Applied Energy 165 (2016) 878–892

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Transient performance evaluation of waste heat recovery rankine cycle based system for heavy duty trucks

Vincent Grelet [a,b,c], Thomas Reiche [a], Vincent Lemort [b,*], Madiha Nadri [c], Pascal Dufour [c]

[a] Volvo Trucks Global Trucks Technology, Advanced Technology and Research, 1 av Henri Germain, 69800 Saint Priest, France
[b] Thermodynamics Laboratory, University of Liège, Campus du Sart Tilman B49, B4000 Liège, Belgium
[c] Universite de Lyon, F-69622 Lyon, France, Universite Lyon 1, Villeurbanne, France, CNRS, UMR 5007, LAGEP, France

HIGHLIGHTS

- The paper presents a waste heat recovery system model for performance assessment.
- A performance evaluation and optimal system configuration methodology is depicted.
- Working fluid selection for this application is shown.
- It is shown that performance should be assessed over dynamic driving cycle.
- Different system configurations are compared and optimized scenario is proposed.

ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form 20 October 2015
Accepted 4 November 2015

Keywords:
Waste heat recovery system
Modeling
Thermodynamic
Rankine cycle
Heavy duty trucks

ABSTRACT

The study presented in this paper aims to evaluate the transient performance of a waste heat recovery Rankine cycle based system for a heavy duty truck and compare it to steady state evaluation. Assuming some conditions to hold, simple thermodynamic simulations are carried out for the comparison of several fluids. Then a detailed first principle based model is also presented. Last part is focused on the Rankine cycle arrangement choice by means of model based evaluation of fuel economy for each concept where the fuels savings are computed using two methodologies. Fluid choice and concept optimization are conducted taking into account integration constraints (heat rejection, packaging, ...). This paper shows the importance of the modeling phase when designing Rankine cycle based heat recovery systems and yields a better understanding when it comes to a vehicle integration of a Rankine cycle in a truck.

1. Introduction

Even in nowadays heavy duty (HD) engines, which can reach 45% of efficiency, a high amount of the chemical energy contained in the fuel is released as heat to the ambient. Driven by future emissions legislation and increase in fuel prices, engine gas heat recovering has recently attracted a lot of interest. Over the last decades, most of the research has focused on waste heat recovery systems (WHRS) based on the Rankine cycle [1–3]. These systems can lead to a decrease in fuel consumption and lower engine emissions [4,5]. Recent studies have brought a significant potential for such systems in a HD vehicle [6,7]. However, before the Rankine cycle based system can be applied to commercial vehicles, the challenges of its integration have to be faced. The work done in [8,9] show that one of the main limitation is the cooling capacity of the vehicle. But other drawbacks, such as the back pressure, weight penalty or transient operation should not be minimized [10,11]. Before tackling the problem of the control strategy of this system [12,4], the architecture and components need to be selected to achieve a certain objective that could be to maximize the fuel savings or minimize the impact on the vehicle. This study focuses more on maximizing the system performance by taking into account the different penalties induced by the integration of the system on a heavy duty truck. Technical challenges and optimization of stationary organic Rankine cycles (ORC) are well adressed [13,14] but for mobile applications only few studies deal with fuel saving potential of WHRS on dynamic driving cycles [15,16] and the latter is generally reduced to a certain number of steady state engine operating points [17,18]. This last approach leads to an

* Corresponding author.
E-mail addresses: vincent.grelet@volvo.com (V. Grelet), thomas.reiche@volvo.com (T. Reiche), vincent.lemort@ulg.ac.be (V. Lemort), nadri@lagep.univ-lyon1.fr (M. Nadri), dufour@lagep.univ-lyon1.fr (P. Dufour).

http://dx.doi.org/10.1016/j.apenergy.2015.11.004
0306-2619/© 2016 Published by Elsevier Ltd.

overestimation of the WHRS performance [3] and therefore of the fuel economy. In [19] different concepts are analyzed taking into account the system integration into the vehicle cooling module. The concepts differ in the number of heat sources used and the temperature level of the cooling fluid. Each is simulated on different steady state engine operating points and the fuel economy is calculated taking into account the increase in cooling fan consumption, exhaust back pressure or intake manifold temperature. Depending on the Rankine configuration and the location of the condenser, improvements from 2.2% (recovering heat only from exhaust gases and condenser placed in front of the cooling package) to 6.9% (exhaust gas recirculation and exhaust heat are recovered and condenser is fed with engine coolant) are achieved. In [15], dynamic fuel economy is evaluated on a light duty vehicle taking into account the main penalties induced by the integration of the WHRS. Fuel savings from 3.4% to 1.3% are presented depending on the level of integration of the system into the vehicle architecture. However, no optimization is proposed either on the system architecture or on the condenser integration into the cooling package. This paper is organized as follows. The second section explains the different considerations to take when designing a Rankine cycle for a HD application. In the third section, the different models used in the rest of the study are explained. In the fourth section, the scope of the study and the different methodologies are explained. In the fifth section, simulation results are analyzed and possible improvements are proposed. Finally, conclusions are drawn and directions for future research work are discussed.

