Assessment, optimisation and working fluid comparison of organic rankine cycle combined with negative CO_2 gas power plant system

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Abstract

This study aims to investigate the application of the Organic Rankine Cycle (ORC) as an alternative to low-pressure expansion in the negative CO_2 power plant (nCO_2PP). The reason for this study is that a detailed analysis of nCO_2PP indicates a certain amount of waste heat present in the exhaust gas from the high-to-intermediate pressure gas turbine. Some of this energy can be used by the application of the expansion in a low-pressure turbine, optionally the application of regenerative water heating, which is further directed to the combustion chamber, and alternatively the combination of the ORC into the main cycle. For the ORC cycle, various configurations are examined, either with or without regenerative water heating and using different working mediums. For the highest cycle efficiency, regenerative heating of high-pressure water is applied, and proper ORC working fluid with optimum saturation point and mass flow is selected. Such modified nCO_2PP power plant hybrid systems with ORC are compared to the original concept of nCO2PP with lower pressure expansion. A hybrid system integrating the advantages of nCO_2PP and an ORC cycle is a promising solution, and modifications are possible, but the main advantage is that an ORC cycle can be introduced as a component to provide electrical power in the lower temperature range. Three ORC mediums were calculated, namely ethanol, refrigerants R236-ea and R245-fa which yielded net efficiency of the whole power plant of 38.35%, 40.16% and 40.39% respectively, while the original nCO_2PP yielded 38.89%.

1 Introduction

At present, due to the fact that mankind creates tonnes of sewage sludge and various restrictions appear in law prohibiting its spreading as fertiliser, new ways of utilising it should be sought [1]. One such solution is to utilise sewage sludge by gasification and produce electricity at the same time. At the receiving end of this technology is the process of CO_2 capture, which leads to the idea of a cycle with a positive impact on the environment. This arrangement has been presented in recent publications by the authors [2,3], and the whole of the issues concerning the new technology [4]. The work in the nCO_2PP grant is multivariate and multifaceted, so the search for efficiency improvement by combining the gas-steam turbine with ORC cycles cannot be missed.

One of the aspects to be considered when selecting the working medium in ORC systems is its operating temperature and the conditions under which the working medium is to operate [5]. There are known works concerning both ORC systems with several hundred MWe as well as micro-CHP plants adapted to prosumer needs, but the common feature is the consideration of several mediums adapted to the unique conditions of the energy system [6,7]. Another issue is the size of the unit, as the introduction of ORC media is very often associated with the compactness of the system, and sometimes the low temperature part of the cycle is even replaced by a low boiling medium unit [8,9]. As literature studies show, the ORC cycle itself can cooperate with a supercritical steam cycle [8,9], with a fuel cell [10] or with a simple Brayton cycle [11,12].

An additional motivation for introducing an ORC cycle into an nCO_2PP system is the fact that cycles with CO_2 capture require the management of a large amount of waste heat. In general, there are three main technologies for capturing CO_2, namely post-combustion [13,14], pre-combustion [15] and oxycombustion [16], and therefore this waste heat is associated with various effects, including: compression and cooling of CO_2 [17], gasification of the fuel and its subsequent cooling [18], production of oxygen in cryogenic stations [19,20]. All these aspects make it worth considering a hybrid system combining the advantages of nCO_2PP and ORC cycles.

The aim of this study is to investigate application of the Organic Rankine Cycle (ORC) as an alternative to low pressure expansion utilising Aspen Plus program with REFPROP property method by NIST for fluid properties calculation. Reason for this study is that certain amount of waste heat is contained in the exhaust gas from the high-to-intermediate pressure gas turbine. Some of this energy can be used by application of the expansion in a low-pressure turbine, optionally application of regenerative water heating, which is further directed to combustion chamber, and alternatively the combination of the ORC into the main cycle. Study on heat duty and temperature distribution for low pressure expansion is conducted. For the ORC cycle various configurations are examined, either with or without regenerative water heating and by using different working mediums. To maximize cycle efficiency, which is calculated according to authors publication presented in [2], regenerative heating of high-pressure water is applied for both applications.

2 Low temperature potential for nCO_2PP

2.1 Primary option with Spray-Ejector Condenser versus nCO_2PP with ORC

Process flow diagram (PFD) of nCO_2PP is shown in Figure 1. Ending of expansion is highlighted by the dotted line. In this configuration application of GT^{bap} turbine is for low pressure expansion, Spray-Ejector Condenser (SEC) has to condense remaining steam, separate CO_2 and create vacuum required by GT^{bap}, and additionally there is HE1 which cools down the exhaust before SEC by regeneratively heating high pressure water directed to Wet Combustion Chamber (WCC) [21].

PFD where Organic Cycle Rankine (ORC) has been introduced instead of low-pressure expansion is shown in Figure 2. In this modification heat exchanger HE1 is in the same place, but it receives exhaust with the pressure of 1 bar and correspondingly higher temperature. From efficiency point of view, it is preferable that HE1 use as much heat as possible. After HE1, ORC cycle is combined to take the remaining heat that could not be used by the HE1 but would be lost instead in condenser. The last device here is the Cyclone Condenser to condense and separate CO_2 which is in place of Spray-Ejector

Condenser, different condensers can be used for example Spray Condenser with optional gas injection to liquid.

