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To cite this article: L Cioccolanti *et al* 2017 *J. Phys.: Conf. Ser.* **923** 012041

Innovative coupling of cogeneration units with fire tube boilers: thermo-fluid dynamics of the fire tubes

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Abstract. Nowadays the thermal energy demand in the industrial sector is usually satisfied by means of fire tube boilers while electricity is supplied from the grid. Alternatively cogeneration units could be adopted for thermal and electrical energy self-production, whilst installing boilers only as back-up units. However, even when cogeneration is profitable, it is not widespread because industries are usually unwilling to accept cogeneration plants for reliability and high investment costs issues. In this work a system aimed at overcoming the above mentioned market difficulties is proposed. It consists of an innovative coupling of a combined heat and power unit with a modified fire tube boiler. In particular, a CFD analysis was carried out by the authors in order to address the most critical aspects related with the coupling of the two systems. More precisely, the following aspects were evaluated in detail: (i) pressure losses of the exhausts going from the prime mover to the boiler due to the sudden cross-section area variations; (ii) thermal power recoverable from the exhausts in the tubes of the boiler; (iii) dependence of the system on the final users' specification.

1. Introduction

Despite the prolonged economic crisis that has affected the world's most advanced countries in the last years, industry remains one of the most energy-intensive sectors worldwide. According to the Energy Information Administration (EIA) [1] indeed in the United States the industry sector accounts for about one third of the energy used in the country while in the EU-28 countries the industry, excluding the energy sector, accounted for more than 25% of the overall final energy consumption in 2015 [2]. Moreover, it will continue to play a key role also in the future since an increase of about 1.2% per year in the industrial sector energy consumption is foreseen in the next decades according to reference case scenarios [3] mainly due to the contributions of the countries outside the Organization for Economic Cooperation and Development (OECD).

As regards the highly industrialized countries energy is used for a wide range of purposes, such as process and assembly, steam and cogeneration, heating and cooling. With respect to the energy supply, when a simultaneous demand of thermal and electrical energy is needed, thermal energy is usually satisfied by means of fire tube boilers while electricity supplied from the grid. Sometimes, cogeneration units are adopted for energy self-production whilst fire tube boilers are also installed for surplus production or as back-up units. However, due to the high investment cost and higher complexity compared to traditional systems, the use of combined heat and power (CHP) units is still limited even when largely profitable. Therefore, also in the industrial sector energy efficiency measures, such as the combined heat and power production, have a very interesting potential in curbing energy consumptions and the related CO_2 emissions.

Taking into account the above mentioned market difficulties, some of the authors patented [4] and designed in cooperation with an Italian engineering company [5] an innovative solution in order to combine the well-known technology of the fire tube boiler with a cogeneration unit. In particular, by means of an adequate conveyor, exhausts from the cogeneration unit are forced into the boiler and intercept a few of its tubes thus recovering the high temperature heat. In this way, it is possible to avoid the auxiliary heat exchanger for the recovery of the exhausts and to reduce of about 10-15% the investment cost of the CHP unit. In addition, even the low temperature heat from the auxiliaries or from the engine cooling system of the prime mover can be recovered to preheat the make-up water of the boiler or the air in the combustion chamber of the boiler in order to reduce the primary energy consumption of the burner. Hence, the proposed solution is a system with a very high flexibility in terms of thermal and electrical power production and lower investment and operating costs compared to the separated configurations of the two systems involved.

Despite the fire tube boilers are by far the most used technology in the industry sector for the steam and heating production, very limited research is published in the literature on such systems. Ortiz [6] developed a dynamic model of a three-pass fire tube boiler in Matlab in order to evaluate the performance of such a system and assist plant engineers in their tasks. On the contrary, Bisetto et al. [7] experimentally investigated and then modelled in Matlab/Simulink a three-pass boiler operating with a single phase energy heating fluid. However, none of them analyzed in detail the pressure drop of the exhausts in the fire tubes which on the contrary is extremely important in order to evaluate the potential coupling with a cogeneration unit. Higher the back pressure of a prime mover indeed lower is its electrical efficiency. For this reason, in the present work authors have carried out a CFD analysis to evaluate in detail the thermo-fluid dynamics performance of several tubes of a boiler specifically designed for such a coupling. After the Introduction, Section 2 reports the detailed description of the innovative system here proposed; then the CFD model to predict the thermo-fluid dynamics performance of the system under investigation is presented in Section 3. Section 4 reports the main results of the analysis while Section 5 draws the conclusions.

