International Journal of Heat and Mass Transfer 87 (2015) 347–358

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Entropy Generation Minimization analysis of oscillating-flow regenerators

Paulo V. Trevizoli, Jader R. Barbosa Jr. *

POLO – Research Laboratories for Emerging Technologies in Cooling and Thermophysics, Department of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis, SC, Brazil

ARTICLE INFO

Article history:
Received 16 December 2014
Received in revised form 14 March 2015
Accepted 25 March 2015
Available online 21 April 2015

Keywords:
Passive regenerator
Effectiveness
Entropy Generation Minimization
Performance evaluation criteria

ABSTRACT

The thermodynamic efficiencies of regenerative cooling cycles are directly linked to the heat transfer effectiveness and thermal losses in the regenerator. This paper proposes a performance analysis for regenerators based on the Entropy Generation Minimization (EGM) theory. The mathematical model consists of the one-dimensional Brinkman–Forchheimer equation to describe the fluid flow in the porous matrix and coupled energy equations to determine the temperatures in the fluid and solid phases. The cycle-average entropy generation contributions due to axial heat conduction, fluid friction and interstitial heat transfer are calculated. The influences of parameters such as the mass flow rate, operating frequency, regenerator cross sectional area, housing aspect ratio, utilization factor and particle diameter are evaluated according to the variable geometry (**VG**) and fixed face (cross-section) area (**FA**) performance evaluation criteria (PEC). Optimal regenerator configurations are found for each PEC for flow rates between 40 and 300 kg/h (0.01 and 0.083 kg/s) and frequencies between 1 and 4 Hz with constraints of regenerator effectiveness equal to 95% and temperature span of 40 K.

1. Introduction

Oscillating-flow regenerators are storage-type heat exchangers in which hot and cold fluid streams flow in alternating directions through a porous matrix. Intermittent heat transfer takes place between the solid and the fluid so that during a hot blow the high-temperature fluid warms up the solid matrix that accumulates thermal energy. In the cold blow, the matrix releases the stored energy as heat, and warms up the fluid [1–3]. Regenerators are widely employed in power and cooling gas cycles such as the Stirling, pulse-tube, thermoacoustic, Gifford–McMahon and Vuillemier cycles. Regenerators that use liquids as thermal fluids are encountered in some magnetic cooling cycles. In the Brayton magnetic cooling cycle, for example, the regenerator can be classified as *active* because the solid matrix is made of a magnetocaloric material that is heated up or cooled down (with respect to the ambient temperature) when the regenerator is magnetized or demagnetized adiabatically [4–6]. The active regenerator concept can be extended to other energy conversion mechanisms, such as the electrocaloric and mechanocaloric effects [7–9]. Although working prototypes exploring the latter effects have not yet reached the development stage of their magnetocaloric counterparts, it is likely that liquids will also be the heat transfer fluid of choice for near room temperature applications [10].

In active regenerators, the structure and the geometry of the solid matrix have to be optimized to reduce the thermal, viscous and other losses and achieve the desired operating conditions of temperature span, cooling capacity and cycle efficiency. An ideal regenerative matrix geometry is one with a large thermal mass, large surface area and high thermal conductance, but negligible viscous and axial conduction losses. Due to the sometimes prohibitive manufacturing and processing costs of magnetocaloric, electrocaloric and mechanocaloric materials, it is not always possible to make systematic experiments with different solid matrix geometries. Nevertheless, experiments with passive solid matrices may help to quantify the influence of the porous medium geometry on the thermal–hydraulic performance of the regenerator independently of magnetic related (or similar types of) losses in the matrix [11,12].

In a heat exchanger, there must be good thermal contact between the fluid and solid phases, but the latter should offer a small resistance to the fluid flow. These conflicting requirements are often equalized using thermal optimization. A regenerator can be designed for optimal performance according to the Entropy Generation Minimization (EGM) method [13]. A recent

* Corresponding author.
E-mail address: jrb@polo.ufsc.br (J.R. Barbosa Jr.).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.03.079
0017-9310/