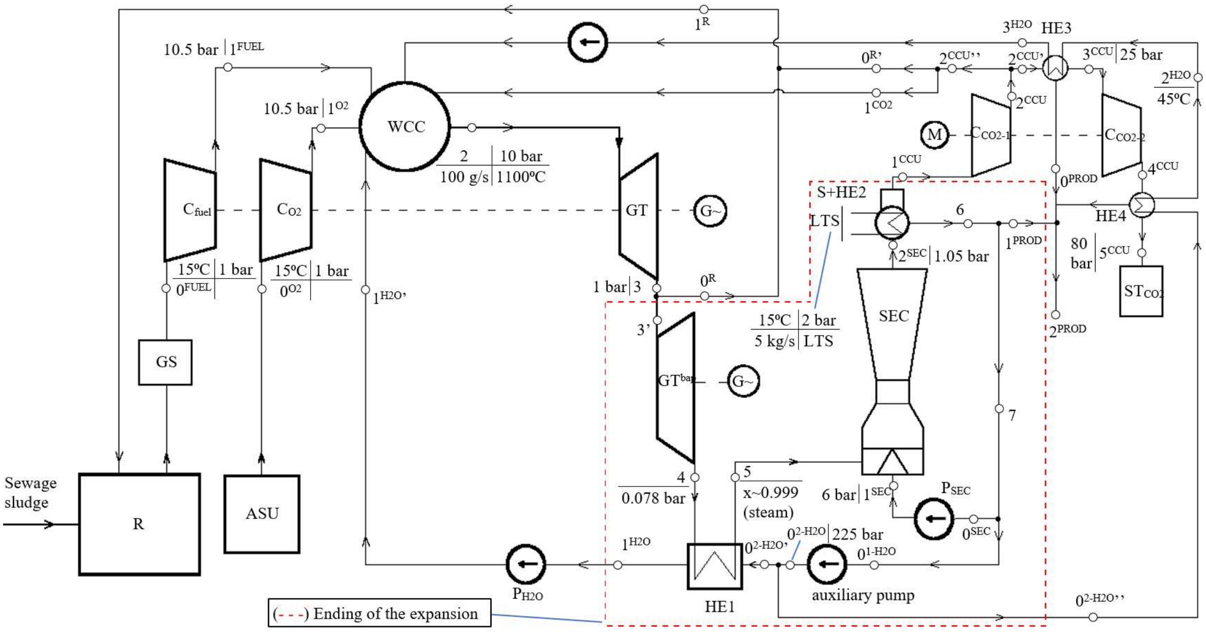

Figure 1: nCO₂PP concept PFD - SEC low pressure expansion [2, 21]

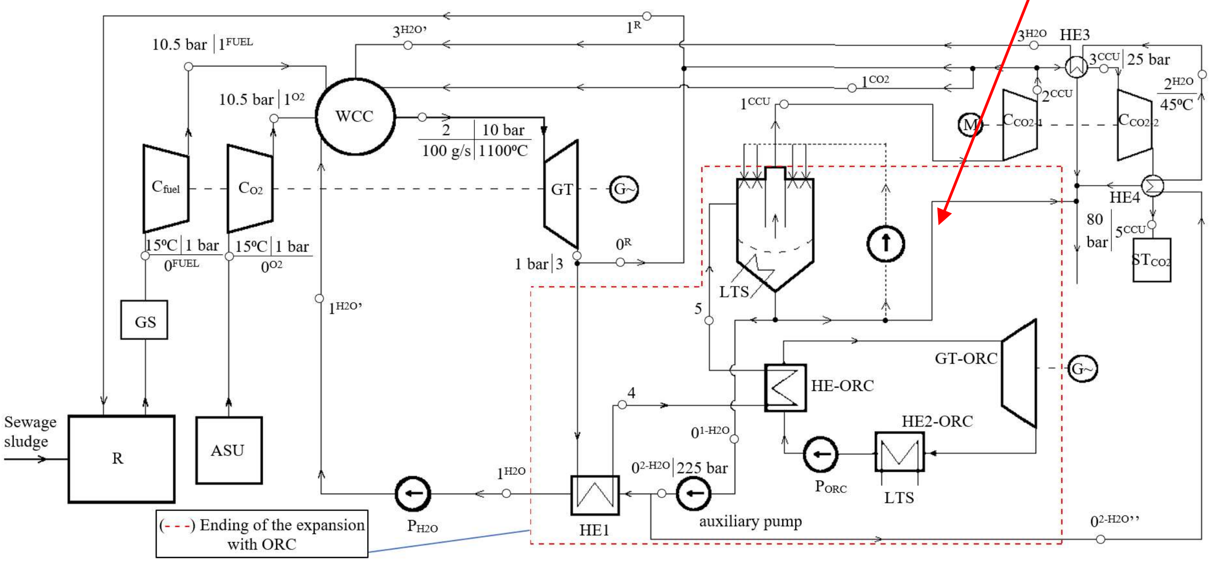

Figure 2: Hybrid nCO₂PP with ORC PFD as an alternative to low pressure expansion [22]

