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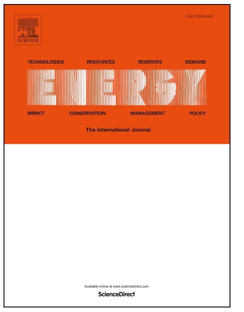

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Thermodynamic potential of twelve working fluids in Rankine and flash cycles for waste heat recovery in heavy duty Diesel engines

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Abstract

A promising method to improve the efficiency of internal combustion engines is the use of thermodynamic cycles for waste heat recovery (WHR). In this study twelve working fluids are evaluated with regards to their thermodynamic potential for four cycles: the Rankine cycle (RC), the transcritical Rankine cycle (TRC), the trilateral flash cycle (TFC) and the single flash cycle (SFC). An energy and exergy analysis of a heavy duty Diesel engine revealed four sources with potential for WHR: the charge air cooler (CAC), the engine coolant, the exhaust gas recirculation cooler (EGRC) and the exhaust gas. Simulations performed for one engine operating mode, showed that the TFC performed best for the CAC with a power output of 2 kW. Owing to the thermal match between source and cycle, the RC outperformed all other cycles for the coolant with a power output of 5 kW. For the EGRC, the TRC with methanol gave the best output of 8 kW. As for the exhaust, all cycles had an output of around 6 kW with much variation between the fluids. A sensitivity analysis of the condensation temperature, source outlet temperature, degree of superheating, operating mode and expander efficiency showed significant impact on the output.

Keywords: energy analysis; internal combustion engine; organic flash cycle; organic Rankine cycle; single flash cycle; transcritical Rankine cycle; trilateral flash cycle; waste heat recovery

1. Introduction

Because of stricter fuel emission requirements and consumer demands for decreased fuel consumption, research and development efforts for improving the efficiency of internal combustion engines have become increasingly important over the years. Since a significant part of the fuel energy is lost as heat inside the engine, engine efficiency can be increased by recapturing the lost heat and converting it to power. A promising way to do this is by using thermodynamic power cycles for waste heat recovery (WHR). Already well-established for WHR in stationary applications is the Rankine cycle (RC) [1–3], a technology that also shows potential for the use in automotive applications [4, 5]. An alternative to this technology is the transcritical Rankine cycle (TRC), where the working fluid is brought to supercritical conditions on the high pressure side. By improving the thermal match between the heat source and thermodynamic cycle, the thermal efficiency can be increased, albeit at the expense of higher pressures [5–7]. Another alternative is the trilateral flash cycle (TFC), where the pressurized fluid is heated to its saturation point and then expanded into the two-phase region. As the working fluid remains in the liquid state during heating, it is possible to improve the thermal match while improving heat transfer and reducing pressure drop [8–10]. Because expanding from a saturated liquid state means lower expander efficiencies, the performance of another flash cycle is evaluated: the single flash cycle (SFC). In this cycle, the fluid is flashed to an intermediate pressure, the vapor and liquid are separated, and then only the vapor is expanded. This technology is already commonly used for electricity production from geothermal sources [11], and previously proposed for WHR in stationary applications under the name OFC [12]. It combines improved thermal matching with more efficient expansion, albeit with the possible disadvantage of reduced temperatures, pressures and mass flows as well as the need for a flash vessel.

Typically, WHR studies using thermodynamic cycles for automotive applications focus on the RC with the exhaust as a heat source [13–16], reporting improvements in fuel consumption between 4 and 8%. Others also include the exhaust gas recirculation cooler (EGRC) [4, 5, 17], either as a separate source or in combination with the exhaust, showing improved fuel consumption figures between 4 and 5%. Other studies gave possible improvements in fuel consumption of 4–15% by including the charge air cooler (CAC) or engine coolant as a heat source [2, 18, 19]. Modelling techniques differ from thermodynamic cycle simula-

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