Journal of Power Sources 196 (2011) 4026–4032

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Numerical study of thermoelectric power generation for an helicopter conical nozzle

Tarik Kousksou[a,*], Jean-Pierre Bédécarrats[a], Daniel Champier[b], Pascal Pignolet[b], Christophe Brillet[c]

[a] Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME – Fédération CNRS IPRA), Université de Pau et des Pays de l'Adour (UPPA) – IFR – A. Jules Ferry, 64000 Pau, France

[b] Laboratoire de Génie Electrique, Université de Pau et des Pays de l'Adour, Technopôle Hélioparc Pau Pyrénées 2, avenue du Président Angot, 64053 Pau Cedex, France

[c] Turbomeca – Groupe SAFRAN, BP 41-64511 Bordes Cedex, France

ARTICLE INFO

Article history:
Received 25 June 2010
Received in revised form 13 November 2010
Accepted 11 December 2010
Available online 8 January 2011

Keywords:
Thermoelectric generator
Power generation
Numerical simulation
Low Mach number
Helipcopter conical nozzle
Waste heat recovery

ABSTRACT

This paper investigates the electric power extractable from an helicopter conical nozzle equipped with thermoelectrical modules. The thermoelectric nozzle is heated by the final exhaust gas from helicopter turbine and cooled by oil. A computer model has been developed to simulate the performance of the thermoelectric system. Results were obtained for various operating conditions showing that the electrical power produced in real operating conditions is significant but currently insufficient if we consider the weight-to-power ratio. The numerical model is also used to optimize the electric power showing a good potential for the future.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The increase in the price of crude oil, accompanied by a better knowledge of environmental problems associated with global warming, resulted in an upsurge of scientific activity to identify and develop environmentally friendly sources of electrical power.

Previous generations of researchers and industrialists have worked on production systems and the use of different energy sources. With the change of economic, energy and environmental constraints, scientists are now trying to rationalize energy consumption by optimizing processes and their functioning.

The aerospace industry is not an exception. A revolution is going through the aviation industry, faced with the obligation to change its methods of production and consumption to reduce energy costs and reduce its environmental footprint. Greenhouse gas emissions, largely responsible for global warming, are particularly affected, while the continued rise in oil prices highlights the need for a better use of energy resources. In addition, the electrical equipments which offer such benefits are now required on board involving additional power generation.

Thermoelectricity has attracted increasing attention as a "green" and flexible source of electricity able to meet a wide range of power requirements [1]. Thermoelectric modules convert a portion of thermal power into electric power and only require to function the presence of a temperature gradient.

In aerospace applications, such generators have been used reliably for over 30 years of maintenance-free operation in deep space probes such as for example the Voyager missions of NASA [2]. Modern versions of these generators are currently used in aeronautics to feed sensors for purposes such as structural health monitoring [3].

Thermoelectric generators capturing waste heat could be used differently in the aircraft industry. Electricity can be generated with a higher power generation by using exhaust heat produced by the main engine. Many of the other transportation sectors and in particular the automobile one [2,4–7] share common waste heat technologies and consequently will share common thermoelectric solutions. But aerospace engine technology along with mission critical safety will require a more careful and lengthy development process.

The use of direct thermal to electric energy conversion offers the following advantages: improve system efficiency, no extra fuel burnt and no moving parts to produce electricity, possibility to operate over the entire aircraft flight envelope, does not affect engine operations.

* Corresponding author. Tel.: +33 629668430; fax: +33 629668430.
E-mail address: tarik.kousksou@univ-pau.fr (T. Kousksou).

0378-7753/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2010.12.015

Nomenclature

A	heat transfer coefficient (W/(m^{2}K))
c	specific heat capacity (J/(kg K))
D	diameter (m)
E	total energy (J)
I	courant (A)
K	thermocouples thermal conductance (W/K)
L	length of the conical nozzle (m)
H	enthalpy (J)
h	specific enthalpy (J/kg)
M	Mach number
$\dot{m}$	mass flow rate (kg/s)
n_{TE}	number of thermocouples
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
P_o	output power (W)
Q	rate of the heat flow (W)
R_{elec}	electrical resistance (Ω)
Re	Reynolds number
R_{load}	load electrical resistance (Ω)
R_{th}	total thermal resistance (K/W)
S	area (m^2)
T	temperature (K)
u	velocity (m/s)
V	volume (m$^{3)}$

Greek symbols

α	Seebeck coefficient (V/K)
λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)

Subscripts

C	cold fluid
H	hot fluid
in	inlet

In the field of aerospace, it is estimated that the solution could reduce fuel consumption by 0.5%, which, if implemented solely in the US, would save passenger and cargo airlines more than $12 million every month, and reduce global carbon emissions by 0.03% [8].

The production of electric power on aircraft turbine is done through the alternator taking a part of the mechanical power on the shaft of the generator. It might be interesting in order to improve the performance of turbine power generation to use another method of electricity generation. The goal is to reduce the usage of mechanical power on the shaft generator and the size of the alternator.

The electric power generated by thermoelectric modules depends obviously on the nature of the modules but also on heat transfers on both sides of these modules.

