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ALTERNATIVE COGENERATION THERMODYNAMIC CYCLES FOR DOMESTIC ORC

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The Organic Flash Cycle (OFC) is suggested as a vapor power cycle that could potentially improve the efficiency of utilization of the heat source. Low and medium temperature finite thermal sources are considered in the cycle. Additionally the OFC's aim is to reduce temperature difference during heat addition. The study examines 2 different fluids. Comparisons are drawn between the OFC and an optimized basic Organic Rankine Cycle (ORC). Preliminary results show that ethanol and water are better suited for the ORC and OFC due to higher power output. Results also show that the single flash OFC achieves better efficiencies than the optimized basic ORC. Although the OFC improves the heat addition exergetic efficiency, this advantage was negated by irreversibility introduced during flash evaporation.

Keywords: microcogeneration, thermodynamic cycle, power generation

1. INTRODUCTION

In recent years there a clear tendency is observed, both worldwide and in the countries of European Union (EU), to increase the importance of so called dispersed cogeneration, based on local energy sources and technologies utilizing both fossil fuels and renewable energy resources. Cogeneration, also known as combined heat and power (CHP), is an efficient, clean and reliable approach to the simultaneous production and utilization of electricity and heat from a single fuel source. The principle of cogeneration is based on the recognition that conventional power generation, at its best, is ~40% efficiency with up to 60% of the energy being lost as waste heat. By harnessing the waste heat from electricity production into useful means can result in higher system efficiencies for fuel utilization of up to 85% or more.

Small-scale cogeneration is part of the distributed energy resource (DER) strategy, which promotes parallel and stand-alone electric generation units located within the electrical distribution system close to the end user. More specifically, DER refers to the decentralized generation of electric power in small- to medium-sized facilities near sites of power demand, in contrast to large centralized electrical generating plants. This has the advantage of minimizing transmission and distribution losses when connected to a centralized grid and promotes increased reliability of supply to the end user in the event of power outages and supply discontinuities. Small-scale cogeneration systems can be operated in two different modes, namely either electricity-driven or heat-driven ones. In the first case, the unit is designed to comply with the electricity demand and the heat is used to contribute to water and central heating purposes. In this case,

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a supplemental peak boiler may be required to meet total heat demand. In the second case, the cogeneration unit is designed to meet the heat demand while electricity is either used internally or sold to a public grid.

Generation of electricity on a small domestic scale together with production of heat can be obtained through employing gas engine units, micro gas turbines, fuel cells with efficient electrolysis, Stirling engines or ORC systems. Micro combined heat and power units (CHP) based on organic Rankine cycle (ORC) fit very well that strategy and in recent years that technology has become a field of intense research. Unlike in the steam power cycle, where vapor of water is the working fluid, ORC use refrigerants, hydrocarbons, solvents or other organic substances. A prototype of such a novel installation of domestic gas boiler fitted with a ORC module has been developed and investigated by Mikielewicz et al. (2014) and Wajs et al. (2016). During the experimental research with ethanol as the working fluid in the ORC module, the gas boiler generated saturated/superheated vapor with temperature of up to 150°C and pressure up to 7 bar, when the ethanol mass flow rate was at the level of 0.022 kg/s. Over 1 kWe of direct current electric power was generated with a supersonic axial turbine.

In the light of the mentioned above DER strategy for production of electricity research into efficient production of electricity from low grade energy sources is important, as at the moment the available efficiencies resulting from conventional technologies of production are not satisfactory. Resources including geothermal, solar thermal and low-enthalpy heat fall into the category of not very prospective heat sources for the purposes of power generation. Amongst the available options the idea of the organic Rankine cycle (ORC), power generating system using binary mixture as a working fluid or the tri-lateral cycles have attracted some attention. ORC technology has proven to be economical and reliable for thermal sources as low as 80°C (Mikielewicz and Mikielewicz, 2014). In addition, there is a great potential for reducing energy consumption by recovering low-grade waste heat that would be otherwise released to the surroundings. It has been estimated that industrial low-grade waste heat accounts for more than 50 percent of heat generated (Mikielewicz and Mikielewicz, 2014).

