Proceedings of the ASME 2009 International Mechanical Engineering Congress & Exposition
IMECE2009
November 13-19, Lake Buena Vista, Florida, USA

IMECE2009-12281

THE α-PROTOTYPE OF AN ULTRA-MICRO-GAS TURBINE AT THE UNIVERSITY OF ROMA 1. FINAL ASSEMBLY AND TESTS

Roberto Capata♦, Enrico Sciubba

Dept. of Mechanical and Aeronautical Engineering - University of Roma "La Sapienza"
Phone:.+39.06.44585271-44585244 fax. +39.06.4881759
roberto.capata@uniroma1.it, enrico.sciubba@uniroma1.it

Abstract

The paper describes the realization of the α-prototype of a portable power device consisting of an electrical generator with a power output of about 300 W driven by a small gas turbine set. The device is so small that it can be properly defined an ultra micro device, capable of supplying electric power in stand alone conditions and for prolonged periods of time (up to 24 hours continuously). In practice the device can be used as a convenient substitute (or replacement) for all current battery storage systems and is significantly smaller, lighter and most likely more reliable than the few existing internal combustion engines of comparable power output. The particular nomenclature is UMGTG-UDR1 (Ultra-Micro Gas Turbine Generator). The final configuration of the prototype (for which a patent is pending) is described in the paper as well, together with some of the results of the final operational tests.

NOMENCLATURE

c	Specific heat [kJ/(kg K)]
C	Compressor
CC	Combustion chamber
D	Diameter [m]
ECU	Electronic Control Unit
EG	Electric generator
EM	Electric motor
F	Fuel
GT	Gas Turbine
m	Mass flow rate [g/s]
MEMS	Micro Electro Mechanical Systems
MST	Micro System Technology
MTBF	Mean time before failure
P	Power [W]
Q	Heat flow [W]
RE	Regenerative heat exchanger
T	Temperature [K]
T	Turbine
TIT	Turbine Inlet Temperature [K]
TOT	Turbine Outlet Temperature [K]
U	Peripheral rotor velocity [m/s]
UDR1	University of Roma "La Sapienza"
UMGTG	Ultra Micro Gas Turbine Generator

♦ corresponding author

1. Introduction

The term MEMS, for Micro Electro Mechanical Systems, was coined in the 1980's to describe new, sophisticated mechanical systems on a chip, such as micro electric motors, resonators, gears, and so on. Today, the term MEMS is used in practice to denote any microscopic device with a mechanical functionality that can be fabricated in a batch process: dimensions are no longer limited to those of a chip, but must be significantly smaller than the smallest commercial units for each technology. In Europe, the term MST for Micro System Technology is preferred, and in Japan MEMS are simply referred to as Micro machines.

In the years 2007-2009, our research group produced a rather complete and detailed feasibility analysis of a UMGTG [1,2,3,4,5] and finally realized the first α-prototype of the device. The UMGTG is to provide electric power in a stand alone operational mode for a period of about 24 hours, with minimal weight and volume.

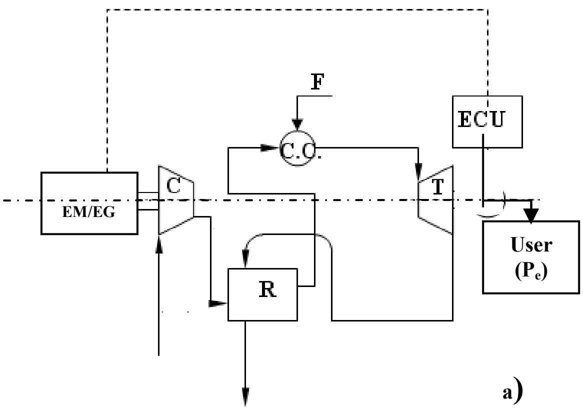
2. UMGTG-UD 1: detailed description

The UMGTG-UDR1 device (figure 1) consists of the following fundamental parts:

- compressor C;
- turbine T;
- combustion chamber CC;
- regenerator RE;
- electrical motor/generator EM/EG;
- electronic control unit ECU;
- case.

