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Prediction of dynamic Rankine Cycle waste heat recovery performance and fuel saving potential in passenger car applications considering interactions with vehicles' energy management

Tilmann Abbe Horst [a,*], Wilhelm Tegethoff [b], Peter Eilts [c], Juergen Koehler [b]

[a] BMW Group Research and Technology, Knorrstr. 147, 80788 Muenchen, Germany
[b] University of Braunschweig, Institut fuer Thermodynamik, Hans-Sommer-Str. 5, 38106 Braunschweig, Germany
[c] University of Braunschweig, Institut fuer Verbrennungskraftmaschinen, Langer Kamp 6, 38106 Braunschweig, Germany

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ABSTRACT

Waste heat recovery (WHR) by means of a Rankine Cycle is a promising approach for achieving reductions in fuel consumption and, as a result, exhaust emissions of passenger car engines. To find the best compromise between complexity and fuel saving potential, methods for predicting the WHR performance for different system configurations and stationary as well as dynamic driving scenarios are needed. Since WHR systems are usually not included in today's car concepts, they are mostly designed as add-on systems. As a result their integration may lead to negative interactions due to increased vehicle weight, engine backpressure and cooling demand. These effects have to be considered when evaluating the fuel saving potential.

A new approach for predicting WHR performance and fuel saving potential was developed and is presented in this paper. It is based on simple dynamic models of a system for recovering exhaust gas waste heat and its interfaces with the vehicle: the exhaust system for heat input, the on-board electric system for power delivery and the engine cooling system for heat rejection. The models are validated with test bench measurements of the cycle components.

A study of fuel saving potential in an exemplary dynamic motorway driving scenario shows the effect of vehicle integration: while the WHR system could improve fuel economy by 3.4%, restrictions in power output due to the architecture of the on-board electric system, package considerations, increased weight, cooling demand and exhaust gas backpressure lead to a reduction of fuel saving potential by 60% to 1.3%.

A parameter study reveals that, in addition to weight reduction and efficiency optimization, combining the WHR system with enhanced electrification of engine peripherals is the most effective approach to improve fuel saving potential. When assuming an increase in power demand of the on-board electric system from 750 to 1500 W, a fuel saving potential of 4% – referring to a 3.6% higher reference fuel consumption – is reached. WHR could therefore play an important role to overcome the challenges of increased electric power demand in future vehicles.

1. Introduction

Increasingly restrictive environmental regulations, rising fuel prices and customer expectations drive the demand for highly efficient powertrains [1,2]. Despite the employment of advanced engine technologies such as direct fuel injection, turbo-charging or variable valve actuation, the peak efficiency of modern internal combustion engines used in passenger cars does not exceed 43% [3]. The remaining energy from the fuel is emitted into the environment mainly in the form of exhaust and coolant waste heat.

The recovery and conversion of this heat into mechanical or electric energy is a promising approach for achieving further reductions in fuel consumption and, as a result, exhaust emissions [4,5]. Among other technologies for waste heat recovery (WHR) such as thermoelectric generators [6,7], the Rankine Cycle promises high potential and is already well established in many industrial applications such as gas and steam, solar, geothermal and biomass power plants as well as marine and railway propulsion systems [8–11]. Recent research also considers the application in on-road vehicles [12–17].

Implementation of a WHR system into trucks or passenger cars requires, however, special attention regarding dynamics and integration. While most power generation systems today are designed for operation with constant boundary conditions, the heat-up

* Corresponding author.
E-mail address: tilmann.horst@gmail.com (T.A. Horst).

