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Analysis of natural convection via entropy generation approach in porous rhombic enclosures for various thermal aspect ratios

R. Anandalakshmi, Tanmay Basak *

Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai 600 036, India

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ABSTRACT

Analysis of 'entropy generation' is an important strategy to build, optimize and operate the heat exchange systems within their maximum operating efficiency. Porous rhombic cavities with various inclination angles, φ and various thermal aspect ratios, A, have been considered for the numerical investigation of thermal processing of various fluids (Prandtl number, $Pr = 0.015$ and 1000) in the range of Darcy number ($Da = 10^{-3}$–10) due to its extensive energy related applications. The effect of A and φ for various governing parameters during convection are discussed in detail via heat transfer irreversibility (S_θ) and fluid friction irreversibility, S_ψ. At lower A, the entropy generation in the cavity is dominated by both S_θ and S_ψ for all φs irrespective of Da and Pr. As A increases, S_θ as well as S_ψ decreases for all φs which in turn decreases S_{total} with A irrespective of Da and Pr. The total entropy generation (S_{total}) is found to be lower for $\varphi = 30°$ and higher for $\varphi = 75°$ for all Pr and Da. Analysis of variations of Be_{av} with A for higher Da ($Da = 10$) indicates that, entropy generation is highly fluid friction dominant irrespective of φ and A. Lesser entropy generation (S_{total}) with larger heat transfer rate ($\overline{Nu_b}$) and reasonable heat transfer rate ($\overline{Nu_b}$) occurs for $Pr = 0.015$ and $Pr = 1000$, respectively at $\varphi = 30°$ cavities with all A irrespective of Da. Current work attempts to analyze energy efficient thermal convection strategies and role of thermal aspect ratio within porous rhombic enclosures based on entropy generation minimization vs heat transfer rates for various fluids.

1. Introduction

Second law analysis in the design of thermal and chemical processes has received considerable attention since last few decades. In a long series of recent publications related to the advancement in energy efficient industrial processes based on thermodynamic analysis, research community drew considerable attention to an important and ever growing industrial process for the application of "Engineering Thermodynamics" to achieve maximum possible efficiency: *Natural convective heat transfer process in energy exchange systems* [1–7]. There are several methods available in Engineering Thermodynamics such as exergy analysis, irreversibility minimization, entropy generation minimization etc. to build, optimize and operate the energy systems within their maximum operating efficiency. Also, several stages are available in the optimization of energy systems: (i) to identify the system(s)/process(s) which are responsible for energy losses, amount of energy losses, minimizing the energy losses subject to constraints of the system(s)/process(s) and minimizing the operating costs of the energy system.

There has been tremendous interest in study of entropy generation analysis after the pioneering work of Bejan [8], who designed heat exchangers based on specified irreversibility rather than specified amount of heat transfer. One of the first analysis of entropy generation in convective heat transfer was also done by Bejan [9] for a number of fundamental applications. In the recent past, approach of thermodynamic optimization known as 'Entropy Generation Minimization (EGM)' was reported by Bejan [10,11] to optimize real systems and processes.

Thermodynamic optimization is extensively useful in areas where the minimization of thermodynamic irreversibility is of vital importance. The classical example is internal heat transfer processes especially, natural convective heat transfer process within fluid or fluid saturated porous enclosures [12–27], where the loss of available energy is proportional to entropy generation in the processes. Earlier researchers used this technique in the field of mixed, forced and magnetohydrodynamic free convection processes [28–30]. Exergy is destroyed (or entropy is generated) whenever fluid streams of larger thermal or velocity gradients interact with each other and with walls of the enclosures. Thermodynamic optimization in heat transfer processes may be used in the preliminary stages of design itself by identifying more appropriate structural characteristics (configuration) for the energy exchange systems. More realistic system model can be designed through subsequent refinements in the optimization based on amount of energy losses, process constraints, cost minimization

* Corresponding author. Tel.: +91 44 2257 4173; fax: +91 44 2257 0509.
E-mail address: tanmay@iitm.ac.in (T. Basak).

