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Research Paper

Numerical investigation of heat transfer and friction factor characteristics from in-line cam shaped tube bank in crossflow

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HIGHLIGHTS

- Thermal performance of cam shaped tubes in cross flow is studied numerically.
- The study is carried out for Reynolds number range from 11,500 to 42,500.
- Heat transfer rate is higher in cam shaped tubes as compared to circular tubes.
- The friction factor in cam shaped tubes is 85% less as compared to circular tubes.

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ABSTRACT

Tube bank heat exchangers are considered to be an effective device for heat transfer between two fluids. Researchers investigated various arrangements and along with different geometries of the tube, so as to improve the thermal performance of the tube bank. In the present study, the numerical investigation is carried out to determine the thermal performance of cam shaped tube. The study is performed for the heat transfer and friction factor characteristics in the Reynolds number range from 11,500 to 42,500. The result of the numerical simulation indicates the superior thermal performance of the cam shaped tube banks over the circular tubes. As the friction factor is reduced by 85–89% as compared to the circular tubes the heat transfer by friction factor (*Nu*/f) is increased by 5 times as compared to circular tubes. However, the efficiency of cam tubes with a pitch ratio of 1.5 is higher than that of the pitch ratio of 2.0. Further, the area goodness factor is also around 9 times higher than circular tubes.

1. Introduction

The design of compact heat exchanger requires in detail analysis of heat and fluid flow characteristics involved in between the two fluids. With the ever-increasing environmental and energy crisis, forced the researchers in the process industry to utilize highly efficient components and subsystems for energy interaction. So the development of the higher effective heat exchanger requires a larger contact area for heat transfer with reduced volume. Such larger contact area is easily achieved by passing one fluid through a number of small channels or tubes. This process with an array of the cylinder leads towards the development of a new class of heat exchanger, as tube banks. The tube banks have numerous applications in the field of the process heat exchanger, cooling towers, oil and gas pipelines, automotive radiators, electronic cooling, along with HVAC&R applications. The tube bank is a special case of the heat exchanger, where the heat interaction is between the hot fluids flowing through a number of small tubes and cold fluid usually passes over the tube surface along the cross direction. So ideal compactness is designed by considering the effect of the upstream and the downstream cylinder on the heat gaining fluid [1]. The significant parameter affecting the performance of the system is usually the placement of the tubes in the vicinity of the cold fluid. Due to large variations in the compactness of the heat exchanger, there is hardly any scope for the change in the longitudinal and transverse pitch of the tubes. Most of the modern-day heat recovery system makes the use of the different geometrical profile of tubes rather than the conventional circular tubes. However, flow across bluff bodies is studied by numerous researchers over last few decades to study the vortex and the turbulent flow past the body [2–4], as cross flow heat exchangers are encountered with heat transfer with bluff bodies such as flow past a cylindrical tube.

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Nomenclature

S_L	longitudinal pitch (mm)
S_T	transverse pitch (mm)
D	circular tube diameter (mm)
D_{eff}	effective diameter (mm)
S_L/D	longitudinal pitch ratio
S_T/D	transverse pitch ratio
C	circumference of the tube (mm)
l	perpendicular distance between the two arcs of cam shaped tubes (mm)
L	length of the tubes (mm)
U	free stream velocity of the air (m/s)
V_m	maximum velocity in tube bank (m/s)
Re	Reynolds number
Q	heat transfer rate (W)
h	average heat transfer coefficient (W/m^2 K)
A	surface area of the tube (m^2)
ΔT	temperature difference
Nu_{avg}	average Nusselt number
Nu_{eq}	equivalent Nusselt number
N	number of tubes in column
Pr	Prandtl number
j	Colburn factor
f	friction factor
N_L	number of tubes in transverse rows
ΔP	pressure drop in tube banks
A_{GF}	area goodness factor
C_p	specific heat at constant pressure
k	thermal conductivity of air (W/m K)

Greek

ρ	density of the air (kg/m^3)
η	thermal hydraulic performance
σ	free flow to frontal area ratio
π	mathematical constant valued 3.14
υ	kinematic viscosity of the air

