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Direct vaporization ORC-evaporator heat transfer model for thermal degradation risk assessment

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Abstract:

For the last decades, Organic Rankine Cycle has been the technological choice of numerous large-scale systems. Due to its characteristics, mainly its simplicity and reliability, the ORC is pointed to be one of the most promising technologies to fulfil the gap of cogeneration systems in domestic dwellings. However, bringing the technology to the domestic scale can raise some difficulties related to its restricted requirements which can go from the system size to the response time. To deal with these questions, the use of direct evaporators is been referenced as an imperative path to follow. The use of these direct evaporators excludes the intermediate circuit that is frequently implemented. The introduction of this is usually justified by the direct exposition of the organic fluid to the high temperatures of the heat source which can degrade it. When the author's objective is to individually study the organic fluid and its properties (including its thermal stability), all the information regarding the system becomes irrelevant. The evaluation of the risk that this option may put to the organic fluid thermal degradation requires the determination of the temperature of the heat-transfer surfaces with which the organic fluid is in contact. As its experimental measure is extremely difficult to accomplish, such determination requires the development of a detailed physical model of the combustion and heat-transfer processes in the ORC-evaporator.Taken this into consideration, the development and validation of such model is presented. This will allow a detailed evaluation of several key features of the combustion and heat-transfer processes as a function of some ORC operating parameters. Among those features is the temperature of the internal surface of the tubes with which the organic fluid is in contact. This temperature, which can be used to assess the risk of the thermal degradation of the organic fluid, has shown to be highly affected by the thermal resistances and by the combustion gases temperature. To reduce that risk, the operating conditions of the ORC should be those allowing the vaporization process to start as early as possible and reducing the superheating phase to the minimum possible.

Keywords:

Organic Rankine cycle, Heat-transfer model, ORC-evaporator, Direct vaporization arrangement, Thermal degradation risk assessment.

1. Introduction

Given the huge dimension of its potential market and the expected economic and environmental benefits associated with its use, the research and development activities on a domestic scale combined heat and power systems (CHP) have increased over the last two decades [1,2]. For the particular case of the systems that are attempting to retrofit the current wall-hang combi-boilers, the most promising solutions involve the use of Organic Rankine Cycles (ORC) [3,4]. Furthermore, due to the extremely demanding requirements imposed on these systems, especially in what refers to the (short) response time and (small) dimensions, it is suggested that the vaporization of the working fluid of the ORC should be done using the high-temperature combustion gases directly [5,6]. One of the major risks associated with this option is the thermal degradation of the organic working fluid [7,8]. The high temperature that these fluids may reach when in contact with the heat transfer surfaces can lead to the disruption of the chemical bonds of its molecules and to the subsequent degradation of their physical properties. In an attempt to minimize this problem, ORC-based micro-CHP systems may be reconfigured into a hybrid arrangement in which the combustions gases are firstly cooled in a combustion gases-water heat exchanger before crossing through the organic fluid heat exchanger [9]. Even so, the evaluation of the magnitude of this problem demands the calculation of the heat-transfer surfaces' temperature with which the organic fluid will be in contact. That risk will be minimum if the temperature of those surfaces is kept below the one of thermal degradation. This limiting temperature,

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however, is normally determined by standard tests where the fluid is at rest and in thermal equilibrium with the wall of its container [10–14]; a quite different situation from what happens in real working conditions [15]. Besides the bulk temperature of the organic fluid at the exit of the evaporator (a well-known parameter since it is easy to measure and required for the evaluation of the cycle efficiency), it is also important to know the temperature of the heat-transfer surfaces with which the fluid is in contact. Contrary to the organic fluid temperature, this is very difficult to measure but it can, and should, be controlled. Despite its importance, heat-transfer surface temperatures are rarely measured or calculated. Since its direct measure is very difficult, as are those of any tubes' internal surface, the only option left is its calculation. That, however, is far from being trivial as it results from the mutual dependency of the internal and external heat-transfer mechanisms and demands for the development of an appropriated heat-transfer model. The development of such model, that is crucial for the determination of the operation conditions that should keep the risk of thermal degradation of the organic fluid at an acceptable level, however, is not yet described in the literature.