Even if thermoelectric generator (TEG) devices have a low energy conversion efficiency of around 2–5%, they are still strongly advantageous as compared to conventional energy technologies, not only for their well-known advantages such as high reliability, silence and low environmental impact but also because of their capability of utilizing amounts of waste heat as an energy source in a simple and easy manner. Total reliability of thermoelectric generators has been demonstrated in many applications [9–11]. For example, Chen et al. [11] worked on the overall conversion efficiency improvements and economic benefits of the integration of TEG into thermal energy systems, especially combined of heat and power production (CHP).

Although the commercial/practical applications of thermoelectric generators still remain marginal in electric generation, significant advances have been made in synthesizing new materials and fabricating material structures with improved thermoelectric performance [9]. Efforts have focused primarily on improving the material's figure-of-merit, and hence the conversion efficiency, by reducing the lattice thermal conductivity [12]. Recent advances in materials and materials processing as summarized in reviews [13,14] have led to higher non-dimensional figure of merit values and, thus, higher theoretical conversion efficiency of TE modules.

In addition to the improvement of the thermoelectric material and module, the analysis of thermoelectric systems is equally important in designing a high-performance of these ones [15–21]. The main works consists in predicting the performance of thermoelectric generators with particular configuration of heat exchangers and in studying the effect of fluid flow rates, fluid properties and inlet temperatures on the power supplied by the system. For example, Suzuki and Tanaka [18,19] studied thermoelectric power generation with multi-panels or cylindrical multi-tubes. The output powers of the proposed system were analytically deduced from heat transfer theory, and written by non-dimensional functions to reflect the characteristics of system design.

The aim of the work is to study the feasibility of generating electricity by thermoelectric modules in turbomachinery for flight applications and in particular for an helicopter. It consists in particular to evaluate the electric power extractable from thermoelectric modules placed in the conical nozzles of helicopter turbines. These conical nozzles are heated by a hot fluid which is the exhaust gas (whose thermal power is currently lost) and cooled by another cold fluid which can be oil. The heat transfer through the conical nozzle and the temperature variation along the fluid path are analyzed mathematically. Applying a heat transfer analysis, their temperature profiles and output electrical power can be determined numerically using the finite volume method. The physical model enables us to select the best system, considering the thermophysical properties of the thermoelectric materials and working fluids.

2. Physical model

The studied system is a nozzle with a short length and a conical geometry. Exhaust gas circulate inside this nozzle with a low reduction in pressure up to the ambient atmospheric pressure. The Mach number is about 0.4–0.5 at the nozzle entry and is reduced to 0.1 at the outlet. The idea is to place thermoelectric modules around the conical nozzle. The modules will be kept pressed against the nozzle through a second wall. This one is cooled either directly by the outside air (convection) or by other fluids such as air or compressed oil (forced convection). The fuel was removed for security reasons. So a coaxial heat exchanger is used around the nozzle.

2.1. Heat transfer analysis

The physical model is illustrated schematically in Fig. 1. As already mentioned, the thermoelectric modules are sandwiched between the hot exhaust fluid and the cold fluid and they are electrically insulated by ceramic plates (see Fig. 2).

Divergent conical nozzles consist for subsonic flows in slightly decreasing the velocity and minimizing the total pressure losses. The conical nozzle performance, flow and heat transfer characteristics are strongly coupled so that the knowledge of flow conditions is absolutely necessary in the interpretation of performance parameters.

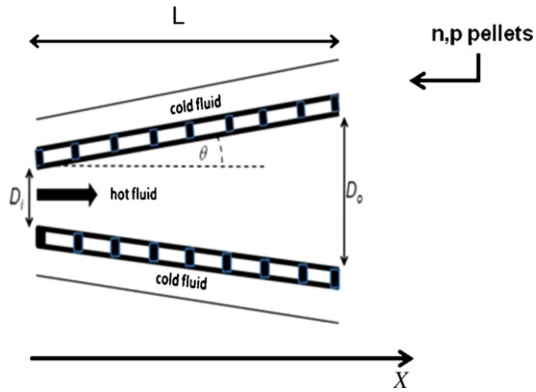

Fig. 1. Schematic layout of the model.

The heat applied at the hot junction is scattered and lost at the cold junction, corresponding to the temperature gradient inside the thermoelectric module. The heat from the hot fluid is transfered to the panel surface by convection, to the cold surface by heat conduction through the solid (metal, ceramic and TE pellets) and finally to the cold fluid again by convection. The fluids are heated or cooled along the flow path, and their temperature profile through the path, $T(x)$, changes as a function of position x.

In order to simplify the physical model of the thermoelectric conical nozzle, the following assumptions were made:

- The fluid flows are considered unidirectional.
- The hot fluid (air) flow is compressible and Newtonian.
- The cold fluid (oil) flow is incompressible and Newtonian.
- All the thermoelectric modules are supposed to be conical and are composed of a single layer of p–n junctions as illustrated in Fig. 2.
- The thermoelectric pellets are homogeneously aligned perpendicular to the heat flow, combined slightly without an open space, and connected electrically in series.
- The electrical contact resistance between the p and n couples is assumed to be negligible.
- The material properties for the TE pellets vary along the length of the conical nozzle with changes in temperature [22].