In general, heat is considered to be moderate-to-low grade if its temperature is below 370°C, which disables production of electricity using the traditional thermodynamic steam cycles based on the Rankine cycle. In that perspective the ORC can be implemented since there exists a wide range of working fluids to be used. ORCs have the advantage of operating with a good relative efficiency over a wide range of temperatures, for example, from 80°C to 350°C. Depending on the application, the heat from a process could be used to generate useful energy such as shaft work, electricity, or cooling that can be utilized by another process. This reduces the energy consumption of the overall system.

Implementation of ORC has proven to be amongst the attractive methods to achieve a relatively high efficiency in converting the low-grade thermal energy into more useful forms of energy. One of the drawbacks in the application of ORC is the temperature matching the heat source. A good temperature matching is important in minimizing the irreversibilities caused by heat transfer across the finite temperature difference. The ways of minimising that effect have been comprehensively addressed by Mikielewicz and Mikielewicz (2014). When using the ORC to produce electricity from a finite capacity heat source, the temperature mismatch often is inevitable because the source stream is single-phase and possesses a near linear temperature profile along the heat exchanger. The mismatch causes the pinch point to develop, destroys potential work or exergy, and reduces the effectiveness of heat exchangers. To minimize temperature mismatch, a number of possible solutions has been postulated, which are regarded as possible alternatives for utilization of low grade heat sources. These can be summarized as follows: use of zeotropic mixtures as the working fluid (Fig. 1b), transferring heat to the cycle at pressures above the critical pressure (Fig. 1c), or finally the incorporation of Organic Flash Cycle (OFC), Fig. 1d. An additional option exists if trilateral flash cycle is used. Generalising, the new approaches to improving the energy conversion of low grade fluids include utilizing unconventional working fluids and innovative cycle configurations and designs.

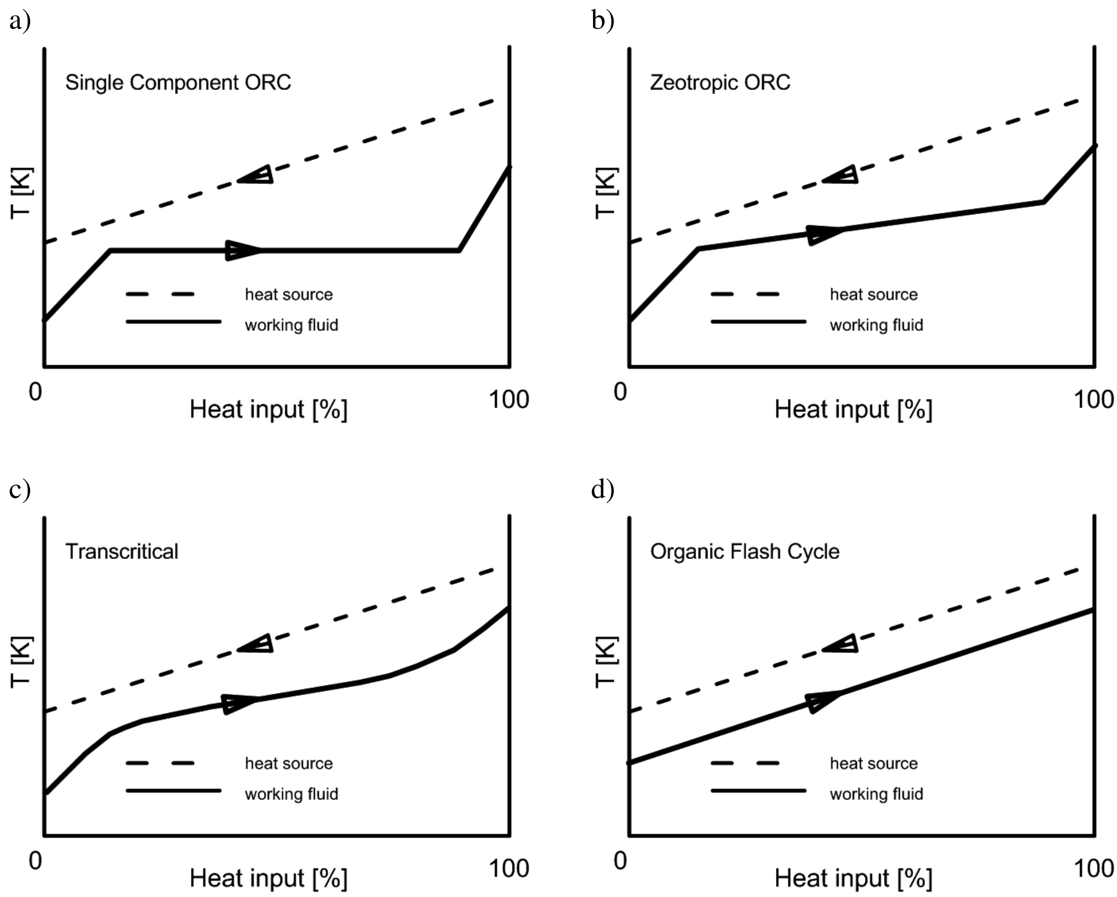

Fig. 1. Variation in source temperatures during heat supply process for single component, zeotropic, transcritical and flash cycles

