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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

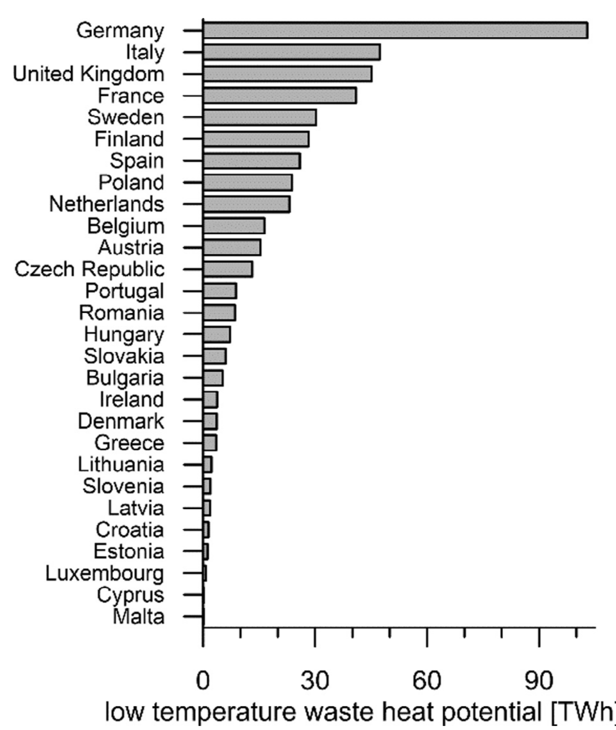

Fig. 1. Low grade waste heat potential (<100 °C) in EU28 by country.

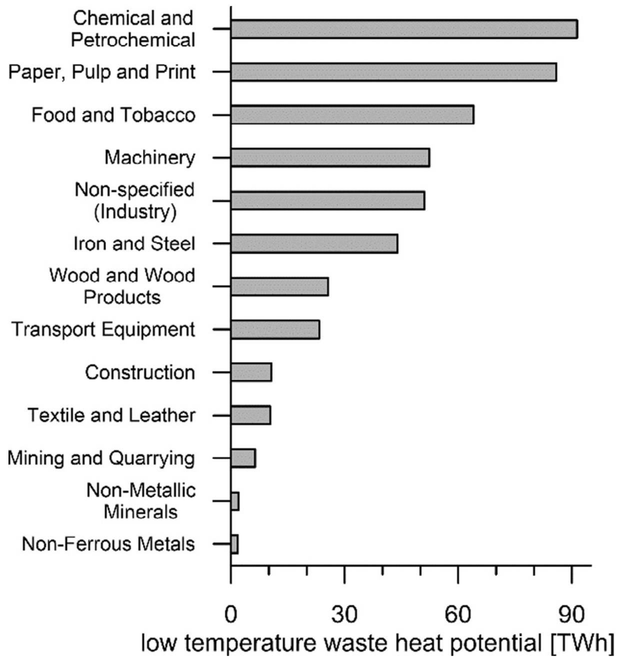

Fig. 2. Low grade waste heat potential (<100 °C) in EU28 by industrial sector.

reasons, Germany dominates the list followed by Italy, UK and France.

Fig. 2 shows that the industrial sectors that are mostly responsible for heat rejection at low temperatures are the chemical and petrochemical (19.4% of the total) as well as paper, pulp and print (18.3%) and, food and tobacco (9.8%). On the other hand, sectors with high overall waste heat potential such as the iron and steel, are not characterized by large amount of low grade thermal losses. In fact, in this particular case, most of the heat rejection occurs at high temperatures at the furnaces.

The heat rejection of the low grade thermal energy may occur in direct or indirect ways. In the first approach, the exhausts or effluents mix with the heat sinks that, having a greater thermal capacity, eventually impose their temperature. Alternatively, an auxiliary device can be used to transfer the thermal power to the heat sinks. These devices are air, evaporative, hybrid and water cooling systems. In general terms, the overall industrial cooling system market is poised to grow at a compound annual growth rate of around 5.8% over the next decade to reach approximately $22.5 billion by 2025 [23]. This means that in the short-term future there will be an increasing demand of rejecting heat. In this scenario, rather than performing an entirely passive dissipation, the TFC technology aims at more sustainable engagement of such request. Furthermore, the electric output from the TFC unit is valuable not only from the overall energy balance of the industrial system but also from an economical perspective since the profits from the waste heat to power conversion are positive cash flows that contribute to accelerate the investment dynamics and its return.