Whereas the replaceable fuel tank F is external to the case.

The reference cycle is a regenerated Brayton cycle [1,3,4]. To insert an efficient regenerator in such a small device proved to be a difficult task: the solution adopted here was that of performing the heat recovery in an annular finned space that surrounds the combustion chamber (see figure 6).



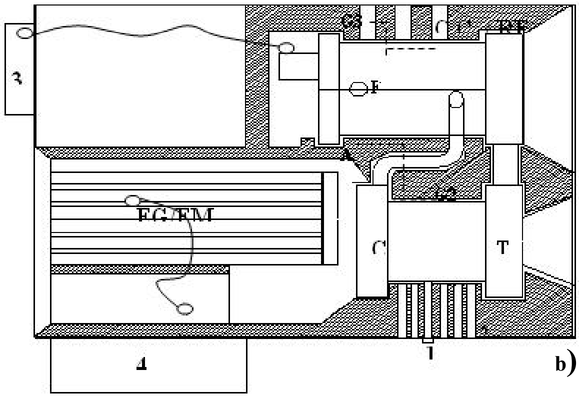


Figure 1 - UMGTG-UDR 1: a) reference cycle; b) final configuration tested – 1. lubrification ; 2. cooling fins; 3. igniters; 4. ECU

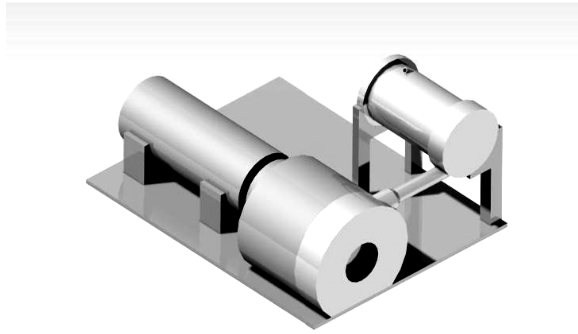


Figure 2 - The 3D sketch of the final assembling

3. Components description

3.1 Case

The case is internally divided in three zones, one for the turbine, one for the compressor and one for the combustor/regenerator. Each zone is delimited by properly placed refractory walls, to minimize spurious heat fluxes, local temperature-induced stresses and efficiency decrease. Furthermore, the electrical and electronic parts benefit from this separation, and their MTBF increases. The base of the case is made of Ergal, while the two supports for the combustion chamber are of Inconel alloy.

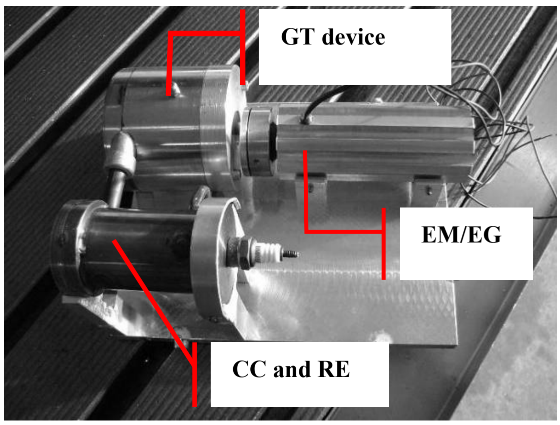


Figure 3 - UMGTG-UDR 1: final assembly

3.2 Compressor

Both rotors compressor and turbine) are fitted on same shaft, with commercial ball hybrid bearings for elevated rotational speed (150000-200000 rpm [GRW ®]).

The compressor is a single-stage radial machine. The starter motor supplies the necessary power to launch the machine at start-up, raising the rotational speed of the compressor with a linear ramp until self-sustaining mode is attained.

Every effort was made in the design phase to properly insulate the compressor from the heat source, and as a result neither thermal stresses nor excessive bearing temperature represent a problem. Table 1 summarizes the rotor characteristics.

