, an average concentration of about 57% is established. The result is a sharp increase of SO_2 and NOx absorption. The presence in them of an equimolar ratio of NO_2 : NO provides passivation of the condensing surface made of carbon steel. This provides a sharp decrease of the LTC intensity, an increase of the operation reliability of these condensing surfaces and the possibility of a sharp increase of the depth of exhaust gases utilization to ~ 80-90°C instead of 160°C (when standard fuels combustion). Thus, the third stage of gas cleaning is carried out.

Further, the gases after the EGB enter to the gas duct. With such a low gas temperature and ensuring the temperature of the gas duct metal after the ICE at a level of 70-80°C, that is, in the presence of sulfuric acid condensate on the inner surface of the gas ducts, the process of absorption of toxic substances will continue with reliable operation of the gas duct metal, and the intensity of the mass flow will additionally decrease H_2SO_4 and LTC (this is the fourth stage of gas purification).

This is due to the fact that in gases there is an equimolar ratio of NO_2 : NO, which means that the passivation of the metal surface and a decrease of the LTC will be ensured with a minimum temperature difference between the gases and the metal of the gas ducts.

Thus, the implementation of these stages of gas purification provides a decrease of the content of toxic ingredients in gases by almost 50% (compared to existing technologies, which provide a decrease of the exhaust gas temperature of the EGB to 160°C) and partial removal of solid particles, contained in gases (when WFE combustion, solid and soot particles are 80% less than standard fuels combustion) (Fig. 7).

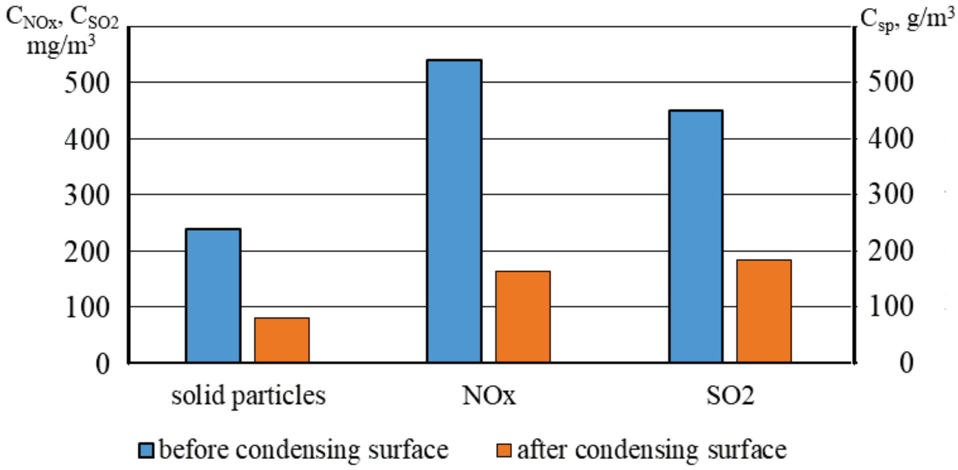


FIGURE 7. *Emission rates of toxic ingredients*

Conclusions

The best burning out of fuel combustible components due to applying a WFE provides decreasing a concentration of solids and soot in the exhaust gases and hence their toxicity.

The kinetics of low-temperature pollution on EGB condensation surfaces with WFE combustion are investigated to obtain approximation equations for predicting processes development.

When WFE combustion with a water content of 30%, the LTC intensity decreases, which makes it possible to install condensing heating surfaces in the EGB. The installation of a condensing heating surface in the EGB reduces the content of NOx in gases by 55%, SO_2 by 50%, and the content of solid particles by 3 times.

The use of a complex system ensures that gases are purified from toxic ingredients and heat emissions to the level recommended by IMO.

Conflicts of Interest: The author declares no conflict of interest.

References

[1] Soot deposits and fires in exhaust gas boilers, MAN Diesel & Turbo, September 2014.