Acknowledging that the thermal degradation of the organic fluid is the key feature opposing the use of direct vaporization in ORC-based micro CHP systems, the main objective of this paper is to show how the operating conditions of those systems (e.g. the organic fluid mass flow rate or the natural-gas burner combustion power) affect the organic fluid vaporization process and the temperatures of the heat-transfer surfaces. These are compared to the temperature limits referenced in the literature to evaluate the risk of organic fluid thermal degradation. This will be illustrated on a particular ORC-evaporator design but the analysis will be kept as general as possible. Given the importance that the evaluation of the heat-transfer surface temperatures may have on the definition of boundaries for the operating conditions, and given the scarcity of heat-transfer models intended to calculate those temperatures, it is also an objective of this manuscript to contribute to the disclosure and widespread of these type of models through the presentation of the approach followed in its development, namely: disclosing the correlations used for the determination of the heat-transfer coefficients and duly presenting the underlying simplifications, calibration and validation.

2. ORC-evaporator heat-transfer model

The ORC-evaporator domain to be simulated in this study comprises the gas-burner and two heat-exchanger sections: one to complete the water heating process initiated in the ORC-condenser, named the water post-heater section (PH), and the other for the organic fluid vaporization, simply named evaporator heat-exchanger (EHE). A 3-D representation of these two sections can be seen in Figure 1.

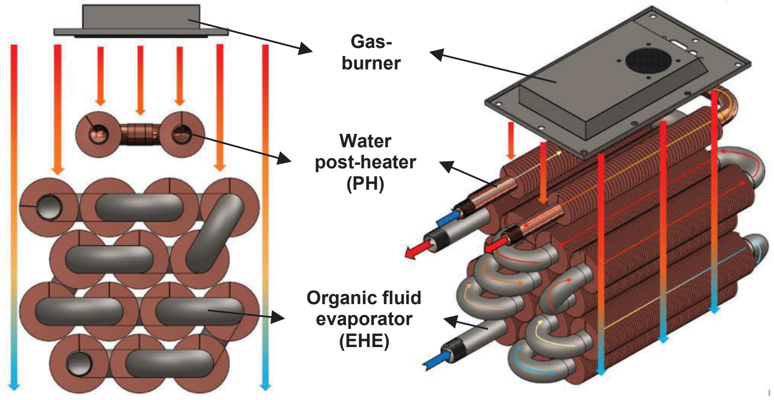

Figure 1. Schematic representation of the two heat-exchanger sections and the natural-gas burner of the ORC-evaporator.

As the PH and the EHE heat-transfer models demand, as input parameters, several combustion gases' characteristics, the thermochemical calculations of the natural gas (NG) combustion process were also included in the overall model. Thus, the overall model includes three different sub-models: i) the gas-burner/combustion model, ii) the PH heat-transfer model and iii) the EHE heat-transfer model. These models were implemented in MatLab® coupled with the RefProp thermodynamic database [16]. According to the physical arrangement, as depicted in Figure 1, the models are run sequentially since the outputs of the combustion model are used as inputs for the PH model and its outputs are used as inputs for the EHE model, as shown in Figure 2.

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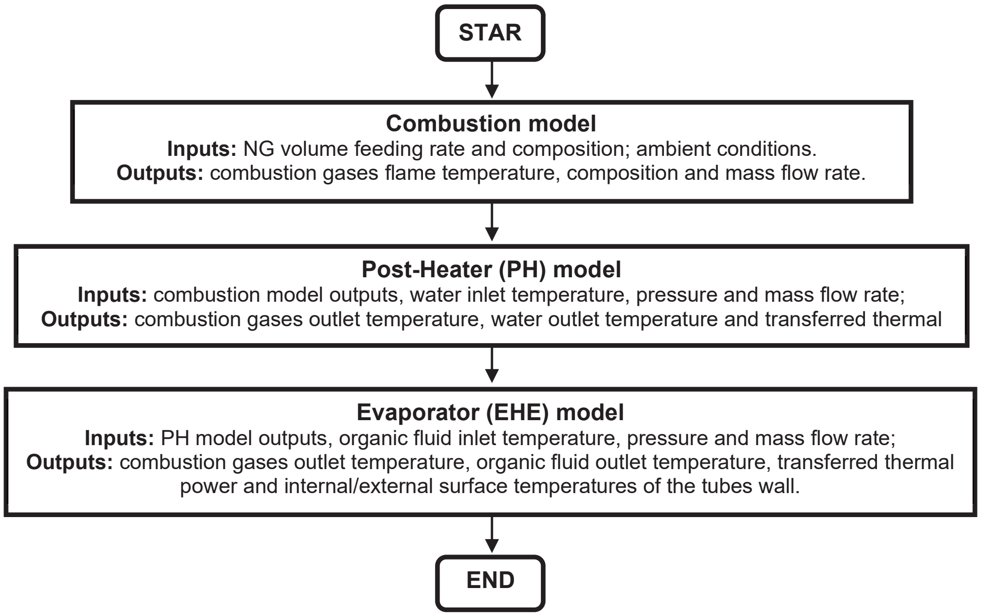

