Thermodynamic Cycle Optimization for an Advanced Micro Turbine Power Plant

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Abstract. Research interest regarding micro turbines has improved, as their development and manufacturing increased due to the rapid expansion of their application range, from military applications to civil ones. This paper aims to present the methodology used for the ascertainment of the optimal configuration for the functional parameters of a micro jet engine, using a mathematical model for the evaluation of the Brayton cycle as well as a commercial software for its investigation. The DevJet micro jet engine is developed for a thrust of 80 daN with an estimated rotational speed of 40,000 rpm. An analytical model of the Brayton cycle for the evaluation of the main parameters of interest is employed and twelve variants are evaluated, considering values for the pressure ratio ranging from 4 and up to 5, while the maximum temperature range is between 1,050 K and 1,200 K. The optimal variant is selected, and the data is transferred to the commercial software GasTurb in order to generate the diagram of the thermodynamic cycle. The outcome of this research paper represents the input data for the 3D modelling and numerical simulation of the main systems of the micro jet engine.

1. Introduction
Due to the expansion of their application range, micro jet engines were the subject for several studies and researches, as engineers attempt to obtain optimal configurations for each of their application [1]. Major applications for micro jet engines are encountered in the military field and commercial aviation [2], as well as in the didactic field [3]. This propulsion system is largely used for the development of Unmanned Air Vehicles (UAVs), that are used for national security, surveillance, telecommunication, agriculture, aerospace engineering, energy etc. [4]. When compared to other propulsion systems, such as reciprocating engines or turbojet engines, micro jet engines have the following advantages: a reduced noise level and pollution level, compatibility with a variety of fuels, light weight and reduced dimensions [5].

The aim of this research is to determine an optimal configuration for the functional parameters of the thermodynamic cycle of the micro jet engine, by analysing several variants. In order to achieve this, a mathematical model for the evaluation of the Brayton thermodynamic cycle is presented and discussed. A total of twelve possible variants are evaluated, varying the pressure ratio and maximum temperature. The data from the optimal variant is implemented in GasTurb in order to proceed with the generation of the cycle’s diagram and its interpretation.

The Brayton thermodynamic cycle has multiple applications and has been improved, optimized and associated constantly with other thermodynamic cycles, such as Rankine or Stirling in order to gain
better results. Yue and Lior present a comparative study between hybrid and non-hybrid Brayton cycles in paper [6]. The hybrid cycles employ the use of various heat sources of different temperatures and the research paper concludes that hybrid Brayton cycles can generate lower emissions and can reduce fuel usage. In terms of efficiency, the authors conclude that the hybrid cycle’s efficiency is proportional with the efficiency of the heat source. An investigation regarding simple and regenerative Brayton cycles with application in the solar power industry is discussed by Javanshir et al. [7]. The paper analyses the performances of both cycles and aims to establish which working fluid is best suited for the maximization of power output, considering its application. In the context of their study, the authors consider Helium to be the best working fluid for the studied Brayton cycles. To generate carbon free energy, Sachdeva and Singh [8] introduce a triple combined thermodynamic cycle with applications in the solar power industry. The three combined cycles include air Brayton cycle, organic Rankine cycle and steam Rankine cycle, the resulted combined cycle runs using only solar radiations to produce power, without using adjacent energy sources. These represent just a few examples of applications for the Brayton cycle in the energy industry. Its applications extend to aerospace engineering, as shown in paper [9]. Yu et al. study the development of a novel hypersonic aeroengine, based on an optimized multi-branch closed Brayton cycle. For the exhaust gas heat recovery in turbomachinery, the employment of supercritical Brayton cycles is investigated by Uusitalo et al. [10]. As all the cited articles imply, amongst many other in literature, the study of the Brayton thermodynamic cycle represents a starting point for the development of efficient power and propulsion systems. A mathematical model for the simple Brayton cycle in accordance with literature specifications [11, 12] is presented in this paper and evaluated using the GasTurb software. As stated previously, the aim of this investigation is to determine the functional parameters for a micro jet engine, that in future work will be used as input data for the designing of the main systems of the developed micro jet, namely its compressor, combustion chamber and turbine.

