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Review

Summary and evaluation on the heat transfer enhancement techniques of gas laminar and turbulent pipe flow

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ABSTRACT

A systematic survey and evaluation on the thermal-hydraulic performance of gas inside internally finned, twisted tape or swirl generator inserted, corrugated, and dimpled, totally 436 pipes is conducted in this work. The gases in the investigations involve air, nitrogen, exhaust gases, and helium. Prandtl number is around 0.6–0.7. It is found that in the Reynolds number of 2×10^3 to 100×10^3, the ratios of Nusselt number over Dittus-Boelter equation for internal finned tubes are typically in the range of 1–6, tubes with twisted tape and other inserts are 1.5–6, corrugated tubes are 1–3 and dimpled tubes are 1–4, including compound enhancement techniques. The ratios of friction factor over Blasius equation is normally in the range of 1.5–14 for internally finned tubes, 2–200 for inserted twisted tapes and swirl generators, corrugated tubes is 1.5–10 and dimpled tubes is 1–8. The heat transfer enhancement ratios for gases are generally similar with liquid, while the friction factor increased ratios for gases are higher than that for liquids. The number of investigations on the tubes fitted with twisted tapes inserts, coil loops, and swirl generators are more than other three enhancement methods. The increment of pressure drop for twisted tape inserts are also the largest. By using performance evaluation plot, different enhancement techniques with the same reference are compared for their effectiveness. It indicates that the efficiency of pipes with different types of inserts for gases are mostly lower than internal finned, corrugated and dimpled tubes in this survey.

Contents

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Nomenclature

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 ($A_n(1-H)^2$), 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
b	half of the fin spacing, m
$\overline{B}(e^+,\alpha)$	friction factor correlating parameter for helical-rib roughness, dimensionless
$\overline{B}(e^+)$	friction factor correlating parameter for geometrically similar roughness and friction similarity function, dimensionless
d_i	internal diameter of tube, m
d_h	hydraulic diameter, m
e^+	roughness Reynolds number $(e/d_i)Re(f/2)^{1/2}$, dimensionless
e	absolute roughness (fin height), m; Fin height on the twisted tapes, m
Gr	Grashof number, $g\rho^2 d_i^3 \beta\Delta T_w/\mu^2$, dimensionless
$\overline{g}(e^+)$	heat transfer correlating parameter for geometrically similar roughness, dimensionless
H	non-dimensional fin height ($2e/d_i$), pitch for 180-deg rotation of tape, dimensionless
n	index of Prandtl number in Dittus-Boelter equation
N_s	number of fins
Nu	Nusselt number
p	Rib pitch ($\pi d_i/N_s$), m
p_i	fin pitch based on fin tip diameter, m
ΔP	pressure drop, Pa
t_b	fin base thickness, m
u	fluid velocity, m/s
w	tape width, m
y	twist ratio, $y = H/w$
α	Helix angle, degree (°)
ν	kinematic viscosity, m^2/s
ϕ	Chamfer angle in [22], degree (°)
λ	thermal conductivity, W/m K
δ	tape thickness, m
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
s	smooth tube
r	reference
t	tape inserts
w	tube wall

1. Introduction

The encouragement and requirement to fabricate ultra-compact heat exchangers have driven the development of many types of surfaces to enhance the heat transfer. Because heat transfer enhancement of gases usually needs large surface area and the intensification from tube side is limited by space, the enhancement techniques typically locate in outside of tubes. However, although the heating or cooling of gas through internal tubes are not as prevalent as that in outside, there are still many applications in industry involving the heat transfer enhancement of gas laminar and turbulent pipe flow. The examples include compressor intercooler, solar air heaters, waste heat recovery from high temperature flue gas, gas turbine regenerator, heat transfer of natural gas in liquefier and vaporizer, earth or solar to air heat exchanger [1,2]. The methods to augment the heat transfer in tube-side usually involve extended surfaces such as internal fins, twisted tape inserts, corrugations and three dimensional roughness or protrusions.

Compared with pipe flow of liquid, gas has its unique characteristics. The thermal properties like Prandtl number, thermal conductivity, density, and specific heat capacity are quite different from liquid. Typically, air-side thermal resistance might constitute more than 80% of the total thermal resistance for heat transfer. Air-side heat transfer usually plays a critical role in the overall thermal resistance. Because there are many factors which can influence thermal-hydraulic performance, the heat transfer enhancement techniques and mechanisms of enhancement for gas might be different from liquid. Prandtl number of air is generally in the range of 0.6–0.7. Thermal conductivity is quite small, mostly within 0.05 W/m K [3,4]. The Prandtl number and thermal conductivity of water at 20 °C is as much as 10 times higher than air. Thus, the heat transfer coefficient of water should be higher than air more than one order of magnitude.

As gas-side thermal resistance is the most influential factor in overall heat transfer process, the heat transfer enhancement of that should contribute the most to the efficiency of heat exchanger. Many investigations were conducted to test the hydraulic and thermal performance of gas pipe flow. A systematic survey on the heat transfer of air turbulent flow inside internally finned tube was conducted by Webb et al. [5]. The parameters of fins and fluid are $0.01 < e/d_i < 0.04$, $10 < p/e < 40$, and $6000 < Re < 130{,}000$. Experimental results indicated that the improvements in heat transfer coefficients for internally finned tube (based on nominal surface area) were 250%. However, pressure drops are as much as 7–13 times higher.

The enhancement techniques for gases include integral-fins, inserted devices like twisted tapes and coils, swirl generators, corrugated or twisted tubes, dimpled or integral roughness and other three dimensional protrusions, which all have been used to improve heat transfer in both laminar and turbulent flow. Each technology has its unique features and the in-detail survey may