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Thermodynamic optimisation of a high-electrical efficiency integrated internal combustion engine – Organic Rankine cycle combined heat and power system

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HIGHLIGHTS

- An ICE-ORC CHP system design tool is developed for optimising total power or fuel use.
- Simultaneous optimisation of ICE-ORC CHP systems can increase total power output by 30%.
- Optimal ICE exhaust gas temperature increases to promote ORC power generation by 7%.
- Optimised ORCs generate up to 15% of the total power and reduce fuel consumption.
- Power optimisation increases fuel consumption; fuel-efficiency optimisation reduces it by 17%.

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ABSTRACT

Organic Rankine cycle (ORC) engines are suitable for heat recovery from internal combustion engines (ICE) for the purpose of secondary power generation in combined heat and power (CHP) systems. However, trade-offs must be considered between ICE and ORC engine performance in such integrated solutions. The ICE design and operational characteristics influence its own performance, along with the exhaust-gas conditions available as heat source to the ORC engine, impacting ORC design and performance, while the heat-recovery heat exchanger (ORC evaporator) will affect the ICE operation. In this paper, an integrated ICE-ORC CHP whole-system optimisation framework is presented. This differs from other efforts in that we develop and apply a fully-integrated ICE-ORC CHP optimisation framework, considering the design and operation of both the ICE and ORC engines simultaneously within the combined system, to optimise the overall system performance. A dynamic ICE model is developed and validated, along with a steady-state model of subcritical recuperative ORC engines. Both naturally aspirated and turbocharged ICEs are considered, of two different sizes/capacities. Nine substances (covering low-GWP refrigerants and hydrocarbons) are investigated as potential ORC working fluids. The integrated ICE-ORC CHP system is optimised for either maximum total power output, or minimum fuel consumption. Results highlight that by optimising the complete integrated ICE-ORC CHP system simultaneously, the total power output increases by up to 30% in comparison to a nominal system design. In the integrated CHP system, the ICE power output is slightly lower than that obtained for optimal standalone ICE application, as the exhaust-gas temperature increases to promote the bottoming ORC engine performance, whose power increases by 7%. The ORC power output achieved accounts for up to 15% of the total power generated by the integrated system, increasing the system efficiency by up to 11%. When only power optimisation is performed, the specific fuel consumption increases, highlighting that high-power output comes at the cost of higher fuel consumption. In contrast, when specific fuel consumption is used as the objective function (minimised), fuel consumption drops by up to 17%, thereby significantly reducing the operating fuel costs. This study proves that by taking a holistic approach to whole-system ICE-ORC CHP design and operation optimisation, more power can be generated efficiently, with a lower fuel consumption. The findings are relevant to ICE and ORC manufacturers, integrators and installers, since it informs component design, system integration and operation decisions.

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Nomenclature

Abbreviations

BDC	bottom dead centre
bmep	break mean effective power
CHP	combined heat and power
DSH	desuperheater
EV	exhaust valve
fmep	friction mean effective power
GHG	greenhouse gases
HEX	heat exchanger
ICE	internal combustion engine
IV	intake valve
ODE	ordinary differential equations
ORC	organic Rankine cycle
PH	preheater
PR	pressure ratio
SH	superheater
TDC	top dead centre

Abbreviations and symbols

A	area (m^2)
AFR	air-to-fuel ratio (–)
b	cylinder bore diameter (–)
C_D	valve discharge coefficient (–)
c_p	specific heat capacity (J/kg K)
D_v	valve diameter (m)
ex	specific exergy (J/kg)
h	specific enthalpy (J/kg K)
h_g	heat transfer coefficient (W/m^2 K)
LHV	lower heating value (J/kg)
l	connecting rod (con-rod) length (m)
L_v	valve lift (m)
$\dot{m}$	mass flow rate (kg/s)
N	rotational speed (1/s)
P	pressure (Pa)
PP	Pinch Point (K)
PR	pressure ratio (–)
$\dot{Q}$	heat transfer rate/thermal load (W)
$\dot{Q}_{jw}$	jacket water thermal load (W)
$\dot{Q}_{loss}$	internal combustion engine losses (W)
$\dot{Q}_w$	thermal losses through the wall (W)
R	gas constant (J/kg K)
r	volume ratio (–)
s	piston stroke (m)
SFC	specific fuel consumption (W/W, –)
SFC_{abs}	absolute specific fuel consumption (kg/kWh)
SHD	superheating degree (–)
U_p	piston velocity (m/s)
V	volume (m^3)
W	power (W)
x	mass fraction (kg/kg, –)
$\dot{X}$	exergy rate (W)

Greek symbols

γ	ratio of heat capacities (–)
ε	effectiveness (–)
η	efficiency (–)
ϑ	crankshaft angle (°)
σ_{Boltz}	Stefan-Boltzmann constant ($W/m^2 K^4$)
ω	rotational speed (rad/s)

Subscripts

Boltz	Stefan-Boltzmann
chd	chocked flow
comb	combustion
comp	compressor
cond	condenser
crit	critical
cw	condenser/cooling water
cyl	cylinder
d	duration
dest	destruction
dis	displacement
el	electrical
elg	electric generator
evap	evaporator
ex	exhaust gases
exp	expansion
f	fuel
g	gas
hs	heat source
ign	ignition
in	input/inlet
int	cylinder intake
intr	intercooler
jw	jacket water
lim	limit
loss	losses
m	motoring
min	minimum
max	maximum
net	net
nchd	non-chocked flow
o	initial conditions
off	valve close
on	valve open
out	output/outlet
p	piston
rec	recuperator
s	isentropic
turb	turbocharger
v	valve
w	wall
wf	working fluid

1. Introduction

In light of recent trends towards increasing the efficiency of primary energy use, reducing energy consumption and reducing emissions worldwide, the distributed cogeneration of heat and power has been identified as a viable alternative to the separate provision of these vectors. The benefits of combined heat and power (CHP) systems include higher overall energy efficiencies, lower primary energy (e.g. fuel) consumption rates, emissions and overall environmental impact, and also lower costs relative to traditional heating systems and centralised power generation, when covering the same end-use energy demands [1–3]. Crucial for the maximisation of a CHP system's overall efficiency is the effective utilisation of the heat rejected by the prime mover. In internal combustion engines (ICE) designed for use in CHP applications, which are at the focus of this present study, more than 55% of the fuel energy is rejected as heat to the cooling jacket water