OXY-FUEL COMBUSTION OF NATURAL GAS: A REVIEW

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The article compares newly developed methods of natural gas combustion through oxy-fuel technologies. It describes in detail the basic technological differences and ordering of technological parts for five different cycles using carbon dioxide and steam as a working medium in expansion turbines in electricity production. Among the procedures using steam as the working medium, attention is focused on GRAZ and CES cycles. In oxy-fuel procedures utilising carbon dioxide produced by natural gas combustion, the focus is on COOLCEP, MATIANS and COOPERATE cycles. For each cycle described, the respective operating conditions and principles are given. Additionally, detailed process diagrams are also provided. Important advantages of all of these cycles include the possibility of the combustion of not only liquefied natural gas but also other gaseous fossil fuels, whose introduction into production is not very time-consuming, and the possibility of connection to power distribution network within a relatively short period of time.

Keywords: Oxy-fuel, Natural gas, CCS, Carbon dioxide

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1. Introduction

In recent years, the transportation of natural gas in the form of liquefied natural gas (LNG) has become increasingly important as a result of the construction of new terminals in Europe as well as with regard to its flexibility, supply safety and the diversification of the energy mix of individual states [1, 2]. Furthermore, the use of LNG as fuel for gas and steam–gas plants is considered, as it reduces its volume approximately 600 times after liquefaction and thus could be transported directly to a power plant and subsequently regasified before it enters the combustion process [3, 4]. Within a gas power plant, some carbon capture and storage (CCS) technologies could also be used to reduce the amount of carbon dioxide released into the atmosphere [5]. In terms of the strategies of the approach to carbon dioxide capture, three technologies based on different principles have been monitored:

1. The capture of carbon dioxide from the flue gases from fuel combustion – the post-combustion technology;
2. The capture of carbon dioxide from the gas before the combustion process – the pre-combustion technology;
3. Co-combustion with pure oxygen – oxy-combustion, or the oxy-fuel technology [6].

The capture of carbon dioxide from the flue gases from fuel combustion – post-combustion – is one of the technologies that capture it using a suitable separation method, mostly based on the principle of absorption or adsorption. After the combustion of fuel with air, the flue gases are fed into a pre-cleaning technology. Here, solid particles are removed from the flue gases (e.g. in an electrofilter). Subsequently, the flue gases are desulphurised (sulphur dioxide is removed). This pre-treatment is followed by the application of one of carbon-dioxide capture technologies (e.g. adsorption, absorption methods, etc.) and the separated carbon dioxide is further utilised.

The removal of carbon dioxide before the combustion process is associated with its removal from the gaseous medium. If the primary raw material is gaseous fuel, the actual energy unit is preceded by the partial-oxidation or steam-reforming process, where syngas containing mainly carbon monoxide and hydrogen is produced from the gaseous fuel. Subsequently, carbon monoxide is converted into carbon dioxide by means of steam oxide (the so-called shift conversion), the product of which is a mixture of hydrogen and carbon dioxide. Carbon dioxide is then separated and the remaining gas, mostly hydrogen, is combusted in the gas turbine of the steam–gas cycle. Carbon dioxide is separated here at high pressure from gas that is relatively rich in carbon dioxide. This decisively affects the choice of capture methods and technologies. In general, carbon dioxide is most often captured from gas by means of absorption methods. Another possibility for the capture are solid sorbents.

The combustion medium used in the case of the oxy-fuel technology is a mixture of pure oxygen (usually with the purity of 95 %) and recirculated flue gases. The flue gases then form a mixture of steam, carbon dioxide and nitrogen oxides, whose amount is lower than in normal combustion, as they are formed only from the nitrogen contained in the fuel. When the oxy-fuel technology is used, the flue gases thus have different characteristics, which are manifested, for example, in the lower formation of nitrogen oxides or a higher flame temperature [7].

2. The Technology of Natural Gas Combustion in the Oxy-Fuel Cycle

The combustion in the oxy-fuel cycle primarily produces carbon dioxide and steam. Carbon dioxide is separated by means of the condensation of water from flue gases. This technological element consumes a small amount of energy in comparison with the energy necessary for oxygen production (7–10 % of the total energy consumption). The main, commonly used recycled working substances are either carbon dioxide or steam. The technologies using carbon dioxide include COOPERATE, MATIANT and COOLCEP cycles, whereas those utilising steam as a working substance comprise CES and GRAZ cycles.

