Diesel Engine Waste Heat Harnessing ORC

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Abstract

Use of ORCs in waste heat recovery is widely seen as a viable and promising solution for increasing energy efficiency and emission reduction efforts, with "on-board" vehicular concepts becoming increasingly popular. In this study, the potential of an ORC harnessing exhaust energy from a diesel generator is considered. Preliminary fluid selection was based on satisfactory thermodynamic performance, and expander size requirement as the limiting parameter. Both simple and recuperative ORC systems were modelled. The effect of the exhaust temperature and the high operational pressure of the ORC model were evaluated in terms of energetic and exergetic performance. For the toluene ORC, moderate pressure values were dictated by the expander size limitation, yet this can be alleviated by high exhaust temperatures. Simple ORCs required a larger heat input and had lower exergetic efficiency. Recuperative ORCs showed better thermal efficiency and lower overall exergy destruction. The expander efficiency was identified as a vital parameter for cycle design and thermodynamic performance.

Keywords — *Organic Rankine cycle; exergetic efficiency; volume ratio*

I. INTRODUCTION

With ever increasing global energy consumption and climate change concerns, reducing greenhouse gases emissions and improving energy efficiency of power systems are immediate priorities. Organic Rankine Cycle (ORC) has been long recognised as a promising technology to support the shift from conventional fossil fuels towards renewable energy sources. A number of published studies evaluated ORC potential in conjunction with biomass, solar and geothermal energy sources [1]. Additionally, ORC is a powerful tool for harnessing waste heat [2, 3].

Basic ORC is founded on well-known transformations found in the conventional steam Rankine systems. However, the use of a volatile organic liquid as the working fluid allows for low-grade heat sources to be used. ORC is considered to be flexible in terms of the type and temperature of the heat source, and requires low maintenance. The versatility of the heat source and its modular design make ORC an attractive option, especially when waste heat is used for power generation [4-9].

Conversion of waste heat into electricity through so-called bottoming ORC improves the overall efficiency of the system whilst reducing heat pollution. The efficiency of the waste heat recovery through an ORC depends on a number of parameters: the state and quantity of the stream matter, its availability and especially its temperature. In fact, waste heat sources are categorized according to their temperature range as: low heat (< 230°C); medium heat (230°C - 650°C); and high heat (> 650°C) [1]. In particular, harnessing of diesel engine exhaust heat has been the focus of recent research. Larsen et al. [10] studied a plethora of potential ORC fluids for waste heat recovery in marine applications. Yu et al. [11] concluded that the thermal efficiency of a diesel engine can be improved up to 6.1% through bottoming ORC implementation. Wang et al. [12] proposed a dual-loop ORC system. Katsanos et al. [13] evaluated the possibility of ORC installation on a diesel truck engine. Feasibility of several on-board vehicular ORC recovery systems has also been performed [14].

Selection of the working fluid in an ORC is a much debated issue [1]. Fluid properties dictate thermodynamic performance, but also have overreaching influence on cycle design. Fluid stability and flammability have to be taken into account in order to ensure the safe operation of the device. Fluid toxicity and environmental impact must also be considered. Thus far, the scientific community agrees an ideal ORC working fluid cannot be selected, and that 'optimal' fluid choice depends on the particular application, nature and temperature of the heat source, cycle operational parameters, etc.

In this paper, an ORC implementation harnessing waste heat from a diesel generator is considered. The analysis was based on a 40 kW direct injection diesel engine. According to the manufacturer's specification, the maximum exhaust temperature is 500°C. In this paper a small-size compact ORC, powered by the above described exhaust waste heat, for additional power generation is considered, simple and recuperative system operation, as shown on Figure 1. Comprehensive fluid selection and evaluation of the cycle energetic and exergetic performance was carried out, with size limitation being the primary factor.

