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A LOW-IMPACT HIGH-EFFICIENCY BRAYTON CYCLE CONCEPT WITH EVAPORATIVE COOLING DURING THE COMPRESSION PROCESS USING H_2/CH_4 FUEL BLENDS

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Towards a low-impact high-efficiency Brayton cycle concept, a gas generator system including a compressor with evaporative cooling, a combustion chamber using H_2/CH_4 fuel blends and a gas turbine is being analyzed at this preliminary stage. The Constructal approach on the effectiveness of compressed air temperature control by evaporative cooling, previously carried out by the authors, shed some light on the potential growth of mechanical power provided by gas turbine power plants of 45.81% and a simultaneous reduction of 2.26% in specific fuel consumption.

The current study, carried out on the combustion chamber, reveals that increasing the H_2 fraction in the fuel blend results in a direct reduction in carbon dioxide production and in a decrease in CO and NO_x emissions when the temperature of the flue gas is maintained at 1450 K. Meanwhile, the exergy efficiency of the combustion chamber remains almost constant at 39.3%. Study of the two components already analyzed, the compressor and the combustion chamber, allows us to move towards a low-impact, high-efficiency Brayton cycle concept as close as possible to its technical implementation.

Keywords: Evaporative cooling; Hydrogen; Brayton cycle; Entropy generation; Constructal Law.

1. INTRODUCTION

A large body of work has been devoted during the last decade to studying evaporative cooling, one of the simplest and least expensive air cooling technologies applied in the gas turbine industry [1-3]. The authors have already developed, based on the Constructal Law, a complete assessment of the maximum potential of evaporative cooling to control the temperature of compressed air in gas turbine power plants (GTPP) [4]. In an attempt to develop a Brayton cycle concept not only aiming at high efficiency but also focusing on lower impact, this work considers evaporative cooling of the compressor and the use of methane and hydrogen blends in the combustion chamber. The thermodynamic optimization method based on the minimization of entropy generation is used to study the operation of a combustion chamber with H_2/CH_4 fuel blends, aiming at the direct reduction in carbon dioxide production and also the reduction of CO and NO_x emissions.

2. PHYSICAL AND MATHEMATICAL MODELING

The physical model of the gas turbine power plant considered in this study is represented by the compressor, the combustion chamber and the turbine assembly shown in Fig. 1. Details of the compressor design are presented conceptually in Fig. 1, where it can be observed how temperature control is physically

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performed during the compression process by means of the evaporative cooling due to the vaporization of liquid water continuously injected along the compressor [4].

The combustion chamber, which is the focus of this study, receives high-pressure saturated humid air in state 2 after its passage through the compressor. To first study the CO_2 emission levels, it is considered in this study that the combustion chamber is fed with H_2/CH_4 fuel blends of various compositions.

The mathematical modeling of the combustion process was performed based on the equations of the Law of Conservation of Energy and the 2nd Law of Thermodynamics for the steady-state operation of the adiabatic CC, assuming the combustion of H_2/CH_4 fuel mixtures with variable excess air (λ) in order to control and maintain constant the temperature of the combustion gases T_3 at the CC outlet. The formation, by dissociation, of the following chemical species was also considered: CO_2, CO, H_2O, OH, H_2, O_2, N_2, NO, NO_2.

