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Research Paper

Mixture of working fluids in ORC plants with pool boiler evaporator

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HIGHLIGHTS

- We assess the feasibility of pool boiler in ORCs operating with mixture working fluids.
- We consider hydrocarbon and siloxane mixtures for low and high temperature ORCs.
- Plants with pool boiler show comparable performances to once through evaporator.

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ABSTRACT

Power generation using Organic Rankine Cycle was studied in this paper in case of both low and high temperature cycles, exploiting respectively a geothermal heat source available at 167 °C, and heat available at 300 °C from the combustion of biomass. In particular we assess the feasibility of employing mixture of working fluids, in the case of replacing the typical once-through (OT) evaporator with the pool boiler (PB) technology, typically adopted for pure fluids. The analysis evidenced that in general the OT evaporator shows a slightly improved cycle performance in comparison to the PB and it results in some cases advantageous with respect to the pure working fluid. For instance in case of low temperature cycle, the best thermodynamic performances are obtained with mixture of i-C_5 and 75% n-C_4 in case of OT evaporator, yielding a recovery efficiency higher than the case with pure i-C_5 (7.7 vs. 7.4%) given the relatively higher values of both the recovery factor and cycle efficiency. Implementation of PB did not affect the plant performance significantly which shows the feasibility of having PB with potentially easier control.

1. Introduction

The Organic Rankine Cycle (ORC) technology is widely employed for the conversion of heat into electricity in several applications such as geothermal plants [1–3], solar [4], biomass and low grade heat recovery [5–7]. As it is known, from a thermodynamic point of view an ORC cycle is similar to a classical steam plant. However, the former is normally preferred as long as the size of the power plant reduces below values of few MW where the realization of a steam plant poses important technological challenges, particularly in terms of the design of a multistage steam turbine.

One main concern in ORC technology is the proper selection of the working fluid. Many aspects need to be taken into account, namely, thermodynamic properties, global warming potential (GWP), thermal stability [8,9], safety and environmental aspects [10–12], toxicity, flammability, auto-ignition temperature, costs [13,14], and availability [15]. Although the use of a pure component is presently considered the common practice in ORCs, mixture of fluids has also been proposed by many authors. The use of mixtures of organic fluids in ORC potentially carries several benefits. First of all, mixtures could lead to an efficiency increase compared to pure fluids due to a glide match of temperature profiles in the evaporator as long as a variable temperature heat source is available [16–18]. Similarly, the temperature glide in the condenser may lead to a reduction of the mass flow rate of the cooling fluid, which in case of air cooling systems may result in a significant reduction of the electricity consumption of the air fan [18]. Another advantage of the mixture is the possibility of suppressing or reducing undesirable properties of a single fluid, such as the flammability or the global-warming potential [19]. Finally and most importantly, it is virtually possible by mixing appropriate amounts of different components to obtain thermodynamic properties of the working mixture that optimize the cycle conversion efficiency and the design of the plant components, in correspondence with the conditions of the heat and cooling sources.

As far as the plant components are concerned, up to now, different studies have introduced various types of evaporator in ORCs, such as plate heat exchangers [20,21], shell and tube heat exchanger [16,18,22–25], and fined tubes heat exchanger [26]. In general, two approaches can be distinguished in the design of the evaporator: (i) the pool boiling system, where the evaporating process occurs in the shell side with a physical separation between the saturated vapor phase (in the upper side of the shell) and saturated liquid phase (on the bottom of the shell); (ii) the once-through evaporator, where the evaporation of the working fluid

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occurs in the tubes side of heat exchanger, typically with a counter flow arrangement with respect to the hot stream. In this case, the working fluid experiences a progressive evaporation along the heat exchanger, with a corresponding increase of the vapor fraction of the two phase flow. As it will be better discussed in the following, the pool boiling solution is the typical choice for pure working fluids [27], in particular because it can cope with load variation with a rather simple control strategy, avoiding unstable conditions of the plant. For instance, an unexpected change of the input heat would result in a corresponding variation of the level of liquid in the evaporator, keeping the vapor always in saturated conditions avoiding any undesirable wet vapor fed to the turbine. Thus, a straightforward control strategy may change the mass flow rate of the working fluid (typically varying the rotational speed of the pump) in order to adjust the level of liquid to the set point value. On the contrary, the once through approach is typically recommended in case of mixtures of working fluids because, thanks to the glide in evaporation, a counter flow heat exchange arrangement improves the heat recovery factor in case of a variable temperature heat source. Heat recovery factor is defined as the ratio of intake and available heat while heat recovery efficiency is the ratio of net power to available heat. On the debit side, since there is no net separation between the liquid and vapor phases during the evaporation process, an effective control is needed in off-design conditions, especially in case of an abrupt reduction of the input heat rate, to avoid wet vapor fed to the turbine. Thus, it is normally necessary to design the once through evaporator with a certain amount of superheating even in cases where, from a thermodynamic point of view, a saturated cycle would be a better choice.

In this paper, we carry out a thermodynamic study of ORC plants operating with mixtures of working fluids that employ the pool boiler evaporator, in order to assess the feasibility of this solution in comparison with the more established once through evaporation technology. To the best of our knowledge, pool boiling represents a new approach in case of mixtures.