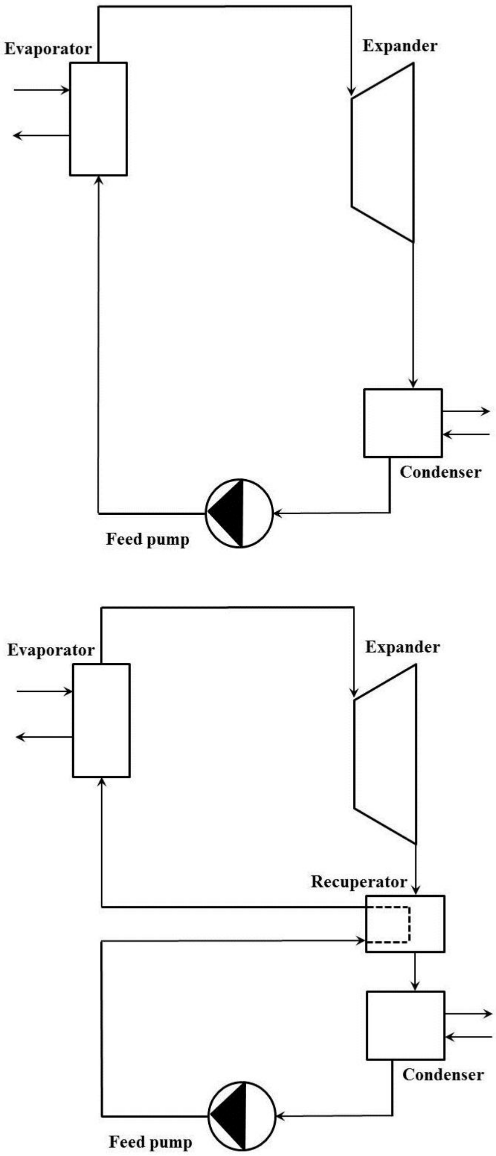

Fig 1: Schematics of simple and recuperative ORC

II. METHODOLOGY

A. ORC Model

Two ORC designs were considered: a simple cycle and a recuperative cycle, as shown in Figure 1. The basic processes of the ORC, and the assumptions made in our model, are as follows: pump pressure increase; isobaric heating in the evaporator by the exhaust stream; expansion; isobaric cooling of the working fluid until saturation and condensation. If the working fluid is in the superheated state at the expander outlet, it is possible to use a recuperator [15]. The recuperator element allows for internal heat transfer between 'hot' low pressure stream from the expander outlet and 'cold' high pressure stream leaving the pump; thus, working fluid is being preheated before entering the evaporator. The pressure drop through the recuperator heat exchanger was assumed to be negligible and the low pressure stream at the outlet of the heat exchanger was assumed to be in a saturated vapour state. Further assumptions which were made included a steady-state steady-flow system, negligible kinetic and potential energy losses as well as negligible heat losses in all components and pipes.

The condenser outlet was assumed to be a saturated liquid at 298K; this assumption was used to set the operational pressure of the condenser. High cycle pressure and temperature were varied in a selected range in order to evaluate ORC performance and size requirements at different operational parameters. In the initial assessment, isentropic efficiency of the pump and the expander were fixed at 80% and 75%, respectively, although these parameters are analysed in more detail. All fluid properties were evaluated using REFPROP 9.1. Work and heat exchanges were calculated from the enthalpy gradient at specified points of the cycle. A detailed set of equations can be found in [16]. Energy and exergy balance was carried out for individual cycle components as well as the whole system

$$w_P + q_{in} = w_E + q_{out}$$

$$ex_{in} + q\left(1 - \frac{T_0}{T}\right) = ex_{out} + w + i$$

in order to evaluate thermal and exergy efficiency

$$\eta_{th} = \frac{w_{net}}{q_{in}}$$

$$\eta_{ex} = 1 - \frac{i_{total}}{ex_{in}}$$

and exergy destruction in individual cycle components [17]

