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An effective engineering computational procedure to analyse and design rotary regenerators using a porous media approach

Ahmed Alhusseny [a,b,*], Ali Turan [a]

[a] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK
[b] Mechanical Engineering Department, College of Engineering, University of Kufa, Najaf, Iraq

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ABSTRACT

A numerical analysis of the fluid flow and heat transport phenomenon through a rotary thermal regenerator is presented using a porous media approach. An aluminium core formed of multi packed passages is simulated as a porous medium of orthotropic porosity in order to allow the counter-flowing streams to flow in a way similar to that inside the regenerator core. Based on empirical equations, geometric properties of the core were transformed into the conventional porous media parameters such as the permeability and inertial coefficient; so, the core has been dealt with as a porous medium of known features. Heat is only allowed to transport within the rotating core, where a local thermal non-equilibrium situation is assumed there between the fluid and solid phases. The use of porous media approach has been found to be sufficient to solve the current problem. The results are presented by means of overall regenerator effectiveness, pressure drop, and the overall system performance. The impact of different design aspects were investigated such as the core geometrical characteristics, core dimensions, and operating conditions. The data obtained reveal an obvious impact of the parameters inspected on both the heat restored and the pressure loss; and hence, the overall efficiency of the regenerator system. Although regenerator effectiveness can be improved considerably by manipulating the design factors, care must be taken to avoid unjustified expenses resulted from potential augmentation in pressure drop.

1. Introduction

Improving performance of power generation plants while reducing the environmental damage caused by using fossil fuels remains of great concern. For achieving a high thermal efficiency in gas turbine systems, there are mainly two options available. The first is via applying a high compression ratio, which is accompanied by an intercooling process but requires higher fuel consumption. The second option is by applying a low compression ratio combined with recirculating heat between the cold stream and exhaust gas to recover a part of its thermal energy instead of releasing it directly to the environment. Heat recirculation is usually accomplished by means of two alternatives. A recuperator, in which a heat exchange between the cold and hot streams takes place across a separating wall between them. The other proposal is the regenerator, which allows heat exchange between the two streams through a common solid surface exposed to the hot and cold streams alternately, Organ [1]. Switching between the two streams can be achieved by several means. One of them, which is sometimes known as the "thermal wheel" or "rotary regenerator", is composed of a permeable core that rotates between two fixed channels carrying hot and cold gases as shown in Fig. 1, Organ [1]. The two streams flow continuously in opposite directions through a porous core, which has an orthotropic porosity to allow both gases to flow simultaneously in separate portions. This configuration was examined experimentally by Iwai et al. [2] and later by Sayama and Morishta [3] in the context of applying gas turbines into vehicular propulsion systems. These studies resulted in a way representing the regenerator effectiveness and pressure drop as functions of core specifications, which can be used for rotary regenerators operating in real engines.

In regard to air-conditioning applications, rotary regenerators have distinct advantages over ordinary recuperators in recovering heat from exhaust air (Worsϕe-Schmidt [4]). They have a substantially larger and comparatively less costly heat transfer area. In general, their efficiency is relatively higher, and hence, they have the potential to combine both compactness and high performance (Skiepko [5]). Also, the amount of heat transported can be regulated by means of adjusting the speed of rotation. A numerical, analytical and experimental study for the impact of rotation rate on the effectiveness of rotary regenerators was presented by

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[*] Corresponding author at: School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK.

