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## A small size combined system for the production of energy from renewable sources and unconventional fuels

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### Abstract

Nowadays, the development of new power plants capable of effectively using non-conventional energy sources is strongly desirable in order to obtain a significant reduction in costs of energy. In this regard, this paper proposes a new small scale (about 100 kW) combined cycle plant which can be fired externally by any kind of biomass. Particularly, the research activity presented here is concerned with the preliminary design of this innovative plant, which will be built, by means of a project funded by “Apulia Region”, at the LabZero Research Centre of Polytechnic University of Bari in the south of Italy. The goal of the paper is to demonstrate the effectiveness of the plant in terms of energy efficiency and availability and reliability of its components. The plant is mainly composed of a centrifugal compressor and a centripetal turbine of an automotive turbocharger, with the working fluid (clean air) being heated in a high temperature heat exchanger (HTHE) by using hot flue gases produced in an external combustion chamber burning biomass. The clean hot air expands in the turbine and then feeds the combustion chamber, where biomass is burned. In order to increase the efficiency, the flue gases exiting the HTHE are delivered into a heat recovery steam generator to generate water steam which can finally expand through a rotary actuator. Two configurations, employing an open Rankine cycle and a close one respectively, are analysed, and the use of biomass is compared with methane.

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**Keywords:** Biomass; Externally fired microturbine; Combined cycle plant.

### 1. Introduction

In spite of the insistent calls of the international community about energy saving, current energy systems are still strongly based on the use of fossil energy. The past years highlighted the long-standing problem of energy supply, especially for those countries that are subject to lack of fossil sources, whose availability is often expensive and jeopardized by geo-political aspects. Thus, it is necessary that research focuses on the development of novel technologies and methodologies for electricity generation that have the potential to save energy and increase eco sustainability. A solution is represented by the decentralization of power generation, employing small size plants

fired by unconventional fuels such as biomass [1,2,3] (i.e. pellets [4] or discarded agricultural by-products) for distributed energy generation. Since biomass is largely available and given its low impact in terms of pollutant emissions [5], a more thorough evaluation of its potentiality is a mandatory step to decouple power generation from large scale plants, which can only be powered by fossil fuels.

In this scenario, the purpose of this work is to design a small size combined cycle power plant that greatly fits with energy demands typical of limited urban areas, i.e. community housing, leisure centres, tertiary sector users, sport centres, hospitals or supermarkets. The pilot plant will be located in Apulia (south of Italy), and this kind of plant is interesting especially for those regions, such as Apulia, that offer a widespread availability of agricultural and forestry waste products to be used as biofuel, e.g. those deriving from the cultivation of olive trees [4,6,7] (in Apulia, the quantity of olive trees is estimated around the 40 millions of units). The strategic aspect of great importance is that the biomass supply can be feasible at competitive costs; however, it must be considered that some typologies of biomass are annually available over a limited period, for example, olive oil by-products (vegetation water, olive pomace, exhausted peanut residue) are available in Apulia only from mid-October to late February. For these reasons, the proposed power plant is designed in order to allow burning of most of the biomass derived from agricultural and forestry wasted products typical of Apulia, such as hazelnut shells, cherry stones, grape seeds, almond shells, olive stones, etc. This multi-fuel approach is allowed by the similar LHV values of such agricultural by-products. It is obvious that, in case of unforeseen lack of biomass fuels (e.g. caused by inefficiency of collection systems, packaging, transport and storage systems [7,8,9,10]), natural gas or other clean fuels can be employed in place of biomass and burned in a commonly used combustor for gas turbines [11]. This strategy can allow both a smart use of the available fuels and maintenance of the biomass combustor, in fact the temporary use of clean fuels can allow cleaning devices to remove ash from the combustor (the biomass combustion implies large production of ash).

The operating principles of this novel small power plant are described in detail in this paper, particularly two different configurations are proposed in the next sections. Afterwards, the mechanical and thermal components are described, and their availability and reliability are discussed. Finally, the results of the numerical simulations, achieved with the Gate-cycle software and an Excel program to predict the efficiency of both the configurations, are shown and discussed critically.