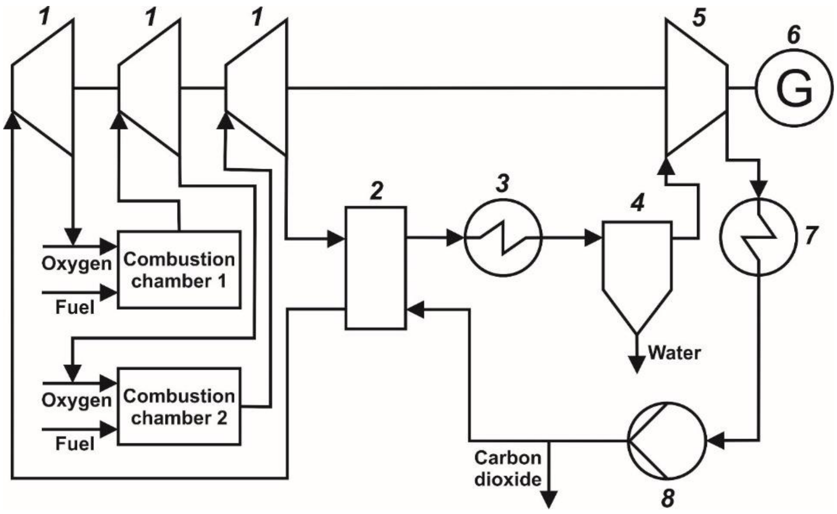

Fig. 1 The scheme of the COOPERATE cycle [8]
1 – Turbines; 2 – Recuperator; 3 – Cooling tower; 4 – Water separator; 5 – Intercooled compressor; 6 – Generator; 7 – CO_2 condenser; 8 – CO_2 pump

2.1. The COOPERATE Cycle

The COOPERATE (CO_2 Prevented Emissions Recuperative Advanced Turbine Energy) cycle is also referred to as a quasi-combined cycle [8]. It consists of an air separation unit, combustion unit, triple expansion turbine, carbon dioxide compressor, and carbon dioxide liquefaction and separation unit. The scheme of the cycle is depicted in Figure 1.

Gas enters the first stage of the turbine at a temperature of 600–700 °C and a pressure of 240 bar. After expansion at this stage, the gas pressure is around 60 bar. If the pressure of 60 bar is too high for the next stage of the gas turbine, the second stage of expansion is included, in which the pressure is reduced from 60 to 15 bar. In this case, the combustion chamber is used only for the heating of the working medium up to the working temperature of the gas turbine [9]. The third stage of the turbine is entered by flue gases from the second combustion chamber, which are further fed into the recuperator after the expansion.

A disadvantage of the cycle is the maximum operating pressure of 240 bar and the maximum operating temperature of 1,250 °C in the gas turbine in the first stage. The production of the turbine for such parameters is complicated. This problem is solved by eliminating the first combustion chamber; in the first turbine, the highly compressed carbon dioxide is subsequently expanded [8].

2.2. The MATIANT Cycle

In the cycle referred to as MATIANT (based on the abbreviation of the names of two designers – MAThieu and IANTovski), carbon dioxide is removed in the liquid state or under supercritical conditions under high pressure from the circulating medium [10]. It can then be used in technologies requiring high pressure. The MATIANT cycle is a variant of the COOPERATE cycle. It consists of the Rankine cycle operating in the supercritical area in combination with the regenerative Brayton cycle. The scheme of the cycle is shown in Figure 2 [11, 12].

The cycle includes two combustion units. In the first, fuel is combusted with oxygen and carbon dioxide at increased pressure. The flue gases contain a mixture of carbon dioxide and steam, whose temperature is 1,300 °C [13]. Subsequently, these flue gases expand in the high-temperature intermediate turbine, before entering the second combustion chamber, in which fuel is incinerated with oxygen. The flue gases are then fed into an expansion turbine (generating electricity). The third expansion turbine using recirculating carbon dioxide is located behind the recuperator; it is connected to the second power generator using recirculating carbon dioxide. Behind the output from the recuperator, there are a cooler and a separator for the removal of steam from carbon dioxide. Subsequently, carbon dioxide is compressed in a three-stage compressor with an intercooler. Here, carbon dioxide is liquefied at a temperature of 30 °C and a pressure of 70 bar. The liquefied carbon dioxide is pumped by a high-pressure pump into a recuperator. Before the recuperator, excess carbon dioxide is removed from the entire cycle. Liquid carbon dioxide subsequently cools the flue gases in the recuperator and then is fed into the expansion turbine [14, 15].