[2] Wojs M.K., Orliński P., Kamela W., Kruczyński P., *Research on the influence of ozone dissolved in the fuel-water emulsion on the parameters of the CI engine* [in:] *IOP Conference Series: Materials Science and Engineering*, 2016, Vol. 148, pp. 1-8.

[3] Baskar P., Senthil Kumar A., *Experimental investigation on performance characteristics of a diesel engine using diesel-water emulsion with oxygen enriched air*, Alexandria Engineering Journal, Vol. 56, Issue 1, 2017, pp. 137-146.

[4] Miao Y.C., Yu C.L., Wang B.H., Chen K., *The applied research of emulsified heavy fuel oil used for the marine diesel engine*, Advanced Materials Research, 2013, Vol. 779, pp. 469-476.

[5] Parsadanov I.V., Solodovnikov V.V., *Application of water fuel emulsion in autotractor diesel. Ecological efficiency (part 1)*, Internal Combustion Engines, 2011, Vol. 2, pp. 118-120.

[6] Zang T., Okada H., Tsukamoto T., Ohe K., *Experimental study on water particles in the combustion of marine four-stoke diesel engine operated with emulsified fuels*, Paper 193, CIMAK, Vienna 2007.

[7] Vellaiyan S., Amirthagadeswaran K.S., *The role of water-in-diesel emulsion and its additives on diesel engine performance and emission levels: A retrospective review*, Alexandria Engineering Journal, 2016, Vol. 55, pp. 2463-2472.

[8] Kornienko V., Radchenko M., Radchenko R., Konovalov D., Andreev, A., Pyrysunko M., *Improving the efficiency of heat recovery circuits of cogeneration plants with combustion of water-fuel emulsions*, Thermal Science, Vol. 25, Issue 1, Part B, 2021, pp. 791-800.

[9] Gupta R.K., Sankeerth K.A., Sharma T.K., Rao G., Murthy K.M., *Effects of water-diesel emulsion on the emission characteristics of single cylinder direct injection diesel engine – A review*, Applied Mechanics and Materials, 2014, Vol. 592, pp. 1526-1533.

[10] Radchenko R., Pyrysunko M., Kornienko V., Scurtu I.-C., Patyk R., *Improving the ecological and energy efficiency of internal combustion engines by ejector chiller using recirculation gas heat* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering. Advances in Intelligent Systems and Computing*, 2021, Vol. 188, Springer, Cham, pp. 531-541.

[11] Patel K.R., Dhiman V., *Research study of water – diesel emulsion as alternative fuel in diesel engine – An overview*, International Journal of Latest Engineering Research and Applications 2017, Vol. 2, Issue 9, pp. 37-41.

[12] Radchenko R., Pyrysunko M., Radchenko A., Andreev A., Kornienko V., *Ship engine intake air cooling by ejector chiller using recirculation gas heat* [in:] Tonkonogyi V. et al. (eds.), *Advanced Manufacturing Processes*, InterPartner-2020, Lecture Notes in Mechanical Engineering, Springer, Cham 2021, pp. 734-743.

[13] Patel N., Modi M., Patel T., *Investigation of diesel engine with water emulsifier – A review*, International Research Journal of Engineering and Technology, 2017, Vol. 4, Issue 2, pp. 879-883.

[14] Kruczyński P., Orliński P., Kamela W., Ślęzak M., *Analysis of selected toxic components in the exhaust gases of a CI engine supplied with water-fuel emulsion*, Polish Journal of Environmental Studies, 2018, Vol. 27, Issue 1, pp. 129-136.

[15] Katin V., Kosygin V., Akhtiamov M., Vol'khin I., *Mathematical models of the output of major pollutants in the process of burning water fuel oil emulsions in boiler plants* [in:] *19th International scientific conference Energy Management of Municipal Transportation Facilities and Transport*, EMMFT, Vol. 692, 2018, pp. 987-997.

[16] Radchenko A., Mikielewicz D., Forduy S., Radchenko M., Zubarev A., *Monitoring the fuel efficiency of gas engine in integrated energy system* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering*, Advances in Intelligent Systems and Computing, Springer, Cham 2020, Vol. 1113, pp. 361-370.

