Applied Energy 205 (2017) 260–279

Contents lists available at ScienceDirect

Applied Energy

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

Transient dynamic modeling and validation of an organic Rankine cycle waste heat recovery system for heavy duty diesel engine applications

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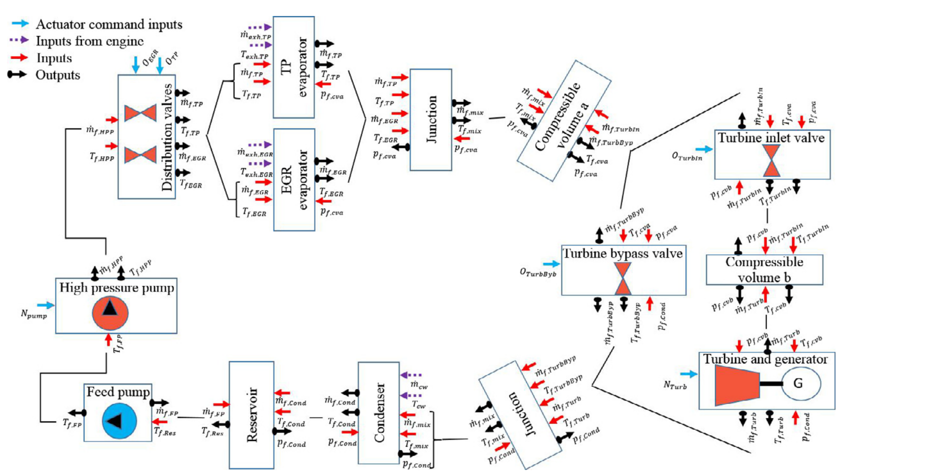
HIGHLIGHTS

- A parallel evaporator organic Rankine cycle Simulink® model is presented.
- Component models are calibrated and validated with experimental data.
- Integration and quasi-transient validation of the component models are given.
- Co-simulation of organic Rankine cycle and heavy-duty diesel engine models.
- Integrated model capability is demonstrated over a transient driving cycle.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 April 2017
Received in revised form 19 June 2017
Accepted 15 July 2017

Keywords:
Waste heat recovery
Organic Rankine cycle
Dynamic finite volume heat exchanger modeling
Heavy duty diesel engine
Transient operation

ABSTRACT

This paper presents a dynamic organic Rankine cycle waste heat recovery (ORC-WHR) Simulink® model and an engine model for heavy-duty diesel applications. The dynamic, physics-based ORC-WHR system model includes parallel evaporators, flow control valves, a turbine expander, a reservoir, and pumps. The evaporator model contains an enhanced pressure drop model, which calculates pressure drop for each working fluid phase via a linear relation to the axial location inside each phase. The ORC-WHR component models parameters are identified over large range of steady state and transient experimental data, which are collected from an ORC-WHR system on a 13 L heavy-duty diesel engine. The component models are integrated into an entire system model and the boundary conditions, inputs and outputs for the individual models are described. A GT-POWER® engine model and its transient validation is presented. The speed and torque profiles of a long-haul, constant speed variable-load heavy-duty cycle are processed through the engine model to produce the exhaust and recirculated exhaust gas transient conditions relevant for the ORC model. The ORC-WHR system then simulated over these highly transient engine conditions. Overall, this paper provides detailed guidelines for ORC-WHR system modeling, model calibration, and component models integration.

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http://dx.doi.org/10.1016/j.apenergy.2017.07.038
0306-2619/

Nomenclature

a	ath boundary of the discretized evaporator
A	area [m^2]
B, n	Blasius factors
c_p	heat capacity [J/kg K]
C	constant of two-phase multiplier correlation
d	diameter [m]
f	friction factor
F	force [N]
G	mass flux [kg/s m^2]
h	enthalpy [J/kg]
H	height [m]
$\dot{H}$	enthalpy flowrate [J/s]
I	momentum [kg m/s]
k	kth time step
l, L	length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
N	revolution speed [rpm]
O	valve opening [%]
p	pressure [Pa]
t	time [s]
T	temperature [K]
u	velocity [m/s], internal energy [J/kg]
U	heat transfer coefficient [J/kg K]
v	dynamic viscosity [m^2/s]
V	volume [m^3]
x	vapor quality
X	Martinelli parameter
z	space coordinate [m]
α	void fraction
Re	Reynolds number
r	ratio
Pr	Prandtl number
Nu	Nusselt number
γ	specific heat ratio
ρ	density [kg/m^3]
∂	partial derivative operator
Ω	intersection angle between horizontal surface and flow direction [radius]
ξ	friction factor
μ	dynamic viscosity [kg m/s]
φ	two-phase multiplier

Abbreviations

ORC	organic Rankine cycle
WHR	waste heat recovery
HDD	heavy duty diesel
CSVL	constant speed variable load
MBM	moving boundary method
FVM	finite volume method
BC	boundary condition
TP	tail pipe
EGR	exhaust gas recirculation
HTC	heat transfer coefficient
turb	turbine
FRM	fast running model

Subscripts and superscripts

f	working fluid
w	wall
e	exhaust gas
v	vapor
l	liquid
i	ith discretized cell
in	inlet/upstream
out	outlet
p	pressure
fr	friction
g	gravitation
exc	exchange
vap	saturated vapor
sat	saturated liquid
tp	two phase
s	single phase
h	hydraulic
U	heat transfer coefficient
is	isentropic
d	discharge
0	reference
vlv	valve
$flow$	flow
sim	simulation
exp	experimental
cw	cooling water
cva	compressible volume a
cvb	compressible volume b
mix	mixed working fluid after junction
HPP	high pressure pump
FP	feed pump
TP	tail pipe
EGR	exhaust gas recirculation
$Cond$	condenser
$cross$	cross or sectional surface
$pump$	pump
$turb$	turbine
$TurbByp$	turbine bypass valve
$TurbIn$	turbine inlet valve
$TPEvapVlv$	TP evaporator distribution valve
$EGREvapVlv$	EGR evaporator distribution valve

1. Introduction

In the past decade, waste heat recovery (WHR) techniques have gained a large amount of attention in the automotive industry, especially in heavy-duty truck applications [1–3]. It is reported that up to 45% of fuel energy is wasted as heat in a heavy duty vehicle [2]. Given such a large percentage of waste heat, WHR technology represents an attractive option for improved fuel economy and reduced CO_2 emission.

Popular WHR technologies include the thermoelectric generators, the turbo-compounding, and the organic Rankine cycle (ORC). Thermoelectric generators utilize the temperature difference between the exhaust gas and the thermoelectric material coolant to produce electricity [4–6]. These devices are compact and can be simply structured, but their thermal efficiency is limited by the low figure of merit value of existing thermoelectric materials. Turbocompounding combines the turbocharger with an electric generator or a crankshaft coupling, respectively, representing the naming convention of electrical versus mechanical turbocompounding [7–9]. Turbocompounding recovers a portion of enthalpy energy from the exhaust gas. After expansion in the turbocharger, the remaining waste heat exists in the form of low availability thermal energy that cannot be efficiently recovered by additional turbocompounding. Additionally, turbocompounding