International Journal of Thermal Sciences 88 (2015) 201–214

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Entropy generation analysis for laminar thermal augmentation with conical strip inserts in horizontal circular tubes

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ARTICLE INFO

Article history:
Received 13 December 2013
Received in revised form
27 August 2014
Accepted 8 October 2014
Available online 3 November 2014

Keywords:
Entropy generation analysis
Thermal augmentation
Thermo-hydraulic performance
Laminar flow
Conical strip inserts
Numerical simulation

ABSTRACT

Our previous investigations demonstrated that conical strip inserts have good thermo-hydraulic performances based on evaluation criteria of the First Law of Thermodynamics. The present work is dedicated to further analyze the performances of these inserts from a viewpoint of entropy generation. Effects of alignment method and geometrical parameters on entropy generations of laminar heat transfer in the tubular flow are investigated. Local entropy generations are presented for discussion. Results show that entropy generation rates caused by non-staggered strips are about 81.1% that of staggered alignment, while the heat transfer rates and PECs of the former are about 33.8% and 13.5% larger than the latter counterparts, respectively. Moreover, the entropy generation rate (and thus irreversible loss) caused by heat transfer process overwhelms the counterpart by viscous flow. The total entropy generation number of enhanced tube, ranging between 0.0657 and 0.0975, is most sensitive to geometry angle with a maximum averaged relative variation of 32.2%. Its variation trend with Re is concave with a pit at Re = ~600. In brief, non-staggered inserts with a larger geometry angle and smaller strip-wall gap and pitch, facilitate a better thermo-hydraulic performance at Re = ~600 from the viewpoint of exergy loss reduction.

1. Introduction

For energy saving and cost reduction, heat transfer enhancement in heat exchangers has been extensively studied for several decades. Numerous thermal augmentation techniques have been developed and applied in various industrial fields to make the heat transfer process more efficient [1–8].

Enhancing the heat transfer rate on the tube side is always highlighted for the improvement of overall performance of heat exchangers. A variety of high efficient tubes, for example, spirally corrugated tube [9], helically rib-roughened tube [10], and micro-fin tube [11], have been developed for better performances on the tube side. Meanwhile, many kinds of tube inserts have been investigated for the tube-side enhancement. The twisted tapes are one type of frequently adopted inserts with good performance [12,13], because they generate spiral flow in tubes, which promotes the blending of bulk fluid and disturbs thermal boundary layer as well. However, the increment of flow resistance induced by a conventional twisted tape is relatively larger. To crack the nut, many developments and modifications have been presented, to name a few, segmented twisted tapes [14,15], broken twisted tapes [16], and center-cleared twisted tapes [17], etc. Wire coil is another type of tube inserts for heat transfer enhancement. It could induce spiral flow near the wall and block the development of viscous sublayer. Thus, the thermal augmentation is efficient in the turbulent regime, while the flow resistance is relatively smaller [18,19].

Usually, the heat transfer enhancement is accompanied by an increment in the flow resistance or required pumping power. In order to comprehensively evaluate the overall thermo-hydraulic performance, both the heat transfer rate and flow resistance should be taken into consideration. Up to now, a variety of performance evaluation criteria (PEC) have been proposed [20], to list a few, $[(Nu/Nu_0)/(f/f_0)]^{1/3}$, $(K/K_0)/(\Delta p/\Delta p_0)$ and $(h/h_0)/[(W/A)/(W/A)_0]^{1/3}$ are some frequently adopted ones, in which the subscript 0 stands for the values before being enhanced.

It is noted that the above-mentioned PECs make use of combined parameters based on the First Law of Thermodynamics, and no considerations are given to the irreversible losses of the energy quality or exergy. As is well known that heat transfer is driven by

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http://dx.doi.org/10.1016/j.ijthermalsci.2014.10.003
1290-0729/

