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Different ways analysis of H_2O injection into a gas turbine

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Abstract
This paper presents a thermodynamic analysis of Brayton cycle and its modernization after the application of H_2O injection into the gas turbine cycle. Modernizations are generally considered to be environmentally-friendly solutions and lead to increase the efficiency, but in the literature items there is no clear answer which one is the best. For numerical analysis of the Brayton simple cycle, the Brayton cycle with water injection into the compressor and with regeneration prior to the combustion chamber, the STIG (steam injection gas turbine), and the CSTIG (combined steam injection gas turbine) system, Computational Flow Mechanics codes has been used. Different ways analysis of H_2O injection into the gas turbine cycle have been discussed.

Keywords: gas turbine, steam injection, regeneration, water injection, water recovery

1. Introduction

Today, almost all developed countries, including Poland, are facing with the problem of insufficient amount of electricity. An additional difficulty is the need to meet environmental standards set by the EU Directive No. 2010/75/EU [1]. Ecological solutions, that ensure the growth of electric power, is to modernize the existing gas unit or units of gas-steam power plants in systems with injection of water or steam to gas turbine [2-5]. The use of STIG (steam injection gas turbine), CSTIG (combined steam injection gas turbine), the injection of water into the compressor and regeneration prior to the combustion chamber and combined cycle provides an increase in power and efficiency of the basic Brayton cycle. STIG and CSTIG are particularly beneficial while the demand for heat and power plants reduces. In turn, STIG and systems of water injection into the compressor and regeneration before the combustion chamber have the potential to increase the power and efficiency of the unit during repair of steam turbine. Moreover, the system STIG and CSTIG provides flexible operation of power plants with optimal utilization of generated steam [6-8]. Many studies have been carried out on a gas turbine with the steam injection. As of 1978, when Cheng proposed a gas turbine with the steam injection, the retrofitted gas turbines have been widely analyzed and developed [4,9]. Cheng suggested that the whole steam produced in heat recovery steam generator HRSG can be used for injection into a gas turbine combustion chamber which results in both power and efficiency increase as well as NOx reduction [9].

However, CSTIG and STIG are gas-steam systems, in which a Brayton gas cycle is combined with steam cycle in the combustion chamber. In a gas turbine, both the exhaust and the steam generated in the heat recovery steam generator expand and, consequently, the power of Brayton cycle increases [9-11]. Specification of these systems makes high electrical efficiency possible to achieve also in small systems. In addition, the exhaust gases leaving the combustion chamber contain small amounts of toxic components, so it is not necessary to install expensive exhaust treatment systems [10,12]. Particular advantages are achieved while reducing the emissions of nitrogen oxides in gas turbines that generate predominantly through Zeldowicz mechanism (called thermal mechanism) [13]. As a result of steam injection into a combustion chamber, temperature of the combustion process decreases and consequently nitrogen oxides emission reduce [4,14]. It should be added that in some application gas turbines are used for heat supply to realize the stripping process in a supercritical CHP plant integrated with a carbon capture installation. There is helping in reduction carbon emission [15].

The first proposal for the modernization of the Brayton cycle with steam injection system, as presented by Saada and Cheng, concerned of General Electric LM2500 turbine [4]. At present, steam injection into the combustion chamber is used in turbines by such leading companies as General Electric, Rolls-Royce, Kawasaki [4,16]. In paper [17] it is shown that entering STIG to a basic gas turbine cycle of General Electric Frame 6B could increase the efficiency from 30% even to 40% and the power of 38 up to 50 MWe. There are known more complex systems, e.g. using water injection to compressed air as inter-or inlet-stage cooling [18-20], in the humid air (Humidified Air Turbine, Evaporating Gas Turbine, Cascade Humidified Air Turbine) [19,20], systems connecting the steam injection with regeneration (RSTIG) [20], systems combining both water and steam injection DRIASI (the dual-recuperated, inter-cooled-after-cooled steam injected cycle) [3] and LOTHECO cycle (low temperature heat combined cycle), using external renewable heat source for heating the water condensed from the exhaust gases [3,12].

