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Experimental investigation on the pressure drop and heat transfer characteristics of a recuperator with offset strip fins for a micro gas turbine

Kyu Hyung Do [a,b], Byung-Il Choi [a,b], Yong-Shik Han [a], Taehoon Kim [a,b,*]

[a] Korea Institute of Machinery and Materials, Daejeon 34103, Republic of Korea
[b] Korea University of Science and Technology, Daejeon 34113, Republic of Korea

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ABSTRACT

In this study, the pressure drop and heat transfer characteristics of a recuperator with offset strip fins for a micro gas turbine were experimentally investigated in the high-temperature range. A unit recuperator with offset strip fins was fabricated using furnace-brazing technology in vacuum atmosphere. Experiments were conducted by varying the mass flow rate and inlet temperature of the hot air stream in the range of 1.5–4 g/s and 250–500 °C, respectively. Based on the experimental data, the total pressure drop results measured at high temperature were much larger than those in ambient-temperature condition, and we showed that the inlet pressure of each air stream should be measured to correctly figure out the pressure drop characteristics of the recuperator in the high-temperature range. Furthermore, the effectiveness was almost constant regardless of the inlet temperature of the hot air stream, which means that the fluid mean temperature variation hardly affected the effectiveness of the recuperator. Two types of analytical models were proposed to predict the pressure drop and the effectiveness of the fabricated recuperator and the model prediction results were also compared with the experimental data. The comparison with the experimental data showed that the results from the simple model may lead to incorrect results for the thermal efficiency of the micro gas turbine because the recuperator effectiveness was overestimated and the pressure drop of the recuperator was underestimated. On the other hand, the modified model proposed in the present work successfully estimated the pressure drop and heat transfer characteristics of the fabricated recuperator with offset strip fins for a micro gas turbine.

1. Introduction

Numerous applications for mobile power sources, such as robots, small unmanned aerial vehicles, and military applications, are available, which require energy density not attainable by batteries. They require higher power and energy densities in the range of 100–600 W/kg and 200–6000 W·h/kg, respectively [1]. Secondary batteries can have relatively large power densities; however, their energy densities hardly reach 250 W·h/kg, which limits their autonomy. Charging time can also be a problem as well as very cold external temperature. For these reasons, much effort has been over the past decade to develop a mobile power generator that could meet the growing demand for portable electricity [2].

Recently, a micro gas turbine has been focused as one of the best choices among various energy sources, including both ordinary and emergency power supplies, because it could reach much a higher energy density than existing batteries, although only a few percentage of the energy density of common hydrocarbon fuels, which is approximately 12 kW·h/kg [3–6]. Because the specific fuel consumption of a micro gas turbine is inversely proportional to the thermal efficiency, we need to improve the thermal efficiency to achieve compactness and lightness. The easiest way to enhance thermal efficiency is to increase either the pressure ratio or the turbine inlet temperature (TIT) from the thermodynamic cycle point of view. However, for the micro gas turbine, both achievable pressure ratio and TIT are significantly lower compared with those of conventional gas turbines due to the limitations in materials and manufacturing processes. An alternative method is to shift into regenerative cycle. The introduction of a recuperator in conventional gas turbines is well known to most often increase the thermal efficiency because it reduces the fuel consumption in the

* Corresponding author at: Korea Institute of Machinery and Materials, Daejeon 34103, Republic of Korea. Fax: +82 42 868 7355.
E-mail address: thkim79@kimm.re.kr (T. Kim).

