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Review

Summary and evaluation on single-phase heat transfer enhancement techniques of liquid laminar and turbulent pipe flow

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ABSTRACT

A comprehensive literature survey on the thermal–hydraulic performance of liquid flow and heat transfer in pipes with internal integral-fins, twisted tape inserts, corrugations, dimples, and compound enhancement techniques is conducted in this paper. The results of recent published papers with the developments of each technology are also included. It is found that for turbulent heat transfer the enhancement ratio of experimental Nusselt number over Dittus–Boelter equation for internal integral-finned tube is generally in the range of 2–4; twisted tape insert is 1.5–6; corrugated tube is 1.5–4 and dimpled tube is 1.5–4, including the compound enhancement techniques. The ratio of experimental friction factor over Fanning equation is mostly in the range of 1–4 for tubes with internal integral-fins, 2–13 for inserted twisted tape, 2–6 for corrugated tube and 3–5 for dimpled tube. The internally-finned tubes yield the best thermal–hydraulic performance compared with the other three types of tube, whose heat transfer rate augmentation over plain tube is more than the increase of friction factor at the same flow rate. For most of the corrugated and dimpled tubes, the heat transfer enhancement ratios are larger than the increment of pressure drop penalties. For the twisted tape inserts, the pressure drop is remarkably increased at the turbulent flow, and most of data have lower efficiency than the other three types of tube, while it is found to be effective in laminar and transition flow and higher viscosity fluid.

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Nomenclature

a	side length of equilateral triangle in the coiled wire cross section, m
A_n	nominal heat transfer area based on the internal diameter as if the fin structure were not present, m^2
A_a	actual heat transfer area, m^2
A_{fa}	actual flow area, m^2
A_{fc}	core flow area through an internally finned tube, m^2
A_{fn}	nominal flow area based on the internal diameter as if the fin structure were not present, m^2
A_{fin}	inner fin flow area through an internally finned tube, m^2
$\bar{B}(e^+, \alpha)$	friction factor correlating parameter for helical-rib roughness, dimensionless
$\bar{B}(e^+)$	friction factor correlating parameter for geometrically similar roughness and friction similarity function, dimensionless
c	distance between inner wall of the tube and twisted tape insert, m
d_i	inside diameter of the tube, m
d_h	hydraulic diameter, m
d_p	diameter of dimples, m
e^+	roughness Reynolds number $(e/d_i)\mathrm{Re}(f/2)^{1/2}$, dimensionless
e	absolute roughness (fin height), m; Fin height on the twisted tapes, m; wire diameter, m
E	inserted tape-to-tube wall gap thickness, m
F	function in the correlation of Carnavos [37] (1980)
f	Fanning friction factor
Gr	Grashof number, $g\rho^2 d_i^2 \beta \Delta T_w/\mu^2$
$\bar{g}(e^+)$	heat transfer correlating parameter for geometrically similar roughness, dimensionless
Gz	Graetz number
H	non-dimensional fin height $(2e/d_i)$, pitch for 180-deg rotation of tape, dimensionless
l_c	characteristic length, m
l_{mc}	modified characteristic length for swirling flows, m
L	length of test section, m
L_p	protrusion spacing, m
$\dot{m}$	flow rate, m^3/s
n	index of Prandtl number in Dittus–Boelter equation
N_s	number of starts
Nu	Nusselt number
Nu_i	axially averaged Nusselt number based on internal diameter of the tube
p	rib pitch, m
p_a	axial pitch of fins, m
p_c	circumferential pitch of fins, m
Pr	Prandtl number
ΔP	pressure drop, Pa
Ra	Rayleigh number, $Gr \cdot \mathrm{Pr}$
Re_{ax}	Reynolds number based on axial velocity, $\rho V_a d_i/\mu$
Re_i	Reynolds number based on internal diameter of the tube
Re_s	swirl flow Reynolds number
SW	modified non-dimensional axial pitch $(N_s \sin\alpha/\pi)$
s	mean fin thickness, (m)
t_b	fin base thickness, (m)
t_t	fin tip thickness, (m)
u^*	shear velocity, m/s
u	fluid velocity, m/s
V_a	mean axial velocity for internal twisted tape tube, $m \cdot/\rho A_c$, $A_c = (\pi d_i^2/4) - \delta d_i$, m/s
X_f	functions in the correlation of Wang et al. [36] (1996)
w	fin width, m; Width of twisted tapes, m, Width of indent, m
W	non-dimensional internal flow area $((\pi/N_s - s/d_i)\cos\alpha)$
Y_b, y_g	functions in the correlation of Wang et al. [36] (1996)

Greek alphabet

α	helix angle, (°)
β	flow attack angle, (°)
ν	kinematic viscosity, m^2/s
θ	fin apex angle or rib included angle in [38], (°)
λ	thermal conductivity, W/m·K
δ	tape thickness, mm
δ_t	wall thickness, mm
ρ	fluid density, kg/m^3
μ	fluid dynamic viscosity, (N·s)/m^2
τ	apparent wall shear stress, $\tau_o = -\frac{d_i dP}{4dx}$

Subscripts

c	corrugated tube
d	dimpled tube
f	fluid or internally finned tube
r	reference(plain) tube
s	smooth tube
t	tape inserts
w	tube wall

1. Introduction

Heat transfer in pipe flow is widely used in refrigeration, air conditioning, power, chemical and petrochemical industries. Various augmentation techniques have been utilized to enhance the single-phase convection heat transfer of pipe flow. Enhancement of heat transfer can reduce the size of heat exchangers, provide higher heat transfer efficiency, and yield savings of operating costs and materials. A great number of researches has been made on different kinds of pipe flow enhanced techniques. The major results of enhancement study, either numerical or experimental, are often expressed by two ratios, friction increase