## Nomenclature

$G_A$	air mass flow rate
$G_B$	fuel mass flow rate
$G_S$	steam mass flow rate
$P_{el}$	electrical power
$p$	pressure
$h$	enthalpy
$T$	temperature
$HRSG$	heat recovery steam generator
$HTHE$	heat temperature heat exchange
$LHV$	lower heating value
$\beta_C$	compression ratio
$\Delta T_{pp}$	$\Delta T$ at pinch point
$\varepsilon$	heat exchanger efficiency
$\eta_g$	plant (electrical) efficiency
$\eta_{is}$	isentropic efficiency
$\eta_B$	Combustion efficiency
$\lambda_V$	water latent vaporization heat

## 2. The small size combined plant

In this section, the proposed novel combined-cycle plant for electricity generation from biomass is described; particularly, two possible configurations are analysed in detail. As mentioned earlier, the final goal of this research project, funded by Apulia Region, is to build a pilot plant at the so-called “*Lab Zero Research Centre*” of Polytechnic University of Bari in the south of Italy. For simplicity and costs reasons, only the first configuration will be realized and tested experimentally. The components will perfectly be harmonized by means of customized solutions that are available on the global market, simplifying the installation and ensuring their efficient operation for long periods. An important step will be the choice of reliable control techniques/strategies fitting with the small scale electricity production [11]. The employment of different devices will require the implementation of an integrated PLC system, in order to centralize the control of the whole plant and make it effective and flexible. The employment of a “*Cloud*” platform will enable a fully monitoring action, meeting the targets defined by the European program “*strategy 2020*”.

### 2.1. First configuration: open Joule Bryton cycle combined with an open Rankine cycle

Figure 1 shows the first configuration of the plant layout, which is constituted by an open Joule Bryton cycle (topping) and an open Rankine cycle (bottoming). The former is performed by means of a small scale externally fired gas turbine (EFGT) which is constituted by an external combustor, a high temperature heat exchanger (HTHE) and a compressor moved by a gas turbine coupled with the first electric generator. After being compressed, the air is conveyed to the HTHE, which recovers the heat from the flue gases exiting the external combustor, in order to transfer it to the compressed air. The clean hot air expands in the turbine and then feeds the external combustor chamber for burning biomass. The exhaust gas exiting the HTHE are used in a heat recovery steam generator (HRSG) to generate water steam which can expand through a steam actuator moving the second electric generator.

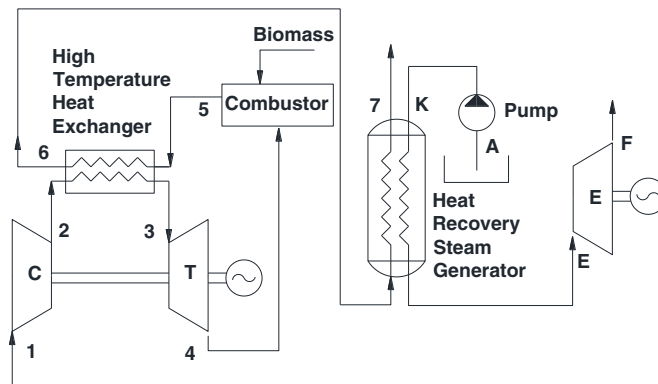


Figure 1 - First layout of the combined-cycle plant, including a compressor coupled with a turbine which provides power to an electrical generator, a gas to gas heat exchanger, and an external combustor. The exhaust gases are then delivered to a HRSG for generation of steam to be delivered to a rotary expander, which moves another electrical generator. Hot steam exiting the expander (outlet section F) can be used for technological purposes.

Because of the small flow rate of steam produced, a rotary expander can be used in place of a steam turbine, which is commonly used in medium and large scale combined cycle power plants. In this configuration, the hot steam discharged from the steam expander can be utilized for technological purposes and the pump refills the plant with new and demineralized water.

## 2.2. Second configuration: open Joule Bryton cycle combined with a closed Rankine cycle

Figure 2 shows the second configuration of the plant layout, constituted by an open Joule Bryton cycle and a closed Rankine cycle. Similarly to the first solution, the bottoming cycle is performed by means of an externally fired gas turbine (EFGT) constituted by a compressor, a high temperature heat exchanger (HTHE), an external combustor, and a turbine coupled with the electric generator. The difference with the former solution is given by the Rankine cycle, which is closed loop, and the typical components of a steam cycle, i.e. a condenser, a degasser, etc., are required. Also in this case, the steam generator (HRSG) generates water steam which then expands through a steam actuator coupled with the second electric generator. The expanded steam is delivered to a condenser and a pump recirculates water from *F* to *K* in a closed loop.