2. System description

The proposed solution is schematically shown in Figure 1 where a fire tube boiler is combined with an upward CHP unit, thus to theoretically recover the whole thermal power output of the exhausts from the cogeneration plant.

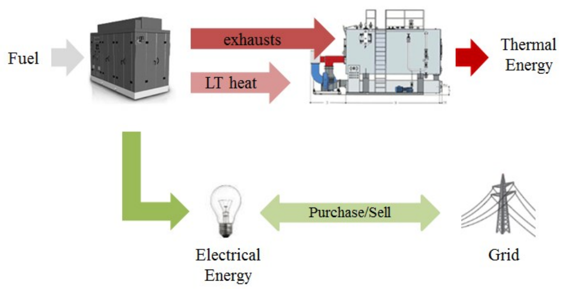


Figure 1. Schematics of the proposed innovative combination of a fire tube boiler with a CHP unit.

Both micro gas turbine and internal combustion engine (ICE) can be used as prime movers. However, a gas turbine has higher air to fuel ratio and lower electrical efficiency compared to an ICE, thus requiring a higher number of fire tubes for the exhausts for the same power range. On the contrary a gas turbine has a lower environmental impact [8,9]. Nevertheless, whenever allowed, ICEs are preferred. Fire tube boilers are widely adopted in industry for hot water and steam production at a rate of few tons per hours. The design of fire-tube boilers consists of a bundle of fire tubes contained in a shell full with water that evaporates to produce steam. Fire-tube boilers are usually distinguished by the number of passes, namely the number of times that the flue gas flows along the length of the vessel transferring its heat. At the end of each pass, the flue gas turns and goes back through the opposite direction of the vessel. In a typical three-pass fire tube boiler, that consists of three sets of horizontal tubes, the internal furnace is placed at the first pass, then the flue gas flows into the second pass and leaves the stack after the third pass.

Since in the proposed solution the exhausts from the CHP unit are directly conveyed into the boiler, the design of the traditional three-pass fire tube boiler is modified accordingly. In a three-pass fire tube boiler the flue gas at the entrance of the third pass has temperatures > 400°C. Even if the exhausts from the CHP unit have temperatures similar to those of the flue gas from the furnace, a separate section to convey the former is needed. Back pressure of a prime mover indeed has to be limited as far as possible and the mixing of the exhausts extremely discouraged.

Figure 2 and 3 report an axonometric projection of the modified fire tube boiler and a cross-section of the front view.

Figure 2. Axonometric projection of the modified fire tube boiler.

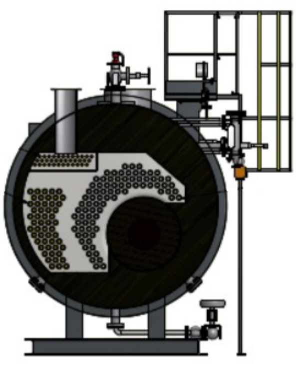


Figure 3. Cross-section of the front view of the modified fire tube boiler.

As clearly shown in Figure 3, the exhausts from the CHP unit have their own entrance and exit. The number and the dimensions of the fire tubes depend on the size of the coupled CHP unit, while the overall dimensions of the boiler do not differ sensibly compared to the standard configuration. Taking into account the different industrial sectors and the market of the two systems, a $5 \cdot 10^3$ $kg \cdot h^{-1}$ third-pass fire tube boiler and a 210 kWe ICE have been considered for the purpose of this analysis. In this way, the operation of the cogeneration plant can be maintained also when the primary burner of the boiler is off. The thermal power of the CHP unit is indeed considerably lower than that of the primary burner, thus allowing the recovering of the heat from the CHP unit also when the steam production is not instantaneously requested. In case of excess, a by-pass valve allows to temporarily discharge the exhausts in the atmosphere. At the same time, the cogeneration plant can be switched off without compromising the life time of the fire tube boiler. The tubes that convey the exhausts from the CHP unit are indeed submerged in the water and their surface temperature is almost constant in steady state conditions if water is in saturated conditions. Thus the operation of the cogeneration plant does not sensibly affect the temperature of the related tubes.

As regards the ICE considered in the present analysis, it is manufactured by MAN Engine [10] with the following technical specifications:

Table 1. Technical specifications of the considered ICE.

