

TWO STAGE ULTRA MICRO TURBINE: THERMODYNAMIC AND PERFORMANCE STUDY

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Abstract: Nomadic portable systems, such as micro drones, require a micro power generation system. Among the potential systems, the micro turbine seems interesting. However, at this scale, thermal fluxes involve a decrease in the performance of the turbine. Hence, we study a unique architecture of two stage ultra micro turbine, called “cocoon architecture”. This paper presents “Hot Die”, the aerothermodynamic program developed in the aim to assess the effects of thermal fluxes in this system. Theory, equations and concept of the program are presented before dealing with the validation and the results of the calculations.

Key Words: micro turbine, cocoon architecture, thermodynamics, thermal fluxes.

1. NOMENCLATURE

Q_m	: Mass flow rate, Kg.s^{-1}
T_t	: Fluid total temperature, K
P_t	: Fluid total pressure, Pa
P	: Power, W
C_p	: Calorific capacity, $\text{J.Kg}^{-1}.\text{K}^{-1}$
η	: Efficiency
ω	: Rotational speed, rad.s^{-1}
r	: Rotor peripheral radius, m
Ψ	: Rotor working coefficient
Π	: Pressure ratio
γ	: Isentropic coefficient

Subscripts:

1	: upstream	comp	: compressor
2	: downstream	turb	: turbine
comb	: combustion	therm	: thermal
fluid	: fluid	solid	: solid part
conv	: convection	cond	: conduction
rad	: radiative	meca	: mechanical
lp	: low pressure	poly	: polytropic
hp	: high pressure		

2. INTRODUCTION

There is an increasing interest in micro power generation systems for small and portable electronics, robots and micro drones. Since all these systems require a miniaturized power supply with high energy density and high power density, the development of an ultra micro gas turbine is attractive.

At this scale, thermal fluxes are no more negligible, and involve a severe decrease in the

output power and the efficiency. Therefore, a two stage micro turbine based on a unique architecture, called “cocoon architecture” is under study at Onera: a schematic 3D cut of the system is shown in figure 1. The purpose of this structure is to limit the thermal fluxes, by limiting the temperature gradients. The arrangement of the elements is then led by the following principle: the hotter the element, the closer to the core of the system. Thus, the combustion chambers are in the core whereas the compressor rotors are at the periphery.

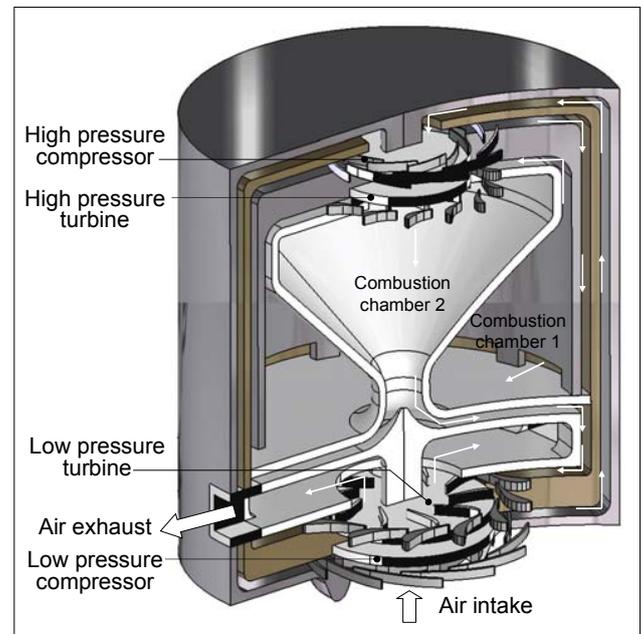


Figure 1 : Schematic 3D cut of the “cocoon architecture” two stage ultra micro turbine

The path of the flow can be seen in figure 1. The air goes first through the low pressure compressor, and the high pressure compressor. Then the flow reaches the first combustion chamber, before being expanded through the high pressure turbine. Finally, the flow is heated again in the second combustion chamber and goes through the low pressure turbine. The corresponding theoretical thermodynamic cycle is a two stage Brayton Joule cycle.

