International Communications in Heat and Mass Transfer 62 (2015) 45–57

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Forced, natural and mixed-convection heat transfer and fluid flow in annulus: A review☆

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ARTICLE INFO

Available online 7 February 2015

Keywords:
Mixed convection
Natural convection
Forced convection
Concentric annulus
Eccentric annulus
Heat transfer enhancement

ABSTRACT

The enhancement of the thermal performance of heat exchanging equipment transport energy at low financial cost by various techniques is presented in this review. Heat transfer is classified into three forms, namely, conduction, convection, and radiation. Convection is one of the major modes of heat transfer that can be qualified in terms of being natural, forced, gravitational, granular, or thermomagnetic. In the past decade, several studies on convection heat transfer in annular pipes with nanofluids have been reported. The effect of eccentricity in horizontal, inclined and vertical directions on heat transfer rate in most numerical and experimental investigations for horizontal, inclined and vertical annular tubes is studied. The effects of heater length, as well as the Darcy, Prandtl, Reynolds, Grashof and Rayleigh numbers on heat transfer in concentric and eccentric annular tubes are also investigated. This paper reviews various researches on fluid flow and heat transfer behavior in an annulus. A basic description of the convection heat transfer is given. Numerical and experimental investigations are conducted according to the concentric and eccentric annuli. Finally, conclusions and important summaries are presented according to the collected data.

1. Introduction

Mixed-convection heat transfer exists when natural-convection currents are in the same order of magnitude as forced flow velocities [1]. Forced flows may be horizontal, vertical, or some angle between them. Mixed-convection flow occurs when both forced and natural (free) convection mechanisms significantly and concurrently contribute to the heat transfer. The relative contribution of each mechanism depends on the flow regime (laminar or turbulent) and the magnitude of the temperature driving force for heat transfer. In aided flows (heating in upward flow or cooling in downward flow), although the Reynolds number (*Re*) based on forced flow average velocity is nominal in the turbulent region, the velocities of forced flow and buoyancy forces are in the same direction and laminar-like flow is preserved. Therefore, aided flow situations are amenable to laminar flow analysis. In vertical internal flows, the buoyancy forces may be directed opposite to the forced flow (i.e., “opposed flow”) or in the same direction as the forced flow (i.e., “aided flow”). In opposed flow situations (heating in downward flow or cooling in upward flow), the velocities in opposite directions create shear instability and turbulence [2,3].

Convection heat transfer and fluid flow in annulus are important phenomena in engineering systems because of their technological applications in heat exchangers, nuclear reactors, thermal storage systems, aircraft fuselage insulation to underground electrical transmission cables, solar energy systems, boilers, cooling of electronic devices, compact heat exchangers, cooling core of nuclear reactors, cooling systems, gas-cooled electrical cables, thermal insulation, and electrical gas-insulated transmission lines [3–7].

Therefore, investigations on the heat transfer improvement in annulus are fundamental [8]. A number of researchers have conducted studies on the improvement of heat transfer characteristics in forced-convection applications. However, the heat transfer improvement in natural-convection applications has received little attention [9].

Heat transfer can be enhanced by employing different methodologies and techniques, such as increasing either the heat transfer surface or the heat transfer coefficient between fluid and surface that allows high heat transfer rates in a small volume. The enhanced thermal behavior of nanofluids could supply a basis for a huge innovation in heat transfer intensification. This technology is important to a number of industrial sectors, including manufacturing, transportation, power generation, micro-manufacturing, solid-state lighting, thermal therapy for cancer treatment, chemical and metallurgical sectors, heating, cooling, ventilation, and air-conditioning. Cooling is one of the most important technical challenges facing various diverse industries, including microelectronics. Therefore, a new improved performance for heat transfer is urgently needed [10,11].