$$i_{total} = i_P + i_B + i_E + i_C \left(+ i_R\right).$$

B. Fluid Selection

The maximum exhaust temperature of the diesel generator is stated by the manufacturers to be 773K, indicated the need for a working fluid appropriate for high temperature application. Suitable candidates have been much debated in the literature. A number of fluids shortlisted in [1] for high-temperature ORC systems were considered. Assuming a high cycle temperature of 616K and a moderate operational pressure of 1MPa, preliminary assessment of fluid behavior in a simple ORC was performed. Results are summarised in Table 1. The toluene cycle yielded the highest thermal and exergy efficiency. The MDM fluid family had the lowest exergetic and thermal efficiency, and the worst work output. The largest net work was calculated for the undecane cycle. However, undecane, and similarly-performing propyl cyclohexane, had unacceptably high volume ratios. Heptane and octane, hydrocarbons with a lower molecular weight, were also evaluated, but were subsequently excluded due to the high exhaust temperatures considered here. Aromatics generally require lower heat input than cycloalkanes. Low volume ratios were found for benzene and cyclohexane expanders. Nonetheless, overall exergy destruction was found to be lower in the toluene ORC.

TABLE I
Preliminary assessment of suitable working fluids

	Benzene	Toluene	MDM
w_net (kJ/kg)	186.3	199.7	110.3
q_in (kJ/kg)	936.5	934.5	761.1
η_th (%)	19.9	21.4	14.5
VR (-)	69.8	238.8	2270.2
i_total (kJ/kg)	496.4	481.7	444.6
η_ex (%)	27.3	29.3	19.9

	Cyclo hexane	Propyl cyclo hexane	Undecane
w_net (kJ/kg)	177.7	200.4	207.7
q_in (kJ/kg)	1029.3	1027.7	1059.2
η_th (%)	17.3	19.5	19.6
VR (-)	72.4	1840.9	20552.7
i_total (kJ/kg)	572.8	548.9	564.6
η_ex (%)	23.7	26.8	26.9

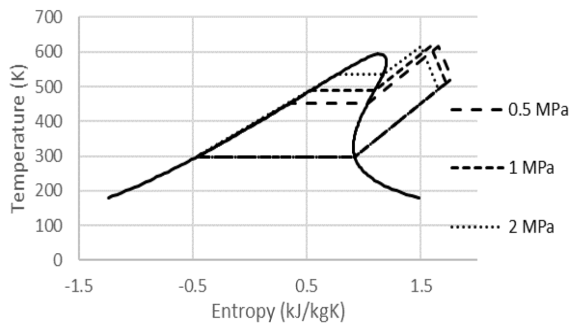

Fig 2: High pressure variation in simple toluene ORC with expander inlet temperature of 616K

Taking everything into consideration, toluene was selected as a fitting and manageable working fluid. Given the critical temperature and pressure of toluene, 591.75K and 4.1263 MPa respectively, only subcritical cycles were considered. Being a dry fluid, as shown on the T-s diagram in Figure 2, there is no risk of toluene condensation occurring at the expander outlet, which allows for the use of the recuperating element in the cycle. Notwithstanding the superior thermodynamic performance of toluene, there are other aspects that have to be considered. According to ASHRAE Standard 34 – Refrigerant safety group classification, toluene is in the A3 group (A – lower toxicity; 3 – higher flammability). Despite this feature, highly flammable fluids are commonly considered in ORC studies [18]. Use of toluene in an 'on-board' ORC device would therefore pose a safety risk. Nonetheless, toluene-based ORC systems are already in use.

C. Cycle Operational Parameters

The performance of a bottoming ORC is directly affected by the state of the exhaust from the diesel generator. Based on the maximum exhaust temperature specified above, the expander inlet temperature was varied between 530K and 670K. Our ORC is to operate on a subcritical cycle; therefore a high pressure limit of 3 MPa was applied. The range of high cycle temperatures and pressures is generous, mostly to allow for comprehensive thermodynamic analysis. Medium temperatures of around 616K, as assumed above, are of practical significance. A reasonably high cycle pressure of 2 MPa is commonly mentioned in literature [10] as a manageable high pressure limit. High pressures are often favoured, especially for dry fluids like toluene, as they improve the cycle performance. However, apart from boosting the efficiency, high pressure levels also increase the expander volume ratio, which requires a large-sized turbine. In our case, space limitation and practicable volume ratios were prerogatives. The high pressure of our ORC is dictated by the expansion ratio it necessitates, rather than being a compromise between the desired cycle performance and the element size. Thus, pressures well below 2 MPa are desirable.

