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Multiple approach to analysis of H_2O injection into a gas turbine

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Abstract

This paper presents a thermodynamic analysis of the Brayton cycle and an upgrade to it involving the injection of H_2O into the gas turbine cycle. Upgrades are generally considered to be environmentally-friendly solutions and lead to an increase in efficiency, but in the literature there is no clear answer as to what type of upgrade is the best. Computational Flow Mechanics codes have been used 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. Different ways of analyzing H_2O injection into the gas turbine cycle are discussed.

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

1. Introduction

Today, almost all developed countries, including Poland, are faced with the problem of an insufficient amount of electricity. An additional difficulty is the need to meet environmental standards set by EU Directive No. 2010/75/EU [1]. Ecological solutions delivering growth in electric capacity include upgrading existing gas unit and units of gas-steam power plants in systems with injection of water or steam to the gas turbine [2–5]. The power and efficiency of the basic Brayton cycle can be increased by using 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. STIG and CSTIG are particularly beneficial, while the demand for heat and power plants is falling. 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 the steam turbine. Moreover, the STIG and CSTIG systems provide flexible operation of power plants with optimal utilization of generated steam [6–8]. Many studies have been carried out on gas turbines with the steam injection. Ever since Cheng proposed a gas turbine with steam injection in 1978, retrofitted gas turbines have been widely analyzed and developed [4, 9]. Cheng suggested that the whole steam produced in the heat recovery steam generator (HRSG) can be used for injection into a gas turbine combustion chamber, which results in an increase in both power and efficiency as well as a reduction in NOx [9].

However, CSTIG and STIG are gas-steam systems, in which a Brayton gas cycle is combined with a 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 the Brayton cycle increases [9–11]. The specification of these systems makes high electrical efficiency achievable in small systems as well. In addition, the exhaust gases leaving the combustion chamber contain only small amounts of toxic components, so expensive exhaust treatment systems are not required [10, 12]. Particular advantages are achieved together with a reduction in emissions of nitrogen oxides in gas turbines that generate predominantly through the Zeldowicz mechanism (called thermal mechanism) [13]. As a result of steam injection into a combustion chamber, the temperature of the combustion process decreases and consequently emissions of nitrogen oxides are reduced [4, 14]. It should be added that in some applications gas turbines are used as a heat supply for the stripping process in a supercritical CHP plant integrated with a carbon capture installation. This helps cut carbon emissions [15].

The first proposed upgrade to the Brayton cycle with steam injection system, as presented by Saada and Cheng, concerned the General Electric LM2500 turbine [4]. At present,

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steam injection into the combustion chamber is used in turbines by leading companies such as General Electric, Rolls-Royce, Kawasaki [4, 16]. In the paper [17] it is shown that applying STIG to a basic gas turbine cycle of General Electric Frame 6B could increase efficiency from 30% to 40% and power from 38 to 50 MWe. More complex systems exist, e.g. using water injection to compressed air as inter- or inlet-stage cooling [18–20], in 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, intercooled-after-cooled steam injected cycle) [3] and LOTHECO cycle (low temperature heat combined cycle), using an 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. During spraying, the water evaporates in contact with the hot and compressed air mass flow rate , which in turn lowers the air temperature and reduces the amount of work required to drive the compressor. This system with inter-stage cooling of air can be successfully used in high-pressure turbines [20].

Moreover, the construction of a Humidified Air Turbine (HAT) is based on the concept of combining the regenerative air preheating for combustion and the injection of water mass flow rate between the compressor and heat exchanger (without changing the flow of compressed air). Injection of water into the air, before the regenerative heat exchanger, lowers the temperature of the compressed medium and therefore increases the efficiency of heat regeneration. Because of the use of the regenerative heat exchanger in HAT, the optimum compression ratios are lower than in the STIG, thereby resulting in a higher temperature after the turbine in the order of 800°C. In HAT systems, the temperature distribution mediums in the regenerative heat exchanger are 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, is observed. But the disadvantage of these systems is that they require changes in construction and, consequently, increased investment outlays [3, 14, 20].