Model	MAN E2876 LE302
Fuel	Natural gas
Electrical power output (ISO conditions)	210 kWe
Power input	538 kWt
Thermal power output from the exhausts	143 kWt
Thermal power output from engine cooling	99 kWt
Thermal power output from intercooling (LT + HT)	41 kWt
Electrical efficiency	39.0%
Thermal efficiency	48.9%
Exhausts temperature	510°C
Exhausts flow rate	1101 $kg \cdot h^{-1}$

In particular, according to the selected CHP unit, 36 tubes were considered to recover the thermal power output of the exhausts from the CHP unit.

3. CFD model

A three-dimensional model of the fire tubes of the boiler crossed by the exhausts from the CHP unit was developed using a mesh generator. The computational domain was discretized using an unstructured grid of tetrahedral elements in the inlet and outlet plenum chambers and structured hexahedral elements in the tubes. In the x direction which corresponds to the longitudinal direction of the tubes, the grid density is reduced moving towards the centre in order to limit the number of the total cells as a compromise of accuracy and computing efficiency. On the contrary, in proximity of each cross-section area variations a layer refinement has been realized to better evaluate the flow field and the pressure loss of the exhausts. Figure 4 reports the mesh of the considered geometry which consists of about 1’310’000 nodes, almost 2’180’000 cells with an overall volume of 0.365 m^3.

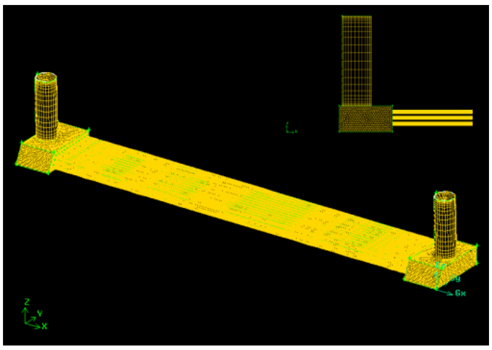


Figure 4. An axonometric projection of the meshed geometry.

IOP Conf. Series: Journal of Physics: Conf. Series **923** (2017) 012041 doi:10.1088/1742-6596/923/1/012041

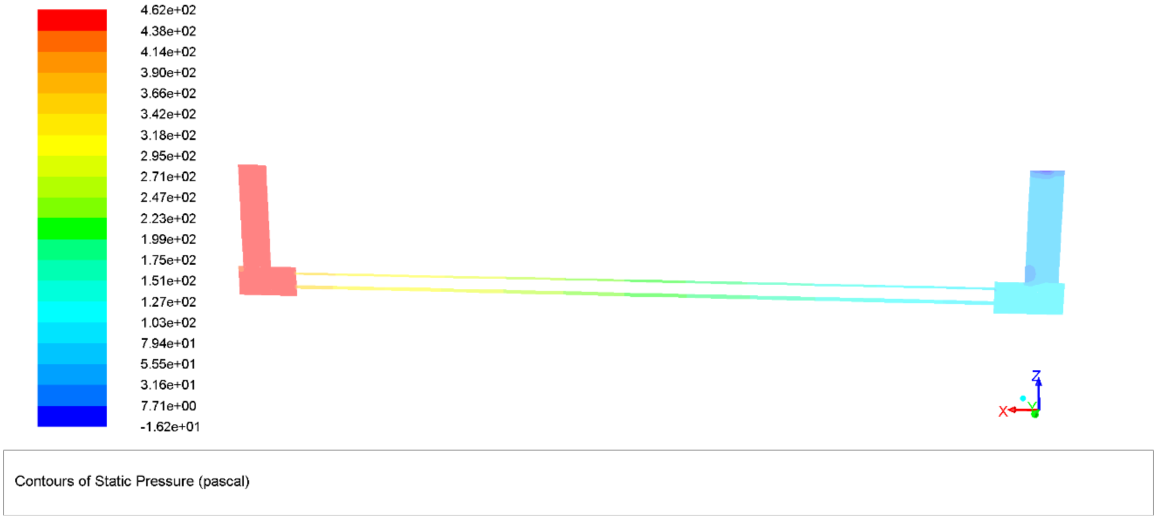
Calculations were assessed by means of a CFD commercial code. With respect to the CFD model the following assumptions have been considered: (i) there is no heat transfer in the vertical tubes that convey the exhausts from the CHP unit and to the chimney; (ii) flow is at steady state conditions; (iii) fire tubes are completely submerged by water at saturated conditions (at 200°C).