The main application of this system being the micro drones' propulsion, the aimed range of mechanic output power is 50-100W. This micro system measures 20mm wide per 20mm high. The volume of each combustion chamber is 1cm³. The compressor and turbine rotors, which are 8mm in diameter, rotate at approximately 1,000,000rpm, and provide compression and expansion ratios around 2.

For the assessment of the thermodynamic behaviour and the performance of this complex system, "Hot Die", an aerothermodynamic program, has been specifically designed. In addition to fluid mechanics and rotor aerodynamics [2], the program has to model accurately enough the conductive, convective and radiative heat transfers.

In a first step, thermodynamic calculations of "Hot Die" were validated on a simple case.

The aim of the "cocoon architecture" being the limitation of the thermal fluxes, two main versions of "Hot Die" have been developed. The first one models the adiabatic behaviour of the system whereas the second one takes into account the various thermal fluxes. The comparison of these two versions allows us to focus on the influence of the thermal fluxes in this micro turbine.

3. THEORY AND VALIDATION

3.1 Theory, concept and equations

The core of the program is based on two types of stationary thermodynamic balances. The first type is applied to flow volumes, delimited by particular sections. These sections are situated along the flow path, upstream and downstream the components of the system. These balances depend on the considered component (combustion chamber, compressor, etc...) and each balance is specific to the considered volume. The generic fluid balance is given by equation 1:

$$Qm.Cp.(T_{t2} - T_{t1}) = P_{comb} + P_{comp} + P_{turb} + P_{thermFluid} \quad (1)$$

where:

$$P_{comb} = \eta_{comb} \cdot Qm_{comb} \cdot PCI_{comb} \quad (2)$$

$$P_{comp} = Qm \cdot \Psi_{comp} \cdot (\omega_{comp} \cdot r_{comp})^2 \quad (3)$$

$$P_{turb} = -Qm \cdot \Psi_{turb} \cdot (\omega_{turb} \cdot r_{turb})^2 \quad (4)$$

$$P_{thermFluid} = P_{conv} + P_{rad} \quad (5)$$

Thermodynamic balances of the second type are applied to each solid part of the turbine: static ones such as walls and mobile ones such as compressors and turbines. Here is the generic solid part balance:

$$P_{thermSolid} = 0 \quad (6)$$

where:

$$P_{thermSolid} = P_{conv} + P_{rad} + P_{cond} \quad (7)$$

Other fundamental relations, used in "Hot Die", are the equations that link pressure ratios to temperature ratios for the rotors. To study more easily the effects of thermal fluxes, we decided to apply a split between heat losses and aerodynamic losses, by using the following formula:

$$T_{t2}/T_{t1} = (P_{t2}/P_{t1})^{(\gamma-1)/(\gamma \cdot C)} \quad (8)$$

where C is given by equation (9) or (10):

$$C_{comp} = \eta_{polyComp} / (1 + \lambda_{comp}) \quad (9)$$

$$C_{turb} = 1 / (\eta_{polyTurb} \cdot (1 - \lambda_{turb})) \quad (10)$$

$$\lambda_{comp} = P_{thermFluid} / P_{comp} \quad (11)$$

$$\lambda_{turb} = P_{thermFluid} / P_{turb} \quad (12)$$

This approach, applied in previous aerodynamic program [3], is based on the hypothesis according which aerodynamic losses do not change with heat transfers.

The unknowns of the equations system are: solid parts temperatures, flow total temperature in each section and fuel mass flow rate for each of the combustion chambers. All versions of "Hot Die" contain one loop, performed on this equations system, until convergence on the fuel mass flow rates. Finally, aero thermal conditions in each section, solid parts temperatures, heat transfers and various powers are obtained.

It is important to notice that all compressor characteristics, such as working coefficient or pressure ratio, come from 3D aerodynamic studies performed at Onera. Concerning turbines, all

aerodynamic characteristics are calculated and satisfy to all the constraints given by their specific equations.

