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# Improvement of energy efficiency and environmental safety of thermal energy through the implementation of contact energy exchange processes

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**Abstract** Energy efficiency improvement and ecological safety of heat power plants are urgent problems, which require scientifically grounded approaches and solutions. These problems can be solved partly within the presented heat-and-power cycles by including contact energy exchange equipment in the circuits of existing installations. A significant positive effect is obtained in the contact energy exchange installations, such as gas-steam installation 'Aquarius' and the contact hydrogen heat generator that also can use hydrogen as a fuel. In these plants, the efficiency increases approximately by 10–12% in comparison with traditional installations, and the concentration of toxic substances, such as nitrogen oxides and carbon monoxide in flue gas can be reduced to 30 mg/m$^3$ and to 5 mg/m$^3$, respectively. Moreover, the plants additionally 'generate' the clean water, which can be used for technical purposes.

**Keywords:** Thermal efficiency; Heat generator; Energy consumption; Contact hydrogen; Contact energy exchange

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### Nomenclature

| | | |
|---|---|---|
| $C$ | – | temperature, °C; |
| CHHG | – | contact hydrogen heat generator; |
| $t_{fg}$ | – | flue gas temperature, °C |
| $Q_{HHV}$ | – | higher heating value, J/kg |
| $Q_{LHV}$ | – | lower heating value, J/kg |
| $Q_m$ | – | density of irrigation, m$^2$/s |
| $q_{fg}$ | – | loss of physical heat through the dry flue gas, J/m$^3$ |
| $x_{fg}$ | – | moisture content in flue gas, kg/kg |

#### Greek symbols

| | | |
|---|---|---|
| $\alpha$ | – | average heat transfer coefficient |
| $\varphi$ | – | specific coefficient of energy transformation |
| $\omega$ | – | gas flow rate |

# 1 Introduction

The modern energy community faces a global problem of increasing energy efficiency and environmental safety of energy production with minimum expenses. Different methods and ways to solve this problem are aimed at obtaining the maximum effect with a minimum payback period simultaneously. In heat and power engineering, where fuel and ecological components significantly influence the payback period it is of particular importance.

This study is focused on the analysis and definition of operating conditions for existing power units and realization technology of contact energy exchange with the purpose of energy efficiency improving and ecological safety of single power objects.

A significant positive effect is obtained in the contact energy exchange installations developed in the National Technical University of Ukraine, at Igor Sikorsky Kyiv Polytechnic Institute, such as gas-steam installation ‘Aquarius’ and the contact hydrogen heat generator (CHHG) that also can use hydrogen as a fuel.

Scientists of National Technical University of Ukraine, at Igor Sikorsky Kyiv Polytechnic Institute have been engaged in the development of contact energy exchange facilities for more than 25 years [1–6]. These developments have both theoretical and practical implications.

## 2 Implementation of contact energy exchange processes

In order to solve the task, the conditions of implementing the contact energy exchange were studied in the following installations:

- boiler plants operating on natural gas and coal [7,8];
- gas-steam installation 'Aquarius' [6];
- contact heat generators operating on natural gas and hydrogen fuel [4].

Thermal calculations and the efficiency analysis, taking into account the dry and humid parameters of the outgoing flue gas, show a significant difference in its values. In boiler plants, operating on natural gas, the flue gas temperature, $t_{fg}$, is in range from 110 to 150 °C, and the moisture content, $x_{fg}$, within the limits of 0.11–0.12 kg/kg. For these conditions, the loss of physical heat through the dry flue gas, $q_{fg}$, is 195–220 kJ/m$^3$ or 7–9%, and with taking into account the moisture content in flue gas, these losses reach 315–325 kJ/m$^3$ or 11–12%.

