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STUDY OF HEAT-RECOVERY SYSTEMS FOR HEATING AND MOISTURING COMBUSTION AIR OF BOILER UNITS

Introduction. *One of the ways to save natural gas and to improve the environmental conditions in the municipal heat-power engineering is to use progressive technologies for recovering the heat of flue gases from boiler plants, in which the condensation mode of operation of heat-recovery equipment is implemented. To increase the ecological effect in some heat-recovery systems, a humidification process of the combustion air occur. This lowers the combustion temperature of the fuel and reduces the concentration of nitrogen oxides in the combustion products.*

Problem Statement. *At humidifying combustion air, the boiler exhaust-gases are characterized by high moisture content. In the known calculation methods, there are no data on heat transfer under these conditions. This is a problem for conducting thermal calculations of such installations.*

Purpose. *Establishing patterns of heat transfer at an increased moisture content of exhaust-gases in heat-recovery equipment, consisting of bundles of transverse-finned pipes, and determining the main parameters of the proposed complex installation.*

Materials and Methods. *Experimental studies of heat transfer were carried out on a specially created stand. For the thermal and hydraulic calculation of a heat-recovery installation, known calculation methods were used, taking into account the experimental data obtained.*

Results. *The laws of heat transfer during deep cooling of exhaust-gases with moisture content X = 0.15—0.30 kg/kg d.g. are established. The thermal, hydraulic and operating characteristics of the proposed complex heat-recovery installation with heating and humidification of the combustion air in different modes of operation of the boiler are determined. This installation has been introduced; its tests have been carried out, which have confirmed high thermal and environmental efficiency.*

Conclusions. *The application of the proposed complex heat-recovery unit allows increasing the coefficient of the use heat of fuel of boiler depending on its operating mode by 13—20%.*

Keywords: heat-recovery of exhaust-gases, increased moisture content, condensation mode, heat-exchange, efficiency use of fuel, and reduction of harmful emissions.

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Currently, in Ukraine, due to the need to reduce fuel consumption caused by the steady increase in its cost and strengthening of requirements to reduce environmental pollution, the development of energy-saving and environmental technologies for fuel-fired facilities has received increased attention. In particular, technologies of deep heat-recovery from flue-gases of boiler plants are used in municipal heat-power engineering, which significantly increases the thermal efficiency of these plants by raising efficiency and improving their environmental performance mainly due to lower fuel consumption [1—7]. Herewith, the deeper the flue-gases are cooled, the higher is the thermal and ecological effect of heat-recovery. The technologies applied often use heat-recovery systems destined to heat the return heat-network water and combustion air before they enter the boiler.

In connection with the planned trend to tighten the requirements for the reduction of nitrogen oxide emissions from boiler plants, last time heat-recovery technologies have been developed, in which an increased environmental effect is achieved by a significant decrease of these emissions with boiler's flue-gases. This effect is due to the use of a part of the heat of the exhaust-gases of the boiler to heat water for humidifying the combustion air [8—10]. The supply of humidified air into the furnace of the boiler leads to a decrease of the temperature in its combustion space and, as a result, to the suppression of the formation of nitrogen oxides. A feature of boiler plants with such heat-recovery systems is the increased moisture content of flue-gases.

For heating and moistening the combustion air, the Institute of Technical Thermophysics has proposed a complex heat-recovery system [11]. Its schematic circuit is shown in Fig. 1. This installation uses surface water heat exchangers for various purposes and a contact apparatus for heating and humidifying the combustion air. Surface heat exchangers are used to heat by cooling the exhaust-gases of the circulating water of this installation (*4, 5*), to heat by this water the air at the entrance (*1*) and exit (*3*) of the contact chamber (*2*), to preheat the exhaust-gases [12] at the exit from the complex heat-recovery system (*6*). The surface of water heat exchangers are bundle of finned bimetallic pipes (steel base and aluminum transverse fins), and the contact exchanger is a filling of corrugated polyvinyl chloride (PVC) plates.

