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8.1 Efficiency of air heat-recovery equipment for glass furnaces

The problem of saving fuel and energy resources is becoming increasingly important for many industrial enterprises in Ukraine. The cost of energy resources for the production of industrial products is quite significant, especially for high-temperature industries [262-264], which include glass-making enterprises that operate glass melting furnaces. At the same time, the majority of fuel-using glass melting furnaces, in order to increase their efficiency, are equipped with regeneration (or recuperation) systems that serve to heat the combustion air. However, the flue gas temperature after such air heating equipment is still too high (usually 300 ÷ 650 ºC [263]).

One of the ways to increase the energy efficiency of glass-making industries, and hence save energy resources, is a deeper utilization of their thermal emissions through the use of heat-recovery technologies. As the main equipment of heat-recovery technologies, for example, glass melting furnaces, hot water heat-recovery units have traditionally been used, in which water is usually heated for heating and hot water supply of glass factories and adjacent residential and industrial facilities. [265-267]. The effectiveness of such technologies is insufficient due to the limited need for heat energy in the form of hot water and the seasonality of its consumption in the heating system. Mostly, the waste heat potential of modern glass melting furnaces is higher compared to that used in traditional heat-recovery technologies for heating water. An increase in the duration of operation of waste heat-recovery systems during the year can be achieved by using it to preheat combustion air before it enters the furnace regenerators.

Until recently, the installation of surface air-heating heat exchangers behind industrial furnaces was problematic due to the significant dimensions and cost of this equipment. However, recently, new designs of air-heating heat exchangers, the socalled terminal heat exchangers, have been developed, which, due to year-round use, can compete with hot water heat exchangers [268].

The aim of the work is to study the efficiency of using fuel heat in heat-recovery systems for recovering waste heat from gas-fired glass melting furnaces by using the developed air-heating heat-recovery exchanger – the terminal recuperator.

To achieve the goal, it was necessary to solve the following research tasks:

- develop software and carry out calculations of the thermal regime of regenerators of glass melting furnaces without the use of heat-recovery systems;
- develop an efficient design of the terminal recuperator;
- perform computational studies of the thermal performance of the system, "regenerator - terminal recuperator" and determine its efficiency indicators.

The well-known methods of thermal calculation of heat exchangers of regenerative and surface types [269, 270], as well as the results of our own studies of the dynamics of the dust content of the working surfaces of heat-recovery units of glass melting furnaces, were used [267].

Computational studies were carried out for regenerative glass melting furnaces for the production of container products. When carrying out these studies, the value of the initial temperature of flue gases at the inlet to the terminal recuperator corresponded to the calculated values of the final temperature of these gases at the outlet of the regenerator when air already heated to a certain temperature enters to the regenerator.

A schematic circuit of the use of the heat of waste gases of a regenerative glass melting furnace for heating combustion air in the terminal recuperator is shown in Fig. 1.