[17] Trushliakov E., Radchenko A., Forduy S., Zubarev A., Hrych A., *Increasing the operation efficiency of air conditioning system for integrated power plant on the base of its monitoring* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering (ICTM 2019)*, Advances in Intelligent Systems and Computing, Springer, Cham 2020, Vol. 1113, pp. 351-360.

[18] Radchenko M., Radchenko R., Tkachenko V., Kantor S., Smolyanoy E., *Increasing the operation efficiency of railway air conditioning system on the base of its simulation along the route line* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering (ICTM 2019)*, Advances in Intelligent Systems and Computing, Springer, Cham 2020, Vol. 1113, pp. 461-467.

[19] Radchenko A., Trushliakov E., Kosowski K., Mikielewicz D., Radchenko M., *Innovative turbine intake air cooling systems and their rational designing*, Energies, 2020, Vol. 13, Issue 23, No. 6201, doi:10.3390/en13236201.

[20] Kornienko V., Radchenko R., Konovalov D., Andreev A., Pyrysunko M., *Characteristics of the rotary cup atomizer used as afterburning installation in exhaust gas boiler flue* [in:] Ivanov V. et al. (eds.), *Advances in Design, Simulation and Manufacturing III (DSMIE 2020)*, Lecture Notes in Mechanical Engineering, Springer, Cham 2020, pp. 302-311.

[21] Kornienko V., Radchenko R., Mikielewicz D., Pyrysunko M., Andreev A., *Improvement of characteristics of water-fuel rotary cup atomizer in a boiler* [in:] Tonkonogyi V. et al. (eds.), *Advanced Manufacturing Processes*, InterPartner-2020, Lecture Notes in Mechanical Engineering, Springer, Cham 2021, pp. 664-674.

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ENERGY EFFICIENT TECHNOLOGIES AT OIL FIELD FACILITIES

Abstract: *One of the most appropriate solutions to reduce diesel consumption is the use of associated petroleum gas, which inevitably accompanies the oil production process. In the analysis performed, the use of APG significantly reduces greenhouse gases emission into the atmosphere.*

Keywords: *diesel, associated petroleum gas.*

It is known, oil is one of the most important minerals ensuring the well-being of many countries including Russia. More than 500 million tons of oil are produced annually in our country. However, a significant number of oil fields are located in the Arctic zone, the border of which runs along the Arctic Circle. The development of such fields is complicated by climatic conditions, difficulties in cargo delivery and oil transportation, as well as distance from powerful energy systems.

The oil production method is chosen depending on the features of the field and the particular well. There are formation characteristics; oil properties; the presence of mechanical impurities, water and associated gas. Currently, the pumping method is mainly used. To prepare oil for transportation, booster pumping stations and separation plants are provided. All equipment of the well facility, complex for preparation of commercial oil and external oil transportation is a powerful consumer of electric and thermal energy.

An analysis of energy consumption of one of the fields within the Nenets Autonomous District shows that up to 95% of electric energy is used to provide process and household consumers. In following pie chart shows share ratio of electricity consumption by areas of use per year is showed (Fig. 1).

