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Transient thermal simulation of counterflow compact recuperator partition plates

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ABSTRACT

Design of high performance recuperators is essential for hybridized Carbonate and Solid Oxide fuel cell power plants. This work is focused on the transient thermal simulation of simplified counterflow recuperator partition plates. A finite difference scheme was written to model heat transfer in two spatial dimensions and one time. Results clearly show the effect of temperature ramping rate on transient thermal behavior. Excessive thermal stress derived from transient operation has been a crucial mode of structural degradation for conventional gas turbine recuperators. Results show that harmful temperature gradients in recuperator plates during transient operation is minimal for high temperature fuel cell ramping rates compared to conventional gas turbine ramping rates. Based on this analysis it is suggested that employing slower temperature ramping permits the use of higher performance recuperators. Stress analysis results from another study affirm this declaration, as well as suggest that plastic strain damage incurred from transient operation may be ignored when determining recuperator service life if its temperature ramping rates are consistent with hybrid fuel cell and gas turbine systems.

1. Introduction

Fuel cell technology has been identified to meet simultaneous demands for more electric power and less pollution. In particular, high temperature fuel cells can utilize existing natural gas infrastructures effectively. Carbonate and Solid Oxide fuel cells operate at high temperature and reject a significant amount of heat so that hybridized fuel cell and gas turbine (FCGT) power plants are under investigation. Ultra high fuel to electricity conversion efficiencies (>70% LHV) of such designs have been projected [1].

On the other hand, high temperature fuel cell systems have much lower power density than competing gas turbine systems, turning recuperator size into an ever more critical issue. Many hybrid FCGT system designs also require a recuperator constructed out of an expensive high temperature alloy, further necessitating optimal performance. Furthermore, to achieve an overall system efficiency of >70% low recuperator pressure drops are generally required, initiating more challenges to creating a compact design.

Compact heat exchangers offer the ability to transfer heat between large volumes of gas with minimum footprint, i.e. minimum area requirement to accommodate the heat exchanger. A gas to fluid exchanger is considered compact if it has a heat transfer area to volume ratio greater than 700 m^2/m^3 on at least one of the fluid sides, Shah [2]. Compactness is a good indication of performance, the higher the compactness generally the higher the effectiveness for a given pressure drop, Oswald [3]. High compactness is desirable for performance, although increased compactness yields increased thermal stress, which can reduce recuperator life, Voss [4]. However, it is shown by the present work that when employing temperature ramping rates consistent with high temperature fuel cells, a recuperator with higher compactness and equal pressure drop can be designed to increase recuperator performance without reducing its service life.

2. Compact heat exchanger technology

For this work, compact heat exchanger technology (CHEX) applicable to hybrid fuel cell and gas turbine technology was extensively reviewed. Comparison of (i) brazed plate-fin, (ii) fin-tube, (iii) microchannel, (iv) primary surface and (iv) spiral designs was performed by rating each exchanger type with a set of essential criteria. Based on this rating procedure two CHEX designs namely, plate-fin and microchannel, were chosen for further review for the FCGT application. Counterflow recuperator size and configuration was evaluated by assuming a CHEX core constructed with the same fin geometry for both hot and cold fluid sides. Plain, strip, louver, and wavy plate-fin surfaces as well as the semicircular (printed circuit) microchannel surface were considered in this performance evaluation. All surface candidates and their properties geometrical and thermal-hydraulic were taken from the extensive

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Nomenclature

dx	Spatial increment across plate thickness (m)
dy	Spatial increment across plate length (m)
dz	Plate width (m)
cp	Heat capacity (J/gm K)
h	Convec. heat transfer coefficient (W/m^2 K)
k	Thermal conductivity (W/m K)
m_d	Mass flow rate (kg/s)
PQ	Percent Heat (−)
Q	Actual heat transfer rate (W)
Q_{max}	Maximum possible heat transfer rate (W)
t	Time (sec)
T	Temperature (K)
x	Horizontal spatial direction (m)
y	Vertical spatial direction (m)

Greek symbols

β	Compactness, ratio of heat transfer area on one side of a heat exchanger to the volume between the plates on that side (m^2/m^3)
ε	Heat exchanger effectiveness (Q/Q_{max})
ρ	Density, (kg/m^3)
ΔQ	Heat lag (W)

Subscripts

c	Cold fluid side
h	Hot fluid side
i	Inlet
o	Outlet
m	Mean
met	Metal

work of Kays and London [5]. Additional surfaces with higher levels of compactness were derived from the original surfaces taken from [5] using complete geometric similarity. Results calculated for the sake of surface comparison included core thermal density (heat duty per unit volume) and flow length as shown in Figs. 1 and 2, the magnitudes of which are exclusive to a particular set of recuperator specifications. The results showed that when considering typical FCGT process conditions, the louver fin surface can yield the highest overall recuperator performance by having the best combination of high core thermal density and long flow length. Thus, a counterflow plate-fin heat exchanger utilizing the louver type fin geometry was considered in this work.