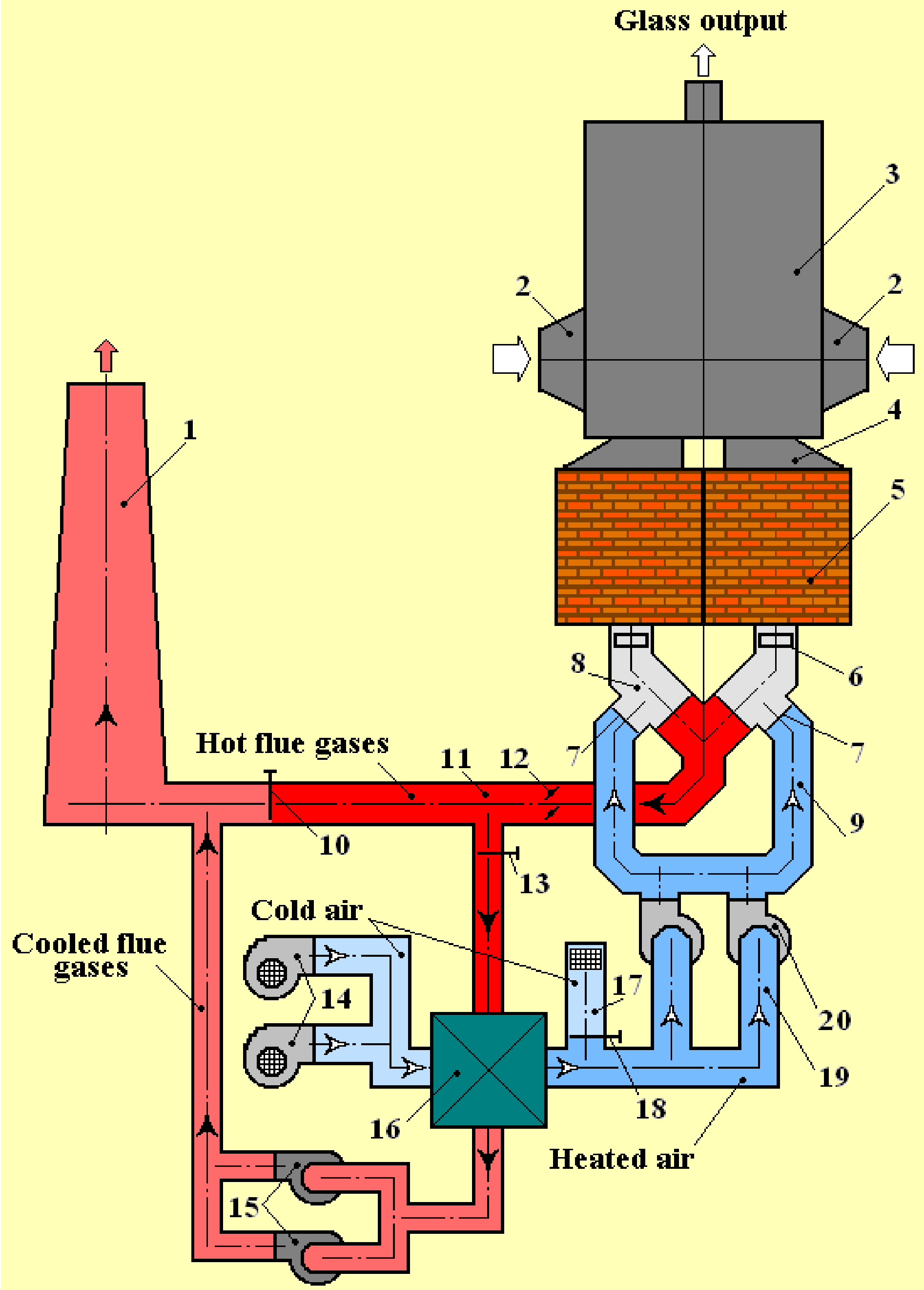


Figure 1. Scheme of waste heat recovery from glass melting furnace:
1 – chimney; 2 – loading pocket; 3 – brewing part of the furnace; 4 – burner device; 5 – regenerator; 6, 7 – transfer and regulating gate; 8 – exhaust-gas channels; 9 – air channels; 10, 13, 18 – shut-off gate; 11 – exhaust-gas ducts; 12 – block of rotary gates; 14, 20 – blowers; 15 – exhaust-gas exhausters, 16 – terminal recuperator, 17 – air intake from the atmosphere; 19 – preheated air duct (from recuperator).

The main initial data for performing thermal calculations of the regenerator and the terminal recuperator are shown in Table 1.

Table 1.

The main initial data of the regenerator and the terminal recuperator

Name of the indicator, dimension	Indicator value
Flue gas consumption, kg/s	2.3
Air consumption, kg/s	2.1
The outlet temperature of flue gases from regenerator (at the entrance to the recuperator), °C	400 ÷ 500
The inlet temperature of air to regenerator, °C	200 ÷ 250
The inlet temperature of air to recuperator, °C	20

In the scheme shown in Fig. 1, the developed terminal recuperator (pos. 16) is used, in which, due to the cooling of the exhaust-gases, air is preheated before it enters the regenerators of furnace. On fig. 2 schematically shows its general view.