Thus, the coefficient of thermal efficiency of the boiler calculated through the lower heating value, $Q_{LHV}$, of the fuel is 90–92% and the coefficient of thermal efficiency of the boiler calculated through the higher heating value, $Q_{HHV}$, of the fuel, taking into account the moisture content of the gas, is 78–81%. The difference between efficiencies corresponds to the difference between the higher and lower heating ability of the fuel, $Q_{HHV}$–$Q_{LHV}$, and equal to 10–12%. This difference is significant and opens wide opportunities for a comprehensive solution of the problem of increasing the efficiency of thermal processes in the boiler, such as:

- reducing the flue gas temperature up to 35 °C, that is less than the dew point temperature and leads to reduction of heat losses down to 4.5%;
- condensation of water vapor from the flue gas, that allows to achieve the increase in boiler efficiency rating to (78–81) + (10–12) = 88–93% (Tab. 1) [5].

An integrated solution is the implementation of contact energy exchange between the flows in a particular power unit.

To all, in the preliminary studies of the contact energy exchange processes, additional positive effects that increase the ecological purity of energy transformations and contribute to obtaining excess technical water,

Table 1: Effect of flue gas temperature and moisture content on the efficiency of the boiler.

| Temperature of flue gas, °C | Moisture content, kg/kg | Physical heat loss with flue gas, kJ/m$^3$ | Heat loss taking into account the moisture content, kJ/m$^3$ | Physical heat loss with flue gas, % | Heat loss taking into account the moisture content ($Q_{HHV}$), % | Heat loss taking into account the moisture content ($Q_{LHV}$), % | Thermal boiler efficiency, % | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | $Q_{HHV}$ | $Q_{LHV}$ |
| 110-150 | 0.11-0.12 | 195-220 | 315-325 | 7-9 | 11-12 | 18-21 | 90-92 | 78-81 |
| 35 | 0.11-0.12 | 55-60 | — | 4 | — | 5 | 106** | 95* |

* – the efficiency calculation takes into account the losses of physical heat of the flue gas without vapors condensation, $Q_{HHV}$;
** – the efficiency calculation takes into account the losses of physical heat of the flue gas with vapors condensation, $Q_{LHV}$.

have been recorded in both gas-steam installation 'Aquarius' and contact heat generator. Thus, it is advisable to develop and improve the technologies for the implementation of contact energy exchange processes in individual heat supply systems as well as in cogeneration transformation systems for the chemical fuel energy with high efficiency, environmental safety and additional positive effects.

The implementation of contact energy exchange technologies into coal-fired power boilers is a particularly urgent task in connection with the acute need to save expensive organic fuels and ensure indicators of environmental cleanliness of energy production. The solution of this task in such boilers is possible with using the combustion catalysts in the furnace [7,8] and installation of the contact mixer at the boiler outlet.

In the first case, the injection of the catalyst into air and the active combustion of coal by increasing the area and volume of the contact energy exchange in the combustion zone of coal dust with oxygen molecules and the evaporated catalyst accelerate and improve the combustion process. This leads to a sizeable decrease of time of the fuel-air mixture in the combustion zone and reduction of the toxic nitrogen oxides, $NO_x$, concentration in flue gas. In the second case, the use of a contact mixer allows us to obtain a synergistic effect. That is the energy efficiency increasing by reducing flue gas temperature and enhancing the environmental effect of cleaning of gases from toxic components due to direct contact between gas and water. The implementation of such contact energy exchange in coal and gas boilers requires additional experimental studies.

The beneficial use of the condensing heat flow any vapor produced after combustion is the thermodynamic basis for increasing the energy efficiency of such heat exchangers (Fig. 1).

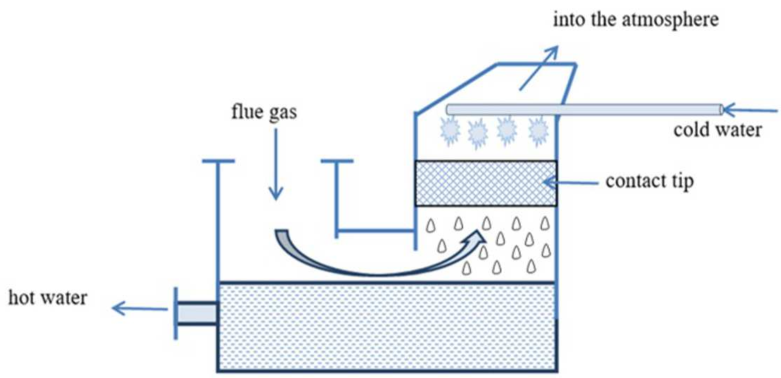


Figure 1: Principle of technological scheme of direct contact energy exchange between flue gas and water.

