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A numerical study of forced convection in a new trapezoidal tube bank arrangement

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ABSTRACT

This work presents a numerical study addressing the hydrodynamic and thermal behaviour of a new trapezoidal tube bank arrangement composed of nine circular cylinders subjected to forced convection. The pressure drop and Nusselt numbers are evaluated aiming to assess the influences of the following parameters: the new trapezoidal factor, the longitudinal and transverse pitches and the free stream velocity (Reynolds number). The second law analysis was also performed by computing the entropy production as function of the trapezoidal factor. The validation of the results obtained with the present methodology was conducted by comparing against empirical correlations available in the literature. The main results indicate that entropy production in the tube bank is very sensitive to the trapezoidal factor. Finally, all results for the global Nusselt number for the new geometry were condensed in an empirical correlation for practical applications with good accuracy (maximum error around ± 1.15%).

1. Introduction

The external cross flow on tube bank arrays is typically found in applications with heat exchangers. The techniques commonly used to increase the heat transfer rate in these devices aim at: (i) devising new tube geometries/geometric arrangements for heat exchangers [1–5] and (ii) improving thermal contact between the heat exchanger fluid and wall using turbulence promoters [6–9]. Apart from enhancing the heat transfer rate, the geometry and flow manipulation generally produces substantial increase in pressure drop [1–9].

In literature, several investigations have been made proposing new geometries for heat exchangers and devising more efficient turbulence promoters. Focusing only on recent works (with practical applications in heat exchangers) that address both hydrodynamic and thermal behaviours one finds: (i) Wejkowski [1] studied heat transfer and pressure loss in a new type of heat exchanger tube bank with triple-finned tubes; Fins were arranged on a tube in three distinct configurations and comparisons between numerical and experimental heat transfer results were performed; The main results show that triple-finned tubes can be used to increase the performance of cross-flow tube banks; (ii) Sinha et al. [2] analysed numerically the air flow through fin-tube type heat exchangers with vortex generators; The simulations were performed using the commercial software Ansys Fluent, being tested two different tube orientations in the heat exchangers – in-line and staggered arrangements of three tube rows; The main results indicate significant improvement in the heat transfer performance due to the nozzle-like flow passages created by the vortex generator pair and the region behind the circular tube which promote accelerating flow; (iii) Ma et al. [3] performed a computational fluid dynamics (CFD) analysis for a novel heat exchanger that consists of semi-circle cross-sectioned tubes that create narrow slots oriented in the streamwise direction; The authors adopted the three-dimensional turbulent flow modelling within the framework of the κ–ε Reynolds-averaged Navier–Stokes (RANS) method; The results indicate that the heat transfer coefficient of the slotted tubes increased by more than 40% when compared to the traditional nonslotted tubes; (iv) Wu et al. [4] studied numerically the heat transfer and fluid flow characteristics of a new type of fin with built-in interrupted delta winglets; The main results show that the heat transfer capacity and overall performance of the heat exchanger increased by 35–60% and 19–64%, respectively; (v) Zhang et al. [5] investigated numerically and experimentally the flow and heat transfer characteristics around a new type of egg-shaped tubes; The results show that the egg-shaped tube has a higher favourable pressure gradient at its front and a lower adverse pressure gradient at its back, which helps delaying flow separation; Besides, empirical correlations for the Nusselt number for each tube were obtained by the authors; (vi) Zdanski et al. [6] investigated experimentally the effects of delta winglet vortex generators on convective heat transfer enhancement at in-line tube bank arrangements; The authors evaluate the effects of the following parameters: the distance from the vortex generators to the tube bank, the

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Nomenclature

A_{tr}	transverse surface area (m^2)
C_1	constant of the new equation
c_p	specific heat at constant pressure (J/kgK)
c_v	specific heat at constant volume (J/kgK)
D, d	tube diameter (m)
f	friction factor
$\bar{h}$	average convective heat transfer coefficient (W/m^{2}K)
H	height of the computational domain (m)
I	turbulence intensity (%)
k	molecular thermal conductivity (W/mK)
L	length of the computational domain (m)
m	constant of the new correlation
$\dot{m}$	mass flow rate (kg/s)
$\overline{N}u_D$	average Nusselt number, $\overline{N}u_D = \frac{\bar{h}D}{k}$
N_L	number of columns
Pr_T	turbulent Prandtl number
P	static pressure (Pa)
$\dot{Q}_{cv}$	heat flux at the control volume (W/m^2)
$\mathrm{Re}_{D,\ max}$	Reynolds number based in the maximum velocity, $\mathrm{Re}_{D,\max} = \frac{\rho U_{\max} D}{\mu}$
$\mathrm{Re}_{D,\ approx}$	Reynolds number based in the approximation velocity, $\mathrm{Re}_{D,approx} = \frac{\rho U_{in} D}{\mu}$
$\dot{S}_{gen}$	entropy generation rate (W/K)
S_l	longitudinal distance of cylinders (m)
S_t	transversal distance of cylinders (m)
Sl/d	longitudinal pitch
St/d	transverse pitch
t	trapezoidal factor (m)
T_∞	free-stream temperature (K)
T_s	surface temperature (K)
T_f	film temperature (K)
$\overline{T}$	average temperature (K)
U_∞	inlet velocity (m/s)
U_{max}	maximum velocity inside tube bank (m/s)
u^*	friction velocity
u'	fluctuation velocity
y	dimensional length of the wall (m)
y^+	non-dimensional length of the wall