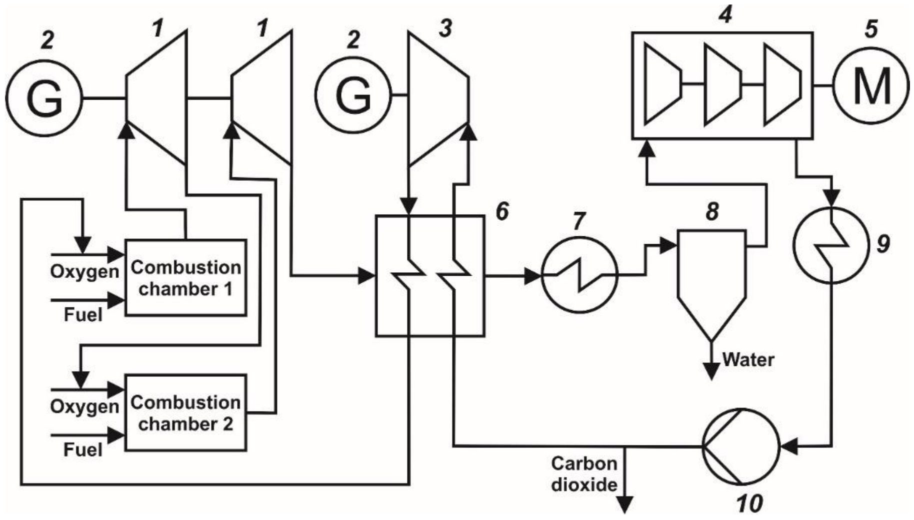

Fig. 2 The scheme of the MATIANT cycle [11, 12]
1 – Expanders with internal cooling; 2 – Generators; 3 – Uncooled expander; 4 – CO_2 compressor; 5 – Motor; 6 – Recuperator; 7 – Cooler; 8 – Water separator unit; 9 – Condenser; 10 – CO_2 pump

2.3. The GRAZ Cycle

The GRAZ cycle (the cycle is designated based on the university where it was developed – Graz University of Technology) is assembled from the high-temperature Brayton cycle involving two compressors, a combustion chamber, a high-temperature turbine and a low-temperature Rankine cycle [16, 17], which consists of a low-pressure turbine, condenser, steam generator, recuperator and a high-pressure turbine – see Figure 3 [18].

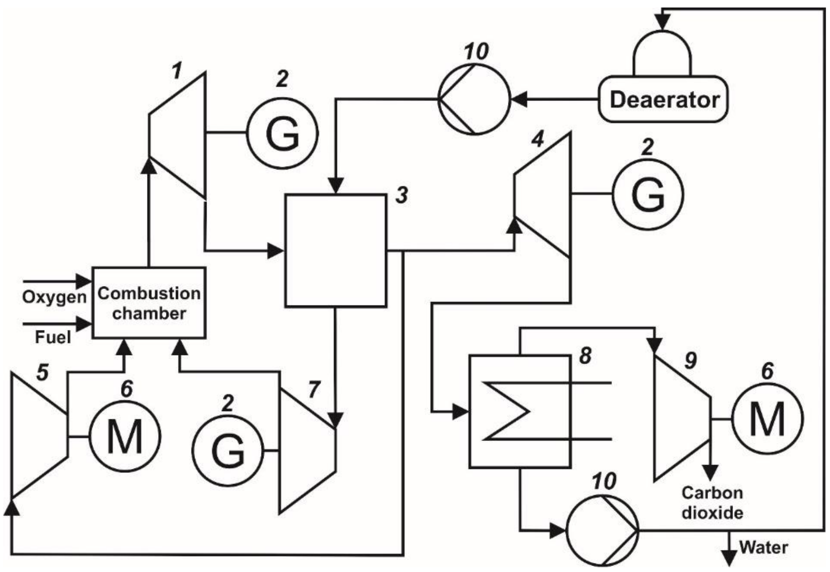

Fig. 3 A scheme of the GRAZ cycle [18]
1 – High-temperature turbine; 2 – Generator; 3 – Heat recovery steam generator (HRSG); 4 – Low-pressure turbine; 5 – Cycle fluid compressor; 6 – Motor; 7 – High-pressure turbine; 8 – Condenser; 9 – CO_2 compressor; 10 – Pump