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.01.006

Nomenclature

A	aspect ratio
AR	aspect ratio
b	dimensionless porous sleeve thickness, R_{porous}/R_i
b/*c*	axis ratio of elliptic tube
$C_{f,\ i}$	local friction factor at the inner walls
$C_{f,\ o}$	local friction factor at the outer walls
Da	Darcy number, K/R_i^2
D_H	hydraulic diameter
D_{in}	inner cylinder diameter
D_o	outer pipe diameter
dp, ds	diameter of particles
F	dimensionless volumetric flow rate
f Re	friction constant
g	gravitational acceleration, m s^{-2}
Gr	Grashof number, $g\beta\Delta TR_i^3/\nu^2$
H	height of the annulus, m
h	heat transfer coefficient W/m^2 K
HR	height ratio H/r_s
HRR	hydraulic radius ratio, R_o/R_i
K	curvature ratio
K	permeability, m^2
k	thermal conductivity, W/m K
k	Von Driest constant
K_{eq}	local equivalent conductivity
K_L	dean number
L	gap between inner and outer cylinder, i.e., $L = r_o - r_i$
L	annulus length, m
Le	Lewis number
N	buoyancy ratio
N	radius ratio, r_i/r_o
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number, hL/k
N_{us}	sensible Nusselt number
N_{uL}	latent Nusselt number
OHP	oscillating heat pipe
Pr	Prandtl number, ν/α
q	heat flux w/m^2
Ra	Rayleigh number, Gr. Pr
Ra^o	modified Rayleigh number
Ra_T	thermal Rayleigh number based on the gab width
Re_a	axial Reynolds number
Re_r	rotational Reynolds number
R_i	Richardson number, Gr/Re^2
R_i	radius of the inner cylinder
R_o	radius of the outer cylinder
R_{porous}	radius of the porous sleeve, m
RR	radius ratio, R_o/R_i
r	radial coordinate
Sh	Sherwood number
S_{total}	total entropy generation number
T	temperature, K
u′	dimensionless fin spacing
U*	resultant velocity
Z_t	dimensionless thermal distance, X/D_h Re Pr

Greek symbols

α	thermal diffusivity, $m^2\ s^{-1}$
ε	turbulent energy dissipation rate $m^2 \cdot s^{-3}$
ϕ	inclination angle
Θ	dimensionless temperature, $\Theta = (T - To) / (Ti - To)$
κ	radius ratio, Ro/Ri, dimensionless
λ	thermal conductivity, W/m K
ε	eccentricity $= e/r_2 - r_1$
σ	annulus gap width ratio $(2R_i / (R_o - R_i))$
φ	nanoparticle volume fraction
ή	radius ratio, R_i/R_o
θ	orientation angle
β	thermal expansion coefficient, K^{-1}

Subscripts

av	average
cond	conduction
eff	effective quantity
f	fluid phase
i	inner cylinder
l	local
m	density inversion point
max	maximum
o	outer cylinder
s	solid phase
x	local
*	dimensionless quantity

After a century of struggling to improve industrial heat transfer by fluid mechanics, the low thermal conductivity of conventional heat transfer fluids, such as water, oil, and ethylene glycol (EG) mixture, is currently one of the major limitations. The thermal conductivity of these fluids plays a significant role in the heat transfer coefficient between the heat transfer medium and surface. Thus, various methods have been proposed to improve the thermal conductivity of these fluids by suspending nano/micro- or large-sized particle materials in liquids. The thermal conductivity of subdivision metallic or nonmetallic materials, such as CuO, Cu, Al_2O_3, TiO, and SiO, is classically an order of magnitude higher than the base fluids even at low concentrations, resulting in important increases in the heat transfer coefficient (Table 1). The results for the three thermal conductivity models with various values of particle volume fraction ϕ are shown in Fig. 1. This figure shows that the thermal conductivity ratio of all models increases with increasing particle volume fraction. A linear relationship is observed among all models. The highest values are obtained by using Hamilton–Crosser model. The models of Hamilton–Crosser and Yu and Choi are relatively comparable, whereas Maxwell predicts lower thermal conductivity ratios than the former two models.

The discrepancy between the models increases with increasing particle volume fraction. Therefore, the effective thermal conductivity of nanofluids improves heat transfer compared with conventional heat transfer liquids [12,13]. This paper summarizes various researches on studying the fluid flow and heat transfer behavior in an annulus and the heat transfer enhancement in the annulus with nanofluids.

Table 1
Thermal conductivities of various solids and liquids [13].

Solids/liquids	Material	Thermal conductivity (W/m·K)
Metallic solids	Silver	429
	Copper	401
	Aluminum	237
Nonmetallic solids	Diamond	3300
	Carbon nanotubes	3000
	Silicon	148
	Alumina (Al_2O_3)	40
Metallic liquids	Sodium @ 644 K	72.3
Nonmetallic liquids	Water	0.613
	Ethylene glycol (EG)	0.253
	Engine oil (EO)	0.145