III. RESULTS AND DISCUSSION

A. Energetic Analysis

The performance of the simple and recuperative ORC was evaluated. The effect of high cycle temperature and pressure on thermal efficiency is presented in Figure 3. As expected, the toluene cycles benefit from high evaporator pressures. The simple cycle is energetically somewhat insensitive to high cycle temperatures; in fact, efficiency decreases with high degree of superheat at the expander inlet. The exception being the combination of high pressure and low temperature, when the fluid is roughly at the saturated vapour state and the efficiency is low. In the whole range of expander inlet temperatures considered with the pressure of 1 MPa, a simple cycle efficiency above 20% is reached. Selecting a high pressure of 2 MPa leads to a 2.0% increase on average, while selecting 0.5 MPa as the operational pressure decreased the efficiency by approximately

2.2%. Naturally, recuperative ORC showed an improved energetic performance. Conversely to the simple cycle, the recuperative cycle efficiency increases with the degree of superheat at the expander inlet, making the high operational pressure a secondary parameter. Minor enhancement of the thermal performance was observed at pressures above 1 MPa (1.5%), and above 2 MPa any enhancement is practically undistinguishable. Decreasing the operational pressure of the recuperative ORC to 0.5 MPa reduces the thermal efficiency by 2.1%, like for the simple ORC.

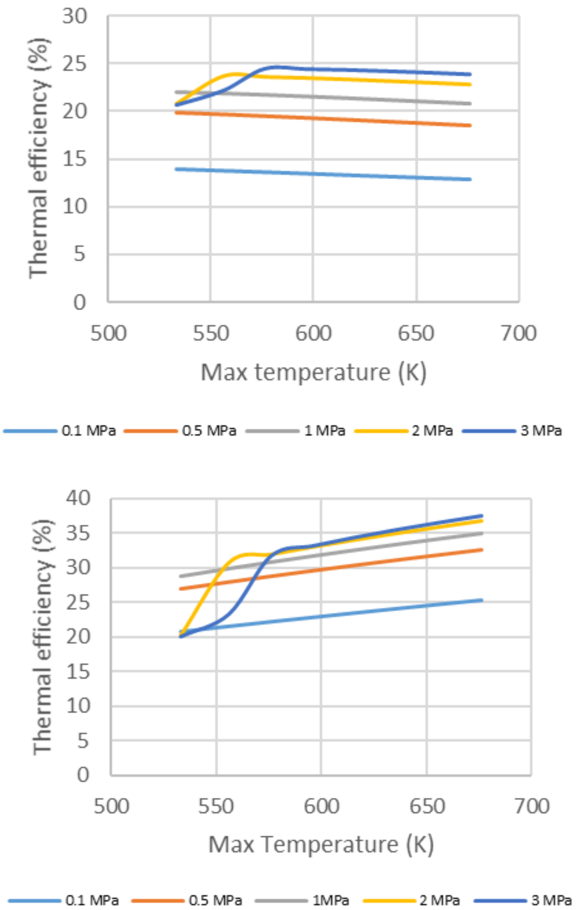

Fig 3: Thermal efficiency of simple ORC (top) and recuperative ORC (bottom)

While the recuperator increases energy efficiency, it does not alter the work output. As shown in Figure 4, net work of the cycle increases with both temperature and pressure. Similarly to the thermal efficiency, the effect of pressure is lessened above 1 MPa. While the increase in high cycle pressure improves thermal performance and work output, it also requires a larger expander. Progression of the volume ratio with high cycle pressure is presented in Figure 4, assuming a high temperature of 616K. The volume ratio grows almost linearly with pressure for the set high temperature. Hence, a compromise between acceptable values of the volume ratio and the high cycle pressure which dictates the overall system performance is necessary. Based on the calculated VR values, and having in mind the size limitation, our optimal high pressure is likely to be in 0.5-1 MPa range. Nevertheless, increase in expander inlet temperature can greatly influence the net work output and therefore act as a high pressure 'substitute'. In a simple ORC this leads to a slightly reduced thermal performance, but not in a recuperative one. Due to the internal heat transfer between expander and pump outlet streams, overall heat input in the system is significantly reduced, as shown in Figure 5. Higher operational pressures generally require larger heat inputs, yet the effect of pressure is minor. Increase of expander inlet temperature entails a greater heat supply. Again, this is largely reduced in a recuperative ORC case.