3. Characterization of heat source and sink

Installation and testing of the TFC system will take place at Cooper Tire & Rubber Company Europe Ltd, Melksham (United Kingdom). Prior to the design of the TFC system, a survey at the industrial site was carried out to scope the size and temperature of potential unrecovered energy streams. It was found that whilst Cooper Tire already recovers thermal energy through schemes such as pre-heating boiler feed water, the resultant thermal energy from tire making is larger than the available heat sinks. It is recognized that this situation occurs throughout industry and as such the case for advances in thermal energy recovery technology is strengthened.

The most promising application for the TFC technology, both technically and economically, was found to be in the tire curing process, shown schematically in Fig. 3. Under current operating conditions, waste water is recovered from rubber curing at atmospheric pressure and approximately 95 °C, and is pumped to two heat-exchangers in the boiler house. Due to losses in pipework and an intermediate buffer vessel, the temperature at the inlet to the heat exchangers is 85 °C. Although the heat exchangers are utilized to preheat the boiler feed water, the required heating does not match the large volumes of high temperature water available, and so some water is bypassed. The now cooled water from the heat exchangers is then mixed with the hot bypassed water, and it is pumped to a pond to further cool down. Once at an acceptable temperature, the water is returned to the local river from which it was originally taken.

It is proposed that the TFC unit is retro-fitted to the plant with the previously bypassed stream passing through the unit. To utilize the existing pipework, the heat-exchangers are located in the boiler house, and it makes sense to situate the unit here also. In doing so there will be several tangible benefits including minimal installation costs, a reduction in thermal emissions from the pond and average pond temperature, electrical power generation for local plant consumption, cost benefits from the provision of electricity. To design the demonstration unit, we have considered a fixed inlet to the rig of 2 MW thermal, with utilization of river cooling water which is already available within the boiler house. Design specifics were gathered during the site survey and are given in Table 1.

4. Theoretical model

In a TFC system, heat gain is achieved without phase change of the organic working fluid, and the expansion process therefore starts from the saturated liquid state rather than a vapor phase. With reference to the plant layout displayed in Fig. 4 and T-s diagram presented in Fig. 5, the working fluid is pressurized, heated at constant pressure to its saturation point, expanded as a two-phase mixture and eventually condensed at constant pressure.

From a theoretical viewpoint, the governing equations that regulate the steady state performance of a TFC system at design conditions are energy balances at the heater (Eq. (1)) and cooler (Eq. (2)) as well as on the isentropic efficiency definitions for pump (Eq. (3)) and expander (Eq. (4)).

$$\dot{m}_{hot}c_{p,hot}(T_8 - T_9) = \dot{m}_{wf}(h_5 - h_4) \tag{1}$$

$$\dot{m}_{cold}c_{p,cold}(T_{11} - T_{10}) = \dot{m}_{wf}(h_6 - h_2) \tag{2}$$

$$\eta_{pmp} = (h_3 - h_2)/(h_4 - h_2) \tag{3}$$

$$\eta_{\exp} = (h_5 - h_6)/(h_5 - h_7) \tag{4}$$

Assuming the same mechanical and electrical efficiencies for pump and expander, the net electrical power output from the TFC system can be expressed according to Eq. (5) while the overall energy efficiency is defined as the ratio of the net electrical power output and the heat recovered, as per Eq. (6).

$$\dot{W}_{net} = \dot{m}_{wf}((h_5 - h_6) - (h_4 - h_2))\eta_{mech}\eta_{el} \tag{5}$$