Based on these assumptions the energy balance equations for the hot fluid and the cold fluid are:

2.1.1. Hot fluid

A one dimensional non-viscous flow in a conical nozzle with variable section $S(x)$ is considered. The equations governing this type of flow are continuity, momentum and energy equations:

$$\frac{\partial(\rho_H S)}{\partial t} + \frac{\partial(\rho_H u_H S)}{\partial x} = 0 \quad (1)$$

$$\frac{\partial(\rho_H u_H S)}{\partial t} + \frac{\partial(\rho_H u_H u_H S)}{\partial x} = -S\frac{\partial p_H}{\partial x} \quad (2)$$

$$\frac{\partial(\rho_H E_H S)}{\partial t} + \frac{\partial(\rho_H u_H H_H S)}{\partial x} = \frac{Q_H}{V_H} \quad (3)$$

where ρ_H, u_H, p_H and E_H, respectively represent the density, velocity, pressure and total energy of the hot fluid. V_H is the volume occupied by the hot fluid. x is the spatial coordinate and t is the time. Q_H is the heat flux at the hot side. Furthermore, the following thermodynamic relations hold:

$$H_H = h_H + \frac{1}{2}u_H^2 \quad (4)$$

$$E_H = e_H + \frac{1}{2}u_H^2 \quad (5)$$

$$\rho_H H_H = \rho_H E_H + p_H \quad (6)$$

where H_H is the total enthalpy, h_H the specific enthalpy and e_H the internal energy. The system of equations (1)–(3) is closed by the equation of state for a perfect gas:

$$p_H = \rho_H r T_H \quad (7)$$

where r is the gas constant and T_H is the temperature of the hot fluid.

2.1.2. Cold fluid

Energy equation:

$$\rho_C c_{p,C}\left(\frac{\partial T_C}{\partial t} + u_C\frac{\partial T_C}{\partial x}\right) = \lambda_C\frac{\partial^2 T_C}{\partial x^2} + \frac{Q_C}{V_C} \quad (8)$$

where ρ_C, $c_{p,C}$, u_C and T_C, respectively represent the density, specific heat capacity, velocity, and temperature of the cold fluid. λ_C is the thermal conductivity of the fluid, V_C the volume occupied by the cold fluid and Q_C is the heat flux at the cold side.

The initial and boundary conditions were chosen as follows:

2.1.2.1. Hot fluid. Since the flow regime is subsonic (0 < Mach < 1), we define the values for the density and velocity at the inlet face [23,24]. At the outlet face we impose the pressure.

2.1.2.2. Cold fluid.

$$T_C(x,0) = T_{C,in}; \quad T_C(0,t) = T_{C,in}; \quad \frac{\partial T_C(L,t)}{\partial x} = 0 \quad (9)$$

2.2. Numerical strategy

The flow domain is subdivided into a finite number of control volumes with length Δx_i for the hot fluid and $\Delta x_j = \left(\cos\left(\theta\right)\right)^{-1}\Delta x_i$ for the cold fluid (Fig. 2). All the variables are stored in the control volume center (collocated arrangement).

For the compressible flows (Mach number, $M > 0.2$) it is well known that the efficiency and the accuracy of computed methods deteriorate drastically when M decreases below 0.2 [23,24]. On the other hand, when the Mach number remains uniformly small (below 0.2), an accurate and useful approximation is to consider the flow incompressible [24]. This observation has led to the development of computing methods exclusively suited to incompressible flows. No class of methods is suitable for computing flows in domains in which incompressible subregions as well as compressible subregions occur simultaneously, or for computing weakly compressible flows. For this, methods are required with uniform accuracy and efficiency whatever the Mach number is [23].

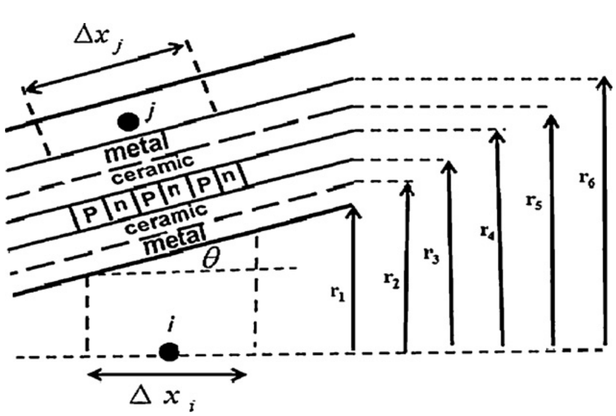

Fig. 2. Control volume of TEG.

We refer to such unified methods for incompressible and compressible flow computation as Mach-uniform methods. In our work, to resolve the Eqs. (1)–(3), we have used a coupled pressure and temperature correction algorithm. The description of this algorithm is largely detailed and presented in references [25,26].

The energy equation (8) is solved using a finite volume solution method. Upwind scheme is used for the convection term and a fully implicit scheme for the time integration [27].

Because the Eqs. (1)–(3) and (8) are coupled, the resulting algebraic equations have been solved using an iteration procedure, at each time step, until the convergence has been achieved.

