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Thermal performance of annulus with its applications; A review

Hamdi E. Ahmed[a,b,*], Mirghani I. Ahmed[a,c]

[a] Department of Mechanical Engineering, International Islamic University Malaysia, 50728 Selangor, Malaysia
[b] Department of Mechanical Engineering, University of Anbar, 31001 Anbar, Iraq
[c] Department of Mechanical Engineering, Faculty of Engineering, Islamic University of Medina, Medina, Kingdom of Sudia Arabia

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ABSTRACT

The topic of heat transfer enhancement has attractive attentions to develop the compact heat exchanger design in order to obtain a high efficiency, low cost, light weight and size as small as possible. Therefore, the energy costs and environment considerations motivate researchers to optimize the thermal systems performance over the existing designs.

This study provides an overview on the investigations published in the last two decades particularly the recent studies published to improve the thermal systems design with minimal negative effects on the environment with high level of energy economic. Several parameters have been reviewed in this paper, which have pronounced effects on the free, mixed and forced convection heat transfer and pressure drop penalty. These parameters are: inner cylinder position, cross-sectional shape of the annulus, straight and curved annuli, moving one of cylinders of annulus, using of porous media, replacing base fluids by nanofluids, design the annuls with narrow gap between the two cylinders, effect of the size of the annulus (mini and micro scale size), using surface roughness, effect of critical heat flux, considering of surface radiation, boiling and refrigeration, and finally effect of surface vibration and applying of external magnetic field on the working fluid.

In addition, this study specifies the weakness points and the gap in this area of research which have not been investigated yet. These uninvestigated areas in annuli are still need more attentions investigations efforts from the researchers in order to get the optimum design for the annuli in different applications. Therefore, this article provides recommendations and hot topics require further investigational efforts to fulfill these gaps for more energy consumption and environment saving.

1. Introduction

The convection heat transfer and fluid flow in concentric and eccentric horizontal annuli is one of the most essential engineering applications. It has attracted great attention from researchers during the past decades due to its very wide and important applications such as solar collectors, heat exchangers, nuclear reactors, thermal energy storage systems and cooling of electronic equipment [1–3]. Kuehn and Goldstein carried out experimental and theoretical studies of natural convection in both concentric and eccentric cylindrical annuli. Their experimental results are still frequently used for validating most of the recent numerical results [4–6].

The numerous applications of helical or curved pipes such as bio-fluid mechanics (the blood flow in the catheterized artery), piping systems, cooling systems of rotating electrical machinery, lubrication systems, aerospace industries, chemical mixing or drying machinery, chemical reactors, chro-matography columns, and other engineering applications, motivated researchers to pay more attention for modifying it. Thus, flows in these configurations are investigated extensively during the last decades. In contrast, physical concepts of fluid flows inside helical or curved pipes are very much complicated due to centrifugal and pressure forces far away from the curvature center. Effects of centrifugal, pressure, inertia, viscous and gravitational forces make the flow pattern more complex [3,7].

The heat transfer and fluid flow through a rotating cylindrical annuli (where the outer or inner cylinder is fixed and the inner or outer cylinder is rotating), which is a classical problem in hydrodynamics. The speed of the rotating cylinder approaches to critical value in which the initial laminar flow becomes unstable to perturbation. The motion of inner or outer cylinder may be radially or axial with flow direction. For the first motions types, secondary flow is created as well as the axial flow direction which makes better mixing between the fluid and wall surface. The axial motion for the surface can be used for flows between two parallel plates to reduce the thermal resistance of boundary layer [8,9].

Buoyancy-driven flow and heat transfer in annular channels filled

* Corresponding author at: Department of Mechanical Engineering, International Islamic University Malaysia, 50728 Selangor, Malaysia.
E-mail addresses: hamdi.ahmed@uoanbar.edu.iq (H.E. Ahmed), mirghani@iium.edu.my (M.I. Ahmed).