3.2 Validation

For the validation of “Hot Die”, the calculations are applied to the case of the simple stage theoretical thermodynamic cycle of Brayton-Joule. “Hot Die” calculates the thermodynamic efficiency from the temperatures of the cycle. When considering that the coefficient Cp is constant, the thermodynamic efficiency can be given by the following formula:

$$\eta = 1 - \Pi_{comp}^{((1-\gamma)/\gamma)} \quad (13)$$

Figure 2 presents the efficiency, given by equation (13), and the thermodynamic efficiency, calculated with “Hot Die”, versus pressure ratio:

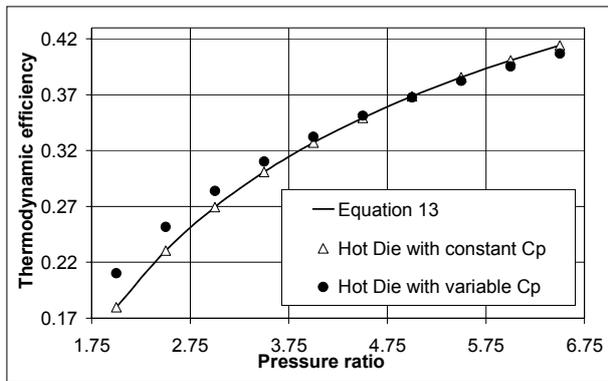


Figure 2 : Validation on the Brayton-Joule cycle: Thermodynamic efficiency versus pressure ratio

Results are identical between equation (13) and the efficiency calculated with a constant Cp. Between equation (13) and efficiency calculated with a variable Cp, the average relative difference is only 4.1%. Thus, this simple case allows us to validate the thermodynamic calculations operated in our program.

4. RESULTS

So as to study the effect of thermal fluxes in the system, two main versions of “Hot Die” have been developed: one deals with the adiabatic case, and the other takes into account the thermal transfers. These versions contain one more loop. For both versions, this loop corresponds to the same constraints, even if the liberty degrees are not the same. The constraints, involving the new loop, are:

$$P_{turbHp} = P_{compHp} \quad (14)$$

which involves equation(15):

$$P_{meca} = P_{turbBp} - P_{compBp} \quad (15)$$

$$\Pi_{compLp} \cdot \Pi_{compHp} = \Pi_{turbLp} \cdot \Pi_{turbHp} \quad (16)$$

4.1 Influence of thermal fluxes, for a given cycle maximum temperature

In “Hot Die”, the temperature of the combustion products, corresponding to the cycle maximum temperature, is fixed by the user before launching the program. For this first study, this temperature has been fixed to 1500K.

Material selection, which has an important influence on thermal fluxes, is also studied at Onera. So as to model this influence in “Hot Die”, we tested different thermal fluxes levels. For this, all thermal fluxes coefficients have been multiplied by a ratio that varies between 0 and 1. Basically, when the ratio decreases, material isolation increases. Results of this study are shown in figures 3 and 4.