2.2 Overview on heat duty and temperature distribution

Heat duty of HE1 for different exhaust temperatures from WCC is shown in Figure 3. Result of 500ºC deviates from the rest due to not using HE1, due to low temperature of exhaust after the turbine.
Temperature distribution of HE1 for two different WCC exhaust temperatures 1100ºC is shown in Figure 4. It can be seen that for 1100ºC from WCC there is no heat left to be used, due to maximizing assumption of regenerative water heating in comparison to "PFD0" (see [2]), where only heating by 100K was assumed.

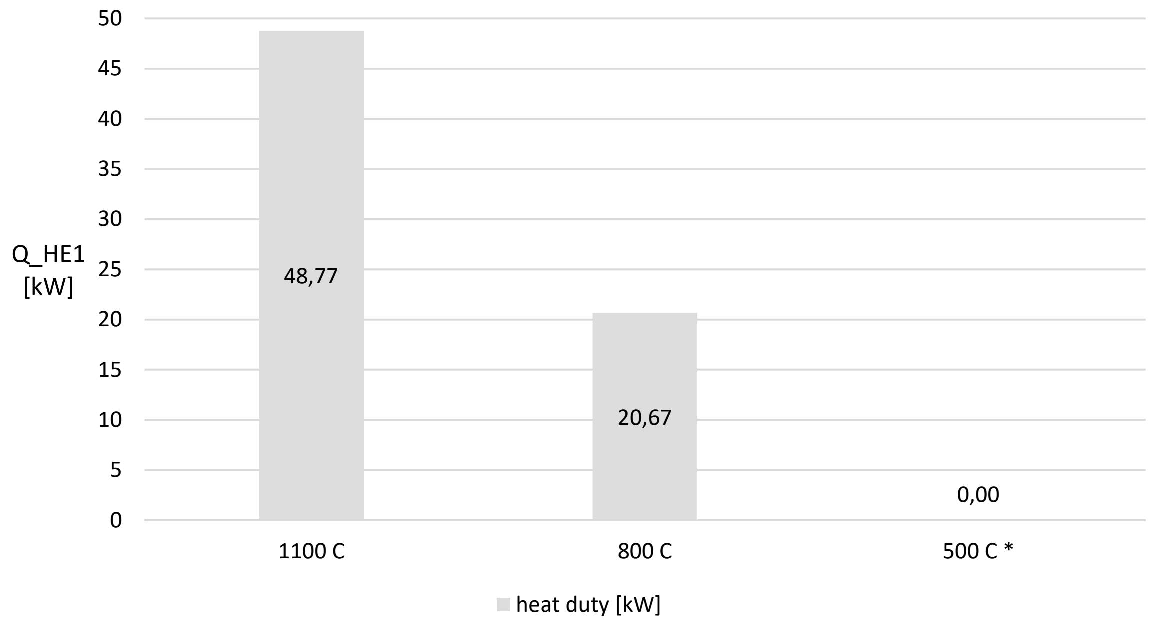

Figure 3: Heat duty of HE1 based on nCO_2PP fuelled by methane

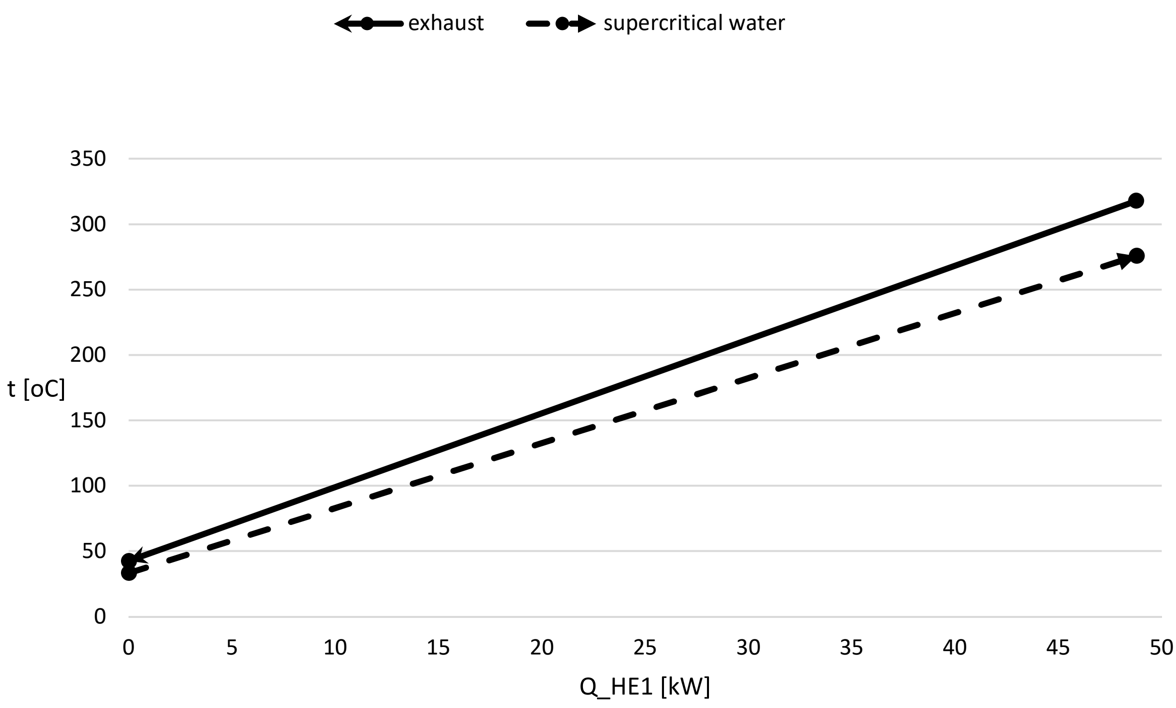

Figure 4: Temperature distribution in HE1 based on nCO_2PP fuelled by methane

3 Results and discussion of calculations for hybrid nCO_2PP and ORC

Due to high potential of heat recovery presented in previous chapter showing temperature distribution in heat exchangers Organic Rankine Cycle (ORC) is proposed with ethanol as primary working medium. In this modification, only GT^{bap} turbine and SEC are disabled. Results from original concept PFD are added to results table for comparison. Results for two different ORC mediums are added, refrigerants R236-ea and R245-fa. There are also two variants of temperature distributions for ethanol depicted, first where only ethanol is heated by exhaust shown in figure 5, and the second ethanol with water heated by temperature of 100K shown in figure 6. The temperature distribution result of the ethanol example from the table 1 are depicted on the figure 7 and 8, figure 7 is logarithmic scale for better view, and figure 8 is the linear scale representation, on these figures maximized water regenerative heating for maximum efficiency of the power plant can be seen.

