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Compact and microchannel heat exchangers: A comprehensive review of air-side friction factor and heat transfer correlations

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ABSTRACT

This review focuses on the thermal-hydraulic performance correlations for the air-side of compact and micro-channel heat exchangers. These correlations are presented in tables, mainly in terms of Colburn *j*-factor and fanning friction factor (*f*), based on each type of fin arrangements with appropriate constraints including Reynolds number ranges, geometrical parameter limits, and fitting uncertainties. The correlations used for air-side arrangements of mini/micro channels, which are constructed in slabs, are the same as those used for the compact heat exchangers. In particular, these correlations are used for louver-fin, wavy-fin, offset strip-fin, and extended surfaces (plain fins and pin fins) arrangements. However, the correlations proposed for fin-and-tube (round) are only valid for the compact heat exchangers. We have also compared some correlations with the experimental data of Kays and London standard reference. Some performance correlations are generalized (as one correlation for each *j*- and *f*-factor) to represent all louver-fin types. However, other fin arrangements have distinct correlations based on their specific geometry. The most reported correlations are valid for dry fin conditions, whereas there are limited correlations devoted to wet or frost surfaces. A guideline based on this study is provided to facilitate the use of correlations for various configurations.

1. Introduction

Heat exchangers are a vital component of many applications including power generation [1], chemical reactors, petrochemical industry [2], solar water heater, food engineering, transportation, air conditioning and refrigeration [3], electronics [4], and process industry [5]. The energy efficiency of heat exchangers contributes enormously to the overall efficiency of a system [6]. However, interrupting the flow path by using different fins leads to increase in the friction power [7,8].

The gas-to-liquid heat exchangers are said to be compact heat exchangers if they have a high surface area density above 700 m^2/m^3 on the air-side; human lungs are the best example to represent one of the most compact heat exchangers, having an area density of about 17,500 m^2/m^3 [9]. Different types of compact heat exchangers, which are augmented by heat transfer surfaces including plain-fins, wavy-fins, offset strip-fins, louver-fins, and fin-tubes, are made of different materials such as aluminum, stainless steel, nickel, copper, etc., depending upon the operating temperatures and pressures. They are used in various fields such as aerospace, automobile, and cryogenic industries because of their compactness, good thermal performance, small space and weight, robust structure, and most importantly low energy requirement and cost [10].

On the other hand, mini/micro channel heat exchangers were designed to have a flow passage less than 1 mm in diameter, in which the heat transfer surface density reaches more than 10,000 m^2/m^3 [11–13]. Because the microchannel heat exchangers have higher heat transfer rate, lower weight and space, higher energy savings potentials, and less materials than the conventional compact heat exchangers (for the main fluid passage such refrigerants and nanofluids), microchannels can solve a lot of thermal-hydraulic challenges [12]. Having small sizes, mini/micro channels could be arranged in non-circular heat sink [14–21] or put together in flat slabs [22–28] for heat exchangers, as shown in Fig. 1 [12]. The slabs contain some mini/micro channels in different geometries, as shown in Fig. 2.

For a gas-to-liquid microchannel heat exchangers, the air-side can be constructed between the microchannel slabs, similar to the air-side of compact heat exchangers; thus, the louver-fins, wavy-fins, strip-fins, plain-fins and pins are augmented heat transfer surfaces used on the air-side of both microchannels and compact heat exchangers [23–34]. Conversely, the finned tube (round) is only used for compact heat exchangers because the tubes have typically high diameters – greater than 6 mm. The thermal-hydraulic performance characteristics of the microchannels were comprehensively reviewed [11,12,35–37] to discuss flow, heat transfer, and design aspects. Moreover, Siddiqui and Zubair