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Nomenclature

a	pore size
a_{sf}	solid-to-fluid interfacial specific surface area
A	cross sectional area
A_f	frontal area of the core
A_s	heat transfer surface area of the rotating core
c_p	specific heat of fluid phase
c_s	specific heat of solid phase
C_f	heat capacity-rate for fluid $C_f = \dot{m}c_p$
C_s	heat capacity-rate for solid matrix $C_s = m_s\, c_s\, \Omega$
C^*	fluid heat capacity-rate ratio $C^* = C_{f,\min}/C_{f,\max}$
C^*_{sf}	solid to fluid heat capacity-rate ratio $C^*_{sf} = C_s/C_{f,\min}$
d_h	hydraulic diameter of passages forming the rotating core
D_i	inner diameter of the rotating core
D_h	hydraulic diameter of the rotating core, $D_h = D_o - D_i$
D_o	outer diameter of the rotating core
f	friction coefficient of passages forming the rotating core
F	inertial coefficient of the rotating core
Fo	Fourier number, $Fo = \alpha_s\, t_c/{D_h}^2$
h_{sf}	solid-to-fluid interfacial heat transfer coefficient
H_{sf}	dimensionless solid-to-fluid interfacial heat transfer coefficient
K	permeability of the rotating core
k	thermal conductivity
L	core length
m_s	mass of the rotating solid core
$\dot{m}$	fluid mass flow rate
n	core cell density or the number of packed passages per in^2
NTU	number of transfer units
OSP	overall system performance, $OSP = 0.5(Q_c + Q_h)/PP$
p	dimensional pressure
P	dimensionless pressure
PP	pumping power
Pr	Prandtl Number, $Pr = \nu_f/\alpha_e$
Q_c	heat rate gained by the colder stream, $Q_c = \dot{m}_c\, (c_{pc,2}\, T_{c,2} - c_{pc,1}\, T_{c,1})$
Q_h	heat rate given by the hotter stream, $Q_h = \dot{m}_h\, (c_{ph,1}\, T_{h,1} - c_{ph,2}\, T_{h,2})$
$Q_{\max}$	optimum heat transported from hot to cold stream, $Q_{\max} = \dot{m}\, (c_{ph,1}\, T_{h,1} - c_{pc,1}\, T_{c,1})$
Re	Reynolds number, $Re = \rho_f\, u_{in}\, D_h/\mu_f$
Re_p	pore Reynolds number, $Re_p = \rho_f\, u_p d_h/\varphi \mu_f$
s	core passages wall thickness
t	time
t_c	characteristic time, $t_c = D_h/u_{in}$
t_0	time required for one revolution
T	dimensional temperature
u, v, w	dimensional velocity components
U, V, W	dimensionless velocity components
$\bar{U}$	overall heat transfer coefficient
$\mathbf{v}$	dimensional velocity vector
$\dot{V}$	fluid volumetric flow rate
$\mathbf{x}$	dimensional position vector
x, y, z	dimensional coordinates
X, Y, Z	dimensionless coordinates

Greek symbols

θ	dimensionless temperature, $\theta = (T - T_{c1})/(T_{h1} - T_{c1})$
ρ	density
α_s	solid thermal diffusivity $\alpha_s = k_{se}/\rho_s\, c_s$
μ_f	dynamic viscosity
φ	core porosity
ε	regenerator effectiveness
κ_e	solid–fluid effective thermal conductivity ratio
γ	distinguishing parameter between the clear and porous regions
ξ	average contamination percentage at both exits of the rotating core
Ω	rotation speed
τ	dimensionless time

Subscripts

0	initial condition, stationary
c	cold stream, characteristic
e	effective
f	fluid phase
fe	fluid effective
h	hot stream
i, j	coordinates indices
in	inlet
s	solid phase
se	solid effective
sf	solid-to-fluid
t	total
w	wall
1, 2	inlet to/out from the core

Superscripts

n	normal to the boundary

Büyükalaca and Yilmaz [6]. It was found that the effectiveness is enhanced sharply with increasing the rotation level if the heat capacity of the rotating solid core or its rotational speed is small enough. A mathematical procedure for evaluating the regenerator effectiveness of rotary regenerators was proposed by Yilmaz and Büyükalaca [7]. The model presented can be applied for different geometrical shapes of channels that form the core of a rotary regenerator. Also, it is valid for a wide range of rotation levels because the influence of rotational speed was taken into account during calculating the values of regenerator effectiveness. In the experimental investigation conducted by De Antonellis et al. [8] for the rotating heat exchanger, correlations were proposed to predict the sensible and latent effectiveness besides pressure loss. It was found that these correlations can be employed to design thermal wheels for HVAC systems due to their simplicity and capability to predict the performance attained properly. Later on,

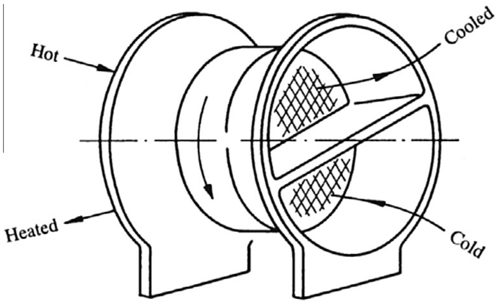

Fig. 1. Operation principle of rotary regenerator, Organ [1].