Another method, that would increase the efficiency and power of a gas turbine, is the process of spraying water between compressor stages. As a result of the spraying, in contact with the hot and compressed air mass flow rate the water evaporates, causing lowering the air temperature and the work required to drive the compressor. This system with inter-stage cooling of air can be successfully used in high-pressure turbines [20].

Moreover, construction of Humidified Air Turbine (HAT) is based on concept combination of the regenerative air preheating for combustion and injects the water mass flow rate between compressor and heat exchanger (without changing the flow of compressed air). Injection of water into the air, before the regenerative heat exchanger, causes lowering of the temperature of compressed medium and therefore increases the efficiency of heat regeneration. Because of the use of regenerative heat exchanger in HAT, the optimum compression ratio are lower than in the STIG, and thereby resulting in a higher temperature after the turbine the order of 800 °C. In HAT systems, the temperature distribution mediums in the regenerative heat exchanger is significantly better adjusted, than in the heat recovery steam generator (HRSG) systems with steam injection or gas – steam cycles, therefore, an increase in efficiency, even above 0.5. But the disadvantage of these systems is the necessity to changes in construction and, related with that, increased investment outlays [3,14,20].

Next, LOTHECO cycle (LOw Temperature HEat COmbined cycle) employs external renewable heat source to heat up and evaporate the water condensed from the exhaust gases [3]. For temperature range of evaporation from below 100 ^{o}C up to 170 ^{o}C, low-quality heat sources are favorably integrated, which, under other circumstances, cannot be utilized for electric power generation, such as: geothermal, solar, etc. Such arrangements are beneficial in terms of enhanced fuel-to-electricity efficiency compared to the efficiency of an equivalent conventional combined cycle [3,12]. Efficiencies above 60% have been recently reported [3].

The purpose of this article is to examine thermodynamic and operating parameters of the Brayton basic cycle and gas and steam cycle by using the available in-house numerical CFM (Computational Flow Mechanics) [5,14,21,22] and a commercial package. Then to analyze the efficiency for three modifications: in the Brayton cycle with water injection to the compressor and the regeneration prior to combustion chamber, in the STIG and CSTIG systems. Additionally, different aspects of H_2O injection into the gas turbine cycle have been presented. Economic analysis of two units, both of the class around 66MWe - for gas-steam unit and unit in Cheng system have been conducted.

2. Theory

To the analysis of thermodynamic cycles, CFM type of numerical codes were used. CFM mathematical models (located for example in the programs COM-GAS and Aspen Plus) use the balance equations of mass, momentum and energy in the integral form (0D, integrated) [23-25]. In previous works of the authors [6,7,23], calculation procedures were presented for the whole components of turbine set, such as compressors, combustion chambers, turbines, pumps and heat exchangers. The power, the efficiency, steam injection rate and other relevant size will be defined.

Figs. 1-3 show schemes of cycles compared in this work. Firstly, Fig. 1 presents the layout of gas and steam power plant with the ability to redirect the steam to the combustion chamber (CC), and thus using STIG solution. Secondly, Fig. 2 shows an arrangement of CSTIG, which is a kind of equivalent STIG, with this exception that the steam generated in the heat recovery steam generator (HRSG), before it reaches the combustion chamber (CC) reworks a part of the enthalpy in a steam turbine (ST). In turn, the last of the analyzed systems using water injection (W) in the double section compressor (low-pressure C1 and high-pressure C2) and with the regeneration (R) before the combustion chamber, is shown in Fig. 3.

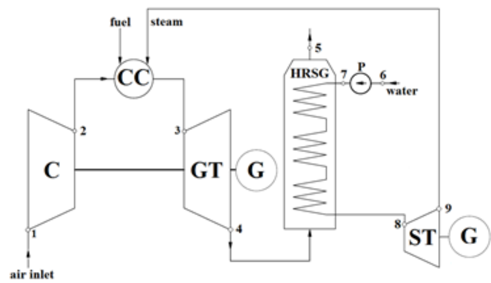

Fig. 1. Scheme of gas-steam cycle with possibility of transition to the STIG, (GT - gas turbine, C - compressor, CC - combustion chamber, G - generator, HRSG - heat recovery steam generator, ST - steam turbine, P - pump, CON - condenser, WH - heat exchanger) [6].