The reference technology for converting waste heat to electricity is the subcritical single component ORC (SCORC), also sometimes regarded as the basic ORC. The corresponding T–s diagram of the basic ORC is given in Figs 1a and 3, whereas the layout is given in Fig. 2. The basic ORC consists of a pump which pressurizes the working fluid and transports it to the evaporator (1). In the evaporator, the working fluid is heated to the point of saturated or superheated vapor (2). Next, the working fluid expands (3) through an expander and produces mechanical work. This shaft power can then be converted to electricity by the generator. The superheated working fluid at the outlet of the expander is condensed to saturated liquid (4) in the condenser. The liquid working fluid is again pressurized by the pump, closing the cycle. The heat sink and heat source are a finite thermal reservoir and are indicated respectively as lines (7)–(8) and (5)–(6).

Zeotropic mixtures exhibit a unique characteristic known as a “temperature glide”, which results in a variation in temperature during isobaric phase change. Adequate selection of working fluid permits a better temperature match to the finite thermal source by avoiding isothermal phase change. Such an approach has been presented for example by Wang et al. (2010) or Wang and Zhao (2009). An example of zeotropic working fluid’s temperature glide has been presented in Fig. 1b, justifying the fact that the temperature profile of the thermal reservoir more closely follows that of the heat source. This reduces the irreversibility in the heat addition process. Additionally, it can potentially improve the net power output and utilization efficiency.

Transferring heat at above the critical pressure is another method that can be used to avoid the phase change region completely (Cayer et al., 2009; Chen et al., 2006; Murugan and Subbarao; 2008). This would essentially avoid the temperature mismatching encountered in the constant temperature phase change process, as shown in Fig. 1c. A vapor cycle that operates partly under supercritical conditions is known as a trans-critical cycle; working fluids that are often suggested for such cycles include carbon dioxide and helium. Other fluids can also be considered. The drawback in using the fluid under supercritical conditions which exhibits both liquid and vapor behaviour is a turbine which must be tailored to one specific condition.

Another method to improve temperature matching between the heat source and the cycle is the trilateral flash cycle (Fischer, 2011; Smith, 1993; Zamfirescu and Dincer, 2008). In the case of trilateral flash cycle, heat addition occurs while the working fluid is a single-phase liquid, thereby avoiding isothermal phase change as shown in Fig. 1d. Once the working fluid is heated to a saturated liquid state, work is then extracted using a two-phase expander. Designs of reliable and efficient two-phase expanders are underway in many research centres, although with limited progress. Most of the success thus far has been made with screw-type, scroll-type expanders and reciprocating engines (Fischer, 2011).

Another option to reduce the irreversibility related to the process of heat addition can be through the use of the Organic Flash Cycle (OFC) (Ho et al., 2012a, 2012b). In the cycle heat addition occurs with the cycle working fluid remaining in the liquid state until the working fluid reaches a saturated liquid state. The fluid would then be flash evaporated to produce the two-phase mixture. The saturated vapor would be separated and then expanded to produce power. In relation to the slope of the vapor saturation line, i.e. depending on whether the fluid belongs to the "wet" or "dry" group of fluids the end of expansion is respectively either in the "wet" vapour region or the superheated vapour region. From the point of view of turbine design the latter form of expansion is the preferred option as the expansion device cost would be significantly reduced for the Organic Flash Cycle (OFC) since blade reinforcing materials are no longer necessary. In the case of OFC the reduction in exergy destruction during heat addition process proves to be an attractive option, contributing to a better utilization of the heat source.

The present study uses thermodynamic analysis to evaluate the effectiveness of the OFC employing an organic "isentropic" or "dry" fluid. A finite thermal source originally at 300°C is considered as it represents typical temperatures for exhaust gas temperature from the gas boiler. Additionally the improved concept of regeneration of the OFC is postulated which improves the efficiency of the cycle by 5–6%.