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Nomenclature

Latin symbols

A	area, m^2
c	specific heat capacity, J/(kg K)
c_p	c at constant pressure, J/(kg K)
c_x	air resistance coefficient, –
d	diameter, m
f_{Tire}	rolling resistance coefficient, –
g	gravitational acceleration, m/s^2
h	specific enthalpy, J/kg
M	torque, Nm
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
P	power, W
p	pressure, N/m^2
$\dot{Q}$	heat flow rate, W
T	temperature, K
t	time, s
$\dot{V}$	volumetric flow rate, m^3/s
v	velocity, m/s

Greek symbols

α	heat transfer coefficient, $W/(m^2 K)$
η	efficiency, –
λ	thermal conductivity, W/(m K)
ξ	utilisation grade of reference exhaust gas heat flow rate, –
ρ	density, kg/m^3
χ	normalized zone area in EHX, –
ω	angular velocity, rad/s

Subscripts, superscripts, abbreviations

AC	air conditioning
amb	ambient
avg	average
Base	evaluation scenario “Base”
Cond	condenser
cond	condensation
cool	coolant
EGR	exhaust gas recirculation
EHX	exhaust gas heat exchanger
Eng	engine
ev	evaporation
exh	exhaust gas
FC	fuel consumption
Gen	electric generator
HTC	high temperature cooler
id	ideal
Imp	evaluation scenario “Improved”
Int	evaluation scenario “Integrated”
LTC	low temperature cooler
max	maximum
min	minimum
OBES	on-board electric system
ph	preheating
PT	powertrain
ref	reference state
sh	superheating
Turb	turbine
Veh	vehicle
wf	working fluid
WHR	waste heat recovery

phase can be a large fraction of typical daily driving profiles and decrease the fuel saving potential [14]. Once heated up, the system has to work under a wide range of exhaust gas conditions [13]. Since WHR is usually not included in today’s vehicle concepts, it is mostly designed as an add-on system. In addition to added weight, the integration may lead to negative interactions due to increased exhaust gas backpressure and increased cooling demand followed by decreased WHR performance, increased power consumption of the cooling system, increased vehicle air resistance and – if applicable – decreased efficiency of charge air and exhaust gas recirculation (EGR) cooling. Furthermore, consequences of coupling with the powertrain or on-board electric system have to be taken into account.

Ultimately, a significant reduction of the positive effect of WHR due to decreased engine performance and fuel efficiency and increased exhaust emissions can be the result [17,18]. The most comprehensive studies of these effects to date are performed on heavy-duty Diesel engines for truck applications.

Katsanos et al. [16] identify geometric vehicle integration and rejection of excess heat as the main technical challenges regarding the development of WHR systems for heavy-duty Diesel engines in large haul trucks. Using quasi-stationary simulation models of the engine including its radiator and a Rankine Cycle with an air-cooled condenser, they analyse these aspects for two layouts with different heat sources: tailpipe exhaust gas only or in combination with heat rejected by charge air and EGR cooling. Integrating charge air and EGR cooling into the WHR system is deemed beneficial because of increased fuel saving potential and reduced demand for heat rejection to the coolant from these sources. It is estimated that the overall heat transfer area of the radiators would nevertheless have to be increased by 20–30% to meet the heat rejection demand of this setup in most engine operating points.

Flik et al. [18] analyse four concepts for integrating a Rankine Cycle into the thermal management system of a truck Diesel engine with indirectly cooled charge air and EGR. They differ in the used heat sources (tailpipe exhaust gas and/or EGR) and the position of the liquid-cooled condenser (engine or charge air cooling circuit). The effects on fuel consumption are simulated for an exemplary steady-state operating point including the effects of increased cooling fan power consumption, charge air temperature and exhaust gas backpressure. The smallest improvement in fuel efficiency of 2.2% is obtained when collecting waste heat only from the tailpipe and placing the condenser in the charge air cooling circuit because of low WHR power output, increased cooling fan power consumption due to increased cooling demand and increased charge air temperature. The biggest improvement of 6.9% is achieved when collecting waste heat from both sources and placing the condenser in the engine cooling system. In this case, a high WHR power output is accompanied by decreased heat rejection from the EGR cooler while charge air temperature remains unchanged.

Both results show that integration effects have to be taken into account when analysing the fuel saving potential of a WHR system. Regarding passenger car applications however, these are usually neglected (e.g. [13,14]). The goal of this paper is therefore to show, for the first time, the impact of vehicle integration on the performance and fuel saving potential of a WHR system for passenger cars. In contrast to the previously mentioned studies dealing with truck applications, all aspects of vehicle integration are included and the analysis is based on a real-world dynamic motorway driving scenario.