The fuel, together with an almost stoichiometric amount of oxygen, is fed into the combustion chamber, which works at a pressure of 40 bar. Steam as well as a mixture of carbon dioxide and water are supplied to cool the burners and the liner. The flue gas contains approximately 74 % of steam, 25.3 % of carbon dioxide, 0.5 % of oxygen and 0.2 % of nitrogen. At the output from the combustion chamber, their temperature is 1,400 °C [19]. In the high-temperature turbine, this mixture subsequently expands to a pressure of 1 bar. A power generator is connected to this turbine. Exhaust gas from the high-temperature turbine is used in a heat recovery steam generator (HRSG) to evaporate and overheat steam for the high-pressure turbine. Only 45 % of the HRSG mixture expand in the low-pressure turbine to the absolute pressure of 0.043 bar. The rest of the mixture is compressed in the compressor and subsequently fed into the combustion chamber with the maximum temperature of 600 °C, thus preventing the release of latent heat when steam evaporates during condensation. In the condenser, the gaseous and liquid phases are separated. The gaseous phase containing carbon dioxide and steam is compressed in the compressor to atmospheric pressure; after further water removal, carbon dioxide is stored for further use. The purity of carbon dioxide is then 94 %. Water from the condenser, which is preheated, is evaporated and overheated in the HRSG. Subsequently, steam is brought into the high-pressure turbine at a pressure of 180 bar and a temperature of 550 °C. After expansion, it is used to cool burners and individual stages of the high-temperature turbine [20, 21].

2.4. The CES Cycle

The cycle labelled as CES (Clean Energy System, Inc.) is very similar to the GRAZ cycle in the circulation of steam into the combustion chamber, but the CES cycle is less complex. The cycle involves the combustion of gaseous hydrocarbon fuel with oxygen in the combustion chamber, whose construction is based on the technology of rocket engines [22]. This combustion at a high temperature and pressure produces a mixture of steam and carbon dioxide [23]. It thus consists of four follow-up steps:

1. fuel processing and compression
2. air separation and oxygen compression
3. power generation
4. carbon dioxide capture.

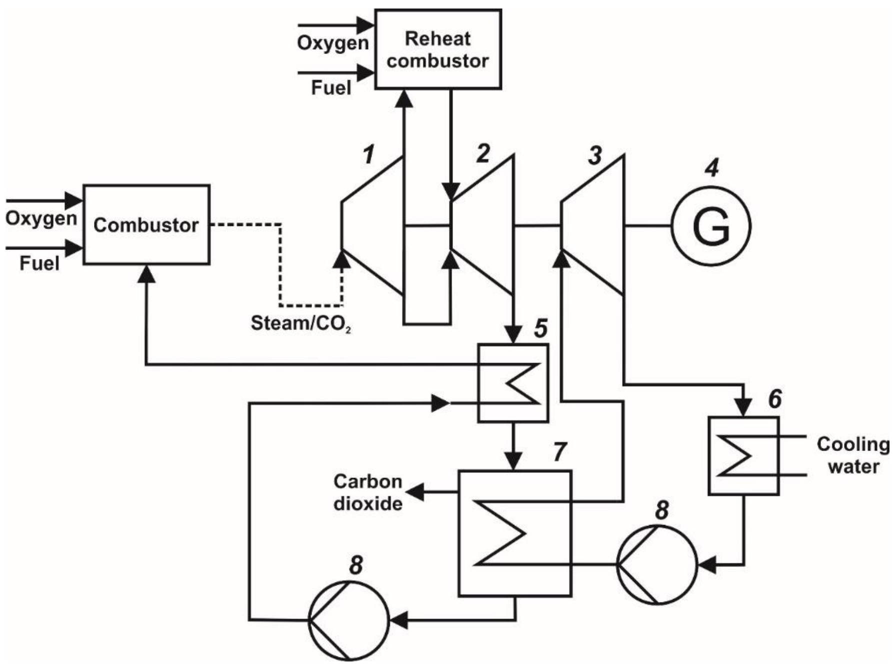

Fig. 4 A scheme of the CES cycle [23]
1 – High-pressure turbine; 2 – High-pressure intermediate turbine; 3 – Low-pressure turbine; 4 – Generator; 5 – Heat exchanger; 6 – Condenser; 7 – Heat recovery steam generator; 8 – Pumps