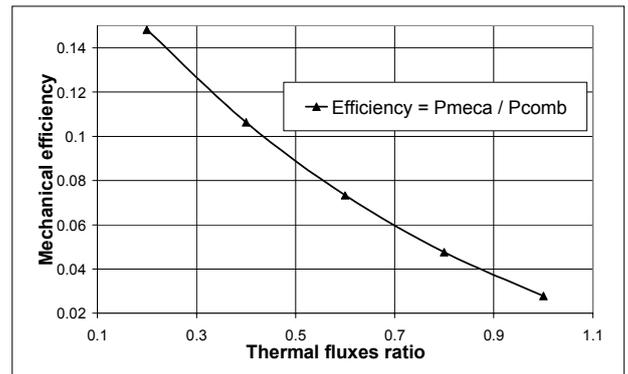


Figure 3 : Mechanical efficiency versus thermal fluxes levels

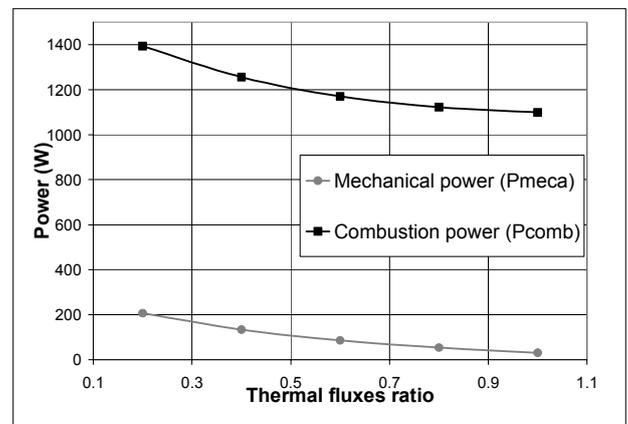


Figure 4 : Mechanical power and combustion power versus thermal fluxes levels

As expected, figure 3 shows that mechanical efficiency severely decreases when thermal fluxes level increases. This is because the mechanical power decreases more rapidly than combustion power. The results of this study confirm that the influence of thermal fluxes on the performance of such a micro system is predominant.

4.2 Influence of cycle maximum temperature

For this second study, thermal fluxes coefficients are not modified by any ratio. The only variable parameter is now the cycle maximum temperature. Results of this study are shown in figure 5:

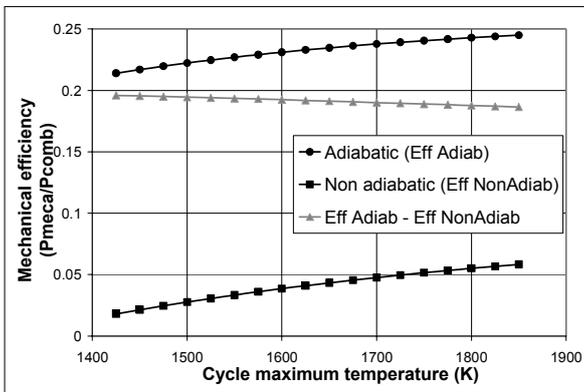


Figure 5 : Mechanical efficiency versus cycle maximum temperature

As we can see, the influence of the cycle maximum temperature is the same for both cases: mechanical efficiency increases with cycle maximum temperature. The gap between the two efficiencies decreases by less than 5% on the considered temperature range and is 19.1 points in average. The effect of thermal fluxes seems to be quite constant on the considered temperature range: whatever the temperature, the effect of thermal fluxes is predominant and actually negative.

Hence, at 1425K, for the adiabatic case, efficiency is over 20%, whereas for the non adiabatic case the efficiency is less than 2%. Such a result shows that, for the considered conditions, the non adiabatic system cannot work with a cycle maximum temperature below 1400K.

Figure 6 shows the evolution of the output mechanical power, for both cases, with the cycle maximum temperature. As expected, whatever the maximum temperature, the effect of thermal fluxes is negative: the average gap between the two cases is over 330W.

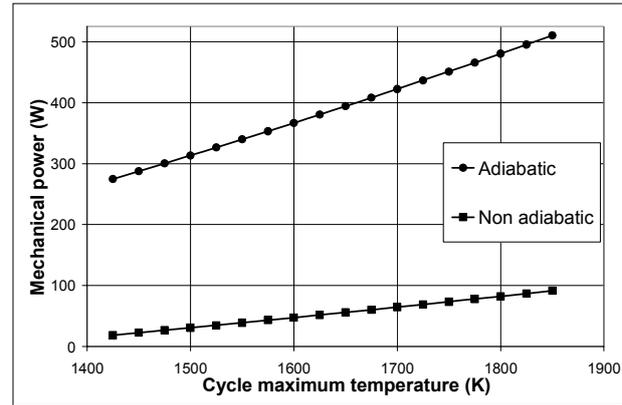


Figure 6 : Mechanical power versus cycle maximum temperature

Moreover, we can notice that the influence becomes higher with increasing maximum temperature. We can conclude that the mechanical power loss increases with thermal level of the system.

5. CONCLUSION

An aerothermodynamic program, “Hot Die”, has been specifically developed to assess the performance of the “cocoon architecture” micro turbine developed at Onera. This program has been validated on the thermodynamic theoretical Brayton-Joule cycle. Comparison between adiabatic and non adiabatic modeling has shown that thermal fluxes are predominant at micro scales and involve a severe decrease in the performances. Such a program, which takes into account the thermal fluxes, allows us to design a micro power generation system like a micro turbine.

The next step will consist in comparing the “cocoon architecture”, specifically created to limit the thermal fluxes, with other architectures.

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