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Computational Modeling of a Segmented-Involute-Foil Regenerator for Stirling Engines

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A microfabricated, segmented-involute-foil regenerator was numerically investigated using the Fluent commercial software under both steady- and oscillatory-flow conditions and using two- and three-dimensional numerical simulations. Steady-state simulations were performed for $Re = 50$–2000. The oscillatory-flow conditions were performed for $Re_{\max} = 50$ and $Re_{\omega} = 0.229$, with the hot end at 310 K and the cold end at 293 K. For the steady-state three-dimensional simulation, both the local friction factor and the local mean Nusselt numbers started to depart from the two-dimensional simulation values upon entering the second layer. At the entrance of every layer, the forced reorientation of the flow results in small rises of both the friction factor and the mean Nusselt number, with subsequent decrease as the flow settles into the new layer. As for the oscillatory-flow simulations, the two-dimensional model was used to study the effects of changing 1) the oscillation amplitude and frequency, 2) the thermal contact resistance between layers, and 3) the solid material. The effects of these parameters on the total regenerator heat loss (convection and conduction) were documented and are expected to be a useful tool for further development of Stirling engine regenerators.

Nomenclature

D_h, d_h = matrix hydraulic diameter, m
f_D = Darcy friction factor $= (\Delta p D_h)/[\rho(u_m^2/2)\Delta x]$
f_F = fanning friction factor $= f_D/4$
Nu = Nusselt number $= hD_h/k$
Nu_m = mean Nusselt number $= h_m D_h/k$
Nu_x = local Nusselt number $= h_x D_h/k$
Pe = Peclet number $= RePr$
Pr = Prandtl number
Re = Reynolds number
$Re_{\max}$ = maximum Reynolds number $= u_{m,\max} D_h/\nu$
Re_{ω}, Va = Valensi number $= \omega D_h^2/4\nu$
T = temperature, °C
T_c = cold end temperature, °C
T_h = hot end temperature, °C
t = time, s
$u_{\max}$ = maximum bulk mean velocity in regenerator, m/s
x = axial distance, m
x^+ = dimensionless length used for friction-factor plots $= x/D_h Re$
x^* = dimensionless length used for Nusselt number plots $= x/D_h Re\, Pr$
β = porosity
Δp = pressure drop, Pa
θ = crank angle, deg
μ = dynamic viscosity, kg/m · s
ν = kinematic viscosity, m^2/s
ρ = density, $\mathrm{kg/m}^3$
ω = angular frequency, rad/s

I. Introduction

THE Stirling engine regenerator has been called "the crucial component" (Organ [1]) in the Stirling cycle engine. The regenerator, which obtains heat from the hot working fluid and releases heat to the cold working fluid, recycles the energy internally, allowing the Stirling cycle to achieve high efficiency. The location of the regenerator within a Stirling convertor is shown in Fig. 1.

Currently, regenerators are usually made of woven screens or random fibers. Woven-screen regenerators have relatively high flow friction. They also require long assembly times which tend to increase their cost. Random-fiber regenerators also have high flow friction but are easy to fabricate and are therefore inexpensive. Figure 2 shows a typical random-fiber annular regenerator, and Fig. 3 shows a close-up of the fibers. Because of the method of fabrication, the fibers are random primarily in a plane perpendicular to the main flowpath. Thus, both woven screens and random fibers experience flow primarily across the wires (cylinders in crossflow). Cylinders in crossflow tend to cause flow separation resulting in high flow friction and considerable thermal dispersion, a thermal loss mechanism that causes an increase in apparent axial thermal conduction. For space engines, there must be assurance that no fibers of this matrix will eventually work loose and damage vital convertor parts during the mission. It is also important that local variations in porosity inherent to random-fiber regenerators not result in local mismatches in flow channels, which would contribute to axial thermal transport. Wire

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