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Dynamic heat exchanger model for performance prediction and control system design of automotive waste heat recovery systems

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HIGHLIGHTS

- A dynamic model of the evaporator in a passenger car waste heat recovery system based on the Rankine Cycle was developed.
- By using the moving-boundary approach and validating the model, high numerical efficiency and accuracy were achieved.
- A steam temperature control system was developed based on the model and implemented at the engine test bench.
- The dynamic operating characteristics of the evaporator were investigated based on measurements and simulations.
- Conclusions regarding system and control design for operation in highly dynamic driving conditions are presented.

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ABSTRACT

Waste heat recovery by means of a Rankine Cycle is a promising approach for achieving significant reductions in fuel consumption and, as a result, exhaust emissions of passenger car engines. This approach is already well established in industrial applications such as gas and steam power plants or ship propulsion systems. While these systems are mainly designed for stationary operation, the behaviour in highly dynamic operating conditions becomes more important when the principle is transferred to a passenger car engine.

Knowledge of the dynamic response of the employed heat exchangers plays an important role in performance prediction and control system design of the steam cycle. Hence, a dynamic model of the exhaust gas heat exchanger employing the moving-boundary principle was developed and is presented in this paper. The model describes both design operation and the heat-up procedure of the component. For achieving high model accuracy in the resulting broad range of operating conditions, new approaches for modelling wall temperature distribution and zone switching were developed.

Simulations of stationary operating points as well as the response to typical disturbances of the system's input variables are in good agreement with test bench measurements. The model is used to develop a control system for dynamic operation on the test bench. Further studies of the operating characteristics reveal varying dynamic behaviour depending on the heat flow rate from exhaust gas to working fluid as well as coupling of evaporation pressure and outlet steam temperature.

1. Introduction

Increasingly restrictive environmental regulations and rising fuel prices drive the demand for highly fuel efficient powertrains. Despite the employment of advanced engine technologies such as direct fuel injection, turbo-charging or fully variable valve actuation, the peak efficiency of modern internal combustion engines used in passenger cars does not exceed 45% [1]. 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 useful energy is a promising approach for achieving further reductions in fuel consumption and, as a result, exhaust emissions [2–4].

Among other technologies for waste heat recovery such as thermoelectric generators [5], 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 ship and train propulsion systems [6–10]. To enable efficient and safe operation, performance prediction and control design based on numerical models play an important role in the development process. In the exhaust system of a passenger car, the heat available for recovery underlies fast dynamics. This means that dynamic models describing the key operating characteristics have to be employed.

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Nomenclature

Latin symbols

A	area, m^2
c	specific heat capacity, J/(kg K)
d	diameter, m
h	specific enthalpy, J/kg
l	length, m
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, –
n	rotational speed, 1/min
P	power, W
PO	position, –
Pr	Prandtl number, –
p	pressure, N/m^2
$\dot{Q}$	heat flow rate, W
Re	Reynolds number, –
S	slip ratio, –
s	thickness, m
T	temperature, K
t	time, s
V	volume, m^3
$\dot{V}$	volumetric flow rate, m^3/s
v	velocity, m/s
w	width, m
x	steam quality, –

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
ε	emissivity, –
χ	normalized zone length, –
γ	void fraction, –
φ, φ', X, η, ζ	auxiliary variables, –
λ	thermal conductivity, W/(m K)
μ	density ratio, –
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts, superscripts, abbreviations

adj	adjacent
amb	ambient
avg	average
bub	saturated liquid state
cond	condensation
cool	coolant
des	desired state
dew	saturated steam state
ECU	electronic control unit
ev	evaporation
EHX	exhaust gas heat exchanger
exh	exhaust gas
gen	electric generator
h	hydraulic
i	inner
hx	heat exchanger
max	maximum
med	medium (exh or wf)
o	outer
ph	preheating
ref	reference state
sat	saturation
sh	superheating
tot	total
wf	working fluid

In response to the demand for increased flexibility in the operation mode of modern power plants, many models for simulating the transient behaviour of steam cycles have been proposed [11–16]. Main focus is usually laid on capturing the dynamics of heat exchangers [17–19] and turbines [20,21]. Applications range from controller design [17,22] and developing new control techniques [23] to studying the heat-up and load change process of entire power plants while predicting thermal stresses in the components [12,20,24]. Regarding fully transient operation with varying parameters of the hot and cold reservoirs, which also holds for mobile waste heat recovery systems, several publications dealing with the dynamic simulation of HVAC systems are known [25–27], mostly employing simplified modelling approaches in order to develop and optimise control strategies.

Concerning the dynamics of kW-scale waste heat recovery systems however, only few studies have been conducted. Ibaraki et. al. [28] presented the design, vehicle integration and dynamic test of a Rankine Cycle waste heat recovery system employing an axial piston machine for steam expansion. Steam pressure and temperature control is achieved by proportional feedback supplemented by feed-forward controllers. During driving cycles, steam temperature and pressure are kept within relatively broad ranges of ±50 K and ±10 bars of the respective setpoints, using these simple control structures. The influence of evaporator dynamics on the operating characteristics of the system is emphasised in more recent works by Pei et. al. [29], Quoilin et. al. [22] and Stegmeier [30]. An additional fluid loop between heat source and evaporator for smoothing the heat input and a water bypass for regulating the superheating are proposed for achieving better temperature control [22,30].

In a passenger car application however, the number of components and their volume has to be reduced due to restrictions in costs, space and weight [31], making the use of an intermediate fluid loop or a water bypass inappropriate. This leads to a system with fast response to engine load changes which, in conjunction with highly variable waste heat flow during normal operation of the car, poses a great challenge for system control. Therefore, for gaining a deeper understanding of the key operating characteristics and creating a base for developing advanced control strategies, a dynamic model of the exhaust gas heat exchanger (EHX) is presented in this paper. The model formulation employs the moving-boundary principle [17,19,27,32–34] and is validated with measurement data of a prototype EHX. It is implemented using the Modelica modelling language.

In Section 2 of this paper, the layout of the waste heat recovery system, its overall operating strategy and the test bench setup are presented. In Section 3, the heat exchanger model and the validation procedure are described. Dynamic characteristics of the EHX are investigated in Section 4 by developing and testing a system for steam temperature control. Finally, conclusions regarding the system and control design to enable efficient and safe operation in highly dynamic driving conditions are presented.

2. Waste heat recovery system for passenger cars

Because of the comparatively low power range of 1–2 kW, the wide range of exhaust gas parameters and restrictions in available space, maximum system weight and costs, a waste heat recovery