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Investigation on heat transfer and flow characteristics of heat exchangers with different trapezoidal ducts

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ABSTRACT

The laminar convective flow and heat transfer in trapezoidal ducts with a rectangular cross-section are studied numerically. Under certain conditions, the temperature difference distribution and pressure drop in trapezoidal ducts are better than that of in rectangular ducts, which leads to an advantage of heat transfer enhancement. At the same heat transfer area, the maximum Colburn (j) factor in trapezoidal ducts increases by 8% when compared with a rectangular duct, and the minimum friction (f) factor decreases by 22.6%. The numerical data also shows that the thermal-hydraulic characteristics for trapezoidal ducts first increases and then decreases while slope angle (β) increases. The airflow is disturbed at the wall showing recirculation flow and separation when $\beta = 30°$, but the thermal-hydraulic performance starts to decrease when $\beta > 40°$. In a word, the thermal-hydraulic characteristics of trapezoidal ducts are better than that of rectangular ducts when $\beta \leq 40°$. On the contrary, When $\beta > 40°$, the rectangular duct has a better performance than that of trapezoidal ducts. The applicability of the above conclusions is proved by using the taguchi method.

1. Introduction

Ducts with rectangle shapes are commonly used in various heat exchangers. The rectangle ducts are shown in Fig. 1(a) and (b). But in those applications, there are several disadvantages by using rectangle shaped ducts: (a) Low energy efficiency. The cold air enters the rectangle duct with a uniform temperature T_{in} from left to right in Fig. 1(a). In this process, heat is transferred from the hot fluid to the cold air through the channel walls, thus the temperature of cold air is getting more and more higher along the flow direction. So T_{out} at the end of the duct is higher than T_{in}. As a consequence, the temperature difference ΔT_{in} ($\Delta T_{in} = T_w - T_{in}$, where T_w is the temperature of wall) between the channel wall and cold air at the beginning of the duct is higher than the temperature difference ΔT_{out} ($\Delta T_{out} = T_w - T_{out}$) between the channel wall and hot air at the end, which is shown in Fig. 1(c). (b) The pressure drop between the inlet and outlet of the duct increases violently as the Reynolds number increases [1]. So the higher the Reynolds number is the higher pressure drop is. (c) Although condensed water can be pushed by air, it is not easy for condensed water to be drained out of a condenser in air-conditioning. It can be seen in Fig. 1(a) that the viscous force between the condensed water and the wall still cannot be ignored.

To overcome the above drawbacks, this paper put up with a new design for heat exchanger with trapezoidal ducts. The trapezoidal duct is presented schematically in Fig. 2(a) and (b). There are three ways to improve the weakness that mentioned above by using the trapezoidal duct: (a) The local heat transfer performance on any cross-section (perpendicular to the flow direction) can be enhanced by increasing the heat transfer area, which increased gradually in the flow direction, as shown in Fig. 2(a). A large area leads to a large rate of heat transfer which is transferred from the hot fluid to cold air, which would make $\Delta T_{in} \approx \Delta T_{out}$, as shown in Fig. 1(c). (b) In a trapezoidal duct, the pressure increases with the increasing of cross-section area/volume. So the pressure drop between inlet and outlet of the duct shown in Fig. 2(a) is smaller than that of rectangular duct. The higher pressure is also of benefit to benefit for condensation. (c) As shown in Fig. 2(a), droplets on the slope can influenced by gravity which can help droplets drain from the slop.

The heat transfer performances in rectangular ducts have been studied widely in the past decades. In Al-Bakhit's [2] study, a parallel stream heat exchanger with rectangular ducts was numerically simulated to figure out the impact of different parameters on the heat transfer performance and the accuracy of constant heat transfer coefficient assumption. Hooman [3] came up with a

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Nomenclature

A	heat transfer surface area [mm^2]
c_p	specific heat capacity [J/kg·k]
D_h	hydraulic diameter [mm]
E	friction power expended per unit of surface area [W/m^2]
g	acceleration of gravity [m/s^2]
g_c	conversion factor [kg·m/N·s]
H_1	short edge of the trapezoidal [mm]
H_2	long edge of the trapezoidal [mm]
h	heat transfer coefficient [W/m^2·k]
h_f	fin height [mm]
L	fin length [mm]
$\dot{m}$	mass flux [kg/s]
ΔP	pressure drop [Pa]
s_f	fin pitch [mm]
T	temperature [K]
t_f	fin thickness [mm]
ΔT	temperature difference [K]
U, u	velocity [m/s]
X, x	stream-wise coordinate
Y, y	fin height coordinate
Z, z	fin pitch coordinate