2. Mathematical model for the evaluation of the simple Brayton thermodynamic cycle
In this section an analytical model for the evaluation of the Brayton thermodynamic cycle is presented, in accordance with the specifications and limitations given by research papers [13,14].

2.1. Input data
In order to start the calculation activities, one must specify the input data in accordance with their application. In table 1 the parameters used in the evaluation of the Brayton cycle for the DevJet micro jet are presented.

| Parameter               | Value          |
|-------------------------|----------------|
| Thrust [daN]            | 80             |
| Pressure ratio          | 4-5            |
| Maximum temperature [K] | 1,050-1,200    |
| Rotational speed [rpm]  | 40,000         |

2.2. Mathematical model
In this section, the mathematical formulas that assist the calculation activities of the simple Brayton thermodynamic cycle are presented. The values for the pressure, temperature and enthalpy (calculated as a function of specific heat at constant pressure and temperature) at the admission entry section are considered as follows:
At the admission exit and compressor entry, the functional parameters can be calculated using equations (2):

\[ T_1^* = T_0 \]
\[ p_1^* = \sigma_{ad} \cdot p_0 \]
\[ h_1^* = c_p \cdot T_1^* \]  

(2)

Where \( \sigma_{ad} \) represents a coefficient that evaluates pressure losses in the admission.

For the compressor exit and combustion chamber entry, the parameters of interest are evaluated using equations (3):

\[ p_{2id}^* = p_1^* \cdot \tau_c \]
\[ T_{2id}^* = T_1^* \left( \frac{P_{2id}^*}{P_1^*} \right)^{\frac{k-1}{k}} \]
\[ h_{2id}^* = c_p \cdot T_{2id}^* \]  

(3)

Before moving forward, to the turbine’s entry, the mechanical work and efficiency of the compressor must be evaluated. For this, equations (4) are used.

\[ l_c^* = \frac{l_{cid}}{\eta_c} \]
\[ h_2^* = l_c^* + l_i^* \]
\[ T_2^* = \frac{h_2^*}{c_p} \]
\[ p_2^* = p_{2id} \]  

(4)

At the combustion chamber’s exit and turbine’s entry, the thermodynamic parameters are calculated using equations (5).

\[ p_3^* = p_2^* \cdot \sigma_{cc} \]
\[ h_3^* = c_{pp} \cdot T_3^* \]  

(5)

The pressure losses in the combustion chamber are considered through the parameter \( \sigma_{cc} \).

For calculations activities in the turbine exit – exhaust entry section, equations (6) are employed.
In the exhaust section the parameters are evaluated using the following equations:

\[ I'_r = \frac{I'_r}{\eta_m} \]
\[ I'_{rad} = \frac{I'_r}{\eta_r} \]
\[ h'_{sid} = h'_s - I'_{rad} \]
\[ T'_{sid} = \frac{h'_{sid}}{c_{pg}} \]
\[ p'_{sid} = p'_s \left( \frac{T'_{sid}}{T'_s} \right)^{\frac{k_s}{k_s-1}} \]
\[ \dot{m} = \frac{\left( h'_s - h'_s \right)}{s_{cc} \cdot P_{cl} - h'_s} \]

Fuel mass flow, as well as air mass flow and specific fuel consumption can be calculated with equations (9):

\[ F_{sp} = \left( 1 + \frac{\dot{m}_s}{\dot{m}_a} \right) \cdot C_s \]
\[ M_a = \frac{F}{F_{sp}} \]
\[ c_{sp} = \frac{3600 \cdot \dot{m}_s}{F_{sp}} \]

In the end, the efficiency of the DevJet micro jet is evaluated with the following equation:
Using this mathematical model, a total of 12 variants were calculated, using various values as input data for the pressure ratio and maximum temperature, as shown in table 1.