$$\eta_I = \frac{\dot{W}_{net}}{\dot{m}_{hot}c_{p,hot}(T_8 - T_9)} \tag{6}$$

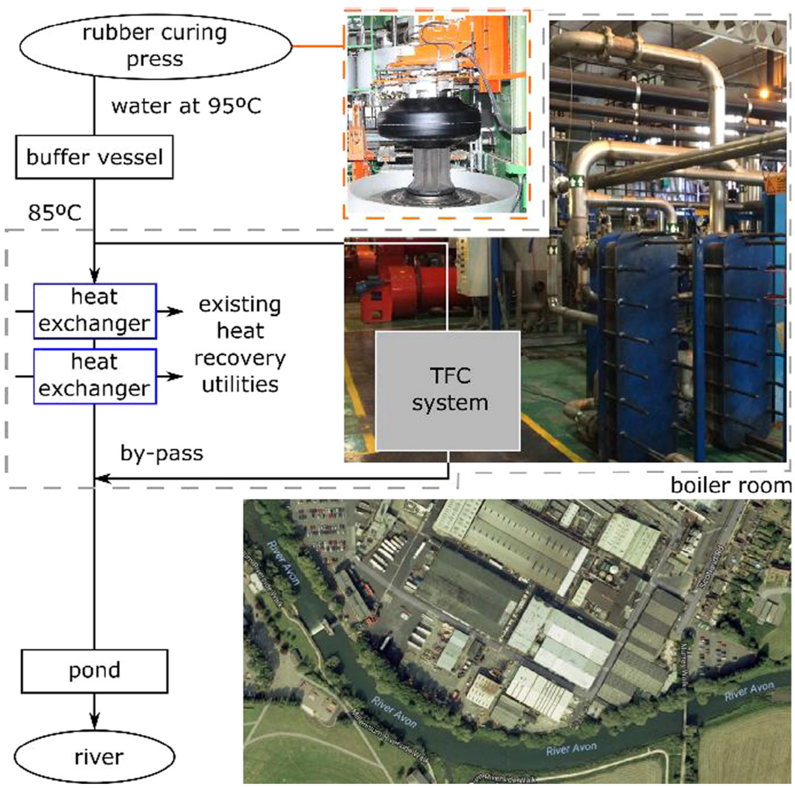

Fig. 3. Retrofit of an existing rubber curing process with a TFC system at Cooper Tire UK [24].

Table 1
Heat source and sink specifics for the test case.

Thermal source	Type	Temperature	Mass flow rate
Hot	Tire press exhaust	85 °C	16.7 kg/s
Cold	River	12 °C	97.2 kg/s

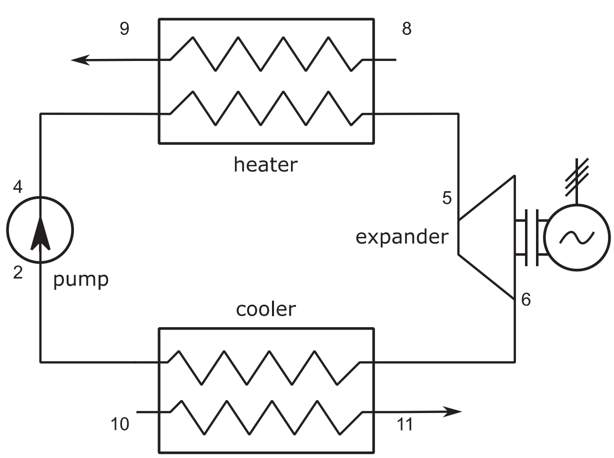

Fig. 4. Plant layout.

In addition to the 1st law analysis, exergy efficiency provides a better insight of the heat utilization. Its formulation is reported in Eq. (7) and relies on the calculation of the irreversibility I_k in each component of the TFC system according to reference [25].

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{net} + \sum_k I_k} \tag{7}$$

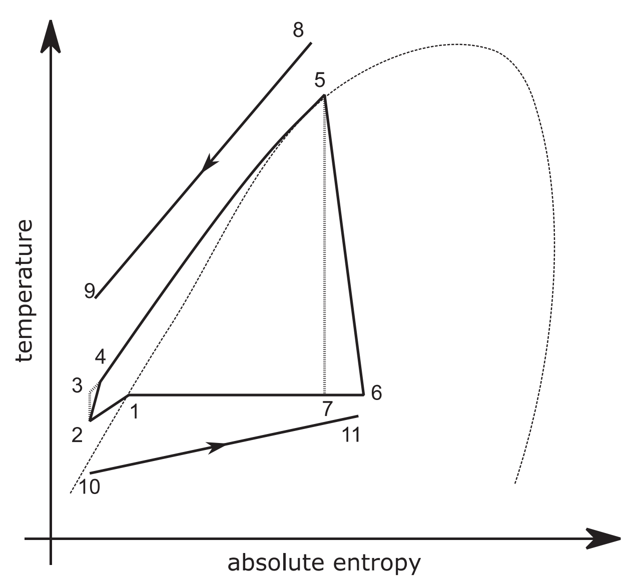

Fig. 5. T-s diagram.

The theoretical thermodynamic model of the TFC system was implemented in the Engineering Equation Solver (EES) software platform, which additionally provides libraries of thermophysical properties for most of the working fluids and mixtures at the state of the art. The solution principle of EES is based on Newton's method and the Tarjan blocking algorithm which breaks the problems into a number of smaller problems that are easier to solve. Sparse matrix techniques are also employed to reduce the number of equations that need to be simultaneously solved [26]. Thermophysical properties of pure working fluids are mostly calculated with reference to the formulation of the fundamental equation of state proposed by Tillner-Roth [27] while for mixtures the equation of state in the formulation of Martin-Hou [28] is adopted.

5. Results and discussion

Prior to the design of the waste heat to power unit according to the input data of Table 1, the theoretical model was exploited to provide insights on the energy and exergy performance of a TFC system in low grade applications and using different working fluids.