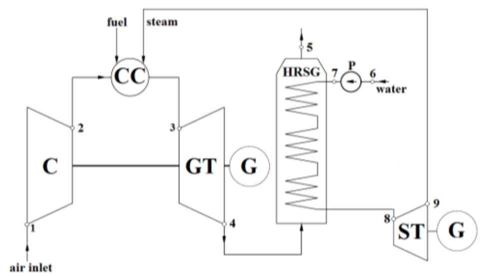

Fig. 2. Scheme of CSTIG system (GT – gas turbine, C – compressor, CC – combustion chamber, G – generator, HRSG – heat recovery steam generator, ST – steam turbine, P – pump).

Each of these systems has its advantages and disadvantages, which will be briefly described. STIG system has a simple design and the possibility of easy redirection of the steam to the gas turbine system. Unfortunately, it does not use the most energy flowing from the steam produced in the heat recovery steam generator (HRSG). The improvement of the present solution is reached after entering the combined system CSTIG, but in this situation there is a problem in designing new a steam turbine adapted to the required pressure drop. In turn, water injection solution does not require the use of heat recovery steam generator (HRSG), but the amount of water introduced and the pressure, at which the water is injected into the compressor, must be optimized. An additional advantage of the mentioned solution is to reduce the temperature behind the compressor and thus reducing the compression work, and rising the degree of regeneration. All these factors make it unclear to identify which solution is better in thermodynamic and ecological terms, without prior analysis and comparison results of all three systems.

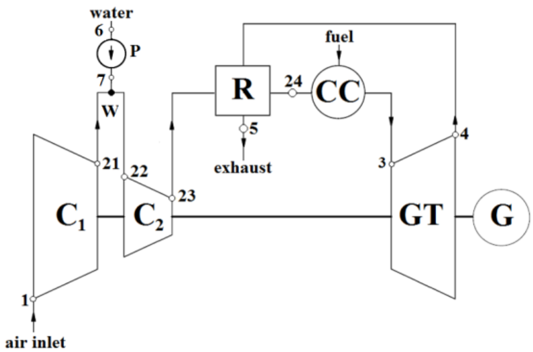

Fig.3. Scheme of system with regeneration and interstage cooling in compressor by using water injection (C1, C2 - low- and-high pressure compressor, R – regenerative heat exchanger, CC – combustion chamber, GT – gas turbine, G – generator, W - water injection, P - pump).

2.1. Water recovery

The disadvantage of above discussed solutions is the need for water recovery from flue gas mixtures. But nowadays we can observe a substantial progress in the design of condensing heat exchangers which can be adopted in these systems. Placing a condenser (condensing heat exchanger) in the cycle makes it possible to recover all the injected steam. Various types of heat exchangers adapted to systems with steam or water injection have been studied in the literature [26]. The most common known are:

- two types of finned tube exchangers: for exhaust cooled by water and for exhaust cooled by air;
- and direct contact condenser.

The finned tube exchangers are used in the case of mediums with a large amount of exhaust and a small amount of steam. The cooling of exhaust and condensation of water occurs inside the shell on the tubes surface [26]. The projects of water recovery installations for turbine class M1A-13CC (2,3 MWe); 501KH (6,8 MWe); LM1600 (17 MWe); LM2500 (26,4 MWe); LM5000 (50,7 MWe) are already tested in STIG systems. It was shown that the water-cooled condenser with finned tubes is the smallest. The advantage of these exchangers (installation) is the lack of moving parts. But in literature items could be also found rotary condenser-separator, which is compact and inexpensive to produce [27].

Usually, after leaving the gas turbine and putting the thermal energy in the heat recovery steam generator, the gas - steam mixture goes to annular inlet channel with lattice guide vanes. Next the mixture is directed into vortex chamber and moves along its circumference toward the center, where is placed pipeline discharging the exhaust, which are separated from the steam. Optimal parameters for operation of device and its detailed characteristics can be found in [27].