2. CONSIDERED ORC AND OFC SYSTEMS

The reference technology for converting heat to electricity is the subcritical ORC, also sometimes defined in literature as the basic ORC. The cycle layout and corresponding T–s diagram of the basic ORC are given in Figs 2 and 3, respectively.

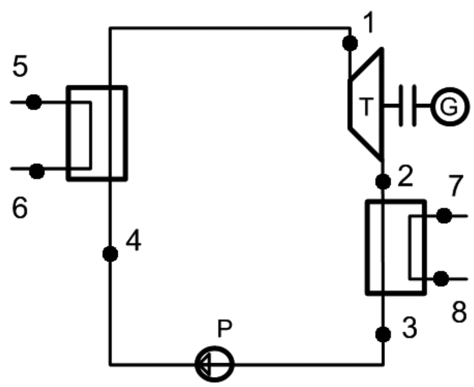

Fig. 2. Schematic of the basic ORC

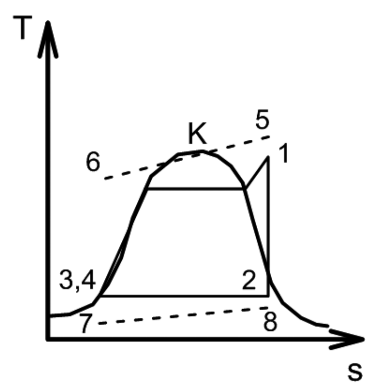

Fig. 3. Processes involved in the basic ORC

The basic ORC consists of a pump which pressurizes the working fluid (4) and transports it to the evaporator, which in the considered case is a heat exchanger where thermal oil transfers heat from the exhaust gases to the ORC working fluid. Selection of the working fluid is of critical importance, as it directly influences the cycle efficiency. Some selection criteria have been postulated by Mikielewicz and Mikielewicz (2010).

ORC case

Negligible work of the turbine is assumed, which is permitted in case of wet fluids, and ethanol in particular. In the heat exchanger the working fluid is heated to the point of saturated or superheated vapor (1). Next, the working fluid expands (2) through an expander and produces mechanical work. This shaft power can then be converted to electricity by the generator. The working fluid at the outlet of the expander is subsequently condensed to saturated liquid (3) in the condenser. The liquid working fluid is again pressurized by the pump, closing the cycle. The heat source and heat sink are a finite thermal reservoir and are indicated respectively as nodes (5)–(6) and (7)–(8).

OFC case

Another option to reduce the irreversibility related to the process of heat addition can be through the use of the Organic Flash Cycle (OFC). In the cycle heat addition occurs with the cycle working fluid remaining in the liquid state until the working fluid reaches a saturated liquid state. The fluid would then be flash evaporated to produce a two-phase mixture. The saturated vapor would be separated and then expanded to produce power. In relation to the slope of the vapor saturation line, i.e. depending on whether the fluid belongs to the "wet" or "dry" group of fluids the end of expansion is respectively either in the "wet" vapor region or the superheated vapor region. From the point of view of turbine design the latter form of expansion is the preferred option as the expansion device cost would be significantly reduced for the Organic Flash Cycle (OFC) since blade reinforcing materials are no longer necessary. In the case of OFC the reduction in exergy destruction during heat addition process proves to be an attractive option, contributing to better utilization of heat source.

A schematic of the proposed OFC configuration and its T–S diagram are shown in Figs 4 and 5, respectively. Note that in Fig. 3 a "wet" fluid had been assumed, as the slope of the saturated vapor curve is negative. Typically in OFC configurations "dry" fluids are used.