At the inlet to the combustion chamber, the pure gaseous fuel is compressed to the required pressure. The air separation unit supplies a flow of high-purity compressed oxygen to the combustion chamber (see Figure 4). The power generation system consists of combustion chambers and turbines in a series and a heat recuperator. The combustion equipment operates at an overpressure of 50–100 bar and its temperature is reduced by injected water and steam. The produced mixture of steam and carbon dioxide has a temperature of 500–600 °C. This mixture is then fed into a high-pressure turbine. The composition of the working substance varies depending on the type of the gaseous fuel and the amount of the injected steam, carbon dioxide and temperature. The typical ratio of steam to carbon dioxide is 91:9 (volume). A part of the mixture coming out of the high-pressure turbine is heated in a combustion chamber (reheated combustor), where additional fuel is combusted with oxygen. Then it is fed into a high-pressure intermediate turbine, from which, depending on the temperature of the exhaust gases, the waste heat is recuperated in the heat exchanger. It preheats recycled water or generates steam, which is used in the combustion chamber. Heat recovery steam generator is placed behind the heat exchanger because of the necessary condensation of flue gases from the high-pressure intermediate turbine. This is where also low-pressure steam is generated for a separate low-pressure steam

Rankine cycle, in which low-pressure steam is expanded into a vacuum [24].

2.5. The COOLCEP Cycle

Liquefied natural gas (LNG) has a temperature of approximately −163 °C, which is much lower than that of the surrounding air. For this reason, it offers a large amount of energy, which can be further transformed into mechanical work – exergy. In reception terminals, instead of the evaporation of LNG by means of heat from ambient hot water or air, it is possible to obtain exergy from LNG evaporation by investing in a process that uses it for subsequent applications. One way to do this is to include it in a heat power cycle that uses an LNG evaporator as a cold reservoir. One of the technologies for obtaining and subsequently using exergy from LNG is COOLCEP (cool clean efficient power). It is basically a cogeneration recuperation Rankine cycle with liquefied carbon dioxide as a working substance [25].

