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Proceeding Paper

Thermo-Fluid Performance Enhancement Using NACA Aerofoil Cross-Sectional Tubes †

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Abstract: Industrial heat exchange applications encounter flow across a bank of tubes in an aligned or staggered configuration. The former arrangement causes boundary layer separation and wake formation in the trailing part of the first tube leading to poor heat exchange. Alternatively, the staggered arrangement is used for heat transfer improvement, accompanied by a rise in the pressure drop. The present study uses tubes of NACA airfoil cross-sections as an alternative solution. The pressure drop and heat transfer rates in aligned aero tubes are improved by 36% and 3% more than in the circular tubes with a staggered arrangement, respectively.

Keywords: aligned tubes; staggered arrangement; heat transfer enhancement; NACA airfoils; pressure drop

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1. Introduction

Cross-external flow heat exchangers are most utilized in various industrial applications such as the generation of steam in a boiler or air cooling in an air conditioner's coil [1]. The thermo-fluid performance of these heat exchangers is regularly affected by the vortex's formation, boundary layer separation, and wake regions that are downstream of heat exchanging tubes in the bank. Moreover, the higher wake formations cause significant damage to the structural stability of the tube arrays inside the bank. Therefore, improving the overall performance of these heat exchangers is critical for increasing their energy efficiency and structural stability. El Gharbi et al. [2] studied the circular, cam-shaped, and ellipsoidal-shaped tubes from the viewpoint of heat transfer characteristics and showed that the circular-shaped tubes are worse and elliptical tubes are the best. Elmekawy et al. [3] demonstrated that attaching the splitter plates at downstream ends of tubes reduces the pressure drop and increases the Nusselt number. Xu et al. [4] and Kim et al. [5] studied the effects of different fin configurations on the heat transfer rate and pressure drop and showed that the staggered configuration is better than the aligned configuration. The previous research motivates the authors to use aero-shaped tubes in the bank for both arrangements. The present study numerically investigates and compares the thermo-fluid performance of tube banks with symmetrical NACA Aero foil and circular tubes in an aligned and staggered arrangement. To the best of the author's knowledge, there is no comparison between these tubes in the literature. The results of numerical simulations are validated by the analytical results. The effect of fluid velocity on the outlet temperature and pressure drop is investigated for all configurations. The streamline contours are plotted for wake region visualization. The purpose of the study is to sustain the aligned arrangement by altering the geometry of the circular tubes instead of going for the staggered one because of the greater pressure drop.

2. Mathematical Model for Flow across Banks of Tubes

The design specifications and operating parameters for the flow across banks of tubes (circular and aero) with aligned and staggered arrangements are given here. Normally, a fluid flows over the tubes with another fluid flowing inside at a different temperature. These tube rows are arranged either in an aligned or staggered configuration with an axis normal to flow. The 2-D geometrical representation of these arrangements is shown in Figure 1. Both aligned and staggered configurations are characterized by the transverse pitch S_T, diagonal pitches S_D, and longitudinal pitch S_L measured between the tube centers. The maximum thickness of the NACA airfoil or aero tube is equal to the circular tube diameter, while the transverse and longitudinal pitches are the same for both cases, as shown in Figure 1. The fluid enters the bank with a certain value of velocity V (range: 6–21 m/s) and inlet temperature (288 K) and moves over the tubes with a surface temperature T_s (343 K) and the phenomena of momentum and energy transport take place inside the bank. The flow conditions inside the bank are dominated by the wake interactions and the boundary layer separation effects which affect the convection heat transfer. Therefore, the rate of convection heat transfer q and pressure drop Δp are evaluated here for each configuration.

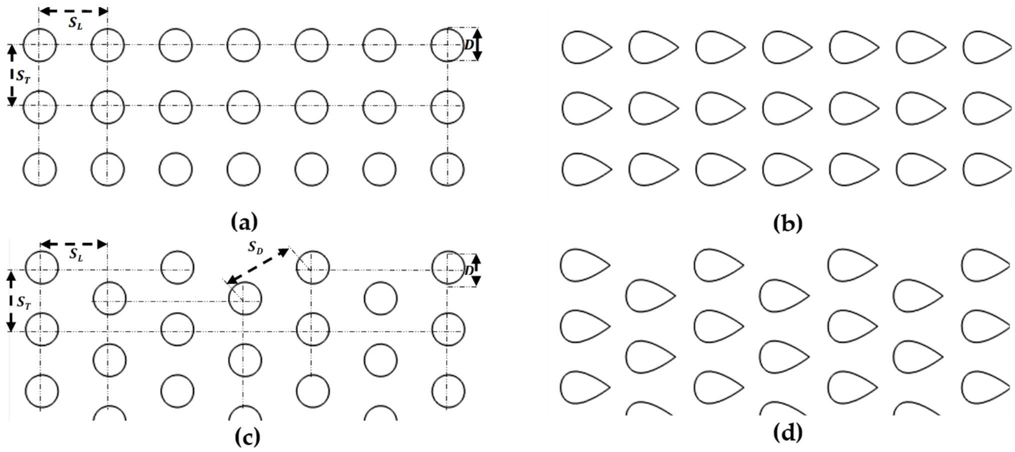

Figure 1. Tube arrangements in a bank: (**a**) circular aligned, (**b**) airfoil aligned, (**c**) circular staggered, and (**d**) airfoil staggered.

