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Low grade thermal recovery based on trilateral flash cycles using recent pure fluids and mixtures

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Abstract

The current work presents a thermodynamic analysis of a Trilateral Flash Cycle (TFC) system for low grade heat to power conversion applications. Novel aspects of the research are the usage of rotary positive displacement expanders as prime movers of the TFC system as well as the reference to working fluids and their mixtures at the state of the art. In particular, the role of a correct built-in volume ratio of the expander with respect to the pressure ratio of the thermodynamic cycle is emphasized. In fact, a mismatching of these two quantities would lead to an isochoric expansion process which, in turn, might negatively affect the overall power recovery. With reference to a transcritical CO_2 stream at 100°C as heat source for the TFC system, parametric and screening studies were carried out using different expander built-in volume ratios and working fluids respectively. Among the fluids analyzed, results showed that pure substances such as R1234ze(E) and propane would provide a greater specific work but, on the other hand, would require built-in volume ratios (8 and 14) that are beyond the capabilities of rotary positive displacement expanders (5). The addition of CO_2 to the afore mentioned working fluids would ease the mismatching issue but, at the same time, would reduce the specific power output. Regarding the built-in volume ratio analysis, it was found that optimal values change in accordance to the working fluid and refer to an expansion process with a slight isochoric phase.

Keywords: trilateral flash cycle; positive displacement expander; refrigeration; waste heat recovery; thermodynamic analysis

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Nomenclature

h	specific enthalpy [J/kg]	β	volume ratio [-]
$\dot{m}$	mass flow rate [kg/s]	**subscripts**	
p	pressure [Pa]	d	discharge
P	power [W]	id	ideal, target
v	specific volume [m^3/kg]	in	intake
$\dot{V}$	volume flow rate [m^3/s]	hs	heat source

1. Introduction

Low and medium grade heat sources demonstrate a huge energy recovery potential into mechanical and electrical forms. They are represented by heat usually wasted into atmosphere in many industrial applications as well as in the transportation and renewable power sectors. Most of the available heat recovery potential falls in a temperature range of the waste heat source below 100 °C [1]. In these conditions, conventional waste heat to power conversion systems based on bottoming Organic Rankine Cycles (ORC) are challenging to operate. In fact, the condition imposed by the pinch point at the evaporator produces a strong irreversibility during the heat transfer between heat source and working fluid, which reduces the work of the cycle and, in turn, its efficiency [2-4]. A more suitable bottoming thermodynamic cycle to recover and transform heat into mechanical energy is certainly represented by the so-called trilateral cycle, (TLC) [3].

The TLC employs the same components than an ORC. Main difference is that the working fluid does not undergo to a phase change during the heat recovery but only reaches saturated liquid conditions. On the other hand, the expansion of the working fluid from such saturation state produces a sudden phase change, referred as a flashing process: for this reason, in literature TLC is often called also Trilateral Flash Cycle (TFC). TLC or TFC have been extensively studied in literature: from a thermodynamic point of view, main benefit is the thermal matching between heat source and working fluid [6] that minimizes the irreversibility produced during the heat transfer (exergy destruction) [7]. In reference [8], a dual loop waste heat recovery circuit, based on the integration of an upper trilateral cycle and a lower organic Rankine cycle, was proposed for an internal combustion engine application: maximum recovery efficiency of 10.9% and exergy efficiency of 58.8%, larger than that of the single loop trilateral cycle, were achieved. A generalization of the TLC, named Power Flash Cycle (PFC), was investigated in reference [9]; in particular, a PFC is a cycle where the compressed liquid delivers power performing a flash expansion. An additional cycle that has been examined is the Organic Flash Cycle (OFC), whereas the working fluid is first flashed in a two-phase mixture and subsequently the saturated vapor is separated and expanded through the high pressure turbine, while the saturated liquid is throttled to the same pressure [10]. This enhancement would yield approximately 20% greater power output than an optimized ORC. Moreover, comparing the performances of TLC with ORC and Kalina Cycle system, it has been demonstrated that TLC can achieve a net power output higher than those provided by the ORC and Kalina cycle, but this is greatly affected by the expander isentropic efficiency [11].

TLC fluid selection is a key point: water is unsuitable due volume ratios required for its expansion. Organic fluids are the best candidates: a TFC with R12 as working fluid demonstrated a high efficiency, also in trans-critical operation, [7]. Different aromatic hydrocarbon and siloxanes were also proposed as working fluids for TFCs demonstrating performances comparable with those of an optimized ORC, [12]. The use of mixtures as working fluid was proposed in trilateral cycle since the temperature glide during condensation better matches the temperature profile of the cooling fluid [13].

The availability of new fluids having a reduced GWP and ODP which have been considered in the literature [14] offers a new room of investigation concerning the potentialities as pure fluids and as mixtures: this possibility remained has been not fully exploited yet and deserves further attention. CO_2, for instance, is used as working fluid in refrigeration units at supercritical state and a similar interest could be expected as working fluid, pure or mixed with more modern CFC fluids.