5.1. Working fluid screening

Fig. 6 analyses the performance of the best available working fluids for a sample low grade waste heat recovery application whereas the hot source is a water stream at 1 kg/s and 90 °C. A main assumption in this analysis was to consider a constant temperature difference at the heater to ensure suitable matching of the temperature profiles and, in turn, to reduce the irreversibility during the heat gain process. For instance, considering 10 K temperature difference throughout the heater, implied a maximum cycle temperature of 80 °C and, in turn, that the maximum cycle pressure was the saturation one at 80 °C.

Output quantities are the specific electrical power output (Fig. 6a), cycle efficiency (Fig. 6b), ratio between enthalpy differences during expansion and pumping (Fig. 6c) and, eventually, the heat transfer surface required for the heater (Fig. 6d). This latter piece of information was retrieved with reference to a brazed plate heat exchanger technology selected using the SWEP's SSP G7 software [29]. The rating methodology implemented in the software is based on calculations in the pressure-enthalpy domain, a one-dimensional discretization and semi-empirical correlations that are reported in [30].

Results are provided for HFO (R1233zd(E), R1234yf, R1234ze (E)) and hydrocarbon working fluids (propane, isobutane, 1-Butene). These working fluids result from a first screening based on thermophysical and environmental criteria reported in Table 2. Siloxanes, which in reference [15] resulted promising not only for