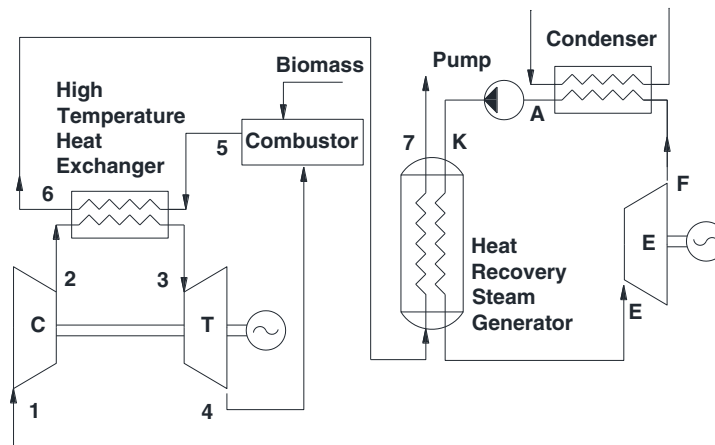


Figure 2 - Second layout of the combined-cycle plant; the scheme is equal to the one of Figure 1, except for the bottoming cycle which is closed and requires a condenser and a degasser.

## 2.3. Availability and reliability of the components

The proposed plant represents a promising and reliable generation system, which offers advantages in terms of flexibility and efficiency [7], and the feasibility is proved by the commercial availability of its components. By virtue of the maximum values of temperature and pressure which are compatible with thermo-mechanical resistance limits of typical automotive turbo-chargers, a cheap turbo-charger can be used in alternative to a more expensive microturbine. In fact, existing micro-turbines are quite expensive and modifications to their structure are not allowed by manufacturers, therefore the prototype will employ an automotive turbo-charger, e.g. type GARRETT GTX5518R (or other ones with similar performance), to perform compression and expansion of clean air.

The external combustion of biomass can be accomplished only by the use of a gas to gas heat exchanger that has to transfer heat from the flue gas to the clean air flow effectively. The design of such a gas-to-gas heat exchanger is not a trivial task, since it operates at high temperature and is interested by significant thermal deformations and stress; furthermore it must ensure low pressure drops on both sides and a low heat loss towards the ambient. Technical solutions provided to date refer to the design of recuperators for small- and micro-turbines, where the employed low pressure ratios make the heat recovery mandatory. Such recuperators can only operate under conditions of very small flow rate and/or low maximum temperature, therefore their use is not possible in large externally fired gas turbines. In contrast, their use is more profitable in the proposed small externally fired plant and their application will be investigated in future works. Alternatively, a high efficiency gas to gas heat exchanger based on ceramic particles as intermediate medium, proposed in [12,13,14], can be used.

An optimization procedure, presented in [15,16], could be utilized in future works to reduce size and increase efficiency of the heat exchanger chosen.

With regard to the biomass combustor, either a fluidized bed combustor or a standard furnace are largely available on the market and can be used to perform combustion of biomass with the high temperature air discharged from the turbine. Nowadays, furnaces for biomass are characterized by excellent efficiency, estimable around the 90%, thanks to sophisticated technologies which allow the combustion process to be constantly monitored in order to minimize losses [17,19]. However, there are still unresolved problems, due to the complexity of the burning process, which need to be faced up, such as the relatively low melting temperature of ash and variation in fuel properties (e.g. moisture content, calorific value, geometric shape and size). Furthermore, the stable biomass combustion is not completely reachable, because of the generation of ash slagging and fouling which negatively affect the lifetime of combustion equipment [17]. A further drawback is represented by the low quality of biomass fuels [17,18], and the large emission of CO and hydrocarbons due to the incomplete combustion. These problems can be overcome by the employment of a furnace that performs the thermal decomposition of the fuel in different stages in order to facilitate the reduction in pollutant emissions.

