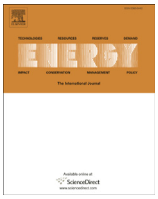
ARTICLE IN PRESS

Energy xxx (2015) 1–16

Contents lists available at ScienceDirect

Energy

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



Parametric analysis and optimization of a small-scale radial turbine for Organic Rankine Cycle

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ARTICLE INFO

Article history:
Received 18 June 2014
Received in revised form
4 February 2015
Accepted 23 February 2015
Available online xxx

Keywords:
Organic Rankine Cycle
Radial turbine
Mean-line modelling
Genetic algorithm optimization
Organic working fluids

ABSTRACT

Organic Rankine Cycle converts low grade heat sources into power utilizing organic fluids with low boiling temperature and pressure. In this cycle the design and performance of the expander has a significant impact on the cycle's overall efficiency. This work presents an integrated mathematical approach for the development of an efficient and compact small-scale radial turbine. This mathematical approach integrates the mean-line modelling with real gas formulation and GA(genetic algorithm) optimisation technique. In this methodology, the mean-line modelling coupled with real gas formulation is employed to perform parametric studies to identify the key variables that have significant effect on the turbine efficiency. Such variables are then used in the GA to optimise the turbine performance. Eight organic fluids are investigated to optimise the performance of the small-scale radial turbine in terms of efficiency. Results showed that the achieved radial turbine efficiencies vary from 82.9% to 84%; which is higher than the reported efficiency values of other types of expanders. R152a showed the highest efficiency of 84% with seven degrees (K) of superheating. However, if the superheating is to be avoided, isobutane exhibited the most favourable characteristics in terms of efficiency (83.82%), rotor size (66.3 mm) and inlet temperature (89.2 °C).

1. Introduction

The ORC (Organic Rankine Cycle) is a promising technology for conversion of low temperature waste heat sources into useful power. The ORC utilizes organic fluids such as hydrocarbons and refrigerants that boil at low temperature and pressure, with the advantages of small size; low capital and maintenance cost and low environmental impact.

Several studies have been conducted to adopt the ORC for a wide range of low-grade heat applications, such as: solar energy [1–5], biomass heat [6–8], geothermal energy [9–12], WHR (Waste Heat Recovery) of IC (internal combustion) engines [13–15], WHR of gas turbine exhausts [16–18] and bottoming of the water/steam Rankine cycle [19,20]. Tempesti et al. [1] and Guzovic et al. [11] carried out thermodynamic modelling of a single and a dual pressure ORC with solar and geothermal heat. They showed that R245fa and isopentane exhibit the best performance in terms of cycle and exergy efficiencies and minimum solar collector area with the dual pressure cycle. Delgado-Torres et al. [3] performed thermodynamic analysis of the ORC to determine the solar energy required for reverse osmosis desalination using four stationary collectors and twelve working fluids. Liu et al. [6] conducted thermodynamic modelling of a 2kWe micro-scale ORC using biomass heat and studied the effect of superheating and sub-cooling of three organic fluids. They concluded that n-pentane has the highest efficiency and both superheating and sub-cooling are detrimental to the cycle efficiency. Tchanche et al. [2], Drescher et al. [7] and Saleh et al. [10] carried out detailed studies for the selection of a proper working fluid by modelling the thermodynamic properties and thermal efficiencies of 20, 700 and 31 different fluids respectively. Cammarata et al. [12] performed thermodynamic analysis of the ORC for a geothermal primary source using flow-chart numerical tool based on a lumped parameters approach and highlighted the potential of numerical tools in predicting the cycle performance. Capata et al. [15] investigated the feasibility of an on-board innovative ORC system suitable for all types of thermally propelled vehicles to recover the heat from exhaust gases and produce extra power. Hettiarachi et al. [9], Rashidi et al. [19] and Wang et al. [20]

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http://dx.doi.org/10.1016/j.energy.2015.02.079
0360-5442/

Please cite this article in press as: Rahbar K, et al., Parametric analysis and optimization of a small-scale radial turbine for Organic Rankine Cycle, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.02.079

optimized various performance indicators of the ORC such as the exergy efficiency, specific work and the ratio of the heat exchanger area to the net power output using various optimization methods such as artificial bees colony, GA (genetic algorithm) and steepest descent method. Even though there have been several studies [1–20] regarding the selection of working fluid, thermodynamic modelling and optimization of the ORC, there has been relatively fewer published work on the modelling of the expander.

