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Modulated heat transfer tube with short conical-mesh inserts: A linking from microflow to macroflow

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ABSTRACT

This paper creates new method that uses microflows through mesh pores to modulate flow and temperature fields. Modulated heat transfer tube (MHTT) was constructed by suspending consecutive conical-mesh inserts in a tube. Because there are too many 3D mesh pores (10–100 μm size) for a conical mesh insert, numerical simulations in laminar flow regime were performed by an 3D to 2D conversion of mesh pores applying equal equivalent diameter criterion and total flow area criterion of mesh pores. The multiscale grid generation linked micron scale of mesh pores and macroscale of the tube. Covering the present data ranges, MHTT had Nusselt numbers which are 1.4–4.1 times of that in a bare tube, *PEC* (performance evaluation criterion) was up to 2.2, demonstrating excellent heat transfer enhancement at low flow rate pumping cost. The perfect MHTT performance comes from the distinct flow field: an attached hydraulic boundary layer having large velocity and its gradient near the tube wall, a weak circulating flow region upstream of the mesh insert and a weakly positive flow region downstream of the mesh insert. A thin thermal boundary layer on the tube wall was reached to enhance heat transfer. The periodic unit length S and diameter of the conical mesh insert δ were optimized. The varied slopes of Nu versus Re were found and explained while increasing Re. There are best matches of *PPI* (pores per inch) and Re (Reynolds number). Low *PPI* mesh insert was suggested at low Re, high *PPI* mesh insert deformed streamlines to deviate from the perfect flow and temperature fields. Meanwhile, high *PPI* mesh insert had better performance at high Re. Low *PPI* mesh insert had good performance, which can be further improved by raising *PPI*. Because metallic mesh screen is commercialized and cheap, MHTT has wide potential engineering applications.

1. Introduction

Heat exchangers are widely used in petrochemical, energy and power industries. Recently, due to the energy shortage and environmental pollution, it is necessary to increase the energy utilization efficiency and decrease the cost of heat exchangers. In the past few decades, many heat transfer enhancement technologies have been developed, including active and passive enhancement technologies. The mechanical agitation, surface vibration, fluid vibration, applied electric and magnetic field belong to the active strategies, while the treated surfaces, rough surfaces, extended surfaces, swirl flow devices and nanofluid are the passive methods [1]. The tube insert is widely used, which is convenient to modify available equipments and clean the fouling. It is also cost-effective. Many researchers worldwide investigated the heat transfer enhancement with tube inserts.

Twisted tape inserts have been applied for a long time. Heat transfer with twisted tape inserts is enhanced by fluid mixing in the main flow region and resisting the boundary layer development near the tube wall. The effects of twisted ratio, pitch, length, width, twisted direction on the heat transfer enhancement were reported in Refs. [2–7]. Kumar & Prasad [2] found the heat transfer coefficients and pressure drops increased by 18–70% and 87–132%, respectively, when twisted ratios were in the range of 3–12. Sarada et al. [3] investigated turbulent heat transfer in a horizontal tube with twisted tape inserts with different widths using air as the working fluid. The heat transfer coefficients were increased by 12% when the widths of twisted tape varied from 10 to 22 mm. Eiamsa-ard et al. [4] found that the higher heat-transfer coefficients and pressure drops were increased with increases in the lengths of twisted tapes. Besides, the winglets were arranged on the surface of staggered/twisted tapes to promote the flow disturbance. It was found that the heat transfer was further improved by raising the contact angle of winglet on the twisted tape surface [5]. Wongcharee and Eiamsa-ard [6] studied the effect of clockwise and

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Nomenclature

A	flow area of total 3D mesh pore, m^2
A'	flow area of total 2D mesh pore, m^2
BT	bare tube without insert
C_p	specific heat, J/(kg K)
D	tube diameter, m
D_e	equivalent diameter of 3D mesh pores
D'_e	equivalent diameter of 2D mesh pores
EF	heat transfer enhancement factor
MHTT	modulated heat transfer tube with mesh inserts
f	friction factor
g	gravity acceleration ($g = 9.81$), m/s^2
L_1	the distance from the tube entrance to the first conical mesh insert, m
L_2	heat transfer tube length with consecutive mesh inserts, m
m	mass flow rate, kg/s
Nu	average Nusselt number (or called bulk Nusselt number)
Nu_x	local Nusselt number
p	pressure, Pa
Δp	pressure drop in a periodic unit, Pa
PEC	performance evaluation criterion
PPI	pores per inch
q	heat flux, W/m^2
q_w	the heat flux added to the wall, W/m^2
r	radial coordinate, m
Re	Reynolds number
S	periodic unit length, m
T_f	fluid temperature, K
$T_{f,ave}$	average fluid temperature, K
T_{grid}	temperature within the first fluid layer, K
T_{in}	inlet fluid temperature, K
T_{out}	outlet temperature, K
$T_{up,f}$	bulk fluid temperature at inlet, K
T_w	wall temperature, K
$T_{w,ave}$	average wall temperature, K
u	axial velocity, m/s
u_{in}	inlet velocity, m/s
u_{ave}	average velocity, m/s
w	square mesh pore width, m
w'	stripe-type mesh pore width, m
x	axial coordinate, m
y	first fluid layer thickness, m