2.3. Thermal resistances

The thermal resistances are calculated by using classical correlations. R_H and R_C are the thermal convection resistances of the hot and the cold fluid, respectively. R_{metal} and $R_{ceramic}$ are the thermal conduction resistance of the metal and ceramic materials, respectively. R_{cont} is the thermal contact resistance and R_{TE} is the thermal conduction resistance of the TEG.

$$R_H = \frac{1}{A_{H,i}S_i}; \quad R_C = \frac{1}{A_{C,j}S_j}; \quad R_{TE} = \frac{\ln(r_4/r_3)}{2\pi\lambda_{TE}\,\Delta x_j}; \quad R_{metal} = \frac{\ln(r_2/r_1)+\ln(r_6/r_5)}{2\pi\lambda_{metal}\,\Delta x_j}; \quad R_{ceramic} = \frac{\ln(r_3/r_2)+\ln(r_5/r_4)}{2\pi\lambda_{ceramic}\Delta x_j}$$

where r, $A_{H,i}$ and $A_{C,j}$ are the radius of the conical tube and the heat transfer coefficient between the fluid and the conical tube, respectively (see Fig. 2). S_i and S_j are the wetted areas for hot and cold fluid, respectively. λ_{TE} is the average heat conductivity of the module, defined by:

$$\lambda_{TE} = \frac{\lambda_p s_p + \lambda_n s_n}{s_p + s_n} \tag{10}$$

where λ_p, λ_n, S_p and S_n are the heat conductivity and the cross-sectional area of p- and n-type elements, respectively.

In order to facilitate the parametric design optimization, the conical nozzle model implements empirical correlations for hot side $A_{H,i}$ and cold side $A_{C,j}$ convective heat transfers.

For the cold fluid flows through an annular section, the heat transfer coefficient is determined using the hydraulic diameter D_h which is defined as:

$$D_h = \frac{4A_c}{P} \tag{11}$$

where A_c and P are respectively the flow cross sectional area and the wetted perimeter. It is this diameter that will be used in calculating parameters such as Re and Nu:

- For turbulent flow regime, which still occurs if Re ≥ 2300 the following correlation is adopted [28]:

$$\mathrm{Nu} = 0.023\,Re^{4/5}Pr^{1/3} \tag{12}$$

- For laminar flow regime, the Nusselt number varies from 3 to 5 with variations in hydraulic diameter and the fluid temperature.

For the hot fluid flow through the inner section of the conical nozzle, the above correlations are used but the hydraulic diameter is substituted by the inner diameter of the conical nozzle.

2.4. Thermoelectric modeling

Since a thermoelectric converter is a heat engine and like all heat engines it obeys the laws of thermodynamics. Taking into account the heat conduction, the Joulean heat loss and the Seebeck effect, the rate of heat supply Q_H and heat removal Q_C in the control volume (i,j) are given by [29,30]:

$$Q_{H,i,j} = n_x n_\varphi n_{TE}\left[\alpha\, IT_{H,i,s} - \frac{R_{elec}I^2}{2} + K\left(T_{H,i,s} - T_{C,j,s}\right)\right] \tag{13}$$

$$Q_{C,i,j} = n_x n_\varphi n_{TE}\left[\alpha IT_{C,j,s} + \frac{R_{elec}I^2}{2} + K(T_{H,i,s} - T_{C,j,s})\right] \tag{14}$$

where I is the current flow through a single thermocouples, α, K and R_{elec} are respectively, the Seebeck coefficient, thermal conductance and electrical resistance of a single thermocouple. n_{TE} is the number of thermocouples in the TE module. n_φ and n_x the number of TE modules in a circumferential circulation, and the number of TE modules in the x direction, respectively. $T_{C,j,s}$ and $T_{H,i,s}$ are respectively, the temperatures of the cold and hot junctions. In practice, it is impossible to measure the temperature of both the hot and the cold junction ($T_{C,j,s}$, $T_{H,i,s}$) as the p- and n-legs are interconnected by metal and are thermally in parallel between two ceramic plates. However, it is feasible to calculate them using the fluid temperatures ($T_{C,j}$, $T_{H,i}$):

$$T_{H,i,s} = T_{H,i} - Q_{H,i,j}\,(R_H + R_{metal} + R_{ceramic} + R_{cont})$$

$$T_{C,i,s} = T_{C,i} - Q_{C,i,j}\,(R_C + R_{metal} + R_{ceramic} + R_{cont})$$

The current flow through the thermocouples aligned in series for a given thermoelectric generator is determined by the number of thermocouples aligned in series and the electrical resistance of circuit load. The total voltage is the sum of the voltages generated in each control volume, which are wired in series along x-coordinate direction. Therefore, the current can be written as:

$$I = \frac{\sum_{i,j=1}^{n}\alpha(T_{H,i,s} - T_{C,j,s})n_{TE}n_x n_\varphi}{R_{load} + \sum_{i,j}^{n}(R_e n_{TE} n_x n_\varphi)} \tag{15}$$

where n is the total number of the control volume and R_{load} is the load electrical resistance. In this work, the load resistance is selected to equal the effective internal resistance of the thermoelectric modules so that the maximum power output of a thermoelectric module could be achieved.

The output power of the thermoelectric generator is:

$$P_o = \sum_{i,j=1}^{n}(Q_{H,i} - Q_{C,j}) \tag{16}$$

Table 1
Parameters for thermoelectric power generation system.

Variables	Values used in this work
Conical nozzle	
Length	0.32 m
Thickness	0.002 m
Inlet diameter	0.236 m
Outlet diameter	0.306 m
Thermal sources	
Hot fluid	Air ($T_H^{in} = 900$ K, $u_{H,in} = 130$ m/s)
Cold fluid	Oil ($T_C^{in} = 358$ K, $\dot{m}_C = 0.21$ kg/s)

3. Results and discussion

In the following numerical simulation, the thermophysical values of Bi_2Te_3 semiconductors will be used for the thermocouples. The thermophysical properties of the metal and ceramic are determined using the temperature of the cold and hot fluids. Table 1 shows the fluid values and the dimensions (real conditions of operation) for the thermoelectric conical nozzle used in this paper. The simulation was carried out only for counter flow type for the conical nozzle.