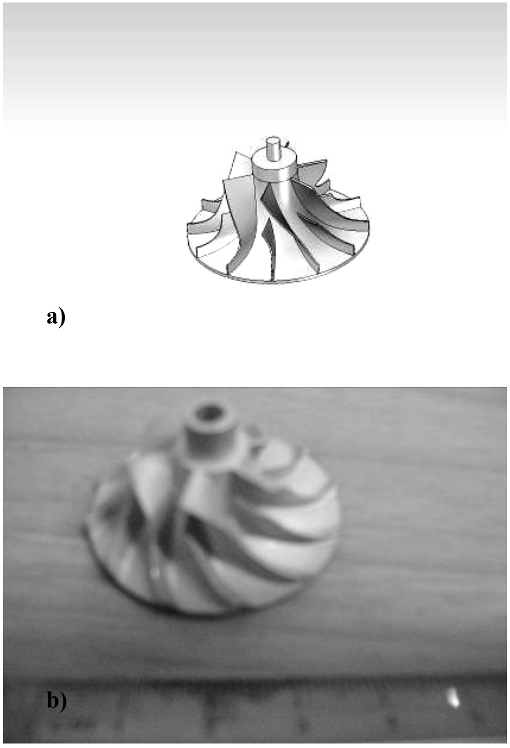


Figure 4 - UMGTG-UDR 1: Compressor – a) PC design layout, b) impeller

Table 1

Material	ERGAL
External diameter [mm]	38
Internal diameter [mm]	22
Shaft diameter [mm]	6
Number of blades	12

3.3 Turbine

Both components are fitted on the same shaft. A particular assembly procedure was devised to mount and align the bearings. The turbine is a high-solidity, single stage radial machine (12 blades). The electric generator supplies the power to drive the compressor and the electronic control unit delivers the rest to the final user. Table 2 reports the turbine geometry.

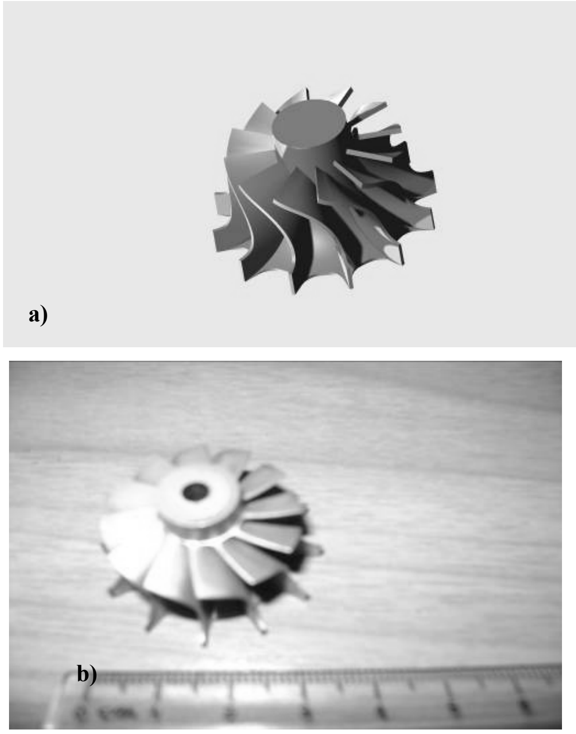


Figure 5 - UMGTG-UDR1: Turbine – a) PC design layout, b) impeller

Table 2

Material	INCOMEL
External diameter [mm]	36
Internal diameter [mm]	27
Shaft diameter [mm]	6
Number of blades	12

3.4 Combustion Chamber & Regenerative Heat Exchanger

The heat exchanger is an ultra-compact, annular type, gas-to-air device made of lamellar steel. Its operating temperatures range from 450 to 1000 K. Its efficiency is in the same range of the large-scale heat exchangers. The combustion chamber is a cylindrical chamber with prewhirl but no premixing. Air intake is tangential while fuel injection is radial. The hot gases exit either axially or tangentially: both solutions have been tested. Table 3 contains the main geometrical data of the combustion chamber.

