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Controlling the heat transfer and pressure drop within economical working conditions for a movable flat tube bundle

Mohamad F. AbdRabo [a], Khaled M.K. Pasha [b,*]

[a] Mechanical Engineering, Zagazig University, Shoubra, Egypt
[b] Mechatronics Department, Faculty of Engineering, October 6 University, Egypt

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ABSTRACT

The present work consists of three stages; in *first* stage, a heat exchanger with a bundle of movable flat tubes is designed to investigate experimentally the variation of Nusselt number and non-dimensional pressure drop with both the air incident angle and the Reynolds number. The Reynolds number is expressed as a function of the maximum air velocity and the air incident angle. The aspect ratio for the flat tubes equals 3/7. In the *second* stage, the experimental data from the first stage, for the heat transfer and pressure drop are supplied into a controlling unit. This unit is guided by a written program, and can vary the incident angle in order to give a prescribed thermal behavior with time, without the need to change the air inlet conditions. In the *third* stage, A numerical model is prepared and verified by both the previous work and present experimental results. This model is used to simulate additional future cases without the need to additional experimental costs and effort. Both the experimental and numerical results showed that, the Nusselt number and the non-dimensional pressure drop increase slightly with the incident angle within the range of incident angle from 0° to 20°, and increase considerably from 20 to about 70°. For every experiment with a certain incident angle value, the ***percentages*** of increase for both, the Nusselt number and the non-dimensional pressure drop, over those of the horizontal tube case, are checked to get the most *economical case, which is* observed when the Reynolds number is 902 RR with incident angle of 20°.

1. Introduction

1.1. Brief survey of previous work

Many researchers has been investigating different designs for heat exchangers in order to obtain higher rates of heat transfer with minimum pressure drop. One of the popular heat exchanger designs is that, which contains a tube Bundle. Tubular heat exchangers are used in many energy economization applications. The most important design parameters of tubular heat exchangers are the external surface heat transfer coefficient of the tube and the pressure drop of the fluid flowing around the tubes. Based on previous studies reported in the literature, the effects of tube shape and arrangement have indicated that they could have a positive influence on heat transfer, but, the case is not the same for pressure losses. Horizontal flat tube heat exchangers, where the larger tube diameter is parallel to the air flow, are expected to have lower air-side pressure drop and better air-side heat transfer coefficients compared to those for the circular tube heat exchangers. That could be interpreted by the longer flat surface for the flat tube, and the smaller wake region, behind it, which helps in reducing the possibility of forming more smaller eddies behind the preceding tube, and consequently, a lower turbulent intensity and turbulent losses which leads to lower pressure drop and vibration than those of the circular tube type. What will be the behavior if the tube larger diameter makes an angle with the flow direction ?.

The present work intends to answer this question. Many researchers investigated the thermal and hydraulic behavior for circular and flat tube banks; Dawid taler, [1] developed a new method for numerical modeling of tubular cross-flow heat exchangers, as a step to introduce a numerical model of a car radiator, which is digitally controlled. His proposed method based on a finite volume method and integral averaging of gas temperature across a tube row is appropriate for modeling of plate fin and tube heat exchangers. Two control techniques were tested to regulate the number of cooling fan revolutions per minute; the first is based on the numerical model of the heat exchanger developed in the paper while the second is a digital proportional–integral–derivative

* Corresponding author.
E-mail address: khmki1@yahoo.com (K.M.K. Pasha).

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Nomenclature

A. Alphabetic

A	area, m^2
C_p	specific heat of air at constant pressure, (kJ/kg K)
C_o	average heat transfer coefficient, ($W/m^2.K$)
D_h	hydraulic diameter, (4 * tube cross section area/ Perimeter), m
d	smaller tube diameter, m
dp	non-dimensional pressure drop, Pa
E	energy, J
H	vertical distance, (between the tube cross section geometric centers),m
K	thermal conductivity, (W/m.K)
L	horizontal distance, (between the tube cross section geometric centers),m
Nu	Nusselt number, (h D_h/k)
n	number of tubes in the domain
P	static pressure, Pa
q′	heat per unit area, W/m^2
Q	total heat rate, W
R	Aspect ratio, ((H/D_h)/(L/D_h))
RR	ratio of Reynolds number calculated at the narrowest passage between tubes, to that at domain inlet, $= \frac{Re_{max}}{Re_{in}} = \frac{\textbf{passage area at domain inlet}}{\textbf{passage area between tubes}} = \frac{1}{1-\beta}$
Re	Reynolds number, ($\rho u D_h/\mu$), where, u = air velocity at domain inlet multiplied by RR
r	tube cross section minor radius
S	source term.
t	time, s
T	static temperature, K.
u	velocity horizontal component, (m/s)
U	average horizontal velocity, (m/s)
v	velocity vertical component, (m/s)