Nomenclature

b	strip pitch, m
c_V	specific heat of constant volume, J/(kg K)
D	tube diameter, m
f	friction factor
g	gravitational acceleration, m/s^2
Gr	Grashof number
h	convection heat transfer coefficient, W/(m^2 K)
K	overall heat transfer coefficient, W/(m^2 K)
L	length, m
Nu	Nusselt number
N_s	entropy generation number
p	pressure, Pa
Δp	pressure loss, Pa
q_T	heat flux, W/m^2
q_V	volumetric flow rate, m^3/s
Re	Reynolds number
s	entropy, J/(kg K)
S_g^c	local entropy generation rate, W/(m^3 K)
S_g^t	tube entropy generation rate, W/K
T	temperature, K
u	velocity, m/s
W	pumping power, W
x, y, z	coordinate axis, m
ρ	density, kg/m^3
μ	dynamic viscosity, N s/m^2
λ	thermal conductivity, W/(m K)
α	slant angle, °
β	geometry angle, °
δ	strip-wall gap, m
γ	mean pressure gradient, Pa/m
α_V	volume expansion coefficient, 1/K

Subscripts

f	fluid
i, j	tensor
in	inlet
m	mean
out	outlet
w	tube wall

temperature difference, and heat amount keeps constant during the transfer process. However, according to the Second Law of Thermodynamics, the quality of thermal energy is degraded and some amount of exergy is dissipated. Meanwhile, extra entropy will be generated. Therefore, for a heat transfer process where the exploitation of exergy is highlighted, the analysis method based on exergy loss should be taken instead to minimize the entropy generation for an optimal design [21–23]. Although the minimal entropy generation principle was proposed several decades ago, many researchers still employ this principle in their studies on thermal augmentation [24–31]. Sahin [24] computed the dimensionless entropy generation to determine the optimum duct shape with constant heat flux and circular geometry was found to be the best. Moreover, he revealed that the viscous entropy generation becomes dominant under the condition of low heat flux [25]. Ko and Ting [26] and Ko [27] made use of the minimal entropy generation principle to optimize laminar forced convection in a rectangular curved duct with longitudinal ribs. They compared various rib arrangements and discovered that mounting a single rib on the heated wall could reduce the entropy generation most effectively.

Fan et al. recently developed a new insert with segmental conical strips for heat transfer enhancement, and demonstrated these inserts had good thermo-hydraulic performances based on the First Law of Thermodynamics in both turbulent and laminar flow regimes [32,33]. The current work is dedicated to further investigate the laminar thermal augmentation with conical strip inserts from the viewpoint of minimal entropy generation, including comparing thermo-hydraulic performances of enhanced tubes with staggered and non-staggered strip inserts, and examining the effects of geometrical parameters of strip inserts on the irreversible losses of convective heat transfer.

2. Numerical model and computational scheme

2.1. Physical model

Fig. 1(a) and (b) schematically shows the horizontal circular tubes fitted with non-staggered and staggered conical strip inserts, respectively. The inner diameters, D, of both tubes are 0.02 m. The dimension of conical strip is characterized by a geometry angle, β (=30°, 45°, 60° and 90°). The slant angle α (=30°, 40° and 50°) refers to the angle between the conical strip and the central rod. The strip-wall gap (δ) and strip pitch (b) are normalized by tube diameter D, with δ/D taking the values of 0.10, 0.15, 0.20 and 0.25, while b/D taking the values of 1.5, 2.25 and 3.0.

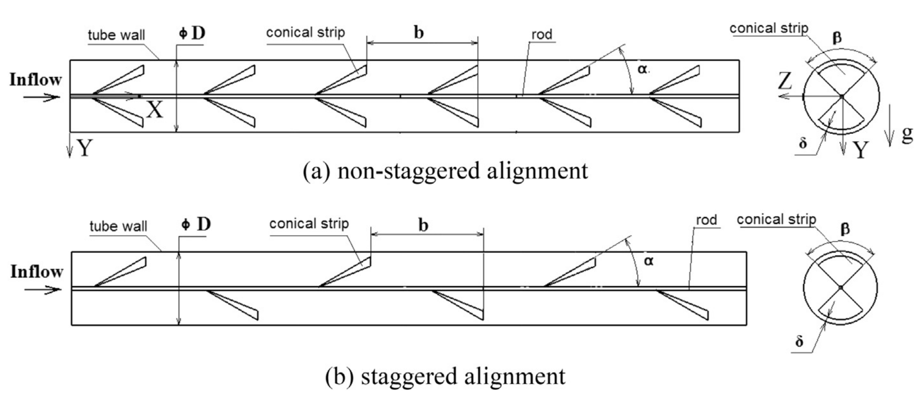

Fig. 1. Schematics of enhanced tubes with conical strip inserts. (a) Non-staggered alignment; (b) staggered alignment.