The results were generated in Aspen Plus process simulation software. Results in the table were adjusted to obtain maximum possible efficiency achieved by modifying ORC parameters. Every calculation was optimised to maintain the exhaust temperature of 1100ºC, at the mass flow of 100 g/s and 10 bar pressure and the fuel for the combustion chamber was syngas "Mixture 2" obtained from sewage sludge gasification (see [3]). Minimum 5K of temperature difference were applied in pinch-points of temperature distribution.

PFD which includes combined ORC instead of low-pressure expansion, and without SEC is shown in figure 2.

Table 1 shows results comparing different configurations. First is the original concept nCO_2PP power plant with SEC and without ORC, the next one is hybrid nCO_2PP with ethanol as ORC working medium, the other one is hybrid nCO_2PP with R236-ea refrigerant as ORC working medium, than there is hybrid nCO_2PP with R245-fa refrigerant as ORC working medium. Additionally, each hybrid nCO_2PP result correspond to maximum net overall power plant efficiency obtained by adjusting best ORC parameters.

Table 1: Results of different configurations.

Parameter	Symbol	Unit	nCO_2PP concept (with SEC, without ORC)	Hybrid nCO_2PP with ethanol ORC medium	Hybrid nCO_2PP with R236-ea ORC medium	Hybrid nCO_2PP with R245-fa ORC medium
Water mass flow injection to WCC	$\dot{m}_{1-H2O}$	g/s	63.11	69.37	69.20	69.20
Water mass flow in exhaust	$\dot{m}_{2-H2O}$	g/s	76.91	80.80	80.70	80.70
CO_2 mass flow in exhaust	$\dot{m}_{2-CO2}$	g/s	23.09	19.20	19.30	19.30
Exhaust temperature	t_5	ºC	323.26	670.12	670.18	670.18
Turbine power GT	N_{GT}	kW	90.45	92.74	92.68	92.68
Turbine power GT^{ORC}	N_{GT-ORC}	kW	65.78 as GT^{bap}	18.75	24.46	24.73
Power for own needs	N_{cp}	kW	47.15	22.18	23.09	22.84
Chemical energy rate of combustion	$\dot{Q}_{CC}$	kW	280.45	232.86	234.15	234.15
Net efficiency	η_{net}	%	38.89	38.35	40.16	40.39
Gross efficiency	η_g	%	54.38	45.52	47.64	47.90