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Nomenclature

$2A$	two times of wavy length amplitude, mm
A_{tot}	total heat surface area ($A_f + A_t$), m^2
A_c	minimum flow area, m^2
A_f	fin surface area, m^2
A_{fr}	frontal area, m^2
A_l	louver surface area, m^2
A_t	external tube surface area, m^2
B	blockage ratio of offset strip-fin
C	foam coefficient, 1/m
c_p	specific heat capacity of air, J/kg K
d	pin diameter, mm
d_f	spiral fin outside diameter, mm
D_c	diameter of outside collar fin ($D_o + 2F_t$), mm
D_h	hydraulic diameter of fin array, mm
D_m (or D_o)	external tube diameter, mm
E	friction power per unit surface area, W/m^2
Eu	Euler number
F_p (or P)	fin pitch, mm
F_d	fin depth, mm
F_l	fin length, mm
F_t (or t)	fin thickness, mm
f	fanning friction factor
G	mass flux, kg/m^2 s
h	height of the offset strip fin, mm
h_e	heat transfer coefficient, W/m^2 K
j	Colburn factor
H	height, m
K	permeability, m^2
K_c	abrupt contraction pressure loss coefficient at inlet
K_e	abrupt contraction pressure loss coefficient at outlet
k	thermal conductivity, W/m K
k_f	fin thermal conductivity, W/m K
l	length or length of the offset strip, mm
L	wavelength of wavy fin, mm
L_d	flow length, mm
L_h	louver height, mm
L_l	louver length, mm
L_p	louver pitch, mm
$\dot{m}$	mass flow rate, kg/s
N_{row}	no. of rows
N_l	no. of louvers over the flow direction
P_d	pore density, PPI
Pr	Prandtl number
P_l	longitudinal spacing, mm
P_t	transverse spacing, mm
Re_{Dh}	Reynolds number based on hydraulic diameter (GD_h/μ)
Re_{Do}	Reynolds number based on outer tube diameter (GD_o/μ)
Re_H	Reynolds number based on the metal foam height (GH/μ)
Re_{Lp}	Reynolds number based on louver pitch (GD_{Lp}/μ)
s	pin spacing in streamwise direction/spacing of the offset strip fin, mm
S_1	non-louvered inlet and exit fin regions, mm
S_2	re-directed length, mm
S_h	slot/slit height, mm
S_l	longitudinal spacing, mm
S_t	Stanton number/transverse spacing, mm
S_w	slot/slit width, mm
T_p	tube pitch, mm
T_d	tube depth, mm
V_c	maximum air velocity, m/s
V_h	height of vortex generator, mm
V_l	length of vortex generator, mm
U	average velocity in a channel, m/s
W	width, mm

Greek symbols

α	attack angle, rad.
β	surface area density – compactness, m^2/m^3
Γ	frost thickness over the fin pitch, mm
Φ	f- or j-factor
θ	louver angle, deg.
θ_A	advancing contact angle, rad.
θ_R	receding contact angle, rad.
ε	A_{tot}/A_t, finning factor/foam porosity/void fraction
ε_1	A_l/A_{tot}
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
η_f	fin efficiency
η_o	overall heat transfer efficiency (air-side)
σ	ratio of minimum free flow area to frontal area
ρ_e	outlet air density, kg/m^3
ρ_i	inlet air density, kg/m^3
ρ_m	mean air density, kg/m^3

Subscripts

1	louvered zones
2	unlouvered zones
F	fin
O	external tube
W	water

Abbreviations

CFD	computational fluid dynamics
FPI	fins per inch
HVAC	heating, ventilation and air conditioning
PPI	pores per inch

[38] reviewed the manifolds of microchannels.

The thermal-hydraulic designs of the air-side of microchannels and compact heat exchanger crucially depend upon the performance of heat transfer surfaces. On account of the complexity of the air-side geometries, the heat and fluid-flow are usually characterized by experimental studies; thus, the relevant correlations (mostly in terms of Colburn – j factor and fanning friction factor f vs. Reynolds number, and geometrical parameters) can be fitted from the experimental data.

The most cited reference which is used to study heat and fluid-flow performance characteristics for the air-side of compact heat exchangers is, Compact Heat Exchanger reference book by Kays and London [40]. However, this source is only limited to represent standardized geometries. Consequently, many experimental and numerical investigations were conducted to cover a wide range of air-side surfaces (e.g. Park and Jacobi [41] used 126 different geometries to develop f- and j-factor correlations for louvered-fin heat exchangers).

This paper aims at representing the air-side thermal-hydraulic correlations (mostly in terms of j- and f-factor) that are used both for compact and microchannel heat exchangers, including those having louver-fin, wavy-fin, strip-fin, plain-fin, and pin-fin arrangements as well as those only used for compact heat exchangers such as finned circular tubes. In this regard, the present study provides extensive