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Influence of flow shedding frequency on convection heat transfer from bank of circular tubes in heat exchangers under cross flow

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ABSTRACT

Numerical study on confined flow over circular tube isolated from the bundle of circular tubes in a compact and widely spaced heat exchangers, to explore the influence of flow shedding frequency under forced convection heat transfer. The flow and heat transfer characteristics such as pressure, frictional and total drag coefficients, skin friction coefficient, Strouhal number, volume goodness factor, convective heat transfer coefficient, Nusselt number and effectiveness are estimated for different dimensionless transverse pitch ratios and Reynolds numbers. The highly confined flow past a circular tube makes the flow steady, highly attached and postponed the flow separation, flow shedding and also advances the laminar to turbulent transition. The increases in flow attachments and transitions have been confirmed by observing the frictional drag and skin friction coefficients and also through various contours respectively. Three different flow shedding nature has been observed when Reynolds number increases at different blockage ratios. It is confirmed that the heat transfer enhancement in compact and widely spaced heat exchanger at blockage ratios less than or equal to 3 does not depend on flow shedding frequency. Also, at low Reynolds number region, the heat transfer enhancement is due to highly attached flow. But the gradual increase in Reynolds number advances laminar to turbulent transition and responsible in heat dissipation.

1. Introduction

Heat exchangers are devices that transfer heat among the substances when they are at different temperatures. Heat exchangers are most commonly preferred in real practice for the wide range of applications such as heating and air conditioning systems, chemical processing plant, electrical and power electronic sectors and also power generation in large thermal plants. Particularly in power electronic sector, electronic components are smaller in size and operational at higher temperatures. In order to increase the performance of an electronic system, the unwanted heat should be removed from the system to the surrounding as quickly as possible. The product miniaturization and heat dissipation are highly contradictory; in this juncture, the compact heat exchangers having an area density over 700 m^2/m^3 are more suitable for heat transfer enhancement. Specifically, a plate-fin compact heat exchanger is widely used in the field of aerospace, cryogenics and IGBT (Insulated Gate Bipolar Transistors) cooling in Light Rail Propulsion System. Our numerical study explores the additional flow behavior and its influence under convective heat transfer, when confined cross flow over circular tube isolated from the bundle of tubes.

2. Literature review

Heat exchangers are standard equipment targeted to transfer the heat from hot fluid to cold fluid in an efficient manner. An intermediate metallic wall and without moving parts are preferred in most of the cases. The detailed structural, thermal and fluid dynamics analysis have been carried out for several decades. This study reviews the literatures and analyses the thermal behavior of flowing fluids in the exchangers. The Nusselt number correlation was established as a function of Reynolds number and Prandtl number for the bundle of circular tubes. Reynolds number range 10–40,000 and number of circular tubes in bundle more than 10 are preferable for Colburn [1] correlation and works well. In between 1937 and 1988, lot of experimental investigation had been carried out on heat transfer in bundle of circular tubes arranged in in-line and staggered form by Huge [2], Pierson [3], Omohundro et al. [4], Bergelin et al. [5–7], Jones and Monroe [8], Gram et al. [9], Zukauskas [10], Aiba et al. [11,12], and Žukauskas and Ulinskas [13]. The experimental data were correlated by Grim-

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Nomenclature

θ	angle (°)
Q_{act}	actual heat transfer (W)
BR	blockage ratio; $BR = H/d$
λ	channel confinement; $\lambda = (BR)^{-1} = d/H$
h	convective heat transfer coefficient (W/m^2 K)
A	constant (−3.3265)
B	constant (0.1816)
C	constant (1.6×10^{-4})
ρ	density (kg/m^3)
ζ^0	dimensional vorticity (s^{-1})
d	diameter of the cylinder (m)
μ	dynamic viscosity (Pa s)
ε	effectiveness (Q_{act}/Q_{max})
U_∞	free stream velocity of fluid (m s^{-1})
T_∞	free stream temperature of fluid (K)
$p(\infty)$	free stream pressure (Pa)
C_{df}	frictional drag coefficient
f	frequency of vortex shedding (s^{-1})
H	height of the channel (m)
D_h	hydraulic diameter (m)
Q_{max}	maximum heat transfer (W)
F_N	normal pressure force (N m^{-1})
Nu	Nusselt number
C_P	pressure coefficient
C_{dp}	pressure drag coefficient
r	radius of the cylinder (m)
Re	Reynolds number
τ_w	wall shear stress
St	Strouhal number
C_f	skin friction coefficient
T_w	surface temperature of circular tube (outer) (K)
$P(\theta)$	surface pressure at an angle of θ (Pa)
F_T	tangential force (N m^{-1})
k	thermal conductivity (W/m K)
α	thermal diffusivity (m^2/s)
C_d	total drag coefficient
t	time
u	velocity component in x direction (m s^{-1})
v	velocity component in y direction (m s^{-1})
h_{std}	volume goodness factor (k × Nu/D_h)