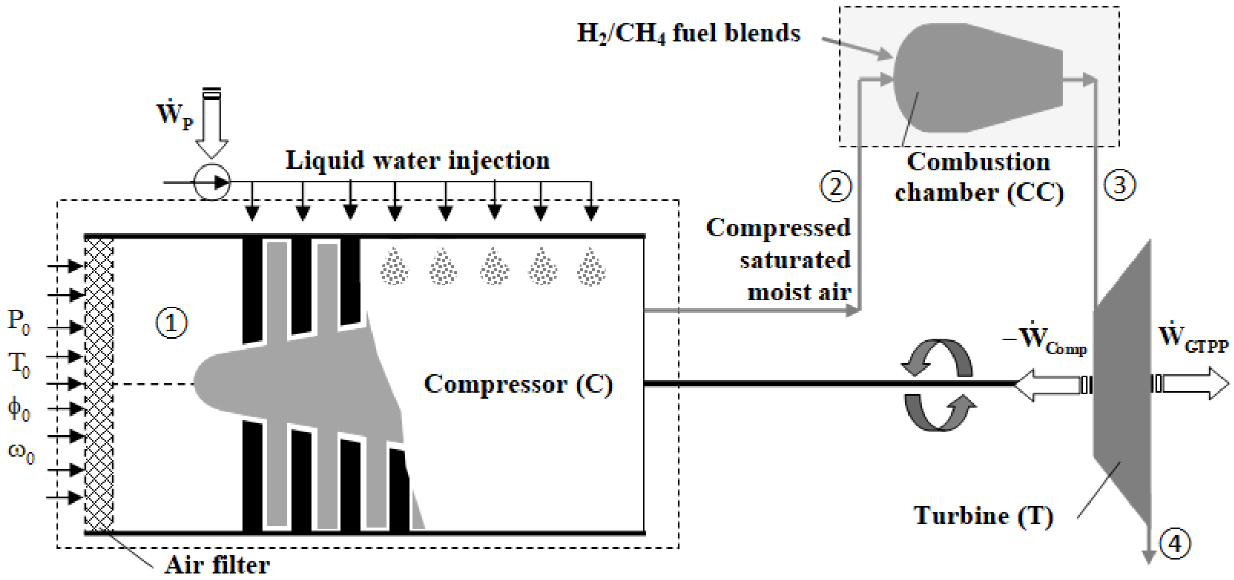

Fig. 1 – Physical configuration of a GTPP using H_2/CH_4 fuel blends, where the liquid water injection develops along the compressor permanently maintaining the relative humidity of the compressed moist air at its maximum possible value.

Table 1

Numerical values of the excess air λ and the chemical composition of the combustion gases

f_{H_2}	λ	y_CO₂ (%)	y_CO (ppm)	y_H₂O (%)	y_OH (ppm)	y_H₂ (ppm)	y_O₂ (%)	y_N₂ (%)	y_NO (ppm)	y_NO₂ (ppm)
0.0	2.02	4.94	0.159	9.88	33.406	0.131	10.053	75.048	680.64	7.572
0.1	2.04	4.77	0.146	10.06	32.934	0.128	10.115	74.982	672.89	7.576
0.3	2.08	4.33	0.118	10.51	31.727	0.120	10.277	74.810	653.54	7.585
0.5	2.13	3.72	0.087	11.15	30.238	0.111	10.511	74.551	629.30	7.607

Based on the mathematical model, the numerical values of the excess air and the chemical composition of combustion gases are calculated when the molar fraction of H_2 in the fuel mixture, f_{H2}, is known.

3. RESULTS

Results of the numerical simulation, performed with the CEA program developed by NASA Lewis Research Center [5], are presented in Table 1. The fuel mixture ratios, as well as the fuel/oxide mixture ratio, were defined by imposing the molar fractions of CH_4 and H_2, and O_2 and N_2, respectively, to maintain a maximum temperature of 1450 K under constant pressure at 0.7MPa. The main chemical species resulting from the dissociation processes during combustion are tracked as molar fractions and studied in relation to compliance with current emission standards. Based on the 2^{nd} Law, the generation of entropy (exergy destruction) was also calculated. The numerical results obtained show a decrease of only 0.2% in the combustion chamber`s exergy efficiency when the fraction of hydrogen in the fuel blend increases to 50%.

