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A comprehensive review of offset strip fin and its applications

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HIGHLIGHTS

- Heat transfer and pressure drop characteristics of offset strip fin were reviewed.
- Both single phase and two phase flow over offset strip fin were analyzed.
- Correlations of heat transfer and pressure drop were summarized.
- Performance of heat exchangers with offset strip fin were reviewed.

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ABSTRACT

Offset strip fin is widely used to enhance heat exchanger's performance. The state-of-the-art of experimental and numerical researches of offset strip fins and its applications were reviewed in the present paper. The characteristics of heat transfer and frictional pressure drop of offset strip fins with different geometries and working fluids were analyzed including single phase flow (water, air, oil) and two phase flow (refrigerant). The proposed empirical correlations from literatures were summarized for both single phase flow and two phase flow. Its application in compact heat exchangers was also reviewed comprehensively.

1. Introduction

Air-cooled heat exchangers are widely used in refrigeration and air-conditioning systems, automobile industry and petrochemical industry. They can achieve remarkable economic benefits in the utilization of thermal energy, recycling of waste heat and saving raw materials. The types and structures of fins assembled in the air-side for the enhancement of heat transfer are various, for example, louver fins, offset strip fins (OSFs), wavy fins, perforated fins and so on, depending on the demands and application conditions. OSFs are often used in the automobile oil cooler, intercoolers and other chemical industrial heat exchangers. Automobile oil cooler is used to cool down lubricating oil which can ensure safe operation and life of the engine. Low-emission diminutive engines are adopted in order to reduce vehicle emissions, so the oil cooler should not only have high efficiency in heat transfer and small pump power, but also be designed in compact structures. The efficient and compact heat exchanger used in engine system for energy saving is of great significance for the mobile industry.

The OSFs are often used in compact heat exchangers to reduce the space, weight and support structures. They can be made in a variety of materials such as aluminum, stainless steels according to the working conditions. OSFs have substantial heat transfer enhancement as a result of the periodic interruption on the boundary layers and the oscillating velocity happening in the fin wakes. So there is also an associated increase in the pressure drop. The characteristics of heat transfer and pressure can be evaluated by Colburn factor j and the Fanning friction factor f. The distributions of the factors according to a specific range of Reynolds Number (Re) can be correlated from the real experimental data.

Separated by Reynolds number range, Wieting [1] developed j and f correlations based on the data from the earlier literatures for $\mathrm{Re} < 1000$ and $\mathrm{Re} > 2000$ respectively. It was concluded that the aspect ratio (l/L) affected thermal-hydraulic performance only in the laminar flow and fin thickness (t) had a significant effect only if the flow pattern was turbulent. Mochizuki and Yagi [2] performed experiments to investigate the thermal–hydraulic performance of seven groups of OSFs with different geometry parameters. The correlations for j and f factors were correlated in the range $1000 < \mathrm{Re} < 8000$. The evaluation criterion, j/f, was utilized to obtain the optimum geometry for OSF. Joshi and Webb [3] defined a criterion to distinguish laminar, transition and turbulent flow in plate-and-fin heat exchanger with OSF. Re_d^* was the 'point of transition', at which the curves began to deviate from the

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Nomenclature

l	strip length, m
L	fin length, m
t	fin thickness, m
h	fin height, m
s	fin space, m
d	flow length, m
$Affe$	front-fin-end area of OSF fin, m^2
D_h	hydraulic parameters, m
h_{TP}	overall heat transfer coefficient, W/m^2K
h_{nb}	nucleate heat transfer coefficient, W/m^2K
h_{cb}	convective heat transfer coefficient, W/m^2K
h_f	single phase heat transfer coefficient, W/m^2K
h_{pb}	pool boiling heat transfer coefficient, W/m^2K
M'	molecular weight, g/mol
q''	heat flux, W/m^2
σ	surface tension, MT^{-2}
ρ	density, kg/m^3

Dimensionless

j	Colburn factor
f	fanning friction factor
Re^*	critical Reynolds number
Re	Reynolds Number
Pr	Prandtl number
JF	thermal-hydraulic performance factor
SN	signal to noise ratio
x	quality
Xtt	LockharteMartinelli parameter
S	nucleate boiling suppression factor
Nu	Nusselt number
K	ratio of fin length to fin interval
M	number of fins along the flow direction
C_D	drag coefficient
N_B	bubble growth factor
Φ	two-phase frictional multiplier