The regenerative section is obtained by arranging the external wall of the combustor to be a three-layers cylindrical shell. The air from the compressor evolves in the internal cylinder, the gas turbine exhaust gas in the external one. This admittedly unusual arrangement is very compact, allows the regenerator to work in practice as a counter flow heat exchanger, and maximizes the heat input into the compressed air, “sandwiched” between two hot streams. Notice that the inner fins (compressed air side) are in direct contact with the external wall of the combustion chamber, and thus increase the degree of regeneration.

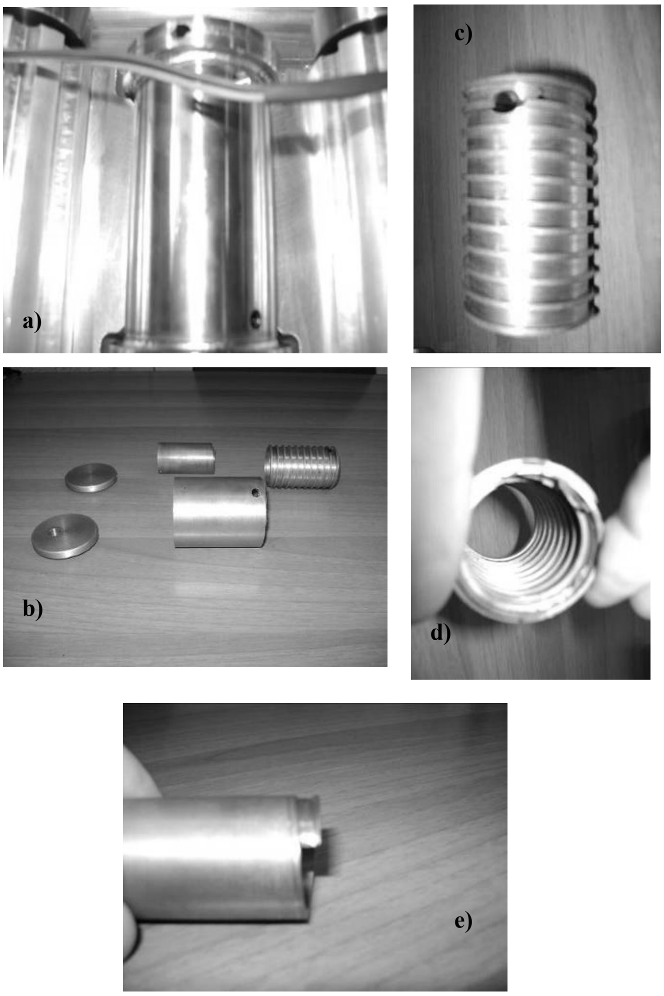


Figure 6 - UMGTG-UDR1 – a) the combustion chamber final assembly; b) components of the combustion chamber/regenerator device (notice the three coaxial cylinders); c) the exhaust gas path; d) the compressed air path; e) the air inlet in the combustion chamber

Table 3

Material	AISI 314
Diameter [mm]	35
Length [mm]	60
CC length [mm]	55
CC diameter [mm]	25

3.5 The Electrical Motor/Generator group

Another interesting feature of the UMGTG-UDR1 is the electric drive group with its "electromagnetic gear". A commercial electric motor with nominal maximum speed to 45.000 rpm, is, coupled to the shaft of the turbogroup (on the compressor side) by means of a cup containing 8 permanent magnets. Since the tip of the compressor shaft bears 2 magnets, a magnetic gear is realized, with a "gear" ratio equal to 4:1 (the 8 magnets in the motor shaft and the 2 in the compressor shaft. A more conventional solution has also been tested, consisting of a crown/pinion coupling with the same gear ratio. Thus the compressor and turbine rotors operate at 160.000 - 180.000 rpm, while the electric motor can be maintained at a maximum speed of 40-50.000 rpm. Figure 7 shows the details of the motor/generator and both of the magnetic and mechanical coupling.