3. Results

With the output data from the previous section, the optimal variant for this specific application is considered the one with a pressure ratio of 4.5 and a maximum temperature value of 1,050K. The choice was based on the materials available for the manufacturing of such a micro jet and their characteristics, as well as on the evaluated efficiency of 34.38%, specific fuel consumption of 0.128 kg/Nh and air mass flow of 1.55 kg/s. The mass flow was slightly reduced when introduced in GasTurb, as this parameter is considered to have a lower value for micro jet engines [15].

The data is transmitted to the GasTurb software, in order to validate the mathematical model and to generate the cycle’s diagram. The aforementioned software can estimate the global performances of a propulsion system based on a set of input data and can also generate diagrams of interest (such as pressure-volume, temperature-entropy) and schematic representations of the main components of the engine [16].

In order to determine the simple Brayton thermodynamic cycle using GasTurb, the efficiency of the compressor and turbine where imposed to be 82% and 85%, respectively, based on previous experience of the authors. The input data for the program is presented in table 2.

| Parameter                          | Value          |
|-----------------------------------|----------------|
| $M_a$ $[kg / s]$                  | 1.4            |
| $\sigma_{DD}$                     | 0.99           |
| $\pi_c$                           | 4.5            |
| $T_i [K]$                         | 1,173          |
| $P_{ct} [MJ / kg]$                | 43.124         |
| $\sigma_{cc}$                     | 0.94           |
| $T_{ci} [K]$                      | 288            |
| $p_{i}^{*} [kPa]$                 | 100.312        |
| $p_{amb} [kPa]$                   | 101.325        |
| $\eta_c$                          | 0.82           |
| $\eta_{t}$                        | 0.85           |
| $n [rpm]$                         | 40,000         |

The results for each section are presented in table 3.
Table 3. GasTurb results for each section.

| Section               | Mass flow [kg/s] | Temperature [K] | Pressure [kPa] |
|-----------------------|------------------|-----------------|---------------|
| 1 – compressor entry  | 1.373            | 288             | 100.312       |
| 2 – combustion chamber entry | 1.373      | 474.89          | 446.89        |
| 3 – turbine entry     | 1.384            | 1,173           | 420.077       |
| 4 – exhaust entry     | 1.384            | 1,015.67        | 205.728       |
| 5 – exhaust exit      | 1.384            | 1,015.67        | 205.728       |

The cycle’s diagrams were generated and are illustrated in figures 1 and 2.

Figure 1. Pressure-Volume diagram of the studied thermodynamic cycle.

Figure 2. Temperature-Entropy diagram of the studied thermodynamic cycle.

The specific fuel consumption is estimated to be 0.101 kg/Nh, whereas for the global efficiency of the micro jet, its value is 23.71%. The software returned a calculated value of the thrust of 91 daN,
bigger than the one established in table 1. This value is explained through the fact that the software automatically assumes the combustion chamber’s efficiency at 100%.

For the graphic representation of the variations of the pressure ratio, mass flow and exhaust velocity as a function of thrust, two parameters were considered. The first one was the pressure ratio, established in a range varying from 4 and up to 5, with a step of 0.25. The other one was the air mass flow, defined in a range from 1.3 kg/s to 1.5 kg/s, with a step of 0.05.

In figure 3, that shows thrust variation with pressure ratio for a given range for the mass flow and pressure ratio, the black point indicates the previously calculated thermodynamic cycle. The thrust’s growth with the mass flow is more accelerated, compared to its growth reported to the pressure ratio. Given this, the air mass flow value of 1.4 kg/s might have been overvalued and can be reduced in order to reduce the thrust of 91 daN. In figure 4, the rapid growth of thrust with the increase of mass flow is better highlighted.
Regarding the velocity exhaust, this parameter is inversely proportional with the pressure ratio, as illustrated in figure 5.

