THE EFFECTS OF TURBULENCE STRUCTURES ON THE AIR-SIDE PERFORMANCE OF COMPACT TUBE-FIN HEAT EXCHANGERS

By

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"A Renaissance flow visualisation study of vortex generators"

Leonardo Da Vinci (1452-1519)

Abstract

Energy is an essential and critical commodity and our reliance on it has fuelled much of the debate and interest in society and academia alike. Environmental concerns, depleted energy resources and higher energy prices are the main factors that drive this interest. Energy efficiency is one of the main avenues to preserve and better utilize this valuable commodity. The energy exchange by employment of heat exchangers is extensive and tube-fin heat exchangers are widely used in industrial and commercial applications. Smarter designs could not only improve energy efficiency but may also save on material costs. Although mass production and improved manufacturing techniques have reduced manufacturing costs, tube fin heat exchangers have not evolved greatly to take advantage of these improvements. There has been a large range of fin surface enhancements proposed, such as waffled fins or louvres and while limited improvements in capacity have been achieved, this is generally accomplished at a much larger pressure drop penalty. Numerous studies have been performed in order to examine the potential of various surface enhancement geometries on an ad hoc basis. These presumably operate on the basis of enhanced convection due to increased turbulence levels. However very few of these studies examine the actual nature of turbulence that is responsible for convection enhancement.

A series of experiments and numerical studies have been conducted to quantify the effect of the turbulence vortex characteristics on the air side heat convection of a tube-fin heat exchanger. Homogeneous, transverse and streamwise vortical structures were investigated. The thermal transfer performance resulting from these flows was compared to that of standard louver fin geometries by considering sensible heat transfer only, applicable to radiator applications. Several novel coils designed to achieve these vortex structures, were developed and their heat transfer characteristics were quantified. These coil designs can be described as the Tube Mesh, Tube Strut and a Delta-Winglet fin surface.

The Tube Mesh heat exchanger consisted entirely of horizontal and vertical tubes arranged in an approximate homogeneous turbulence generating grid. While they had a lower heat transfer of between 53% to 63% of that of the louvre fin surface, they had an extremely low pressure drop of 25% to 33%. This has the potential to make them suitable for certain low pressure drop applications, especially if energy saving is a prerequisite.

The range of Tube Strut coils consisted of a tube bundle with interconnecting heat conducting struts to form a parallel plate array were also investigated. Three different strut thicknesses and strut spacing were trialled. In general these had similar performance to the tube mesh at 45% to 65% the heat transfer capacity of the louver fin surface. The resulting pressure drop was 38% to 42% of that of the louver fin surface.

A delta-winglet design which positioned the deltas in a flow up configuration just in front of the tubes was examined. It was found that this configuration had an almost comparable capacity of 87% to a louver surface having the same fin pitch. On the other hand it had approximately half the pressure drop of 54% of the similar louver fin surface. This particularly low pressure drop makes this design preferable from an energy utilisation perspective. While a slight increase in coil area is required, this is offset by an almost 50% reduction in operating costs by reducing the parasitic energy requirements of the convection fans.

The experimental data gathered for this Delta-Winglet design served to validate a succession of numerical simulations which were performed to estimate the performance of other configurations of multiple vortex generators. In addition the performance of combining a delta-wing with a louvred surface was investigated. It was found that increasing the number of delta-winglets or combining deltas with a louvred surface provided little improvement in heat transfer but increased pressure drop substantially.

The louvre design itself was examined, and simulations were undertaken to estimate the effect of louvre angle, as well as louvre pitch. A hitherto unexamined concept was to investigate the effect of having louvres with serrated edges. It was found that an increase in louver angle by 5 degrees had negligible effect on heat transfer but increased the pressure drop by 17%. A variation in louver pitch showed a minimal variation in both heat transfer and pressure drop. Surprisingly a serrated louver showed a slight reduction in both heat transfer and pressure drop but this was miniscule.