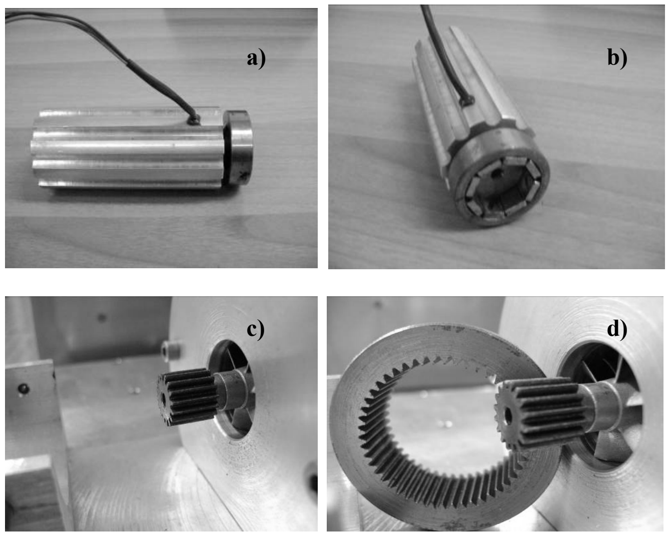


Figure 7 - UMGTG-UDR 1 – a) particular of EG/EM; b) particular of the electro magnetic gear; c) second solution of the EG/EM gas turbine device coupling; d) particular of the gear

4. Tests on the UMGTG-UDR 1 device

4.1 Compressor cold tests

A dedicated test bench was built [5] (figure 8) to reproduce the operation of the device in "cold" conditions (the turbine being driven by a jet of compressed air at room temperature) and derive the compressor map.A volumetric high-precision flow meter, a pressure gage and a thermocouple are inserted on the turbine inlet channel to evaluate the inlet conditions and to ensure steady operation. Similar devices are inserted in the compressor outlet channel, to measure the pressure ratio and the compressor outlet temperature. A thermocouple and a pressure gage are inserted on the turbine exhaust as well. The following table [4] reports the tests data

Table 4: Summary of the measured data - "cold" compressor test [5]

Compressor	**outlet air velocity[m/s]**	58
	Air inlet temperature [°C]	18
	Air outlet temperature [°C]	≈ 60
	Inlet air pressure [bar]	1
	Outlet air pressure [bar]	1.8

