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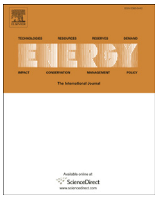

An innovative organic Rankine cycle approach for high temperature applications

Angad Singh Panesar

School of Computing, Engineering and Mathematics, University of Brighton, United Kingdom

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Organic Rankine Cycles (ORC) using toluene and hexamethyldisiloxane (MM) are put forward as a means of improving the efficiency of automotive heavy duty engines, and provide a reference for comparison in this study. Despite an efficiency improvement potential of 4–4.7%, the current ORC approach is not reaching the required fuel savings within the expected costs. As such, innovative pathways to improve the ORC performance and cost-effectiveness are of great importance to the research community. This paper presents a partial solution by means of a conceptual overview and simulation results for ORCs especially tailored for high-temperature applications. A fundamental revision of the heat transfer and expansion characteristics is presented, without increasing the system integration complexity. These characteristics are attributed to the use of formulated organic blends with toluene and MM as a significant blend component. The developed 22 criteria blend screening methodology is presented. Simulation results show that for an equivalent expansion volume flow ratio, and product of heat transfer coefficient and area, the blends offer a 22–24% improvement in the net power. This resulted in a 15–18% cost savings compared to the reference ORC. The simulations were conducted in Aspen HYSYS V8 using the Peng-Robinson and Wilson fluid property packages.

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1. Introduction

The modern automotive Internal Combustion Engine (ICE) rejects up to 50% of the total fuel chemical energy in the form of waste heat, with a significant portion of this as high quality exhaust gases. Due to increasing greenhouse emissions and impending worldwide fuel consumption regulations, there is a growing interest in technologies that can even partially utilise the exhaust heat to improve the overall Brake Thermal Efficiency (BTE). This has been an intensified area of research in the last decade, where numerous methods including turbocompounding, thermoelectric generators and fluid bottoming cycles have been proposed and demonstrated for on-road vehicles [1,2]. The potential fuel consumption reduction using any heat-to-power conversion technology is firstly dependent at least on the ICE application and the duty cycle. Highest benefits are expected in long-haul trucking which involves extended time of running at near steady speeds. As a result, it has been shown that such technologies can play a significant part in achieving future BTE goals for Heavy Duty Diesel Engines (HDDE) [3,4]. With a focus on automotive exhaust applications, the following overview is divided into five themes: the preferred fluid bottoming cycle, optimisation of ORCs, selection of working fluids, component developments, and integration with other energy technologies and heat sources.

Amongst the fluid bottoming cycle options, Rankine, Kalina and Organic Rankine Cycles (ORC) are typically proposed. The conventional Rankine cycle presents an environmentally friendly and thermally stable solution. However, it offers challenges relating to freezing temperatures, reduced performance under cooler exhaust temperatures, requirement of higher superheating levels, relatively poor transient response and poor turbine efficiency for low capacity applications [5,6]. The Kalina cycle, which has been initially applied to geothermal applications, offers the advantage of a good temperature match in the heat exchanger using an ammonia-water mixture. Additionally, variation in the composition of the mixture allows adapting the cycle to possible fluctuating heat source and/or sink temperatures. However, it presents challenges relating to packaging of the separator and the Internal Heat Exchanger (IHE), complexity in exploiting different heat streams simultaneously, higher system pressures, and corrosion and stress cracking with some common engineering materials [7,8]. The frequently cited

E-mail address: A.Panesar@brighton.ac.uk.

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Nomenclature

A	heat transfer area (m^2)
c_p	specific heat (kJ/kg°C)
D	diameter (m)
h	specific enthalpy (kJ/kg)
H_{vap}	latent heat of vaporisation (kJ/kg)
$\dot{I}$	irreversibility (kW)
L	volume (L)
$\dot{m}$	mass flow rate (kg/s)
M_{wt}	molecular weight (g/mol)
P	absolute pressure (bar)
$\dot{Q}$	thermal duty (kW)
S	turbine size parameter (m)
s	specific entropy (kJ/kg°C)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 °C)
$\dot{V}$	volume flow rate (m^3/s)
$\dot{W}$	power (kW)

Greek symbols

η	efficiency
ρ	density (kg/m^3)
λ	thermal conductivity (W/m°C)
μ	viscosity (cP)