With regard to the HRSG, actual heat recovery boilers are certified in accordance with the Pressure Equipment Directive, and usually consist of a highly efficient tubular heat exchanger. Because of its compact dimensions, this choice could fit with the aforementioned attempt to minimize the size of the whole plant. Given the usual easy installation, typical of small size steam generators, this component will be effectively harmonized with the system, and should be insulated with effective heat-insulating materials. Furthermore, a wide range of services such as customized maintenance packages are available on the global market to ensure long maintenance of this component. In order to reduce corrosion and fouling in the boiler, the plant needs to be also equipped with demineralization and degassing systems, which require the use of special solvents that maintain acceptable values of both the pH and the water hardness.

Concerning the steam expander, it can be chosen among available micro steam turbines or rotary air compressors (e.g. a screw compressor or, alternatively, a vane compressor), working in reverse mode, and suitable to the steam expansion compatibly with the low mass flow rate of steam.

### 3. The numerical models

The performance of the two configurations was predicted by using an Excel program, capable of solving the governing equations by means of the “false position” method, and by using the Gate-Cycle® software [20]. With regard to the Excel program, it is essentially based on a system of equations with the assumption that the working fluid is semi-perfect. Specifically, concerning the combustor, the energy balance is governed by the following equation:

$$\eta_B G_B LHV = (G_A + G_B)(h_5 - h_4) \quad (1)$$

The left-hand side of this equation represents the thermal power generated by the combustion, with  $\eta_B$  representing the combustion efficiency and  $LHV$  denoting the lower heating value of the employed fuel. The right-hand side is indicative of the enthalpy variation of the air mass flow rate,  $G_A$ , mixed with the fuel mass flow rate,  $G_B$ . The terms  $h_5$  and  $h_4$  denote the enthalpies at the combustor outlet and at the turbine outlet, respectively. With regard to the HTHE, the power balance is given by the following equation:

$$G_A (h_3 - h_2) = (G_A + G_B)(h_5 - h_6) \quad (2)$$

with  $h_2$ ,  $h_3$  being the enthalpy of the air at the inlet and outlet of the HTHE, and  $h_6$  being the enthalpy of the flue gas at the exit of the HTHE before being conveyed to the HRSG. Its effectiveness is defined by the efficiency  $\varepsilon$  according to the following expression:

$$\varepsilon = \frac{(h_3 - h_2)}{(h_5 - h_2)} \quad (3)$$

Since current HRSGs excel in terms of effectiveness because of the effective heat-insulating materials employed, the heat dispersion can be neglected, and the thermal power balance in the HRSG can be written as:

$$(G_A + G_B) (h_6 - h_7) = G_S (h_C - h_K) + G_S \lambda_v + G_S (h_E - h_D) \quad (4)$$

where  $\lambda_v$  is the latent heat of vaporization of water,  $h_7$  is the enthalpy of the exhaust gas at the exit of the HRSG,  $h_C$  and  $h_K$  denote the enthalpies of the water at the exit and inlet of the economizer respectively, while  $h_E$  and  $h_D$  are the enthalpies of the steam at the outlet and inlet of the superheater. The steam enthalpies  $h_E$  and  $h_F$  (enthalpy at the outlet of the steam expander) can be retrieved from the *Mollier* diagram after the steam pressure and temperature are set. Knowing the values of  $h_E$  and  $h_F$  and the steam mass flow rate,  $G_S$ , the available power output from the expander is easily calculable. With regard to the pressure condensation  $p_K$ , it is equal to the atmospheric value in the first configuration (Figure 1), while it can become lower in the second configuration (Figure 2).

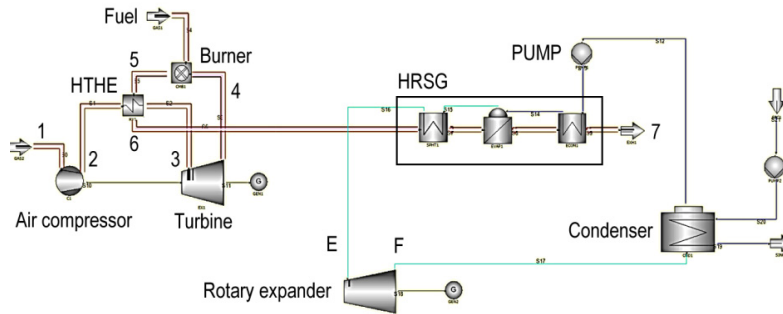


Figure 3 - Model of configuration 2, screenshot from the Gate Cycle Software. The numbers and symbols are reported in the diagram coherently to the analytical equations

The thermodynamic simulations were also carried out by means of the Gate-Cycle software [20] for different types of fuel, in order to find the best efficiency point and to compare the results with the Excel program.

