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PREDICTED PERFORMANCE OF A CERAMIC FOAM GAS PHASE HEAT RECUPERATOR FOR A SOLAR THERMOCHEMICAL REACTOR

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ABSTRACT

The efficiency of solar thermochemical cycles to split water and carbon dioxide depends in large part on highly effective gas phase heat recovery. Heat recovery is imperative for approaches that rely on an inert sweep gas to reach low partial pressures of oxygen during thermal reduction and/or use excess oxidizer to provide a higher thermodynamic driving potential for fuel production. In this paper, we analyze heat transfer and pressure drop of a tube-in-tube ceramic heat exchanger for the operating conditions expected in a prototype solar reactor for isothermal cycling of ceria. The ceramic tubes are filled with reticulated porous ceramic (RPC). The impacts of the selection of the composition and morphology of the RPC on heat transfer and pressure drop are explored via computational analysis. Results indicate a 10 pore per inch (ppi), 80–85% porous alumina RPC yields effectiveness from 85 to 90 percent.

INTRODUCTION

Water and carbon dioxide splitting thermochemical cycles driven by concentrated solar energy are a promising means of storing solar energy in chemical form. Of specific interest here is an isothermal non-stoichiometric cerium dioxide (ceria) cycle [1–3] in which the swing in non-stoichiometry between reduction and oxidation is accomplished by cycling between reducing and oxidizing atmospheres while operating continuously on-sun. Compared to a temperature swing redox cycle, isothermal cycling eliminates the need for solid-phase heat recovery and reduces thermally induced stresses in the reactor. However, based on thermodynamics of ceria [4], a lower partial pressure of O_2 over the ceria is required during reduction to produce an equivalent amount of fuel. Thus, when sweep gas is used, effective gas phase heat recovery is essential to reach solar-to-fuel efficiencies of 5% or higher [1,2]. The challenge is to design a heat exchanger with high effectiveness for operating temperatures as high as 1500 °C and to integrate the heat exchanger with the solar reactor. Compact heat exchangers have been developed for other high temperature applications including gas turbines[5,6], diesel combustion systems [7] and hydrogen production from sulfuric acid decomposition [8–11], but these designs are made of metals or SiC, neither of which is suitable for the current application because of temperature limitations or incompatibility with the reactants.

In the present work, we analyze the potential of using a counter-flow heat exchanger comprising two concentric alumina tubes filled with reticulated porous alumina (foam).

APPROACH

As an initial scoping study to select the foam and to predict heat exchanger effectiveness, we present a computational fluid dynamic study for the geometry and operating conditions planned for operation of a $3kW_{th}$ reactor. The geometry of the heat exchanger is shown in Fig. 1 and specified inlet conditions and property values are listed in Table 1. We note that spectral optical properties of alumina are not well characterized.

The steady, two-dimensional, governing equations of mass, momentum and energy transport are solved in an axisymmetric cylindrical domain using Ansys Fluent to obtain temperature and velocity distributions and overall effectiveness (eq. (1)), and pressure drop (eq. (2)). The dense alumina walls are treated as opaque. The foam is treated as an absorbing-scattering-emitting homogenous medium with isotropic, gray, diffuse radiative properties. The optical thickness varies between 2 – 8 and 5 – 15 for the annulus and the inner channel depending upon the porosity and ppi of the foam[12]. The P_1 model is used to evaluate the radiative source term in the energy equation [13]

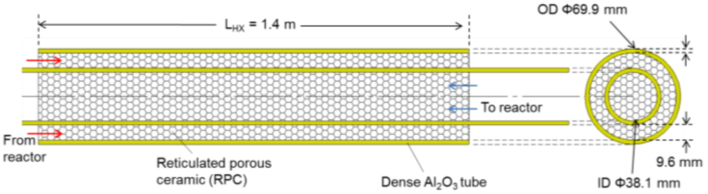

Fig. 1 Ceramic foam filled heat exchanger

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Table 1 Fixed model parameters

Parameter	Baseline value
Sweep gas (N_2) mass flow rate	1.8×10^{-3} kg s^{-1}
Oxidizer (CO_2) mass flow rate	9.0×10^{-4} kg s^{-1}
T_{in}	1500 °C
Scattering albido, ω [12,14]	0.8
Surface emissivity of dense alumina walls, ε_w[15]	0.6

RESULTS

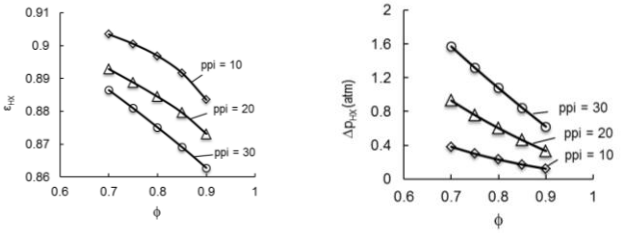
The effectiveness of heat recovery, $\varepsilon_{\mathrm{HX}}$, and pressure drop, Δp_{HX}, are determined for ppi = 10, 20 and 30 and ϕ = 0.7 – 0.9. Effectiveness is defined as

$$\varepsilon_{\mathrm{HX}} = \frac{\bar{h}_{\mathrm{g}}\left(T_{\mathrm{g,out}}\right) - \bar{h}_{\mathrm{g}}\left(T_{\mathrm{amb}}\right)}{\bar{h}_{\mathrm{g}}\left(T_{\mathrm{in}}\right) - \bar{h}_{\mathrm{g}}\left(T_{\mathrm{amb}}\right)} \tag{1}$$

and the pressure drop includes the Darcy and inertial losses,

$$\frac{\Delta p_{\mathrm{HX}}}{L} = \frac{\mu}{K}\mathbf{u} + F_{\mathrm{DF}}\rho_{\mathrm{f}}\,|\,\mathbf{u}\,|\,\mathbf{u} \tag{2}$$

Results are shown in Fig. 2 for the flow of sweep gas with conditions listed in Table 1. The 10 ppi foam provides the best performance, from the perspective of both heat transfer (Fig. 2a) and pressure drop (Fig. 2b). The larger pores enhance radiative heat transfer, creating a more uniform temperature distribution within the foam, and reduce viscous drag. Lower porosity increases heat exchange and negatively impacts pressure drop (Fig. 2(a) and (b)). Despite improved penetration of radiation for higher porosity, the reduction in solid phase conductivity is detrimental to heat exchange. Although, the trends for effectiveness (Fig. 2(a)) support the choice of lower porosity foams, the consequent increase in pressure drop is unfavorable to the overall reactor performance due to decreased driving force for oxygen release during the reduction step and increased pumping power of the gases. Based on initial efficiency estimates, we predict that, a10 ppi foam with 85-90% porosity will result in reasonable pressure drop (0.12-0.17 atm).



(a) (b)

Fig. 2 Dependence of (a) $\varepsilon_{\mathrm{HX}}$ and (b) Δp_{HX} on ppi and ϕ for sweep gas

CONCLUSION

The performance of a ceramic foam heat exchanger has been evaluated using a CFD model. The results indicate that large pores and low foam porosities increase heat exchanger effectiveness. We observe that conduction is the limiting mode of heat transfer. Further investigation will be conducted to better quantify the tradeoffs between pressure drop and heat exchanger effectiveness on overall reactor efficiency. For an overall flow length of 1.4 m, heat recovery effectiveness is 89 to 92% for the reducing and oxidizing operating conditions listed in Table 1.

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