Figure 2. General flowchart of the entire ORC-evaporator model with the main inputs and outputs.

The Post-Heater (PH) is a cross-flow heat exchanger placed between the gas burner and the EHE (see Figure 1). It is composed of a pair of finned tubes within which water, previously heated in the ORC condenser, flows. To calculate the outputs described in Figure 2, the overall heat-transfer coefficient must be determined. This demands the calculation of the heat-transfer coefficient for the water and combustion gases sides. In order to make that determination easier and since it is known that the water inside the PH tubes will remain in the liquid state and its temperature will not drastically rise, the water's physical domain was divided into two control volumes (CV) – one for each tube. For the combustion gases side, however, the physical domain was not divided and the temperature is assumed to have a uniform/ homogeneous distribution in the horizontal direction. The CVs in which the PH domain is divided are illustrated in Figure 3.

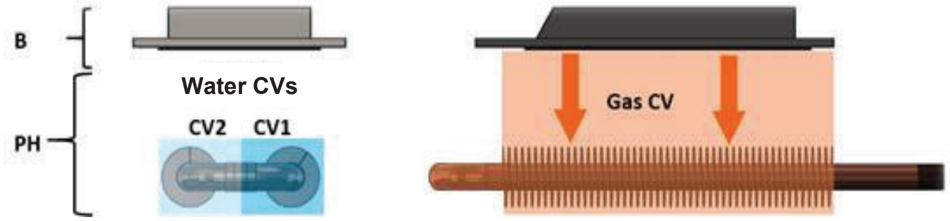

Figure 3. 2D view of the gas-burner (B) and PH assembly with the CVs defined for the water and the combustion gases flow.

The EHE is a compact heat exchanger made of stainless-steel tubes with copper fins presenting a mixed configuration regarding the interaction between the external and internal flows since it can be classified neither as a counter-flow nor as a cross-flow arrangement. Figure 4 shows a detached schematic representation of the EHE with the flow directions for both fluids.

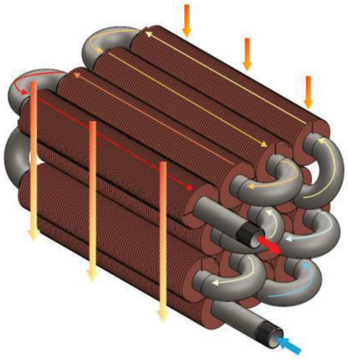

Figure 4. Schematic representation of the (detached) EHE section.

The EHE contains four levels of stainless-steel tubes with copper fins. Each level contains a different number of tubes, as shown in Figure 5. Since the variation of the organic fluid properties is expected to be much bigger than those observed for the water in the PH section (mainly due to the vaporization process), the volume occupied by this inside the EHE tubes was split into a large number of CVs. On the other hand, the volume occupied by the combustion gases was split into as many CVs as levels of tubes.

All the equations and details regarding the model developed are shown in [17].

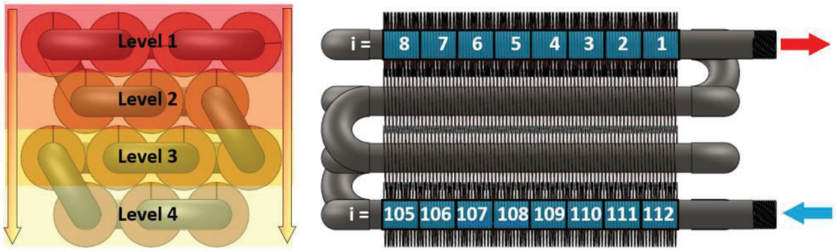

Figure 5. 2D view of the EHE section with the discretization of the gas and organic fluid per CV.