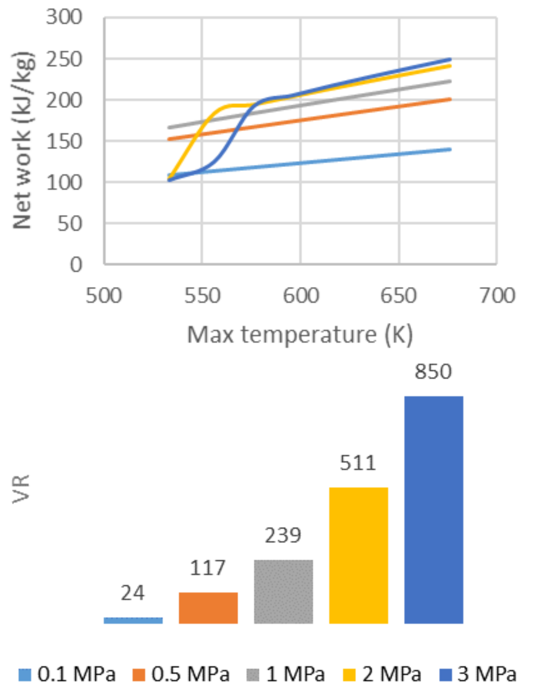

Fig 4: Effect of the high cycle pressure on net work and expander volume ratio

B. Exergetic Analysis

Second law efficiency and specific exergy destruction in individual cycle components was evaluated for both simple and recuperative toluene cycles. Internal heat transfer improves the thermal performance of the ORC, but does not necessarily lead to higher exergy efficiency. Hence, use of the recuperator appears to be a much debated issue in scientific community [19]. Comparison of exergetic performances as a function of high cycle temperature and pressure is given in Figure 6. The recuperative ORC achieved higher exergetic efficiencies than the simple one. Notwithstanding the peculiarity of low temperature - high pressure combination, an increase in evaporator pressure in the recuperative cycle raises the exergy efficiency. For the simple ORC, even at high operational pressures, exergetic efficiency did not reach 35%, whereas higher exergetic efficiencies were achieved at 0.5 MPa pressure in the recuperative case. Exergetic performance also improves with an increase in the expander inlet temperature for a recuperative ORC. The opposite trend is observed for the simple ORC system, in which case exergy efficiency slightly decreases with increasing high temperature.

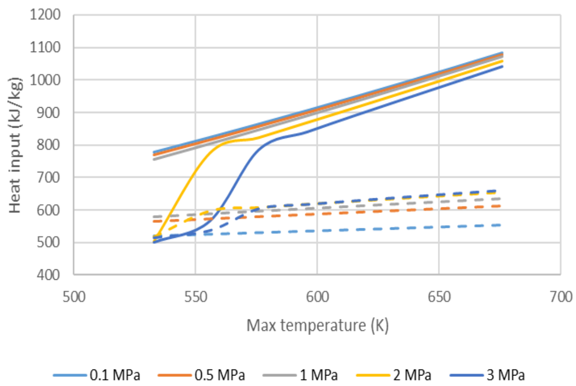

Fig 5: Required heat input in simple ORC (solid line); recuperative ORC (dashed line)