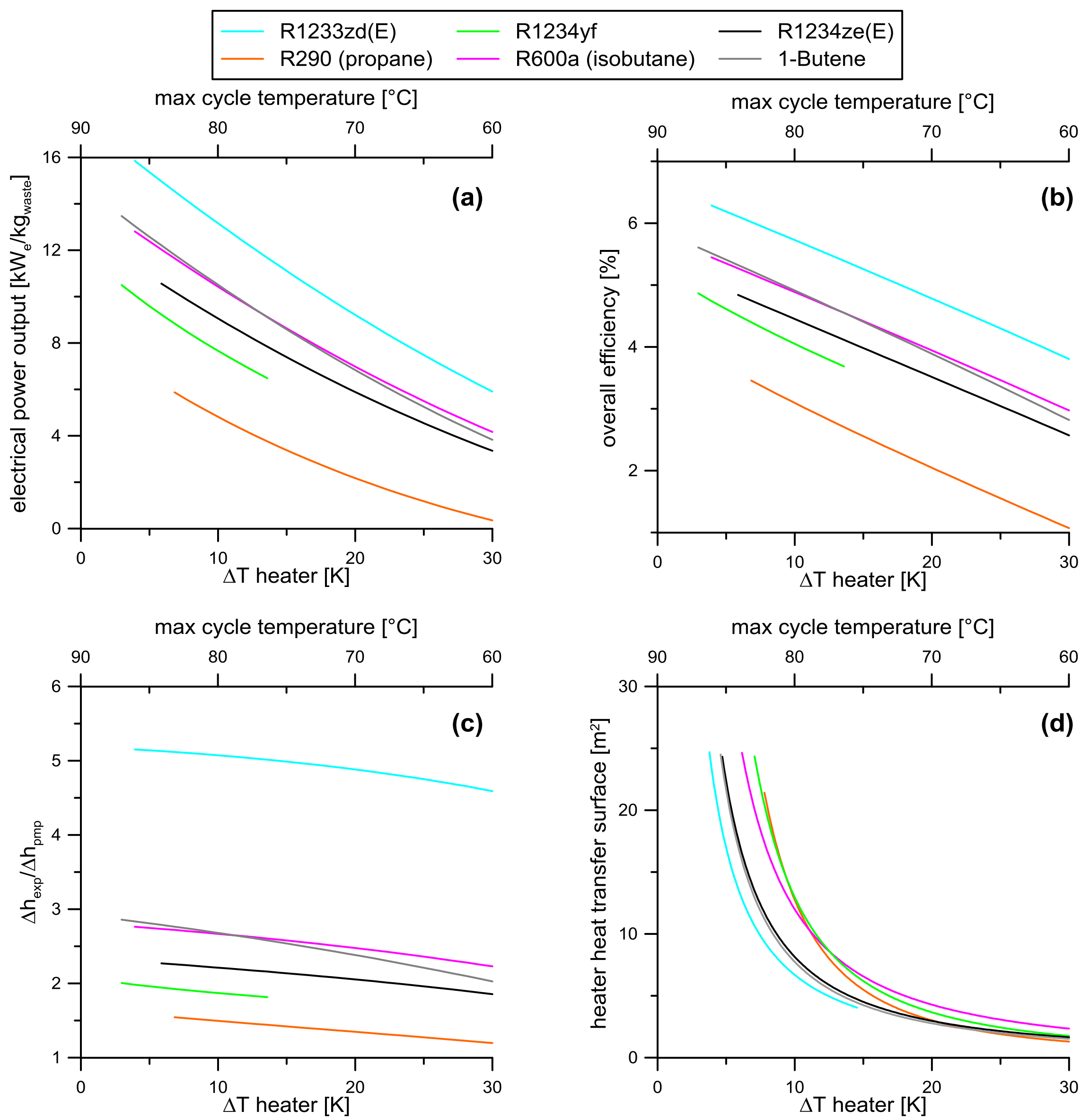

Fig. 6. Impact of maximum cycle temperature on TFC performance for different working fluids: net electrical power output per kg/s of thermal waste (a), cycle efficiency (b), expander-pump enthalpy ratio (c), heat transfer surface of the heater (d).

Table 2
Working fluid selection criteria.

Global Warming Potential	<6
Ozone Depletion Potential	0
Maximum operating temperature	>30 °C
Minimum operating temperature	<−30 °C
Critical temperature	>50 °C
Saturation pressure at 25 °C	>1 bar

high temperature heat to power conversion systems but also for low temperature ones, were discarded due to their flammability and a saturation pressure at ambient conditions below the atmospheric one. Indeed, such features might lead to additional design complexity that would penalize the overall economic feasibility of the heat recovery system.

Fig. 6a and b show the linear decrease that net specific power output and cycle efficiency experience when maximum cycle temperature and, in turn, cycle pressure ratio reduce. On the other hand, the ratio between expansion and pumping powers in Fig. 6c does not significantly vary because of the small variations that enthalpy has with pressure when the working fluid is in liquid phase. Hence, the linear decrease essentially depends on the lower heat recovery from the hot source that highly affects the mass flow rate of the working fluid. This statement is confirmed by Fig. 6d that shows an exponential decrease of the heat transfer surface with the maximum cycle temperature regardless of the working fluid. The simulations eventually confirm that R1233zd(E) is the best candidate for the TFC technology at these temperature levels. Indeed, with reference to a temperature difference at the heater of 10 K, a TFC operating with a maximum temperature of 80 °C would produce 13.3 kWe for each kilogram per second of waste heat stream, with an overall cycle efficiency of 5.7%. R600a (isobutane), that is highly flammable and toxic, is also the second best working fluid among the ones taken into account: in the same operating conditions, a TFC system operating with R600a would produce 10.5 net kWe with an efficiency of 4.9%.

Although the results of Fig. 6 would encourage the usage of R1233zd(E), R245fa has lower cost, higher global warming potential and, at the same time, similar thermophysical properties [31,32]. Indeed if one had reported an additional line for R245fa in Fig. 6, its curves would have nearly overlapped with the ones of R1233zd(E) [33]. Hence, since R245fa provides comparable performances at lower costs, this working fluid was taken as reference for the parametric analyses presented in Section 5.2 as well as in the design of the industrial TFC unit.

5.2. Parametric analysis

Parametric studies on the impact of heat source and sink temperatures are reported in Fig. 7 in terms of net electrical power output (a), overall energy efficiency (b) and overall exergy efficiency (c). Similarly, in Fig. 8 the effects of pump and expander efficiencies are investigated. In both the analyses, apart from the independent variables, a series of assumptions were made and are summarized in Table 3. Greater heat source and lower heat sink temperatures have a positive benefit to all the output quantities reported in Fig. 7. In fact, the cycle pressure ratio will increase to deliver an energy efficiency of 7% for a hot stream at 100 °C and a cold at 10 °C. Similarly to steam or ORC-based power generation plants, the most affecting parameter is the condensation temperature.

As shown in Fig. 8, for a given application, expander isentropic efficiency is the key parameter to enhance the TFC energy and exergy performance. In fact, pump isentropic efficiency has a low impact even on the net power output. Nevertheless, although conventional ORC technology can be used for TFC pumps, the two-

