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ScienceDirect

Energy Procedia 129 (2017) 224–231

Energy Procedia

www.elsevier.com/locate/procedia

IV International Seminar on ORC Power Systems, ORC2017
13-15 September 2017, Milano, Italy

# Dynamic modeling and optimization of an ORC unit equipped with plate heat exchangers and turbomachines

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**Abstract**

Nowadays environmental concerns call for a transition towards an economy based on fossil fuels to a low carbon one. In order to achieve this goal, efficiency optimization of existing energy systems through waste heat to power conversion units based on bottoming Organic Rankine Cycles (ORC) is one of the actions that appears to be suitable and effective both from cost and environmental perspectives. Indeed, these units are able to increase the overall efficiency of production processes, existing facilities and renewable power plants with a limited payback time. However, despite the increasing number of ORC installations at megawatt scale, the waste heat rejected by industrial processes has rather a widespread nature. Hence, ORC units with a power output in the range of kilowatts should be developed to address this opportunity for heat recovery and for business.

In the current research activity, a dynamic model of an ORC system was developed in a commercial 1D Computer Aided Engineering software platform. Sub-models of the two plate heat exchangers and of the multi-stage centrifugal pump were developed and calibrated using performance data of industrial components at design and off-design conditions. On the other hand, the R245fa radial turbine design was accomplished using a design procedure that provided geometrical and performance data for the mapping of the device by means of a 1D tool. A steady-state off-design analysis at different operating conditions at the evaporator was further carried out optimizing pump and turbine speeds to maximize the net power output. Furthermore, the thermal inertial effects at the evaporator were assessed with reference to a sample heat load profile of the water hot source and at different time scales.



*Keywords:* Waste heat recovery; Organic Rankine Cycle; Dynamic modelling; Efficiency optimization; turboexpander

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10.1016/j.egypro.2017.09.146

## 1. Introduction

The growing energy demand in the world, the scarcity of natural resources and the increasing environmental concerns due to the excessive pollutant emissions led governments, national and international organization to more sustainable and eco-friendly energetic and industrial policies. As a consequence, many research activities have been carried out in order to investigate reliable solutions capable to effectively exploit renewable energy sources and to improve the overall efficiency of existing power generation and industrial facilities.

Among these, since the heat rejected by industrial processes is still a remarkable share of the world energy consumption, waste heat to power conversion systems represent one of the most promising and effective ways to contribute to the achievement of these targets. In particular, the organic Rankine cycle (ORC) technology has proven to be reliable, cost-effective and easy to maintain [1] both for low grade and ultra-low grade waste heat recovery applications [2, 3]. For large scale heat sources between few hundreds of $kW_{th}$ up to few $MW_{th}$, an ORC power system is a mature and economic-optimized technology to convert heat into electricity from geothermal reservoirs [4-7], concentrated solar power plants [8, 9] and in biomass combined heat and power installations [10].

However, considering smaller units, whose thermal power input range is between few kilowatts to 100 kW, there are aspects which have not been fully addressed yet and the research is still undergoing. Among them, one of the most relevant topics is undoubtedly the accurate modeling of the system dynamics, especially of the heat exchangers and the expander side, for design, optimization and control purposes [11]. In fact, in applications as the automotive ones, ORC systems are asked to be flexible and reliable for several working conditions, since the heat load supplied to the system can change rapidly in a periodic or random way, as it occurs in engine ORC systems under transient driving cycle conditions. For these reasons, the proper modeling and analysis of transients, is strongly needed, also to allow the optimization of the power plant in several operating points.

Among the research works that have been carried out in this area, in [12] a dynamic model of a small scale ORC power plant for WHR applications using a scroll expander as power conversion unit has been proposed. The aim of the work was the validation of a control strategy able to optimize the system overall efficiency varying the heat load supplied. In [13] a 150 $kW_{el}$ ORC system using an innovative turbogenerator has been presented with the same purpose. In [14, 15] the effects of the introduction of an 11 $kW_{el}$ screw expander in a ORC system have been analyzed, while in [16, 17] the authors presented the dynamic model of the same system and designed a control strategy acting on the pump frequency in order to regulate the working fluid superheating. In [18, 19], a dynamic model able to predict the behavior of a few $MW_{el}$ scale ORC WHR systems has been proposed, with the aim of reproducing and analyzing its performance and behavior at off-design conditions without having the control actions affecting the system dynamics. The tools used in these aforementioned studies were Modelica and Matlab/Simulink.

Although these simulation platforms allow to model and analyze all the ORC components, they also require an extensive effort and time to implement customized or mere literature models that are not anymore innovative. Therefore, when the goal is to look into the interactions between conventional components, commercial software platforms become equally attractive and timewise effective. For these reasons, in this work a modeling methodology to predict the steady-state and transient behavior of a small scale ORC system is proposed. The approach adopted permits to consistently reduce the model implementation time and it has the additional benefit to be highly replicable both in research and in industry. The approach refers to a radial turbine, which presents several advantages as compactness, economic convenience and ease of maintenance. Besides the modeling methodology and implementation, this study shows the ORC performance at off-design conditions due to different hot source mass flow rates and temperatures and achieved through an optimization of turbine and pump speeds. The transient response of the water-R245fa plate heat exchanger evaporator and the effects on the turbine inlet temperature have been eventually assessed with reference to a series of heat loads at different time scales.

## 2. System description

The model presented in this work describes an ORC power plant for stationary waste heat recovery applications. With reference to the modeling scheme in Figure 1, the heat recovery takes place through a plate heat exchanger having water on the hot side and the working fluid of the system, which is R245fa, on the cold side. After being pressurized in a multi-stage centrifugal pump, the working fluid undergoes to a full vaporization during the heat