THERMO-ECONOMIC OPTIMIZATION OF SMALL SCALE ORC SYSTEMS FOR HEAT RECOVERY FROM NATURAL GAS INTERNAL COMBUSTION ENGINES FOR STATIONARY POWER GENERATION

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Highlights: Thermo-economic optimization of small-size ORC systems for heat recovery from stationary internal-combustion combined heat and power plants based on cost component correlations, design optimization, whole system integration constraints and working fluid performance comparisons

Key words: combined heat and power; organic Rankine cycles (ORC); working-fluid selection; thermo-economic analysis; heat-transfer coefficients.

EXTENDED ABSTRACT

Introduction

Distributed (decentralized) small- and medium-scale energy generation systems, such as internal combustion (IC) combined heat and power (CHP) plants, have an important role to play in a decarbonised energy future, while heat recovery and the further exploitation of this thermal energy is important in increasing the overall electrical efficiency of these energy systems which is important in applications that demand low heat to power ratios. Such a possibility is offered by bottoming organic Rankine cycles (ORCs), and is transferable to many other applications reducing primary energy use and pollutant emissions.

ORC systems range from micro-scale (less than 10 kW), for automotive sector or domestic cogeneration to large multi-megawatt applications of geothermal and biomass power plants. Today, the development of ORC plants with power output above a few hundred kW is in a quite advanced stage, whereas the downsizing of this technology to micro and small-scale (between 10 and 100 kW) presents high costs and limited energy conversion efficiency, that represent the main drawback to achieve a reasonable payback time of the investment.

Methods, approach and results

A case study is considered in the present work of waste heat recovery from the exhaust gases of a 375-kWe natural gas reciprocating IC engine for stationary energy generation. A thermo-economic optimization is performed in order to select the thermodynamic parameters, cycle configuration and working fluid that minimize specific investment costs, with specific constraints on the minimum outlet temperature of the exhaust gases.

In particular, thermodynamic and heat-transfer performance, component sizing, and capital costs are analysed employing several working fluids in order to capture the trade-offs between higher efficiency and lower investment costs. In addition to Toluene and R245fa that are common working fluids studied in the literate for these systems, other fluids such as Cyclohexane, Cyclopentane and R227ea have been evaluated taking into account thermodynamic performance as well as other aspects (ODP, GWP, flammability).

The thermo-economic assessment has been carried out on the basis of a detailed cost component analysis, and particular attention has been paid to the expanders and heat exchangers as crucial components for determining the cost of ORC systems. Cost correlations for heat exchangers and pumps have been taken from Seider et al. [1].

Since this work focuses on systems in the range from 10 to 100 kW, a volumetric screw device has been chosen as the expander, thanks to its cost-performance compared to others technologies at this scale. The cost correlation for the screw device used in this work has been derived from several commercial compressors in the range of 3.7-184 kWe [2], which can be operated in reverse mode as expanders.

Firstly, thermodynamic optimization aimed at maximizing the net power output was performed.

An optimization exercise based on a cycle with a single-stage expansion process (single expander) demonstrates the limit of this configuration with the expander efficiency dropping to very low values for high volume ratios and this limiting the maximum temperature of the cycle, leading to high exergy losses during the heating process.

For this reason, a two-stage stage expansion process using two expanders in series has been considered. A revised thermodynamic optimization of this configuration shows a remarkable increase in the cycle efficiency since the two expanders, working with the same pressure ratio, allow higher temperatures and therefore lower exergy losses (see Table 1).

However, this approach leads, as expected, to high investment costs, such that a full thermo-economic optimization is necessary to understand the trade-offs in this application. This optimization exercise shows that the parameters that make the system cost effective are very different from those obtained by the thermodynamic performance optimization (see Table 2).