ison [14], Kays and London [15], Hausen [16], and those correlations are compiled and sequentially presented in the literature by Khan et al. [17]. The cross flow and heat transfer on bundle of circular tubes are numerically analyzed and reported by Launder and Massey [18], Fujii et al. [19], Dhaubhadel et al. [20], Wung and Chen [21], Murray [22] and Beale [23] for the wide range of longitudinal pitch, transverse pitch, Prandtl number and Reynolds number. Wilson and Bassiouny [24] investigated numerical simulation of laminar and turbulent flow through the bank of tubes. They have estimated the influence of an increase in longitudinal pitch on the drop in pressure and friction factor. Longitudinal pitch ratio less than or equal to 3 in an in-line arrangement is highly compact and gives the best performance. Similarly, in staggered arrangement pitch ratio less than 1.5 is needed to reduce the friction factor and enhances the convection heat transfer. Mandhani et al. [25] numerically analyzed the influence of porosity, Prandtl number and Reynolds number on average Nusselt number for single tube isolated from the bundle of circular tubes. It is observed that the surface averaged Nusselt number increases when Prandtl and Reynolds numbers increases and porosity decreases. The obtained results are good agreement with numerical and experimental results for single tube and for the bundle of circular tubes. Khan et al. [26] investigated analytically the cross flow confinement effect on circular tube under isothermal and uniform heat flux condition at different blockage ratios ($0.1 \leqslant BR \leqslant 0.9$) at higher Reynolds numbers such as 500, 750 and 1000. The results are validated with numerical and experimental data also reported that the effect of blockage ratio controls the flow and convective heat transfer and also postponed the flow separation. In addition, three correlations were found for total drag coefficient and Nusselt number at two different thermal boundary conditions. The flow and heat transfer of circular tube kept inside the bundle of circular tubes arranged in staggered and in-line manner [26]. Here also analytical study has been carried out for a control volume isolated from the bundle of circular tubes under constant temperature boundary condition. Khan et al. reported that heat transfer rate is higher for staggered arrangement rather than the in-line and also compactness of tube banks enhances the forced convection heat transfer [26]. Experimental studies of local convective heat transfer of circular tubes are in staggered arrangement had been carried out. The heat transferring ability of second and third tube is 30% and 65% greater than the first tube [27]. Fornarelli et al. [28] reported flow and heat transfer of six cylinders arranged in in-line and they have achieved 25% heat transfer enhancement by decreasing the spacing ratio from 4 to 3. Bundle of externally finned heat exchanger with elliptical tubes under cross-flow was numerically investigated. The effect of fouling on local heat transfer was analyzed and addressed [29–31]. Pressure drop characteristics of rod bundles under vertically upward flow were investigated [32,33]. The flow past heated circular tube kept in-between two walls has been sufficiently studied numerically and experimentally. The role of blockage ratio and Reynolds number has been numerically investigated by Chen et al. [34], Zovatto and Pedrizzetti [35] and also Sahin et al. [36]. The confined fluid effect on circular tube excluding the wall proximity effect, which was achieved by moving the walls at free stream flow velocity for the practical application of free fall of the circular tube on stagnant fluid medium. Steady state numerical computations were carried out by Jyoti et al. [37] with uniform inlet velocity profile and retained in the entire domain except nearer to the cylinder vicinity and various flow characteristics have been analyzed. Similarly, the influence of blockage ratio and Reynolds number on heated circular tube has been studied by Lange et al. [38], Mettu et al. [39] and Bharti et al. [40]. Specifically, the numerical study on asymmetrically confined heated circular tube and they reported that the asymmetric confinement does not influence the heat transfer [39]. But the heat transfer has been increased by increasing the blockage effect, even though the shedding frequency decreases at the maximum blockage. T. Vít et al. also confirmed that the vortex shedding frequency changes the temperature gradient in the boundary layer [41]. Dhiman and Ghosh [42] analyzed flow past heat circular cylinder and reported that heat transfer enhancement taking place when shedding frequency increase (Strouhal number). The increase in heat transfer from channel wall, due to fluid flow acceleration and vortex shedding phenomena were performed by Cheraghi et al. [43]. Comparing the literature in heat exchangers having the bundle of circular tubes, particularly the analysis does not focus the influence of shedding frequency on heat transfer