As is well known, GateCycle is commercial software for quick and easy monitoring of plant performance and for predicting design and off-design performances of combined cycle plants, fossil boiler plants, cogeneration systems, combined heat-and-power plants, advanced gas turbine cycles and many other energy systems. Figure 3 shows the component-by-component approach used to model the second configuration (Figure 2).

#### 4. Results and discussion

Since the purpose of this work is to evaluate the efficiency of the new small size combined system employing unconventional fuels, the calculations were carried out changing the design parameters and comparing the results obtained with methane and those obtained with biomass.

A first calculation was performed to compare the two proposed configurations assuming that the fuel is methane. The calculation was performed using the map of a typical automotive turbocharger, specifically GARRETT GTX5518R, suited to achieving an electrical power of about 100 kW.

The results of the calculations performed with methane fuel are shown in Table 1, which compares configuration 1 with configuration 2.

Note that, as expected, the efficiency is higher in configuration n. 2, because of the lower pressure at the exit of the expander. However, the layout proposed in configuration n. 2 is more complex than configuration n. 1 for the presence of a steam condenser, which can become a limiting factor for the commercialization of small-scale plants. Furthermore, the open Rankine cycle proposed in configuration n. 1 can allow the utilization of the hot steam discharged from the steam expander for technological purposes thanks to its high temperature (about 100 °C). In contrast, the steam discharged from the expander in configuration n. 2 is characterized by very low temperature (about 45 °C), for which cogeneration is unusual.

To demonstrate the feasibility and flexibility of the proposed plant to burning biomass, the following calculations were carried out employing pellets, whose LHV is estimable around 19000 kJ/kg and is similar to the one of other agricultural wasted products, for instance hazelnut shells, cherry stones, grape seeds, almond shells, olive stones, etc.

The results of these simulations are shown in Table 2 and compared with the numerical predictions achieved assuming that the fuel is methane; both cases are concerned with configuration 1. It is noteworthy that the values of the main parameters are not significantly different in the two cases, apart from the higher value of  $G_B$  required by the use of biomass, due to its lower LHV. In particular, the similar values of the temperature in the critical points allow the use of a multi-fuel supply. In fact, similar values of temperature also imply similar thermal stresses for the materials employed in this kind of application, which can consequently afford the multi-fuel strategy, stemming the risk of early corrosion and oxidation of the components [18,19,21,22,23].

Table 1 – Thermal parameters firing Methane (comparison between configuration 1 and configuration 2).

Parameter	Units	Values config. 1	Values config. 2
$G_A$ Inlet air mass flow	kg/s	0.6804	0.6804
$\beta_c$ Air compression ratio	-	3	3
$\eta_{is,c}$ Isentropic compressor efficiency	-	0.75	0.75
$\eta_B$ Combustor efficiency	kW	0.98	0.98
$\varepsilon$ heat exchanger efficiency	-	0.80	0.80
$G_B$ Fuel mass flow rate	kg/s	0.006468	0.006468
$P_{el,tg}$ Turbogas electrical power	kW	76.54	76.54
$\eta_{is,e}$ Expander isentropic efficiency	-	0.5	0.5
$\Delta T_{pp}$ $\Delta T$ at pinch point	°C	15	15
$G_s$ Steam mass flow rate	kg/s	0.05375	0.05375
$p_v$ Steam pressure	Bar	10	10
$T_E$ Steam temperature	°C	225	225
$p_k$ Condensation pressure	Bar	1	0.1
$T_s$ Discharge temperature	°C	168.4	151
$P_{el,st}$ Steam expander power	kW	10.93	19.18
$P_{el}$ Overall electrical power	kW	87.47	95.72
$\eta_g$ Plant efficiency	-	0.2705	0.2960

Table 2 – Comparison between Methane and Biomass (predictions of configuration n. 1)