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Nomenclature

A	thermal aspect ratio
Be_{av}	average Bejan number
c_p	specific heat capacity, kJ kg^{-1} K^{-1}
c_f	drag coefficient
d	diameter of the packing materials in the porous bed, m
dS_1	small elemental lengths along the left wall, m
dS_2	small elemental lengths along the right wall, m
D_e	equivalent diameter of the porous bed, m
Da	modified Darcy number
Ec	Eckert number
f^e	any function over an element
g	acceleration due to gravity, m s^{-2}
Ge	Gebhart number
k	thermal conductivity, W m^{-1} K^{-1}
K	Permeability, m^2
K_m	modified medium permeability, m^2
L	side of the rhombic cavity, m
N	total number of nodes
n	normal vector to the plane
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
Ra	modified Rayleigh number based on effective properties
Ra'	modified Rayleigh number
S	dimensionless distance along inclined walls
S_θ	dimensionless entropy generation due to heat transfer
S_ψ	dimensionless entropy generation due to fluid friction
S_{total}	dimensionless total entropy generation due to heat transfer and fluid friction
T	temperature of the fluid, K
T_H	maximum temperature at the center of the bottom wall, K
T_o	bulk temperature, K
T_h	temperature of hot wall, K
T_c	temperature of cold wall, K
u	x component of velocity, m s^{-1}
U	x component of dimensionless velocity
v	y component of velocity, m s^{-1}
V	y component of dimensionless velocity
X	dimensionless distance along x coordinate
x	distance along x coordinate, m
Y	dimensionless distance along y coordinate
y	distance along y coordinate, m

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
γ	penalty parameter
ϵ	medium porosity
θ	dimensionless temperature
τ	temperature difference number
μ	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
ϕ	irreversibility distribution ratio
φ	inclination angle with the positive direction of X axis
Φ	basis functions
ψ	dimensionless streamfunction
Π	dimensionless heatfunction

Subscripts

av	spatial average
b	bottom wall
eff	effective properties of fluid saturated porous media
f	fluid phase
i	global node number
k	local node number
l	left wall
r	right wall
s	solid phase
$total$	summation over the domain

Superscript

e	element

etc. The thermodynamic non-ideality of the heat transfer processes within the selected configurations is due to flow currents that must overcome resistances of fluid flow and heat flow in and out of the selected configurations. Therefore, performance of the heat transfer process within the system of selected configurations can be maximized in such a way that the flow resistances are minimized by optimal distribution of non-idealities within the system. This is due to the fact that the flow resistances are strongly interrelated through the geometric characteristics. Optimal spatial distribution of non-idealities i.e irreversibilities due to heat transfer and fluid friction in natural convection processes provides the system with optimal geometrical configuration, which further improves energy exchange systems toward better performance.

Industrial processes have long recognized the importance of natural convective heat transfer, which needs no additional energy during heat transfer. But it is also very well known that the amount of heat transfer during convection is proportional to the temperature gradient and that is further proportional to the fluid motion in order to sustain the required temperature gradient during heat transfer. Therefore, the fluid flow irreversibilities (or rate of exergy destruction) during fluid motion tend to be optimized for minimum rate of available energy consumption and maximum rate of energy transfer. Energy transfer and exergy destruction are closely related and this is why it is important to minimize energy consumption (i.e. exergy destruction) in all the flow systems that majorly constitute energy exchange.

The objective of this study is to analyze the entropy generation due to natural convection in rhombic enclosures filled with fluid saturated porous medium for various thermal aspect ratios between bottom and side walls in order to minimize entropy generation with the constraint of maximum heat transfer for various applications. Rhombic enclosures have attracted current attention due to the fact that the geometrical orientation of free and porous domains plays vital role in the ability to design optimal thermal systems in order to avoid possible device failures after the design has been finalized. Also, this geometry may find direct engineering applications (cooling of electronic devices) and natural applications (geothermal flows). Natural convection within the rhombic cavity is induced via various wall heating situations based on practical applications [31–34] and a generalized heating procedure at various walls may be implemented based on 'thermal aspect ratio (A)'.

Thermal aspect ratio (A) is defined as the ratio between non-isothermality of side walls to the total non-isothermality of bottom and side walls. Thermal aspect ratio (A) is varied from 0 to 1, thereby the corresponding thermal boundary conditions are maintained on the bottom and side walls in order to consider the effect of varying