Power units with full CO2 utilization

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Abstract. The forecasts for the development of renewable energy and conventional energy with fossil fuels have significant discrepancies in quantitative indicators, but agree on the need to reduce CO2 emissions. In this direction, a great number of developments are associated with hydrogen energy. Alternative proposals are cycles on methane-oxygen fuel with CO2 capture from the concentrated stream at the outlet of the condenser-separator: high-temperature gas-steam turbine unit of CJSC SPC «Turbocon», Allam, and JIHT RAS cycle. A 100 kW gas-steam turbine with an initial mixture temperature of up to 800° C has been developed and tested. To develop a method for calculating steam condensers from a mixture with CO2 (common to all three schemes), tests were carried out on a special stand; the heat transfer coefficient experimental data have been used to design a highly efficient steam condenser from a mixture with a converging flow path to maintain its high speed, a heat transfer coefficient of 2700 W/m²K was achieved. It is planned to create a prototype installation containing a steam boiler, a gas-steam turbine and a steam condenser with CO2 capture from the concentrated stream at the compressor outlet.

Currently, the prospects for the development of energy up to 2040-2050 are actively discussed against the background of environmental problems and forecast of climate change. In the forecasts of energy consumption and electricity production, there is a significant variation, which can be associated with certain aspects. So, Figure 1 shows the energy consumption charts (a) and the production of electricity from renewable energy sources (RES) (b) [1]. The growth of resource consumption and moderate growth of RES are predicted by BP and Shell oil refineries. International Energy Association (Paris) and Irena Get (Abu Dhabi), where renewable energy is intensified, predict reducing energy consumption and rapid growth of renewable energy. Nevertheless, both sides of the discussion, differing in quantitative estimates of the transition process, recognize its inevitability and, as a result, the presence of signs of the IV energy transition and the increase in the share of renewable sources in general energy balance.

Thermal power engineering and transport are the most important anthropogenic sources of mass emission of carbon dioxide. The struggle for the reduction of these emissions is carried out in three directions:
- transition to "pure" types of fuel (hydrogen, natural gas);
- increasing the efficiency of thermodynamic processes (more energy, less emissions);
- calming or disposal of carbon dioxide at the exit of power unit.
In modern scientific and technical prospects marked by the Russian Government Resolutions, the focus is on the first direction. Similar trends take place abroad. Two other areas are equally important: an increase in the efficiency of energy complexes and economically justified systems of capture and disposal of CO$_2$.

The technological basis of the gas transition is illustrated in Figure 2. Among those proposed in Figure 2, hydrogen energy, being the cleanest in terms of hydrogen production, transportation and storage, remains very vulnerable.

In addition to the absence of CO$_2$ emissions, hydrogen fuels can significantly increase the initial temperature of water vapor in steam-turbine complexes and, as a result, to increase significantly their efficiency.

The fundamental technical solutions based on such units were formulated by E.E. Spielrain [2] in the 80s of the 20th century. The main idea is the combustion of hydrogen and oxygen in the water vapor environment after the classic steam boiler.
A cycle with a hydrogen overheating of steam is shown in Figure 3a, and the T-S diagram is shown in Figure 3b. The latter illustrates an important feature of hydrogen overheating: the cycle consists of two components: a classic "boiler version" with a flow rate \( G = 1 \), in which the steam turbine regeneration system plays significant role in increasing the efficiency, and the cycle of additional fuel \( G = \alpha \), where there is no regeneration, and the effectiveness of which is significantly lower than that of the "boiler room".

The development of this idea was the burning of natural gas and oxygen in the steam moving from the boiler (Figure 4). There are no problems specific to hydrogen overheating, but a mixture of steam and dioxide comes into the condenser. After condensation, we obtain substantially pure carbon dioxide, which can be recycled. In this case we can have CO\(_2\) utilizing only for additional fuel.

As a result of the work in this direction, an experimental sample of a high-temperature installation of a power of 100 kW for steam parameters \( p = 3.4 \) MPa and \( T_0 = 800^\circ\text{C} \) was created. Figure 5 shows the cut of the high-temperature steam turbine unit HSTU-100.

The two-rim Curtis stage and the three pressure stages provide operation of the unit at 24,000 rpm and pressure in the condenser of 10 kPa. The project of a high-temperature unit with a capacity of 300 MW for parameters \( P_0 = 30 \) MPa, \( T_0 = 1250^\circ\text{C}/1450^\circ\text{C} \), with the net efficiency (minus a booster and air separation unit) amounted to 54% was developed together with the NRU «MPEI».
Figure 5. High-temperature steam turbine HST-100

At the heat electro power station HES-16 PJSC "Mosenergo" a system of gas steam overheating using methane - oxygen fuel was tested, a steam temperature of 720°C was achieved, and the performance of gas overheating technology was confirmed. The photo of the gas overheating unit before installing on the HES-16 is shown in Figure 6.

Other works in this regard are represented by the Allam cycle (Figure 2), the JIHT RAS cycle idea is similar. These two series share a common working body: carbon dioxide.

A schematic generalized cycle of Allam and JIHT RAS is shown in Figure 7. At a mixture temperature of 1100°C and a pressure in the circuit of up to 30 MPa, the authors of the cycle predict an efficiency of up to 54%.

When analyzing the Allan cycle, an estimate was made of the dimensions of the heat regenerator operating at temperatures of up to 800°C and pressures of up to 30 MPa. The design of this apparatus is not presented in the literature, our estimate shows that the length of the heat exchange tubes will be 90 - 130 m with a counter-current flow of the spent working fluid (the mixture of CO₂ and H₂O, p = 3.0 MPa) and carbon dioxide into the combustion chamber (p = 30.0 MPa).

Transfer of hydrogen problems to the problem of separating carbon dioxide from water vapor in a
condenser/separator is common to all three cycles with natural gas and oxygen. To develop a methodology for calculating such devices, a tube bundle was tested on a special stand during condensation of water vapor from a steam-gas mixture (SGM). The design of the working section of the stand is shown in Figure 8.

The steam flows through an equalizing grid. First four rows of tubes $\varnothing 26x3$ used to stabilize the flow, steam condenses on the cooled tubes of 5 - 6 rows, prepared by thermocouples (4 per tube) located in grooves 1.5 mm deep. The obtained experimental data almost repeat the experiments of L.D. Berman made 40 years ago [4] for pure moving steam. The test results are summarized in [5]. The condensation of steam from the SGM is well intensified by the dynamic effect of the moving mixture. To maintain a constant mixture velocity as it condenses, it is necessary to have a narrowing steam channel, the configuration of which is shown in Figure 9.
Figure 9. Channel shape of a highly efficient steam condenser for a steam-gas mixture.

Figure 10a shows a prototype of a highly efficient steam condenser at the factory bench, and Figure 10b shows the test results of this apparatus. The heat transfer coefficient at the rated load was 2.7 kW/(m²K), which is comparable to an industrial condenser for almost pure steam.

Thus, Turbocon currently has all the necessary units for creating a prototype of a gas-steam turbine plant consisting of a steam boiler, a system for additional gas steam superheating, a gas-steam turbine, and a highly efficient steam condenser from an SGM with an output of concentrated CO₂ stream from the condenser.

Acknowledgments
This work was supported by the Russian Science Foundation (grant No. 17-19-01604)

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