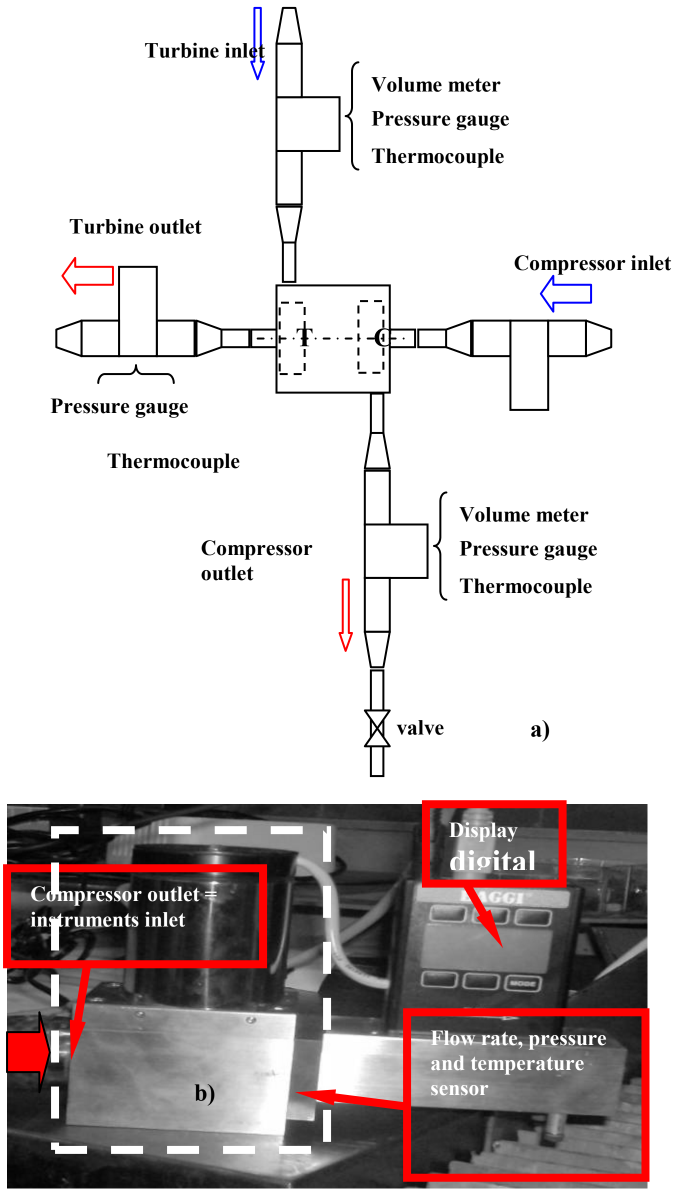


Figure 8 - a. Functional sketch of the test bench for the UMGT; b. the instruments device

4.2 Combustion chamber cold tests

The friction losses in the combustion chamber have been measured by the experimental setup represented in figure 9.

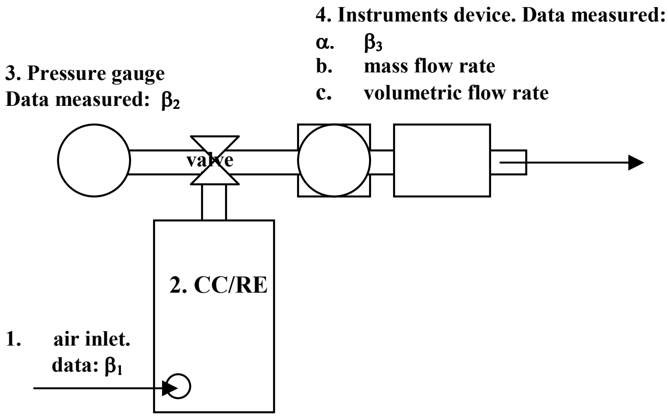


Figure 9 - test bench reference lay out

Table 5: Reference data to calculate the head losses

β_3	$\Delta\beta_3$	V_3	m_3	e%
kPa	*kPa*	*cm^3/s*	*cm^3/s*	*%*
159	0	1040,0	1065,0	0,2
223	1	1463,3	1508,3	0,7
270	2	1688,3	1766,7	0,9
308	4	1991,7	2113,3	1,3
359	5	-	-	1,5
404	7	-	-	1,7

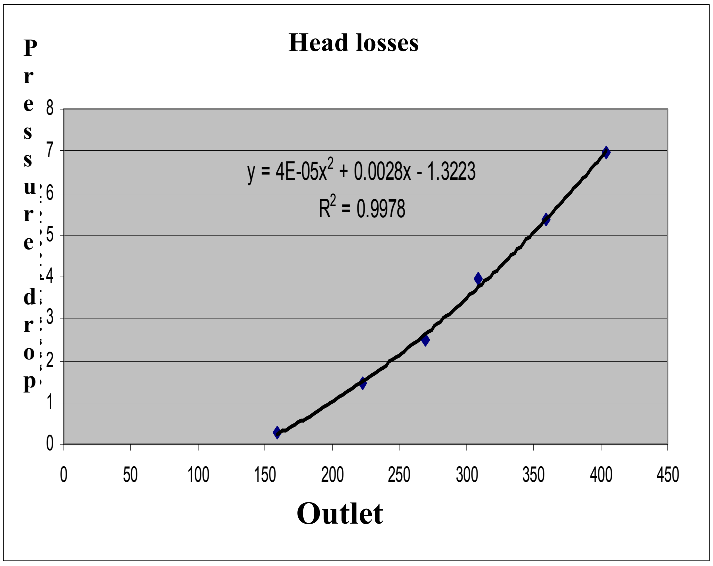


Figure 10: evaluation of the pressure drop in the combustion chamber

The data could be fitted by a second order polynomial (see Figure 10) with an accuracy equal to 0.9978. The head losses vary with the second power of the outlet pressure and are of the order of 2% at steady conditions (see column " e%" of Figure 10).