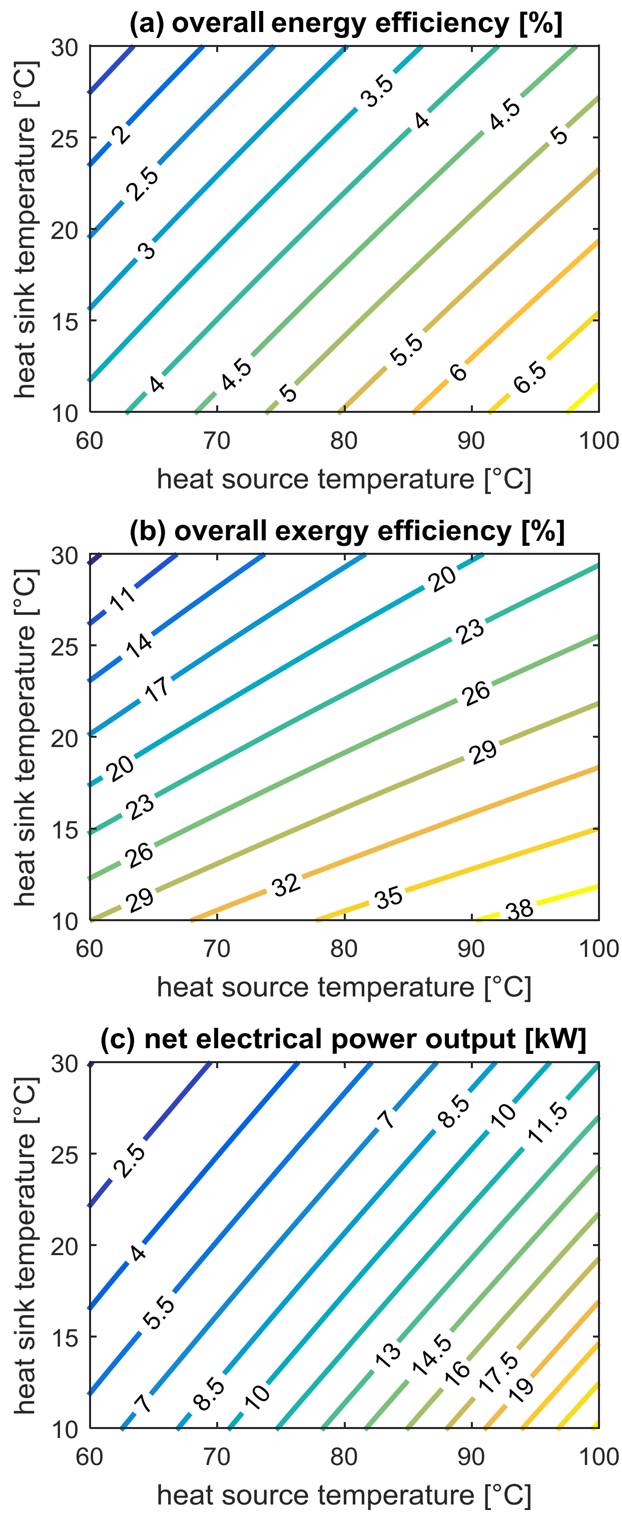

Fig. 7. Effects of heat source and sink temperatures.

phase flash expander is undoubtedly the greatest challenge to address in the TFC field.

5.3. TFC system design

The operating conditions of the heat source and sink gathered through the site survey presented in Section 3 and the theoretical model developed in Section 4, supported the thermodynamic design of the TFC system whose summary is presented in Table 4.