3.1 Temperature distribution for different cases with ethanol as ORC medium

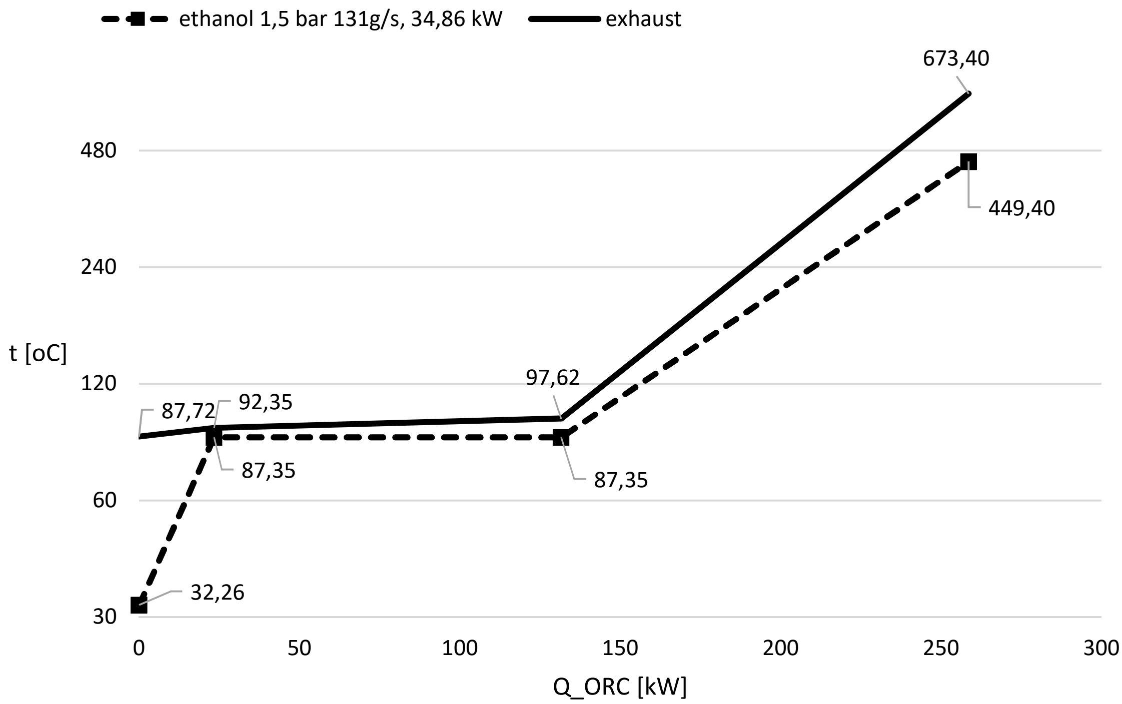

Figure 5: Logarithmic scale chart temperature distribution of heat exchangers with ORC, and no HE1

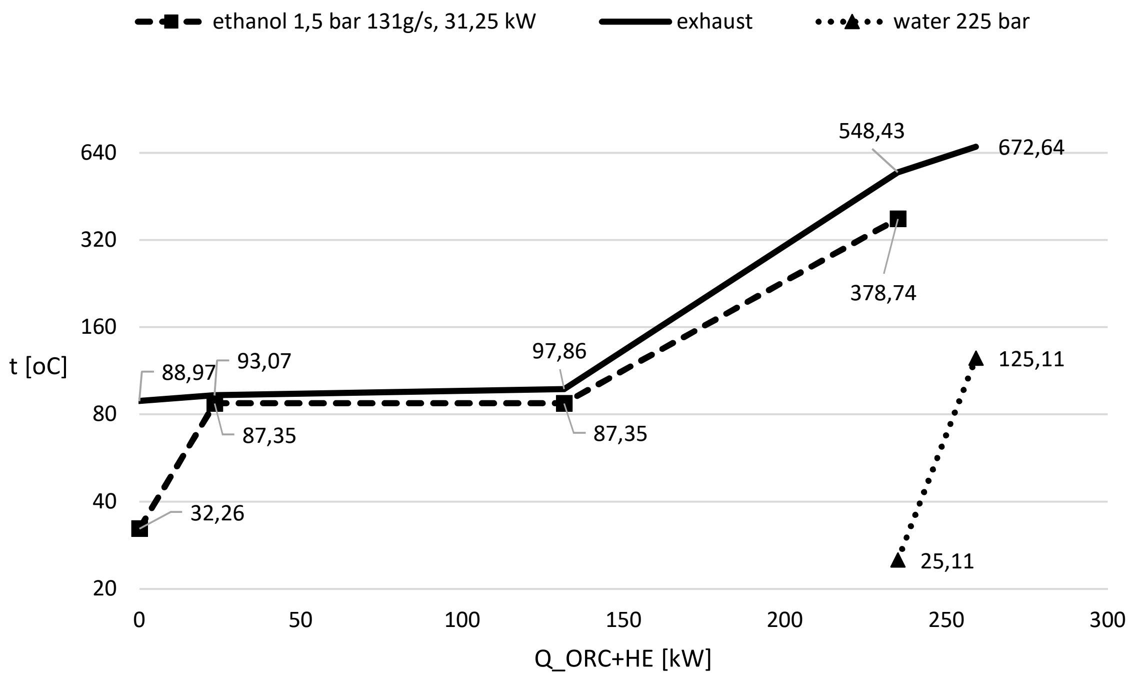

Figure 6: Logarithmic scale chart temperature distribution of heat exchangers with ORC and HE1 increasing water temperature by 100K

