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Research paper

Numerically-based parametric analysis of plain fin and tube compact heat exchangers

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HIGHLIGHTS

- The increase in efficacy of compact heat exchangers is numerically investigated.
- An analysis methodology based on local and global energy balances is provided.
- Quantitative assessment of the heat transfer streamwise-allocation is supplied.
- The energy transferred before the fluid reaches the fins and tubes is identified.
- Influence of Re number, tube diameter, fin spacing and tube layout is examined.

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ABSTRACT

In the present study, the hydrodynamic and heat transfer characteristics of six-tube-row compact fin and tube heat exchangers have been investigated numerically by introducing a methodology of analysis based on local and global energy balances, from three-dimensional velocity and temperature fields. The aim is to analyze the influence of operating conditions and the geometry to design more efficient devices. Tube diameter, fin spacing and tube layout are the geometrical parameters; the over-tube fluid velocity, via Reynolds number, is used as the parameter of operation. Using the procedure, along with the concept of *fraction of the total heat rate* available for the specific device, the results have shown that, fluid velocity plays an important role, whereas the role of tube layout is minor, and that the effects of tube diameter and fin spacing are closely related to the magnitude of the fluid velocity. For small velocities, 99% of the heat rate that could be potentially achieved occurs closer to the inlet of the device, whereas for large velocity-values, nearly the entire length is necessary. In addition, the influence of the tube-diameter on both heat transfer and pressure drop is negligible at small velocities but progressively increases at bigger velocity-values; a similar —but less pronounced— effect is produced by fin spacing, where the influence of tube-diameter is relevant only for larger fin spacings. The approach introduced here is useful in providing, at the expense of some generality, high accuracy and clear information on the thermal convection process in these devices, since intermediate steps via Nusselt numbers and heat transfer coefficients are not needed.

1. Introduction

Compact heat exchangers are widely used in industrial applications since they form an integral part of heating, cooling, ventilation and air conditioning (HVAC), power generation and manufacturing systems. In these thermal devices a common geometry is the plate-fin and tube configuration, in which a liquid is usually driven inside tubes that are exposed to an external flow of a gas, being the fluids at different temperatures. The two typical tube alignments; i.e., in-line and staggered, are illustrated schematically in Fig. 1. Thermo-physical properties of the gas; e.g., air, and the often laminar nature of the flow in these systems cause the over-tube thermal resistance to critically constrain the transfer of energy. To alleviate the problem the heat transfer area per unit volume is usually very large. Thus, an important design objective for compact heat exchangers is to maximize device compactness

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Nomenclature

A	cross sectional area [m^2]
c_p	specific heat at constant pressure [J/kg K]
D	tube diameter [mm]
H	height of heat exchanger [m]
k	thermal conductivity of fluid [W/m K]
L	length of heat exchanger [m]
L_L	center-tube distance to leading edge [m]
L_T	center-tube distance to trailing edge [m]
L_{x1}	extended computational domain ahead of fins [m]
L_{x2}	extended computational domain after fins [m]
ΔL	length of fin section [m]
N_T	number of tubes
Nu	Nusselt number
$\mathbf{n}$	unit vector
P_l	longitudinal tube pitch [m]
P_t	transverse tube pitch [m]
p	pressure [Pa]
Δp	pressure drop [Pa]
Q	heat transfer rate [W]
Q_{Lx1}	heat transfer rate in section L_{x1} [W]
Q_T	total heat transfer rate [W]
Re_D	Reynolds number based on tube diameter
Re_δ	Reynolds number based on fin spacing
T	fluid temperature [K]
T_s	surface temperature [K]
$\mathbf{u}$	Cartesian velocity vector [m/s]
u,v,w	Cartesian velocities [m/s]
u_{in}	inlet frontal velocity [m/s]
x	streamwise coordinate [m]
x,y,z	Cartesian coordinates [m]

Greek symbols

δ	fin spacing [mm]
μ	dynamic fluid viscosity [kg/m s]
ν	kinematic fluid viscosity [m^2/s]
ρ	fluid density [kg/m^3]

Subscripts and superscripts

b	baseline values
$\overline{(\cdot)}$	mean values
in	inlet
j	j-th fin section
out	outlet

while ensuring efficient heat transfer; in this way, operating and manufacturing costs can be significantly reduced while minimizing environmental impact.