2.1. Durability and transient operation

Historically, gas turbine recuperators have had very poor reliability. Plastic and creep deformation is derived in recuperator components primarily from thermal stress. The highest thermal stresses can occur during transient operation if the ramp rate is high enough. A recuperator life cycle analysis can be evaluated only when temperature distributions during steady state and ramp periods are obtained. Ideally, a representative stress strain cycle would be constructed for the various recuperator components. For the plate-fin design, three major components to consider are the partition plates, fins, and plate-fin connections. In this work, a thermal model was developed to analyze transient counterflow recuperator operation, which was used to evaluate the transient temperature profiles of the working fluids and partition plate.

Temperature ramping rates in FCGT system recuperators can be several orders of magnitude slower than conventional gas turbine recuperators if they follow the same transients as the fuel cells. Given a slow ramping rate, a more compact recuperator with the same pressure drop can be designed while still maintaining sufficient recuperator life. The configuration of which will be characterized by having a short flow length and large frontal area. The point to which thermal performance can be increased or pressure drop decreased (both coincident with shortening partition plate flow length) can be evaluated subsequent to the analysis discussed in this paper.

3. Mathematical formulation

To evaluate service life, calculation of thermal profiles during transient operation is needed to calculate peak stress levels, followed by plastic and creep deformation. To address this task for counterflow recuperator partition plates, an alternating direction implicit (ADI) finite difference scheme was written to model transient heat flow between the partition plate and the hot and cold working fluids.

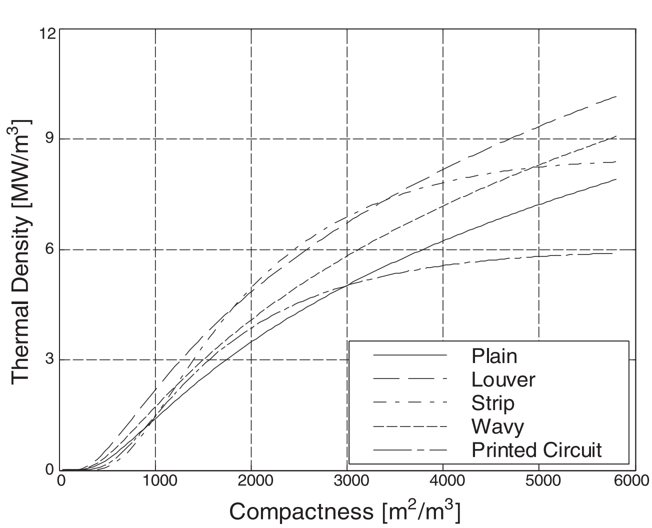

Fig. 1. Fin comparison, resultant core thermal density versus fin compactness.

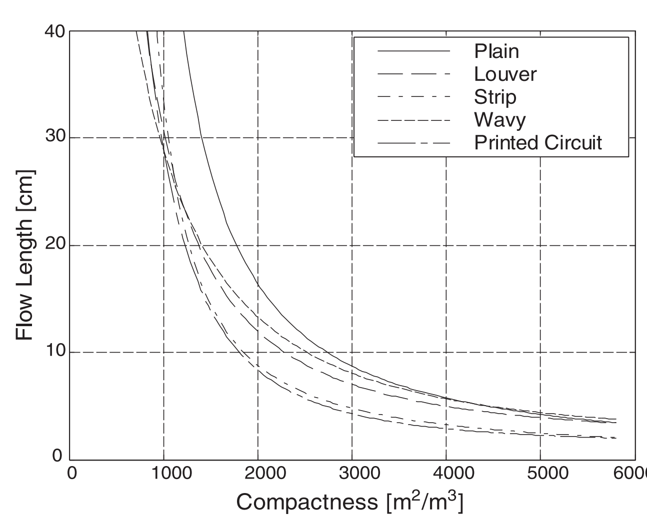

Fig. 2. Fin comparison, resultant core flow length versus fin compactness.