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Two-phase plate-fin heat exchanger modeling for waste heat recovery systems in diesel engines

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HIGHLIGHTS

- A dynamic model for a modular plate-fin heat exchanger is presented.
- The model combines a finite difference modeling approach with a moving boundary one.
- Multiple phase transitions along a single pipe flow are captured.
- The model is validated on a highly dynamic world harmonized transient cycle.
- The model computational complexity is low, suitable for embedded control purposes.

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ABSTRACT

This paper presents the modeling and model validation for a modular two-phase heat exchanger that recovers energy in heavy-duty diesel engines. The model is developed for temperature and vapor quality prediction and for control design of the waste heat recovery system. In the studied waste heat recovery system, energy is recovered from both the exhaust gas recirculation line and the main exhaust line. Due to the similar design of these two heat exchangers, only the exhaust gas recirculation heat exchanger model is presented in this paper. Based on mass and energy conservation principles, the model describes the dynamics of two-phase fluid flow. Compared to other studies, the model is able to capture multiple phase transitions along the fluid flow by combining finite difference approach with moving boundary approaches. The developed model has low computational complexity, which makes it suitable for control design and real-time implementation.

To validate the model, experiments are performed on a state-of-the-art Euro-VI heavy-duty diesel engine equipped with the waste heat recovery system. Simulation results show good accuracy, over the complete engine operating range, with average error below 4%. This is demonstrated on transitions between stationary operating points and on a dynamic response to a standard world harmonized transient cycle for both cold-start and hot-start conditions.

1. Introduction

Due to stringent CO_2 emissions regulation, increased fuel costs and concerns about energy security, the automotive industry invests much effort in developing fuel efficient powertrains. Despite that, for trucks the fuel efficiency has been stagnating for the last two decades. However, for CO_2 emissions, USA legislation indicates a 20% reduction by 2020. In Europe, similar requirements are expected to be introduced. Studies [1,2] show that even with advanced engine technologies around 60–70% of the fuel energy is still lost through the coolant or the exhaust system. Thus, energy recovery from the exhaust is a promising technology allowing a 4–5% increase in the engine efficiency [3–5]. These energy recovery systems are called Waste Heat Recovery (WHR) systems.

The technologies used in a WHR system are various: from mechanical turbo-compounding [6] and electrical turbo-compounding [7] to thermoelectric systems [8] and Rankine Cycles [9]. For heavy-duty applications, the Rankine Cycle promises high potential in terms of costs and overall efficiency improvement of the engine [10]. Moreover, it has been shown in [11] that on a truck diesel engine, due to the low temperature sources, the use of an Organic Rankine Cycle (ORC) appears to be favorable in comparison

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Nomenclature

A	cross-sectional area, m^2
L	length, m
M	mass, kg
S	surface area, m^2
T	temperature, K
V	volume, m^3
$\dot{Q}$	heat flow rate, W
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, –
Pr	Prandtl number, –
Re	Reynolds number, –
c_p	specific heat capacity, J/(kg K)
d	diameter, m
e	error, %
h	specific enthalpy, J/kg
n	number of cells, –
p	pressure, Pa
t	time, s
x	system state, –
z	space coordinate, m

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
χ	vapor quality, –
δ	thickness, m
η	dynamic viscosity, Pa s
γ	auxiliary variable, –
λ	thermal conductivity, W/(m K)
ϕ	system state derivative, –
ρ	density, kg/m^3
τ	time constant, s

Subscript and superscript

*	dimensionless
amb	ambient
avg	average
c	constant
corr	correction
cs	casing
f	working fluid
g	exhaust gas
h	hydraulic
i	cell index
in	inlet
ins	insulation
l	liquid
loss	losses
max	maximum
meas	measurement
out	outlet
q	quality
r	ratio
s	sampling
sat	saturation
sim	simulation
ss	steady-state
v	vapor
vel	velocity
w	wall

with the classical Rankine Cycle. The main difference between the ORC and classical Rankine Cycle is the use of an organic working fluid instead of water [12]. Regardless the Rankine Cycle type, a control design is necessary to optimize the efficiency of the overall WHR system and to ensure safe operation, i.e., no liquid at the heat exchanger outlet. In automotive, control of engines with WHR systems is challenging due to the large number of sensors and actuators, strong coupling between the engine and WHR system and continuous changes in time of the heat available for recovery. Moreover, to maximize the WHR efficiency the system is required to be operated close to the constraint boundaries, while safety is still guaranteed. Thus, dynamical modeling of such systems plays an important role for control and performance prediction.

The dynamic behavior of a WHR system is mainly influenced by the heat exchanger and condenser. These components are most commonly modeled using two approaches: moving boundary models and discretized models. The Moving Boundary (MB) models [13–15] divide the heat exchanger in three regions: liquid, two-phase and vapor separated by boundaries. Due to dynamical conditions, the regions will expand or contract while the position of each phase transition will change. The main idea of MB models is to either track or capture the phase transitions position. However, when the volume of one region becomes much smaller than the others, the MB models become singular [16]. A more robust approach during start-up and shut-down processes is obtained using discretized models, most commonly based on the Finite Volume (FV) [17–19] or Finite Difference (FD) formulation [20,21]. A disadvantage is that discretized models are more computationally expensive due to a larger number of system states.

Many of the heat exchanger models have been designed for large-scale power plants and refrigeration systems. For small-scale applications characterized by highly dynamic conditions, e.g. automotive applications, only a few studies have been reported. In [22], a dynamic heat exchanger model has been developed and validated for a passenger car application. The model represents a tube-finned heat exchanger based on the MB principle. The studied heat exchanger is non-modular meaning the two flows travel the complete heat exchanger length uniformly. In contrast, we consider a modular heat exchanger design, in which the working fluid side is divided into three sections called modules. These modules are shifted along the heat exchanger length to improve the heat transfer between the flows and to avoid high temperatures in the wall material. In such a design, multiple phase transitions in a single pipe flow can occur, especially during transients. As a result, the modeling of modular heat exchangers using only the MB approach is not straightforward.

In this paper, a dynamic model for a modular plate-fin heat exchanger is presented. The model is developed by combining the FD approach with the MB approach to capture the effect of multiple phase transitions induced by the modular design. The contributions are as follows. First, the mass and energy balance equations for the exhaust gas side, working fluid side, and heat exchanger wall are reconsidered. At the heat exchanger wall, the energy balance includes the transverse conductivity through the wall. To reduce the model complexity a dynamic range analysis is performed. Second, the resulting model is discretized in space and time using a staggered grid approach based on a FD method. Third, to account for the multiple phase transitions, a phase-change detection algorithm is implemented that mimics the MB approach within each discretization cell. Fourth, the model is validated on a state-of-the-art Euro-VI heavy-duty diesel engine equipped with a WHR system. The model validation is performed