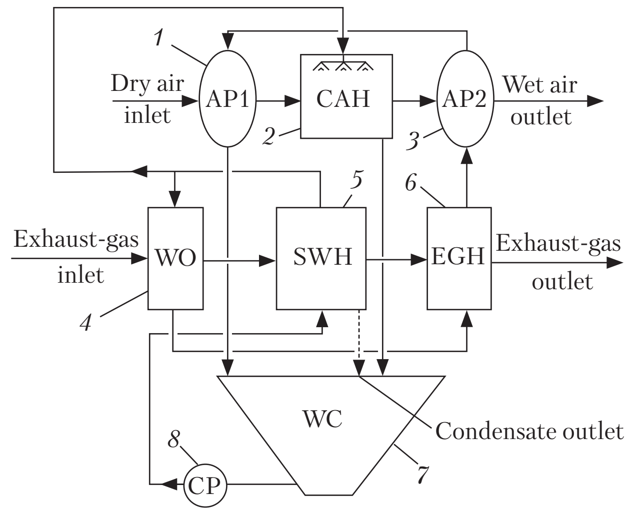

Fig. 1. Schematic circuit of the complex heat-recovery installation for heating and humidifying the combustion air: *1* — first air preheater; *2* — contact air heater; *3* — second air preheater; *4* — water-overheater; *5* — surface water heater; *6* — exhaust-gas heater; *7* — water collector; *8* — centrifugal pump; AP1, AP2, WO, SWH, EGH — water heat-exchangers from finned bimetallic pipes bundles; CAH — contact chamber with a filling of corrugated (PVC) plates

During the operation of such complex heat-recovery systems, as noted, the flue gases used in them are characterized by increased moisture content (0.15—0.30 kg/kg dry gases). In the well-known computational methods [13], there are no data regarding the heat transfer patterns in bundles of transverse-finned tubes in the condensation mode at this moisture content.

The purpose of this work is to establish patterns of heat transfer in bundles of transversely finned tubes from which water heat exchangers are completed, by conducting experimental studies and determining on their basis the main parameters of the proposed integrated installation.

The studies were carried out on the experimental bench, whose scheme, description of work and characteristics of pipes and tube bundles are given in [14]. Data on the main quantities studied on the experimental bench are presented in Table 1.

In the course of the research, the average values of the total heat transfer coefficient α_g over the surface were determined depending on the values of mode and geometric parameters given in Table. 1. The averaged over the surface values of the Nusselt numbers Nu_g from the side of the gases to be determined in the course of the research were presented as the sum of the Nusselt numbers Nu_d and Nu_c in the absence and presence of condensation of water vapor contained in the exhaust-gases:

$$Nu_g = Nu_d + Nu_c. \qquad (1)$$

In this case, the number Nu_d was calculated using the known methods for purely convective heat exchange.

Characteristic results of the performed experimental studies are shown in Fig. 2 and 3. Here are presented the dependences of the number Nu_c on the dimensionless temperature of the heated water Θ and the number Re_g. At the same time

Table 1. **The Studied Parameters and Range of Their Variation**

Parameter	Dimension	Symbol	Value range
Inlet exhaust-gas moisture content	kg/kg d.g.	X_{in}	0.15—0.30
Inlet exhaust-gas temperature	°C	t^g_{in}	100—150
Inlet water temperature	°C	t^w_{in}	5—50
Average Reynolds number for exhaust-gas	—	Re_g	5000—10000
The number of rows of tubes in the bundle	—	M	6—15
Diameter of fins	m	D	0.049—0.053
Diameter of base for finning	m	d	0.029—0.031
Fin spacing	m	S_f	0.003—0.005

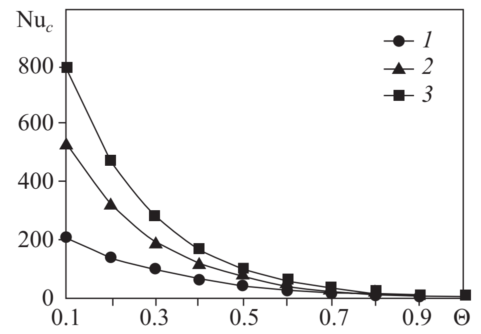

Fig. 2. The dependence of the number $Nu_c = f(\Theta)$ at Re_g = = 8000: *1* — X_{in} = 0.15; *2* — 0.25; *3* — 0.30 kg/kg d.g.

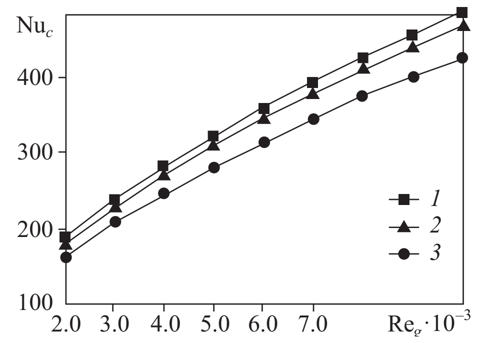

Fig. 3. The dependence of the number $Nu_c = f(Re_g)$: *1* — X_{in} = 0.15 kg/kg d.g., Θ = 0.172; *2* — X_{in} = 0.25 kg/kg d.g., Θ = 0.153; *3* — X_{in} = 0.30 kg/kg d.g., Θ = 0.146

