Purification of thermal power plant emissions from carbon dioxide by the liquefaction method as part of a turbo-expander unit

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Abstract. The purpose of this work is to estimate the energy costs for the utilization of carbon dioxide generated by thermal power plants operating on various types of fuel by the liquefaction method as part of a turbo-expander installation, as well as a general assessment of the efficiency of the TPP during the utilization of carbon dioxide. The energy costs for the liquefaction of carbon dioxide in the turbo-expander unit from the combustion products of thermal power plants running on coal, natural gas and heating oil differ slightly and amount to about 5 MJ/kg of fuel burned. The practical application of purification of combustion products of thermal power plants from carbon dioxide by the liquefaction method as part of a turbo-expander installation is possible as part of combined-cycle power plants with a simultaneous reduction in electrical efficiency by more than 10 % to a level of less than 50 %.

1. Introduction

As the analysis of the works shows, the problem of reducing carbon dioxide emissions is considered from various points of view, starting from the economic [1-2] and ending with the consideration of the consequences of using various forms of utilization of atmospheric carbon dioxide [3-4].

A significant number of works are devoted to the consideration of various methods of carbon dioxide utilization [5-8], implementing chemical, physical, physico-chemical methods, as well as combined methods based on them, but rarely contain an assessment of the overall efficiency of thermal power plants working together with plants for the utilization of carbon dioxide from fuel combustion products by such installations.

The purpose of this work is to estimate the energy costs for the utilization of carbon dioxide generated by thermal power plants operating on various types of fuel by the liquefaction method as part of a turbo-expander installation, as well as a general assessment of the efficiency of the thermal power plants during the utilization of carbon dioxide.
2. Materials and equipment

The developed installation is shown in figure 1. The developed installation works as follows. The gas mixture from the source of the gas mixture 1 with a temperature above normal and a slight overpressure is fed through the pipeline 2 to a low-pressure heat exchanger 3, where heat is removed on the gas-liquid type heat exchange surface 4 and on the gas-gas type heat exchange surface 5 until the temperature of the gas mixture is close to normal. Further, the gas mixture at normal temperature is fed through the pipeline 6 to the inlet of the compressor 7, where the pressure of the gas mixture increases to a value greater than the condensation pressure of carbon dioxide under normal conditions. Then the gas mixture is fed through the pipeline 8 to the high-pressure heat exchanger 9, where heat is removed from the gas mixture to normal temperature through the gas-liquid heat exchange surface 12 and the gas-gas heat exchange surface 13. The pressure of the gas mixture created by the compressor 7 should be sufficient so that after lowering the temperature of the gas mixture in the high-pressure heat exchanger 9 to normal, carbon dioxide condensation occurs. The condensed carbon dioxide is discharged through the condensed carbon dioxide outlet channel 10 to the reservoir 11.

Figure 1. Installation for cleaning the gas mixture from carbon dioxide. 1 - source of the gas mixture; 2, 6, 8, 14, 17 - pipelines; 3 - low-pressure heat exchanger; 4, 12 - gas-liquid type heat exchange surfaces; 5, 13 - gas-gas type heat exchange surfaces; 7 - compressor; 9 - high-pressure heat exchanger; 10 - condensed carbon dioxide discharge channel; 11 - reservoir; 15 - turbo expander; 16 - output channel; 18 - gas mixture output channel to the atmosphere.

From the high-pressure heat exchanger 9 through the pipeline 14, the gas mixture purified from carbon dioxide is triggered at the expander 15, where it lowers its temperature and is sent through the pipeline 16 to the gas-gas heat exchange surface 13 of the high-pressure heat exchanger 9, from where it is sent through the pipeline 17 to the gas-gas heat exchange surface 5 of the low-pressure heat exchanger 3, from where it is removed into the atmosphere through the gas mixture output channel 18.

The liquid is supplied to the gas-liquid heat exchange surface 4 of the low-pressure heat exchanger 3 and to the gas-liquid heat exchange surface 12 of the low-pressure heat exchanger 9 from external
sources (not shown in figure 1), the liquid is discharged to external heat exchangers (not shown in figure 1).

3. Results
We calculate from the known dependencies [9] the content of individual components in the products of complete combustion of 1 kg of the main components of coal, natural gas and heating oil. The results are summarized in table 1.

Table 1. Calculation results.

| Fuel name  | CO₂   | H₂O   | N₂     | Total weight, m | μ, kg/mol |
|------------|-------|-------|--------|-----------------|-----------|
| Coal       | 3.42  | 0.6   | 11.44  | 15.46           | 0.031     |
| Natural gas| 2.75  | 2.25  | 11.44  | 16.44           | 0.029     |
| Heating oil| 3.08  | 1.44  | 11.44  | 15.96           | 0.030     |

The temperature of the combustion products at the outlet of thermal power plants can have different values, which take the minimum values for combined-cycle gas power plants at a level of just over 100 °C and more than 130 °C for thermal power plants (TPP).

