The efficiency analysis of the turbo air refrigerators for producing solid carbon dioxide from the boiler combustion products flow

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Abstract. The paper considers the efficiency analysis of the turbo air refrigerators for producing solid carbon dioxide from the boiler combustion products flow. The process of obtaining solid carbon dioxide in the turbo air refrigerating machine was modelled. A numerical study of the process and degree of solid carbon dioxide freezing in the turbo air refrigerating machine was performed. The range of the boiler power characteristics, where the most effective solid carbon dioxide freezing is possible within the technical specifications of the turbo air refrigerating machines, was determined.

Key-words: solid carbon dioxide, fuel combustion products, turbo air refrigerating machine, degree of freezing, crystallization, boiler

1. Introduction
In recent years, much more attention has been paid to developing the technologies and ways to reduce CO₂ emissions. From 75 to 80 % of global CO₂ emissions are caused by burning organic fuels. Under the influence of the multimolecular gases accumulating in the atmosphere, such as water vapour, carbon dioxide, nitrogen oxides, etc., which absorb infrared radiation from the Earth's surface, a greenhouse effect occurs. It contributes to the atmospheric temperature increase, glaciers melting and weather formation disruption. Besides, CO₂ emissions make the greatest contribution to the greenhouse effect (80%).
Carbon dioxide (CO₂) is the main element which huge environmental emissions (about 30 Gt annually [2]) during burning organic energy carriers result in global warming.

The objective of the energy strategy of Russia to 2030 is to establish the effective energy sector that meets both the needs of the growing economy in the energy resources and Russia's foreign economic interests for the country's innovative development.

One of the ways of implementing this objective is to solve the problem of improving the energy and environmental efficiency of the Russian economy and energy including by the structural changing and activating the technological energy saving [3].

These circumstances require the intensification of research on reducing CO₂ emissions.

One of the promising ways to reduce CO₂ emissions into the atmosphere is to freeze it out of the fuel combustion products (FCP) flow expanding in a turbo expander (TE) and subsequently store it in the solid form [1, 6-8].

The efficiency analysis of the turbo air refrigerators (TAR) application for producing solid carbon dioxide from the boilers combustion products flow was carried out in the paper.

Based on the research results, the following tasks were solved:
• the technological process of obtaining solid CO$_2$ from the FCP flow in TAR is presented;
• the degree of CO$_2$ freeze-out of the FCP when using TAR was determined;
• the recommendations on the use of TAR at the heat and power facilities are made depending on the generated heat capacity of boiler units and TAR characteristics.

2. Theory
TARs are used in the industrial plants for obtaining low temperatures (figure 1). The equipment includes a turbocharger (T), a gearbox (G), a rotary heat exchanger (RHE), a turbo expander (TE), a fan (F), drive motors. Atmospheric air is used as a refrigerant.

The operation principle of TARs is as follows: atmospheric air is compressed in the turbocharger with an increase in temperature. Then the air passes into the heat exchanger, where it is cooled by the return flow and enters the turbo expander. In the turbo expander, the air expands and is cooled to the temperature of -80 °C, followed by entering the cold consumer. Then the air enters the rotary heat exchanger where it is heated by the direct flow and released into the atmosphere.

For the application of TAR-11 to produce solid CO$_2$, the air heat exchanger (AHE) with a fan is installed after the compressor and bag filter (BF) used for separating the solid phase of CO$_2$ from the FCP flow is installed after the turbo expander (figure 2).

![Figure 1. The basic scheme of the turbo air refrigerating unit.](image-url)
Figure 2. Turbo refrigerating machine used for CO₂ freezing out of the FCP.

To freeze out the solid phase of CO₂, the expander inlet temperature is required to be equal to the saturation temperature of \( T_S = 180 \text{ K} \) [4]. When the machine reaches this temperature mode, after the extremely non-equilibrium expansion of the FCP in a TE, solid CO₂ will be freezed out [5].

The temperature of the FCP behind the TE stage without CO₂ crystallization is defined by the following formula:

\[
T_{WC} = T_S \left( \frac{p_2}{p_0} \right)^{\frac{(K_{mix}-1)}{K_{mix}}} = 180 \left( \frac{10^5}{2 \times 10^5} \right)(1.392-1)/1.392 = 149.5 \text{ K} \quad (1)
\]

where \( K_{mix} \) is the FCP adiabatic index.