Many numerical and experimental studies have aimed at analyzing compact heat exchangers to enhance their performance. Fiebig et al. [1] examined, via Nusselt numbers, the conjugate heat transfer of a finned tube for different Reynolds numbers and fin efficiencies, indicating that a more efficient transfer of energy is obtained in the fin section upstream of the tube. The influence of various geometrical parameters of multi-row heat exchangers was studied by Jang et al. [2], He et al. [3] and Xie et al. [4]. The results from Ref. [2] show that the average transfer coefficient and the pressure drop are both larger for staggered arrays than for in-line, whereas all the aforementioned studies report that, when the number of tube-rows is larger than four [2,4], and three [3] from the field synergy principle viewpoint, its effect on the average transfer coefficient is small. The impact of fin height, tube location and ellipticity of the tube was investigated by Erek et al. [5] for one-tube section of the device under a single operating condition. They observed that by placing the tube at the downstream region of the fin, or increasing ellipticity of the tube, the transfer of heat is enhanced. Abu Madi et al. [6] analyzed the effect of fin-type and number of tubes on the system performance and correlated their experimental results using Colburn j- and friction f-factors. A comparable work by Saboya and Saboya [7] was carried out for one- and two-row arrangements of plate-fin devices using Nusselt numbers and a naphthalene sublimation technique. The influence of flow behavior on heat transfer in a two-row tube configuration was studied by Tsai et al. [8] using topological theory. Their findings show that flow structure, particularly the horseshoe vortex, has a direct effect on the span-averaged Nusselt number and pressure drop. Similar studies to those of [2] and [8] were carried out by Tutar and Akkoca [9] and Zhang et al. [10], with emphasis in transient effects and horseshoe vortex formation on Nusselt number and pressure coefficient, reporting a local enhancement of both quantities.

In this study, we perform numerical simulations over plain-fin and tube heat exchangers and explore the heat transfer enhancement in these devices from a different angle; i.e., the increase in the efficacy of the system by identifying the regions in a complete device where most of the heat transfer takes place, and potentially eliminating those that do not contribute significantly. We also propose a methodology of analysis on the basis of local and global energy balances from the field quantities, and use the heat transfer rate instead of the common Nusselt number as the basis for the calculations; it enables higher accuracy [11–14] since neither transfer coefficients nor characteristic temperatures are needed. Using an earlier version of the approach, Motamedi et al. [15] examined a fifteen-tube heat exchanger system for constant values of diameter and fin spacing, and showed that it was possible to reduce the size of the device. The governing equations in Cartesian coordinates are first formulated and then solved on a representative computational domain by the finite element method. From the computed velocity, pressure and temperature

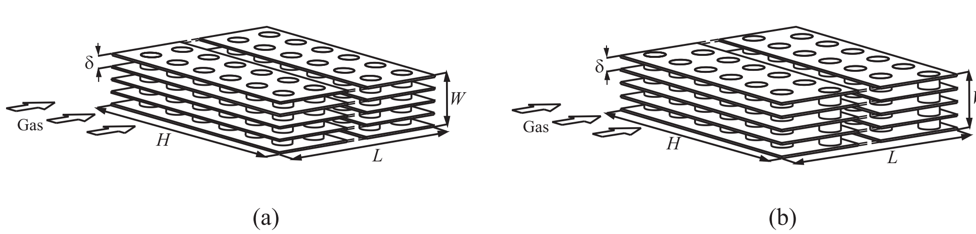

Fig. 1. Schematic of a compact fin-tube heat exchanger. (a) In-line alignment. (b) Staggered alignment.