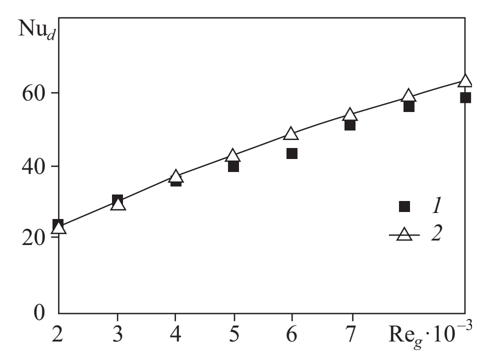

Fig. 4. Dependence $Nu_d = f(Re_g)$: *1* — the obtained experimental data; *2* — calculated data according to [15]

the temperature Θ was defined as the ratio the average water temperature t^w_m and the dew point temperature t_{dp}.

According to the experiments, a generalized dependence was obtained:

$$Nu_c = A \cdot Re_g^{0,6} \exp(B \cdot \Theta), \qquad (2)$$

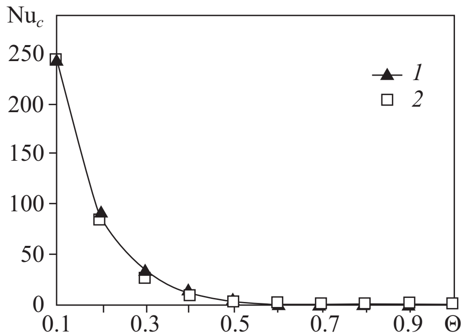

Fig. 5. Dependence $Nu_c = f(\Theta)$: *1* — the obtained experimental data; *2* — experimental data on [14]

where A, B are values dependent on moisture content X:

$$A = 8.15 \cdot e^{2.99 \cdot X} - 10.17; B = 4.71 \cdot e^{-9.65 \cdot X} - 10.86.$$

To assess the reliability of the data obtained, they were compared with the results of other researches. Fig. 4 shows the results of such a comparison at dry heat exchange (without water vapor condensation). Here are the characteristic data on the number of Nu_d depending on the change in Re_g.

Fig. 5 illustrates the dependence of Nu_c on the dimensionless temperature Θ at heat-exchange with condensation for boilers without humidification of the combustion air.

The comparative analysis of these results suggests that the discrepancy in the data does not exceed 8.5%. Thus, we can conclude that the experimental studies carried out allowed us to obtain reliable results to summarize the laws of heat transfer and thus expand the understanding of heat transfer and mass transfer during deep cooling of vapor-gas mixtures with initial moisture content X = 0.15—0.30 kg/kg d.g .

In order to determine the performance characteristics of the complex heat-recovery system for heating and humidifying the combustion air (see Fig. 1), taking into account the experimental data obtained, computational studies of the «boiler — heat-recovery installation» system were carried out. These calculations are performed depending on the load of the boiler, since an increase in the temperature of the combustion air and its humidification in the surface-contact part of the heat-recovery system affect the combustion temperature, the heat balance of the boiler, the output parameters of exhaust-gases, fuel consumption, boiler efficiency, etc. Therefore, the boiler and the

Table 2. **Regime Parameters of the Heat-Recovery Unit at 100% Boiler Load (natural gas consumption G_{ng} = 70.17 m³/h; coefficient of excess air ά =1.2)**

Parameter	Dimension	Heat generating part			Heat consuming part			
		WO	SWH		EGH	AP1	CAH	AP2
			I level	II level				
Heat productivity	kW	17.7	41.1	21.7	5.4	8.2	61.2	5.7
Water consumption	kg/s	0.20	0.92	0.92	0.20	0.20	0.72	0.20
Inlet water temperature	°C	69.1	58.5	52.8	90.2	77.0	69.1	83.8
Outlet water temperature	°C	90.2	69.2	58.5	83.8	67.2	48.8	77.0
Exhaust-gas (combustion air) consumption	kg/s	0.36	0.36	0.36	0.36	0.29	0.29	0.29
Inlet exhaust-gas (combustion air) temperature	°C	159.3	114.1	64.8	62.0	10.0	37.2	50.0
Outlet exhaust-gas (combustion air) temperature	°C	114.1	64.8	62.0	76.0	37.2	50.0	68.9
Aerodynamic resistance	Pa	41.8	65.2	42.8	33.8	9.1	149.9	15.1
Hydraulic resistance	kPa	0.2	7.9	7.9	0.1	0.1	17.0	0.1
Increase boiler efficiency	%	2.8	6.5	3.5	—	—	—	—

complex heat-recovery unit were considered as interrelated elements of a single system. The peculiarity of this calculation is that the exhaust-gas output parameters of the boiler are input to the heat-recovery installation, and the output parameters of the combustion air from the installation become the input to the boiler.