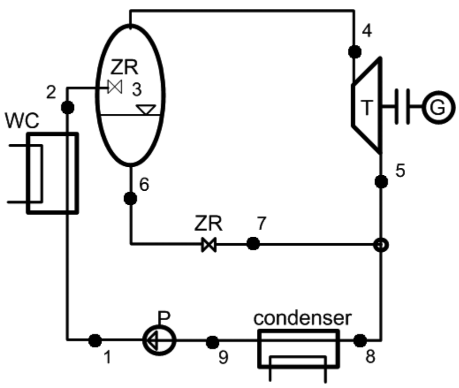

Fig. 4. Schematic of the basic OFC

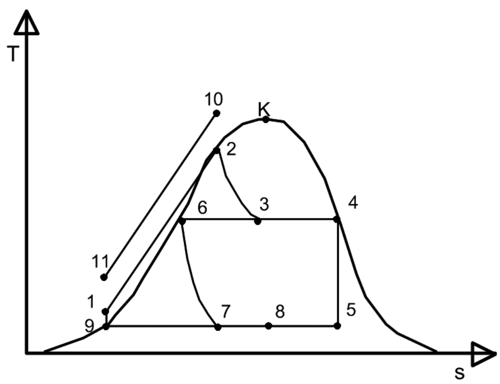

Fig. 5. Processes involved in the basic OFC

It can be seen from Fig. 4 that the OFC design is not more complex than the basic Rankine cycle. The OFC cycle brings the saturated liquid working fluid at a low pressure at state 9 to a high pressure at state 1 as shown in Fig. 5 using the feed pump. In reality, state 1 should be slightly subcooled to prevent the pump cavitation. Next, from states 1 to 2, the high pressure liquid absorbs heat from the finite thermal source and is then throttled, or flash evaporated, to a lower pressure liquid vapor mixture at state 3. The mixture is separated into its saturated vapor and liquid components at states 4 and 6, respectively. From state 4 to 5, the saturated vapor is expanded to the condensing pressure and work is extracted. The saturated liquid at state 6 is brought to the condenser pressure using a throttling valve from states 6 to 7. The liquid and vapor are then recombined in the mixer and then condensed back to a low pressure saturated liquid from states 8 to 9. It should be noted that energy in the saturated liquid can be further utilized by using an internal heat exchanger (IHE) as is often done in ORCs. The flashing process could also be performed in two steps to extract more work; this is sometimes done in higher temperature geothermal plants to boost power output. Also examples of implementation are known where instead of the flash evaporation the two-phase flow expansion machine is used.

OFC case with regeneration

In order to improve the operation of the OFC an original way to improve its efficiency has been postulated by Mikielewicz (2016). The new concept of heat management in the system is based on the fact that hot liquid with thermal parameters corresponding to state 6 from Fig. 4 is used to preheat low temperature liquid with state 1 (Fig. 4). A schematic of the new cycle layout is presented in Figs 6 and 7.

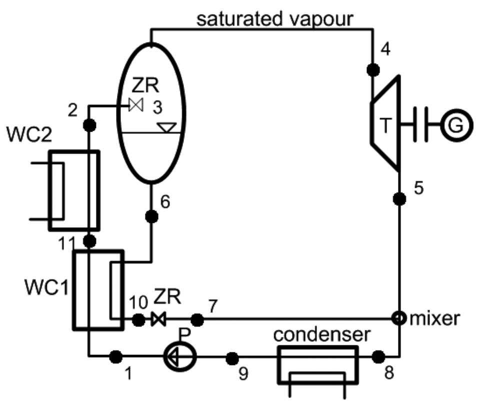

Fig. 6. Schematic of the OFC with regeneration

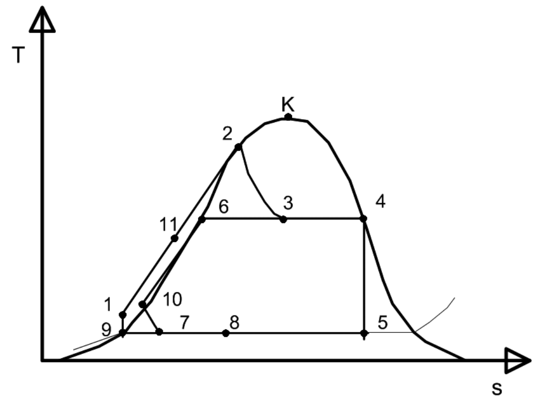

Fig. 7. Processes involved in the basic OFC with regeneration

3. RESULTS OF CALCULATIONS

Calculations have been accomplished for several fluids, but here presented are the results for two of them. Considered have been fluids from the so called wet group of fluids as well as from the dry group of fluids. Ethanol and water have been considered to be wet fluids, whereas from the dry group of fluids R245fa and SES36 have been examined. Brief characteristics of the fluids is given in Table 1 and the temperatures corresponding to pressures before the flash evaporation in Table 2.