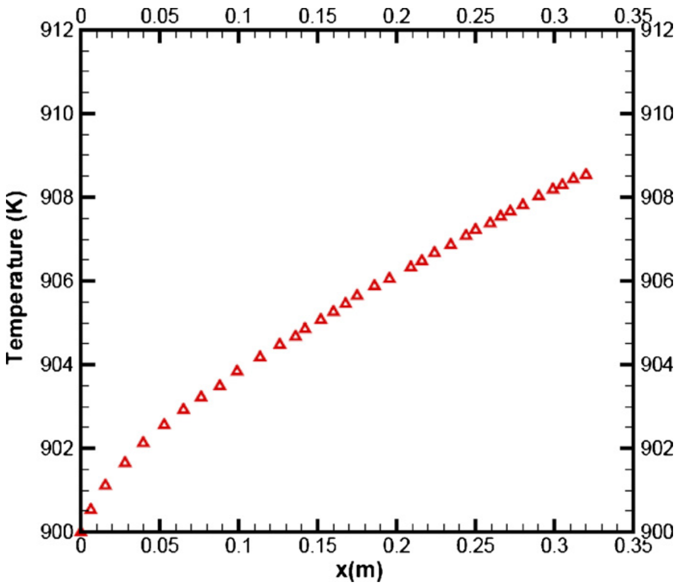

Fig. 3. Temperature profile of the hot fluid along the conical nozzle.

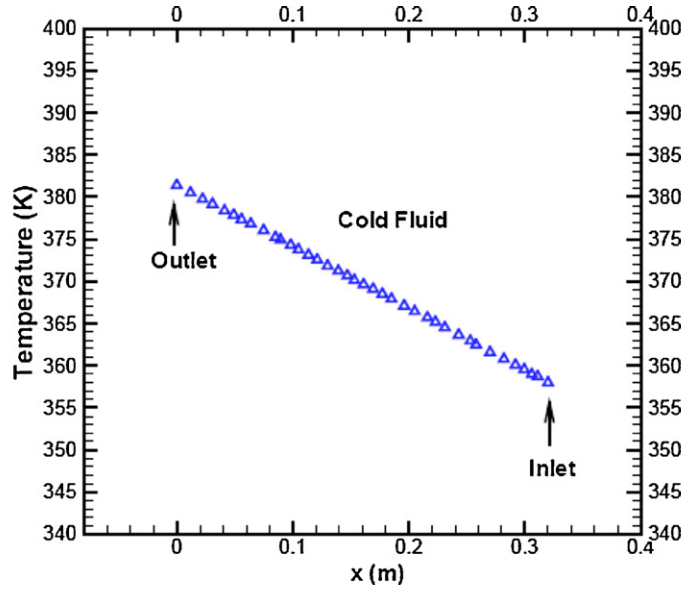

Fig. 5. Temperature profile of the cold fluid along the conical nozzle.

Figs. 3 and 4 show the temperature and the velocity variation of the hot fluid through the conical nozzle. For subsonic flows, increasing the cross-sectional area causes the flow to decrease the velocity and increase the temperature. The increase in the hot fluid temperature is a direct result of the energy conservation. From knowledge of the conservation of mass for subsonic flows, the test section can be designed to produce a desired velocity or Mach number since the velocity is a function of the cross-sectional area.

Fig. 5 presents the evolution of the temperature of the cold fluid through the conical nozzle. As can be seen in this figure, the temperature variation tendency of the cold fluid flow along the axis of a thermoelectric generator is similar to that in an ordinary heat exchanger. Nevertheless, the variations in temperature are almost linear. This special feature in the conical nozzle of thermoelectric power generation is due to the Seebeck effect: a certain amount of energy from high-temperature fluid is taken away as electricity. Thus the heat flow from the high temperature (hot fluid) is not equal to the heat flow to the low temperature (cold fluid).

Fig. 6 shows the temperature variation on the hot and cold sides of the thermoelectric modules along the axis of the conical nozzle for counter flow type. We note that the temperature on the hot side of thermoelectric modules decreases from the inlet to the outlet of the conical nozzle. As the value of the hot fluid velocity decreases along the nozzle (see Fig. 4), the heat transfer coefficients between the hot fluid and the hot side of the thermoelectric modules decreases along the conical nozzle. Therefore, all this process results in a change in the temperature profile on the hot side of thermoelectric modules. On the cold side of the thermoelectric modules, the temperature increases from the inlet to the outlet of the conical nozzle for the counter flow type. Seebeck effect can generate the thermoelectric power depending on a temperature difference between the hot and cold junctions. The Seebeck electromotive force is the sum of multiplication of the relative Seebeck coefficient and the temperature difference ΔT over all the serial connections. The problem to obtain the larger power is, therefore, how to give the larger ΔT to all the thermoelectric modules existing

