EFFECT OF TUBE INCLINATION ANGLE ON THE THERMAL AND FLUID DYNAMIC PERFORMANCE OF FLAT TUBE HEAT EXCHANGER

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LIST OF SYMBOLS

α	Tube inclination angle (˚), thermal diffusivity (m^2/s)
β	Heat transfer surface density (m^2/m^3)
δ	Fin thickness (mm)
θ	Angle of attack, fin inclination angle
μ	Dynamic viscosity, (kg/m.s)
ρ	Density (kg/m^3)
σ	Deviation
∞	Fluid
A	Heat transfer surface area (m^2)
Al	Aluminum
c	Characteristics
Cu	copper
$cond$	Conduction
$conv$	Convection
$elec$	Electrical
F	Friction factor
F_p	Fin pitch (mm)
$F_h.$	Fin height (mm)
h	Convection heat transfer coefficient
in	Inlet
J	Heat transfer factor
k	Thermal conductivity of the tube (W/m.K)
K	Turbulence kinetic energy(m^2/s^2W
L	Length of the tube (m)
$\dot{m}$	Mass flow rate (kg/s)
n	Number of terms in the model
N	Number of tube rows
Nu	Nusselt number
out	Outlet
P_l	Longitudinal tube pitch
Pr	Prandtl number
Q	Heat transfer rate (W)
rad	Radiation
Re	Reynolds number
s	Surface
t	Total
T	Temperature (˚C)
U	Overall heat transfer coefficient
v	Kinematic viscosity (m^2/s)
V	Air velocity (m/s)
w	wall
x	Predictor
X	Thickness (mm)
y	response

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
CCD	Central Composite Design
CDWVGs	Curved delta winglet vortex generators
CHEs	Compact heat exchangers
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
CPU	Central Processing Unit
CRVGs	Curved rectangular vortex generators
DO	Direct optimization
DOE	Design of Experiment
DWLVGs	Delta Winglet longitudinal Vortex generators
DWRVGs	Delta Winglet Vortex generators
DWVGs	Delta Winglet rectangular Vortex generators
EU	European Union
Exp	Experimental
Fkm	Fakulti Kejuruteraan Mekanikal
FTHEs	Flat tube heat exchangers
HVAC	Heating ventilation and air conditioning
HE	Heat exchanger
HEs	Heat exchangers
IR	Infrared thermography
LMTD	Log Mean Temperature Difference
LVs	Longitudinal Vortex
NCWPs	Novel combined winglet pairs
PEC	Performance Evaluation Criteria
PID	proportional–integral–derivative
PIV	Particle image velocimetry
PRVG	Punched rectangular vortex generators
PTVG	Punched triangular vortex generators
RSM	Response Surface Methodology
RWVG	Rectangular Winglet Vortex generators
Simu	Simulation
UMP	Universiti Malaysia Pahang
VGs	Vortex generators

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ABSTRACT

At the present time, the performance of finned and flat tube heat exchangers (HEs) has become a very important issue in the thermal industrial sector. Finned-and-flat tube heat exchangers have gained great interest from many researchers due to their role in any thermal engineering system. Some geometrical and process parameters such as fin spacing, tube spacing, tube inclination angle, etc. affects the performance of fin-and flat tube heat exchangers. Significant number of research have been done to study the effect of such geometrical and process parameters. However, the effect of flat tube inclination angle on the thermal-hydraulic performance of fin-and-tube HE is not fully examined. Thus, the aim of this study was to investigate the effect of flat tube inclination angle, air velocity and tube configuration on the thermal and flow characteristics of compact fin-and-flat tube heat exchangers. A series of experimental and numerical investigations were carried out to evaluate the influence of the aforementioned parameters on the thermal-hydraulic performance between the tube bundles. Moreover, Response Surface Methodology (RSM) was used to determine the optimum parameter condition for the fin-and–tube HE. The range of the parameters considered in the study were tube inclination angle from 0˚ to 150˚, inlet air flow velocity from 1.8 to 3.8 m/s and tube configuration (inline and staggered). For the experiments, the wind tunnel available at the Faculty of Mechanical Engineering, UMP was used. The wind tunnel was equipped with a blower of capacity 50 W, flow straightener, test section and measuring sensors. Twelve plate fin and nine flat tube heat exchangers test sections were designed and manufactured at various inclination angles and configurations. Temperature, velocity, and pressure measurements were recorded at various positions in the test section as well as before and after the test section. For the numerical analysis, the CFD commercial software called ANSYS FLUENT-15 was used to solve the Navier-Stoke and energy equations together with proper turbulent equations. The parameters are similar to the experimental investigation. The experiment and numerical analysis used Nusselt number, pressure drop, and area goodness factor to evaluate the thermal-hydraulic performance of fin-and-flat tube heat exchangers. The major findings showed that flat tube inclination angle has significant impact on the heat transfer enhancement. However, the results from both experimental and numerical analysis revealed that increasing the tube inclination angle from 0˚ to 90˚ augments the convective heat transfer coefficient. While 120˚ and 150˚ provide thermal performance close to 60˚ and 30˚, respectively. The average deviations of Nusselt number between experimental and numerical results were 5.42% and 4.44% for inline and staggered configurations respectively. Moreover, due to the air flow blockage caused by inclining the tube angle, the pressure drop increases dramatically for all cases studied. From all acquired results, the best thermal performance occurred at 0˚, while 90˚ provided the minimum thermal performance. Therefore, inclining the tube is beneficial for enhancing the heat transfer performance but is not beneficial in term of pressure drop as it requires higher pumping power. The developed correlations from the RSM can predict experimental data with average deviation of 2.78% for *Nu* for both configurations. Moreover, it can predict the numerical data with average deviation of 0.554% and 0.92% for inline and staggered configuration, respectively. The optimum parameters are found to be with high air velocity and low tube inclination angle which provide maximum heat transfer enhancement and low-pressure drop penalty. Thus, it is recommended for the design of fin-and-flat tube HEs.