Greek symbols

α	diverging angle of the conical mesh insert
β	pressure gradient within a periodic unit length, Pa/m
δ	diameter of conical mesh insert at maximum plane, m
η	3D mesh wire thickness, m
η'	2D mesh wire thickness, m
θ	temperature gradient, K/m
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3

Subscript

ave	average
b	bare tube
f	fluid
in	inlet
out	outlet
w	wall
x	axial coordinate

counterclockwise twisted tape inserts on the heat transfer, indicating better performance of staggered axis twisted tape inserts than common inserts. Guo et al. [7] studied effects of the width and hollowing center of twisted tape inserts on the heat transfer, showing the reduced flow resistance by reducing the insert width and increasing the hollowing center area. But, for the tube with narrow twisted tape insert, the heat transfer enhancement is weakened. For the tube with hollowing-center twisted tape insert, the heat transfer is apparently enhanced. There is no fluid mixing in radial direction for laminar flow. The fluid mixing in radial direction is enhanced for turbulent flow. For both flows the thermal resistance comes from the boundary layer thickness. For the tube with twisted tape inserts, heat transfer is enhanced due to strong swirl flow in bulk flow region and enhanced mixing in radial flow direction. Thus, tubes with twist tape inserts are more effective in heat transfer for laminar flow than for turbulent flow. Spiral coil is a new type of insert. Refs. [8,9] experimentally investigated convective heat transfer in tubes with spiral coil inserts in laminar, transition and turbulent flow regions. The performance is better for turbulent flow than that for laminar flow. Pressure loss was mainly influenced by the coil pitch. The smaller the pitch, the greater the pressure loss is. Promvonge [10] studied the heat transfer by inserting coils and twisted tapes in tubes, showing obvious heat transfer enhancement at low Reynolds numbers. Other tube inserts such as ribs, conical nozzle and vortex generator show better heat transfer performance in turbulent flow region [11–13].

It is known that the key issue related to convective heat transfer in tubes is the low velocity and velocity gradient near the tube wall. Cao et al. [14] proposed the flow field modulation concept using a porous mesh membrane insert, dividing the tube cross section into an annular region and a core region. Numerical simulation was performed in laminar flow regime at constant heat flux boundary condition with water as the working fluid. The results show double-peak velocity distribution over tube cross section. The near wall region has larger velocity and velocity gradient, accounting for the heat transfer enhancement mechanism. For a given Reynolds number, there is a critical length beyond which heat transfer is deteriorated. Thus, short mesh membrane inserts were recommended in the tube, ensuring significant heat transfer enhancement over the whole tube length. Xing et al. [15] experimentally studied forced convective heat transfer in tubes with porous mesh membrane insert. Constant heat flux boundary condition was applied with water as the working fluid. Reynolds numbers are varied from 2109 to 20,175 for transition and turbulent flow regimes. Heat transfer was enhanced over the whole tube length. The enhancement ratios were from 1.21 to 1.84. The largest enhancement ratio occurred in the transition flow regime. The heat transfer enhancement mechanism are due to the multiscale heat transfer tube, the modulated flow field with larger velocity and velocity gradient near the wall, and the enhanced flow turbulence intensity.

Here we created a new method using microflows through mesh pores to mitigate flow field. Consecutive conical-mesh inserts were suspending in a long tube, dividing the tube cross section into a near wall region and a bulk flow region. The central idea had the following aspects: (1) *Flow field modulation*: Microflows through mesh pores with suitable throttle effect decrease flow rate over the bulk flow region. Velocities and velocity gradients are significantly large near the tube wall. The method generated a totally inverse velocity distribution to that in a bare tube. (2) *Pressure*