3. Experimental test rig

In order to verify and validate the options taken and the simplification made in the development of the ORC-evaporator physical-mathematical model, a comparison needs to be done between the results retrieved with it and those obtained from the experimental tests. To perform such a task, the designed ORC-evaporator was integrated into a test rig emulating a micro-scale ORC-based CHP system. A schematic diagram, including the instrumentation used, is presented in Figure 6.

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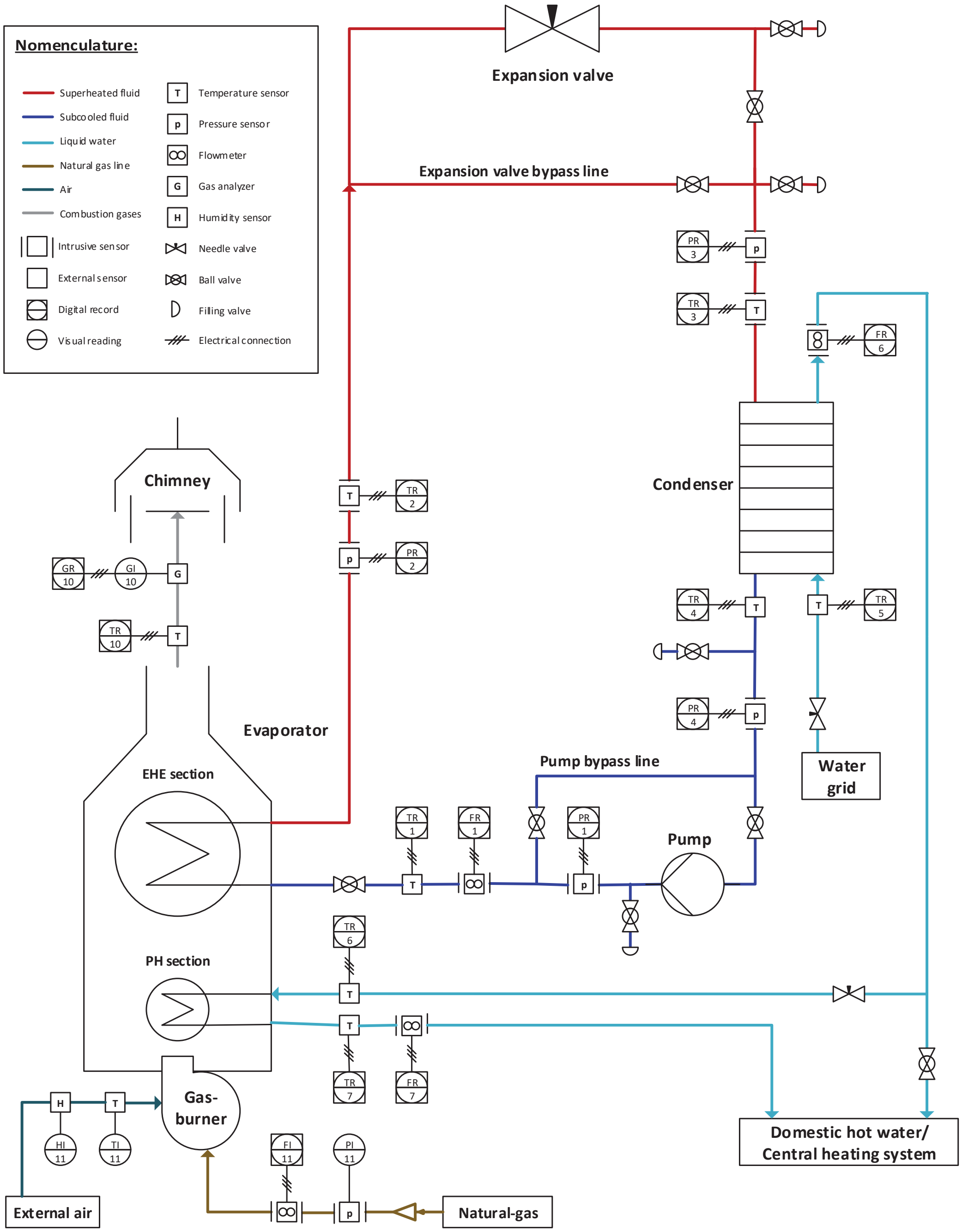

Figure 6. Schematic diagram of the hybrid CHP configuration with the new ORC-evaporator.

