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Numerical optimization of heat exchangers with circular and non-circular shapes

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ABSTRACT

A circular tube bundle is one of the simplest geometries that is widely used for heat transfer applications. However, in the recent years, cross-flow heat exchangers with non-circular tube arrangement have been receiving increased attention. The main purpose of this work is to gain insight into the characteristics of heat transfer and fluid flow in different tube bundles arrangements: circular, ellipsoidal and wing-shaped, for heat exchangers taking into account local and bulk entropy generation. All tube shapes are investigated under similar operating condition. This could provide a new way for engineers to design an optimal network of heat exchangers allowing the enhancement of heat transfer and recovery in industrial applications.

We conduct a two-dimensional numerical CFD model using finite volume discretization to evaluate the performance of these systems. The effects of pressure drop, exergy and enthalpy balances are both investigated. Entropy generation is sought in order to find the best tube bundles arrangement. Heat transfer correlations are obtained for different situations of tube shapes and suggestions are made for the best geometry that minimizes the total entropy generation (i.e. the irrevesibilities).

1. Introduction

Numerous industrial applications include Heat exchangers. They are used as evaporators, condensers, super-heaters, economizers or they provide other essential engineering functions in all industrial systems that involve heat energy. In many of these applications, cross-flow tube bundle heat exchanger are used In a bank of tubes, the tubes arrangement is an in-line array or a staggered array and each tube has neighbors in both longitudinal and lateral directions.

In their papers, Jayavel and Tiwari [1], Aiba et al. [2] concluded that for high Reynolds numbers, staggered arrangements of tubes in a tube bundle provide more heat transfer and causes less pressure drop compared to an in-line arrangement of tubes. They pointed out the fact that the design of heat exchangers must be focused on increasing heat transfer while minimizing pressure loss. The problem is that when a fluid flows over the tubes, these two objectives go inversely with the main characteristics of the flow, i.e. Reynolds numbers and tubes geometry and arrangement. There is a trade of between

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Nomenclature

a dimensionless transverse pitch
b dimensionless longitudinal pitch
Cp specific heat, J/kg K
D tube diameter, m
Eu Euler number
H heat transfer coefficient, W/m^2 K
L length of numerical test section, m
Nu Nusselt number
Pr Prandtl number
$Re_{D.eq}$ Reynolds number based on equivalent tube diameter
p pressure, Pa
Q total heat transfer rate, W
S entropy, J/K kg
S_D diagonal pitch, m
S_L longitudinal distance between two consecutive tubes, m
S_T transverse distance between two consecutive tubes, m
T temperature, °C
U axial velocity, m/s

Greek symbols

λ Thermal conductivity, W/m K
μ viscosity, Pa s
ρ density, kg/m^3

Subscripts and superscripts

a air
eq equivalent
gen generation
in inlet
max maximum
out outlet
t tube

those two goals and optimums shall be found.

Regarding the tubes geometry, due to their ease of manufacture, circular tubes have been generally used in the past. However, this shape causes severe separation, large wakes, and hence high pressure drops. In the recent years, several studies report on non-circular tubes in cross-flow heat exchangers. Merker and Hanke [3] showed that cross-flow heat exchanger with elliptic-shaped tubes had smaller frontal areas on the shell-side compared to those with circular tubes in the range of $10^3 < Re < 5 \times 10^4$. Ota et al. [4,5] concluded that for Reynolds number ranged from about 8000 to 79,000, the minimum mean heat transfer rate for an elliptic tube was higher than the one of a circular tube. Brauer [6] reported that there is an 18% relative reduction in the pressure drop for elliptical tubes compared to circular ones. Horvat et al. [7] studied the transient heat transfer and fluid flow for circular, elliptical, and wing-shaped tubes with the same cross sections. Comparing the performances of those three types of tubes, they reported that the values of the average Stanton number (St_a) were lower for the ellipsoidal and the wing-shaped tubes than those for the cylindrical ones. Hasan and Sirén [8] showed that a bank of oval-shaped tubes has a better combined thermal hydraulic performance than corresponding circular tubes. Bouris et al. [9] proposed a new tube cross-section with a parabolic upstream shape and a semi-circular one downstream. They carried out experimental and numerical simulations on the novel tubes bank heat exchanger to study the thermal, hydraulic and fouling characteristics. Their results indicate that they attain higher heat transfer levels with 75% lower deposition rate and 40% lower pressure drop. Sayed et al. [10], experimentally and numerically, studied the flow and heat transfer characteristics of a cross-flow heat exchanger employing staggered wing-shaped tubes with zero angle of attack. The results indicated that, the bundle of wing-shaped tubes has better performance over other bundles for similar parameters and conditions.

It can be concluded from this literature review that non-circular tubes offer less flow resistance and higher heat transfer rates in cross-flow heat exchangers than circular tubes. The main objective of the present work is to study the effect of tube geometry on the average Nusselt Number while proposing an appropriate correlation for each case. We also investigate the effect on flow resistance. The whole performance on heat transfer and pressure drop for each geometry is assessed by the computation of the total entropy generation, i.e the entropy due to the heat transfer and the one due to the head losses, in the fluid while flowing across the tubes and exchanging heat with them. The tubes we consider are smooth.

Among the many correlations that can be found in the literature for heat transfer and pressure drop over tubes bundles that can be found in the literature, the most widely-used ones had been proposed by Zukauskas [11] and Zukauskas and Ulinskas [12]. They studied heat transfer and pressure drop rates for a cross-flow over bundles of smooth tubes and suggested correlations for both heat transfer and pressure drop for in-line and staggered banks of circular tubes. Their study covered the range of $1000 \le Re_{D.eq} \le 2 \times 10^6$, and $0.7 \le Pr \le 500$, as well as a wide range of relative transverse and longitudinal pitches. In the present work, we used these correlations for our comparison purposes.

The existing correlations are mostly related to the case of circular tubes and have been developed for a specific fluid, longitudinal and transverse pitches, and particular ranges of Reynolds and Prandtl numbers. The user cannot extrapolate those correlations beyond their respective ranges of applicability. For the configurations that we investigate, we develop new correlations for the ranges considered. The computation of the total entropy generation is a fruitful tool that permits us to derive important conclusion about the best designs for the heat exchangers with tube bundles.