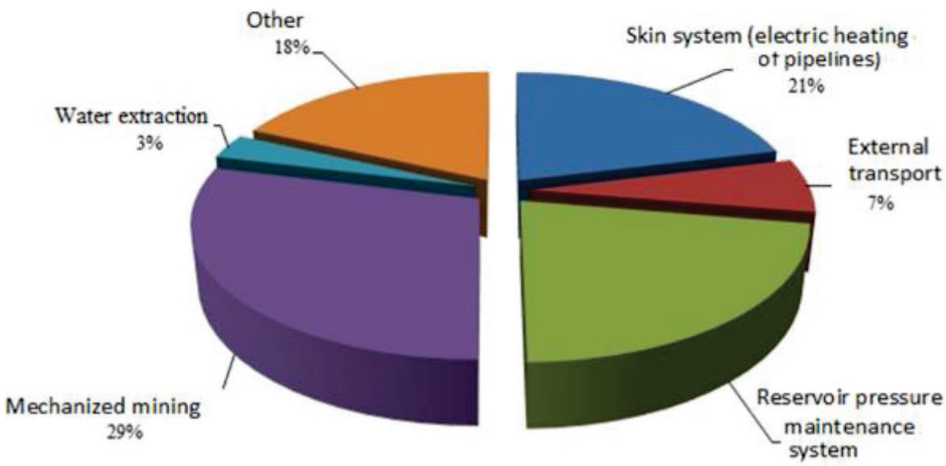

FIGURE 1. *Ratio of electricity consumption by areas of use per year*

Electricity generation is provided by diesel power plants. A significant amount of diesel fuel is also spent for thermal energy generation, taking into account the low temperature for heating calculation (–39°C) and, accordingly, the duration of a heating period of 289 days. Bar chart shows the data on specific energy consumption for the production of oil-containing liquid and oil in tons of oil equivalent per thousand tons of oil per year. According to the data, it can be seen that the increased specific energy consumption in the winter period is primarily associated with the cost of thermal energy generation (Fig. 2).

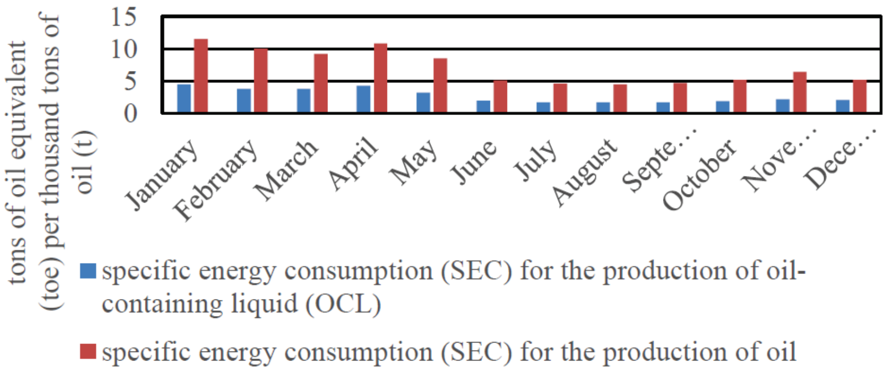

FIGURE 2. *Specific energy consumption*

Difficulties in diesel fuel delivery, the state policy in the field of improving the energy efficiency of production processes, the need to solve environmental problems in oil fields specify the search for alternative methods of heat and electricity generation.

One of the most appropriate solutions to reduce diesel consumption is the use of associated petroleum gas, which inevitably accompanies the oil production process. In the analysis performed, the use of APG significantly reduces greenhouse gases emission into the atmosphere. Moreover, in Russia, the volume of greenhouse gas emissions due to APG flaring is more than the total amount of the fields of Nigeria, Iraq and Iran. There are objective reasons for this related to oil production, distance of domestic fields from settlements – potential energy consumers.

In Russia, APG is used primarily for oil heating in special process furnaces at the stages of marketable product obtaining and during preparation for transportation. However, such furnaces do not provide heat recovery for a system for exhaust gases, the temperature of which reaches 583°C. The use of gas-water heat exchangers widely used at compressor stations would provide the rotational field camp and production facilities with thermal energy, thereby reducing diesel fuel costs. However, currently, for heating, its own hot-water boiler-house using diesel fuel is used, and electric heaters are used at distant sites (Fig. 3).