Table 1. Comparison between ORC systems with a single expander (left) or two-stage expander (right). $\dot{W}_{\mathrm{net}}$ *is the net power output;* p_{evap}, p_{cond} *are the evaporation and condensation pressure;* $\dot{m}_{\mathrm{wf}}$ *is the mass flow rate of the working fluid;* d_{sh} *is the degree of superheating; and* η_{th} *the thermal efficiency.*

	Single expander				**Two-stage expander**			
	Toluene	**R245fa**	**Cyclopentane**	**Cyclohexane**	**Toluene**	**R245fa**	**Cyclopentane**	**Cyclohexane**
$\dot{W}_{\mathrm{net}}$ **(kW)**	24.8	23.5	27.3	25.4	41.8	30.9	42.5	41.0
p_{evap} **(bar)**	2.75	15.81	5.44	2.48	5.06	27.74	26.70	9.87
p_{cond} **(bar)**	0.37	2.29	0.71	0.33	0.10	2.38	0.66	0.23
$\dot{m}_{\mathrm{wf}}$ **(kg/s)**	0.49	0.86	0.46	0.50	0.41	0.95	0.34	0.40
d_{sh}	0.00	0.99	0.10	0.00	0.00	1.00	0.81	0.00
η_{th} (%)	10.5	9.9	11.5	10.7	17.7	13.0	17.9	17.3

Table 2. Rated costs and thermodynamic parameters obtained maximizing the power output (left column) or minimizing the specific investment costs for cyclopentane cycles and both a single screw expander (left) and two-stage screw expander (right).

	Single expander		Two-stage expander	
	Opt. max power	**Opt. min spec. cost**	**Opt. max power**	**Opt. min spec. cost**
Rated cost ($/kW)	3350	1900	2500	1800
$\dot{W}_{net}$ (kW)	27.3	23.1	42.5	33.6
p_{evap} (bar)	5.44	23.7	26.70	42.7
p_{cond} (bar)	0.71	4.27	0.66	2.66
$\dot{m}_{wf}$ (kg/s)	0.46	0.51	0.34	0.40
d_{sh}	0.10	0.05	0.81	1.00
η_{th} (%)	11.5	9.8	17.9	14.5

With these considerations in mind, a multi-objective optimization considering power and costs has also been performed. The Pareto frontier obtained shows that an increase in the power output leads to an increase of the cost of the ORC system. The optimum design solution coming from the single objective thermo-economic optimization has been plotted on the Pareto frontier. This makes it possible to explore other optimal solutions that can be evaluated with different individual criteria.

The power optimization of the cycle and the minimization of the specific investment costs are performed using an interior point algorithm [3] whereas the multi-objective optimization is performed using a controlled elitist genetic algorithm (a variant of NSGA-II [4]).

Conclusions

A thermo-economic modelling and optimization of heat recovery from a reciprocating IC engine for stationary energy generation via an ORC engine in small-scale applications has been performed, with a specific focus on the minimization of the specific investment costs of the system.

Specific cost equations have been introduced for screw expanders, which resulted the best option in such small-scale ORC plants. Several working fluids have been considered in order to optimize the specific cost of the ORC system.

The use of a two-stage expander has shown that the increase of the power output can overcome the rise of the system cost leading to a more cost effective system.

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Background of the research and development team

Dr. Christos N. Markides is the Head of the Clean Energy Process (CEP) Laboratory, which is based in the Department of Chemical Engineering at Imperial College London, and numbers approximately 35 members (post-doctoral, doctoral and post-graduate students). He has written more than 200 papers that have been either published in international journals or presented at international conferences, often as keynote talks including at the previous EORCC at Belfast in 2016, and has secured total funding of approximately £30M as Principal Investigator (PI) or as part of collaborative teams to work on aspects of waste-heat and solar energy systems, most recently as PI on the £2M project on 'High Performance Heat-Power-Cooling' in the context of industrial waste heat. Previous to his academic position at Imperial College, he was involved in co-founding and directing a spin-out company developing innovative two-phase thermofluidic conversion devices for waste-heat applications.