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Development and analysis of a packaged Trilateral Flash Cycle system for low grade heat to power conversion applications

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ABSTRACT

The current research tackles the energy trilemma of emissions reduction, security of supply and cost savings in industrial environments by presenting the development of a packaged, plug & play power unit for low-grade waste heat recovery applications. The heat to power conversion system is based on the Trilateral Flash Cycle (TFC), a bottoming thermodynamic cycle particularly suitable for waste heat sources at temperatures below 100 °C which, on a European scale, account for 469 TWh in industry and are particularly concentrated in the chemical and petrochemical sectors. The industrial test case refers to a UK tire manufacturing company in which a 2 MW water stream at 85 °C involved in the rubber curing process was chosen as hot source of the TFC system while a pond was considered the heat sink. The design of the industrial scale power unit, which is presented at end of the manuscript, was carried out based on the outcomes of a theoretical modelling platform that allowed to investigate and optimize multiple design parameters using energy and exergy analyses. In particular, the model exploitation identified R1233zd(E) and R245fa as the most suitable pure working fluids for the current application, given the higher net power output and the lower ratio between pumping and expander powers. At nominal operating conditions, the designed TFC system is expected to recover 120 kWe and have an overall efficiency of 6%.

1. Introduction

Industrial processes involve a series of energy transformations that are inherently characterized by energy losses of different types: thermal excluding radiation, radiation, electrical transmission, friction etc. The first category includes exhausts (flue gas, vapor) and effluents (cooling water or air) that on a global scale, currently account for 30% of the primary industrial energy consumption, or 8.9 PWh in absolute terms [1,2]. Therefore, together with the energy saving measures that must be implemented to lower energy consumptions and corresponding greenhouse gas emissions in industry, the recovery of thermal waste streams is an attractive opportunity both for business and academia to fulfil the environmental targets imposed by international agreements [3].

Waste heat recovery technologies can mainly be divided into two categories. The first one, by means of conventional [4] and innovative heat exchangers [5], aims at transferring part of the thermal energy from the waste source to another location of the same industrial process or site, or alternatively to export the heat recovered over the fence. The second strategy aims at a conversion of the waste heat to electrical energy using bottoming thermodynamic cycles, direct expansion in auxiliary power turbines, as well as thermoelectricity [6,7]. In the last two decades, bottoming thermodynamic cycles, especially Organic Rankine Cycles (ORC), have experienced substantial interest from the industrial and scientific communities. This is thanks to the availability of new working fluids, and that most of the ORC equipment could be developed starting from the know-how and components already available in other industrial sectors, such as the steam power generation and refrigeration industries.

ORC systems have been successfully applied for large scale heat sources in the medium-low temperature range, i.e. between 100 °C and 300 °C [8,9]. Nowadays, even medium scale ORC units (electrical power range 10–100 kW) are starting to become commercially viable [10]. Nevertheless, per recent estimations of the global waste heat potential, most of the heat rejection occurs at low

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Nomenclature

c_p	specific heat at constant pressure [J/kgK]	exp	expander
h	specific enthalpy [J/kg]	hot	hot source
$\dot{m}$	mass flow rate [kg/s]	mech	mechanical
I	irreversibility [W]	net	net
$\dot{W}$	power [W]	pmp	pump
T	temperature [K]	wf	working fluid
η	efficiency	I	energy analysis
cold	cold source	II	exergy analysis
el	electrical		

temperature ranges, namely below 100 °C. At these operating conditions, ORC systems experience lower performance than the ones of those bottoming thermodynamic cycles that do not involve a two-phase heat recovery and that are characterized by a two-phase expansion process. Since the shape of such thermodynamic architectures resembles the one of a triangle and because of the flashing phenomena involved in the expansion of the saturated liquid, these alternative cycles are commonly referred in literature as Trilateral Flash Cycles (TFC).