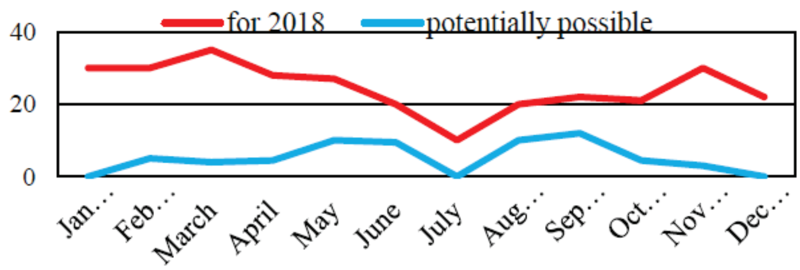

FIGURE 3. *The use of gas-water heat exchangers widely used*

The boiler house also is not provided with the heat recovery system, while significant heat losses are associated with the above-ground laying of heating networks, poor insulation and non-compliance of burning characteristics of rotational field camps enclosing structures with the current energy saving requirements (Fig. 4).

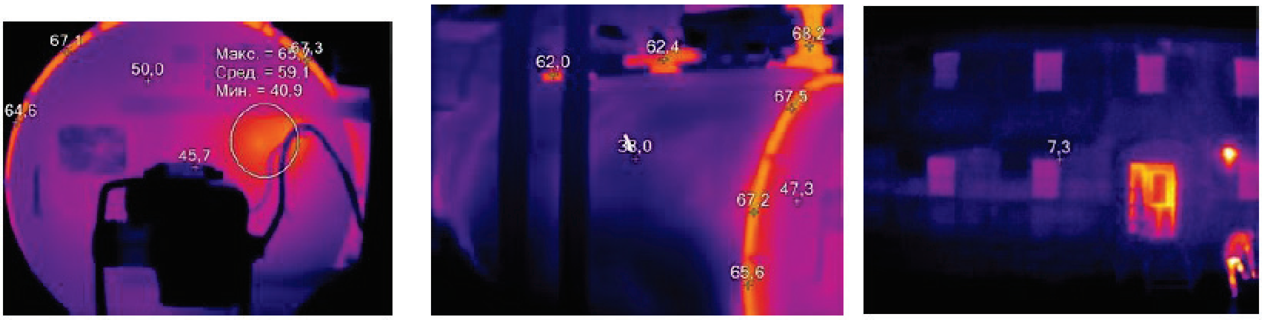

Figure 4. *Modern automated heat points with weather control*

As a result, excessive consumption of thermal energy also leads to an excessive consumption of diesel fuel. In addition, to reduce thermal energy consumption, it is possible to use modern automated heat points with weather control.

When using gas power plants, currently the gas turbine exhaust gases with a temperature of about 500°C are removed without recovery, increasing thermal pollution in the atmosphere. In addition, the non-regenerative cycle has a rather low efficiency (28-32%). In order to save energy, it is proposed to use a regenerative cycle to heat cyclic air, which is also widely used in gas turbine units for gas blower driving at compressor stations of gas mains (Fig. 5). The use of the regenerative cycle according to the analysis will decrease the specific consumption of fuel gas corresponds to an increase in efficiency up to 37%.

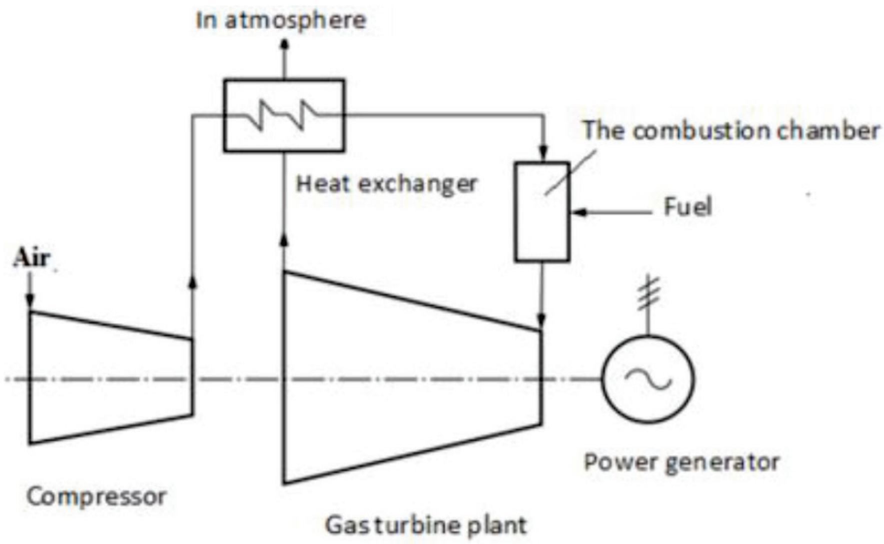

FIGURE 5. *Regenerative cycle*

Another possible vector of energy saving in the development of energy resources in the oil field is the use of the combined cycle providing for reduction of exhaust gases temperature and increase in plant efficiency up to 60%.