In the gas-steam installation 'Aquarius' contact energy exchange occurs due to the use of a contact capacitor providing isothermal condensation, and in the gas-steam installation 'Aquarius' contact implementation of energy occurs in the capacitor, wherein another important process occurs – water formation.

Active hydrogen 'liberated' during the natural gas combustion reacts chemically with air oxygen forming $H_2O$. For example, the gas-steam installation 'Aquarius' with a capacity of 16 MW can generate up to 30 tons of water per day under favorable conditions.

The gas-steam installation 'Aquarius' is implemented on the base of a 10 MW gas turbine with steam supply into the combustion chamber. This steam supply increases turbine power up to 16 MW. Water vapor is obtained in the cycle of installation due to the use of the flue gas heat. After the steam generator, flue gas comes into the condenser where contact energy exchange takes place and additional technical water is generated.

The first 'Aquarius' was installed in 2003. The gas compressor station 'Stavishchenskaya' in the system of trunk gas pipelines, which were intended for transportation of natural gas from Russia to European countries was selected as the installation site.

Contact heat generators are the prominent examples of the use of contact energy exchange [4]. These heat generators provide high heat exchange characteristics of the heat exchange surface, which allows us to cool flue gas down to 35 °C. This temperature is much lower than the dew point temperature and improves the process of vapor condensation from combustion products under any thermal loads. It is useful to use the heat of condensation for heating water and to increase the indicators of ecological purity of energy transformations.

Relying on the positive effects of direct contact energy exchange, the authors developed a heat generating plant –CHHG. The main feature of CHHG is the use of hydrogen fuel for heat production in heating and hot water supply systems for consumers. The main positive features of using hydrogen in CHHG are the following:

- coefficient of thermal efficiency can reach 106% (based on the $Q_{LHV}$ of hydrogen combustion);
- specific coefficient of energy transformation, $\varphi$, can reach up to 7–8 (for the heat pump system, the best result is $\varphi = 5$);
- high purity of heat production is characterized by the absence of carbon monoxide (CO = 0) and the concentration of nitrogen oxide emissions $NO_x$ is at the level of 10–20 mg/m$^3$;
- 'generation' of additional technically clean water reaches 25 liters per hour;
- cost price of 1 Gcal/h of heat is 5–7 times less in comparison to boilers operated with natural gas.

Thus, CHHG is able to create a new heat generation platform to provide consumers with heat supply and domestic hot water heating. High indicators of energy efficiency and environmental safety of heat production in CHHG using contact energy exchange technologies are an objective basis for the commercial development of residential CHHG of various capacities and their introduction into public supply system. At the same time, objective prerequisites arise for the implementation of the principle of ecological balance [9] and the new energy-ecological paradigm of energy production in thermal power engineering [10].

The implementation of contact heat exchange technology in existing boilers operating with natural gas is possible with various designs of direct contact devices installed in the outlet of chimney (Fig. 2).

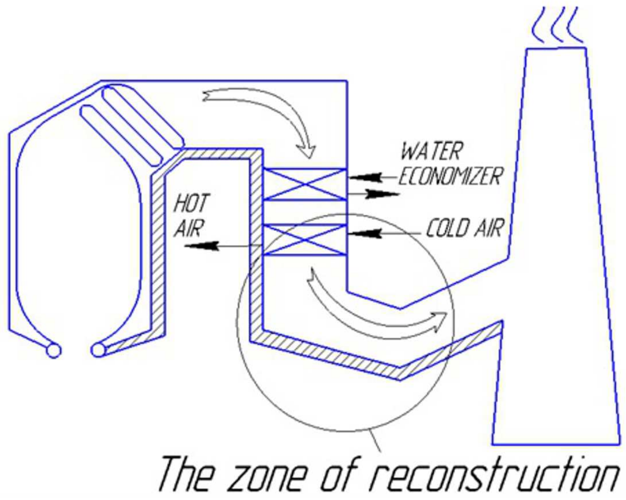


Figure 2: Scheme of a heat exchanger realising the technology of direct contact heat exchange.