Parameter	Units	Methane config. 1	Biomass config. 1
$G_B$ Fuel mass flow rate	kg/s	0.006468	0.01887
$\eta_B$ Combustor efficiency		0.98	0.9
$T_3$ Turbine air inlet temperature	°C	878.9	878.9
$T_5$ HTHE gas inlet temperature	°C	1047.3	1047.3
$T_6$ HTHE gas outlet temperature	°C	354.4	367.5
$T_s$ Discharge temperature	°C	168.4	166.2
$R_p$ Power ratio ( $P_{el,st}/P_{el,tg}$ )	-	0.1428	0.1575
$P_{el}$ Overall electrical power	kW	87.47	88.60

Table 3 – Thermal parameters firing Methane and Biomass comparing the Excel program with GateCycle (configuration 1).

Parameter	Units	Excel program	GateCycle	Excel program	GateCycle
$FT$ Fuel type	-	Methane	Methane	Biomass	Biomass
$G_B$ Fuel mass flow rate	kg/s	0.006468	0.006468	0.01887	0.01887
$P_{el,tg}$ Turbogas electrical power	kW	76.54	78.80	76.54	78.2
$P_{el,st}$ Steam expander power	kW	10.93	10.05	12.05	11.45
$P_{el}$ Overall electrical power	kW	87.47	88.85	88.60	89.65
$\eta_g$ Plant efficiency	-	0.2705	0.2747	0.2471	0.2500



Finally, Table 3 reports the comparison between the results of the calculations achieved by the Excel program and the numerical predictions provided by the GateCycle model [20], in the case of Methane and Biomass. The results show a good agreement between the two models, proving the validity of some simplifications assumed in the Excel program (e.g. semi-perfect gas).

## 5. Conclusions

This paper presented an innovative small scale combined cycle power plant (about 100 kW), externally fired by biomass such as agro-industrial by-products, largely available on the national territory and particularly on Apulia Region. The plant is expected to be realized at the laboratory “*LabZero Research Center*” of Polytechnic University of Bari very soon. Two configurations were analysed in the paper: the first one is constituted by an externally fired gas turbine (topping cycle) and an open steam cycle (bottoming cycle), whereas the other one combines the fired gas turbine with a closed steam cycle. The availability and reliability of the plant components proves the feasibility of both the solutions. Particularly, a cheap turbo-charger can be used in place of a more expensive microturbine, while the difficulties related to the design of the high temperature heat exchanger can be overcome by using some of the solutions proposed in the scientific literature such as the immersed particle heat exchanger. A crucial component is the steam expander, which can be chosen among the available micro steam turbines or rotary air compressors (e.g. a screw compressor) to be used in reverse mode. With regard to the biomass combustor, either a fluidized bed combustor or a standard furnace are largely available on the market and can be used to perform combustion of different types of biomass. In order to allow both a smart use of the available fuels and maintenance of the biomass combustor, natural gas or other clean fuels can be used in place of biomass and it burned in a commonly used combustor for gas turbines. Accurate numerical predictions achieved with a program realized in Excel show that the novel small combined cycle is capable of providing high energy efficiency with respect to typical small scale plants for distributed energy production.