Greek letters

κ	turbulent kinetic energy (m^2/s^2)
ν	molecular kinematic viscosity (m^2/s)
ε	turbulent kinetic energy dissipation rate (m^2/s^3)
ω	specific turbulent kinetic energy dissipation rate (1/s)
γ	ratio of specific heats
χ	correction factor
ρ	specific mass (kg/m^3)
μ	molecular dynamic viscosity/(Ns/m^2)
Δp	pressure drop (Pa)

pitch and the incidence angle of the delta winglet; The main results indicate that the Nusselt number was enhanced around 30% in the presence of vortex generators; Besides, all experimental results were condensed in a new empirical correlation for the Nusselt number; (vii) Salviano et al. [7] studied numerically the optimization of vortex generators position and angles in a fin-tube compact heat exchanger using a Genetic Algorithm; Four vortex generator parameters which impact heat exchanger performance were tested: longitudinal vortex generator positions, angle of attack and angle of roll; The results indicate that the optimized vortex generator configurations led to heat transfer enhancement rates higher than reported in the literature; (viii) Promvonge et al. [8] studied experimentally the heat transfer characteristics in a heat exchanger fitted with combined twisted tape/winglet vortex generators; The main results indicate that the application of combined (twisted tape/winglet) vortex generators leads to thermal performance around 17% higher than the twisted tape alone; (ix) Li et al. [9] analysed numerically and experimentally the thermal-fluid characteristics of a heat sink with a pair of delta winglet vortex generators; The main results obtained by the authors show that the best performance is achieved when the distance between the vortex generator trailing edges equals the length of the heat sink; Besides, the results indicate that an attack angle of 30° is preferred to optimize both the thermal resistance and pressure drop.

Aiming at to conclude the Introduction section, it is important to emphasize that the present authors have applied experimental/numerical methods for developing more efficient thermal systems. Some recent author's results dealing with applications of turbulence promoters (the main focus was to develop expressions for heat transfer/pressure drop predictions) may be found in Zdanski et al. [6,10] and Silva et al. [11]. Besides, it is worth mentioning that most literature works addressing convection heat transfer in tube bank arrangements are focused on discussing results for Nusselt number and pressure drop, generally downplaying the second law analysis. Within this framework, the main focus of the present work was to study numerically a new trapezoidal tube bank arrangement assessing the effects of a new parameter (the trapezoidal factor) on the Nusselt number, pressure drop and entropy production. Besides, it was found that all the numerical results for the global Nusselt number collapse in a new empirical correlation for heat transfer prediction.

2. Theoretical formulation

2.1. Governing equations

In order to keep the focus on the discussions of the important physical aspects of the incompressible flow over trapezoidal tube bank arrangement, the governing equations and the numerical scheme are only briefly discussed. The flow is modelled by the classical incompressible Reynolds-averaged Navier-Stokes equations. For computation of turbulent flow, the low Reynolds SST (Shear Stress Transport) turbulence model was adopted [12]. The SST approach interchanges between the κ–ε model in the flow core region and the κ–ω model near solid walls [12]. Furthermore, the numerical validation indicates that the SST model offers a good prediction for this class of flow. Besides, for determination of the turbulent thermal conductivity we have adopted the definition of constant turbulent Prandtl number, i.e., $Pr_T = 0.9$ [13].

The numerical simulation was carried out with support of the commercial software ANSYS CFX, which uses the cell vertex element-based finite volume method. The solution was accomplished with a

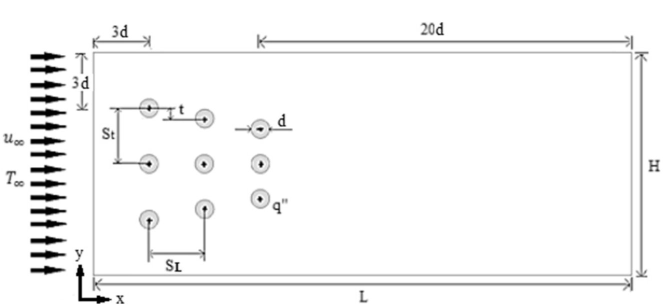

Fig. 1. Trapezoidal tube bank arrangement with main dimensions.

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