Therefore, it will not be difficult to obtain the saturation temperature at the inlet of the TE without crystallization of CO₂, since the temperature at the inlet of the RHE will be equal to 149.5 K and all the resulting cooling capacity in the TE will be used for cooling the direct flow of the FCP. But as soon as the solid CO₂ freezing process starts, the part of the cooling capacity will be used for CO₂ crystallization heat compensation.

The cooling performance is calculated by the heat balance equation:

\[
Q_{TE} = Q_{RES} + Q_{CHC}
\]

where \( Q_{TE} \) is the TE cooling performance obtained during the FCP extension; \( Q_{RES} \) is the residual cooling performance caused by the temperature difference at the TE inlet and outlet equilibrium temperature \( T_E \); \( Q_{CHC} \) is the cooling performance used for CO₂ crystallization heat compensation.

\[
Q_{TE} = \eta_{TE} G c_{PMX} T_0 \left[ 1 - (1/\pi_{TE})^{K_{mix}-1} \right] \quad (2)
\]

where \( \eta_{TE} \) is the expander efficiency; \( G \) is the flow rate of the FCP; \( c_{PM} \) is the heat performance of the FCP.
\[ Q_{\text{CHC}} = G_S L \]  

where \( G_S \) is the mass of the frozen CO\(_2\).

\[ Q_{\text{RES}} = (G - G_S)c_{\text{PMIX}} (T_0 - T_E) \]  

where \( T_E \) is the equilibrium temperature.

When solving the last equations with relation to \( T_E \), the following formula is obtained:

\[ T_E = T_0 - \frac{Q_{\text{TE}} - G_S L}{(G - G_{\text{TE}})c_{\text{PMIX}}} \]  

Mass of the frozen CO\(_2\) is calculated by the equation:

\[ G_S = G_C - \left( G_0 \frac{\mu_C}{\mu_0} r_C + G_N \frac{\mu_C}{\mu_N} r_C \right) / (1 - r_C) \]  

where \( \mu_C, \mu_O, \mu_N \) is the molecular mass of the gas mixture; \( G_C, G_O, G_N \) is the initial mass of the FCP components; \( r_C \) is the volumetric concentration of CO\(_2\).

Volumetric equilibrium concentration of CO\(_2\) is defined by the following formula:

\[ r_C = \exp(23.957 - 3163.72 / T_E + 0.06577 \cdot T_E - 3.667 \cdot 10^{-4} \cdot T_E^2 + 6.661 \cdot 10^{-7} \cdot T_E^3) / p_0 \]  

3. Results and discussion

The initial data are as follows:

- FCP pressure at the TE inlet is \( p_0 = 2 \times 10^5 \) Pa, the pressure behind the TE is \( p_2 = 1 \times 10^5 \) Pa.
- mass concentration of CO\(_2\) is \( g_C = 0.2 \)
- FCP consumption is \( G = 0.32 \) kg/s
- FCP mass composition at the TE inlet is \( G_C = 0.064, G_O = 0.24, G_N = 0.0064 \)
- turbo expander efficiency is \( \eta = 0.75 \)
- FCP heat capacity is \( c_{\text{PMIX}} = 974.3 \) J/(kg K)
- specific heat of crystallization is \( L = 584200 \) J/(kg K)

1. The cooling performance of the TE is defined by the equation (2)

\[ Q_{\text{TE}} = 7463.7 \text{ W} \]

2. The equilibrium temperature is calculated according to the equations (5, 6) by the method of successive approximations taking into account that \( T_2 < T_E < T_0 \).

Let us accept that \( T_E = 172.7 \) K

The volumetric equilibrium concentration of CO\(_2\) according to the equation (7) is:

\[ r_C = 0.124 \]

3. Mass of the frozen CO\(_2\) according to the equation (6) is:

\[ G_S = 0.009 \text{ kg/s or } G_S = 32.4 \text{ kg/h} \]

The equilibrium temperature according to the equation (5) is:

\[ T_E = 172.7 \text{ K} \]

The temperature \( T_E \) corresponds to the previously accepted value.

4. The cooling performance used for CO\(_2\) crystallization heat compensation is:

\[ Q_{\text{CHC}} = G_S L = 5255.6 \text{ W} \]

5. The residual cooling performance is:

\[ Q_{\text{RES}} = 2208.1 \text{ W} \]

6. The specific yield of solid CO\(_2\) is:
The degree of CO₂ freezing out of the FCP is:

\[ \frac{G_s}{G} = 0.009/0.32 = 0.028 \]

7. The degree of CO₂ freezing out of the FCP is:

\[ \frac{G_s}{G_c} = 0.009/0.064 = 0.14 \]

Due to the fact that for obtaining the solid CO₂ it is necessary to significantly lower the temperature at the TE inlet (-99 °C) compared to the same operating temperature of the TAR-11 (-35 °C), the auxiliary air heat exchanger that will help to lower the RHE inlet temperature should be installed after the compressor. Since \( \Delta t_{RHE} = 125 \) °C, the temperature of the FCP at the RHE inlet should be equal to the following \( T_{IN} = T_S + \Delta t_{RHE} = -93 + 125 = 32 \) °C.