The basic design of a contact heat exchanger is shown in Fig. 3.

The experimental data of dependence of the average heat transfer coefficient, $\alpha$, on gas flow rate, $w$, and density of irrigation, $Q_m$, for various cases of thermal mass exchange in such equipment are presented in Figs. 4 and 5.

For coal boilers implementation of the contact energy exchange technologies is an especially urgent task in connection with exigence of economy of expensive organic fuel and supplying the ratings of ecological power production cleanliness.

The solution of the problem of increasing energy-efficiency in coal-fired boilers is possible with using a combined approach: injection of the catalyst into the furnace during the combustion process and the implementation of the contact energy exchange technology at the boiler outlet (Fig. 6).

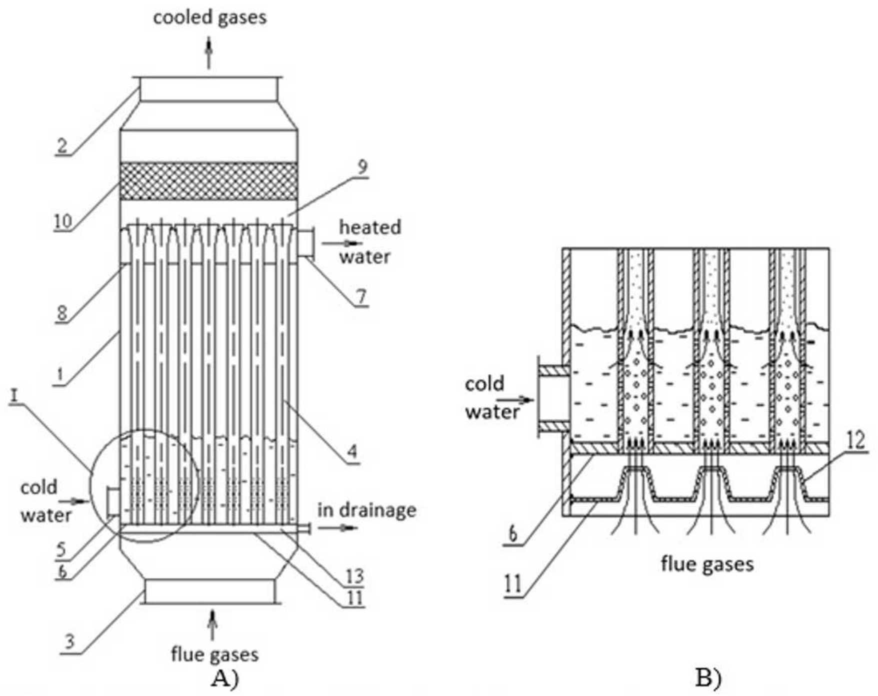


Figure 3: Outline of implementation of contact energy exchange (A) and movement of liquid and gas (B) in heating apparatus for small capacity boiler: 1 – frame, 2 – top tube, 3 – bottom tube, 4 – punched pipes, 5 – cold water supplying tube, 6 – bottom tube panel, 7 – outlet of heated water, 8 – top tube panel, 9 – chamber of water collection, 10 – separator, 11 – additional tube panel, 12 – confuses, 13 – drainage chamber with confuses.

In the first case, the injection of the catalyst into air and the active combustion through increasing the area and volume of the contact energy exchange of coal dust with oxygen molecules, and the evaporated catalyst in the combustion zone improve the combustion process. This leads to a sizeable decrease of time in which the fuel-air mixture staying in the combustion zone and reduction of the concentration of toxic nitrogen oxides $NO_x$ in flue gas.

In the second case, the use of a contact mixer allows us to obtain a synergistic effect. That is the energy efficiency increasing by reducing flue gas temperature and enhancing the environmental effect of cleaning off gases from toxic components due to direct contact between gas and water.