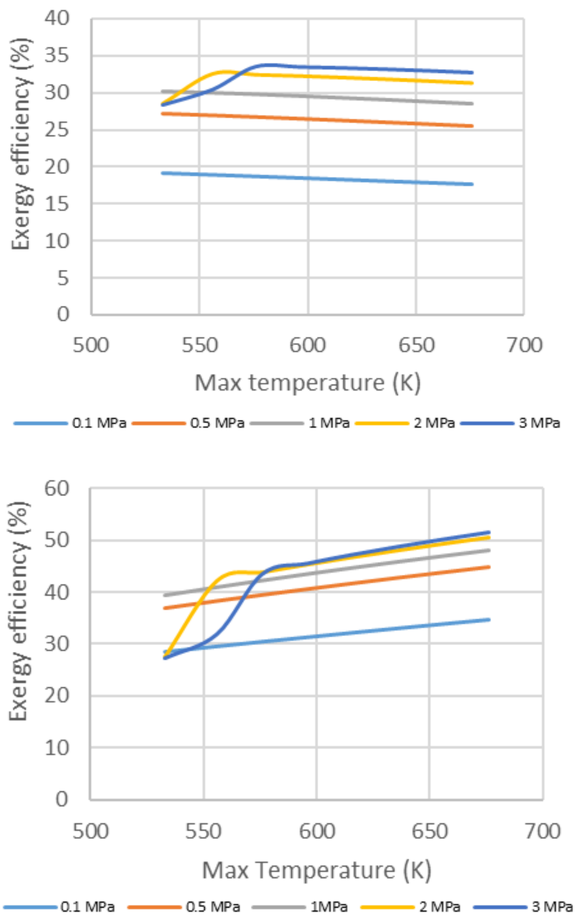

Fig 6: Exergetic efficiency of simple ORC (top) and recuperative ORC (bottom)

The extent and distribution of the exergy destruction in individual cycle elements is of interest. While exergy efficiency is lower for the recuperative cycle, the overall exergy destruction is greatly reduced, as shown in Figure 7. Irreversibilities decrease with increasing pressure, marginally so for the recuperative ORC. Naturally, the greatest exergy destruction rate is observed for the evaporator, which decreases with increasing pressure, for both the simple and the recuperative ORC. Approximately 10% of total irreversibilities in the simple ORC occurred in the condenser. Given that the condenser inlet state in the recuperative cycle was fixed at the saturated vapour point, the exergy destruction during the heat removal process was the same in all inspected cases, comparable to minor irreversibilities commonly evaluated for the pump. In a recuperative ORC, the heat exchanger is a more significant source of irreversibilities. The turbine destruction rate remains the same regardless of the use of the recuperating element, and it increases with the pressure. However, in the recuperative ORC exergy destruction during the heat addition process is lower, as less of heat is needed to power the cycle. Hence, the expander exergy destruction becomes more significant.

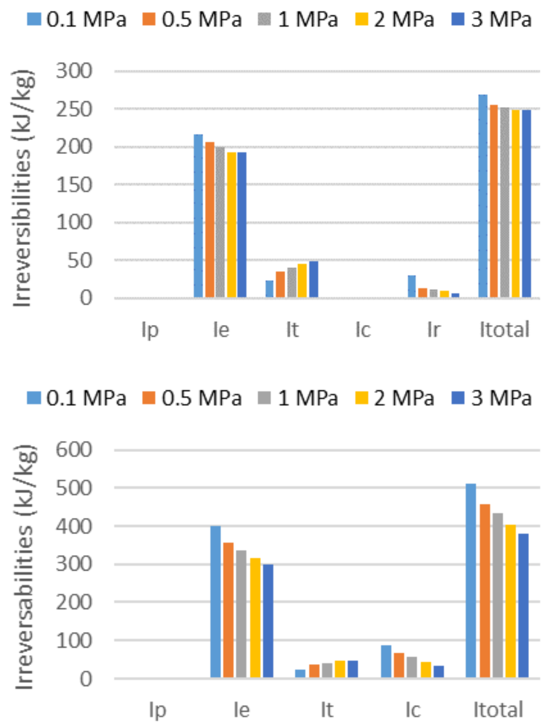

Fig 7: Exergy destruction in simple ORC (top) and recuperative ORC (bottom)