The degree of CO₂ freezing out of the FCP was calculated taking into consideration the technical specifications of TAR-11. For a broader analysis of applying the TAR with the cooling performance in the range from 10 to 100 kW, the technical specifications of three types of TAR listed in table 1 [10] will be considered.

When using the TAR for CO₂ freezing out, FCP from the chimney of boiler units are used. Hence, the air flow utilized as a characteristic of TAR will be replaced by the FCP flow.

### Table 1. The technical specifications of the TAR.

| Technical specifications          | TAR-11 | RTAR1-25P | TR1-75 |
|----------------------------------|--------|-----------|--------|
| Cooling performance, kW         | 11     | 30        | 87     |
| Air temperature at the turboexpander outlet, °C | -35    | -80       | -80    |
| Air consumption/FCP emissions consumption, kg/s | 0.32   | 0.94      | 2.3    |

As in a steady-state operation of TAR, the FCP consumption is uncontrolled and can vary within the following range \( G_B = 0.2-2.5 \) kg/s depending on the type and cooling performance of TAR, it is important to be aware of the boilers capacity range extent to which the TAR operation is the most efficient according to the degree of freezing the solid CO₂ out of the FCP.

Figure 3 shows the dependence of the hot-water boilers total heat capacity on the mass flow rate of the FCP emissions. The higher the boiler unit power, the higher the consumption of the FCP formed during the fuel combustion [9].

The analysis of the dependence reveals that the efficient application of TARs is possible in the boilers of medium capacity in the range from 0.5 to 5 MW.

Boiler units of this capacity allow to provide the necessary FCP consumption of \( G_B = 0.2-2.5 \) kg/s. Within the given range one TAR will freeze out CO₂ as efficiently as possible.

Figure 4 presents the dependence of the TAR cooling performance on the mass flow rate of the FCP emissions [10].

![Figure 3. Dependence of the hot water boilers total heat capacity on the mass flow rate of the FCP emissions.](image-url)
Figure 4. Dependence of the TAR cooling performance on the mass consumption of the FCP emissions.

Figure 5 shows the dependence of the total heat capacity of hot water boilers on the TAR cooling performance. Joint analysis of the graphs presented in figures 4 and 5 makes it possible to evaluate the cooling performance parameters of TARs of various types and the total heat capacity of hot water boilers based on the flow of the FCP through the TAR.

The analysis of the above dependencies allows to conclude that the efficient use of TAR with the cooling performance ranging from 10 to 100 kW is possible in the boilers of mean power ranging from 0.5 to 5 MW.

The application of TAR will be less efficient in the boilers with a capacity of less than 0.5 MW due to the fact that there will not be enough FCP flow rate for the maximum possible degree of CO₂ freeze-out.

It should be noted that TAR can be used CO₂ freeze-out in the boiler units with a capacity of more than 5 MW as efficiently as in the medium-powered boilers. But this will require controlling the FCP flow rate in accordance with the technical specifications of the air/FCP flow rate of various types of TARs.

Figure 5. Dependence of the total heat capacity of hot water boilers on the TARs cooling performance.

4. Conclusions
The following conclusions have been formulated based on the conducted research:

- taking into account the above calculations, it is advisable to use the TAR for CO₂ freeze-out of the FCP flow, provided that the air heat exchanger with a fan is installed after the
compressor and the bag filter used for separating the solid phase of carbon dioxide is installed after the turbo expander;

- the TAR application will make it possible to obtain the solid phase of CO$_2$ out of the FCP flow with a degree of freezing within 14%;
- the most efficient use of TAR with a cooling performance ranging from 10 to 100 kW is possible in the boiler units of the mean power ranging from 0.5 to 5 MW;
- the TAR application will be less efficient in the boilers with a capacity of less than 0.5 MW due to a decrease in the degree of CO$_2$ freeze-out;
- TAR can be efficiently used for CO$_2$ freeze-out in the boiler units with a capacity of more than 5 MW provided that FCP flow rate is controlled according to the technical specifications of TARs.

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