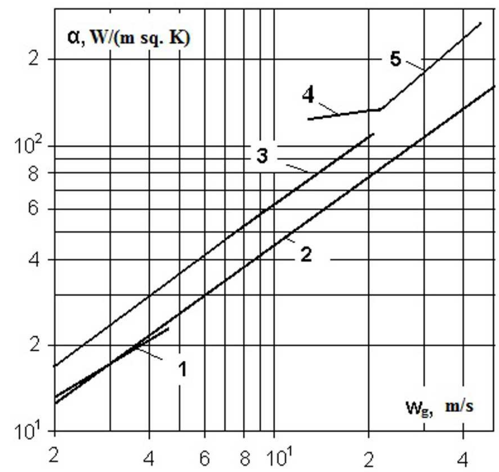


Figure 4: Dependence of the average heat transfer coefficient, $\alpha$, on the gas flow rate, $\omega$, for various cases of thermal mass exchange: 1 – Rashing's ceramic ring, 2 – dry tube, 3 – thermal mass exchange on porous nozzle (descending direct flow), 4,5 – ascending direct flow).

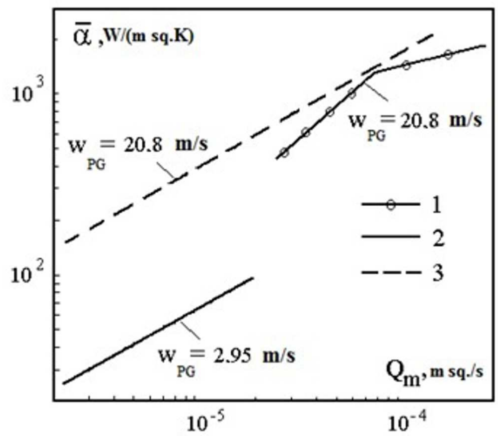


Figure 5: Dependence of the average heat transfer coefficient, $\alpha$, on the density of the irrigation, $Q_m$, for various vases of thermal mass exchange: 1 – contact thermal mass exchange at unidirectional ascending flow of gas-steam and liquid mix, 2 – contact thermal mass exchange at countercurrent flow of gas-steam and liquid mix on porous nozzle, 3 – conventional dependence (extrapolation of the counter flow).

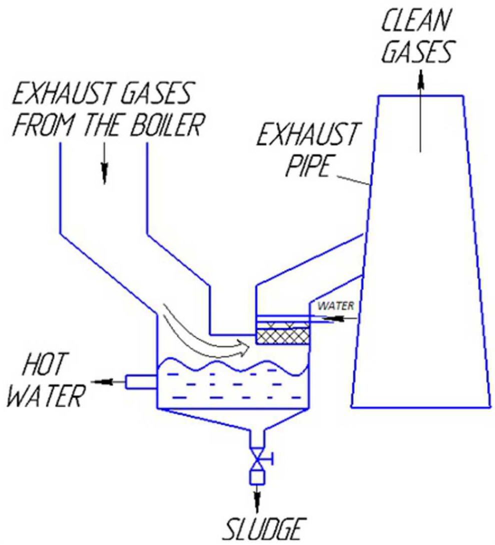


Figure 6: Scheme of implementation of direct contact energy exchangein coal-fired boilers.

# 3 Conclusions

1. Power plants using direct contact energy exchange can significantly improve the energy and environmental indicators of energy conversion and the generation of electrical and heat energy for individual and decentralized energy consumption. They open a wide horizon of environmentally friendly power generation.

2. Preliminary studies of contact energy exchange processes have shown us additional positive effect that increases the ecological purity of energy transformations and contribute to the production of excess technically pure water (GPU 'Aquarius', contact heat generator TWAC).

3. The feasibility of developing and implementing devices and installations with the application of contact energy exchange processes for boilers has been proved through calculations and experiments. Particularly expedient is using of contact energy exchange equipment for coal-fired boilers, since this allows us obtaining a flue gas with a high level of cleaning from both toxic CO and $NO_x$ components, as well as from coal dust and ash.

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