4.3 Ignition tests and evaluation of the temperature field

Before the final assembling, the last test carried out on the combustion chamber consisted of the measurement of the outlet gas temperature. The device used is a “K” thermocouple (acquisition range -40°C +1300 °C) directly located in the exhausts current and connected to electrical multimeter that supplies, in real time, the trend of the temperature.

Three different operational conditions were tested:

- ignition
- steady state combustion
- combustion shut down

The total acquisition times are different for each test:

- ignition: 30-45 seconds ($T_{ignition}$ evaluated)
- steady state combustion: 10-15 minutes
- combustion shut down: T measured after 5 minutes

The results are summarized in Table 6:

Table 6

Operational condition				
Ignition	T_{ign} (°C)	510		
Steady state	T_{max}(°C)	1080	$T_{average}$ (°C)	1000
Shut down	T (°C)	480		

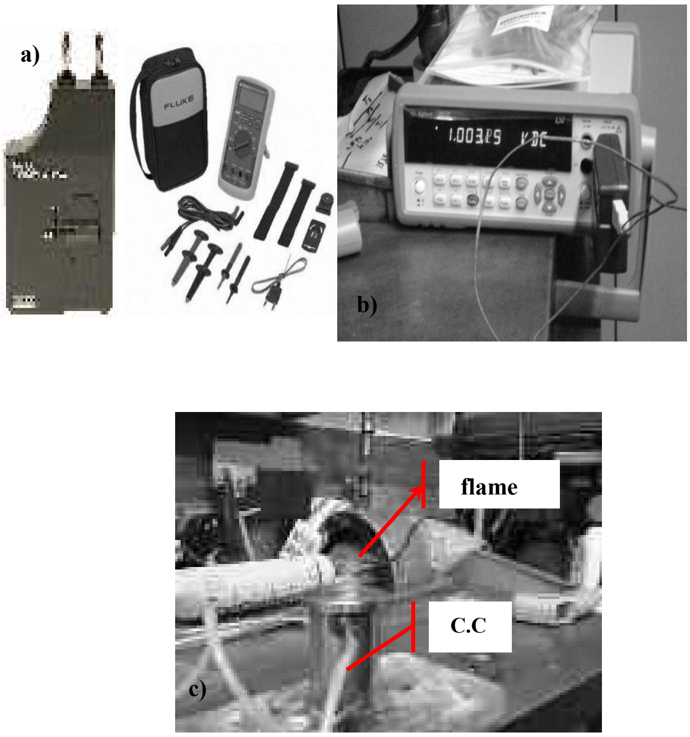


Figure 11: a) K thermocouple device; b) multimeter; c) combustion ignition tests

5. Conclusions

All components having been tested separately, they have then undergone final. An additional "final test" campaign is underway at the time of this writing, its goal being both that of obtaining prototype acceptance by the customer and of indicating future possible improvements to introduce in the device before its pre-commercialization.
The economic impact of UMTG devices will depend both on their performance levels and the manufacturing costs, both of which have yet to be proven. It is certainly possible, however, that ultra micro GT sets may one day be competitive with conventional machines for what the installed kW cost is concerned. Even if their cost scales "up" rather than "down" with smaller and smaller sizes, they have already no competitors as compact power sources for portable electronics equipment and ultra-small vehicles.
Competing with a 50-60% efficient central power plant clearly requires much higher performance levels. Excluding cogenerative use of the waste heat, an ultra micro gas turbine ought to attain an efficiency of 20% to be considered feasible for niche applications: such a level of efficiency looks futuristic at this time. Should however these levels be approached, then the redundancy and extreme quietness and compactness may make an array of millimeter-scale machines an attractive solution.
The drawback is that UMGTG sets are very expensive to develop. Though these costs may be amortized over many units, manufacturing cost is still a major issue for mass-produced devices.