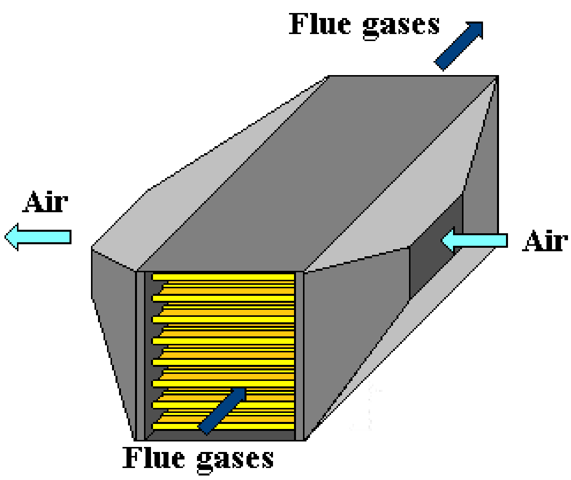
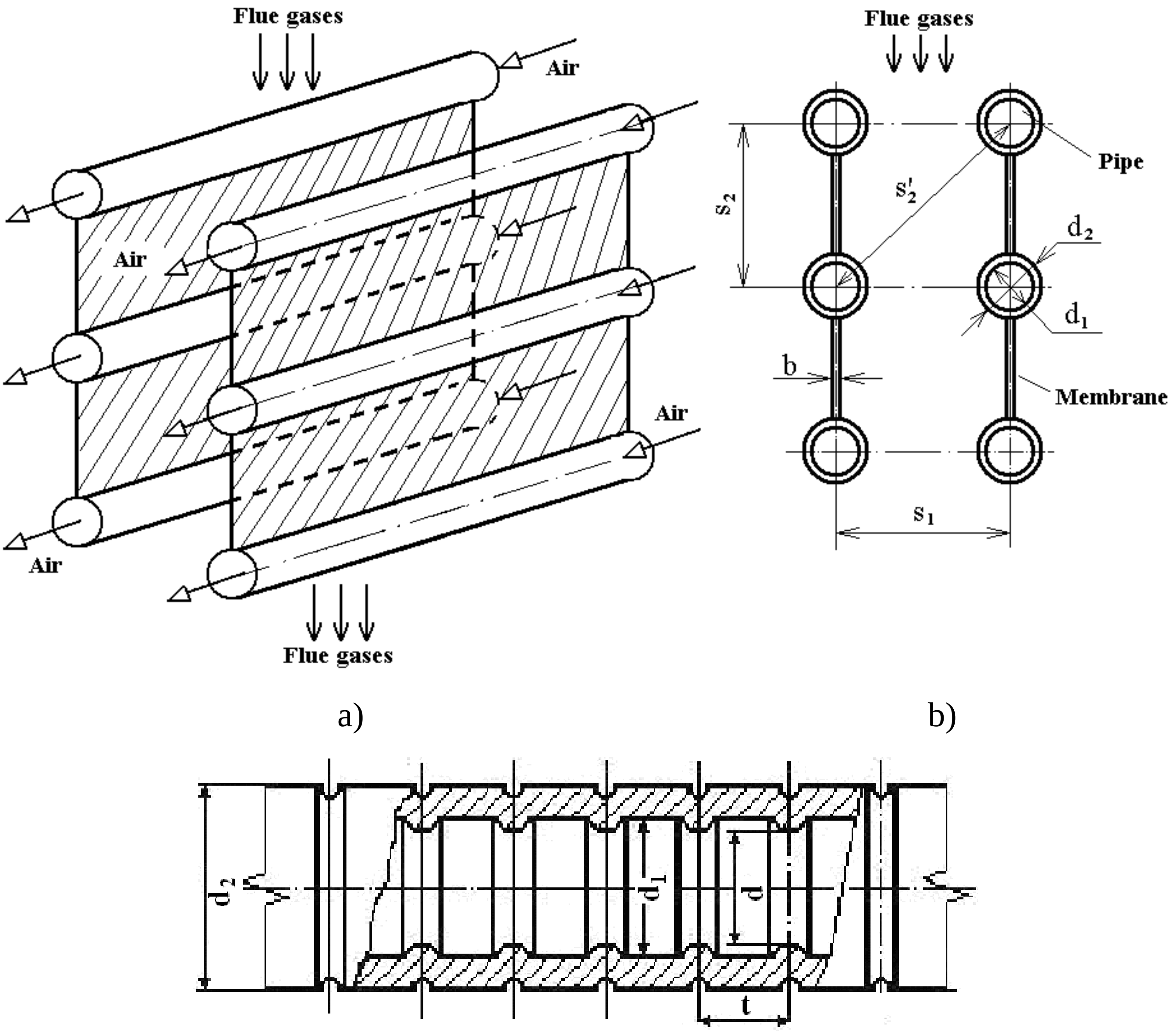


