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Airside heat transfer and pressure loss characteristics of bare and finned tube heat exchangers used for aero engine cooling considering variable air properties

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ABSTRACT

Numerical studies have been conducted to investigate the airside thermal-hydraulic characteristics of bare tube bank and plain finned tube heat exchangers intended for use in aero-engine cooling. The exchangers use small diameter tubes (3.0 mm) with compact tube layout and operate at high temperatures with large temperature changes over the exchanger depth. Calculations are performed for frontal air velocities between 5 and 20 m/s, yielding tube diameter based Reynolds numbers from 4898 to 19,592. Calculations are implemented using the Realizable k-ε turbulence model with consideration of the air physical property variations caused by the air temperature changes. The results show that ignorance of the air property variability leads to overestimations of both heat transfer and pressure loss, with a smaller air velocity yielding a more serious overestimation. The numerical fin efficiency agrees with the Schmidt fin efficiency within 7.0%. The plain finned tube heat exchanger is superior to the bare tube bank heat exchanger if the exchanger performance is evaluated using the heat transfer rate to pressure drop ratio.

1. Introduction

With the development of the aero engine technologies, fin-tube heat exchangers show potential applications in aero engines for their high efficiency and security. As compared with the traditional heat exchangers used on the ground, those used in aero engines are more compact and suffer higher temperatures and larger temperature differences. The temperature change over the exchanger depth and the temperature gradient in the near wall region are more conspicuous, they may reach several hundred degrees. Large temperature change means significant fluid property variation, which must be considered when evaluating the exchanger performance.

The air from compressor is often used for turbine airfoil cooling in aero engines. When the air temperature increases, which may be caused by increased compression ratio, the air flowrate has to be increased in order to guarantee the air cooling capacity, this is disadvantageous to the performance of engine thrust. For example, the cooling air of E^3 engine accounts for 18.87% of the total air, such a large amount of air damages the improvement of engine thrust. Bruening and Chang [1] proposed the concept of pre-cooling the compressor bleed air before it is channeled to cool the turbine, which is called the cooled cooling air (CCA) system. Their results suggest that the CCA system can improve the overall engine performance. A key device included in such a system is a heat exchanger, which may be a fin-tube heat exchanger, in which the fluid to be cooled is air and that serving as cold source is likely to be fuel oil. Since the dominant thermal resistance is on the airside, the airside flow and heat transfer performance is critical to the exchanger design and optimization. Puterbaugh et al. [2] studied the heat exchanger impact on aero engine performance, they used the bare tube bank heat exchangers for the CCA system. Huang et al. [3] performed conceptual design studies over a wide range of potential fuel-air heat exchanger concepts for fuel-cooled thermal management system, they stated that the metal foam tube heat exchanger was one of the most promising designs. In fact, a fin-tube heat exchanger may be superior to a foam-tube heat exchanger because the fin has well-designed structure while the foam is random in structure, so a fin-tube heat exchanger is more likely to have higher fin efficiency and less pressure drag as compared to a foam-tube heat exchanger. For fuel-air heat exchanger used in aero engine, the in-tube fuel pressure is commonly at a level of 5 MPa

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Nomenclature

A	total heat transfer surface area, m^2
A_f	fin surface area, m^2
D	tube diameter, mm
F_p	fin pitch, mm
h	heat transfer coefficient, $W/(m^2 K)$
N	number of tube rows
P_t	transverse tube pitch, mm
P_l	longitudinal tube pitch, mm
P	pressure, Pa
Pr	Prandtl number
$\triangle P$	pressure drop, Pa
q	heat transfer rate, W
Re	Reynolds number
T	temperature, K
$\triangle T_{lm}$	logarithmic mean temperature difference, K
u, v, w	velocity, m/s
V	air velocity, m/s
u_{max}	maximum velocity at minimum cross-section, m/s

Greek symbols

ρ	density, kg/m^3
λ	thermal conductivity, $W/(m{\cdot}K)$
μ	viscosity, $Pa{\cdot}s$
η_f	fin efficiency
η_0	surface efficiency
δ_f	fin thinkness, mm

Subscripts

ave	average
f	fin
i	serial number of slit planes, $i = 1,2,\ldots,13$
in	inlet
m	mean
n	normal direction
out	outlet
w	wall

while the airside pressure is much lower than it, this large pressure difference may expend the tube, which can improve the contact between the tube and fin and consequently reduce the fin-tube thermal resistance. The fin-tube type heat exchanger is thus chosen for study in this research. The present paper deals with small diameter tube heat exchangers without and with fins intended for use in the CCA system and numerically studies their airside thermal-hydraulic performances with consideration of the air physical property variations caused by the air temperature variations.