Figure 5. Thrust variation with nozzle exit velocity.

4. Conclusions
This paper evaluated the simple Brayton thermodynamic cycle both through a mathematical model and an automatic software. The purpose was to determine the optimal functional parameters for a micro jet engine with an 80daN thrust.

After evaluating the thermodynamic cycle using both methods, the values of 4.5 for the pressure ratio and 1.4 kg/s for the air mass flow were considered appropriate, as figures 3 to 5 concluded that modifications directly affect the micro jet’s thrust and nozzle exit velocity, as well as its overall efficiency. The thrust is slightly overvalued in the GasTurb analysis.

The results represent the input for future work regarding the designing and numerical simulation of the micro jet engine’s components.

5. References
[1] Gerendas M and Pfister R 2000 Development of a Very Small Aero-Engine, *Proc. Of ASME Turbo Expo 2000: 45th ASME International Gas Turbine Aeroengine Technical Congress and Exposition* Germany paper no. 2000-GT-0536.

[2] Boyd D I 1990, Adaption of a Small Commercial Fan Jet Trainer for Military Applications, *The American Society of Mechanical Engineers* New York doi: 10.1115/90-GT-391

[3] Cican G, Toma A, Puscasu C and Catana R 2018 Jet CAT P80 Thermal Analyses and Performance Assessment Using Different Fuels Types, *Journal of Thermal Science* 27 389-393

[4] Davidson C R and Birk A M 2004 Set up and Operational Experience with a Micro-Turbine Engine for Research and Education *Proc. ASME Turbo Expo 2004: Power for Land, Sea and Air*, Austria doi: 10.1115/GT2004-53377

[5] Large J and Pesyridis A 2019 Investigation of Micro Gas Turbine Systems for High Speed Long Loiter Tactical Unmanned Air Systems *Aerospace* 6(5) https://doi.org/10.3390/aerospace6050055

[6] Yue T and Lior N 2018, Thermal hybrid power systems using multiple heat sources of different temperature: Thermodynamic analysis for Brayton cycles, *Energy* 165 639-665
[7] Javanshir A, Sarunac N and Razzaghpanah Z 2018 Thermodynamic analysis of simple and regenerative Brayton cycles for the concentrated solar power applications Energy Conversion and Management 163 428-443
[8] Sachdeva J and Singh O 2019 Thermodynamic analysis of solar powered triple combined Brayton, Rankine and organic Rankine cycle for carbon free power Renewable Energy 139 765-780
[9] Yu X, Wang C and Yu D 2020, Thermodynamic design and optimization of the multi-branch closed Brayton cycle-based precooling-compression system for a novel hypersonic aeroengine Energy Conversion and Management 205 112412
[10] Uusitalo A, Ameli A and Turunen-Saaresti T 2019, Thermodynamic and turbomachinery design analysis of supercritical Brayton cycles for exhaust gas heat recovery Energy 167 60-79
[11] Pimsner V 1988 Turbomachinery (Bucharest: Tehnica Publishing House)
[12] Walsh P P and Fletcher P 2004, Gas Turbine Performance. Second Edition (Oxford, UK: Blackwell Publishing Company)
[13] Japikse D and Baines N C 1994 Introduction to turbomachinery (UK: Oxford University Press)
[14] Hitt P and Peterson C 1992 Mechanics and Thermodynamics of Propulsion (USA: Addison Wesley Publishing Company)
[15] *** JetCat Americas, JetCat Turbines – Products and characteristics. Available at: jetcatamericas.com Accessed at: 19.03.2020
[16] Byerley A R, Rouser K P and O’Down D O 2017 Exploring GasTurb 12 for Supplementary Use on an Introductory Propulsion Design Project Proc. Of the ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition 6 (North Carolina, USA) doi: 10.1115/GT2017-63465