Figure 2. Schematic picture of the terminal recuperator

In the heat exchanger, air is preheated by cooling the exhaust-gases before it enters the furnace regenerator. The heat-exchange surface of this heat exchanger is assembled from packs of panels formed by pipes with membranes on the outer surfaces (Fig. 3 a, b). The panels use pipes with annular heat exchange intensifiers (Fig. 3c). The movement of heat carriers is cross with the passage of air in the pipes, and exhaust-gases in the annulus. In these pipes, the intensification of heat transfer inside the pipes by 1.6 ÷ 1.9 times is ensured with a moderate (compared to other methods of heat transfer intensification) increase in aerodynamic resistance from the side of the heated air.



a) b)

c)

Figure 3. Membrane panels: a) – arrangement of membrane panels; b) – profile of the channel for the passage of flue gases; c) – pipe with annular heat exchange intensifiers

The choice of heating surfaces for furnace air heaters (terminal recuperators) is determined by the characteristics of the exhaust-gases, which are usually characterized by a high level of solid technological carryover [267].

The layout of the heating surfaces from membrane panels provides the formation of slotted channels for the passage of exhaust-gases and the possibility of organizing effective cleaning of the heat exchange surface from the side of gases from possible dust deposits. The design of the recuperator allows it to be used for industrial furnaces with high levels of flue gas dustiness and to periodically clean the heating surfaces [267, 271]. Thermal calculations of the terminal recuperator were carried out at an average level of dust content of working surfaces between cleanings.

When using heat-recovery systems, especially with hot air equipment, there is a problem of choosing structural materials for heat-recovery exchangers. According to the results of studies [267], the temperature of air heating in metal recuperators is limited by the heat resistance of the materials used. In unalloyed metal recuperators, it is advisable to heat the air no higher than 250 °C. When using alloyed steel, the cost of recuperators increases significantly. Obviously, an increase in the level of air heating in the recuperator leads to its rise in price due to an increase in the heating surface, the need to change the flow pattern of heat carriers (counterflow to forward flow) and, finally, the need to manufacture the inlet part of the heat exchanger from heat-resistant alloys or ceramics.

As calculations have shown, in Ukraine the payback period for the introduction of a recuperator for a glass melting furnace is minimal at cold air is heated by 200 °C and does not exceed 0.5 years.

When developing the design of the terminal recuperator, at the preliminary stage of work, studies were carried out due to the need to determine the optimal design parameters of membrane panels (Fig. 3) for various parameters of flow turbulence on the inner surface of the pipes. On fig. 4 shows data on the thermal efficiency of these surfaces depending on the size of the turbulators. Optimal ratios of pipe and knurling parameters correspond to the maximum heat output of membrane heating surfaces. The studies were based on experimental data on heat transfer and hydrodynamics in pipes with annular flow turbulators found in the literature [272].