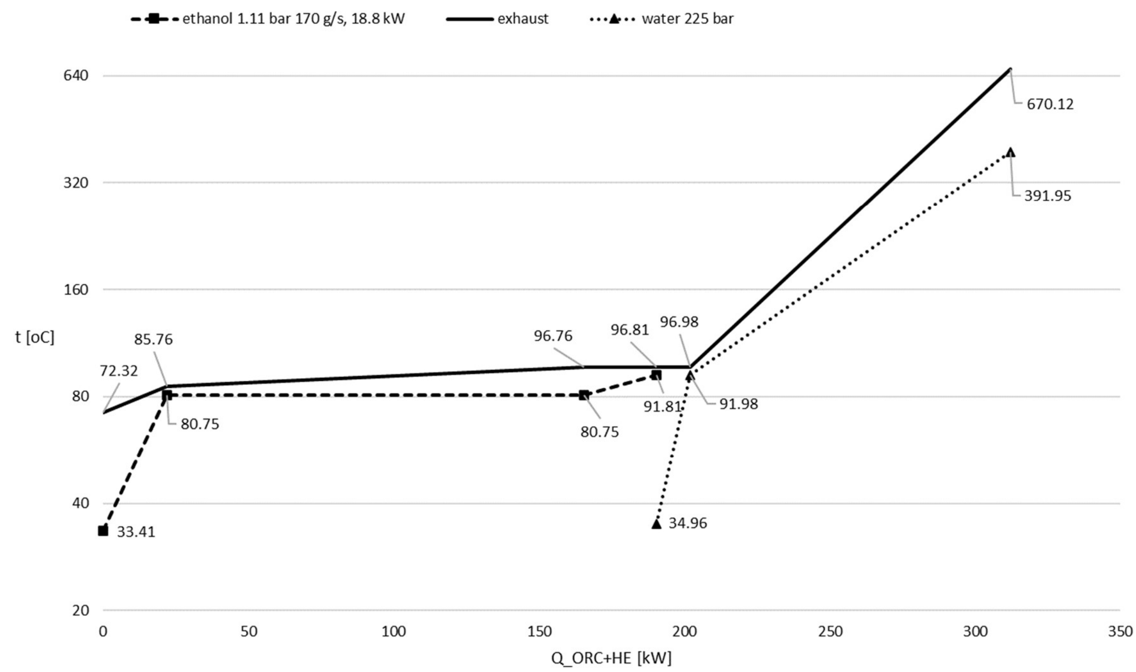

Figure 7: Logarithmic scale chart temperature distribution of heat exchangers with maximized HE1 and ORC

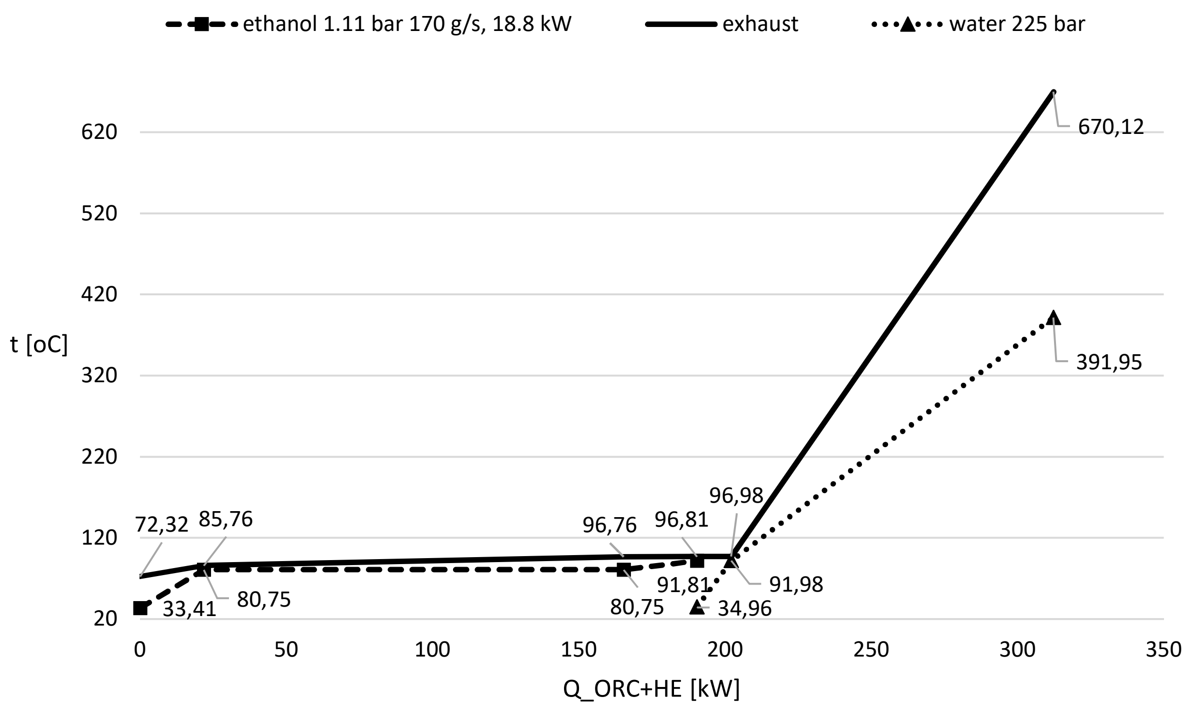

Figure 8: Linear scale chart temperature distribution of heat exchangers with maximized HE1 and ORC

