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Thermal–hydraulic evaluation of oscillating-flow regenerators using water: Experimental analysis of packed beds of spheres

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ABSTRACT

Thermal regenerators that use liquid heat transfer fluids are being researched for their application in active caloric cooling/heat pumping systems. The performance of active caloric devices is significantly influenced by the regenerator thermal effectiveness and by viscous losses. The present paper is the first part of a study on the thermal–hydraulic evaluation of packed bed regenerators that use water as a thermal fluid. Here, a detailed experimental analysis of the thermal–hydraulic performance of regenerative matrices composed of packed beds of stainless steel spheres is carried out. A laboratory apparatus was developed to quantify the viscous losses and thermal effectiveness in oscillating-flow regenerators that use water as the heat transfer fluid. Operating parameters such as frequency and mass flow rate were varied to cover broad ranges of utilization and number of transfer units (*NTU*). The diameter of the spherical particles and the dimensions of the regenerator housing were also changed in order to evaluate their influence on the behavior of the time-dependent and time-average performance parameters.

1. Introduction

An oscillating-flow regenerator is a storage-type heat exchanger where hot and cold fluids flow at alternating periods through a porous matrix, giving rise to intermittent heat transfer between the solid and the fluid. During a hot blow the fluid at a higher temperature exchanges heat with the solid phase, warming up the matrix that stores thermal energy from the fluid phase. In the cold blow, the matrix releases the stored energy as heat, which warms up the fluid [1–4]. While it is easy to increase the thermal performance by using larger regenerator beds, there are penalties associated with pressure drop and matrix volume [5,6].

One of the main applications of oscillating-flow regenerators that use liquids as thermal agents is in active caloric cooling systems, such as the active electrocaloric [7], elastocaloric [8] and active magnetic regenerators [9–11], which are being researched by several groups worldwide. The search for regenerator configurations and operating parameters capable of giving satisfactory values of temperature span and thermal efficiency at reasonable manufacturing costs has been the main focus of some of the latest developments [11–13].

The thermal–hydraulic performance of an active magnetic regenerator (AMR) is directly linked to the regenerator pressure drop and heat transfer, which can be studied experimentally and numerically by means of passive devices. Without having to consider the magnetocaloric phenomena, the regenerator matrix can be manufactured with more conventional materials, at a lower cost [5,13]. This way, new data on the thermal–hydraulic performance of regenerators using liquids can be a valuable source of information to the development of improved methods for AMRs [14], including a more thorough evaluation of the effect of carryover (void volume) losses and effectiveness imbalance on the regenerator thermal performance [5,15].

Passive devices can be designed as single-blow or as oscillating-flow regenerator systems. Marconnet [16] designed and built a single-blow regenerator test setup to study heat transfer in packed beds of spheres using water and water-glycol mixtures as heat transfer fluids. The proposed approach was to perform an experimental data regression to find a new Nusselt number correlation for liquids ($Pr \approx 10$). Using the same apparatus, Refs. [14,17,18] evaluated the friction factor and Nusselt number correlations for packed spheres. The general conclusion was that the Wakao and Kaguei [19] correlation overestimated the Nusselt number for

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Nomenclature

Roman	
A_{HT}	interstitial heat transfer area [m^2]
c	specific heat capacity [J/kg K]
$D_{h,Reg}$	regenerator housing diameter [m]
d_p	particle diameter [m]
f	cycle frequency [Hz]
f_D	friction factor [–]
h	convective heat transfer coefficient [W/m^2 K]
j	Colburn j-factor [–]
L_{Reg}	regenerator length [m]
m	regenerative matrix mass [kg]
$\dot{m}$	mass flow rate [kg/h]
NTU	number of heat transfer units [–]
Nu	Nusselt number [–]
P	pressure [kPa]
Re_{dp}	Reynolds number based on the particle diameter, $=ud_p/\nu_f$ [–]
t	time [s]
T	temperature [K]
u	superficial (Darcy) velocity [m/s]
U	overall heat transfer coefficient [W/m^2 K]
V_{pump}	displaced volume [cm^3]
$\dot{W}_{pump}$	pumping power [W]
Greek	
β_ϵ	effectiveness imbalance [–]
ΔT_{span}	$= (T_H - T_C)$ reservoir temperature difference [K]
ϵ	effectiveness
ε	porosity [–]
ϕ	utilization factor [–]
ν	dynamic viscosity [m^2/s]
ς	number of cycles [5 cycles]
ρ	density [kg/m^3]
τ	cycle period [s]
ϑ	total void volume size [cm^3]
ϑ^*	void volume fraction [–]
ζ_{Reg}	aspect ratio [–]
Superscripts and subscripts	
C	cold reservoir or cold side
CB	cold blow
CE	cold end
dp	based on particle diameter
f	fluid phase
H	hot reservoir or hot side
HB	hot blow
HE	hot end
Hex	reservoir temperature span
i	internal temperature reading
in	inlet flow
out	outlet flow
Reg	regenerator
s	solid phase
tot	total
tub	tubing
$\bar{x}$	indication of average value