Many studies have been done on the airside heat transfer and pressure drop characteristics of finned tube heat exchangers, most of them are for those having tubes in conventional dimensions and operating with small temperature changes. Wang et al. [4,5] experimentally investigated the effects of tube row number (1–4), tube outer diameter (7.53, 8.51 and 10.23 mm) and fin pitch (1.19–2.31 mm), and reported that the heat transfer characteristics was related to the fin pitch depending on the tube row number while the friction performance was nearly independent of the tube row number. Kim [6] did tests on samples having large fin pitches and found that over a Reynolds number range from 500 to 900, the airside heat transfer coefficient increased with reducing fin pitch and decreased with increasing tube row number from 1 to 4. The heat transfer coefficient of staggered tube arrangement was 10% higher than that of in-line arrangement. Wongwises and Chokeman [7] found that the heat transfer coefficient increased with reducing fin pitch as it changed from 1.41 to 2.54 mm, but the effect was insignificant. The Colburn factor and friction factor decreased with increasing number of tube rows for $Re < 4000$. Jang et al. [8] studied the effects of tube layout on heat transfer characteristics and found that the heat transfer coefficient of staggered arrangement was 15–27% higher than that of in-line arrangement. Ay et al. [9] performed an experimental study to investigate the effects of tube arrangement on heat transfer coefficient and came to the same conclusion but the percentage was 14–32%. He et al. [10] analyzed the effects of Reynolds number, fin pitch, tube row number, transverse and longitudinal tube pitches from the view point of field synergy and pointed out that the less the tube row number, the better the synergy between the fluid velocity and temperature gradient fields. Kang et al. [11] numerically investigated the pressure drop and heat transfer of compact tube bundle heat exchangers used for advanced sodium-cooled fast reactor, they compared the flow and heat transfer characteristics of different configurations. Min and Webb [12] numerically predicted the airside heat transfer and pressure drop characteristics of wavy finned tube heat exchangers, they [13] further discussed the effects of tube geometry on the exchanger performance. Min et al. [14] calculated the fin efficiencies of finned oval tube heat exchangers using sector method and developed correlations for determining the fin efficiencies of such exchangers.

Researches are also seen on tube bank heat exchangers used in aero engines. Puterbaugh et al. [2] proposed a CCA system containing a tube bank heat exchanger and discussed the possible influences of the exchanger pressure loss on aero-engine overall performance, but they provided no information on the exchanger thermal-hydraulic characteristics. Albanakis et al. [15] experimentally investigated the performances of elliptical tube bank heat exchangers working as heat recuperators by taking advantage of the thermal energy of the exhaust gas from turbine, the results showed that the effect of the angle of attack on pressure drop was significant while that of the angle of inclination was negligible. Murray et al. [16] built a highly compact tube bank heat exchanger using 0.38 mm diameter tubes for air breathing rocket engine of the SKYLON aerospaceplane, they discussed the exchanger manufacturing techniques and experimentally investigated its thermal-hydraulic performance.

As stated above, most of the previous researches on bare tube or finned tube heat exchangers were conducted for those using tubes in conventional dimensions and operating with fluid temperature changes that were not so large, so the fluid physical property variability was commonly ignored. The present research focuses on both bare tube bank and plain finned tube heat exchangers that use small diameter tubes with compact tube layout and operate at high temperatures with large temperature changes over the exchanger depth, it numerically investigates the heat transfer and pressure loss characteristics of such exchangers with consideration of the air property variability caused by the air temperature changes. The specific objectives of this research are: (1) to better understand the airside thermal-hydraulic characteristics for both bare and finned tube heat exchangers that use small diameter tubes with compact geometry configuration and operate with large temperature changes over the exchanger depth, (2) to reveal the