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Nomenclature

A	total heat transfer surface area [m^2]
AER	area enhancement ratio
A_f	extended surface area [m^2]
A_k	total wall cross-sectional area for longitudinal conduction [m^2]
A_o	minimum free-flow area [m^2]
A_w	total wall area for heat conduction [m^2]
C	heat capacity rate
C^*	heat capacity rate ratio
C_D	drag coefficient
C_o	Kozeny coefficient
c_p	specific heat capacity [kJ kg^{-1} °C^{-1}]
D_h	hydraulic diameter of subchannel [m]
D_h'	hydraulic diameter of bypass channel [m]
d_h	hydraulic diameter of offset strip fin array [m]
f	friction factor for the longitudinal flow through the offset strip fins
$f\,\mathrm{Re}$	Poiseuille number
f'	friction factor for the transverse flow through the offset strip fins with bypass channels
G	mass velocity [m^2s]
H	recuperator height [m]
h	heat transfer coefficient [W m^{-2} °C^{-1}]
h'	height of offset strip fins [m]
j	Colburn j factor for the longitudinal flow through the offset strip fins
j'	Colburn j factor for the transverse flow through the offset strip fins with bypass channels
K_c	contraction coefficient
K_e	expansion coefficient
k_s	thermal conductivity of an offset strip fin [W m^{-1} °C^{-1}]
L	recuperator length [m]
l_s	strip length of an offset strip fin [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
N	number of fluid passages
NTU	number of transfer units
Nu	Nusselt number
Pr	Prandtl number
p	pressure [Pa]
Δp	pressure drop [Pa]
$\dot{q}$	heat transfer rate [W]
Re	Reynolds number
s	fin spacing [m]
T	temperature [°C]
ΔT	temperature difference [°C]
t_{end}	end plate thickness [m]
U	uncertainty or overall heat transfer coefficient [W m^{-2} °C^{-1}]
W	recuperator width [m]
W_{out}	outlet channel width [m]

Greek symbols

α^*	aspect ratio of rectangular ducts
$\Delta\varepsilon$	effectiveness deterioration factor
δ	fin thickness [m]
δ_w	separation sheet thickness [m]
δ_f	filler material sheet thickness [m]
ε	effectiveness
ϕ_{trans}	bypassing channel fraction
η	fin efficiency
λ	longitudinal wall conduction parameter
μ	viscosity [Pa s]
ρ	density [kg m^{-3}]
$(1/\rho)_m$	fluid mean specific volume [m^3 kg^{-1}]
σ	ratio of free flow area to frontal area

Subscripts

C	cold air stream
cf	creeping flow
ch	bypassing channel
H	hot air stream
i	hot or cold air stream
in	inlet
m	mean
max	maximum
min	minimum
out	outlet
R_I	Region I
R_{II}	Region II
R_{III}	Region III
s	solid
tot	total
$trans$	transverse flow
w	wall
wet	wetted

combustor to achieve a certain TIT [7]. In contrast, the presence of a recuperator leads to additional pressure drops at both cold and hot sides, resulting in reduced output power of the micro gas turbine. Normally, when the recuperator effectiveness increases by 1%, the overall thermal efficiency of the micro gas turbine would increase by 0.35%. On the other hand, a 1% decrease in the pressure loss of the recuperator would improve the thermal efficiency by 0.33% [8]. Therefore, a thermal design of a recuperator with high effectiveness and low pressure loss is needed to achieve higher thermal efficiency.

The present work mainly focuses on a recuperator with offset strip fins for a micro gas turbine among the various types of recuperators such as the Swiss-roll, microchannel, and primary-surface recuperators [7,9,10]. Many studies have extensively investigated the pressure drop and heat transfer characteristics of rectangular offset strip fin heat exchangers in the past decades. Kays and London [11] were the first to demonstrate a correlation of offset strip fins based on experimental results. Manson [12] conducted experiments using fin geometries in addition to the experiments of Kays and London. Using a power method, Wieting [13] obtained a correlation using 22 fin geometries. Mochizuki and Yovanovich [14] presented more accurate correlations by modifying those of Wieting [13]. Webb and Joshi [15] suggested correlations in both laminar and turbulent regimes, but these correlations could not be applied to the transition regime. Manglik and Bergles [16] presented a correlation that could be applied to laminar, transition, and turbulent regimes using experimental data from the literature. Despite this broad investigative effort, few experimental studies were conducted on a recuperator with offset strip fins, which can be applied to micro gas turbines. Furthermore, previous experimental data for the friction factor f and Colburn j factor were obtained in low or moderate temperature ranges, which may not be applicable to the actual operating temperature range of a micro gas turbine.

Therefore, the main objective of the present work is to experimentally investigate the pressure drop and heat transfer characteristics of a recuperator for a micro gas turbine. For this purpose, a