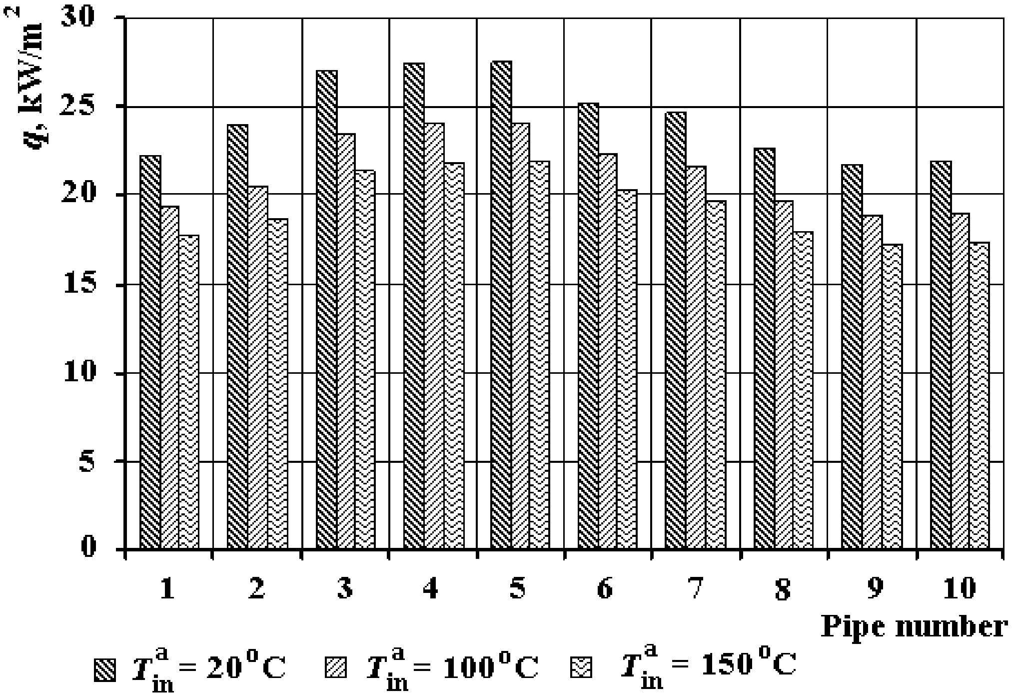


Figure 4. Specific thermal power q of the terminal recuperator depending on the parameters of the turbulators and the initial temperature T_{in}^{a} of the heated air: 1 – d/d_1 = 0.983; t/d_1 = 0.496; 2 – 0.966;0.498; 3 – 0.943; 0.497; 4 – 0.922; 0.523; 5 – 0.875; 0.496; 6 – 0.912; 0.992; 7 – 0.946; 0.998; 8 – 0.944; 1.987; 9 – 0.942; 3.989; 10 – smooth pipe.

In the work, computational studies on the aerodynamic characteristics of the indicated heat exchange surfaces were carried out. On fig. 5 shows the data on the aerodynamic resistance on the air side of bundles of membrane panels from pipes with annular turbulators.

As can be seen from the diagrams, the values of the parameters of the turbulators have a significant impact on the thermal performance of the equipment under study. For the conditions of application of terminal recuperators, pipes No. 3 turned out to be the most successful for use, which provide sufficiently high thermal performance with relatively low aerodynamic resistance. A somewhat lower, but acceptable efficiency in this respect is characterized by heat exchange surfaces with pipes No. 2 and No. 7.