Expanders are the key components of the ORCs and their performance have significant effects on the overall system's efficiency. Modelling and experimental study of the ORC using scroll expanders was carried out in Refs. [21–25], with a maximum scroll efficiency of 67% reported in Ref. [22]. Compared to scroll expanders, radial turbines can offer the advantages of high efficiency, light weight, mature manufacturability and high power capacity [26]. Sauret et al. [27] performed the modelling of candidate radial turbine rotors for a geothermal power system using five organic fluids. R143a showed the maximum turbine static efficiency of 78.5% with the turbine inlet total temperature and pressure of 413 K and 60 bars respectively. Kang [28] accomplished the design and experimental study of a 30 kW radial turbine for the ORC using R245fa working fluid and obtained the turbine static efficiency of 75% with the turbine inlet total temperature and pressure of 353 K and 7.3 bars respectively. Pei et al. [29] carried out the experimental study of a small-scale ORC using R123 and radial turbine. They examined the heat transfer and power conversion process through the ORC and achieved the turbine isentropic efficiency of 71% with the turbine inlet total temperature and pressure of 373 K and 7.8 bars. Rahbar et al. [30,31] developed a procedure for the preliminary and detailed design of radial turbines for low power capacity systems such as ORC using mean-line modelling and CFD (computational fluid dynamics) analysis. Pan et al. [32] replaces the constant radial turbine efficiency with an internal efficiency to enhance the reliability of the ORC analysis results. R152a showed the maximum turbine efficiency of 75.8% at the turbine inlet total temperature and pressure of 323 K and 11.8 bars respectively. Fiaschi et al. [33] built a model to design a 50kWe radial turbo-expander for the ORC in which the fluid dynamics design input data are computer-aided adjusted by the operator. The maximum total-to-static turbine efficiency of 83% was achieved by R134a with the turbine inlet total temperature and pressure of 420 K and 38 bars respectively. In most of the studies [27–30,32,33] that carried out modelling of the radial turbine, the designer adjusted the turbine design parameters iteratively in order to achieve desirable results and if unacceptable the process was repeated. However, this procedure has several deficiencies as it does not necessarily assure that the optimum combination of the turbine design parameter is achieved for the maximum turbine performance and it is extremely reliant upon the designer experience. Moreover, it does not consider a broad range for the input parameters which increases the possibility of overlooking the best solution. In addition, the results should be manually checked by the designer to ensure that the application and geometrical constraints are satisfied.

The aim of this study is to develop a robust methodology for the true optimization of a small-scale radial turbine performance that can be used for ORC applications. This approach integrates the mean-line modelling, real gas formulation and GA to carry out the modelling of the radial turbine for eight organic fluids and allows the optimization of the radial turbine efficiency based on a wide range of turbine fluid dynamics design parameters. Imposing the geometrical and aerodynamics constraints on the optimization process guarantees the manufacturability of the optimized turbine geometry with minimum aerodynamic losses. In addition, unlike [27–30,32] that used a conventional rotor with zero inlet blade angle, the present study utilized a rotor blade geometry with non-zero inlet blade angle to achieve higher specific work output and a more compact rotor.

2. Working fluid selection

An important factor when designing an expander for the ORC is the selection of the working fluid. The properties of the working fluid have a major effect on the turbine performance and geometry. Due to the low temperature of the heat source, dry and isentropic fluids are more favourable for the ORC systems because of the superheated condition after the expansion in the turbine. This eliminates the concerns regarding the existence of liquid droplets in the rotor compared to the wet fluids such as water and the need for superheating equipment. Moreover, the working fluids should satisfy the environment related issues and safety criteria. These include zero ozone layer depletion, minimal GWP (global warming potential), low atmospheric life time, non-flammable and non-toxic characteristics. Table 1 shows the properties of the selected organic working fluids. The temperature - entropy diagram of the selected fluids is shown in Fig. 1.

3. Radial turbine mean-line model

Mean-line modelling is based on a one-dimensional assumption that there is a mean streamline through the stage, such that conditions on the mean streamline are the average of the passage conditions [34]. Then the thermodynamic properties, geometry parameters and flow features are determined at key stations throughout the stage. Euler's turbomachinery equation, conservation of mass, momentum and energy, are the basic equations that form the mean-line model. Also, losses and blockage in the rotor, nozzle and volute, have been taken into account. Fig. 2 represents the cross section of the radial turbine stage with the corresponding enthalpy–entropy diagram that detailed the expansion process.

Mean-line modelling is a highly iterative process as it requires comprehensive studies of many different configurations by variation of a large group of input variables in a specified range. Fig. 3 shows the flow chart of the mean-line model, detailing the overall procedure.

Inputs to the mean-line model consist of power output; turbine inlet total temperature and pressure; non-dimensional design parameters, as loading and flow coefficients and geometry ratios. With the provided input parameters shown in Table 2 and the initial guess of stage total-to-static efficiency, the preliminary design of the rotor is carried out. Based on the calculated velocity triangles and basic geometry of the rotor, the overall characteristics for the remaining components such as the nozzle and volute are determined. Using these results and the loss correlations, the model determines a more accurate estimate of the turbine stage efficiency. This value is then used as an initial guess for the efficiency and the process is repeated until convergence is achieved. For high expansion ratios that can lead to a choked nozzle and/or rotor throat, the mean-line code includes an additional subroutine to address this effect. The mean-line model is implemented into the EES (engineering equation solver) software [35]. This allows the use of its extensive and reliable thermodynamic property functions throughout the model and accurately predicts the real gas behaviour of working fluids during the expansion.

3.1. Rotor modelling

The modelling of radial turbine rotor is outlined in the literature [36–40], based on the ideal gas relations and with very high turbine inlet temperatures (600–1000 °C) suitable for gas turbine

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