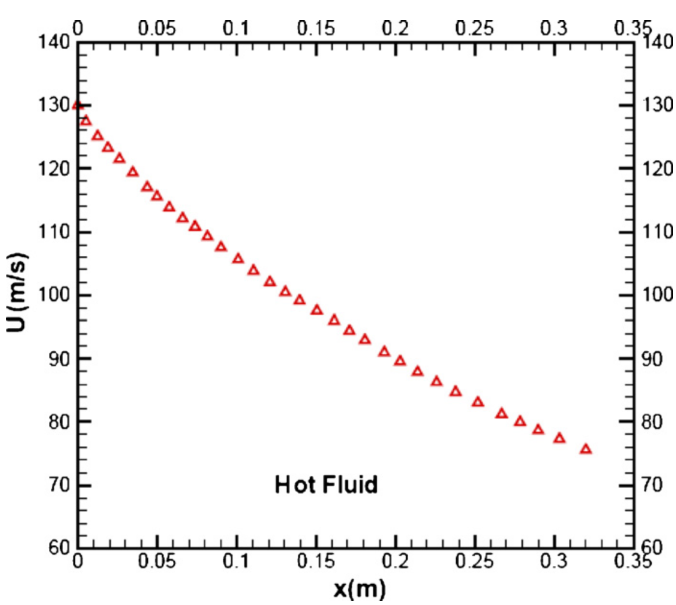

Fig. 4. Velocity profile of the hot fluid along the conical nozzle.

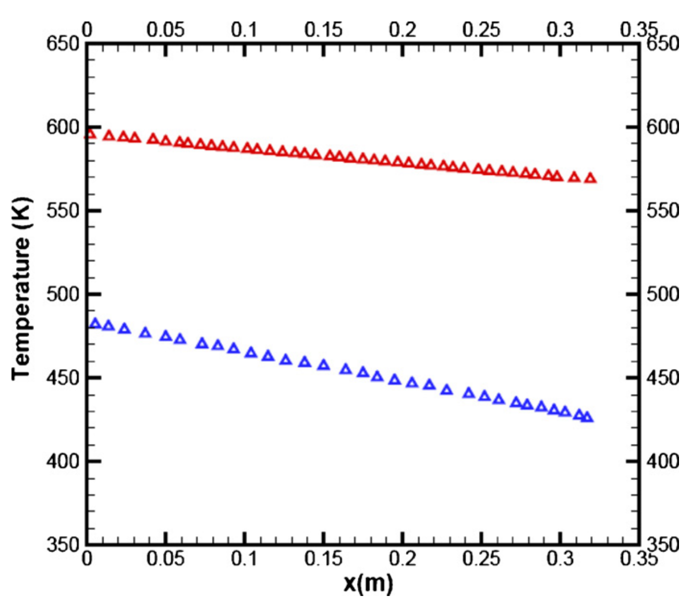

Fig. 6. The temperature variation on hot and cold side of thermoelectric modules.

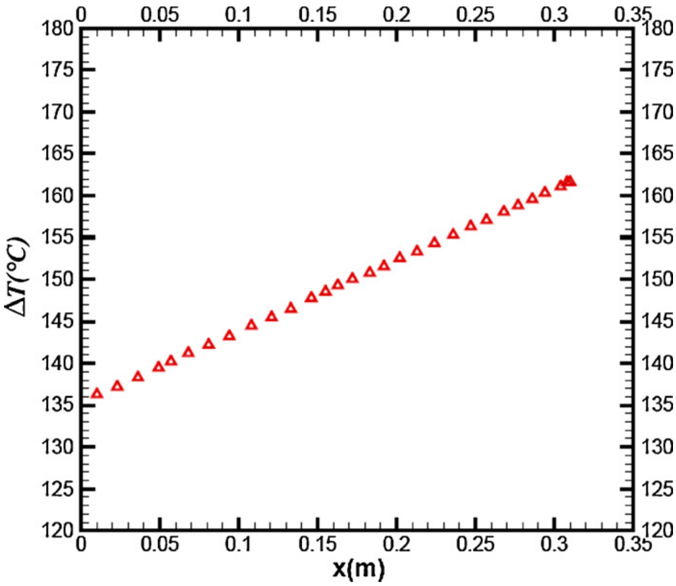

Fig. 7. The comparaison of temperature difference across thermoelectric modules for the conditions of Table 1.

between two hot and cold fluids. Fig. 7 shows the variation of the temperature difference of the thermoelectric modules. As shown in Fig. 7, for a given inlet temperature and velocity of the fluids, we note an increase in temperature difference through the conical nozzle. These results show that depending of their positions; each module does not supply the same electric power which will probably need the use of electronic converters [31].

In general, the output power depends mainly on the inlet temperature and the inlet velocity of the hot and cold fluids for a given thermoelectric generator. Fig. 8 illustrates the variation of the output power with the inlet velocity of the hot fluid. We note that the output power increases with the increase in the inlet velocity. This result can be explained by the fact that the convective heat transfer coefficient is increased when increasing the velocity of the hot fluid through the conical nozzle. This increase also brings an increase in the difference temperature through the modules and therefore, an increase in the output power. Fig. 9 presents the variation of the output power with the inlet temperature of the hot fluid for counter flow type when the inlet velocity of the hot fluid is 130 m/s. We note that the output power decreases with decreasing the inlet temperature of the hot fluid for a fixed inlet velocity. This result is due to the fact that the decrease in the inlet temperature of the hot fluid leads to a decrease in the average temperature difference through the modules, and thus the output power can be increased. Fig. 10 illustrates the effect of the cold flow rate on the output power for two inlet temperatures of the cold fluid. It can be observed that for a given inlet temperatures, the output power increases with increasing the cold flow rate. We note that the increase in the output power is significant at the beginning, but the increase trend becomes smaller as the flow rate increases, especially at lower inlet temperature of the cold fluid. It is also found that the output power decreases with increasing the inlet temperature of the cold fluid for a fixed inlet velocity.

