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Development of a direct concept helical-coil evaporator for an ORC based micro-CHP system

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Abstract

The combined production of heat and power (CHP) has been considered the major alternative to traditional systems in terms of energy savings and environmental conservation. Micro-CHP systems are those suitable for a scale that ranges from the thermal demands of public/commercial buildings down to the needs of individual household. The residential market represents the most promising sector for the micro-CHP systems which has the potential to meet a number of energy, social and policy goals. Considering the available technologies, ORC based CHP solutions are recognized as one of the simplest and less likely to raise difficulties to retrofit the current residential heating systems. ORC based CHP systems points to a residential implementation almost with market available components. In fact, two of the most important components, the pump and the condenser, are considered off-the-shelf products while the expander has been adapted from a scroll compressor with success. On the other hand, for the ORC-evaporator there isn't a ready-to-use component within this power range and the overwhelming majority of the ORC based systems developed by universities or research centers use an indirect way to vaporize the organic fluid which involves the implementation of an intermediate circuit, usually with water or oil, between the heat source and the ORC-evaporator. This intermediate circuit appears to be far from the ideal solution because it increases the thermal inertia, the system complexity and costs. This paper presents the conceptual design and the preliminary characterization results of a special developed heat-exchanger to be incorporated in an ORC cycle and work as an evaporator.

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Keywords: ORC-based micro-CHP systems; Natural-gas combustion, Direct ORC-evaporators.

1. Introduction

In recent years, the world's primary energy demand has significantly increased not only due to technological and industrial development but also due to a tremendous population growth [1]. Furthermore, the conventional resource, mainly petroleum derived products, corresponds to a large fraction of that primary energy demand which its price have been suffering a gradual rise. The consumption of such conventional energy resources (gas, oil, coal, etc.) contributes to a large portion of the world greenhouse gas emissions that lead, together with other contributors, to the climate change problem [1]. This shows that there is an imperative necessity to change the energy production and consumption patterns into an alternative or renewable energy resources which have highly efficient means of energy production and usage.

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This paper will focus on one, and very specific, low carbon and efficient solution: the Combined Heat and Power (CHP) production, at a micro scale and using the Organic Rankine Cycle (ORC) technology. Micro-CHP aims for the combined production of electricity and thermal energy at a scale that ranges from the thermal demands of public buildings down to the needs of the individual household. This appliance is substantially more efficient than current condensing boilers (which only serves thermal demands), leading to lower household energy bills and to a reduction of energy use and carbon emissions.

Micro-cogeneration systems have attracted the attention not only of scientists in research centers but also of big industrial players during the last two decades [2]. External combustion (e.g. ORC and Stirling cycles), internal combustion (e.g. Otto and Brayton cycles) and fuel cells based systems are being developed all over the world, at Universities and Industry research centers with the objective to reach an economically viable device able to retrofit the existing heating systems. Among these options, and excluding fuel cell based solutions since due to their actual stage of development have prohibitive costs [3,4] and they are not likely to be available in the near future [2], ORC based solutions, although not being the systems with the greatest efficiency in electricity production but rather with greater thermal efficiency [5], are recognized as the most suitable and promising methods to convert low-grade heat into power [6] as well as the simplest and less likely to raise difficulties for retrofitting the actual systems [7], overcoming the typically severe vibration and noise issues that occur on Stirling and Otto cycles based solutions. The simplicity of the ORC based solutions gives hope that it will be possible to implement it using market available components. In fact, two of the most important parts of these systems, the pump and the condenser are off-the-shelf components while the expander can be adapted from a scroll or a vane compressor with success [8,9]. On the other hand, the ORC-evaporator, at least in this power range, is not a ready-to-use component. Therefore, the ORC-evaporator is clearly identified as a critical component and the research work carried out on burners liquid-gas heat exchangers, allowed to verify that none of the currently existing sets, and emerging embedded in household boilers, meets the requirements to be implemented in a micro-CHP system because of temperature limits (standard or condensation boilers only heat water to temperatures around 60 or 80 °C at maximum), pressure limits (standard or condensing boilers only work with pressures between 3 and 4 bar), the use of an organic fluid and its physical state changes. The inexistence of the ORC-evaporator meant that the overwhelming majority of the ORC based systems developed by universities or research centers use an indirect way to vaporize the organic fluid which involves the implementation of an intermediate circuit, usually with water or oil, between the heat source and the power cycle [6,7,10,11]. This intermediate circuit appears to be far from the ideal solution because it increases the thermal inertia, the system complexity and costs [12]. The resolution of this technological gap implies the development of a specific evaporator design with consequent concept proof.