Next, the LOTHECO cycle (LOw Temperature HEat COmbined cycle) employs an external renewable heat source to heat up and evaporate the water condensed from the exhaust gases [3]. For a temperature range of evaporation from below 100°C to 170°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% were 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

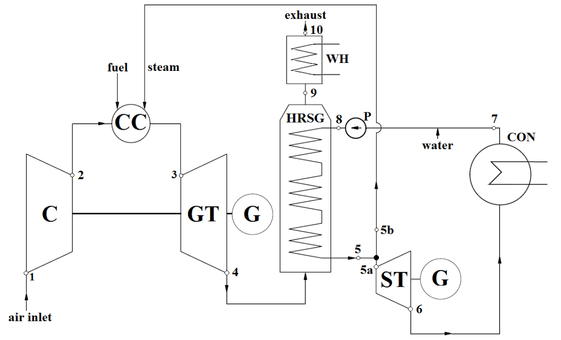

Figure 1: Schematic diagram of gas-steam cycle with a possibility of transition to the STIG, (GT—gas turbine, C—compressor, CC—combustion chamber, G—generator, HRSG—heat recovery steam generator, ST—steam turbine, P—pump, CON—condenser, WH—heat exchanger) [6]

CFM (Computational Flow Mechanics) [5, 14, 21, 22] and a commercial package. Then an analysis of efficiency for three modifications is conducted: in the Brayton cycle with water injection to the compressor and the regeneration prior to the combustion chamber, and in the STIG and CSTIG systems. Additionally, different aspects of H_2O injection into the gas turbine cycle are presented. An economic analysis was carried out in respect of two units, both approximately 66 MWe – for a gas-steam unit and a unit in the Cheng system.

2. Theory

CFM type numerical codes were used in the analysis of thermodynamic cycles. CFM mathematical models (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, 24], calculation procedures were presented for all components of the turbine set, such as compressors, combustion chambers, turbines, pumps and heat exchangers. The power, efficiency, steam injection rate and other relevant values have been defined in previous papers of the authors [6, 7, 24].

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

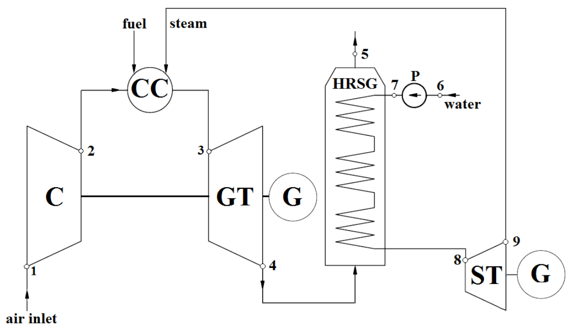

Figure 2: Schematic diagram of CSTIG system (GT—gas turbine, C—compressor, CC—combustion chamber, G—generator, HRSG—heat recovery steam generator, ST—steam turbine, P—pump)

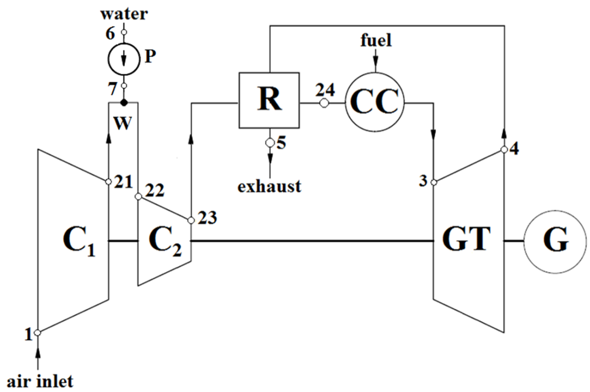

Figure 3: Schematic diagram of the system with regeneration and interstage cooling in the compressor through water injection (C1, C2—low- and-high pressure compressor, R—regenerative heat exchanger, CC—combustion chamber, GT—gas turbine, G—generator, W—water injection, P—pump)