Studies have been conducted for the system «boiler—heat—recovery installation» with a boiler with a nominal heating capacity of 0.63 MW. Wherein, the boiler efficiency calculated by the highest calorific value of fuel is from 70 to 82%. It was accepted that in the range of heat load of the boiler from 40 to 100% the value of the coefficient of excess air ά in the boiler furnace varies from 1.65 to 1.2, respectively. The heat-recovery system implements a condensation mode of operation of the equipment. Therefore, all calculations are carried out according at the highest calorific value of fuel. The computational studies were carried out on the basis of the Institute of Engineering Thermophysics of National Academy of Sciences of Ukraine method of thermal calculation of surface and contact type condensation heat-recovery exchangers developed in the Department of Thermophysics of Energy Efficient Heat Technologies. For an example, in the Table 2 shows the main performance characteristics of such a calculation at nominal mode of boiler.

The obtained data allowed us to determine the thermal, hydraulic and operating characteristics of the system «boiler — heat-recovery installation» for complex heat-recovery systems with heating and humidification of the combustion air.

According to the results of the research, a comprehensive heat-recovery installation for heating and moistening the combustion air in the boiler house of the branch of PSC «Kyivenergo» at the boiler type E-1.0-9Gn-2 was developed and implemented [16]. Tests of such an installation confirmed its high thermal and environmental efficiency. The payback period of the proposed complex heat-recovery system is up to three years.

Summarizing the foregoing, the following should be attributed to the main scientific results obtained for the first time: regularities of heat exchange in bundles of transversely finned tubes during cooling below the dew point temperature of the exhaust-gases of boilers with a moisture content of X = 0.15—0.30 kg/kg d.g. are established; depending on the change in the operating parameters of the boiler unit, corresponding to the temperature schedule of the boiler house, the design studies of the main performance characteristics of the complex heat-recovery system for heating and humidifying the combustion air at its installation for the gas-fired boiler with a nominal power of 0.63 MW; it is shown that the application of the proposed installation allows increasing the coefficient of the use heat of fuel of boiler depending on its operating mode by 13—20%.

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ДОСЛІДЖЕННЯ ТЕПЛОУТИЛІЗАЦІЙНИХ СИСТЕМ ДЛЯ ПІДІГРІВАННЯ ТА ЗВОЛОЖЕННЯ ДУТТЬОВОГО ПОВІТРЯ КОТЕЛЬНИХ УСТАНОВОК

Вступ. Одним зі шляхів економії природного газу й поліпшення умов довкілля є застосування в комунальній енергетиці прогресивних технологій утилізації теплоти відхідних димових газів котельних установок, в яких реалізується конденсаційний режим роботи теплоутилізаційного обладнання. Для підсилення екологічного ефекту в деяких теплоутилізаційних системах відбувається процес зволоження дуттьового повітря, що зменшує температуру горіння палива та знижує концентрацію оксидів азоту в продуктах згоряння.

Проблематика. При зволоженні дуттьового повітря відхідні гази котла характеризуються підвищеним вмістом вологи. У відомих розрахункових методиках відсутні дані щодо теплообміну за цих умов. Це є проблемою для проведення теплових розрахунків таких установок.

Мета. Встановлення закономірностей теплообміну при підвищеному вологовмісті димових газів в теплоутилізаційному обладнанні, що складається з пучків поперечно оребрених труб, і визначення основних параметрів запропонованої комплексної установки.

Матеріали й методи. Експериментальні дослідження теплообміну проводилися на спеціально створеному стенді. Для теплового та гідравлічного розрахунку теплоутилізаційної установки застосовано відомі розрахункові методики з урахуванням отриманих експериментальних даних.

Результати. Встановлено закономірності теплообміну при глибокому охолодженні димових газів із вологовмістом X = 0,15—0,30 кг/кг сухих газів. Визначено теплові, гідравлічні та режимні характеристики запропонованої комплексної теплоутилізаційної установки з підігріванням і зволоженням дуттьового повітря в різних режимах роботи котла. Розробку було впроваджено, проведено її випробування, які підтвердили високу теплову та екологічну ефективність.

Висновки. Застосування запропонованої комплексної теплоутилізаційної установки дозволяє підвищити коефіцієнт використання теплоти палива котла на 13—20 % залежно від режиму його роботи.

Ключові слова: утилізація теплоти димових газів, підвищений вологовміст, конденсаційний режим, теплообмін, ефективність використання палива, зниження шкідливих викидів.