During analytical modeling, the following assumptions were made. The air is selected as a working fluid and uniform velocity is applied at the inlet of each bank. The thermophysical properties of air (ρ = 1.217 kg/m^3, c_p = 1007 J/kg-K, ν = 14.82 $\times$ 10^6 m^2/s, and k = 0.0253 W/m-K) are assumed to be constant. The fluid flow inside the bank is two-dimensional, and the heat transfer is steady state.

The Nusselt number (N_u) correlation for the fluid flow across banks of tubes in the aligned and staggered arrangement is proposed by Zukauskas [6]:

$$N_u = C_2 C {Re_{max}}^m Pr^{0.36} \left(\frac{Pr}{Pr_s} \right)^{\frac{1}{4}} \tag{1}$$

where Pr represents the Prandtl number and all properties are determined using the average inlet and outlet temperatures of fluid [1].

The Reynolds number (Re_{max}) for the aforementioned correlation depends upon the maximum fluid velocity (V_{max}) happening inside the bank and is given by Equations (2) and (3) as follows [1]:

$$Re_{max} = \frac{V_{max} D}{\nu} \tag{2}$$

$$V_{max} = \frac{S_T}{S_T - D} V \tag{3}$$

The convection heat transfer coefficient (h) and fluid outlet temperature (T_o) are determined using Equations (4) and (5) as follows [1]:

$$h = N_u \frac{k}{D} \tag{4}$$

$$T_o = T_s - (T_s - T_i)\exp\left(-\frac{\pi DNh}{\rho V N_T S_T c_p}\right) \tag{5}$$

where N represents number of tubes in the entire bank and N_T is the number of transverse plane tubes.

Log-mean temperature difference (ΔT_{lm}) and the rate of heat transfer (q') per unit length of the tubes are evaluated using Equations (6) and (7) as follows [1]:

$$\Delta T_{lm} = \frac{(T_s - T_i) - (T_s - T_o)}{ln\left(\frac{T_s - T_i}{T_s - T_o}\right)} \tag{6}$$

$$q' = N(h\pi D\Delta T_{lm}) \tag{7}$$

The pressure drop (Δp) is computed using the equation as follows:

$$\Delta p = N_L x \left(\frac{\rho V_{max}{}^2}{2}\right) f \tag{8}$$

where N_L is the number of longitudinal plane tubes, x is the correction factor, and f is the friction factor [1].

3. Results and Discussion

Figure 2a shows the variation in the weighted average temperature at the outlet as a function of the velocity of air. The maximum temperature is observed in the case of airfoil tubes in a staggered arrangement, and the minimum in the case of circular tubes in the aligned arrangement. The outlet temperature decreases by increasing the velocity because the contact time for convection heat transfer decreases inside the bank. Therefore, momentum diffusivity dominates the thermal diffusivity by increasing the velocity of fluid.

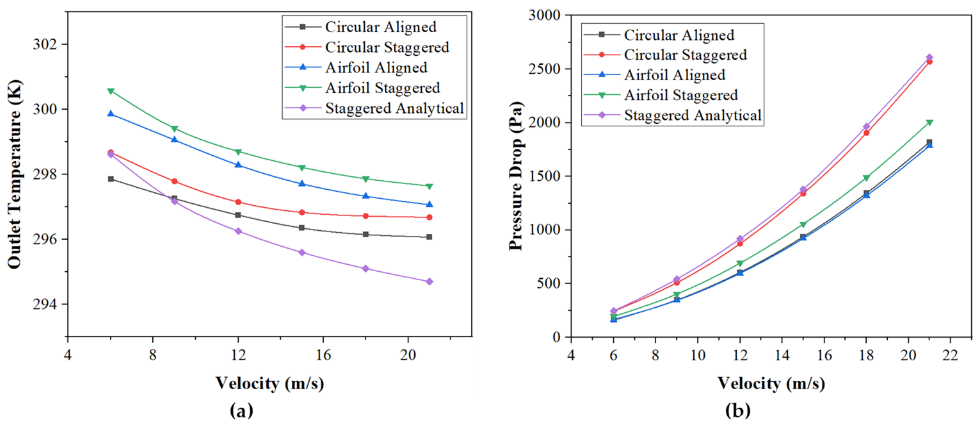

Figure 2. Effect of the fluid inlet velocity on (**a**) outlet temperature and (**b**) pressure drop.