These systems all have their own advantages and disadvantages, which will be briefly described. The STIG system has a simple design and the possibility of easy redirection of steam to the gas turbine system. Unfortunately, it does not use most of the energy flowing from the steam produced in the heat recovery steam generator (HRSG). An improvement of the present solution is reached in the combined system of CSTIG, but in this situation there is a problem with designing a new steam turbine adapted to the required pressure drop. In turn, the water injection solution does not require a 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 this solution is that it reduces the temperature behind the compressor, thus reducing the compression work and increasing the degree of regeneration. All these factors make it difficult to identify the better solution in thermodynamic and ecological terms, without prior analysis and comparison of the results of all three systems.

2.1. Water recovery

The disadvantage of the solutions discussed above is the need for water recovery from flue gas mixtures. However, there has been substantial progress in the design of condensing heat exchangers, which can be adapted for the purpose of these systems. Placing a condenser (condensing heat exchanger) in the cycle means all the injected steam can be recovered. Various types of heat exchangers adapted to systems with steam or water injection have been studied in the literature [26]. The ones most commonly 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 with 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]. Projects of water recovery installations for turbine classes M1A-13CC (2.3 MWe); 501KH (6.8 MWe); LM1600 (17 MWe); LM2500 (26.4 MWe); LM5000 (50.7 MWe) have already been 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 the literature there is also a 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 an annular inlet channel with lattice guide vanes. Next the mixture is directed into a vortex chamber and moves along its circumference toward the center, where there is a pipeline discharging the exhausts, which are separated from the steam. Optimal parameters for the operation of the 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, which leads to condensation of the water and utilization of the latent heat [28].

3. Results

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

Fig. 4 shows the relationships between emission of CO_2, NO_x and temperature before the gas turbine t_{TIT} depending on k. In the present case there was a decrease in carbon

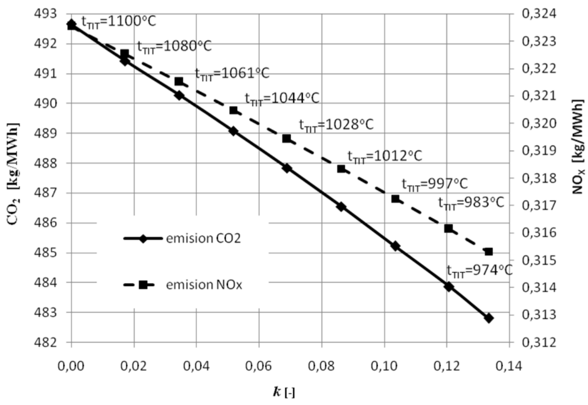

Figure 4: Relationships between emissions of carbon dioxide CO_2 and nitrogen oxides NO_x and temperature before the gas turbine t_{TIT} depending on k, with $\dot{m}_f = const$

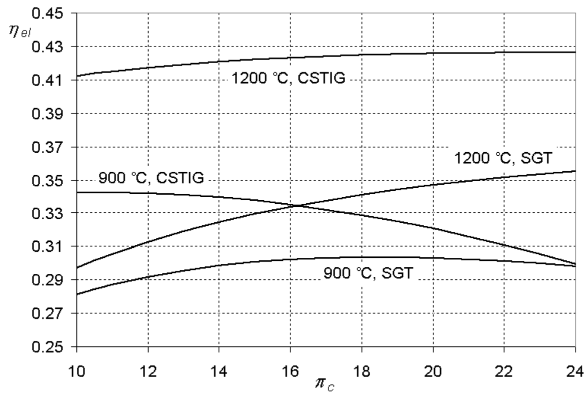

Figure 6: The correlation between the electrical efficiency η_{el} of CSTIG ($k = 0.04$) and a simple gas turbine SGT ($k = 0.0$) and the compressor pressure ratio π_c for the turbine inlet temperature $t_{TIT} = 900°\mathrm{C}$ and $1200°\mathrm{C}$

