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The fluid flow and heat transfer characteristics in the channel formed by flat tube and dimpled fin

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ABSTRACT

The steady laminar fluid flow and heat transfer characteristics in the channel formed by the flat tube and the dimpled fin are investigated numerically. The results show that the dimple radius, the dimple pitch and the fin spacing affect the average Nusselt number and friction factor, while the effect of the dimple radius and the fin spacing is larger than that of the dimple pitch. The average Nusselt number, the friction factor and the intensity of secondary flow in the dimpled fin case are larger than those in the plain fin case at the same *Re*, respectively. The correlations of Nusselt number, the friction factor with *Re* and other parameters are reported. The significant result is that whenever the same intensity of secondary flow is produced by increasing the radius of the dimples or other structural parameter such as increasing the fin spacing and the dimple pitch, the same heat transfer intensity is obtained. This implies that the intensity of secondary flow determines the heat transfer characteristics on the fin surfaces.

1. Introduction

Finned tube heat exchanger has been widely used in refrigeration, air conditioning, chemical industry, electricity power plants and other fields due to the advantages of compact structure and convenient operating. The direct air cooling system is the main component of most electricity power plant. This system uses mostly the heat exchanger with brazed silicon aluminum alloy fins on both sides of single flat tube as the condenser. Because of the single tube bundle has many characteristics, such as compact, high thermal efficiency, easy maintenance, easy cleaning, long working life and so on, it has broad application prospect.

The existing fin types of heat exchanger such as louver [1,2], herringbone [3,4], slit [5,6], etc. improved the heat transfer performance of heat exchanger at the cost of large increase of pressure drop. To improve the heat transfer performance of heat exchanger, new fin structure is studied by many scholars. In recent years, the vortex-based dimple heat transfer enhancement was introduced as a new heat transfer enhancement technique. It has been found that punching some dimples on fin surface can enhance the disturbance on fluid, destroy the development of the boundary layer, and the increase of pressure drop is not too much. The major characteristics included high heat transfer coefficients, low friction factors and high overall thermal performances [7]. Therefore, this kind of fin structure has been studied by many researchers.

Mahmood et al. [8] measured the local heat transfer of the surface having dimples and presented that lower Nusselt number ratios were located over the upstream halves of the depressions, while higher Nusselt number ratio was located the downstream halves, the highest values were located near the downstream rims of each dimple. Burgess and Ligrani [9,10] investigated the effect of the dimple depth on heat transfer and obtained the correlations of Nusselt number and friction factor ratio with the dimple depth. Moon et al. [11] investigated the surface heat transfer augmentation with an array of concavities in a rectangular channel using a transient thermo chromic liquid crystal technique, and stated that the heat transfer enhancement was lowest on the upstream concavity wall and highest in the vicinity of the downstream rim of the concavity. Fan et al. [12] predicted the air-side performance of dimpled fin surfaces with three-row staggered arrangement dimples in different inlet velocity. Yu et al. [13] studied the effect of different dimple shapes on hydrodynamic pressure generation between two parallel sliding surfaces by using a numerical method. Rao et al. [14] conducted comparative experimental study on the

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Nomenclature

A	cross-section area of flow passage [m^2]
c_p	specific heat capacity [kJ/(kg K)]
CRVGs	curve rectangular vortex generators
D	short axis length of flat tube [m]
D_{minor}	dimple diameter on minor axis [m]
d_e	hydraulic diameter, characteristic length [m]
F	total surface area involved in heat transfer in the computational domain [m^2]
f	friction factor: $f = 2\Delta P\ d_e/\rho\ u^2{}_{in}L$ [−]
J^n_{ABS}	volumetric average absolute vorticity flux in the normal direction
JF_1	evaluation criterion under identical pumping power
JF_2	evaluation criterion under identical flow rate
H	width of dimple wave fin [m]
h	convective heat transfer coefficient [W/(m^2 K)]
L	length of dimple wave fin [m]
Nu	Nusselt number: $Nu = hd_e/\lambda$ [−]
P	pressure [Pa]
R	dimple radius [m]
Re	Reynolds number: $Re = \rho\ u_{in}\ d_e/\eta$ [−]
S	Dimple pitch [m]
S_1	long axis length of flat tube [m]
Se	The intensity of secondary flow [−]
S_L	stream wise pitch [m]
S_T	span wise pitch [m]
T_p	fin spacing [m]
T	temperature [K]
U_s	characteristic velocity of secondary flow [m/s]
u_i, u, v, w	components of velocity vector [m/s]
VGs	vortex generators
x_i	x, y, z coordinates axes [m]