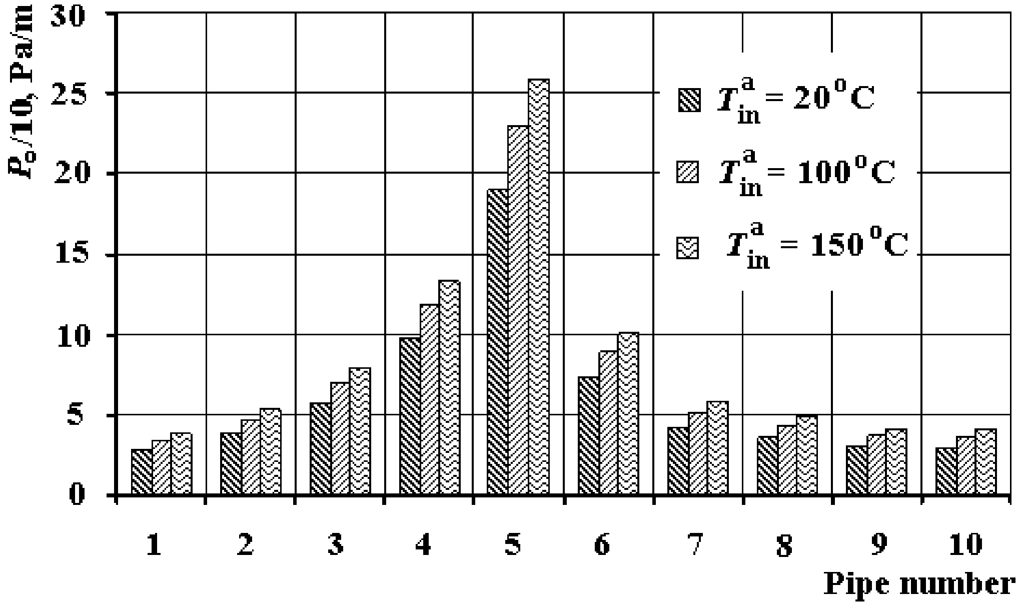


Figure 5. Aerodynamic air resistance P_o of the heat exchange surface of the terminal recuperator depending on the parameters of the turbulators and the initial temperature T_{in}^a of the heated air:

1 – d/d_1 = 0.983; t/d_1 = 0.496; 2 – 0.966; 0.498; 3 – 0.943; 0.497; 4 – 0.922; 0.523; 5 – 0.875; 0.496; 6 – 0.912; 0.992; 7 – 0.946; 0.998; 8 – 0.944; 1.987; 9 – 0.942; 3.989; 10 – smooth pipe.

Consequently, the conducted studies made it possible to determine the optimal parameters of turbulators when they are used in membrane panels of terminal recuperators of furnaces.

Computational studies were carried out on the thermal characteristics of the terminal recuperators for the one shown in Fig. 1 heat-recovery system when using this heat-recovery equipment during the entire period of operation of the furnace. The results of calculations in the characteristic range of ambient temperatures during the year are given in Table 2.

The results obtained indicate that the use of terminal recuperators can significantly increase the efficiency of the furnace by cooling the exhaust-gases leaving the furnace regenerators. As can be seen from Table 2, under the considered conditions during the operation of the terminal recuperators, the waste gases are cooled by 180 °C, and the combustion air is heated by 200 °C.

Table 2.

Technical characteristics of the terminal recuperator

Name of the indicator, dimension	Indicator value
Thermal productivity, kW	430
Flue gas consumption, kg/s	2.3
The coefficient of excess air in gases	1.2
The inlet temperature of flue gases, °C	500
The outlet temperature of flue gases, °C	320
Air consumption, kg/s	2.1
The inlet temperature of air, °C	20
The outlet temperature of air, °C	220
Aerodynamic resistance of gases, Pa	350
Aerodynamic resistance of air, Pa	400
Overall dimensions, mm:	
length	2800
width	1500
height	3200
Mass, t	4200
Efficiency of the regenerator	39.0
Efficiency of the recuperator	9.0
Efficiency of the regenerator with recuperator	48

This makes it possible to reduce the consumption of fuel for the furnace, which is spent on heating the air to a temperature of 200 °C. At the same time, a decrease in fuel consumption per furnace does not directly correspond to an increase in the efficiency of the recuperator, but is somewhat lower. This is due to some decrease in the efficiency of the regenerator when heated air enters it.

Conclusions:

1. It is proposed to use in heat-recovery systems for fuel-using industrial furnaces of a regenerative type new air-heating equipment (terminal recuperator), the

heat exchange surface of which is composed of panels formed by pipes with heat transfer intensifiers on the inside and membranes on the outside. This design makes it possible to effectively clean the working surfaces of the heat exchanger from deposits of process dust contained in the waste gases of the furnace.

2. Rational geometrical parameters of heat exchange intensifiers are determined to ensure high thermal efficiency of the recuperator.

3. It is shown that the use of terminal recuperators in the "regenerator-recuperator" system provides a total increase in the efficiency of the furnace by 48 %, where 39 % is an increase in efficiency in the regenerator, and 9 % – in the recuperator.