Figure 2b depicts the variation in the pressure drop inside the bank as a function of the velocity of air. The numerical model is validated with the analytical results of circular tubes in a staggered arrangement. The pressure drop increases by increasing the velocity because the maximum fluid velocity increases at higher velocities as defined by Equation (8). The pressure drop is at a maximum in the case of circular tubes arranged in a staggered arrangement, and at a minimum for aero tubes in the aligned arrangement. Therefore, more pumping power is required for the fluid flow across the banks of circular tubes in a staggered arrangement and minimum in the case of aero tubes in the aligned arrangement.

Figure 3 shows the velocity streamlines across the banks of tubes for all configurations. The wake regions are at a maximum in the case of aligned circular tubes, and at a minimum in the case of staggered aero tubes. These boundary layer separation effects and wake interactions with the fluid flow affect the convection heat transfer inside the bank. Therefore, the net heat transfer rate is at a maximum in the case of staggered aero tubes and vice versa.

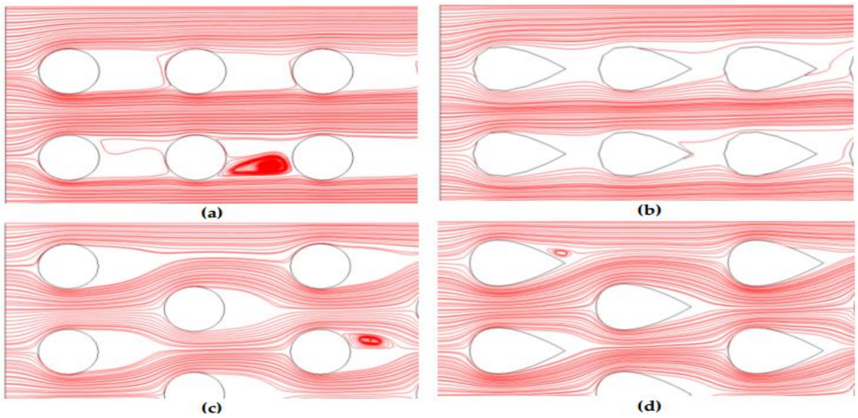

Figure 3. Streamlines around (**a**) circular aligned, (**b**) airfoil aligned, (**c**) circular staggered, and (**d**) airfoil staggered.

4. Conclusions

In the present study, the numerical results are validated with the analytical results that show a fair argument between them. The aero tubes reduce the pressure drop and increase the heat transfer rate inside the bank. The pressure drop in aligned aero tubes is 36% less than the staggering circular tubes at all velocities. Similarly, at lower velocities, the heat transfer rate is 3% greater in aligned aero tubes than in the staggering circular tubes. Therefore, at lower velocities, an aligned arrangement with aero tubes is better to use than going for circular tubes in a staggered arrangement which increases the pressure drop.

Author Contributions: Conceptualization, methodology, and analysis has been carried out by M.H.T., F.K. helped in the preparation of initial draft while H.M.R. contributed in the validation of results. Overall, this study has been completed under the supervision of T.A.C. All authors have read and agreed to the published version of the manuscript.

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References

1. Incropera, F.P.; De Witt, D.P.; Bergman, T.L.; Lavine, A.S. *Introduction to Heat Transfer*, 5th ed.; Wiley: Hoboken, NJ, USA, 2002.
2. El Gharbi, N.; Kheiri, A.; El Ganaoui, M.; Blanchard, R. Numerical Optimization of Heat Exchangers with Circular and Non-Circular Shapes. *Case Stud. Therm. Eng.* **2015**, *6*, 194–203. [CrossRef]
3. Elmekawy, A.M.N.; Ibrahim, A.A.; Shahin, A.M.; Al-Ali, S.; Hassan, G.E. Performance Enhancement for Tube Bank Staggered Configuration Heat Exchanger—CFD Study. *Chem. Eng. Processing—Process Intensif.* **2021**, *164*, 108392. [CrossRef]
4. Xu, X.; Ma, T.; Li, L.; Zeng, M.; Chen, Y.; Huang, Y.; Wang, Q. Optimization of Fin Arrangement and Channel Configuration in an Airfoil Fin PCHE for Supercritical CO2 Cycle. *Appl. Therm. Eng.* **2014**, *70*, 867–875. [CrossRef]

5. Kim, T.H.; Kwon, J.G.; Yoon, S.H.; Park, H.S.; Kim, M.H.; Cha, J.E. Numerical Analysis of Air-Foil Shaped Fin Performance in Printed Circuit Heat Exchanger in a Supercritical Carbon Dioxide Power Cycle. *Nucl. Eng. Des.* **2015**, *288*, 110–118. [CrossRef]
6. Žukauskas, A. Heat Transfer from Tubes in Crossflow. *Adv. Heat. Transf.* **1972**, *8*, 93–160. [CrossRef]