As there is a particular interest in the characterization of the ORC-evaporator behaviour, this component is specially monitored and, in addition to the instruments presented in Figure 6, both of its sections have a series of contact thermocouples partially embedded in the wall of the elbows that connect their finned tubes. These thermocouples are kept out from the direct exposition of the combustion gases and are externally surrounded by a quasi-adiabatic media, as is shown in Figure 7. The main characteristics of the instruments used are presented in Table 1.

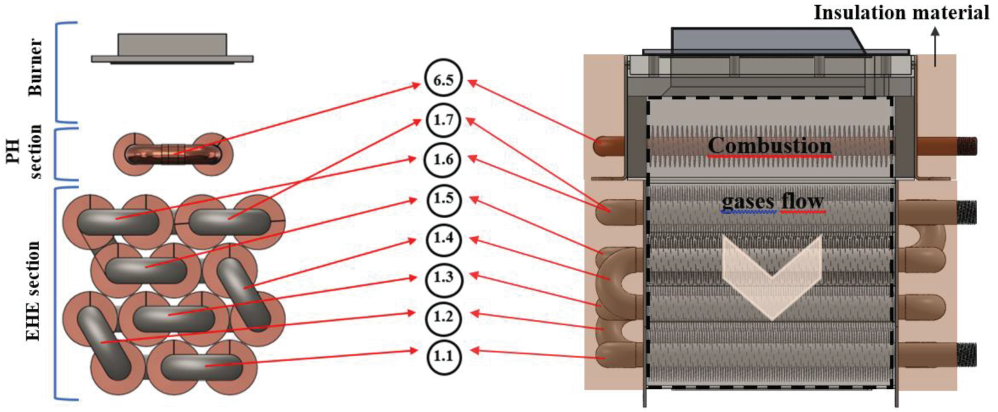

Figure 7. Schematic representation of the ORC-evaporator with the location of the contact thermocouples alongside the PH and EHE sections.

Table 1. Main characteristics of the instruments used in the experimental test rig.

Line number (see Figure 6)	**Measurement**	**Stream**	**Type**	**Range**	**Accuracy**
1	Mass flow rate	Organic fluid	Coriolis	[0 – 2.2] kg/s	0.4 %
[1-4]	Pressure	Organic fluid	Diaphragm	[0 - 10] bar	0.05 % FS
[All]	Temperature	Organic fluid / PH water / combustion gases	Thermocouple type T	[-40 - 300] ºC	0.0075.|T| or 1 °C
7	Volumetric flow rate	PH water	Turbine	[1 - 25] L/min	2 %
10	Oxygen sensor	Combustion gases	Infra-red	[0 - 25] %	1 %
11	Temperature / humidity	Ambient air	Thermistor/ polymer film	[-20 - 40] ºC / [20 - 80] %	5 %
11	Volumetric flow rate	Natural-gas	Diaphragm	[0 – 1.7] dm^3/s	1 %

4. Model validation

The comparison between the experimental and the model results will be done for the water and organic fluid temperatures gathered along the PH and EHE sections of the ORC-evaporator (see Figure 8), respectively. Besides those temperatures, the transferred thermal power in each section will also be used to assess the match between the experimental and the model results as it allows solving the problems arising from the use of temperatures to compare the heat-transfer process when a two-phase state is presented (see Figure 9).

The data shown reveals differences between the calculated and the experimental results smaller than 2% regarding the transferred thermal power, for both sections and, concerning the temperatures, values smaller than 2% and 8% for the PH and EHE sections, respectively. These results end up reflected in the model's capacity to predict the starting point of the organic fluid vaporization process within the ORC-evaporator tubes. This can be seen in Figure 10, in which the measured and calculated temperatures of the organic fluid retrieved along the EHE section are shown for one specific operating point. The error in the identification of the beginning of the phase transition process is less than 1 tube.