Abbreviations

B100	mid-speed high-load
BTE	brake thermal efficiency
GWP	global warming potential
HDDE	heavy duty diesel engine
HEX	heat exchanger
ICE	internal combustion engine
IHE	internal heat exchanger
MM	hexamethyldisiloxane
MM80	organic blend containing 80% hexamethyldisiloxane by mass
ORC	organic Rankine cycle
PRV	pressure reducing valve
T80	organic blend containing 80% toluene by mass
VFR	volume flow ratio
VLE	vapour-liquid equilibrium

Subscripts

amb	ambient
cond	condenser
exh	exhaust
exp	expander
pp	pinch point

above reasons hinder the adoption of Rankine and Kalina cycles for automotive applications. As a result, the literature review indicated that the use of relatively simple ORC systems appears to be the leading heat-to-power conversion technology for long-haul truck applications when considering, quality of heat sources (<450 °C), output capacities (5–25 kW), conversion efficiencies (10–15%), transient driving conditions, technology readiness level, absolute fuel consumption, space availability and weight penalty [9,10].

The overall conversion efficiency of an ORC largely depends on the selected working fluid (e.g. refrigerant, hydrocarbon), its associated cycle operating mode (e.g. subcritical, supercritical), the chosen expansion machine (e.g. piston expander, radial turbine) and the system architecture (e.g. thermal, sub-system) [9,11]. This presents a complex multi-dimensional challenge to find universal solutions, which are vital to reach the economies-of-scale. Attempts using, regression models for evaluating design implications, parametric and thermo-economic optimisation using genetic algorithms and energy integration methodologies coupled with multi-objective optimisation, have all been considered in the literature [12–15]. Adding to the above challenge, organic fluids present the drawbacks of thermal stabilities much below the exhaust gas temperatures, and/or environmental and safety concerns.

For low-temperature exhaust heat, Domingues et al. suggested the use of R245fa due to the higher heat exchanger effectiveness over water [5]. Whereas, for medium-temperature exhaust heat, Larsen et al. showed ethanol as a suitable option [11]. With an increased emphasis on Global Warming Potential (GWP), Yang et al. recently indicated an ultra-low GWP refrigerant (R1234yf) optimal from a thermo-economic point of view [16]. To offer improved thermal stability options, Fernandez et al. recommended hexamethyldisiloxane (MM), while Seher et al. showed a higher performance potential using toluene [17,18]. Additionally, the modelling study to provide optimisation guidelines by Maraver et al. also suggested the use of toluene [19].

Key ORC components such as heat exchangers and expanders are additionally becoming more viable due to a series of recent technological advancements and similarity to the current automotive components. Yang et al. and Zhang et al. have recently demonstrated prototypes of fin-tube and spiral-tube evaporators, respectively [12,20]. Zhang et al. have additionally achieved adiabatic efficiencies in excess of 70% with a single-screw expander [20]. While, Wang et al. demonstrated a nominal 5 kW heat activated cooling unit under laboratory conditions and achieved isentropic efficiencies in excess of 80% with a scroll expander [21].

ORCs have also been proposed in combination with other technologies including refrigeration cycles and thermoelectric generators. Simulation results by Yılmaz et al. showed that the air-conditioning needs of an intercity bus can be realised using the exhaust gas energy in combination with R134a and R245fa as the working fluids [22]. While, Shu et al. considered the use of thermoelectric generators for higher temperature heat recovery, followed by ORCs for lower temperature heat recovery in a theoretical study [23]. This architecture was suggested primarily to address the thermal stability issue of organic fluids. To exploit exhaust gas and engine coolant heat simultaneously, dual-loop cascade arrangements and thermal-oil loop transferring the coolant and exhaust heat were also theoretically considered [24,25]. These configurations allowed higher heat exploitation, however, the challenges relating to system size, weight, cost, control and complexity could be prohibitive for automotive applications.

It is important to highlight that the above reviewed simulation and experimental studies were found to produce a broad range of overall BTE increase (1–6% in absolute terms) for the considered base engines. This was because different studies have utilised different engine platforms, engine speed-load points, heat sources, qualities, quantities, working fluids, ORC system architecture, boundary conditions and component efficiencies, giving different overall conversion efficiencies. Furthermore, the rebound effect was acknowledged in very few of the reviewed studies, i.e. fuel

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