Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 129 (2017) 746–753
Energy Procedia
www.elsevier.com/locate/procedia

IV International Seminar on ORC Power Systems, ORC2017
13-15 September 2017, Milano, Italy

Thermodynamic potential of Rankine and flash cycles for waste heat recovery in a heavy duty Diesel engine

Jelmer Rijpkema[a,*], Karin Munch[a], Sven B. Andersson[a]

[a]*Chalmers University of Technology, Hörsalsvägen 7B, 41280 Göteborg, Sweden*

Abstract

In heavy duty Diesel engines more than 50% of the fuel energy is not converted to brake power, but is lost as heat. One promising way to recapture a portion of this heat and convert it to power is by using thermodynamic power cycles. Using the heavy duty Diesel engine as the waste heat source, this paper evaluates and compares the thermodynamic potential of different working fluids in four power cycles: the Rankine cycle (RC), the transcritical Rankine cycle (TRC), the trilateral flash cycle (TFC) and the single flash cycle (SFC). To establish the heat input into the cycle, operating conditions from an actual heavy duty Diesel engine are used as boundary conditions for the cycle heat source. A GT-Power model of the engine was previously developed and experimentally validated for the stationary points in the European Stationary Cycle (ESC). An energy analysis of this engine revealed that it has four heat sources with the potential for waste heat recovery: the charge air cooler (CAC), the coolant flow, the exhaust gas recirculation cooler (EGRC), and the exhaust flow. Using fixed heat input conditions determined by the selected engine operating mode, the TFC performed best for the CAC with a net power increase of around 2 kW, while the RC performed best for the coolant flow, with a net power increase of 5 kW. For the EGRC, ethanol performed especially well with both the RC and TRC, leading to an 8 kW net power increase. When using the exhaust as heat source, all four cycles provided a power output of around 5 kW with some variation depending on the working fluid. This study shows that for most cases, considering the different heat sources, the choice of cycle has a larger impact on the cycle performance than the choice of working fluid.

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

Ever increasing consumer demands for lower fuel consumption and more stringent legislation on emissions drive developments for continuous improvements in internal combustion engine efficiency. A promising way to increase engine efficiency and thus reduce CO_2 emissions is to use thermodynamic power cycles for waste heat recovery (WHR). The Rankine cycle, a well-established technology for WHR in stationary applications [1–3], also shows

* Corresponding author. Tel.: +46-(0)31-772 50 37
E-mail address: jelmer.rijpkema@chalmers.se

10.1016/j.egypro.2017.09.110

promising efficiencies for the use in automotive applications [4,5]. A possible way to increase the thermal efficiency of the RC is to bring the working fluid to supercritical conditions in the transcritical Rankine cycle (TRC). This has the potential to improve the thermal match between the heat source and the cycle, albeit often at the expense of higher system 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. Since only liquid is heated, there are opportunities to improve the thermal match while simultaneously improving heat transfer and reducing pressure drop [8–10], leading to smaller heat exchangers, an important consideration for WHR in automotive applications. Finally, to address the main drawback of the TFC - the inefficient expansion of the wet mixture - the performance of an alternate flash cycle is investigated: the single flash cycle (SFC). Instead of expanding a wet mixture from the saturation point, 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 an extra component in the form of a flash vessel.

This work evaluates and compares the thermodynamic potential of these four cycles using heat input conditions based on the heat sources available in a heavy duty Diesel engine. An energy analysis of different operating modes of the engine is performed and used to evaluate the potential heat sources in the engine, and one operating mode is selected for further analysis. The thermodynamic cycle models are simulated with a number of different working fluids, spanning a range of thermodynamic properties. Boundary conditions and cycle constraints have been chosen so that the thermodynamic potential of both low and high temperature heat sources can be evaluated and compared.

The paper aims to provide insight into the relative performance of the different thermodynamic cycles by making a direct comparison between the cycles. By considering all the relevant heat sources for the operating conditions in a heavy duty Diesel engine, including the low, intermediate and high temperature sources, it can be identified which combination of cycle and working fluid gives the highest thermodynamic potential for each heat source.

Nomenclature

h	specific enthalpy, J/kg
$\dot{m}$	mass flow rate, kg/s
M	molecular mass, kg/kmol
P	pressure, Pa
$\dot{Q}$	heat transfer rate, W
T	temperature, K
$\overline{T}$	mean temperature, K
$\dot{W}$	power, W
x	vapor mass fraction
$\dot{X}$	exergy rate, W

Greek symbols

η	efficiency

Subscripts

0	reference state
con	condensation
cr	critical
ev	evaporation
eng	engine
exh	exhaust
exp	expander

Subscripts (continued)

is	isentropic
pp	pinch point
sup	superheating
th	thermal
tot	total

Abbreviations

CAC	charge air cooler
EATS	exhaust aftertreatment system
EGR	exhaust gas recirculation
EGRC	exhaust gas recirculation cooler
ESC	European stationary cycle
GWP	global warming potential
ODP	ozone depletion potential
OFC	organic flash cycle
ORC	organic Rankine cycle
RC	Rankine cycle
SFC	single flash cycle
TFC	trilateral flash cycle
TRC	transcritical Rankine cycle
WHR	waste heat recovery