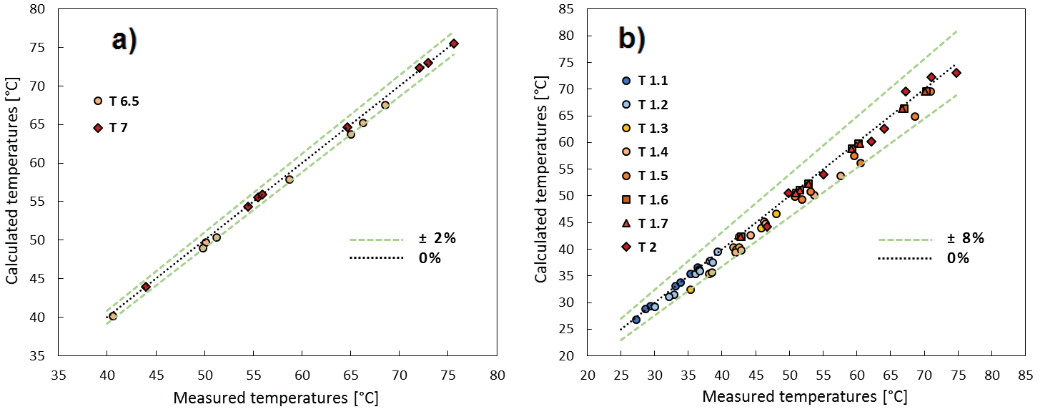

Figure 8. Calculated versus measured temperatures for a) PH and b) EHE.

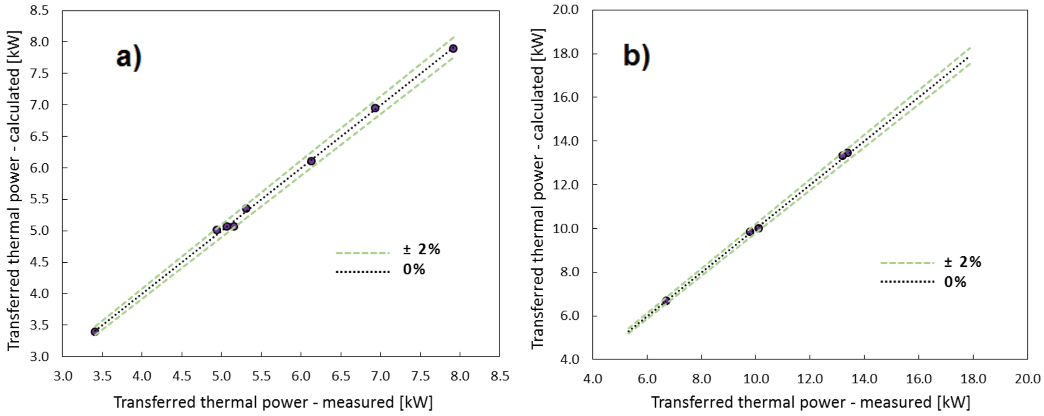

Figure 9. Calculated versus measured transferred thermal power for a) PH and b) EHE.

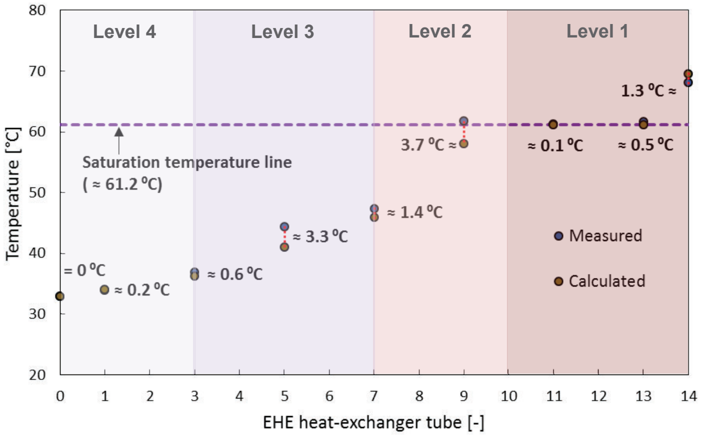

Figure 10. Calculated and measured values of the organic fluid temperatures along the EHE section.

