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Organic Flash Cycles: Off-design behavior and control strategies of two different cycle architectures for Waste Heat Recovery applications



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ABSTRACT

Off-design characterization of energy systems has become interesting, especially for waste heat recovery application, where the heat source temperature and mass flow rate can vary over time. Low-grade heat is generally converted into power through ORC modules: the problem of the constant temperature evaporation lead to the definition of alternative architectures, among which organic flash cycles.

In this work, the off-design behavior of two different architectures of single-stage Organic Flash Cycles has been analyzed in steady-state condition, for small scale waste heat recovery (WHR) purposes. The main difference between the two architecture is the regeneration: in the first architecture (Single-Stage Organic Flash Cycle SS-OFC), the liquid of the flash evaporator, after lamination is mixed with the vapor from the expander and then sent to the condenser; in the second architecture Single-Stage Organic Flash Regenerative Cycle, SS-OFRC, the liquid from the flash evaporator is mixed with the liquid from the condenser, to regenerate the cycle. The most appropriate fluid for the two cycles was selected from a list of sixteen fluids with the objective of minimizing volume flow rates and maximizing the system efficiency and i-Pentane was chosen. For the off-design behavior, a rotary volumetric expander derived from a Wankel engine was considered, taking into account the performance variation of the device at various rotating speed and pressure ratios. Three different control strategies were considered and compared in off-design analysis for both the cycle architectures: sliding-pressure, in which the expander speed was constant and flash pressure varied with the load; sliding-velocity, in which the load was controlled by the speed variation of the expander and flash pressure was retained constant; combined strategy in which the expander speed was varied to drive the flash pressure according to a function which maximized the system efficiency. Results showed that the efficiency of the two cycles was similar in all the operating field whatever was the control strategy considered: SS-OFRC demonstrated a better behavior at low temperatures of the heat source (< 170 °C), while SS-OFC had a better efficiency at higher temperature. The maximum absolute efficiency difference in off-design conditions between the two cycles was lower than 0.3%. SS-OFRC however had a wider field of operation than SS-OFC, due to the better flexibility of this type of cycle. As for the control strategy, with both the architectures, combined strategy maximized the system efficiency and flexibility for every temperature and mass flow rate of the heat source considered.

1. Introduction

ORCs play a major role in the exploitation of low-temperature heat source, due to the favorable proprieties of organic fluids, resulting in compact and simple components, reducing system size [1,2] and proved to be one of the most reliable and efficient solutions for low and medium temperature waste heat recovery systems [3]. However, the presence of the constant temperature evaporation in the heat transfer process causes a bad match of the heat transfer curves, which implies exergy destruction. In the case of WHR system, the pinch point at evaporating temperature cause the discharge of the hot stream at a much higher temperature than the lowest temperature of the cycle [4]. To overcome these problems, several authors in the literature have proposed various solutions: Kalina cycles, ORC with zeotropic mixtures, supercritical ORCs, multiple level ORCs, organic trilateral cycles and organic flash cycles.

Kalina cycles have been introduced in the 1980s and work in an analogous way to Rankine cycles, but with a mixture of water and ammonia, to obtain a temperature glide during evaporation and condensation [5]. The main issue of this type of architecture is related to the complicated layout, which involves additional heat exchangers, absorber and desorber, providing however a small gain in efficiency

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Nomenclature		η_c	cycle efficiency
Ċ Ŵ h	thermal power, kW mechanical or electrical power, kW specific enthalpy, kJ/kg	η Subscript:	overall efficiency
ṁ v _g	mass flow rate, kg/s specific volume, m ³ /kg	av exch	available exchanged
Greeks		NET in	net exchanger inlet
E	recovery efficiency	0	ambient conditions

respect to subcritical ORC [6] and operating at high pressure [7].

To obtain the same glide effect of the Kalina cycle, but with a more simple architecture, different zeotropic organic mixtures have been proposed: the use of these type of fluids has been widely studied in the literature, serving various heat source [8–10]. Due to the better match of the exchange curves, the efficiency reached by this type of cycles are higher than those of the simple ORC, however there are still some issues in their practical realization, due to uncertainty in the fluid properties, unknown heat coefficient values, cost effectiveness and above all composition and fractioning of the two fluids [11].

Supercritical ORCs represent another possibility in improving the performance of the system, reducing the entropy production during the heat exchange [12]. Moreover, the high temperature of the cycle allows to achieve a better cycle efficiency than that of subcritical ORC, if a recuperator is employed [13] and to operate with a smaller turbine [14]. The high pressure achieved in the cycle [15] and the lack of a specific design for transcritical turbines however limit the spread of this technology.

Multiple pressure level ORCs, are another solution to improve the heat transfer, by splitting the evaporation on more than one pressure level. Performance of multiple level ORC are similar to that of other advanced solutions (supercritical ORC and ORC with zeotropic fluids), but with a much larger complexity which limits their use just to large scale applications [16].

Trilateral organic cycles were introduced by Smith et al. in 1993 [17,18] with the purpose of developing a thermodynamic cycle which was as close as possible to the Lorentz cycle, which is the cycle with the best recovery efficiency for sensible heat sources and isothermal condensing conditions. The lack of an efficient two phase expander represents a great limit for this type of technology and a practical application has never been developed.

Organic Flash Cycle, are a modification of Trilateral Organic Cycle, where the saturated liquid at the end of the heat exchanger is flashed and the vapor from the flash evaporator is expanded in a conventional expander. This type of cycle is widely used in geothermal application where the heat source is composed of superheated water at very high pressure. Ho et al. in [19] hypothesized the use of the flash cycle with organic fluids for high temperature (300 °C) waste heat recovery applications: they tested several fluids and concluded that the system second law efficiency was slightly lesser than that obtained with ORC, due to exergy destruction during the lamination process. However, they concluded that with some improvements both in the cycle layout and in the replacement of the throttling valve with a two-phase expander a better efficiency can be reached. This conclusion was validated by the results obtained in further works [20,21] where they demonstrated the superiority of two-stage flash cycles and of single-stage flash cycle with two phase expander respect to ORC. The major issue with this type of cycle is represented by the large exchanging surface required: in fact, in flash cycles, both in single and double-stages, the working fluid is heated from the condensing temperature up to the maximum cycle temperature and exchange curves are parallel. To reduce the heat exchanger area and reduce the costs, a different cycle architecture, with regeneration was designed and proposed in a previous paper [22]. The results indicated that the regenerated cycle has the same thermodynamic performance of the organic flash cycle, but achieved a largely lower specific cost, similar to subcritical ORCs.

The results obtained in the previous paper encourages further studies on this technology where an off-design analysis is still lacking.

Off-design characterization is important to understand the evolution of many thermodynamic variables as well as of the system production. The off-design behavior of subcritical ORCs has been widely investigated in the literature, both in steady-state and transient conditions: Hu et al. in [23] analyzed the off-design behavior of a small scale ORC for geothermal purposes with radial turbine equipped with Variable Inlet Guided Vanes (VIGV) to evaluate different control strategy and to define the optimal angle of incidence of the VIGV. The analysis was carried in steady-state. Other authors [24–28] analyzed the offdesign of various ORC systems in transient condition to define the dynamic behavior and evaluate different control strategies and variables to drive the system.



Fig. 1. OFC scheme (A) and OFC T-s diagram (B).

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