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Comparative study and multi-objective optimization of plate-fin recuperators applied in 200 kW microturbines based on non-dominated sorting and normalization method considering recuperator effectiveness, exergy efficiency and total cost

Peyman Maghsoudi[a], Sadegh Sadeghi[b,*], Hamid Haghshenas Gorgani[c]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran
[b] School of Mechanical Engineering, Iran University of Science and Technology (IUST), Narmak, Tehran, Iran
[c] Engineering Graphics Center, Sharif University of Technology, Tehran, Iran

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ABSTRACT

The current study aims to simultaneously and comprehensively investigate the performance of four types of recuperative heat exchangers applied in 200 kW microturbines by using numerical method. Different fin configurations including rectangular, triangular, louver and offset strip fins are employed in the recuperators to enhance the heat transfer rate. Additionally, the calculations are separately undertaken for both counter and cross-flow arrangements. To achieve the best performance, a three-objective optimization problem is solved using Non-dominated Sorting Genetic Algorithm (NSGA-II). Recuperator effectiveness and exergy efficiency and total cost are considered as the objective functions. The recuperator effectiveness and exergy efficiency are maximized and the recuperator total cost is minimized, simultaneously. The results of each optimization are delineated by a set of designs using three dimensional Pareto-optimal fronts. Maximum cycle thermal and exergy efficiencies and NPV occur in the counter-flow recuperator employing offset strip fin and the values are found to be 39.1275%, 36.7431% and 3088164 $, respectively. A sensitivity analysis of variation in recuperator effectiveness and exergy efficiency and total cost with changes in design parameters of the plate-fin recuperators employing louver and offset strip fins with counter-flow arrangement is performed. Finally, all the optimal designs obtained from the Pareto diagrams are compared to determine the optimum designs using normalization method and non-dominated sorting concept. According to the comparisons, offset strip fin and louver fin with counter flow arrangement show better performance.

1. Introduction

Gas turbines are one of the most widely-used fuel-burning engines that produce both heat and power. These engines operating based on Brayton cycle are employed in many of today's natural-gas-fueled power plants. A typical gas turbine basically consists of a compressor, combustion chamber and turbine. With respect to the size and net power output, gas turbines are classified into microturbines and mini-turbines. Power output of microturbines ranges from 5 to 200 kW while the net power output of miniturbines is between 200 and 500 kW [1]. In comparison to other technologies, microturbines offer several potential advantages in for small-scale power generation such as small number of moving parts, compact size, light weight, lower electricity costs and greater efficiency [2]. The energy efficiency of a simple micro gas turbine is normally in the range of 16–20% [3]. Recovering waste heat from micro gas turbines can considerably enhance the overall efficiency by adding a high-efficiency and cost-effective heat recovery system [2]. Using recuperators is one of the efficient heat recovery strategies for preheating the inlet air of microturbine combustors that reduces the fuel consumption leading to an increase in microturbine total thermal efficiency. Although utilizing a recuperator with efficiency of about 87% can improve the total thermal efficiency of a power plant up to 30%, it also boosts the plant total cost up to 30% [1]. Shell-and-tube, plate-fin and primary surface heat exchangers are the common types of recuperators can be applied in microturbines [4]. Since shell-and-tube recuperators are typically large and weighty, they are rarely used in gas turbines. However, due to their higher effectiveness, compactness and lower weight, plate-fin and primary surface

* Corresponding author.
E-mail addresses: p_maghsoudi@alumni.u.ac.ir (P. Maghsoudi), SadeghSadeghi@MechEng.iust.ac.ir (S. Sadeghi), h_haghshenas@sharif.edu (H.H. Gorgani).

