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Heat transfer performances of cryogenic fluids in offset strip fin-channels considering the effect of fin efficiency

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ABSTRACT

This paper numerically explores the heat transfer behaviors of cryogenic fluids in offset strip fin (OSF) channels considering the important effect of fin efficiency that combines the factors of low thermal conductivity of fin material at cryogenic temperatures and the fin geometry. A series of numerical simulations, which involve three kinds of fin materials with different thermal conductivities and the cryogenic fluids including both gases and liquids of nitrogen, normal hydrogen and classic helium 4, are carried out with well-validated 3D models. The results show that lower thermal conductivity of solid material at cryogenic temperature causes a considerable reduction in heat transfer performance of OSF fins especially for the liquids with high Prandtl number. Further analysis of the results reveals that for different cryogenic fluids, Nusselt number is strongly related to Prandtl number and fin efficiency. In particular, Nusselt number is proportional to the $Pr^{0.235}\eta_f^{0.9}$ in laminar region, regardless of Reynolds number and fin geometries. The results for different fin geometries suggest that larger fin thickness-to-length ratio can help to improve the heat transfer performance, while smaller fin thickness-to-height ratio and higher fin density no longer contribute to higher *j* factor (or Nusselt number) of OSF fin, especially in the case of lower thermal conductivity of fin material. There exist optimum fin thickness-to-height ratio and fin density that correspond to the maximum value of *j* factor for the cryogenic fluids.

1. Introduction

Offset strip fins (OSF) have been extensively used as heat transfer cores in plate-fin heat exchangers for many years. Their high compactness and lightweight have made these devises well suited for applications in aerospace, electronics and automobile industries. Besides, their high thermal performance has also made them available for use as precooled and main heat exchangers in air separation systems and refrigeration and liquefaction systems for cryogenic mediums (i.e. H_2, He). Interests in applications of the devices have prompted many studies on flow and heat transfer characteristics of OSF fins.

Kays and London [1], Dejong and Jacobi [2], Dong et al. [3] and Peng and Ling [4–6] investigated the airside thermal hydraulic performances of actual OSF fins, and provided a mass of experimental data for the design of plate-fin heat exchangers. The data were employed to develop and validate the models for the performance prediction, and many semi-theoretical or empirical correlations were reported in Ref. [7–14]. Mandrusiak and Carey [15], Hu and Herold [16,17], Kim and Sohn [18] and Saad et al. [19] examined the flow and heat transfer of water in OSF fin geometries over a wide range of flow conditions. In most of the studies, the experimental results were compared with the predictions provided by conventional airside correlations. The performance data obtained using HCFC refrigerants and oils as tested fluids can be seen in literatures [16–18,20–22].

In contrast to the studies mentioned above, few reports were published on heat transfer of cryogenic fluids in OSF fin cores. Robertson [22] conducted experiments with cryogenic nitrogen flowing in an electrically heated OSF fin-channel test-section and obtained some *j* data for gaseous nitrogen and liquid nitrogen. The temperature of the sub-cooled liquid nitrogen is about 77.3 K, and the flow rate was controlled by adjusting the pressure of liquid nitrogen tank. This is a preliminary study to understand the characteristic of heat transfer performance of the cryogenic fluid. The general behavior of the cryogenic heat transfer in OSF fin-channels remains unknown.

Due to the very little information on the heat transfer performances of OSF fins for cryogenic fluids, airside models are usually employed for designing the plate-fin heat exchangers used in cryogenic systems [23]. However, the heat transfer behaviors of OSF fins for cryogenic fluids, which are affected not only by the thermal

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Nomenclature

A	area (m^2)/total heat transfer area (m^2)
A_{ffe}	the front-fin-end area of OSF fin (m^2)
$A_{w,cp}$	the wall area of the covered plate (m^2)
b	the thickness of coved plate (m)
C	a constant (–)
C_p	specific heat at a constant pressure (J kg^{-1} K^{-1})
D_h	hydraulic diameter of fin channel (m)
G	mass flux (kg m^{-2} s^{-1})
h	height of the OSF fin (m)
h_c	mean heat transfer coefficient (W m^{-2} K^{-1})
l	fin length of the OSF fin (m)
j	Colburn factor (–)
k	turbulent kinetic energy (m^2 s^{-2})
Nu	Nusselt number (–)
p	pressure (Pa)
Pr	Prandtl number (–)
Q	heat transfer rate (W)
R	thermal resistance (K W^{-1})
Re	Reynolds Number (–)
S_ϕ	source term of ϕ
s	fin spacing (m)
T	temperature (K)
T_{bulk}	bulk temperature of fluid (K)
t	fin thickness (m)
U	heat transmittance coefficient (W m^{-2} K^{-1})
u	velocity (m s^{-1})
x	Cartesian coordinates (–)