The objective of the work partially described in this paper is to fulfil the technological gap that is preventing the ORC based micro-CHP systems of performing a direct vaporization of the organic fluid. In this paper the solution developed to perform that task, taking in consideration the specificities of the micro-CHP systems for residential use, like the small size and thermal inertia, will be described and the preliminary data of its characterization will be presented.

2. Operational requirements and working principle

The development of a direct ORC-evaporator for micro-CHP is made in order to open the possibility of this systems to retrofit the combi-boilers already installed in residential dwellings. The current research efforts made in order to develop micro-CHP systems include the use of an intermediate circuit, with oil or water, to transfer the energy from the heat source (combustion gases) to the power cycle. The direct evaporation of the organic fluid is an attempt to avoid that intermediate circuit reducing the thermal inertia, the system complexity and the energy losses.

Briefly, the direct ORC-evaporator involves the assembly between a natural-gas burner (natural-gas is the most common residential energy source [13]) and a heat-exchanger. The gas-burner can be easily found in the market however the heat-exchanger needs to specifically design for this purpose.

This work is the first step in the development an ORC-evaporator for residential purposes and so only three of the main design features were considered: the direct contact of the ORC-evaporator with the high temperature combustion gases, the use of a natural-gas burner to help retrofit the conventional systems already implemented and a modulation capacity to quickly adapt the system to the end-user thermal requests.

To fulfil the previous requirements a helical-coil heat-exchanger with two passages for the combustion gases presented in Fig. 1 a) was developed. The working fluid enters in the ORC-evaporator in the end of the outer helical coil advancing toward the inner coil against the flow of the combustion gases in a counter-current arrangement. To reduce the burner head surface temperature and ensure a proper and safer operation of the gas-burner and to reduce the combustion gases temperature and the risk of the working fluid thermal degradation an water cooled external chamber was designed. The selected pre-mixed gas-burner can produce a thermal power ranging between 6 kW and 35 kW. The power rate of the gas-burner was chosen based on the data provided from Maghanki et al. [12] that refers thermal needs between 8 kW and 44 kW to micro-scale systems.

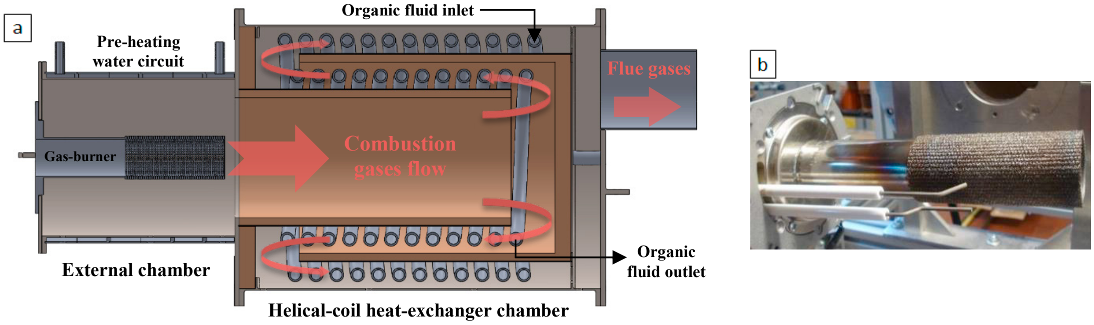

Fig. 1. (a) Schematic sectional scheme of the ORC-evaporator; (b) premix gas-burner head with the ignition sparks.

3. Experimental characterization and results

The characterization of the ORC-evaporator was performed in two stages. In the first one the evaporator was tested with water in an open cycle. In addition of providing real values for validation of the combustion gases side heat-transfer correlations, the first experimental part, which has a twofold objective, also pretended to guarantee a proper and safer operation by performing a small commissioning test of all the sensors and controls connected to this developed component. The second experimental stage was performed with the evaporator inserted in a micro-CHP test bench, with the organic fluid R245fa flowing in a close cycle as a real micro-cogenerator system.

For the first part of the experimental tests, with water, the evaporator was tested along the entire range of the gas-burner power (also called by the combustion power) and no safety problems were verified. On the other hand, when working integrated in a real ORC, in the second stage of the experimental tests, due to limitations in the electrical generation group, the variation of the power of the gas-burner was limited. The values of the different energy fluxes for the first, with water, and for the second, with R245fa, experimental tests are shown on the graphic of the Figure 2 and on the graphic of Figure 3, respectively.