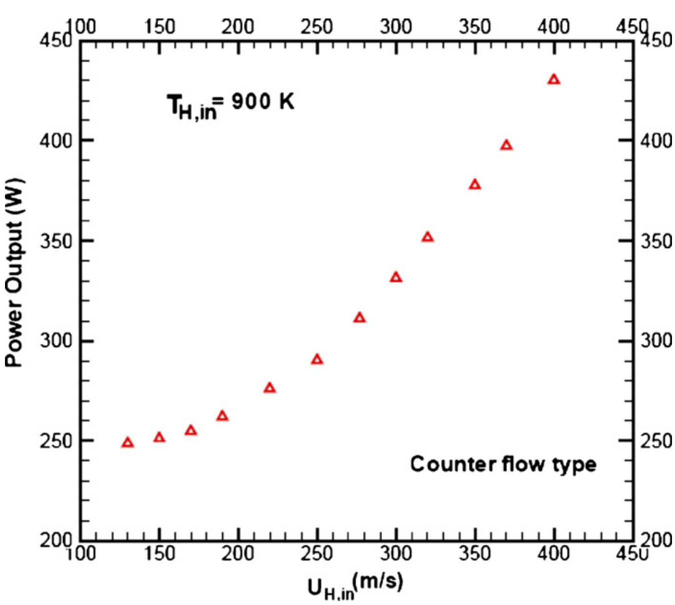

Fig. 8. The variation of power output with the hot fluid inlet velocity (Oil: T_C^{in} = 358 K, $\dot{m}_C = 0.21$ kg/s).

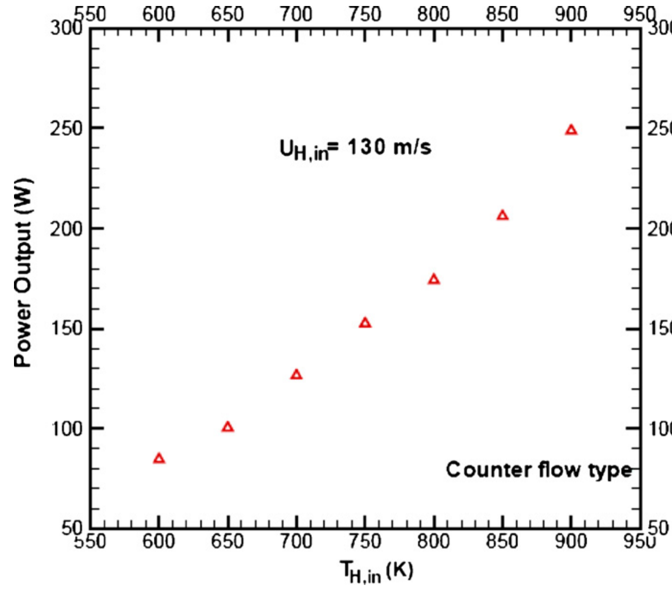

Fig. 9. The variation of power output with the hot fluid inlet temperature (Oil: T_C^{in} = 358 K, $\dot{m}_C = 0.21$ kg/s).

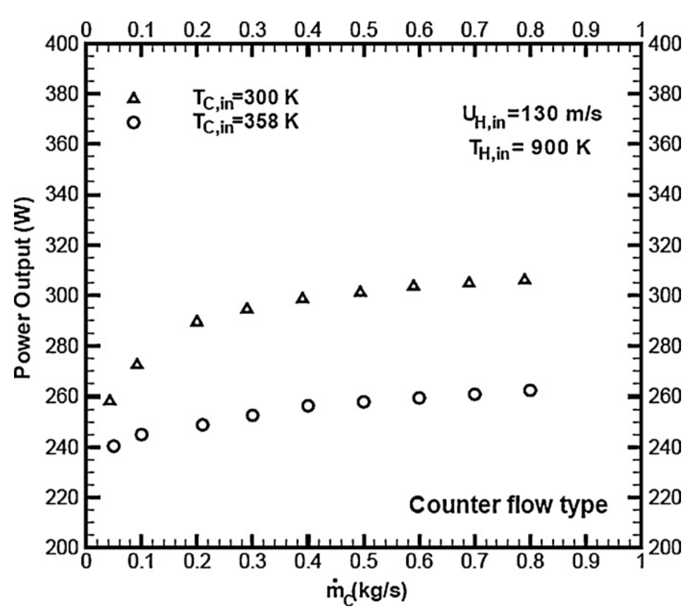

Fig. 10. The variation of output power with the cold flow rate.

The model permits to evaluate the output power for different inlet velocities and inlet temperatures met in real flight operating conditions.

4. Conclusion

Current needs for fuel efficient, low emission, power sources for applications in sensors and subsystems in all-electric aircraft and on-board spacecraft has brought forth a renewed interest in the thermoelectric technology.

A numerical model for a thermoelectric generator installed at the conical nozzle level of an helicopter was proposed. This model is based on one-dimensional differential equations representing conservation equations for the compressible hot fluid (exhaust gas) and the incompressible cold fluid. These equations are restructured and linked to the formulations of thermoelectric modules. The proposed model gives much more detailed predictions for the temperature variations through the thermoelectric modules along the conical nozzle.