Table 1. Characteristics of considered fluids

Fluid	M, kg/kmol	p_{cr}, bar	T_{cr}, °C	p_{cond}, bar
R245fa	134.05	36.51	154.01	3.440
C_2H_5OH	46.00	61.48	240.75	0.300

In Figs 8–11 the distributions of thermal efficiency of the OFC cycle for different considered fluids have been presented. For each case of the initial value of pressure before flashing it can be seen that there is the maximum value of efficiency observed for varying values of flashing pressure. The trend of obtained maxima shifts towards higher pressures of flashing with increasing initial pressure. The greater the initial pressure before the flashing process the greater the value of efficiency. In many waste heat applications though, where energy left in the source stream is discarded or unused after heat is transferred to the vapor cycle, a more appropriate parameter is the utilization efficiency, where the exergy of the outlet exergy of the heat is replaced with the source heat dead state exergy. The results of exergetical calculations have been presented in Table 2.

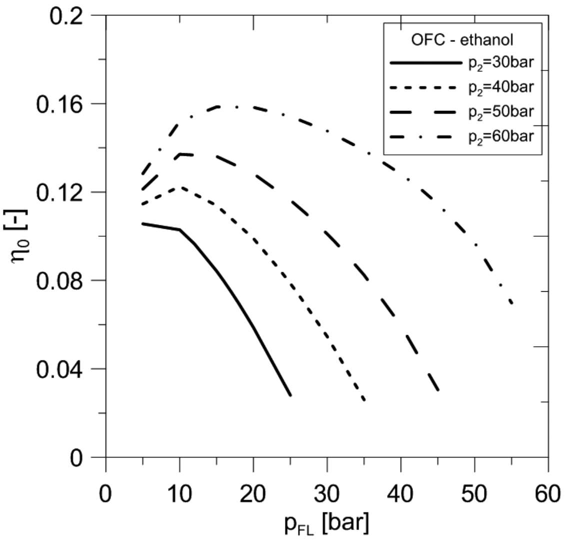

Fig. 8. Distribution of thermal efficiency in function of flashing pressure for the case of ethanol

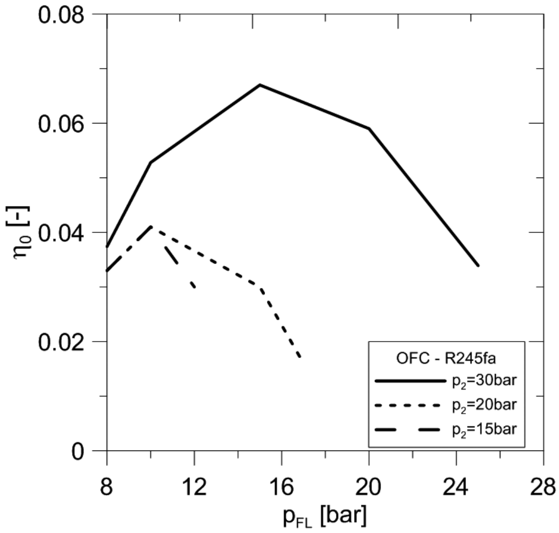

Fig. 9. Distribution of thermal efficiency in function of flashing pressure for the case of R245fa

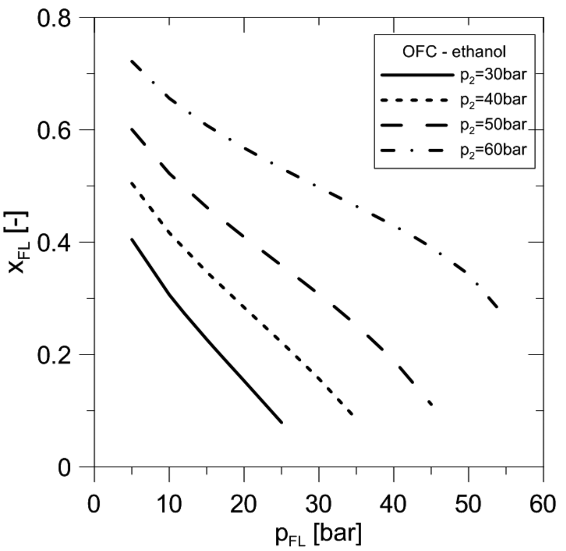

Fig. 10. Distribution of flashing quality in function of flashing pressure for the case of ethanol