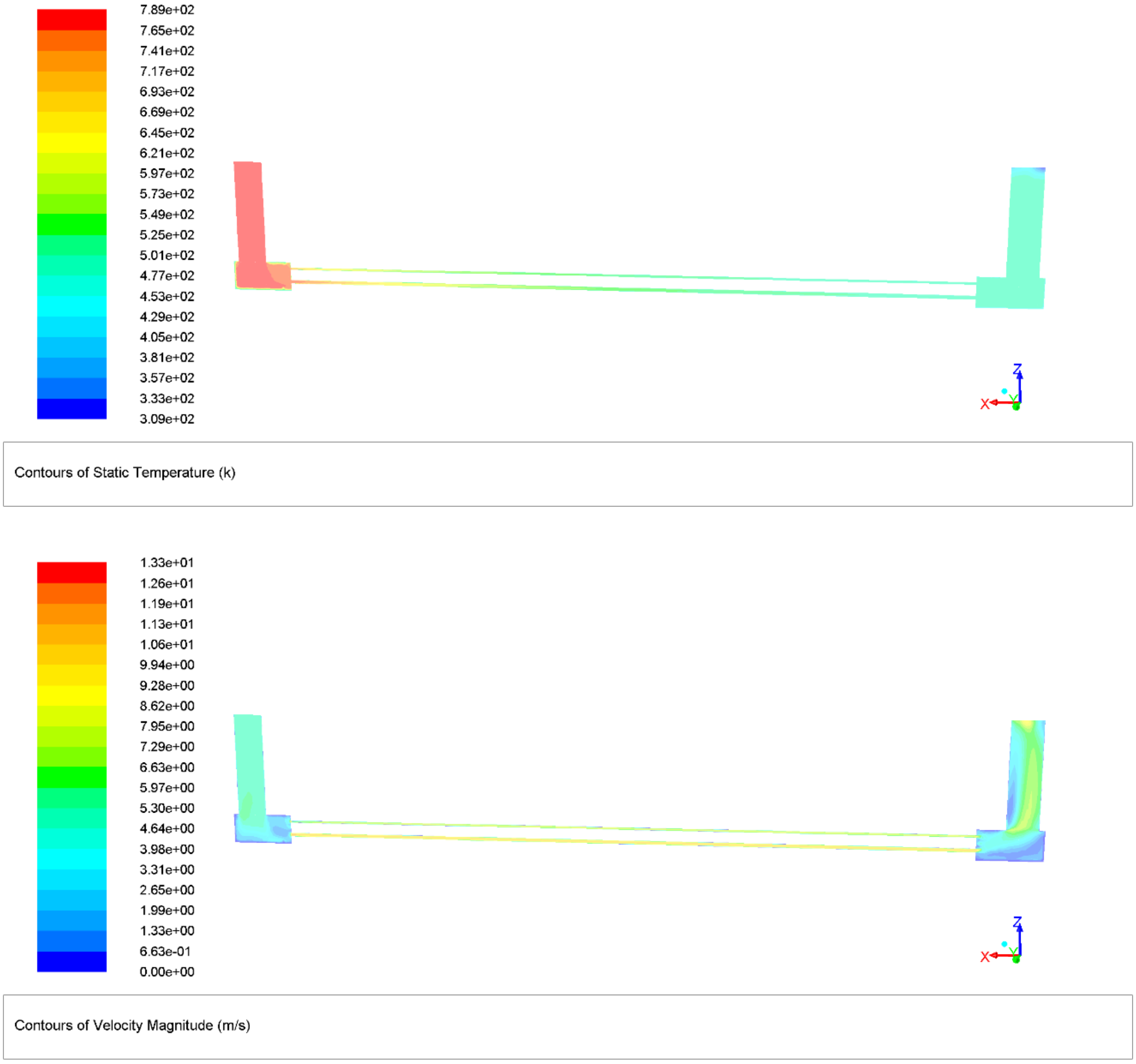
The steady state Reynolds Averaged Navier – Stokes (RANS) equations were solved for the computation of the turbulent flow, using the realizable k-ε turbulence model. The PRESTO! pressure interpolation scheme was adopted for pressure–velocity coupling equations. As regards the boundary conditions, the inlet surface of the vertical tube was set as mass flow inlet while the outlet surface as pressure outlet at atmospheric pressure. The vertical tubes are adiabatic surfaces while all the other tubes were set as wall. The wall was no-slip boundary shear condition.