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Nomenclature

Ar	aspect ratio
Bi	Biot number, Bi=h. L/k
Br	Brinkman number, Br=μu^2/2δq
CHF	critical heat flux
C_f	friction coefficient
CFD	computational fluid dynamics
c_p	specific heat capacity, J/kg K
D	diameter, m
Da	Darcy number, Da=K/d^2, K: permeability of the medium, d: diameter of particle.
De	Dean number, De=(ρ.u. D/μ).(D/2r)$^{0.5}$
D_h	hydraulic diameter, m, D_h=2δ
Eck	Eckert number, Eck=k.u^2/(c_p.q. D_h)
Fr	Froude number, Fr=u/w, w: characteristic water wave velocity.
Gr	Grashof number, Gr=g.β.q.r^4/k.ν^2
h	convection heat transfer coefficient, W/m^2. K
Ha	Hartmann number, Ha=M.L(σ/μ)$^{0.5}$
k	thermal conductivity, W/m. K
Kn	Knudsen number, Kn=kB. T/
L	characteristic length, m
M	magnetic field
Nu	Nusselt number, Nu=h. D_h/k
Pe	Peclet number, Pe=Re. Pr
Pr	Prandtl number, Pr =μ.c_p/k
q	heat flux per unit area, W/m^2
r	radius of curvature of the channel path, m
Ra	Rayleigh number, Ra=Gr. Pr
Re	Reynolds number, Re=ρ.u. D_h /μ
R_e	eccentricity ratio
R_g	gap ratio
R_r	radius ratio (r / R)
T	temperature, K
u	Fluid velocity, m/s

Greek symbols

δ	gap size of annulus, m
β	thermal expansion coefficient, 1/K
ν	kinematic viscosity, m^2/s
ρ	fluid density, kg/m^3
μ	dynamic viscosity, N/m.s
ϕ	nanoparticles volume fraction
ε	emissivity
σ	electrical conductivity

Subscript

eff	effective
f	fluid
s	solid

Abbreviation

Ar	aspect ratio
CFD	computational fluid dynamics
CHF	critical heat flux
CHX	co-axial heat exchanger
FDM	finite difference method
FEM	finite element methods
FIV	flow induced vibration
FVM	finite volume method
H_r	heat flux ratio
R_e	eccentricity ratio
R_g	gap size ratio
R_r	radius ratio

with a porous medium is the topic of many investigations in recent decades due to their technological applications. Because of the numerous industrial applications of porous medium during last few decades such as heat exchangers, cooling of electronic systems, energy recovery of petroleum resources, chemical reactors, thermal insulation of buildings, screw extrusion process and cooling of nuclear reactor solar collectors, which forced researchers to pay attention on it. In addition, radiation has a significant effect and cannot be ignored when convection is relatively small [10–12].

Solid ultra-fine metallic or nonmetallic particles with 1–100 nm in diameter are called nanoparticles, which dispersed in a base fluid to get what called nanofluids. Nanofluids have higher thermal conductivity compared to that of the base fluid. For this reason, nanofluids have been applied in many wide engineering applications, and one of them is in the annuli [13]. To the best knowledge of the authors, the initial experimental work on thermal conductivities of ultra-fine powder dispersed in base fluids was by Masuda et al., [9]. A tremendous number of investigations have been carried out to report higher thermal conductivities and subsequently higher heat transfer associated with nanofluids [14].

Narrow channels are also extensively used in nuclear industry. The heat transfer and fluid flow characteristics of these channels have a key role in the security and reliability of the nuclear equipment, particularly in the recent; the nuclear plants became widely used for electrical power generation. Many researchers have found that the heat transfer characteristics of narrow annuli are unlike those of conventional channels [15]. Narrow annular channel uses double-tubes for heat exchange and the gap size between these tubes is very small with range from 0.5 to 2.5 mm. In this narrow annular channel, flow patterns and heat exchange mechanisms are quite different from common tubes because of fluid restriction by the narrow gap [16].

Forced convection heat transfer and fluid flow characteristics through micro devices is still interesting research. A remarkable amount of researches has been devoted to this field due to a broad range of applications such as in micro-fluidic system components, micro heat exchangers, micro heat pipes, biomedical sample injection, and etc. [17]. The miniaturization of annulus heat exchangers to mini-, micro, and nano-scale led to increase the heat and mass transfer performance, saving material, low cost, and eventually larger heat transfer area per unit of volume. They are used in many applications such as cooling systems, biomedical applications, chemical reactors, and physical particle separation applications. The diameter of mini-channel heat exchanger is equal or smaller than the capillary constant. However, the heat transfer and fluid flow characteristics in mini-channel annuli has not received attention from researchers yet [18,19].

Helical fluted configurations are commonly implemented in co-axial heat exchangers (CHX) designs due to its better heat transfer coefficients and subsequently advantage of compactness. Since the heat transfer performance of CHX is dramatically influenced by the inner tube design, various outer surfaces of inner tube have been designed such as micro-finned tube, inner tube wrapped with fine wire, corrugated tube and fluted tube, etc. From literatures, these configurations led to better heat transfer rate with reasonable pressure drop penalty [20]. In addition, the wire generates a circulatory motion in which the swirling fluid flow disrupts the growth of thermal boundary layer. Therefore, the annulus wrapped with helical wire was considered as a heat transfer enhancer device (surface roughness) [21].

Forced convection subcooled boiling in annular channels is among