3.2 Optimal results for ethanol, R236-ea and R245-fa

In order to obtain maximum overall efficiency of the entire power plant, maximum waste heat has to be effectively utilized. Two factors play crucial role in maximizing efficiency on the ORC side, namely pressure and mass flow. Pressure corresponds to temperature boiling point and thus proper value of this parameter allow to better fit to exhaust in temperature distribution. Mass flow allows to effectively maximize heat stream in the given level of ORC boiling temperature. Below figures 9, 10 and 11 present optimization technique to search for optimal point yielding maximum net overall power plant efficiency.

Ethanol as ORC working medium shown the highest overall net power plant efficiency of 38.35% for 1.11 bar, 170 g/s what gave 18.8 kW of ORC turbine brake power, this sensitivity analysis is shown on the figure 9.

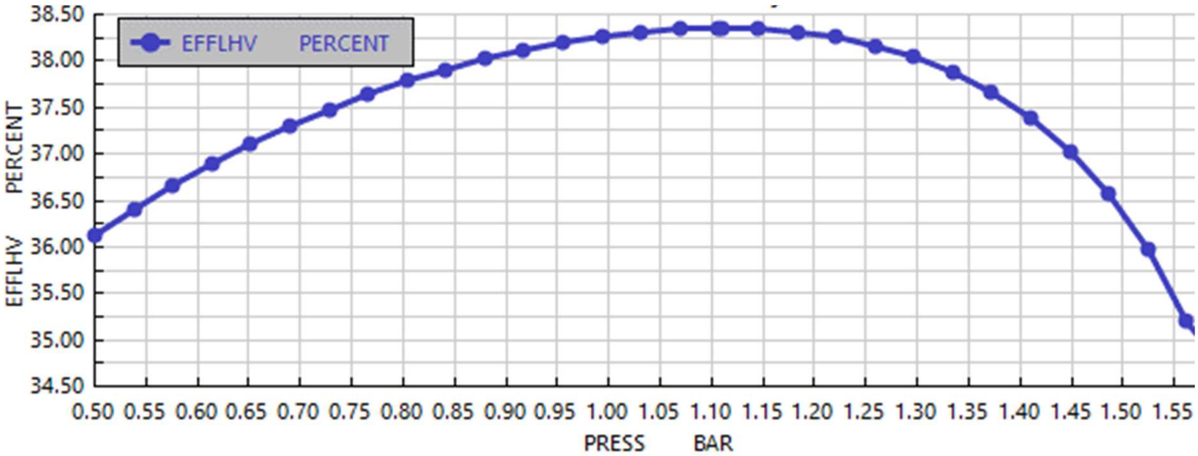

Figure 9: ORC ethanol working medium maximum nCO_2PP hybrid net efficiency sensitivity analysis

R236-ea refrigerant as ORC working medium shown the highest efficiency for 11.86 bar, 966 g/s and gave 24.5 kW ORC of turbine brake power and maximum overall hybrid net efficiency of 40.16% and sensitivity analysis is shown on the figure 10. This sensitivity analysis ends at 11.86 bar as higher pressure resulted in higher boiling point which breached the minimum temperature difference of 5K pinch-point in the heat exchanger and ORC medium would not evaporate fully under these conditions, thus figure 10 is cut on the pressure of 11.86 bar.

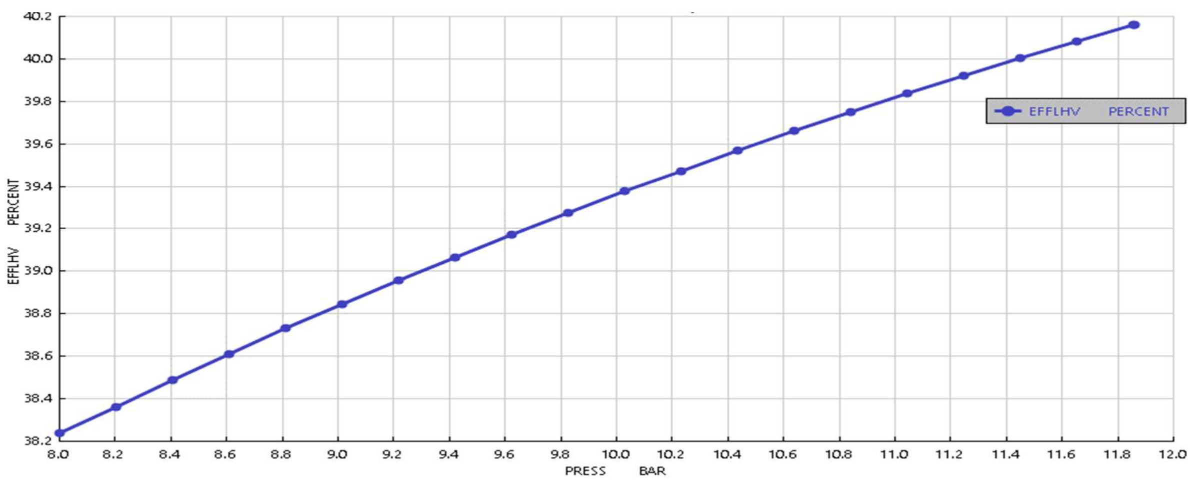

Figure 10: ORC R236-ea working medium maximum nCO_2PP hybrid net efficiency sensitivity analysis