2. Design aspects to consider

Fig. 1 shows a simple waste heat recovery system mounted on a 6 cylinder heavy duty engine. Working fluid flows through four basic components which are: the pump, the evaporator linked to the heat source, the expansion machine and the condenser linked to the heat sink. For sake of clarity, the link between the expander and the engine driveline is represented by a dashed line since it can be either mechanical or electrical (by coupling a generator to the expansion machine and reinject the electricity on the on board network).

2.1. Working fluid choice

There are several aspects to take into account when choosing a working fluid for this application. Unlike stationary power plants where the main consideration is the output power or the efficiency, here other aspects have to be considered such as fluid deterioration, environmental aspects or freezing. Up to now, several studies have tried to identify the ideal fluid for WHRS [20–22] but no single fluid has been found. Recently, new performance indicators have been introduced [14,23], where cost and design issues enter into consideration.

2.2. Heat sources

On a commercial vehicle, a certain number of heat sources can be found such as exhaust gases, cooling water or engine oil. These ones have several grade of quality (temperature level) and quantity (amount of energy). If the number of heat sources often yields higher fuel savings, it also brings more complexity and more challenges for the design of the system (fluid, expansion machine, control).

2.3. Heat sink

On a HD Truck, the only heat sink available is the vehicle cooling package which is a module including radiators for the compressed air and the engine coolant and cooled down by means of the ram air effect and the cooling fan. Integration of a WHRS into the cooling module results on a higher load on the latter and limits the amount of waste heat that can be converted into useful work. As such, complete system analysis is necessary to find the optimal way of recovering heat from a vehicle.

2.4. Subsystem interaction

The engine operation is influenced by the introduction of a WHRS. For example, as the WHRS shares the cooling system of the vehicle, the charge air cooling capacity can be lower, which has a negative behavior on the engine performance. Another example is the use of exhaust gas recirculation (EGR) as heat source. This

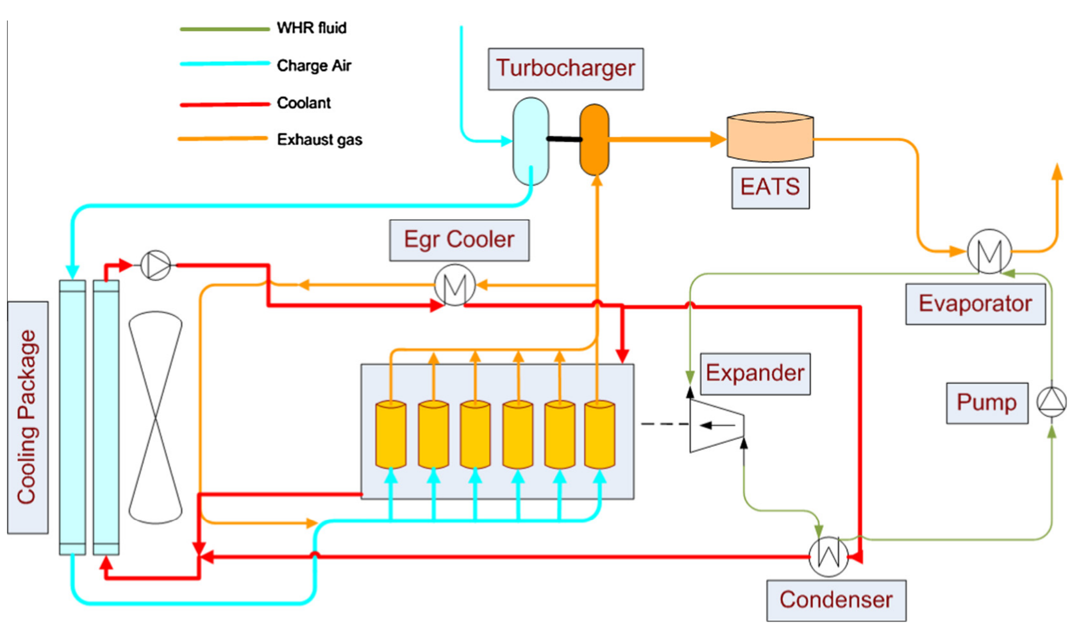

Fig. 1. Simple waste heat recovery Rankine based system.