Steel was used for the tubes while air was considered for the exhausts.

4. Results and discussion

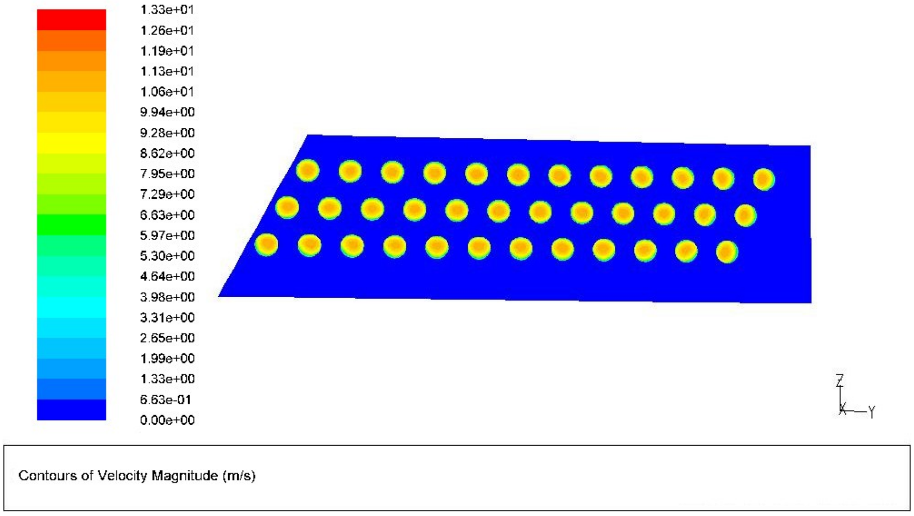
The objectives of the present numerical simulation analysis were to evaluate: (i) the pressure losses of the exhausts from the CHP unit due to the sudden cross-section area variations of the fire tubes inside the boiler; (ii) the thermal power recovered from the exhausts in the tubes; (iii) the dependence of the system on the final users' requests. The CFD analysis indeed was oriented to obtain a first guess solution of the back pressure of the CHP unit and the thermal power that can be recovered from the exhausts in order to estimate the potential of such a coupling prior to a subsequent experimental test campaign. Figures 5a-c report the contours of the static pressure, static temperature and the velocity magnitude of the flow along the tubes.





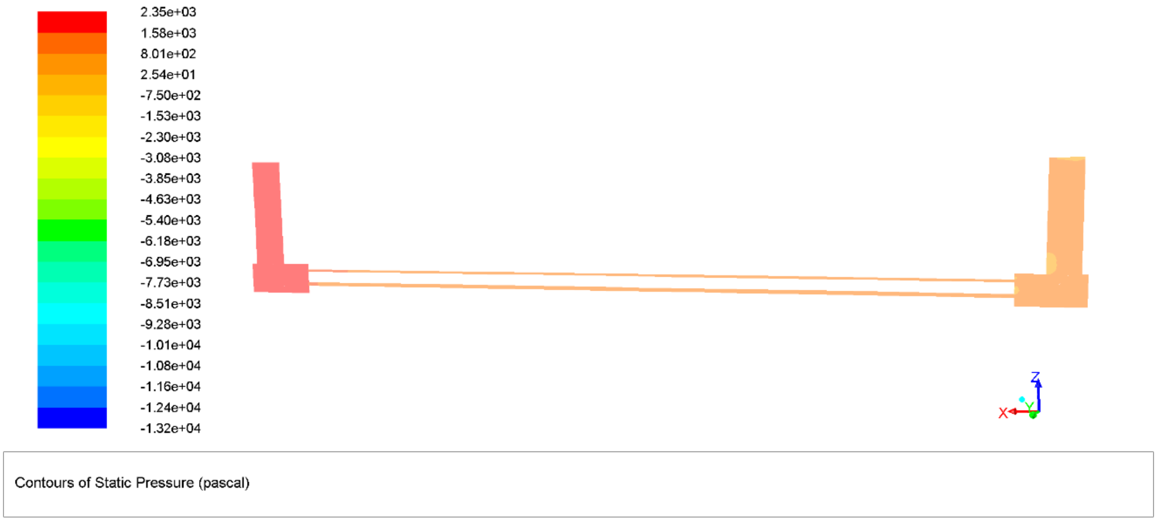
Figures 5. CFD results: a) static pressure; b) static temperature; c) velocity magnitude.