Greek symbol

α	$= s/h$ fin geometric parameter
δ	$= t/l$ fin geometric parameter
γ	$= t/s$ fin geometric parameter
θ	fin angle
β	blockage ratio
β'	$= d/l$ fin geometric parameter

straight laminar line. It can be obtained using multiple regression corresponding to the slope changes of the j and f curves. The upper limit for laminar regime was Re_{d^*}, while the lower limit for the turbulent regime was $Re_{d^*} + 1000$. And the correlation for Re_{d^*} was summarized in Table 3. Analytical models were developed to predict j and f factors in the laminar flow regime and turbulent flow regime. The correlations for j and f factors based on a different definition of hydraulic diameter predicted 85% of the data within ± 15% deviation compared with experimental data. Based on the asymptotic behavior of the data in the deep laminar and fully turbulent flow regimes, equations for j and f factors were correlated by power law expressions in terms of Re and the dimensionless geometric parameters α, δ and γ by Manglik and Bergles [6]. Muzychka and Yovanovich [10] developed analytic models for predicting the thermal-hydraulic characteristics for high pressure flow, combining the creeping or low flow asymptotic behavior with laminar and turbulent boundary layer wake models.

In this review, many experimental and simulation researches of single phase flow have been conducted to obtain new forms of correlations, which can accurately predict the thermal and hydraulic performance. Especially it was found that the critical Reynolds was about 800 which was an appropriate number to distinguish the laminar flow and turbulent flow in the OSFs. The experimental researches on the thermal-hydraulic performance of two-phase flow are also included. And the new correlations of j and f factors including the corresponding hydraulic parameter and the application Reynolds region are summarized.

The major objectives of the present review are to summarize the recent advances on the thermal-hydraulic performance study of OSFs and its applications in compact heat exchangers. The review, covering the experiments, correlations and numerical simulations, is organized as the following:

(1) Heat transfer and pressure drop performance of single phase flow.
(2) Heat transfer and pressure drop performance of two phase flow.
(3) Performance analysis of heat exchangers with OSFs.

2. Structures of offset strip fin

The structures of offset strip fins normally can be catalogued as Type Z and Type H as shown in Fig. 1(a) and (b), respectively. Both them can be described by the fin height (h), the fin thickness (t), the fin length (l) and the fin space (s). The dimensionless geometric parameters $\alpha = s/h$, $\delta = t/l$, and $\gamma = t/s$ were established to describe the offset strip fin geometry by Joshi and Webb [3]. The surface shape of offset strip fins depends on the fin angle θ. When $\theta = 90^\circ$, then the shape is rectangle as shown in Fig. 1(c); when $\theta < 90^\circ$, then the shape is trapezoid as shown in Fig. 1(d). Although the surface shape is different according to fin angle, it is merely used to distinguish offset strip fins and there is no open literature to show the effect of fin shape on the thermal-hydraulic performance of offset strip fins. In addition, there are some new parameters proposed to describe the thermal-hydraulic performance, for example, entropy generation distribution factor and block ration, which will be illustrated in the following section.

3. Heat transfer and pressure drop characteristics of OSFs

OSFs are mainly used for air side heat transfer enhancement which could be assembled for internal and external sides. In engine cooling system, OSFs could be used as air side heat transfer with air/compressed air flowing over outside or inside tubes as well as in lubricant cooling system even working fluid is oil.

3.1. Single phase (air, water, lubricant oil)

Most of experimental researches were carried out in the wind tunnel as shown in Fig. 2. The wind tunnel apparatus consisted of a centrifugal fan, a water/lubricant oil circulation system and a data acquisition system. The test section was a compact heat exchanger, of which the cross section area was medium size. Sometimes, the sucked air conditions could be justified by cooling/heating system. For data acquisition system, the air/liquid inlet and outlet temperatures were measured by thermocouples and RTDs. Pressure drop were measured by two types of differential pressure transducers. The energy balance should be testified before experimental procedures and data reduction method would be used to analyze all the test results [4]. The main experimental matrix of the important parameters in single phase study was summarized as Table 1.

Sixteen types of offset strip fins with various parameters were tested