It is known that to obtain high-temperature carbon dioxide, it is necessary to have a pressure not lower than \( p_2 = 7.4 \) MPa and a temperature not higher than 31 °C. Thus, the main task of a low-pressure heat exchanger is to lower the temperature of the gas mixture coming out of the heat and power plant as much as possible. Suppose that the temperature of the gas mixture in the low-pressure heat exchanger was lowered to 31 °C (\( T_1 = 304 \) K), and the pressure was close to the normal atmospheric \( p_1 = 101.3 \) kPa, while the dew point of water vapor will not be passed due to the low relative humidity of the gas mixture.

The achieved level of the effective efficiency of large compressors reaches \( n = 85\% \) with an average value of the compression polytrope \( n = 1.3 \). Let's determine the energy costs for compressing and pushing 1 kg of the gas mixture to the pressure into the high-pressure heat exchanger:

\[
A_{\text{compression}} = \frac{n}{n-1} \cdot \frac{p_1 V_1}{\eta} \cdot \left( \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right) = \frac{n}{n-1} \cdot \frac{m}{\mu} \cdot R \cdot T_1 \cdot \left( \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right),
\]

where \( R \) – universal gas constant; \( m \) – mass of the compressible gas mixture; \( \mu \) – the average molar mass of the compressible gas mixture.

The calculation results are summarized in table 2. There we will also put the calculations of the volumes occupied by gas mixtures before compression \( V_1 \) and after compression \( V_2 \).

Table 2. Calculation results.

| Parameters   | Coal | Natural gas | Heating oil |
|--------------|------|-------------|-------------|
| \( A_{\text{compression}} \), MJ | 10.9 | 12.3        | 11.6        |
| \( V_1, m^3 \) | 12.4 | 14.0        | 13.2        |
| \( V_2, m^3 \) | 0.45 | 0.51        | 0.48        |

The volume occupied by the compressed gas mixture will be. After lowering the temperature of the gas mixture in the high-pressure heat exchanger 9 to a temperature below 31 °C, carbon dioxide will condense from the gas mixture and be diverted to the tank 11, and the remaining mixture of nitrogen and non-condensed water vapor is directed to expand into the expander. We calculate the expansion
work $A_{\text{expansion}}$ of the mixture of nitrogen and water vapor in the expander, taking into account the achieved efficiency of the expanders at the level of $\eta = 85 \%$ with the polytrope of expansion $n = 1.3$:

$$A_{\text{expansion}} = \eta \cdot \frac{n}{n-1} \cdot p_2 \cdot V_{21} \cdot \left[ \left( \frac{p_2}{p_1} \right)^{\frac{n}{n-1}} - 1 \right],$$

(2)

where $m_1$ and $\mu_1$ – the mass and molar mass of a mixture of nitrogen and non-condensed water vapor, respectively; $V_{21}$ – the volume of the mixture of nitrogen and non-condensed vapors.

The results of the calculations $V_{21}$, $A_{\text{expansion}}$ will be summarized in table 3. There we will also put the results of calculating the spent of the work of $A_{\text{spent}}$ directly on the release of carbon dioxide from the gas mixture of combustion products of 1 kg of fuel.

### Table 3. Calculation results.

| Parameters     | Coal  | Natural gas | Heating oil |
|----------------|-------|-------------|-------------|
| $V_{21}$, m$^3$ | 0.35  | 0.42        | 0.39        |
| $A_{\text{expansion}}$, MJ | 6.04  | 7.4         | 6.7         |
| $A_{\text{spent}}$, MJ   | 4.7   | 4.9         | 4.8         |

We will compare the work expended with the useful mechanical work generated at electric power stations, converted into electrical energy, taking into account the calorific value of fuels and the achieved coefficient of efficiency values of thermal power plants, the results will be summarized in table 4.

### Table 4. Calculation results.

| Parameters                        | Heating oil-fired thermal power plant | Coal fired thermal power stations | Fas-fired power station | Natural gas |
|-----------------------------------|---------------------------------------|----------------------------------|-------------------------|-------------|
| Heat of combustion, MJ/kg         | 40.6                                  | 27.0                             | 48.0                    | 48.0        |
| Electrical efficiency, %          | 30                                    | 34                               | 39                      | 60          |
| Specific Power Output, MJ/kg      | 12.2                                  | 9.2                              | 18.7                    | 28.8        |
| Efficiency after carbon dioxide utilization, % | 18.2                                  | 16.6                             | 28.8                    | 49.8        |

Thus, cleaning the combustion products of thermal power plants and from carbon dioxide based on liquefaction processes as part of a turbo-expander unit is associated with significant energy costs and, if used, can lead to a significant decrease in electrical efficiency. In practical terms, it is possible to use the method of purification from carbon dioxide by liquefaction on the basis of a turbo-expander installation as part of combined-cycle power plants.

### 4. Conclusions

The energy costs for the liquefaction of carbon dioxide in the turbo-expander unit from the combustion products of thermal power plants running on coal, natural gas and heating oil differ slightly and amount to about 5 MJ/kg of fuel burned.

The practical application of purification of combustion products of thermal power plants from carbon dioxide by the liquefaction method as part of a turbo-expander installation is possible as part of combined-cycle power plants with a simultaneous decrease in electrical efficiency by more than 10 % to less than 50 %.

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