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Nomenclature

thickness of separation plate, m a
overall heat transfer area, m^2 A
fin heat transfer area, m^2 A_{fin}
wall heat transfer area, m^2 A_w
fin height, m b
specific heat capacity, J/kgK Cp
ratio of heat capacity rate c^*
heat exchanger cost coefficient, W/K C
profit of heat recovery, \$ c_f
total cost, \$ $Cost$
operational cost, \$ c_{ope}
purchase cost, \$ $c_{purchase}$
capital cost, \$ $c_{Capital}$
maintenance cost, \$ $c_{Maintenance}$
Hydraulic diameter, m D_h
specific exergy rate $^{W}/_{kg}$ ex
recuperator exergy destruction rate W $Ex_{D,R}$
friction factor f
inflation rate, % f^*
mass flux, kg/m^2s G
convective heat transfer coefficient, W/m^2K h
interest rate, % i
colburn number j
exit pressure loss coefficient K_e
entrance pressure loss coefficient K_c
price of electrical energy, \$/MWh k_{el}
price of fuel, \$/kg
fluid thermal conductivity, W/mK k_{fin}
wall thermal conductivity, W/mK k_w
non-flow stream length, m L_n
cold flow stream length, m L_c
hot flow stream length, m L_h
louver pitch, m L_p
fin length, m L_f
louver height, m L_l
fuel lower heating value, kJ/kg LHV
mass flow rate, kg/s m
recuperator expected life time, year n
net present value, \$ NPV
number of transfer unit NTU
nusselt number Nu
Pressure, kPa P
Cycle pressure outlet, kPa $P_{o,cycle}$
plate pitch, m p_t
rate of heat transfer, W Q
fouling factor, m^2K/W R_f
Reynolds number Re
fin pitch, m s
stanton number St
temperature, K T
turbine inlet temperature, K T_{TIT}
reference temperature, K T_0
fin thickness, m t
overall heat transfer coefficient, W/K UA
volumetric flow rate, m^3/s V_t
louver length, m w_t
offset length, m x

Greek abbreviation

corrected temperature, K ΔT_m
pressure drop, kPa ΔP
recuperator effectiveness, % ε
recuperator exergy efficiency, % $\eta_{ex,r}$
single-fin efficiency, % η_{fin}
overall fin efficiency, % η_s
compressor efficiency, % $\eta_{comp.}$
cycle thermal efficiency, % η_{th}
cycle exergy efficiency, % η_{ex}
louver angle, degree θ
mean specific volume, m^3/kg ϑ_m
Density, kg/m^3 ρ
ratio of minimum free flow area to frontal area σ
hours of operation per year, hour τ

Subscripts

air a
first year value A
cold c
fuel f
gas g
hot h
inlet i
outlet o
present value P
wall w

heat exchangers are widely applied in microturbine systems [5].

In the last decades, many studies have been undertaken to develop and optimize plate-fin heat exchangers and heat recovery systems. Manglik and Bergles [6] proposed valuable correlations for the calculation of friction factor and Colburn number in a rectangular offset strip fin compact heat exchanger over laminar, transition, and turbulent flow regimes. Chang and Wang [7] presented a generalized correlation to investigate the thermal performance of a louvered fin heat exchanger. Segundo et al. [8] performed a thermodynamic analysis and optimization to minimize the entropy generation in plate-fin heat exchangers. They considered some geometrical parameters as the optimization variables [8]. Chang et al. proposed a generalized correlation to analyze friction factor in louvered fin heat exchangers [9]. Traverso and Massardo conducted an optimization for plate-fin and primary surface recuperators taking into account some technical and economic criteria. They used different terms including cost, volume and pressure drop as the objective functions and solved a single-objective optimization problem [10]. Malapure et al. [11] numerically investigated the fluid flow and heat transfer over louvered fins employed in a compact heat exchanger. In their study, simulations were carried out for different geometries and Reynolds number with varying louver pitch and louver angle [11]. A single-objective optimization was conducted by Qiuwang et al. for a primary surface recuperator applied in a 100 kW microturbine employing genetic algorithm [12]. Compactness and weight were considered as the main factors in their study [12]. Considering entropy principles, Wen et al. [13] analyzed and optimized the design of serrated fins in a plate fin heat exchanger using genetic algorithm. They also studied power consumption and heat transfer rate in various Reynolds number at a certain mass flow rate [13]. Rao and Patel [14] conducted a thermodynamic optimization for a cross-flow plate-fin heat exchanger employing PSO algorithm. According to their study, total number of entropy generation units, total volume and total annual cost were minimized [14]. Sanaye and Hajabdollahi performed a multi-objective optimization for a certain plate-fin heat exchanger considering heat exchanger effectiveness and annual cost as the objective functions [15]. Xie et al. [16] optimized the structure of a plate-fin compact heat