## References

- [1] Camporeale, S. M., Fortunato, B., Pantaleo, A. M., & Sciacovelli, D. (2011, January). Biomass utilization in dual combustion gas turbines for distributed power generation in mediterranean countries. In ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition (pp. 573-582). American Society of Mechanical Engineers.
- [2] Zimmermann, P., Cardenas, A., Hirsch, C., and Sattlemayer, T., 2009. “Simulation of a Micro Turbine’s Dynamic Behavior in a Biomass Incineration Power Plant Based on the Pebble Heater Technology” ASME Paper GT2009-59305, Orlando, FL, USA.
- [3] Warnecke, R. (2000). Gasification of biomass: comparison of fixed bed and fluidized bed gasifier. *Biomass and Bioenergy*, 18(6), 489 - 497.
- [4] Carone, M. T., Pantaleo, A., & Pellerano, A. (2011). Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of *Olea europaea* L. *Biomass and bioenergy*, 35(1), 402-410.
- [5] Nussbaumer T. Combustion and co-combustion of biomass: fundamentals, technologies and primary measures for emission reduction. *Energy Fuels* 2003;17:1510 – 1521.
- [6] Vera D, Jurado F, Carpio J. Study of a downdraft gasifier and externally fired gas turbine for olive industry wastes. *Fuel Process Technol* 2011;92(10): 1970 – 1979.
- [7] Franco, A., Giannini, N. Perspectives for the use of biomass as fuel in combined cycle power plants (2005) *International Journal of Thermal Sciences*, 44 (2), pp. 163-177.
- [8] Al-attab KA, Zainal ZA. Turbine startup methods for externally fired micro gas turbine (EFMGT) system using biomass fuels. *Appl Energy* 2010;87:1336 – 1341.
- [9] Meher-Homji, C. B., & Gabriles, G. A. (1998, September). Gas Turbine Blade Failures—Causes, Avoidance, and Troubleshooting. In Twenty-Seventh Turbomachinery Symposium, Houston, TX, September (pp. 22-24).
- [10] Jeong, J. H., Kim, L. S., Lee, J. K., Ha, M. Y., Kim, K. S., and Ahn, Y. C. 2007. “Review of heat exchanger studies for high-efficiency gas turbines.” *Proceedings of ASME Turbo Expo 2007, Power for Land, Sea and Air*, May 14-17, Montreal, Canada, GT2007 - 28071.
- [11] Amirante, R., Catalano, L. A., & Tamburrano, P. (2012). Thrust control of small turbojet engines using fuzzy logic: Design and experimental validation. *Journal of Engineering for Gas Turbines and Power*, 134(12).
- [12] Catalano, L. A., De Bellis, F., Amirante, R., & Rignanese, M. (2011). An immersed particle heat exchanger for externally fired and heat recovery gas turbines. *Journal of Engineering for Gas Turbines and Power*, 133(3), 032301.
- [13] Amirante, R., & Tamburrano, P. (2014). High Temperature Gas-to-Gas Heat Exchanger Based on a Solid Intermediate Medium. *Advances in Mechanical Engineering*, 2014.
- [14] L. A. Catalano, R. Amirante, P. Tamburrano, and S. Copertino, “Analysis of the complementary energy losses of a high temperature gas to gas heat exchanger based on a solid intermediate medium,” *WIT Transactions on Engineering Sciences*, vol. 75, pp. 109 – 120, 2012.



- [15] F. de Bellis and L. A. Catalano, “CFD optimization of an immersed particle heat exchanger,” *Applied Energy*, vol. 97, pp. 841 – 848, 2012.
- [16] R. Amirante, L.A. Catalano, C. Poloni, P. Tamburrano, “Fluid-dynamic design optimization of hydraulic proportional directional valves”, *Engineering Optimization* Vol. 46, Iss. 10, 2014
- [17] Dare P, Gifford J, Hooper RJ, Clemens AH, Damiano LF, Gong D, et al. Combustion performance of biomass residue and purpose grown species. *Biomass Bioenergy* 2001;21:277 – 87.
- [18] Strzalka R, Erhart TG, Eicker U. Analysis and optimization of a cogeneration system based on biomass combustion. *Appl Therm Eng* 2013;50(2):1418 – 26.
- [19] Nussbaumer T. Combustion and co-combustion of biomass: fundamentals, technologies and primary measures for emission reduction. *Energy Fuels* 2003;17:1510–21.
- [20] GateCycle 6.1.1 User’s Guide, GE Enter software for Windows version (www.gepower.com) 2014.
- [21] Stein-Brzozowska G, Flórez DM, Maier J, Scheffknecht G. Nickel-base superalloys for ultra-supercritical coal-fired power plants: fireside corrosion, laboratory studies and power plant exposures. *Fuel* 2013;108:521 – 533.
- [22] Birks N, Maier GH, Pettit FS. *Introduction to the high temperature oxidation of metals*. 2nd ed. Cambridge University Press; 2006. ISBN-13: 978-0-521-48042-0.
- [23] Mao C, Scarpellini R, Valarani M. Design, construction and testing of a ceramic high temperature heat exchanger for an externally fired cycle plant. In: 7th Liege conference on materials for advanced power engineering, Liege, Belgium, vol. II; 2002. p. 845 – 852. ISBN 3-89336-312-2.