Nomenclature

Roman

A_c	cross-section area [m^2]
A_s	interstitial heat transfer area [m^2]
A_t	amplitude of the pressure waveform [m/s^2]
c	specific heat capacity [J/kg K]
c_p	specific heat capacity at constant pressure [J/kg K]
c_E	Ergun constant [–]
$D_{\parallel}$	longitudinal thermal dispersion coefficient [m^2/s]
$D_{h,h}$	regenerator housing hydraulic diameter [m]
D_p	particle diameter [m]
f	cycle frequency [Hz]
$\hbar$	convective heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
K	permeability of the porous medium [m^2]
L	regenerator length [m]
$\dot{m}$	mass flow rate [kg/h]
NTU	Number of heat transfer units [–]
Nu	Nusselt number [–]
p	pressure [kPa]
Pe	Péclet number [–]
Pr	Prandtl number [–]
Re	Reynolds number [–]
S_g	cycle average entropy generation [J/K]
$\dot{S}_g'''$	entropy generation rate per unit volume [W/K m^3]
t	time [s]
T	temperature [K]
T_C	cold source temperature [K]
T_H	hot source temperature [K]
u	superficial (Darcy) velocity [m/s]
$\vec{v}$	velocity vector [m/s]
z	axial coordinate [m]

Greek

α	thermal diffusivity [m^2/s]
β	surface area density [m^2/m^3]
ϵ	effectiveness [–]
ε	porosity [–]
ϕ	utilization factor [–]
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ω	angular frequency [rad/s]
ρ	density [kg/m^3]
τ	cycle period [s]
ζ	regenerator housing aspect ratio [–]

Subscripts and superscripts

D_p	particle diameter
f	fluid phase
FAC	fluid axial conduction
HT	heat transfer
min	minimum
s	solid phase
SAC	solid axial conduction
VD	viscous dissipation
eff	effective
$\bar{x}$	average value (overbar)

review of applications of the method in the context of heat exchangers and storage systems was presented by Awad and Muzychka [14]. Krane [15] evaluated the performance of regenerators using gases as working fluids and concluded that the storage and removal processes need to be analyzed together to determine the optimum characteristics of these devices, which were observed to be quite inefficient (i.e., 70–90% of the available exergy is destroyed by the end of a cycle). Das and Sahoo [16] used the EGM method in the thermodynamic optimization of regenerators under single blow operation. Their model disregarded the axial heat conduction and was valid only for low values of *NTU*. An optimum operating condition was identified in terms of the cycle time and *NTU*. In a subsequent work, Das and Sahoo [17] included the time dependence and the axial conduction in the EGM analysis, thus extending the validity of their model to more densely packed regenerators operating at higher values of *NTU*.

de Waele et al. [18] and Steijaert [19] applied the EGM method to pulse-tube cryocoolers, taking into consideration the entropy production in every component (orifice, heat exchangers, regenerator, switching valves). The model was used to evaluate the thermodynamic performance of a cryocooler prototype. Based on the work of de Waele et al. [18], Nam and Jeong [20] employed the EGM method in the analysis of parallel-wire (segmented and unsegmented) mesh regenerators. They observed a better performance of the unsegmented parallel-wire configuration (in comparison to a screen mesh matrix) as a result of lower values of porosity and friction factor. However, axial heat conduction was identified as the main source of irreversibility in the parallel-wire case. To overcome this loss, a segmented parallel-wire geometry was used to decrease the axial conduction irreversibility and improve the thermodynamic performance of the parallel-wire regenerator.

The present work proposes a calculation procedure based on the EGM method to design optimal passive oscillating-flow regenerators. The mathematical model is composed of the one-dimensional Brinkman–Forchheimer equation for momentum transfer in porous media coupled with energy balance equations for the fluid and solid phases. The local instantaneous velocity and temperature fields are used in the calculation of the local rates of entropy generation per unit volume due to fluid friction, axial heat conduction in both media and interstitial heat transfer with a finite temperature difference between the phases. Since the ultimate application of the present method involves the optimization of active magnetic regenerators, the thermal fluid has been treated as water. As performed by Pussoli et al. [21] in the optimization of peripheral-finned tube recuperators, the total entropy generation, S_g, was used as the objective function in a calculation procedure to identify optimal regenerator configurations making use of the performance evaluation criteria (PEC) of Webb and Kim [22]. In these PEC, the heat exchange device can be optimized according to variable geometry (**VG**), fixed face area (**FA**) or fixed geometry (**FG**) constraints, which may be useful in the context of regenerator design for both passive and active magnetic applications. For instance, while the **FA** PEC can be used to evaluate the most suitable operating conditions of existing devices (i.e., those whose physical dimensions cannot be changed), the **VG** PEC is applicable in the earlier stages of system design in order to determine the optimal aspect ratio of the regenerator for a given volume of solid material.

It is worth pointing out that the so-called "entropy generation paradox" [23] is not applicable in the present analysis because the heat transfer rate (heat duty) is a fixed constraint in all calculations and the rate of entropy generation due to fluid friction can be of the same order of magnitude (i.e., non-negligible) as those associated with heat transfer. As shown in [24] for recuperators, there is an optimum *NTU* associated with the minimum entropy generation rate. Additionally, the heat exchanger