Nowadays, shell and tube heat exchangers or finned tube exchangers are mostly used in the case of water condensation from exhaust, especially when it happens in the condensing heat exchanger, in which the temperature of the exhaust gas flowing out of the boiler decreases what leads to condensation of the water and the latent heat utilization [28].

3. Results

As previously mentioned, Fig. 1 shows gas-steam unit with the possibility of the use of steam in STIG system. A part of the mass flow of steam generated in the heat recovery steam generator (HRSG) is redirected to the combustion chamber (CC), where is used to reduce the emissions of nitrogen oxides (Fig. 4), and further to increase the power and efficiency of the Brayton cycle in gas turbine (GT) . Thus, we reduce the steam directed to a extraction-backpressure steam turbine and the heat stream supplied to recipient decreases.

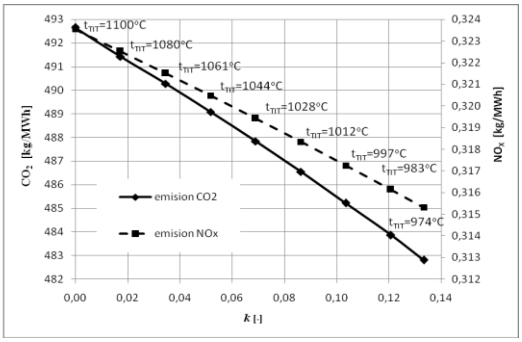

Fig.4. Relationships of the emission of carbon dioxide CO_2 and nitrogen oxides NO_x, and temperature before the gas turbine t_{TIT} depending on k, with $\dot{m}_f$ =const.

Fig. 4 shows the relationships of the emission of CO2, NOx and temperature before the gas turbine t_{TIT} depending on k. In the present case there has been a decrease in carbon dioxide emissions by ΔCO2 = 10 [kg / MWh] and nitrogen oxides emissions by ΔNOx = 0.008 [kg / MWh]. The tendency of NOx emissions is linear depending on the temperature in the combustion chamber, instead of exponential [5], but while lowering the temperature, such arrangements may be adopted.

In turn, while analyzing Fig. 5 it should be noted that electrical efficiency of gas-steam cycle in power plant is η_{el} = 0.4121 [-] and after the transformation of them in the STIG system, the efficiency increases to η_{el} = 0.4205 [-]. The highest efficiency is achieved at a ratio of steam injection at the level of k =0.13 (η_{el} =0.4205 [-]) , where the power of a steam turbine is equal to zero, and the stream produced in the heat recovery steam generator (HRSG), is injected into the combustion chamber (CC). More information about this cycle, and results thermodynamic analysis is presented in works [5,6].

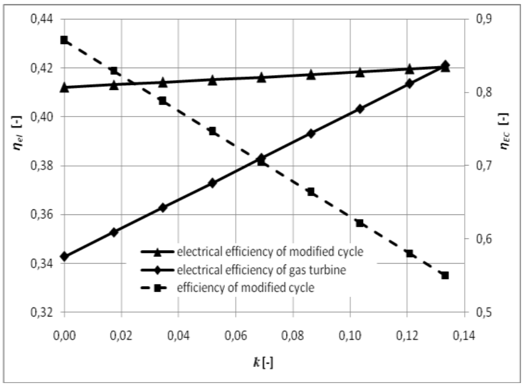

Fig.5. Electrical efficiency η_{el} and the efficiency of the entire power plant η_{EC} depending on k, with $\dot{m}_f$ = const.

In turn, fig. 6 presents the dependence of electrical efficiency η_{el} of CSTIG and simple gas turbine (SGT) from compressor pressure ratio π_c. The efficiency of simple Brayton cycle amounts to a maximum η_{el} = 0.304 and η_{el} = 0.366 if respectively t_{TIT} =900˚C and t_{TIT} =1200˚C. Then, after the transformation of Brayton cycle into the CSTIG system the efficiency increases to η_{el} =0.342 and η_{el} =0.428 if respectively t_{TIT} =900˚C and t_{TIT} =1200˚C. The highest efficiency is achieved with pressure ratio at level of π_c=22. In case of CSTIG, the reduction in emission is achieved slightly better than with introduced STIG system.