4. DISCUSSION AND CONCLUSIONS

The first step in developing the new low-impact high-efficiency Brayton cycle concept was to investigate the limits and conditions in which the real axial compressor's design may evolve in order to make the gas compression as close as possible to an isothermal process. Based on the Constructal Theory the compressor`s physical modeling was carried out as an ensemble of adjacent elemental compressors that"...provides easier access to the imposed currents that flow through it". Compressed moist air temperature control within each of the elemental compressor is done based on the evaporative cooling principle. The results obtained based on the Constructal approach, with indirect evaporative cooling at the compressor aspiration and "inter-stage water spraying", show comparatively that during most of the compression process a temperature of the compressed moist air 45% lower. Providing a "globally easier flowing configuration", the Constructal approach with indirect evaporative cooling at the compressor aspiration and "inter-stage water spraying", shed some light on the potential of growth in the mechanical power delivered by the GTPP of 45.81% and a simultaneous reduction of 2.26% in the fuel specific consumption. Numerical results on the entropy generation due to the compressor functioning confirm the realism of the adopted assumptions and the adequacy of the mathematical formulation of the proposed model for numerical simulation purposes. Application of water injection in each compressor stages involves miniature holes drilled on stators and a sophisticated water injection system. The experiments regarding water injection through TV2-117A intake, reconfigured from kerosene to methane showed not only a power augmentation but also NO_x emissions reduction similar to the work presented in [6]. Thus the introduction of water into the gas turbine intake at idle generates a reduction of averaged turbine inlet temperature of about 5 ^{0}C and also NO_x emissions fall by approximately 4 ppm. The results also agree well in terms of variation of cross-sectional area, isentropic efficiency, maximum temperature and pressure, with the data available for the axial compressors of the following widely produced and "in service" gas turbine engines: TV2-117, TV3-117, RU19A-300 and AI20 [7]. The numerical results presented in this work compare well with those of other authors [8] and show advantages in terms of emission reduction when H_2/CH_4 fuel mixtures are fed into gas turbine power plants. Therefore, it is feasible to integrate the two components studied so far, compressor and combustion chamber, into a single low-impact, high-efficiency equipment. Next, this research will be continued following the principles of finite-speed irreversible thermodynamics [9], focusing on the optimization of gas turbine blade geometry. Thus, minimizing the generation of entropy in order to maximize the mechanical power of the turbine, the expansion process of the gases passing through the turbine must be carried out as close as possible to an isentropic expansion.

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REFERENCES

1. Barigozzi G. *et al*., Techno-economic analysis of gas turbine inlet air cooling for combined cycle power plant for different climatic conditions, *Applied Thermal Engineering*, **82**, 57–67 (2015).
2. Ibrahim M. A., Varnham A., A review of inlet air-cooling technologies for enhancing the performance of combustion turbines in Saudi Arabia, *Applied Thermal Engineering*, **30**, 1879–1888 (2010).
3. Bhargava *et al*., Gas turbine compressor performance characteristics during wet compression – influence of polydisperse spray, *Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air* (GT2009), June 8–12, 2009, Orlando, FL USA.
4. Stanescu G., Ene B., Vilag V., Andreescu T., Constructal approach on the feasibility of compressed air temperature control by evaporative cooling in gas turbine power plants, *Proceedings of the Romanian Academy, Series A*, Special Issue, 2018, pp. 201–206
5. Gordon S. and McBride B.J., *Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications*, NASA Reference Publication, 1311, 1996.
6. Barbu E. *et al*., The influence of inlet air cooling and afterburning on gas turbine cogeneration groups performance, *Gas Turbines – Materials, Modeling and Performance*, Dr. Gurrappa Injeti (Ed.), InTech, 2015.
7. Stanescu G., Barbu E., Vilag V. and Vilag J., Achieving Temperature Control by Direct Injection of Liquid Water in Axial Compressors of "in-service" Gas Turbine Engines, *Proceedings of the 16th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, 2022.
8. Lopez-Ruiz G., Castresana-Larrauri J., Blanco Ilzarbe, J.M., Thermodynamic Analysis of a Regenerative Brayton Cycle Using H_2, CH_4 and H_2/CH_4 Blends as Fuel, *Energies*, *15*, p. 1508 (2022), https://doi.org/10.3390/en15041508
9. Petrescu S. *et al*., *Advanced Thermodynamics of Irreversible Processes with Finite Speed and Finite Dimensions*, Edit. AGIR, 2015.