ACKNOWLEDGMENT

The work presented in this paper has been partially sponsored by the Technical Division of the Italian Army Head Quarter, within the frame of contract n. 714. All opinions reported in this paper do not necessarily reflect the opinions of the Funding Agency, and are sole responsibility of the Authors.

REFERENCE

1. R. Capata, E. Sciubba, *Preliminary Considerations on the Thermodynamic Feasibility and Possible Design of Ultra-Micro and Nano Gas Turbines*, Proc of 2nd Int. Conf. of Appl. Thermodynamics., Istanbul, May 12-15, 2005.
2. R. Capata, E. Sciubba, *Effects of the Reynolds Number on the performance of a Nano Compressor*, Proc of 20th ECOS Conf. Padova, Italy, June, 25-28, 2007
3. R. Capata, E. Sciubba, *Progress in the development of a prototype "Ultra-Micro" Gas Turbine Set for Portable Power Generation*" 21th ECOS Conf., Gliwice, Poland, June, 24-27, 2008
4. R. Capata, E. Sciubba, *Design and Performance Prediction of a Ultra-Micro Gas Turbine for Portable Power Generation*, Proc of IMECE 2007 Conf. Seattle, Washington, November, 11-16, 2007
5. R. Capata, E. Sciubba, *Further development and preliminary testing of the α – prototype of an ultra-micro gas turbine for portable power generation*, Proc of IMECE 2008 Conf. Boston, Massachussetts, November, 2-7, 2008
6. Epstein *Millimeter-Scale Gas Turbine Engines* , Proc. ASME Turbo Expo 2003 Power for Land, Sea, and Air, June 16-19,2003, Atlanta, Georgia, USA.
7. Epstein, S.D. Senturia, G. Anathasuresh, A. Ayon, K. Breuer K-S Chen, F.F. Ehrich, G. Gauba, R. Ghodssi, C. Groshenry, S.A. Jacobson, J.H. Lang, C-C Lin, A. Mehra, J.O. Mur Miranda, S. Nag1e, D.J. Orr, E. Piekos, M.A. Schmidt, G Shir1ey, S.M. Spearing, C.S. Tan, y -S Tzeng, I.A. Waitz, *Power Mems And Microengines,* IEEE Transducers '97 Conference, Chicago, IL, June 1997

8. D. Foresti, *Preliminary design and 3D fluid dynamic simulations of ultra micro radial compressor and turbine* (in Italian), M. Thesis Dept. Of Energetics, May 2008
9. M. Ishihama, Y. Sakai, K. Matsuzuki, T. Hikone *Structural Analysis Of Rotating Parts Of An Ultra Micro Gas Turbine* , Proc. of the Int. Gas Turb. Congr. 2003 Tokyo, November 2- 7, 2003.
10. J Peirs, T Waumans, P. Vleugels, F. Al-Bender, T. Stevens, T. Verstraete, S. Stevens, R. D'hulsts, D Verstraete, R. Van den Braembussche, J. dressen, R. Puers, P. Hendrick, M Baelmans, D. Reynaerts, *Micropower generation with microturbogasturbines: a challenge*, JMES472, Proc. of IMechE Vol 221 part C, Pagg. 489-497.
11. G. Silva Caveeiro, *Ultra micro Gas Turbines analysis*, M. Thesis, Dept of Mechanics and Aeronautics, Oct 2006 (in Italian)
12. Y. Wang, M. Wu, R.A. Yetter, V. Yang, *An integrated experimental and numerical study of meso scale vortex combustor dynamics*, 43rd AIAA Meeting 2005, AIAA 2005-941