C. Effect of Expander Efficiency

The expander, as a core component of the ORC system, has received significant scientific attention [20], and references within. In order to better assess the effect of the expander behavior, energetic and exergetic cycle performance was evaluated by modifying the expander isentropic efficiency to 65%, 70% and 80%. For brevity, only the results for 616K and 1MPa, as a representative temperature and pressure, are presented in Figures 8 and 9. Naturally, power output increases with improved expander efficiencies, namely ~7% higher net work is achieved per 5% expander efficiency increase, as shown in Figure 8. An equivalent rise in the cycle efficiency is found for the simple ORC. The volume ratio decreases by 1.4% on average, across all examined pressures. In the recuperative cycle, a higher expander efficiency results in less heat being available for preheating the fluid in the heat exchanger. Hence, the heat input increases by 2%, which reduces the overall improvement in the recuperative cycle efficiency to ~5%. Exergetic efficiency in a simple ORC increases due to a reduction in expander irreversibilities. In the case of the recuperative cycle, the total exergy input is higher, yet exergy destruction in the heat exchanger is lower for higher expander efficiency, and the overall exergetic efficiency improves. Still, exergetic efficiency increase is reduced compared to the simple ORC.

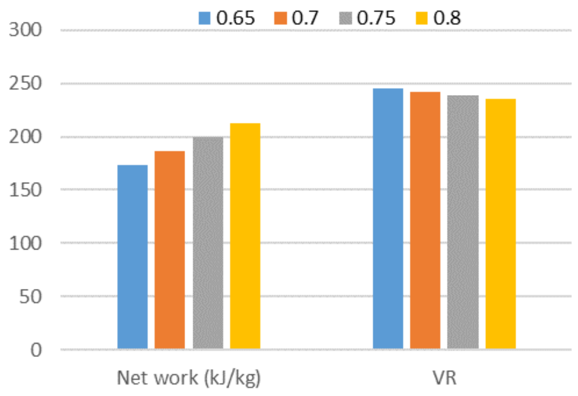

Fig 8: Net work and volume ratio of simple and recuperative ORC for variable expander efficiency at operating parameters of 1MPa and 616K

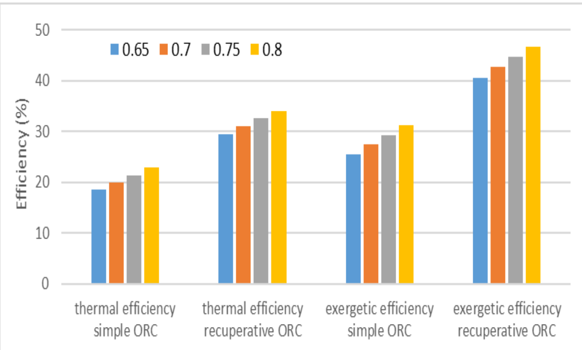

Fig 9: Thermal and exergetic efficiency of simple and recuperative ORC for variable expander efficiency at operating parameters of 1MPa and 616K

IV. CONCLUSIONS

The high temperature toluene ORC is a promising solution for diesel exhaust waste heat recovery. As a dry fluid, toluene achieves better thermodynamic performance at high pressures. However, for 'on-board' applications, size of the device is critical, and high pressures may result in an unacceptably large expander volume ratio. Hence, a compromise has been made between maximization of desired power and required expander size, indicating intermediate pressures, around 1MPa, may be the best solution. Additionally, the high temperature of the available exhaust stream may compensate for lower selected pressures.

Both simple and recuperative ORC systems were considered. The recuperative ORC reached a higher thermal efficiency, which was further augmented by the temperature increase, and required a lower heat input. Total exergy destruction was significantly reduced for the recuperative ORC, which resulted in better exergetic efficiency. Considerable effect of expander efficiency was evaluated: better thermal and exergetic performance, higher power output and a reduction in the volume ratio.

NOMENCLATURE

ex	specific exergy	(kJ/kg)
i	irreversability	(kJ/kg)
q	specific heat	(kJ/kg)
T	temperature	(K)
VR	volume ratio	(–)
w	specific work	(kJ/kg)
η	efficiency	(–)
0	dead state	
B	boiler	
C	condenser	
E	expander	
ex	exergetic	
in	input	
out	output	
P	pump	
R	recuperator	
th	thermal	

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