Considering the energy transferred in the helical-coil and in the sleeve of the external chamber as useful energy, the overall efficiency of the heat-exchanger working with water ranges from 81% to 92% at high and low power, respectively. In a similar analysis for the experimental test with the R245fa, the ORC-evaporator reaches an overall efficiency between 72% and 82% at high and low power, respectively. The large difference regarding the overall efficiency between the experimental tests can be justified by limitations in the experimental ORC test bench once the operation conditions were very limited (e.g. the organic fluid flow rate). However, this experimental procedure was essential to perform the proof of concept of this ORC-evaporator showing that is capable to vaporize an organic fluid using directly the high-temperature natural-gas combustion gases in the helical-coil heat-exchanger. The difference between the combustion power and the sum of all the energy fluxes shown in Figure 2 and in Figure 3 is related with energy losses to the surroundings. These losses appears to be significant because the insulation project was not properly optimized in this on-working phase, due to, essential, the necessity to easily access to some sensors and to have the opportunity to make a visual inspections of some critical parts of the gas burner.

Considering the average values of the energy fluxes of the experimental tests, a schematic Sankey diagram with the energy partition within the developed ORC-evaporator was built and is shown in the Figure 4.

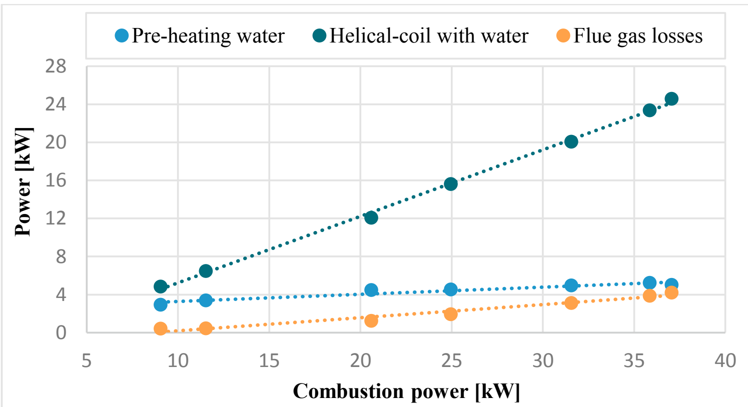

Fig. 2 - Preliminary results of the ORC-evaporator working with water.

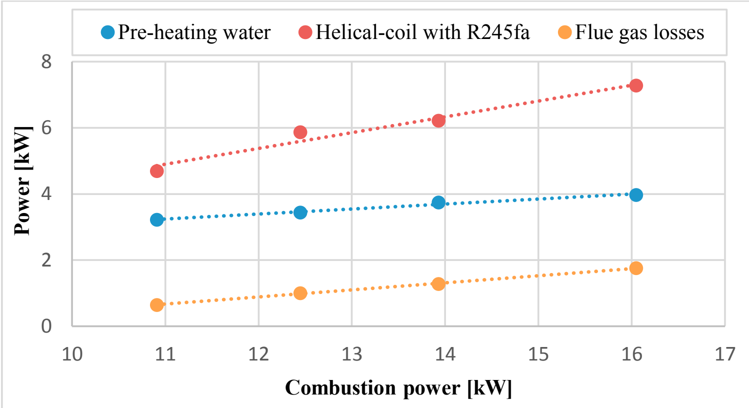

Fig. 3 - Preliminary results of the ORC-evaporator working with R245fa.

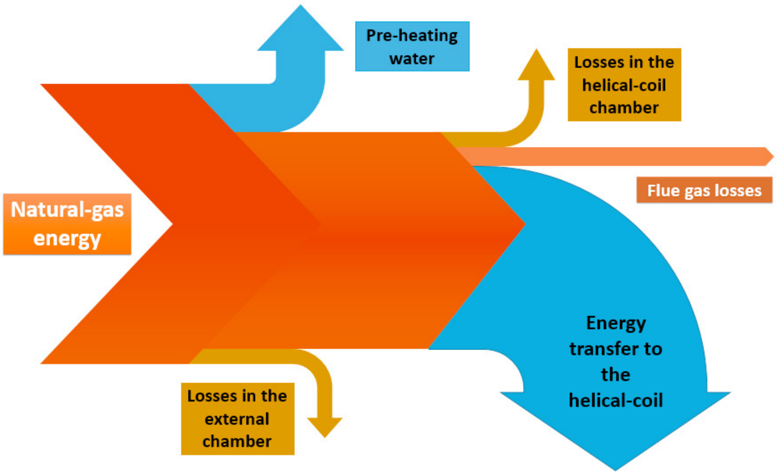

Fig. 4 - Sankey diagram of the developed ORC-evaporator.