Greek symbols

ΔP	pressure drop [Pa]
δ	thickness of fin, tube [m]
δ_t	Thickness of flat tube [m]
δ_f	Thickness of dimple wave fin [m]
$\xi - \eta - \zeta$	body-fitted coordinator axes [m]
λ	thermal conductivity [W/(m K)]
ρ	fluid density [kg/m^3]
μ	dynamic viscosity [kg/(m s)]

Subscripts

ave	average
bulk	cross section averaged value
f	fin
in, inlet	inlet
local	local value
m	mean or average value
out, outlet	outlet
s	span-average or cross-section-average value
t	tube
w	wall or fin surface

pressure drop and heat transfer characteristics in the pin fin dimple channels with various dimple depths. The comparisons showed that, compared to the pin fin channel, the pin fin-dimple channels with all three studied dimple depths have further improved convective heat transfer performance by up to 19.0%, and the pin fin-dimple channel with deeper dimples shows relatively higher Nusselt number values. Lee and Lee [15] investigated the friction factor and Nusselt number in a plate heat exchanger with dimples and protrusions according to geometric and operating conditions. They found that the numerical results of a steady-state laminar model for the laminar region and a steady-state SST (shear stress transport) $k-\omega$ turbulence model for the turbulent region were in good agreement with an unsteady analysis. Rao et al. [16] made experimental and numerical studies of flow and heat transfer in channels with pin fin-dimple and pin fin arrays, and showed that, compared with the pin fin channel, the pin fin-dimple channel has further improved convective heat transfer performance by about 8.0%, and whereas lowered flow friction by more than 18.0%. Shen et al. [17] studied the effect of bleed hole on flow and heat transfer performance of U-shaped channel with dimple structure. Dimple structures are effective for heat transfer enhancement of the coolant channel. Fluid flows separate near the windward edge under the effect of negative pressure gradient and impinge at the dimple leeward side. Chen et al. [18] studied the heat transfer and flow structure characteristics on periodically dimple–protrusion patterned walls in turbulent channel flow. It was founded that larger depth/height induced higher friction factor and heat transfer, furthermore, the highest Nusselt number was found to be located at the upstream portion of protrusion and the downstream portion of dimple. Katkhaw et al. [19] investigated heat transfer behavior of the flat plate having 45 ellipsoidal dimpled surfaces. The results showed that the highest heat transfer coefficients for dimpled surfaces are about 15.8% better than the smooth surface. The dimple pitches of $S_T/D_{minor} = 1.875$ and $S_L/D_{minor} = 1.875$ (D_{minor} is dimple diameter on minor axis, S_L is stream wise pitch and S_T is span wise pitch) yielded the highest heat transfer coefficient values. Bi et al. [20] studied the local heat transfer characteristics in the mini-channels with enhanced dimples, cylindrical grooves and low fins. It is suggested that the deep dimple with large diameter can enhance heat transfer greatly.

Isaev et al. [21] analyzed numerically the vortex intensification of heat transfer in micro channels with oval dimples in the range of Reynolds numbers from 100 to 2500. The thermo hydraulic efficiency of the channel with oval dimples has been substantiated. Ligrani et al. [22] studied experimentally the dimpled surface which contains 13 staggered rows of dimples in the stream wise direction. Instantaneous, dynamic and time-averaged characteristics of the vortex structures which are shed from the dimples placed on one wall of a channel were described. They found that there is an important connection between the vortices, Reynolds normal stress, and mixing. Chen et al. [23] numerically studied the heat transfer in turbulent channel flow over dimpled surface for a series of Reynolds numbers between 4000 and 6000. It is found that the heat transfer enhancement is closely related to ejection with counter-rotating flow, intensified secondary flow and vortex structures at the downstream rim of asymmetric dimple. Dye flow visualization was conducted for dimples with depth to diameter ratios ranging from 5% to 50% by Tay et al. [24] as the Reynolds number varies from 1000 to 28,000. Six different stages in flow development of the large scale structures within the dimple are observed in the experiments. Not all six of these development stages occur for all dimples. Dimples with low depth to diameter ratios show fewer development stages than deeper ones. Sparrow et al. [25] simulated numerically the fluid-flow phenomena that