Some results of the computations for the total compression π_c=15.0, temperature of the medium at the entry to the turbine t_{TIT} = 1200 ˚C and regeneration degree r = 0.7 are illustrated. The system's electrical efficiency η_{el} versus compression ratio of the compressor's low-pressure part π_{LP} and relative humidity (eq. 7) of the humidified air φ_{22} are shown in Fig. 7. The effect of humidification cooling of the compressed air is clearly visible but it is not identical for efficiency and internal unit power. The largest increasein efficiency – about 0.045 – occurs for the compression ratio π_{LP} = 5. The humidification of air at higher compression ratios π_{LP} results in smaller efficiency increments.

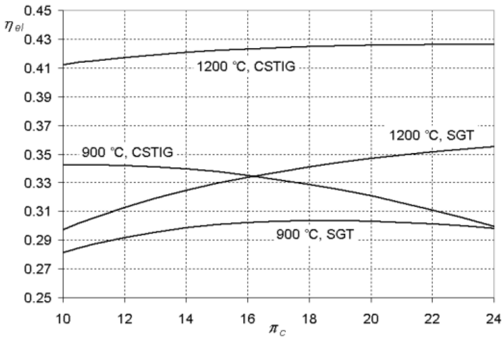

Fig.6. Dependence of the electrical efficiency η_{el} of CSTIG (k = 0.04) and simple gas turbine SGT (k = 0.0) from compressor pressure ratio π_c for the turbine inlet temperature t_{TIT} = 900 ˚C and 1200 ˚C.

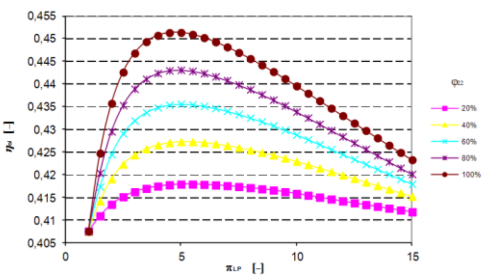

Fig.7. System electric efficiency η_{el} versus compressor low–pressure part compression ratio and relative air humidity φ after humidification, with $\dot{m}_f$ = *const*.

As fig. 7 shows, the lower the relative humidity the weaker the effect of humidification. Considering that the rate of evaporation of water from the surface of droplets decreases as relative humidity increases, in order to keep the humidification chamber's size small, humidification is terminated once suitably lower values of relative humidity φ_{22} are obtained. To estimate an accurate level of relative air humidity after humidification φ_{22}, it is necessary to use a 3D model of humidification chamber in CFD (Computational Fluid Dynamics) framework [23,24]. On the other hand, to estimate a lifetime of combustion chamber, it is necessary to use three dimensional CSD model of solid part of combustion chamber while changing exhaust gas composition and with other variables parameters relating to the combustion and humidification process [29-30].

An equally important aspect is the economic analysis. Examples are presented in detail in the literature [2,30-33]. We adopted the methodology presented in [31]. However, some examples are available in papers: [34-39]. The calculation results shows that building of a gas turbine in Cheng system, based on GT8C turbine, there could be considered as profitable (NPV>0). For this construction variant, the period after which investments will be recovered (SPBP) is shorter than for the variant of conventional gas-steam unit construction.

4. Conclusions

By using water or steam injection, electrical power and electrical efficiency of both the gas turbine and the entire CHP unit, working as power plant, increases. An additional advantage of these solutions is the reduction in emission of pollutants such as nitrogen oxides and carbon dioxide. Thus, the use of steam or water in order to increase the flow of working medium in the Brayton cycle is the preferred way in terms of thermodynamic, economic and ecological in traditional cogeneration systems. Additionally, utilization of waste heat recovered from the exhaust gases of the power generation unit by means of low-temperature heat exchanger can be realized [40,41]. The disadvantage of these solutions is the need of water recovery from the exhaust gases, but currently we observe substantial progress in the design of condensing heat exchangers, which could be used in such systems. To the final and full comparison of these systems there is required 3D CFD analysis of key elements of cycle, under which water or steam are entered.

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