The TFC has been mostly investigated for geothermal applications using working fluids that, however, nowadays are phased out [11,12]. Later theoretical works compared the performance of TFC over conventional Organic Rankine Cycles (ORC). In particular, for a heat source at 150 °C and using propane as the working fluid, TFC showed an exergy efficiency 30% greater than that of an ORC. Volume flow rates and, in turn, size of heat exchangers and machines are, however, larger in TFC systems [13]. Water was found to be the best performing working fluid. However, the low saturation pressure at ambient temperature would lead to extraordinarily large volumetric flow rates [14]. The greater exergetic efficiency of TFC over ORC was confirmed by a similar study: after an analysis of multiple potential working fluids, despite their flammability siloxanes were found to be more suitable both for ORC and TFC applications [15]. An exergo-economic comparison of TFC, ORC and Kalina cycles using a low-grade heat source, restated that the main advantage of TFC is the good temperature match during the heat recovery, and that the TFC power system can be useful if the expander has an isentropic efficiency close to that of conventional turbines; otherwise the ORC is the most advantageous option [16]. In addition to the analysis of pure working fluids for TFC systems, in references [17,18] the potential of mixtures is investigated with the aim of minimizing the irreversibility during the heat gain and heat rejection processes. Nevertheless, choosing suitable fluids for a mixture is a task that goes beyond the evaluation of the thermophysical properties using the available databases. In fact, the miscibility potential of a given set of fluids should be first verified from a chemical viewpoint [19–21].

Despite the knowledgeable contributions, the above-mentioned research works did not pursue an executive design of the TFC system that, however, is a challenging step to exploit the capabilities of the waste heat to power conversion unit at experimental and industrial level. In the current research, a TFC system for low-grade heat to power conversion in a tire manufacturing company has been designed using a thermodynamic software platform that allowed to investigate the impact of design variables including working fluids on theoretical energy and exergy performances of the TFC unit. In addition to that, a novel aspect presented in the paper is the development of a packaged, plug & play design configuration that not only required the selection of the equipment but also involved design challenges from acoustic, space and grid connection viewpoints.

2. The opportunity

Forman et al. [2] proposed a methodology to estimate the waste heat potential based on primary energy consumptions and considering only exhausts or effluents as suitable sources for waste heat recovery. In particular, the Authors considered three temperature ranges to rank the wastes: high (>300 °C), medium (100–300 °C) and low grades (<100 °C). On a global scale, industrial low grade waste heat potential has a magnitude of 3.7 PWh, 42% of the global industrial waste heat potential (8.9 PWh). Therefore, 12.6% of the industrial primary energy supply is eventually rejected at temperatures below 100 °C.

To further detail the assessment of the low grade waste heat potential, Forman's methodology was herein applied to recent energy statistics in the European Union [22]. In particular, the analysis resulted in Figs. 1 and 2, which respectively break down the low grade industrial waste heat potential in EU28 by country and sector.

The total European industrial low grade waste heat potential is 469 TWh, 12.7% of the global amount. The trend noticed in Fig. 1 essentially depends on the primary energy consumptions in the different countries, which are in turn proportional to number of citizens, gross domestic product, carbon intensity etc. For these

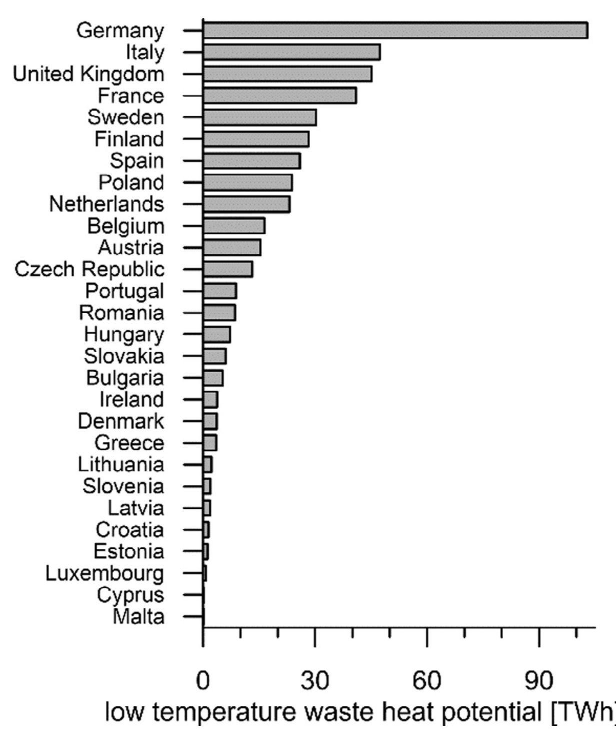

Fig. 1. Low grade waste heat potential (<100 °C) in EU28 by country.