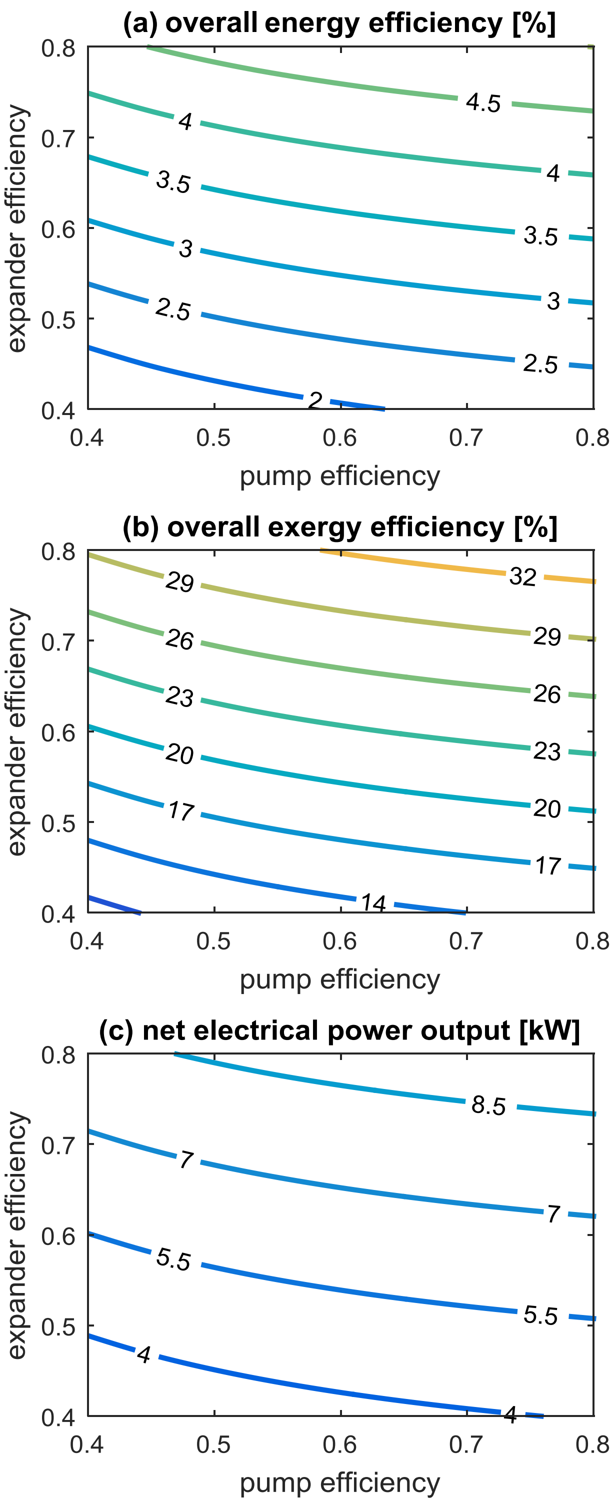

Fig. 8. Effects of pump and expander isentropic efficiencies.

Assuming pump and expander isentropic efficiencies both equal to 75%, expected theoretical performance is a net electrical power output of 120 kW and an overall energy efficiency of 6%.

6. Packaged design

Due to the magnitude of the thermal and electrical powers involved in the TFC system for the Cooper Tire application, the release of a commercial-oriented prototype unit required the careful selection and arrangement of the equipment. Detailed views are reported in Figs. 9 and 10.

As concerns the water-R245fa heater and cooler, plate heat exchangers were considered thanks to the compactness, performance (high effectiveness, low pressure drops) and cost benefits that characterize this family of devices. The selection of these components is further supported by literature in the ORC field, according to which plate heat exchanger generally perform better than other technologies such as the shell and tube ones [34]. These consideration apply when heat source and sink are liquid streams, as in the current application. On the other hand, plate heat exchangers would not be suitable for gaseous streams since they would lead to large gas pressure drops. In these cases, technologies such as heat pipes, finned coils as well as plate and shell heat exchangers are some of the available alternatives on the market. Moreover, if the heat source is a process or flue gas that is going to be cooled below its dew point, potential corrosion issues must be taken into account in the heat exchanger selection.

Due to the large mass flow rate involved, a centrifugal pump driven by a variable speed electric motor was chosen and located at the bottom of the plant. In addition to that, a receiver was installed upstream the pump to prevent any cavitation issue. In the ORC field, where R245fa is one of the most employed working fluids, positive displacement pumps also exist but mostly for small-scale units (<10 kWe) [35]. In fact, positive displacement pumps such as sliding vane, gear, gerotor and diaphragm ones are suitable for large pressure ratios and small flow rates while centrifugal pumps (single or multi-stage) are preferable for larger scale systems.

The selection of the expander technology had to accommodate the large mass flow rates and high pressure ratios of the working fluid. Turbines were reviewed and whilst on one hand they are able to handle large quantities of fluid, on the other they struggle with two-phase expansions and, consequently, they were discarded. Some turbo-expander technologies (e.g. Euler turbine) are suitable in niche and large scale applications such as the cryogenic transportation of liquefied natural gas presented in [36]. As concerns positive displacement technology, although these machines can

Table 3
Constant parameters.

	Fig. 7	Fig. 8
T_8	N/A	70 °C
T_{10}	N/A	15 °C
η_{pmp}	0.40	N/A
η_{exp}	0.75	N/A
$\dot{m}_{hot}$	1 kg/s	
η_{mech}	0.98	
η_{el}	0.95	
ΔT_{8-5}	5 K	
ΔT_{9-4}	5 K	
ΔT_{2-1}	0 K	
ΔT_{2-10}	5 K	
ΔT_{6-11}	2 K	

Table 4
TFC Design Specifics for Cooper Tires installation.

	Hot water	R245fa	Cold water
Mass flow rate [kg/s]	7.84	25.34	89.56
Inlet/max Pressure [bar_a]	4.00	7.22	4.00
Outlet/min Pressure [bar_a]	3.50	1.18	4.00
Inlet/max Temperature [°C]	85.0	76.5	12.0
Outlet/min Temperature [°C]	24.0	19.0	17.0