It is found that the output electrical power is sensitive to the physical properties of the hot fluid at the inlet face of the conical nozzle. But the appropriate inlet velocity should be determined to meet the optimal operating conditions of the helicopter turbine.

The results of this study show that the electrical power produced in real operating conditions is significant but currently insufficient and in particular if we consider the electrical power obtained per unit of added mass (the weight-to-power ratio).

But we may hope thermoelectric device improvements to have a better efficiency. For the moment, available thermoelectric devices on the market have a relatively low efficiency and generally cannot compete with alternative approaches.

These powers can be increased first by improving the exchange between the fluids, further reducing the thermal resistance on the cold side (increase in the flow rate, reducing the flow area of the cold fluid).

It is also necessary to improve the occupation of the modules because completely cover the nozzle to obtain the greatest power is not the better solution.

Further work could be done on the simulation of a thermoelectric generator (generator and heat exchangers) which can be adapted to different places to operate over the entire helicopter flight envelope.

Finally, it is important to emphasize that all calculations performed by simulation need an experimental approach to fully validate the results. We project to carry out an experimental study.

In conclusion, the key challenges to push forward this technology include: high ZT materials, high temperature modules, and effective heat exchangers.

References

[1] D.M. Rowe, Renewable Energy 16 (1999) 1251–1256.
[2] D.M. Rowe, International Journal of Innovations in Energy Systems and Power 1 (November (1)) (2006) 13.
[3] D. Samson, T. Otterpohl, M. Kluge, U. Schmid, T.H. Becker, Journal of Electronic Materials 39 (9) (2010).
[4] S.B. Riffat, Xiaoli Ma, Applied Thermal Engineering 23 (2003) 913–935.
[5] K.M. Saqr, M.K. Mansour, M.N. Musa, International Journal of Automotive Technology 9 (2008) 155–160.
[6] M.A. Korzhuev and I.V. Katin, On the Placement of Thermoelectric Generators in Automobiles, Vol. 39, No. 9, 2010.
[7] Y.Y. Hsiao, W.C. Chang, S.L. Chen, Energy 35 (2010) 1447–1454.
[8] J. Huang, Aerospace and Aircraft Thermoelectric Applications, The Boeing Company, Thermoelectrics Applications Workshop September 29–October 1, (2009) San Diego, CA.
[9] D.M. Rowe, Thermoelectrics Handbook: Macro to Nano, CRC Press, Taylor & Francis Group, 2006.
[10] S. Kametani, T. Fujita, T. Kajikawa, K. Yamaguchi, 25nd International Conference on Thermoelectric (2006).
[11] M. Chen, H. Lund, L.A. Rosendahl, T.J. Condra, Applied Energy 78 (2009) 1231–1238.
[12] C.M. Bhandari, D.M. Rowe, Thermal Conduction in Semiconductors, Wiley Eastern Ltd., 1988.
[13] L.E. Bell, Science 231 (2008) 1457–1461.
[14] G. Chen, Int. Mater. Rev. 48 (2003) 45–66.
[15] K.T. Chau, Y.S. Wong, C.C. Chan, Energy Conversion and Management 40 (1999) 1021–1039.
[16] J.W. Stevens, Energy Conversion and Management 42 (2001) 709–720.
[17] D.G. Crane, G.S. Jackson, Energy Conversion and Management 45 (2004) 1565–1582.
[18] R.O. Suzuki, D. Tanaka, Journal of Power Sources 122 (2003) 201–209.
[19] R.O. Suzuki, D. Tanaka, Journal of Power Sources 124 (2003) 293–298.
[20] J. Yu, H. Zhao, Journal of Power Sources 172 (2007) 428–434.
[21] J. Esarte, G. Min, D.M. Rowe, Journal of Power Sources 23 (2001) 72–76.
[22] Melcor, available from: http://www.melcor.com/pdf/thermoelectric%20-Handbook.pdf (2007).
[23] K. Nerinckx, J. Vierendeels, E. Dick, International Journal for Numerical Methods in Fluids 47 (2005) 1205–1211.
[24] T.J. Chung, Computational Fluid Dynamics, Cambridge University Press, (2002).
[25] Y. Mougen, T. Kousksou, E. Dick, P. Bruel, Fifth European Conference on Computational Fluid Dynamics (ECOMAS CFD), Lisbon, Portugal (2010).
[26] K. Nerinckx, J. Vierendeels, E. Dick, Journal of Computational Physics 12 (2006) 597–623.
[27] T. Kousksou, J. Majid, P. Bruel, AIAA Journal of Thermophysics and Heat Transfer 43 (2010) 31–41.
[28] R.K. Shah, M.S. Bhatti, Handbook of Single Phase Convective Heat Transfer, Wiley-Inter-Science (1987) (Chapter 3).
[29] S.W. Angrist, Direct Energy Conversion, 4th ed. Allyn and Bacon, Boston (1982).
[30] D.M. Rowe, CRC Handbook of Thermoelectrics, CRC Press, London, 1996.
[31] H. Nagayoshi, K. Tokumisu, T. Kajikawa, Novel Maximum Power Point Tracking Control System for Thermoelectric Generator and Evaluation of Mismatch Power Loss Reduction, The 5th European Conference on Thermoelectrics, Odessa House of Scientists, Odessa, Ukraine, September 10–12, (2007).