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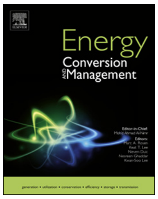

Economic optimization of Organic Rankine cycle with pure fluids and mixtures for waste heat and solar applications using particle swarm optimization method

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A R T I C L E I N F O

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A B S T R A C T

The optimization criterion for designing the thermodynamic layout of an organic Rankine cycle is often based on either achieving maximum thermodynamic efficiency or incurring minimum initial specific investment costs. Such designs, however, need not lead to the maximum utilization of waste heat potential or an optimal investment. For full potential utilization of a waste heat source, its temperature should be brought down to near ambient temperatures via transfer of enthalpy to the organic Rankine cycle working fluid. In the limit, however, pursuit of complete source utilization may lead to capital intensive organic Rankine cycle layouts that demand infinitesimal temperature gradients in heat exchangers leading to massive heat transfer areas. This paper defines a new objective function that reveals the tradeoffs between specific investment cost and the extent to which waste heat is utilized. A particle swarm optimization algorithm is used to optimize 7 and 8 dimensional search space for pure and mixture based working fluids, respectively, for case studies involving power capacities of 5, 50 and 500 kWe, waste heat source temperatures ranging from 75 to 275 °C and a number of working fluids. As a practical aid to designers, a methodology for generating high isentropic efficiency scroll geometries corresponding to optimized cycles is presented, and the optimization analysis is further extended to solar thermal applications.

1. Introduction

Rising electricity demand, finite fossil fuel reserves and environmental concerns regarding carbon emissions motivate the switch to renewable energy sources, increased efficiency in energy conversions, and recovery of previously unused energy streams, in particular thermal, to produce higher value energy such as electricity. Consequently, thermal resources available in various industrial processes at temperatures previously termed 'waste heat' (due to low exergy potential) is now considered as a potential source for electricity generation [1–6]. While the work of Cayer et al. [1], Hung et al. [2] and Babus'Haq [3] terms heat which is available at temperatures above 100 °C as waste heat, Badr et al. [4], T.C. Hung [5] and Chen et al. [6] consider temperatures as low as 80 °C as potential sources of heat through which useful work can be drawn. Cayer et al. [1] consider operating with high pressure working medias e.g. CO_2, ethane and R125, in transcritical Rankine cycle configurations and conclude that multi-point optimization and comparison is required to design an adequate transcritical power system. Hung et al. [2] emphasize using isentropic fluids for converting low temperature heat to work in order to avoid wet-expansion in turbo-expanders with wet fluids and the need for a regenerator that becomes an inevitable requirement for efficiency improvement when dry fluid is used. Babus'Haq [3] emphasizes adding an organic Rankine cycle (ORC) as a key component in CHP applications in order to ensure energy efficiency. Badr et al. [4] consider R11, R12, R22, R113, R114 and R502 as potential ORC working fluids for recovering heat from 80 °C heat source. T.C. Hung [5] report R123 to be the most optimized ORC working fluid among dry fluids. Chen et al. [6] found cyclopentane as the most promising fluid for recovering waste heat of truck diesel engines.

The extraction of work from a low exergy thermal source is technically feasible using an ORC at an efficiency proportional to the temperature potential, whereas the viability for a given application is a combination of technical factors, economics and scale of the deployment [7–12]. Investigations by Wang et al. [7] identified the ORC as a preferred technology among a variety of approaches e.g. turbo-charger/turbo-compounding, thermoelectric system, steam Rankine cycle, for recovering thermal exhaust heat. Saidur et al. [8] found the ORC to be a promising waste heat recovery solution in comparison with thermoelectric generator, and exhaust gas recovery using waste heat from

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Nomenclature

amb	ambient
c	cost (USD)
C_1 and C_2	PSO coefficients
H	enthalpy (J)
i	iteration number
j	particle number
k	dimension number
p	pressure (bar)
S	entropy (J/K)
T	temperature (°C)
y	randomness limit
1 to 6	states in ORC

Greek letter

ε	*effectiveness*
Ψ	objective function for waste heat applications

Subscript

sp	specific
wf	working fluid

Superscript

$'$	states on real thermodynamic cycle

Abbreviations

ACC	Air Cooled Condenser
CAPEX	Capital Expenditure
HEX	Heat Exchanger
HTF	Heat Transfer Fluid
ORC	Organic Rankine Cycle
PSO	Particle Swarm Optimization
TES	Thermal Energy Storage

internal combustion engine. Sprouse et al. [9], considered various thermodynamic cycle alternates such as Stirling engine, Kalina cycle, supercritical carbon dioxide cycle, and steam Rankine cycle for recovering waste heat from automobile engines. In a similar study, Feng et al. [10] and Rahbar [11] found ORCs to be a pragmatic waste heat solution based on its applicability to a number of heat sources across a wide range of scale. Lecompte et al. [12] cited flexibility in the choice of thermodynamic architectures as a key feature of ORCs facilitating customization opportunities applicable to various types of waste heat sources.

