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A novel design methodology for waste heat recovery systems using organic Rankine cycle

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ABSTRACT

This paper discusses a comprehensive design methodology for optimization of organic Rankine cycle designs using a new design to resource method. The objective of the design to resource method is to obtain the best designs, which are the closest match to the resource and the most cost-effective. The design analysis is constrained by the available main components and heat resource. The ratio of net power output to the total heat exchanger area is used as the objective function. The new design methodology was implemented on an existing lab-scale as a case study. Experiments were conducted to obtain the data to identify the heat transfer coefficients of the real processes and validate the simulation model results. Design evaluations were carried out on the plant by using three Capstone gas turbine load conditions and four design alternatives. The results indicate that design 1 has the highest objective function of all the alternatives. It is able to increase the objective function from 100% to 391% of the base case depending on the Capstone gas turbine load conditions. The results also reveal that the current small scale plant is more suitable to Capstone gas turbine load condition 1 with the highest waste heat utilization rate of 76.9%.

1. Introduction

Industries ultimately discharge about 20–50% of their energy consumption as waste heat [1]. Thermal power generation plants necessarily release waste heat to the environment, but fuel utilization could be improved if the waste heat stream is sufficient to drive a bottoming cycle. The waste heat recovery using a bottoming organic Rankine cycle (ORC) is technologies especially in the field of heavy duty stationary engines and gas turbine power generators [2]. ORC energy conversion plants are commercially available for high temperature thermal resources. Successful companies like Ormat and Turboden possess a great deal of in-house knowledge based engineering gained from decades of experience. Utility-scale ORC's also benefit from a well-developed supply chain for the standard working fluids and systems components, in particular the turbomachinery. Waste heat resources are usually lower temperature and are rejecting heat to the environment as part of a required cooling operation. Thus, the engineering of waste heat recovery ORC's will have challenging constraints on the system integration, thermodynamic cycle efficiency, available components, working fluids and the cost. The main aim of this research project is to use commercially available thermal systems modelling tools to develop a design investigation methodology for a given low temperature resource with strict requirements on inlet and outlet temperature, and which considers all five key design variables where each has constrained available operating conditions.

Thermo-economic optimization of ORC waste heat recovery (WHR) systems has been approached in several different ways, but most find that there is a trade-off between thermodynamic efficiency and plant cost. Li and Dai [3] investigated the effect of recuperator and superheat degree for a range of zeotropic mixtures. Imran et al. [4] analysed the choice of basic and regenerative thermodynamic cycles under a constant heat source condition to optimize the choice of working fluid. Hajabdollahi et al. [5] modelled and optimized a WHR ORC for a diesel engine to select a working fluid. Quoilin et al. [6] proposed a fluid selection based on thermo-economic considerations instead of a simple thermodynamic objective function to select the working fluid.

There are five main design variables for an ORC preliminary design:

1. Working fluid (e.g. *n*-pentane, R245fa, or a zeotropic mixture)
2. Cycle configuration (e.g. basic cycle or including recuperator)

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Nomenclature

A	heat transfer area (m^2)
AU	heat transfer conductance (W/K)
Bo	boiling number (-)
C_p	specific heat (J/kg K)
Co	convection number (-)
Fr	Froude number (-)
H	specific enthalpy (J/kg)
h	heat transfer coefficient (W/m^2 K)
HE	heat exchanger
$\dot{M}$	mass flow rate (kg/s)
$\dot{m}_{oil}$	mass flow rate of oil (kg/s)
N	rotating speed (RPM)
n	number of experiments (-)
Out	output
P	pressure (kPa)
PP	pinch point (°C)
Q	total energy transfer by heat (J)
$r_{,v,in}$	build-in volume ratio (-)
T	temperature (°C)
T_{loss}	torque (Nm)
U	overall heat transfer coefficient (W/m^2 K)
UR	utilization rate (%)
v	specific volume (m^3/kg)
$\dot{V}$	volume flow rate (m^3/s)
W_{net}	net electrical power output (W)
W_p	power of pump (W)
W_T	power of turbine (W)

Subscripts

1, 2, 3, ...	state point in the system
amb	ambient condition
calc	calculated data
cond	condenser
eV	evaporator
ex	exhaust
HE	heat exchanger
In	inlet
l	liquid
max	maximum
meas	measured data
n	number of main components
P	pump
T	turbine/expander
tp	two-phase
r	refrigerant
s	isentropic, swept
sf	secondary fluid
su	supply
sh	superheating (°C)
tot	total
v	vapour
w	wall

Greek symbols

Δ	delta
Δp	pressure drop (kPa)

Acronyms

LMTD	Log-Mean Temperature Difference Method
ORC	Organic Rankine Cycle
WHR	waste heat recovery

3. Type of each of the main components, (e.g. air cooled condenser vs. shell and tube liquid cooled condenser, vs. water cooling tower)
4. Design parameters (e.g. degree of superheat, pinch degrees, condenser pressure)
5. Size of main components (e.g. heat exchanger surface area and fan flow rate).

These design variables affect the ORC performance and economy in different and interactive ways and make the optimization process challenging. There are a limited number of ORC design investigation methodologies reported in the literature at the time of writing. Macián et al. [7] described a methodology for the optimization of a WHR system for vehicles. The methodology is used to select waste heat sources, the optimum working fluid, expander machine, the pump and the heat exchangers and thermodynamic characteristics of the cycle based on the problem specification from an initial step. Amicabile et al. [8] proposed a design methodology to optimize the ORC considering a wide range of design variables and practical aspects. The design process consists of three steps: heat source selection, fluid selection and thermodynamic cycle optimization. Bendig et al. [9] proposed a methodology that is capable of choosing the design-point, selection of working fluid, and a type of cycle using a genetic algorithm for the multi objective optimization. None of these current methodologies uses all five design variables in a design guideline of the ORC development. Moreover, the current ORC methodologies do not consider selection and design as two terms that are interchanged during the ORC development. According to Jaluria [10], selection and design must be employed simultaneously in the development of a system. Design involves starting with a basic concept, modelling and evaluating different designs and obtaining a final design that fulfils the given requirements and constraints. Based on design results, the requirements and specifications of the desired component or equipment are matched with whatever is available in the markets. If an item possessing the desired characteristics is not available, design revision is needed to obtain one that is acceptable for the specific purpose.

The design investigation approach proposed in this work is called "design to resource" (DTR) methodology considers all five design variables and optimises both thermodynamic efficiency and economic viability. The objective of the DTR methodology is to obtain a preliminary design which has the best resource utilization, is the most cost-effective and which can be built from available components. The methodology is applied to a small-scale ORC system for WHR of the Capstone gas turbine. Main components are modelled in detail according to real products. The models are validated by experimental data and reliable prediction of the system performance is demonstrated.

2. Design to resource (DTR) methodology

Fig. 1 shows a design methodology for optimizing the ORC plant based on the DTR method for WHR applications. All five design variables involved in design are considered. There are ten sequential steps in the methodology. Constraints on components or processes are considered at each step. Optimization of the