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A numerical study on the aero-thermal performance of a slanted-pin-fin cooler under a high-speed-bypass condition

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ABSTRACT

The aero-thermal performance of a slanted-pin fin heat exchanger under high-speed-bypass stream condition was investigated numerically. A channel-shaped computational domain with a periodic boundary condition in the translational direction was adopted. A parametric study was conducted for a Reynolds number ranging from 33,000 to 164,000, a bypass height ratio of 1.5–30, and the tilted angle of the fin in a range of 0–45°. The calculated pressure drop and the heat transfer rate are summarized by correlation forms of the friction factor and the Nusselt number. Details of the flow structure and the thermal characteristics of the slanted-pin fin models were assessed as well as the irreversibility loss by the entropy generation. The results showed the advantage of slanted-pin fins for application to aero-engines where the weight penalty and the size of the cooler are critical.

1. Introduction

For aero-gas-turbine engines, the demand for high efficiency for environmental protection and energy savings is increasing rapidly. It is well known that a high efficiency gas-turbine engine can be achieved by using advanced thermal cycles, such as intercooled and/or recuperated Brayton cycles. For an aero engine, however, the weight penalty due to the addition of heat exchangers for advanced cycles can have a negative effect on the specific fuel consumption (SFC). Furthermore, as the SFC is closely related to the operating pressure ratio (OPR) and the turbine inlet temperature (TIT), future highly efficient engines should be operated at high temperature and high pressure conditions. Due to these reasons, the development of an ultra-light heat exchanger for aero engines that can be operated in extreme environmental conditions is essential.

Min et al. [1] reviewed existing and possible candidate heat exchanger technologies using recuperator, intercooler, and cooling-air cooler applications in the aero engine. Another way to improve the efficiency of the turbo-fan type gas-turbine engine is to increase the bypass ratio (BPR) of the engine. Recent research on a high BPR civil large engine incorporating a geared fan provided 25% greater fuel efficiency than an existing engine by Haselbach [2], Ryemill and Min [3]. This large BPR engine presents a new challenge for the heat management system in the engine due to dramatically increased heat loads from the oil system corresponding to the gear box and power generator in the transmission system. The surface air-oil heat exchanger (SAOHE), also known as the surface cooler, of the aero engine is installed inside the nacelle in order to cool the oil flow using a bypass stream of air (Fig. 1). The design of the surface cooler becomes complex due to this installation configuration, however, as there is an additional pressure drop in the bypass flow that is detrimental to the SFC [4].

A number of studies on the surface cooler performance in an aero engine have been reported. Outirba and Hendrick [5] conducted an experimental study on the SAOHE, describing a new test rig that allowed complete tests of surface cooler breadboards. Ko et al. [6] studied the effect of SAOHE installation using a numerical method. Kim et al. [7] investigated the effect of cooler installation location by experimental and numerical tests, for a plate-fin-type heat exchanger. In this paper, an efficient numerical model for the installation studies of a cooler incorporating bypass ducts was suggested and important design variables for the installation location were identified. Kim et al. [8] carried out a numerical study on the performance of a surface cooler having various pin-fin shaped geometries. In this study, a pin-fin slanted forward in the stream-wise direction showed possibility of achieving light weight due to the accelerated air flow near the bottom of the fin. Kim et al. [9] proposed an effective numerical method for the preliminary design of a surface cooler using a one-dimensional flow and thermal network analysis for the aero gas-turbine engine configuration. Seo et al. [10] studied the characteristics of flow and heat transfer for a rectangular pin-fin slanted to the flow direction.