4. Conclusions

The development of an ORC-evaporator capable of vaporizing an organic fluid has proved to be feasible and capable of closing the technological gap that exists for this specific component.

The burner-heat exchanger set was tested for the entire range of the power of the burner with water without any safety problems. If we consider the energy transfer to the external chamber, the efficiency can be as high as 92% with water as working fluid. Due to several constrains related with the ORC test bench the range of power for which was possible to test the evaporator with R245fa was very limited. However, considerer again the energy transfer to the external chamber, the efficiency value can overpass 75% without any optimization of the system.

This direct ORC-evaporator achieved its main purpose of performing a safer operation when inserted in a micro-CHP test bench. Still it is clear that this first lab prototype requires more tests and optimization to reach the commercial market however, according to the results presented in this paper, it appears to have the potential to be easily upgraded and bring all the benefits of performing the direct vaporization of an organic fluid to the micro-scale commercial systems.

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References

[1] World Energy Council - Conseil mondial de l'énergie. World Energy Resources - 2013 Survey. 2013.

[2] Barbieri ES, Spina PR, Venturini M. Analysis of innovative micro-CHP systems to meet household energy demands. Applied Energy 2012;97:723–33. doi:10.1016/j.apenergy.2011.11.081.

[3] Staffell I, Green R, Kendall K. Cost targets for domestic fuel cell CHP. Journal of Power Sources 2008;181:339–49. doi:10.1016/j.jpowsour.2007.11.068.

[4] Staffell I, Green R. The cost of domestic fuel cell micro-CHP systems. International Journal of Hydrogen Energy 2013;38:1088–102. doi:10.1016/j.ijhydene.2012.10.090.

[5] Maghanki MM, Ghobadian B, Najafi G, Galogah RJ. Micro combined heat and power (MCHP) technologies and applications. Renewable and Sustainable Energy Reviews 2013;28:510–24. doi:10.1016/j.rser.2013.07.053.

[6] Pei G, Li J, Li Y, Wang D, Ji J. Construction and dynamic test of a small-scale organic rankine cycle. Energy 2011;36:3215–23. doi:10.1016/j.energy.2011.03.010.

[7] Algieri A, Morrone P. Energetic analysis of biomass-fired ORC systems for micro-scale combined heat and power (CHP) generation. A possible application to the Italian residential sector. Applied Thermal Engineering 2014;71:751–9. doi:10.1016/j.applthermaleng.2013.11.024.

[8] Clemente S, Micheli D, Reini M, Taccani R. Energy efficiency analysis of Organic Rankine Cycles with scroll expanders for cogenerative applications. Applied Energy 2012;97:792–801. doi:10.1016/j.apenergy.2012.01.029.

[9] Declaye S, Quoilin S, Guillaume L, Lemort V. Experimental study on an open-drive scroll expander integrated into an ORC (Organic Rankine Cycle) system with R245fa as working fluid. Energy 2013;55:173–83. doi:10.1016/j.energy.2013.04.003.

[10] Peterson RB, Wang H, Herron T. Performance of a small-scale regenerative Rankine power cycle employing a scroll expander. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 2008;222:271–82. doi:10.1243/09576509JPE546.

[11] Tańczuk M, Ulbrich R. Implementation of a biomass-fired co-generation plant supplied with an ORC (Organic Rankine Cycle) as a heat source for small scale heat distribution system - A comparative analysis under Polish and German conditions. Energy 2013;62:132–41. doi:10.1016/j.energy.2013.09.044.

[12] Quoilin S, Broek M Van Den, Declaye S, Dewallef P, Lemort V. Techno-economic survey of Organic Rankine Cycle (ORC) systems. Renewable and Sustainable Energy Reviews 2013;22:168–86. doi:10.1016/j.rser.2013.01.028.

[13] CODE 2 - Cogeneration Observatory and Dissemination Europe. Micro-CHP potential analysis - European level report. 2014.