While the ORC is a well understood heat engine in practical usage for well over a century, the ORC developer often encounters a number of design choices specific to realizing the objectives of a proposed project. These design choices include variables such as working fluid, operating conditions in terms of temperature and pressure specifications at various stages of the cycle along with the pinch temperatures in the heat exchangers, and component type and design, particularly the expander as the core converter of pressure volume work. A large body of work suggests as a starting point to consider first law of thermodynamic efficiency [13–17] or second law of thermodynamic efficiency [18–21] as the basis to realize an optimum ORC design. Wei et al. [13] emphasized operating ORC engines at lower condenser temperatures in order to optimize the first law efficiency. Chacartegui et al. [14] selected first law efficiency as a figure of merit for improving efficiency of combined cycle and recuperated gas turbines. Zhang et al. [15] analyzed 16 different working fluids in subcritical and transcritical configurations for optimizing ORC performance based on first law indicators. In a study of efficiency based optimization schemes conducted by Cheng et al. [16], R245fa and R134a are found to be more suitable working fluids for geothermal applications. Similarly Vivian et al. [17] developed a general framework for selecting a working fluid for various types of ORC layout alternates such as sub-, trans-, super- critical cycles. Hettiarachchi et al. [18] found Ammonia to be the most suitable ORC working fluid for geothermal applications based on exergy analysis. In a similar study based on exergy analysis, Heberle et al. [19] found high critical temperature working fluids such as isopentane to be exergetically more efficient in the case of series layout-based energy extraction schemes from a geothermal reserve whereas for parallel type energy extraction schemes, fluids like isobutane and R227ea realize higher efficiency. Isam H. Aljundi [20] found hydrocarbons such as pentane, butane, neo-pentane to be more efficient than conventional refrigerants. Sun et al. [21] proposed using cooling cycles such as absorption refrigeration cycle or ejector refrigeration cycle in conjunction with ORC to improve the second law efficiency of the waste heat recovery process.

Efficiency is a figure of merit that is only indirectly linked to viability for an ORC project yet it is generally proposed as the most common objective function for optimizing ORC based waste heat recovery solutions. In practice however, industrial projects are evaluated on the basis of maximizing real economic returns to capital, and from a capital perspective it would be more prudent for the engineering design and development of ORCs to proceed according to an economic as opposed to thermodynamic objective function. While the two are often correlated, they are not the same, as shown in recent work conducted by Quoilin et al. [22,23], Hajabdollahi et al. [24], and Imran et al. [25] exploring an approach based on thermo-economic optimization to facilitate the ORC design based on economic objectives. These studies establish the fact that an ORC design corresponding to the maximum efficiency (based on either first law or second law of thermodynamics) need not correspond to the one that incurs the minimum specific investment costs. For example, the overall efficiency for ORC design that incurs minimum specific costs is found to be ~1% lower than the best efficiency point in [22]. Hajabdollahi et al. [24] compared numerous working fluids on the basis of efficiency and cost, and found that the cost trends do not match with the corresponding efficiency trends. Imran et al. [25] reported that operating conditions can significantly affect the thermo-economic performance of the ORC and therefore, operating conditions should be judiciously selected to maintain lower specific costs.

A few studies have also used multiple objective functions to present the results in a simultaneous way to facilitate the decision making process [26–29]. Feng et al. [26] optimize ORC performance for maximum exergy efficiency while minimizing the levelized energy costs. Galindo et al. [27] considered optimizing ORCs by minimizing specific investment costs, area of heat exchangers and volume coefficient with the weighting factors of 0.5, 0.3 and 0.2, respectively. In a similar study, Wang et al. [28] optimized R134a based ORCs for maximum exergy efficiency while incurring minimum overall capital costs. Shu et al. [29] conducted a detailed study comparing performance of numerous working fluids on the basis an objective function that accounts for both the first and second law of thermodynamics.

Noting the divergence between temperature-based efficiency and economic objectives, a related question is the extent to which complete utilization of a waste stream is consistent with economic goals. One can realize the maximum potential recovery of the waste heat source by extracting energy to the point where the temperature of the waste heat stream approximates the ambient heat sink. An ORC designed with this approach in mind is significantly distinct from the designs