We consider two reference plants in order to address low temperature and high temperature ORC applications. The first is an existing geothermal plant operating with iso-pentane (i-C_5) as working fluid, which exploits a variable temperature heat source available at 167 °C [28]. The second case study is based on a biomass power plant with octamethyltrisiloxane (MDM) as working fluid, with maximum cycle temperature of 300 °C. In both cases, we study different mixtures of fluids and compare the power plant performances in case of both once through and pool boiler evaporators. All the thermodynamic calculations were carried out by the program Aspen Plus v8.0 [29,30].

At the end, it is noticeable that the suggested ORC plant with pool boiler evaporator shares some similarities with the Kalina cycle in that both utilize a binary mixture of working fluids. However, there are main differences between the two cases. First of all the selected fluids are different. Second, the composition of the mixture is constant at all states of the ORC plant while it changes in the case of Kalina cycle, as explained in [31–34]. Moreover, the straightforward plant configuration of the PB solution remains the same in low and high temperature cycles, while the Kalina cycle becomes more complicated when high temperature sources are exploited [31]. Ultimately, the ORC plant with PB evaporator has a potentially easier control than that Kalina as it has been explained in Section 2.2.1.

2. Low temperature ORC analysis

2.1. Description of the reference plant and model validation

The ORC assumed as reference for the low temperature analysis is a geothermal plant operated with pure i-C_5 as working fluid, described in the book of DiPippo [28]. The power plant is composed of a pump, an evaporator, a turbine, and a water cooled condenser as sketched in Fig. 1a, while the corresponding Temperature–Entropy diagram is reported in Fig. 1b considering the enthalpy changes of hot source fluid. Calculation assumptions are reported in Table 1.

Table 1
Calculation assumptions for the geothermal i-C_5 ORC plant defined in Fig. 1 [28].

Hot source temperature, T_7 in Fig. 1a (°C)	167
Net Power (kW)	1200
Cooling water temperature, T_5 in Fig. 1a (°C)	25
Evaporation pressure (bar)	20
Condensing pressure (bar)	1.9
Condensing temperature, $T_{cond.}$ (°C)	47
Turbine isentropic efficiency, η_T (%)	85
Pump isentropic efficiency, η_P (%)	75
Minimum temperature of evaporator, $\Delta T_{min, evap}$ (°C)	5
Minimum temperature of condenser, $\Delta T_{min, cond.}$ (°C)	5

*Note: there are no pressure and heat losses in the heat exchangers.

Thermodynamic properties of i-C_5 are evaluated by means of the well-known Peng–Robinson equation of state (EoS). ASME steam tables 1967 is considered for the properties of the geothermal fluid and cooling water – which are assumed as pure water – and ideal gas model for cooling air. The mass flow of the working fluid and of the cooling water is varied in order to match the 5 °C minimum temperature at the evaporator and the condenser respectively. The

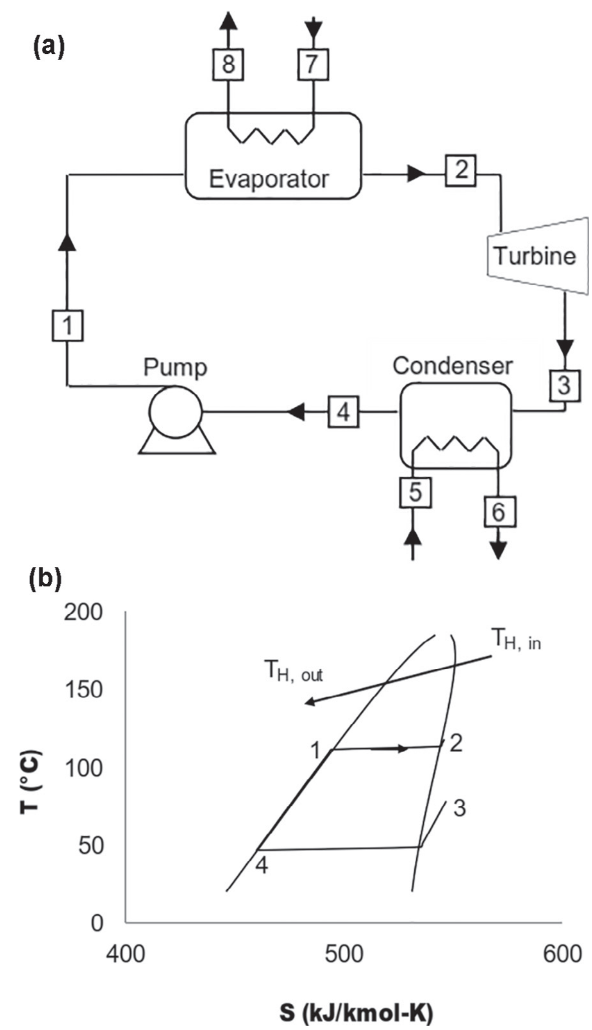

Fig. 1. (a) Plant layout of the geothermal i-C_5 ORC plant [28]. (b) Related T-S diagram.