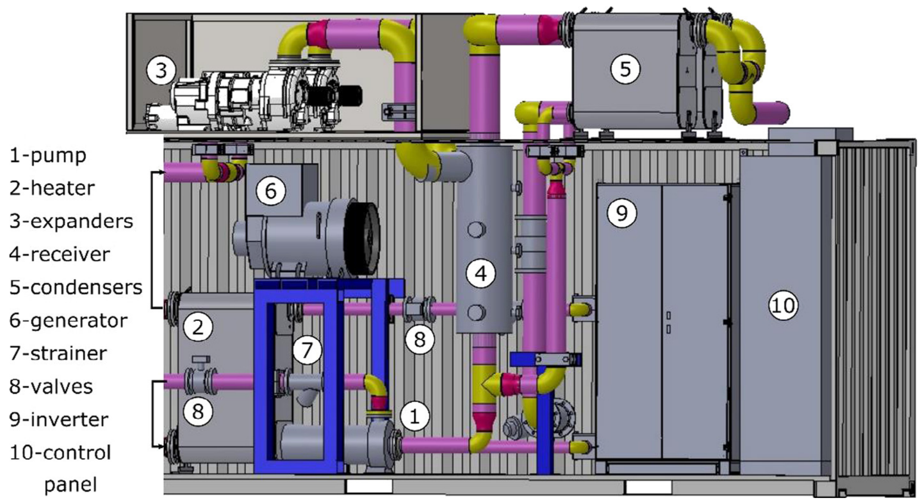

Fig. 9. Packaged plug & play TFC unit.

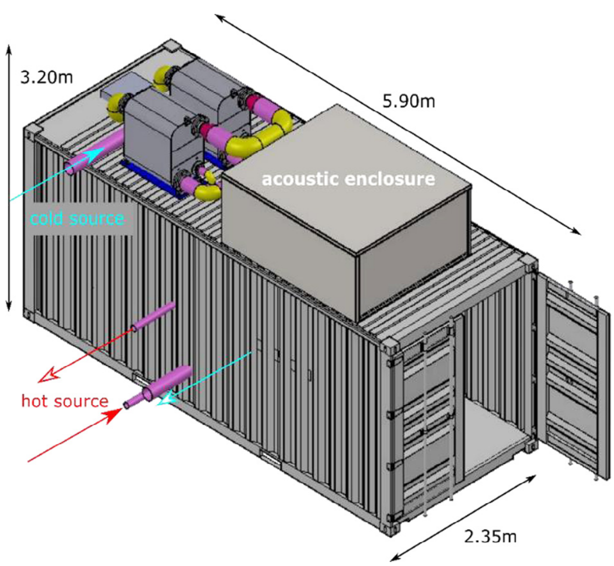

Fig. 10. External view of the TFC power unit with connections and overall dimensions.

operate at high pressure ratios, the amount of mass flow rate that they can work with is generally very limited [37]. For these reasons, the most suitable positive displacement expander technology was concluded to be the twin-screw one. This choice is also supported by the past [12] and current literature, which is now focusing on the fundamental physics of the flash expansion [38] as well as in the multi-phase simulation of screw expanders for TFC applications [39]. Although, a twin-screw expander can reach high revolution speeds without significant reduction in performance, the large amount of mass flow rate involved in the current TFC application required the installation of two expanders operating in parallel. In particular, both the machines are connected to the same electrical generator via a belt coupling. An inverter eventually ensures that, regardless of the expander revolution speed, the electricity generation always fulfils the standards imposed by the grid.

The TFC system components and electronics were eventually designed to be assembled in a shipping container that has the advantages of safety, durability, and ease of transportation. Furthermore, the expanders were set to be installed in a separate acoustic enclosure located at the top of the container (Fig. 10).

7. Conclusions

The current paper investigated the design stages that an industrial application of the Trilateral Flash Cycle (TFC) technology requires; after a site survey to assess the nature and features of the waste heat source and heat rejection stream, a TFC power unit was designed using a custom built software platform developed in Engineering Equation Solver. This platform further enabled 1st and 2nd law analyses of the TFC system as well as a detailed investigation of the effects of several design parameters on net power output. In particular, after a screening procedure, R1233zd(E) and R245fa were identified as the most suitable working fluids. Despite the greater GWP, R245fa was eventually considered as working fluid of the TFC industrial unit due to lower costs. With reference to a tire manufacturing site located at Cooper Tire in UK, and a waste heat source of 2 MW at 85 °C, the designed TFC system is expected to recover 120 kWe and have an overall efficiency of 6%.

In addition to the thermodynamic design, other development aspects of the packaged TFC-based waste heat recovery unit were discussed in terms of selection of components, space, noise and electrical issues. In particular, plate heat exchangers were identified as the best cost effective heat exchanger technology for the heater and cooler while a centrifugal pump was considered to pressurize the working fluid from 1.18 to 7.22 bar. The most suitable expander technology for the reference TFC application was identified to be a twin screw expander since these types of machines are able to work efficiently even at high speeds and, in turn, to operate with the large mass flow rates that a TFC application involves.

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