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Nomenclature

Symbols

Be	Bejan number
C_p	specific heat
c_f	skin friction factor
c_p	pressure coefficient
D	inside tube diameter
e	roughness
f	Fanning friction factor
G_a	area goodness factor
G_v	volume goodness factor
H_b	bypass height
H_f	fin height
h	heat transfer coefficient
k	turbulent kinetic energy
L_f	fin length
L_{sp}	spanwise pitch
Nu	Nusselt number
p	static pressure
Q	heat transfer rate
Pr	Prandtl number
Re	Reynolds number
S	entropy
St	Stanton number
T	static temperature
t_f	fin thickness
U	inlet velocity
u, v, w	dimensionless velocity components in x, y and z direction
x_i	Cartesian coordinate system, $x_i = (x, y, z)$

Greek symbols

α	thermal diffusivity
λ	thermal conductivity
μ	fluid viscosity
θ_t	tilted angle of fin
ν	fluid kinematic viscosity
ρ	fluid density
τ	shear stress

Sub/superscripts

i, j	tensor notation

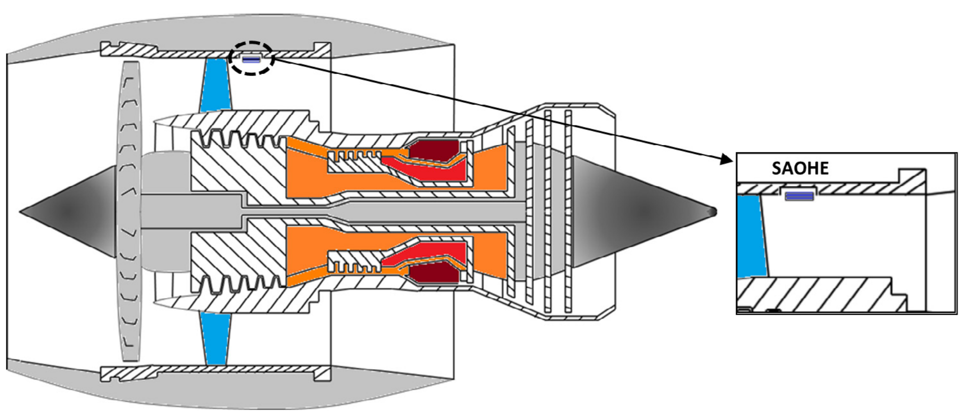

Fig. 1. Schematic configuration of conventional surface air-to-oil heat exchanger (SAOHE) in an aero-engine.

In this study, a simplified channel computational model without a bypass region was used, and the effect of the tilted angle was investigated numerically.

It was found that a modified fin surface may have a high heat transfer coefficient, but that its pressure drop is sometimes too large for wide applications. Regarding the shapes of fins and their effect on the aero-thermal performance of heat exchangers, numerous studies have been reported. Kang et al. [11] compared four kinds of plate-fin surfaces (plain, corrugated with a triangular-cross-sectional channel, corrugated with a sinusoidal cross-sectional channel, and a slotted fin). They found that the slotted-fin surface enhanced the heat transfer rate by 30–40% compared to the plain plate-fin, for identical pumping power. For pin-fin models, Shaukatullah et al. [12] calculated the performance of in-line square pin-fins and plate heat-sinks for different fin thickness, spacing, height, and angle of approach for velocities under 5 m/s, allowing the flow to partially bypass the exchanger. Jonsson and Moshfegh [13,14] experimentally studied characteristics of plate fin and circular-, rectangular- and strip-pin fins, in both staggered and in-line configurations, for different dimensions. Jeng and Tzeng [15] carried out an experimental study on the performance of rectangular pin-fins in a channel and compared their characteristics with those of cylindrical pin-fins. More recently, Abdoli et al. [16] investigated the effect of micro pin-fins having six different shapes on the cooling of high heat flux electronic chips with a single hot spot. They found that the hydrofoil shape micro pin-fin design showed a 30% reduction in pumping power and a 3% increase in the ratio of convection heat removal over total heat load, compared to the conventional circular shape micro pin-fin design.

There have not been many studies on the effect of inclined pin-fins. Fowler and Bejan [17] carried out a study on the characteristics of pressure drop and heat transfer for an inclined cylinder having angles of 0° to 60° relative to the flow direction for low Reynold numbers. They considered two different pin-array types such as staggered and equilateral, and compared their results with the Zukauskas correlation for a Reynolds number of 30. Park et al. [18] experimentally examined the effects of pin inclination angle of both 60° and 90° on the heat and mass transfer characteristics in a pin-fin channel with and without rotation. For the inclined case of 60°, the fin-base region where the upstream most pin-base situates inherits higher heat and mass transfer than the upper wall surface, by about 10–15%.