R245-fa refrigerant as ORC working medium shown the highest efficiency for 9.12 bar, 804 g/s and gave 24.7 kW ORC of turbine brake power and maximum overall hybrid net efficiency of 40.39% and sensitivity analysis is shown on the figure 11. Similarly to R236-ea in figure 10, this sensitivity analysis ends at 9.12 bar as higher pressure resulted in higher boiling point which breached the minimum allowance 5K pinch-point temperature difference, thus figure 11 is cut on the pressure of 9.12 bar.

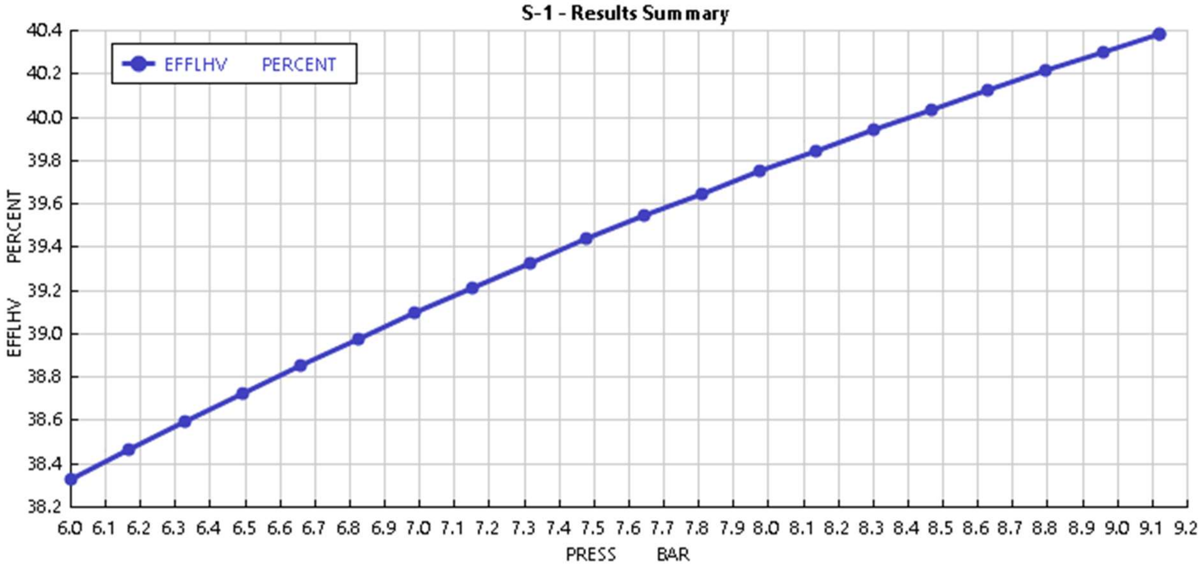

Figure 11: ORC R245-fa working medium maximum nCO₂PP hybrid net efficiency sensitivity analysis

4 Conclusions and perspectives

1) Exhaust mixture of CO_2 and H_2O decrease its temperature gradually during steam condensation.
2) Organic Rankine Cycle is more appropriate than combined steam cycle due to lower temperature of evaporation what translates to better fitting of the temperature distribution along the recovery heat exchanger for the given process conditions.
3) Organic Rankine Cycle can be further optimized, e.g. by selection best working fluid and according to changing exhaust conditions (changing syngas fuel conditions).
4) Low pressure expansion with maximized heat recovery by high-pressure water allows to achieve better efficiency and is priority regenerative heat destination.
5) A significant part of the net efficiency drawdown in the original concept low pressure expansion comes from SEC pump high power consumption to drive to SEC large amounts of motive fluid water what gives opportunity to ORC modifications without low pressure exhaust expansion.
6) ORC combined hybrid plant achieves similar or better net efficiency to original concept nCO_2PP low pressure expansion (when counted SEC pump power consumption). ORC with ethanol net efficiency 38.35%, while original concept 38.89%, while ORC with refrigerants yielded even higher net efficiency R236-ea 40.16% and R245-fa 40.39%.

Due to high potential of heat recovery presented in this report showing temperature distribution in heat exchangers and SEC, the Organic Rankine Cycle is also considered as an alternative to low pressure expansion turbine with ethanol, R236-ea or R245-fa as working fluids.

Hybrid system integrating the advantages of nCO_2PP and the ORC cycle is a promising solution and modifications are possible, but the main advantage is that the ORC cycle can be introduced as a component to provide electrical power in the lower temperature range.

Analysis of other refrigerants such as R1233zd(E) is the next step for this study.

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