5. Model exploration and conclusions

It is presumed that the reliability shown by the model on the prediction of the organic fluid temperature and of the transferred thermal power is inferable for the prediction of the temperatures of the inner surface of the evaporator tubes since they are mutually dependent. Thus, it will be possible to use it to identify what is and where occurs the maximum value of the inner surface temperature of the evaporator tubes, so that considerations about the risk of thermal degradation of the organic fluid may be taken into account. This temperature, together with both the outer surface and the organic fluid temperatures, is shown in Figure 11 for one specific operating point, as an example. The combustion gases' temperature values, for each of the levels in which their domain is divided, are also shown in that figure. As their behaviour is essentially determined by the thermal resistances involved in the heat-transfer process, the values of those, evaluated for each of the EHE control volumes, are shown in Figure 12 together with the cumulative transferred thermal power.

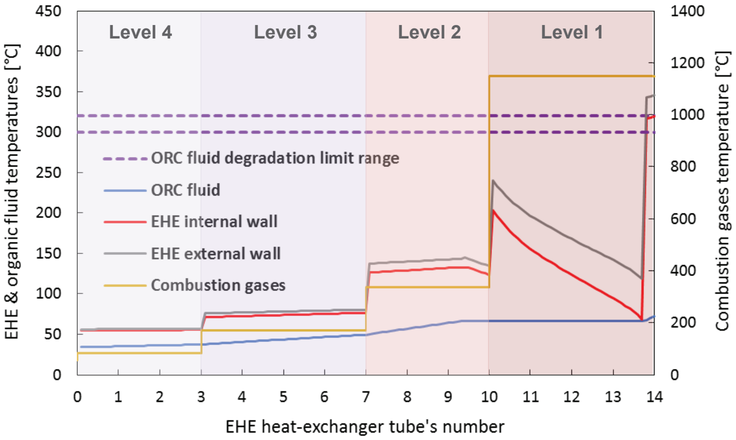

Figure 11. Combustion gases, organic fluid (bulk) and tubes internal and external wall temperatures along the EHE tubes.

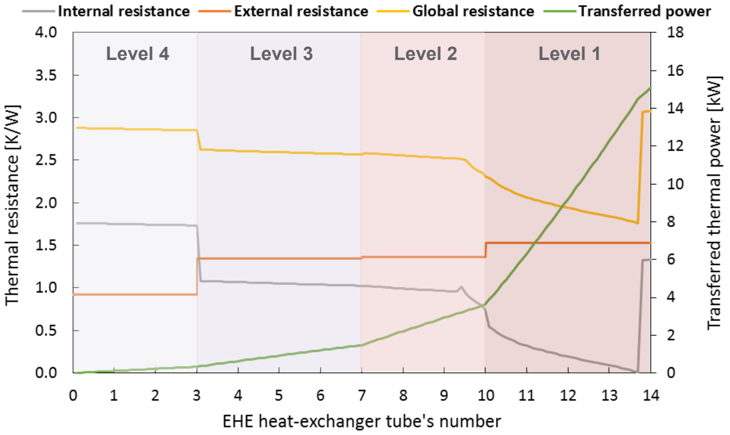

Figure 12. Internal, external and overall thermal resistances and cumulative transferred thermal power along the EHE tubes.

From this analysis, it can be said regarding the main objective of this work, the characterization of the temperature of the internal surface of the EHE tubes, that this parameter is essentially determined by the internal thermal resistance (since the external is essentially constant) and by the combustion gases' temperatures. As the non-boiling heat-transfer processes, occurring when the organic fluid is either in liquid or in gaseous phases, are characterized by similar values of the internal thermal resistance (see Figure 12), the combination of these heat-transfer regimes with high temperatures of the combustion gases may originate very high internal surface temperatures of the EHE tubes (see Figure 11). Therefore, efforts should be made to avoid or, if not possible, to minimize those. That means, reducing the superheating degree to the minimum value possible and avoiding the presence of the organic fluid in a liquid phase on the 1st level of the tubes. It is also important to notice that any reduction in the temperature of the combustion gases in contact with the tubes of this 1st level, as the one induced by the PH section in this case, will help to reduce the maximum temperature of the inner surface of the tubes' wall and with that, the risk of fluid degradation.

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