There are also potential opportunities for energy conservation in the power supply system of the main production sites of the enterprise. Technical losses in electric networks are load losses (37%) and idle losses (62%) due to uneven energy consumption.

A modern energy-efficient automated induction-resistive system, which allows maintaining the necessary temperature conditions for transportation of oil (40°C,..., 45°C) and water (+10°C) is implemented at the enterprise for electric heating of the main pipelines. However, in order to avoid inefficient energy consumption, the system requires modernization, which consists of installation of additional temperature sensors on each parallel pipeline upstream of a common collector.

In terms of using alternative energy sources at the fields under question, wind generators can be used to generate electric energy, since the facilities are located in the way of the Bolshezemelskaya Tundra with a flat relief. The average wind speed is 4-8 m/s, which determines the feasibility of wind generators application. The calculation for one production site presents that the energy saving potential will be 2102.4 t·hous·kWh/year when installing wind generators with a total capacity of 396 kW.

One of the latest trends in energy saving, in particular in the European Union, is the use of energy cogeneration. Thus, as of 2020, the contribution of cogeneration had planned in the field of energy saving of about 15% and as for reduction of greenhouse gases – 24%. In this case, the share of cogeneration using equivalent energy sources is growing. The feasibility of distributed energy application is based on the conventional selection of equipment for peak conditions, while the structure of energy consumption is uneven. The use of distributed energy based on gas engine generator plants (GEGP) with gas-diesel engines and waste modules is a particularly rational solution for experiencing power shortages of oil fields development. Starting from the production drilling stage, this solution will allow stopping usage of boiler houses. The modular technology will provide for the possibility of a gradual increase in generators and energy consumers, and will make it possible to replace the electrical heating of pipelines with heat using antifreeze.

However, distributed power generation does not currently exclude the need for the delivery of diesel fuel, preparation for the respective generators of fuel gas energy (APG), "crude" oil or its highly viscous derivative products. To solve this problem, it is proposed to use the well-known Stirling heat engine, which does not require special fuel preparation and uses any source of heat, such as solar energy, associated petroleum gas.

The Stirling thermodynamic cycle is based on the periodic heating and cooling of the working fluid, with energy extraction from the resulting pressure change.

External heat supply is carried out through a heat-conducting wall. The working fluid is in an enclosed space during operation.

Among the advantages of Stirling engines, the simple design, economical operation, environmental friendliness can be noted. However, bulkiness and material consumption, inertia when changing the heat flux, the need to create high pressures introduce limitations in the use of Stirling engines.

The energy-saving technologies associated with the need for temperature stabilization of rocks in permafrost conditions to avoid deformation of production wells and potential emergencies have the special place in the development of oil fields.

Permafrost rocks in the Bolshezemelskaya Tundra of the Nenets Autonomous Area occupy almost the entire central and northeastern parts of the district –95%. The thickness of permafrost rocks reaches 500 meters, the temperature ranges from −5°C to −2°C.

Currently, the following technical solutions are used to prevent permafrost thawing: strapping and suspension of casing strings, thermal insulation of casing strings and construction of seasonal cooling devices (heat pipes). A more reliable method to prevent soil from thawing is to use geothermal heat pumps, while heat can be used for heating and hot water supply facilities.

Conclusion

The use of the proposed energy-saving technologies in the operation of oil fields will allow reducing costs for fuel, amount of hazardous emissions and heat pollution of the atmosphere.

Conflicts of Interest: The author declares no conflict of interest.