Greek symbols

α	t/h
γ	t/s
δ	t/l
Γ_ϕ	diffusivity variable
ε	dissipation rate of turbulent kinetic energy (m^2 s^{-3})
η_f	fin efficiency (–)
η_o	surface efficiency (–)
λ	thermal conductivity of fluid (W m^{-1} K^{-1})
λ_s	thermal conductivity of solid (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
ϕ	general-dependent variable

Subscripts

app	apparent
base	the base wall of the covered plate
cp	covered plate
ht	heat transfer
in	inlet of fin channel
i, j, k	unit vectors
out	outlet of fin channel
pri	primary surfaces in fin channel
sec	secondary surfaces in fin channel
t	turbulence

properties of fluids and the geometrical parameters but also by the lower thermal conductivity of solid materials at cryogenic temperature, cannot be consistent with the airside characteristics under any conditions. Arbitrarily using the airside models may cause an inappropriate selection of fin-surface and determination of heat transfer area when designing a plate-fin heat exchanger operating at cryogenic temperature. Therefore, it is important to investigate the heat transfer characteristics of cryogenic fluids in OSF fin channels. In addition, comprehensively understanding the heat transfer of cryogenic fluids will also help to facilitate the prediction of the boiling heat transfer coefficient.

The heat transfer in cryogenic plants is characterized by the low mass and heat fluxes and the very low temperature differences between streams [22]. It is difficult to measure the heat transfer coefficients of cryogenic fluids in OSF fins accurately. In addition, the tests can be cost-prohibitive considering the complexity of experimental systems and the safety of the testing mediums (i.e. H_2). With the development of computational capacities, the heat transfer characteristics of different fluids in OSF fin channels can be investigated more efficiently by using CFD technique. In recent studies [13,14,24], numerical models were even employed for generating the design data, as a result of which the experimental work could be reduced to some extent. In view of this, the investigation on the heat transfer of cryogenic fluids in OSF fins can be extended further according to CFD simulation.

The present study is undertaken to explore the heat transfer characteristics of cryogenic fluids in OSF fin-channels numerically. The numerical models are well validated by comparing with the experimental data for gaseous and liquid nitrogen in Ref. [22]. The studied fluids include gaseous and liquid N_2, H_2 and ^4He. According to the study, the reason why thermal conductivity of fin material affects the heat transfer performance of OSF fin will be revealed in detail, and how Prandtl number and fin performance affect the heat transfer coefficient will also be analyzed carefully. Finally, the effects of fin-channel geometry on the thermal performance for the cryogenic fluids will be discussed. The results of the present study can provide a strong support in theory and data for the design and development of plate-fin heat exchangers operating at cryogenic temperature.

2. Model

2.1. Physical model

A diagram of typical OSF fin used in plate-fin heat exchangers is shown in Fig. 1(a). The fin geometry is described by four parameters: fin height h, fin space s, fin thickness t and fin length l. The non-dimensional design parameters include fin thickness-to-height ratio α (=t/h), fin density γ (=t/s) and the fin thickness-to-length ratio δ (=t/l). With the assumptions of the rectangular fin-channels without round corners and the uniform fin offset that is equal to a half-fin spacing [10], the hydraulic diameter, D_h, is defined as:

$$D_h = \frac{4l(h-t)(s-t)}{2(l(h-t)+l(s-t)+t(h-t))+t(s-2t)} \quad (1)$$

Fig. 1(b) schematically shows the computational domain of OSF fin. The cover plates and entrance and exit parts are added in the 3D models, and the studied fin arrays have at least 24 rows of periodic fins in order to guarantee that the ratio of flow length to hydraulic diameter is more than 60. The thickness of the covered plate, denoted by b, is 1 mm in the study.

2.2. Governing equations

The assumptions required in the CFD simulation are as follows:

(1) The flow and heat transfer are in steady state with no phase transition,