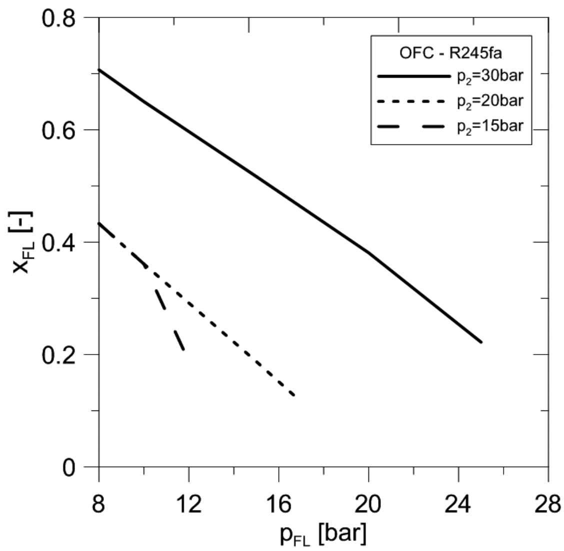

Fig. 11. Distribution of flashing quality in function of flashing pressure for the case of R245fa

At this stage the only outstanding issue in calculations is to properly assume the value of evaporation temperature and related to that the value of latent heat of evaporation $h_{lv}(T_1)$. If the evaporation temperature is not correctly assumed the outlet heat source temperature will be too high, indicating poor utilization

Table 2. Considered parameters for the OFC calculations, condensation temperature 60°C

Fluid/ Condensation pressure	Pressure before flashing, bar	Tempe-rature, °C	ORC efficiency	Max OFC efficiency	Carnot efficiency	Max Exergy efficiency OFC	Exergy efficiency ORC
R245fa (4.6 bar)	15	107.85	0.105	0.032	0.126	0.254	0.833
	20	121.85	0.124	0.041	0.157	0.261	0.790
	30	143.20	0.145	0.065	0.201	0.323	0.721
ethanol (0.46 bar)	30	200.33	0.237	0.105	0.298	0.352	0.795
	40	215.70	0.248	0.120	0.320	0.375	0.775
	50	228.35	0.254	0.140	0.337	0.415	0.754
	60	239.09	0.254	0.160	0.351	0.456	0.724

of the heat source. In such a case the calculation procedure requires iterative selection of other values of evaporation temperature.

Comparison of the data presented in Figs 8 and 12 for the case of ethanol, as well as Figs 9 and 13 for the case of R245fa indicates that the incorporation of the effect of regeneration is quite significant, rendering that the modified way of realizing the OFC cycle is becoming attractive with respect to the basic OFC. As can be seen in Figs 12 and 13 the maximum of efficiency shifts towards the higher values of the flashing pressure. In general the efficiency is by about 8% higher for highest pressure p_2 before flashing ($p_2 = 30$ bar) to about 5% for the lowest pressure as compared to the basic cycle. That must be regarded as a positive result. In Figs 14 and 15 the distributions of heat source temperature after flashing are presented. Again the lowest values of the temperature are obtained for the highest values of pressure p_2 and the flashing to the lowest values of pressure.

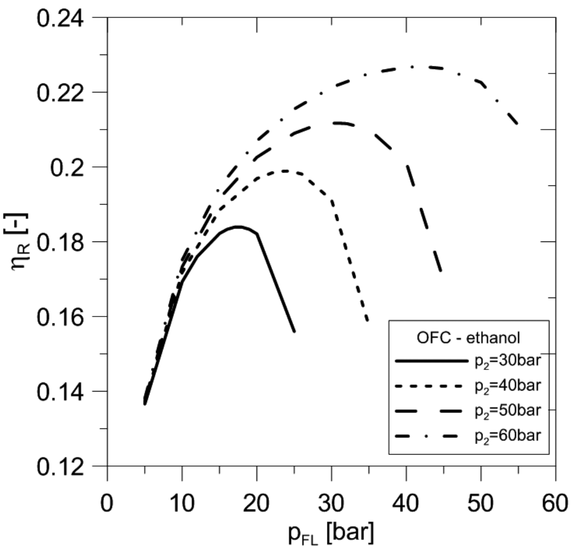

Fig. 12. Distribution of thermal efficiency in function of flashing pressure for the case of ethanol