aqueous solutions at low Reynolds numbers ($Re_{dp} < 100$). On the other hand, the well established correlation of MacDonald et al. [20] for the friction factor in packed bed porous media gave satisfactory results, with deviations of the order of the experimental uncertainties.

Schopfer [13] investigated experimentally and theoretically the thermal–hydraulic behavior of oscillating-flow regenerators using water. Two different matrix geometries were studied: packed beds of spheres and micro-channels. A new Nusselt number correlation was proposed for both geometries in terms of the kinetic Reynolds number. The Nusselt number results for the packed bed of spheres exhibited different trends with respect to the single-blow experimental results of Engelbrecht [17].

Engelbrecht et al. [21] investigated the effects of porosity, corrugation angle and the presence of dimples on the performance of parallel plate regenerators. The plates were made of aluminum with 0.4 mm thickness. The experimental analysis was carried out for wide ranges of cycle period and utilization. The best performance was found for a 90° corrugated plate regenerator. They also found that a decrease in porosity by reducing the plate spacing did not result in a significant increase in performance, although the heat transfer coefficient was expected to increase with the plate spacing.

Sarlah et al. [22] carried out experiments to compare the thermal–hydraulic characteristics of six passive regenerator geometries (the matrices were made of copper) in terms of the Colburn j-factor and the friction factor, f_D. The results were incorporated in a numerical model to predict the performance of active magnetic regenerators. They concluded that parallel-plate regenerators had the best COP performance due to their high j/f_D ratio. Packed bed regenerators, on the other hand, exhibited the highest temperature span, but the lowest values of COP.

Trevizoli et al. [5] performed experiments with passive regenerators using water as the thermal fluid. Three different packed beds were used: 1-mm stainless steel spheres, 0.5-mm lead spheres and 0.5-mm gadolinium spheres. For equivalent ranges of utilization, all matrices presented a high effectiveness, with the lead matrix showing the highest effectiveness and the smallest pumping power, due to a combination of large surface area per unit volume (small particle diameter) and low mass flow rates (large NTU). However, due to the low fluid velocities, the lead matrix was more susceptible to axial conduction losses. The gadolinium matrix exhibited a large effectiveness imbalance between the cold and hot blows due to a strong variation of the solid specific heat capacity with temperature. The Gd matrix also exhibited the highest viscous losses due to the small particle size and high superficial velocities, for the same utilization ranges.

As part of an ongoing research project at the Federal University of Santa Catarina, a new laboratory apparatus was designed and built to quantify the viscous losses and heat transfer effectiveness in oscillating-flow regenerators using water as the heat transfer fluid. The regenerator was designed to host different matrix geometries such as packed beds of spheres, parallel plates and pin arrays. The system performance was evaluated over a broad range of operating conditions in terms of the operating frequency, f, and utilization factor, ϕ, where the latter, for a fixed bed regenerator, is given by [4,23]:

$$\phi = \frac{\dot{m}c_p\tau_{blow}|_f}{mc|_s} \quad (1)$$

where $\dot{m}$ is the mass flow rate, c is the specific heat capacity, τ_{blow} is the time period of one blow and m is the mass of the regenerative matrix. The subscripts f and s stand for the fluid and solid phases, respectively. The utilization factor is the ratio of the thermal capac-