B. Subscript

a	air
av	average
b	bulk
h	hydraulic
i	index for X-coordinate
in	inlet condition
j	index for Y-coordinate
max	maximum velocity at minimum area
o	outlet condition
s	tube outer surface area
tot	total

C. Greek symbols

α	air incident angle
β	blockage ratio $= \frac{(\textbf{distance between the tubes cross section centers})\times \sin\alpha + 2\mathbf{r}}{\mathbf{H}}$
ε	turbulent energy dissipation rate
Γ	diffusion coefficient
κ	turbulent kinetic energy.
μ	viscosity
ρ	density, (kg/m^3)
ν	kinematic viscosity

control, which becomes frequently unstable if the water flow rate varies. Anna Korzeń and Dawid Taler, [2] introduced a new equation set describing transient heat transfer process in tube and fin cross-flow heat tube exchanger, and subsequently solved them using the finite volume method. They could develop a numerical model of a single-row heat exchanger and double-row car radiator with two passes. Junqi Dong, [3] studied experimentally the air side thermal hydraulic performance of 16 sets of the wavy fin-and-flat tube aluminum heat exchanger. He introduced correlation equations for the heat transfer and pressure drop performances using the multiple regression method, and concluded that, the amplitude and length of a wavy fin were the most important factors for the heat exchanger's overall thermal hydraulic performance. Lijun Yang, [4] proposed a new configuration of wave-finned flat tube, in which the fin surface rotates to be perpendicular, to prevent the fouling from gathering on the finned tube. He investigated the influences of the fin pitch, height and the Reynolds number on the flow and heat transfer performances, and recommended the correlations of the friction factor and Nusselt number. They concluded that, buoyancy effect should be taken into account for the correlation of the friction factor at low Reynolds numbers, but this buoyancy force can be ignored for the Nusselt number. Prediction of turbulent flow in a staggered tube bundle was introduced by Zeinab S. A, [5,6]. She investigated the average Nusselt number and pressure drop for a circular and flat tube bank, with different aspect ratios. She correlated the Nusselt Number to Reynolds number, based on the hydraulic diameter, and the Prandtl number through; Nu = 0.683 $Re^{0.618}$ $Pr^{1/3}$. Andrej Horvat [7], analyzed 100 cases of heat exchanger segments with cylindrical, ellipsoidal and wing-shaped tubes in a staggered arrangement, he calculated the average values of the time distributions of the Reynolds number, the drag coefficient and the Stanton number. Based on these average values, he constructed the drag coefficient and the Stanton number correlations as polynomial functions of the Reynolds number and the hydraulic diameter. Haitham M. S. Bahaidarah [8], used a finite volume based FORTRAN code to investigate the steady laminar two-dimensional incompressible flow over both, in-line and staggered flat tube bundles used in heat exchanger applications. He concluded that, the overall performance of the in-line configuration tube bundle for lower height ratio ($H/Da = 2$) and higher length ratio ($L/Da = 6$) is preferable since it provides a higher heat transfer rate for all Reynolds numbers except for the lowest Re value of 2. Sundaresan [9], developed a numerical model to predict the overall performance of an advanced offset strip-fin type compact high temperature heat exchanger made of liquid silicon impregnated carbon composite (SiC). He concluded that; Increases in fin thickness increased the pressure drops quite significantly, and the fin thickness did not affect the thermal performance. Wilson [10], Modeled a heat transfer procedure for two-dimensional elliptic flow to predict the pressure drop and heat transfer characteristics of laminar and turbulent flow of air across tube banks. His model was extended to cover the case of two rows of tubes undergoing cross flow with in-line and staggered tube arrangements. The prediction agreed well with different previous work, when investigating the effects of different variables, such as; Reynolds number (Re), the normal and parallel tube spacing-to-diameter ratios on the friction factor and the local and global Nusselt number. Watterson [11], excuted calculations, using a pressure-based finite volume algorithm, for the turbulent, incompressible flow around a staggered array of tubes, and periodic flow is allowed to develop