ABSTRAK

Pada masa kini, prestasi penukar haba tiub bersirip dan rata (HES) telah menjadi satu elemen yang amat penting dalam sektor industri haba. Penukar haba bersirip dan tiub rata telah menarik perhatian ramai penyelidik kerana peranan nya dalam sistem kejuruteraan pengurusan haba. Beberapa geometri dan parameter proses seperti jarak sirip, jarak tiub, sudut kecenderungan tiub, dan lain-lain memberi kesan kepada prestasi penukar haba tiub sirip-dan rata. Sejumlah besar penyelidikan telah dijalankan untuk mengkaji kesan geometri dan parameter proses. Namun, kesan sudut kecenderungan tiub rata ke atas prestasi haba-hidraulik sirip dan tiub HE tidak diperiksa sepenuhnya. Oleh itu, tujuan kajian ini adalah untuk mengkaji kesan sudut kecenderungan tiub rata, halaju udara dan konfigurasi tiub kepada ciri-ciri haba dan aliran penukar haba tiub sirip-dan-rata padat. Satu siri kajian eksperimen dan numerikal telah dijalankan untuk menilai pengaruh parameter yang dinyatakan di atas prestasi terma-hidraulik antara bundle tiub. lebih-lebih lagi,Response Surface Methodology (RSM) telah digunakan untuk menentukan keadaan parameter optimum untuk sirip dan tiub HE. Pelbagai parameter dipertimbangkan dalam kajian ini iaitu: sudut kecenderungan tiub dari sudut 0˚ hingga 150˚, halaju masuk aliran udara 1.8-3.8 m/s dan konfigurasi tiub (dalam baris dan berperingkat-peringkat). Untuk eksperimen ini, terowong angin yang terdapat di Fakulti Kejuruteraan Mekanikal, UMP telah digunakan. Terowong angin ini telah dilengkapi dengan blower kapasiti 50 W, pelurus aliran, bahagian ujian dan sensor ukuran. Dua belas plat tiub sirip dan penukar haba rata bahagian ujian telah direka dan dihasilkan di pelbagai sudut kecenderungan dan konfigurasi. Suhu, halaju, dan tekanan ukuran telah direkodkan pada pelbagai kedudukan dalam ruang sebelum ujian dan selepas bahagian ujian. Untuk analisis numerikal, perisian CFD yang dipanggil ANSYS FLUENT-15 telah digunakan untuk menyelesaikan persamaan Navier-Stoke dan persamaan tenaga bersama-sama dengan persamaan bergelora yang betul. Parameter yang digunakan adalah sama dengan penyiasatan eksperimen. Ujikaji dan analisis berangka menggunakan nombor Nusselt, kejatuhan tekanan, dan kawasan faktor kebaikan untuk menilai prestasi haba-hidraulik penukar haba tiub sirip-dan rata. Dapatan utama menunjukkan bahawa rata sudut tiub kecenderungan mempunyai kesan besar kepada peningkatan pemindahan haba. Walau bagaimanapun, keputusan daripada analisis kedua-dua eksperimen dan numerikal mendedahkan bahawa peningkatan sudut kecenderungan tiub dari 0˚ hingga 90˚ menambahkan kadar pemindahan haba perolakan. Manakala 120˚ dan 150˚ memberikan prestasi haba hampir kepada 60˚ dan 30˚. Purata sisihan nombor Nusselt antara keputusan eksperimen dan yang berangka adalah 5.42% dan 4.44% untuk masing-masing sebaris dan konfigurasi berperingkat. Selain itu, disebabkan oleh penyumbatan aliran udara yang disebabkan oleh kecenderung sudut tiub, pernigkatan kejatuhan tekanan secara mendadak untuk semua kes yang dikaji. Dari keputusan semua yang diperolehi, prestasi terma yang terbaik berlaku pada 0˚, manakala 90˚ disediakan prestasi termal yang minimum. Korelasi yang diperolehi dari RSM boleh meramalkan data eksperimen dengan sisihan maksimum 2.78% untuk Nu untuk kedua-dua konfigurasi. Selain itu, ia boleh meramalkan data berangka dengan sisihan purata 0.54% dan 0.92% yang sebaris dan konfigurasi berperingkat, masing-masing. Parameter optimum yang diperoleh akan menjadi dengan halaju udara lebih tinggi dan sudut kecenderungan tiub rendah yang menyebabkan peningkatan pemindahan haba maksimum dan tekanan rendah drop penalti. Oleh itu, reka bentuk HEs tiub sirip dan tiub rata adalah disyorkan.

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