Subscripts

cam	cam shaped tube
cir	circular
avg	average
eff	effective
eq	equivalent

Shinya Aiba et al. [5,6] 1982 experimentally investigated the heat transfer around the tubes arranged as an in-line and staggered orientation in the tube bank, and estimate the effect of the pitch ratio on the Nusselt number. Aswatha Narayana et al. [7] 1998 performed the finite element simulation of transient flow and heat transfer past an in-line tube bank and studied the pressure drop and Nusselt number variation in the tube bank by changing the pitch to diameter ratio from 1.5 to 2.0. Balabani et al. [8] 1996 experimentally studied, the mean flow and turbulence structure of cross flow over the tube bank with increasing longitudinal pitch ratio from 1.6 to 2.1. Buyruk [9] 2002 performed numerical study of heat transfer characteristics on tandem cylinders, inline and staggered tube bank in the cross flow of air with a pitch ratio of 1.13–6. Xu et al. [10] 2004 experimentally studied the vortex formation and the Strouhal number in the wake of the two inline identical cylinders at various pitch ratio and Reynolds number. Moller et al. [11] 2009 performed studies on the characteristics of the flow in the first row of the tube bank with a pitch ratio from 1.26 to 1.6 and confirm the bistable flow modes within the pitch ratio of 1.5–2.0. It has been observed that the flow over the cylindrical tubes in case of the tube bank reports early separation of the fluid from the wall boundary, which is undesirable. Further, the wake formation at the downstream reduces the heat transfer capacity by increasing the pressure drop within the tube bank. Hence this forced the researchers to make the use of non-bluff bodies, to enhance the heat transfer rate.

Simultaneously, the research is involved in the selection and performance of the suitable non-bluff bodies in the heat exchangers. The streamline cross-section of the tubes is believed to enhance the performance of the circular tubes. The elliptic cross section of the tubes is considered to be the most streamline, and hence the researcher tried to investigate the performance of an elliptical tube in the tube bank. Terukaza Ota et al. [12]1984 studied the heat transfer and flow around an elliptical cylinder with an axis ratio of 1:3 along with the varied attack angle from 0° to 90°. The attack angle from 60° to 90° reports the maximum enhancement. As with the advancement in the manufacturing processes, the researcher tried multiple passive enhancement processes, which make use of the streamline tube along with the fins to enhance the heat transfer rate. He et al. [13] 2007 performed the three-dimensional numerical study on wavy fin heat exchanger with elliptical tubes and estimated the rise of 30% increase in the heat transfer and 10% decrease in the friction factor as compared to circular tubes. Berish [14] 2011 studied the heat transfer and flow behavior around four staggered elliptic cylinders in cross flow and variation in the maximum Nusselt number at the two attachment points on each side of the tested cylinder with variation in the Reynolds number. Wang et al. [15] 2014 performed experimental studies on the air inlet angle of the air side performance for cross flow oval tube heat exchangers of double row tubes and three row tubes. The air inlet angle of 60° and 45° is best for low and high Reynolds number in case of double row tube heat exchanger, while 90° air inlet angle is best for three row heat exchanger. Wang et al. [16] performed three-dimensional numerical simulations of flow and heat transfer characteristics in smooth wavy fin and elliptical tube heat exchanger using different vortex generators. It is found that the attack angle of the vortex significantly affects the thermal performance of the elliptical tubes. Zhang et al. [17] numerically compares the overall thermal performance of the elliptical and circular finned tube condensers and found that the increase of 3.6–6.7% in the coefficient of performance (COP) was observed by using elliptical tubes.

Some of the researchers also make use of the flattened tube in the tube bank to increase the net effective contact area of the wall surface with the cross fluid as Toolthaisong et al. [18] studied the effect of attack angles and aspect ratio on the air side thermal and pressure drop of cross flow heat exchanger in a staggered arrangement. The heat transfer is maximum and minimum for the attack angle of 90° and 0° for 0.18 aspect ratio. The aspect ratio 0.18 provides the maximum area normal to flow attack. Wang et al. [19] performed the numerical study between the heat transfer enhancement and absolute vorticity flux in flat tube bank fin with vortex generators. It is observed that the absolute vorticity flux indicates the intensity of the secondary flow.

Horvat et al. [20] 2006 numerically compared the heat transfer conditions for the tube bundle in cross flow for different tube shapes as – cylindrical, ellipsoidal, and wing shaped. The pitch to the diameter ratio in the staggered arrangement was from 1.125