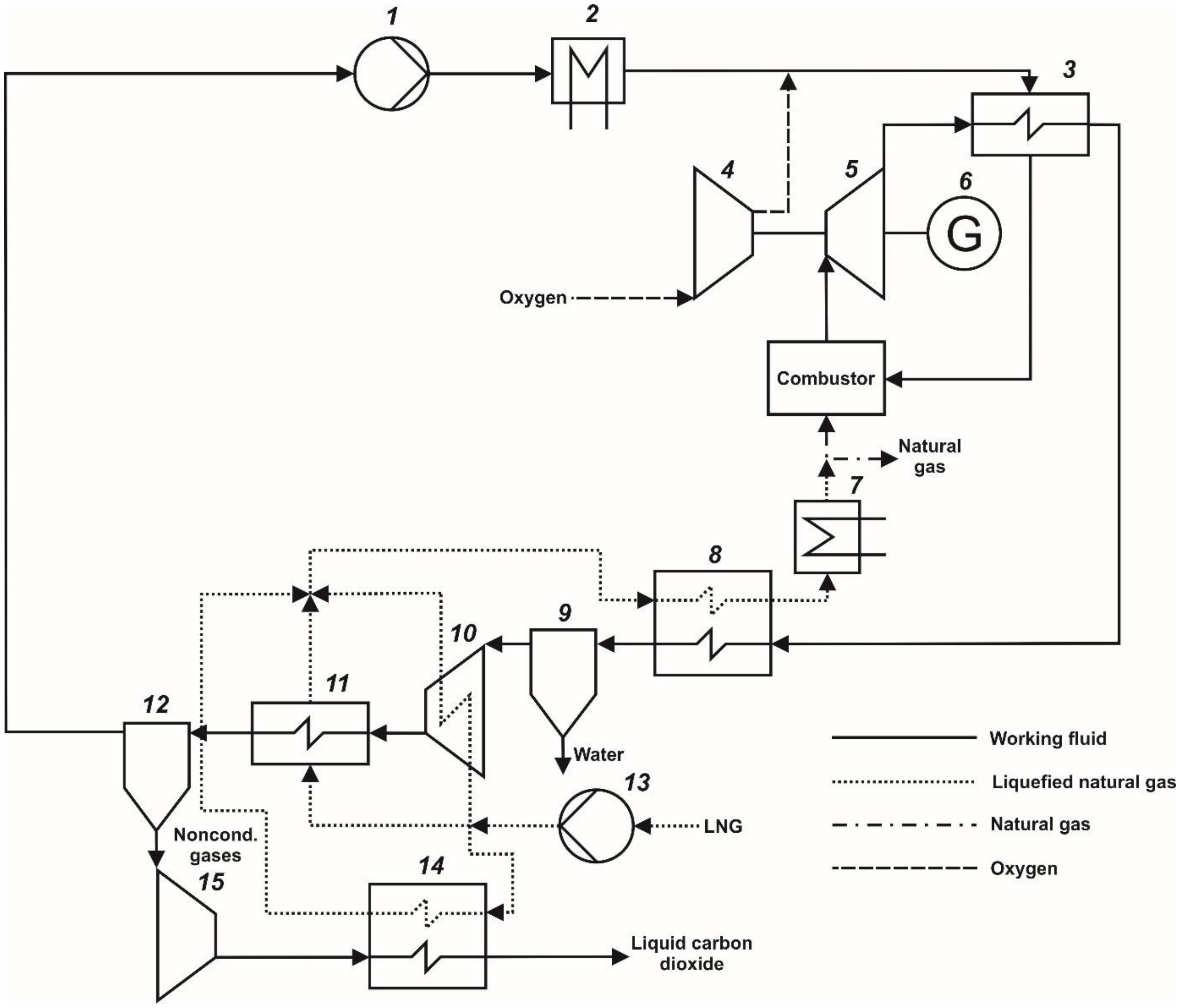

Fig. 5 A scheme of the COOLCEP cycle [26, 27]
1 – Pump; 2 – Evaporator; 3 – Recuperator; 4 – Oxygen compressor; 5 – Turbine; 6 – Generator; 7 – Heat exchanger; 8 – LNG-cooled heat exchanger; 9 – Condenser; 10 – Compressor; 11 – Condenser; 12 – Separator; 13 – Pump; 14 – Heat exchanger; 15 – High-pressure compressor

The COOLCEP cycle is shown in Figure 5, consisting of a power subcycle and an LNG evaporation process. Between the two processes, there is a carbon dioxide condenser, heat exchanger and fuel supply to the combustion chamber.

Liquid carbon dioxide at −50 °C, which forms the working substance, is pumped at a pressure of 30 bar into the evaporator. The produced oxygen in the air separation unit is compressed in the compressor and admixed to liquid carbon dioxide. The gas mixture is heated in the recuperator by waste heat from the turbine. The temperature of the working substance is further increased in the combustion chamber. The substance then expands in the turbine to approximately ambient pressure and is then cooled in the recuperator. Carbon dioxide is then liquefied in the heat exchanger and steam is removed from it in the condenser. The remaining working substance is compressed to condensation pressure in a single-stage internally cooled compressor for the reduction of compression work. Subsequently, the working substance is liquefied in the condenser, where LNG evaporation is used. In the separator, non-liquefied gases (mainly nitrogen, oxygen and argon) are separated from the working fluid. This mixture is then compressed in a high-pressure compressor to a pressure at which carbon dioxide is condensed and captured. LNG is pumped to the pressure that is typical of reception terminals (73.5 bar) and is subsequently evaporated using heat from the energy cycle. The evaporated natural gas transfers a small amount of cold in the heat exchanger if its temperature at the exit from the heat exchanger is still low enough. Finally, gaseous natural gas is divided into two parts. Most of the natural gas is pushed into the transmission system; the rest is used as fuel in the combustion equipment [28].

3. Conclusion

From the strategic aspect of the approach to the currently highly monitored capture of carbon dioxide from the processes of combustion of gaseous and fossil fuels, oxy-fuel technology appears to be very promising. The text summarizes and compares the basic principles of the five most important cycles using carbon dioxide or steam as a working medium in variously interconnected expansion turbines in the production of electricity. Among the procedures using steam as the working medium, attention is focused on GRAZ and CES cycles. In oxy-fuel procedures utilising carbon dioxide produced by natural-gas combustion, the focus is on COOLCEP, MATIANS and COOPERATE cycles. Important advantage of the processes discussed is the fact that they can be brought into operation and thus also connected to the power distribution network, from which renewable energy sources are being disconnected. [29]

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