Dimensionless

f	fanning friction factor
j	Colburn factor
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Greek letters

α	heat transfer surface area to volume ratio [m^2/m^3]
β	slope angle [°]
η_o	surface efficiency
λ	thermal conductivity [W/m·k]
μ	dynamic viscosity [kg/(m·s)]
υ	kinetic viscosity [m^2/s]
ρ	air density [kg/m^3]
σ	contraction ratio of the fin array

Subscripts

w	wall
in	inlet
out	outlet
t	temperature
m	average value
max	maximum value

closed-form solution for fully developed velocity and temperature distribution in a porous-saturated micro-duct with rectangular cross-section in the slip flow regime by using a Fourier series. Wen et al. [4] applied an improved algorithm combing a Kriging response surface and multi-objective genetic algorithm to investigate the effect of fin parameters on the performance of plate-fin heat exchangers with rectangular ducts.

While the studies about flow and heat transfer characteristics for rectangular ducts are sufficient, the research on that for trapezoidal ducts is relatively scarce. Farhanieh et al. [5] numerically solved laminar convective flow and heat transfer in a duct with a trapezoidal cross-section, which has various geometrical dimension of that. Pohlhausen et al. Falkner et al. [6] were the first to investigate the flow field of the wedge-shaped flat by using similarity solution method to obtain partial differential equation of velocity. In a subsequent study, Hartree [7] and Stewartson [8] analyzed the solution of the partial differential equation which obtained by Falkner et al. in detail. And they concluded that the boundary layer would separate from the slope while the slope angle of the wedge $\beta = -0.199\pi$. Several years later, Schlichting [9] summarized and analyzed a variety of shapes for the boundary layer including the wedge-shaped channels. Waltrich et al. [10] investigated nine accelerated flow evaporators by reducing the free flow areas to improve local heat transfer coefficient, where the

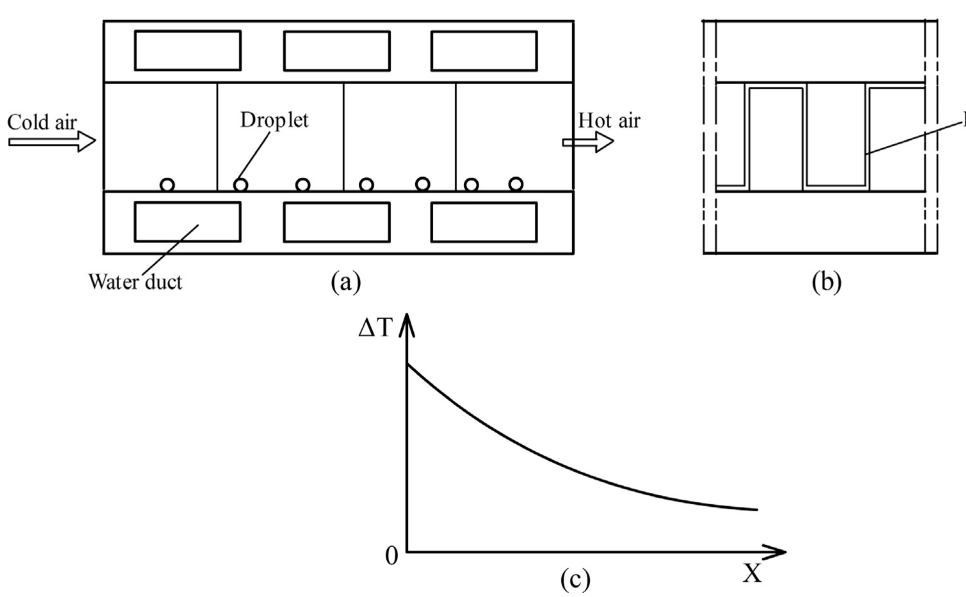

Fig. 1. Rectangle duct. (a) Front view; (b) left view; (c) distribution of temperature difference.