It was established throughout the course of the investigations that the bulk of the coil heat transfer is performed by the first tube row. Therefore the potential for increasing heat transfer by shifting some heat exchange to the down stream rows was examined. This was attempted by having progressively increasing louvre angles from the front of the coil to the rear. While a slight increase in heat transfer performance was achieved, this accomplished at the expense of a 13%-14% increase in pressure drop.

The outcomes have shown that substantial net improvement of heat exchanger energy efficiency can be achieved through optimization of the turbulence generation along the fins of a tube fin heat exchanger.

Statement of Originality

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To those who I have omitted unintentionally, forgive my oversight.

Abbreviations

UPPER CASE

AP	Array Parameter
AFV	Air Face Velocity
AHU	Air Handling Unit
CFD	Computational Fluid Dynamics
CL	Chord Length
DDC	Direct Digital Control
DWVG	Delta Wing Vortex Generator
DX	Direct Expansion
FUDW	Flow Up Delta Winglet
FDDW	Flow Down delta Winglet
HE	Heat Exchanger
LES	Large Eddy Simulation
LMTD	Log Mean Temperature Difference
NTU	Number of transfer units
Sp	Strut Pitch
TM	Tube Mesh
TS	Tube Strut

Lower case

fpi	fins per inch

Notation

A	area	m^2
A_c	minimum flow area	m^2
A_o	total surface area	m^2
A_t	external tube surface area	m^2
C	heat capacity rate	W/K
C^*	$C_{\min}/C_{\max}$	-
c_p	specific heat at constant pressure	$J/(kg.K)$
D_c	fin collar outside diameter	m
D_f	equivalent fin diameter	m
D_h	hydraulic diameter	m
D_i	inside tube diameter	m
f	fanning friction factor	-
F_p	fin pitch	mm
G_c	mass velocity of air based on minimum flow area	kg/m^2s
h	heat transfer coefficient	$W/m^2\ K$
h_o	air side heat transfer coefficient	$W/m^2\ K$
I	Intensity of inlet turbulence	-
j	Colburn j factor	-
k	fluid thermal conductivity	$W/m\ K$
K_c	abrupt contraction pressure-loss coefficient	-
K_e	abrupt expansion pressure-loss coefficient	-
L_L	Louvre length	mm
L_p	Louvre pitch	mm
$\dot{m}$	mass flow rate	kg/s
N	number of longitudinal tube rows	-
ΔP	pressure drop	Pa
ΔT	temperature difference	°C

P_l	longitudinal tube pitch	*mm*
Pr	Prandtl number	-
P_t	transverse tube pitch	*mm*
$\dot{Q}$	heat transfer rate	*W*
Re_i	Reynolds number based on internal tube diameter	-
Re_{Dc}	Reynolds number based on tube collar diameter	-
r	radius of tube including collar thickness	*mm*
R_{eq}	equivalent radius for circular fin	*mm*
P_t	Transverse tube pitch	*mm*
T	temperature	^{o}C
U	Overall heat transfer coefficient	$W/m^2\ K$
V	velocity	*m/s*
V_c	velocity through minimum flow area	*m/s*
V_f	coil face velocity	*m/s*
X_L	$\sqrt{(P_t/2)^2 + P_l^2}$ for staggered tube layout	*mm*
X_m	$P_t/2$	*mm*

Greek

α	Delta angle of incidence	*degrees*
Δ	Delta angle	*degrees*
δ_F	fin thickness	*mm*
δ_w	thickness of tube wall	*mm*
ε	thermal exchanger effectiveness	-
η	fin efficiency	-
η_o	surface efficiency	-
μ	dynamic viscosity of fluid	*kg/m s*
ν	kinematic viscosity of fluid	m^2/s
ρ	density	kg/m^3
σ	contraction ratio of x-sectional area	-
Θ	Louvre angle	*degrees*
φ	Delta-Winglet off vertical angle	*degrees*

Subscripts

a	air
i	coil inlet conditions
o	coil outlet conditions
w	water

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