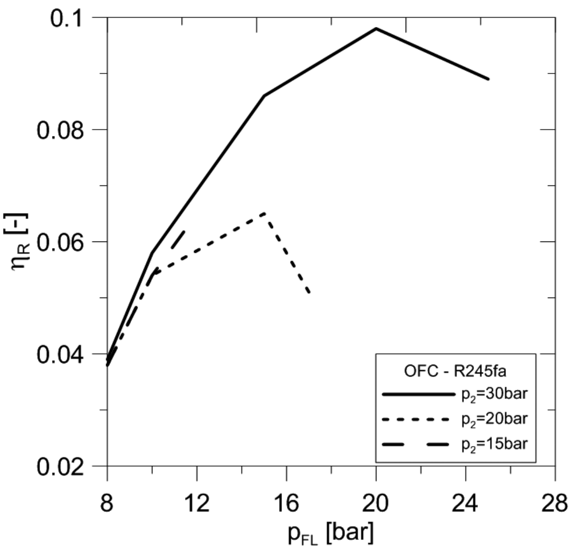

Fig. 13. Distribution of thermal efficiency in function of flashing pressure for the case of R245fa

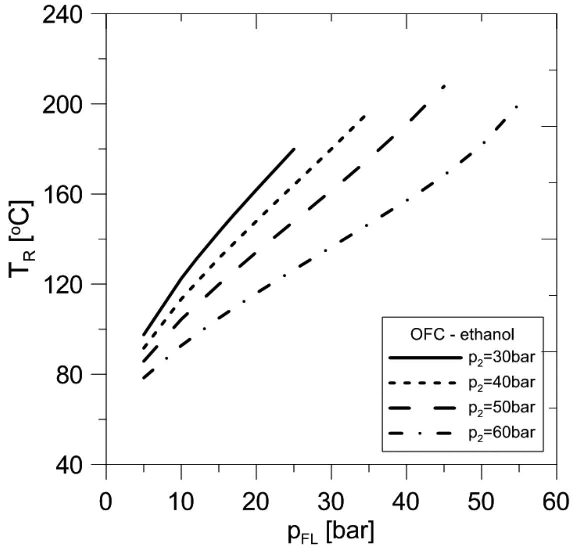

Fig. 14. Distribution of final temperature of the heat source in function of flashing pressure for the case of ethanol

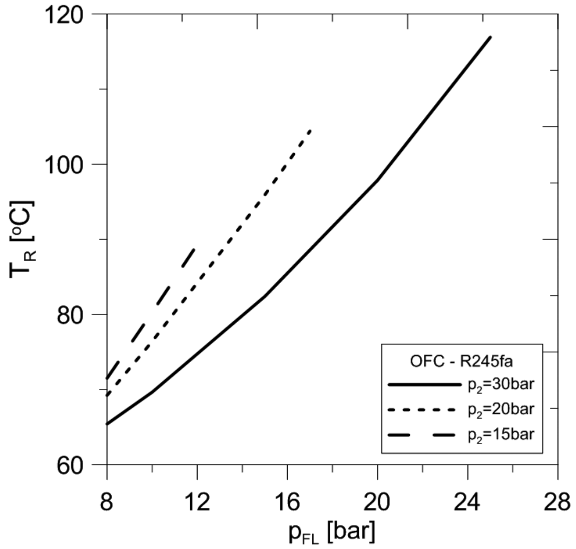

Fig. 15. Distribution of final temperature of the heat source in function of flashing pressure for the case of R245fa

4. SUMMARY

On the basis of presented calculations the following conclusions can be postulated:

- efficiency of OFC cycle strongly depends on the type of working fluid. In case of wet fluids significantly higher efficiencies are obtained than in case of dry fluids;
- in general thermal efficiencies of OFC fluids are smaller than those of ORC fluids, both for the case of wet and dry cycles. Values of efficiency vary with the value of flashing pressure. A maximum of efficiency is found in function of the flashing pressure;
- thermal efficiency values related to maximum efficiency values in OFC elements of installation exhibit lower values than the corresponding ORC;
- at a given initial pressure before flashing the subsequent vapor content decreases with increase of pressure;
- incorporation of internal regeneration leads to significant improvement of the efficiency of OFC cycle in comparison to ORC cycle.

SYMBOLS

h_{lv} latent heat of evaporation, kJ/kg
M molar mass, kg/kmol
p condensation pressure, bar
T temperature, °C

Subscripts

cond related to condensation
cr critical
FL flashing

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