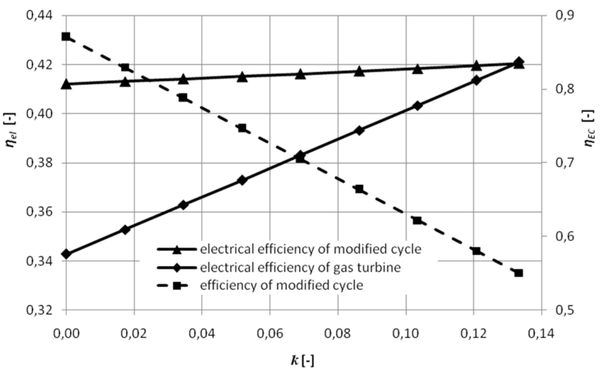

Figure 5: Electrical efficiency η_{el} and the efficiency of the entire power plant η_{EC} depending on k, with $\dot{m}_f = const$

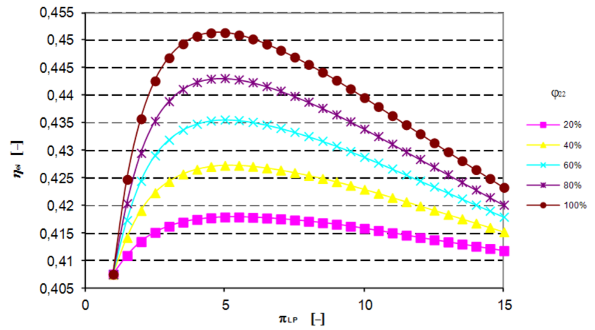

Figure 7: System electrical efficiency η_{el} versus the compression ratio of the compressor's low–pressure part and relative air humidity φ after humidification, with $\dot{m}_f = const$

dioxide emissions by $\Delta CO_2 = 10$ kg/MWh and nitrogen oxides emissions by $\Delta NO_x = 0.008$ kg/MWh. The tendency of NO_x emissions is related to the temperature in the combustion chamber and is linear, instead of exponential [5], but when lowering the temperature, such arrangements may be adopted.

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

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

Some results of the computations for the total compression $\pi_c = 15.0$, temperature of the medium at the entry to the turbine $t_{TIT} = 1200°\mathrm{C}$ and the regeneration degree $r = 0.7$ are illustrated. The system's electrical efficiency η_{el} versus the compression ratio of the compressor's low-pressure part π_{LP} and relative humidity 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 increase in efficiency—about 0.045—occurs for the compression ratio $\pi_{LP} = 5$. The humidification of air at higher compression ratios π_{LP} results in smaller efficiency increments.

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 size of the humidification chamber 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 a humidification chamber in a CFD (Computational Fluid Dynamics) framework[23, 24]. On the other hand, to estimate the lifetime of a combustion chamber, it is necessary to use a three dimensional CSD model of the solid part of a combustion chamber while changing the composition of the exhaust gas, with other variable 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 show that building a gas turbine in the Cheng system, based on the GT8C turbine, 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 a conventional gas-steam unit construction.

4. Conclusions

By using water or steam injection, the electrical power and electrical efficiency of both the gas turbine and the entire CHP unit, working as a power plant, increase. An additional advantage of these solutions is the reduction in emissions of pollutants such as nitrogen oxides and carbon dioxide. Thus, the use of steam or water in order to increase the flow of the working medium in the Brayton cycle is preferred in terms of thermodynamics, economics and ecology in traditional cogeneration systems. Additionally, utilization of waste heat recovered from the exhaust gases of the power generation unit by means of a low-temperature heat exchanger can be realized [40, 41]. The disadvantage of these solutions is the need for water recovery from the exhaust gases, but there has been substantial progress in recent years in the design of condensing heat exchangers, which could be used in such systems. For a full and final comparison of these systems, a 3D CFD analysis is required so as to determine the key parameters of the cycle under which the water or steam enters.

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