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Working Fluid Selection and Optimal Power-to-Weight Ratio for ORC in Long-Haul Trucks

Roberto Pili[a]*, Castro Pastrana Jesus D.[a], Alessandro Romagnoli[b], Hartmut Spliethoff[a], Christoph Wieland[a]

[a]*Institute for Energy Systems, School of Mechanical Engineering, Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany*
[b]*School of Mechanical & Aerospace Engineering, College of Engineering, Nanyang Technological University (NTU), 50 Nanyang Avenue, 637820 Singapore*

Abstract

In 2013, about 82% of the total CO_2 emissions from transportation systems in the U.S. were caused by road transportation, highly based on internal combustion engines (ICE). Organic Rankine Cycles (ORC) are a waste heat recovery (WHR) technology that can contribute significantly to reduce environmental impact of road transportation. A trade-off has to be found between the improved fuel energy utilization and the weight and volume of the ORC, which increase the vehicle load and reduce the available space for transportation. In the present work, 17 working fluids are analyzed as possible candidates for WHR with direct-evaporation ORC in long-haul trucks. The preheater/evaporator is modelled as a finned shell-and-tube heat exchanger, while the condenser is an air-cooled finned flat-tube heat exchanger, as in common truck radiators. The ORC process is optimized for each fluid in terms of maximum power output, taking into account the impact of the working fluid on the heat exchanger weight and volume. The heat exchangers are modelled in MATLAB®. The results show that acetone and ethanol can recover more than 6 kW of mechanical power, but the system would present large weight and required space. Isobutane shows the highest power-to-weight and power-to-volume ratio (234 W/kg and 277 W/dm^3 resp.), but the net power output is lower. Cyclopentane and pentane allow a good trade-off between power output and space requirement. The discussed procedure can be also applied to other transportation systems, where the condenser might have to be adapted to different boundary conditions.

Keywords: Organic Rankine Cycle; truck; heat exchanger; weight; volume; mobile

* Corresponding author. Tel.: + 49 89 289 16312; fax: + 49 89 289 16271.
E-mail address: roberto.pili@tum.de

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1. Introduction

In the United States, the transportation sector accounted for 26% of the greenhouse gas emissions in 2014 [1]. The largest source of CO_2 emissions in this sector is road transportation, highly based on diesel and gasoline internal combustion engines (ICE), which accounted for about 82% of the total transportation emissions in 2013 [2]. Since 80% of the goods in the U.S. are hauled by means of long-haul trucks, measures to reduce the fuel consumption and emissions of long-haul trucks are of major importance [3]. The two goals might counteract each other; studies report that the increase in efficiency of heavy-duty vehicles has been slowed down by e.g. $DeNO_x$ after-treatment [4].

A significant reduction in fuel consumption can be achieved by utilizing the waste heat, which is generally transferred to the environment by means of the exhaust gases and engine cooling system [5–7]. The exhaust gases are typically more attractive because of the higher exergy content [8]. Organic Rankine Cycle (ORC) are a valuable option to convert the waste heat into either mechanical or electrical energy [3, 9]. Recently, most of the research has been driven towards the thermodynamic and turbomachinery optimization of ORC [10–12]. The impact of the working fluid on the weight and size of the system has been instead hardly studied [13]. It has been pointed out in previous work by the authors, that weight and space requirement of the ORC system can be critical for the economic performance of the ORC integration, especially for road transportation [14]. The weight of the ORC has in fact not only a negative effect on the waste heat recovery because of the increased vehicle load, but it also represents an important indicator of the purchase costs. It is therefore interesting to compare different working fluids not only in the achievable power output, but also in the ORC compactness and weight. The present works compares the performance of different organic working fluids for waste heat recovery from ORC. The power-to-weight (PTW) and power-to-volume ratio (PTV) of different working fluids is determined for common exhaust gas conditions for heavy-duty trucks on highway. Varying driving conditions might change the net power output, and hence the effective PTW and PTV. The methodology can be also used for other applications, where weight and space availability are of major concern. In future work, the part-load behavior of the working fluids will be considered, and the results of the present analysis will be extended.

Nomenclature

ORC	Organic Rankine Cycle	C	constant	α	heat transfer coefficient
ICE	Internal Combustion Engine	H	tube/fin height	λ	thermal conductivity
PTW	Power-to-Weight	W	width	fin	finned
PTV	Power-to-Volume	T	tube d tube outer diameter	cc	counter-flow
LMTD	Logarithmic Mean Temp. Diff.	t	wall thickness	cf	cross-flow
Re	Reynolds number	p	operating pressure	k	condensation
Pr	Prandtl number	σ	material ultimate tensile strength	fg	flue gas
A	surface area	η_{fin}	fin efficiency	g0	tube bare surface

2. Waste Heat Recovery from Long-Haul Trucks with ORC

More than 99% of the heavy-duty trucks in Germany are driven by diesel engines [15]. The main waste heat sources of diesel engines consist of the engine jacket coolant and the exhaust gas, which can be found either on the exhaust pipe or in the Exhaust Gas Recirculation loop (EGR) [7, 8]. All the heat sources can be coupled and recovered in an ORC power system. The coupling is however challenging for system control, to ensure optimal cooling of the main engine, and to keep as low as possible weight and space requirements. A summary of the proposed waste heat recovery configurations with ORC can be found in [16]. To reduce system complexity and achieve light and compact design, only the flue gas will be considered as heat source for the ORC in the present analysis. The layout of a simple ORC is shown in Fig. 1. The main components are the preheater/evaporator, where the working fluid is vaporized by cooling down the flue gas; an expander, where the thermal energy of the fluid is converted into mechanical power; a condenser, which condenses the working fluid and a pump, which forwards the working fluid to the evaporator to close the thermodynamic cycle. The ORC might also be equipped with a recuperator, which heats up the liquid at the pump outlet by cooling down the vapor leaving the expander, before it is condensed. This can result in a higher efficiency,