Figure 5a clearly shows that for the considered size of the systems the back pressure is very low and limited to a maximum of about 4.6 mbar which is considerably lower than the maximum back pressure tolerable by the prime mover (50 mbar). In terms of temperatures, the heat transfer in the plenum chambers are also limited and the most part of the temperature reduction occurs along the tubes. For an inlet temperature of the exhausts of about 510°C the outlet temperature of the exhausts is in the range of 220-230°C. This means that the recovered thermal power is about 90 kWt which corresponds to more than 60% of the thermal power input of the exhausts. Of course, the recovered thermal power would be even higher if lower temperatures of the water/steam inside the boiler were considered. In any case, this represents an interesting amount of energy that can be recovered from the CHP unit, thus contributing to operate at valuable overall efficiencies and reaching important Primary Energy Savings (PES) [11]. As regards the velocity of the exhausts, the magnitude was evaluated also in proximity of the plate that connects the entrance plenum chamber with the fire tubes. In particular, the maximum velocity magnitude was about 13.3m·s^{-1} which does not represent an issue in terms of noise and vibrations.



Figures 6. Contours of the velocity magnitude at the entrance of the fire tubes.

Finally, although the boiler was designed to be coupled with a 210 kWe ICE, sensitivity with users' needs was evaluated in terms of different flow rates. For the same size of the boiler indeed a different size of the ICE could be required or even micro-turbine technology preferred. In particular, such analysis showed that the back pressure reaches the maximum tolerable by an ICE with an exhausts flow rate of about 0.712 $kg{\cdot}s^{-1}$ which corresponds to two times the design flow rate of the proposed configuration. Figure 7 reports the contours of the static pressure for an exhausts flow rate of 0.712 $kg{\cdot}s^{-1}$.



Figures 7. Contours of the static pressure for a flow rate of 0.712 kgs^{-1}.

Therefore, on the basis of the obtained simulation results some conclusions can be drawn prior to the subsequent experimental phase. The flow field showed a good homogeneous distribution of the exhausts into the different fire tubes. Moreover, since the back pressure and the maximum flow velocity are low even at the nominal operating conditions of the CHP unit, the numbers of the tubes could be also reduced in order to keep the extra-costs of the modified boiler down.

5. Conclusions

Coupling a CHP unit with a fire tube boiler allows to overcome some skepticisms of the industries that are sometimes unwilling to accept cogeneration plants for reliability and high investment costs issues. The proposed solution presents higher complexity compared to the separate configuration of the two systems but allows to reduce the investment cost and assure reliable supply. In this work, the main criticisms arisen from such a coupling were addressed by means of a CFD analysis. In particular, the simulation analysis showed that at nominal operating conditions the back pressure of the ICE is < 5 mbar which is far lower than the maximum tolerable pressure loss by an ICE usually in the range of 50 mbar. Also in terms of temperatures, the fire tubes are able to extract the medium-high temperature heat of the exhausts from the prime mover with outlet temperatures that are close to those of the flue gas from the furnace. From the energetic point of view, for the considered temperatures of the exhausts and the water inside the boiler, the heat recovered in the fire tubes is >60% of the thermal power output of the exhausts from the CHP unit. Finally, in order to appreciate the sensitivity of the proposed configuration of the fired tubes boiler with the users' requests, the pressure losses were evaluated also with varying the mass flow rates of the exhausts from the prime mover. In particular, it was found that pressure losses still remain lower than the admissible level even at a flow rate of about 0.712 $kg \cdot s^{-1}$ which corresponds to two times the flow rate at the design conditions.

Therefore, the present analysis allows to assess that the proposed solution can be adopted to reduce the investment cost of the CHP unit (because the heat exchanger for heat recovery can be avoided) with interesting overall energy performance. Nevertheless, prior to a potential subsequent industrialization and commercial phase experimental analysis are needed to confirm the numerical performance of the designed configuration.

Acknowledgements

The authors wish to thank S.TRA.TE.G.I.E. srl for funding the patent application and also INVITALIA for partially funded the patent development under the program Brevetti+.

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