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Experimental study of surface heating by a high speed exhaust plume

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ABSTRACT

Airframe surface heating by gas turbine plume is an ongoing issue in aerospace applications. This paper presents the practicability of a smaller scale system based on a micro gas turbine which offers verisimilitude and realism to the actual airframe surface heating by a full scale engine exhaust plume flow. A thin flat plate made from 7075-T6 aluminium alloy was placed at $X = 7D$ downstream of the nozzle exit of the gas turbine. Nozzle exit flow temperature ranged from 850 K to 920 K and Reynolds number over the sample plate ranged from 3.8×10^4 to 2.6×10^5. The average Nusselt number was found to be correlated to $CRe^m Pr^n$ with $m = 0.42$, $n = 0.33$, $C = 0.094$ for parallel plume flow over the sample plate at $X = 7D$ and $Z = 0D$. It was also found that coefficient C can be scaled by velocity magnitude ratio with respect to the plume centre if the sample was positioned away from the centre of the jet plume. Heat transfer by infrared radiation was found to be less than 2% compared to the overall heat flux.

1. Introduction

The major infrared signature source of a jet-powered aircraft is typically the infrared emission from engine exhaust surfaces. However, at times, exhaust surfaces are not in direct line-of-sight which raises the importance of other secondary infrared signature sources such as the heating of the airframe by the engine exhaust plume [14]. Because of its relative ease of detection, and also because of the difficulty in suppression, airframe infrared signatures degrade the ability to maintain the stealth of an aircraft. There is therefore a need to understand the processes that work to generate the source of the signature.

In most aerospace application cases, the exhaust plume impinges parallel to the airframe surfaces. For instance, the tail boom of a helicopter is being heated up by unintended weak plume impingement due to exhaust plume deflection in rotor downwash. In high-lift structures application such as on airlift aircraft, the jet plume is redirected to flow over the upper surface of extended flaps to enhance lift by the Coanda effect. This method of generating extra lift creates surface heating which contributes to infrared emission.

Early research on impinging heated jet transfer was done to simulate the high temperature entry of high speed space vehicles into Earth's atmosphere [7]. Subsequent studies focused on improving industrial processes such as metal heating and melting [6], and synthetic diamond coatings [3]. In 1986, Rauenzahn [16] extended this work to supersonic high energy flames used to fracture rocks. High velocity flame jets have also been studied to model large scale fires impinging on structures caused by ruptured piping in the chemical process industry [10]. Low speed and intensity impinging flames such as those used in fire safety research were also studied to simulate buoyant fires impinging on walls and ceilings [21]. Research on parallel impingement by a jet exhaust plume flow is largely missing from the available jet heat transfer literature [1].

Examining aircraft infrared signatures has had the problem of there being a limited range of easily adaptable, realistic laboratory scale systems that enable investigation of a large parameter space at low cost. However, the development of the micro gas turbine for model aircraft has now made this possible. Micro jet gas turbines are single spool pure jet engines. They typically have a centrifugal compressor driven by an axial single stage turbine which supplies an annular propelling nozzle. Similar to the full scale engines, these engines also use Jet A1 fuel, but unlike large engines they rely on a small amount of oil mixed with the fuel to provide spool lubrication. Except for this small amount of oil, the exhaust plume produced from these engines is a direct experimental analogue of that produced from a full scale engine in terms of speed, temperature and composition. Their size, ease of use and controllability make them an ideal laboratory scale test engine for investigation of airframe infrared signatures.

An additional benefit following from the use of these engines is the ability to accurately map the characteristics of the plume and

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Nomenclature

γ	specific heat ratio
λ	electromagnetic wavelength [µm]
μ	viscosity of fluid [kg/m s]
$\bar{h}$	average heat transfer coefficient [W/m^2 K]
$\overline{Nu}$	average Nusselt number
ϕ	azimuthal angle [rad]
ρ	local density of the flow [kg/m^3]
σ	Stefan–Boltzmann constant [W/m^2 K^4]
θ	zenith angle [rad]
ε	paint emissivity
C	constant C
C_p	heat capacity [J/kg K]
D	one nozzle diameter
d	element thickness [m]
E_b	blackbody emissive power [W/m^2]
E_p	sample plate emissive power [W/m^2]
F_m	mass concentration of soot per volume gas [mg/m^3]
F_v	soot volume fraction per volume gas [m^3/m^3]
F_λ	blackbody radiation function
h	local heat transfer coefficient [W/m^2 K]
$I_{\lambda,b}$	blackbody spectral intensity [W/m^2 µm strad]
k_e	thermal conductivity of element [W/m K]
k_f	thermal conductivity of fluid [W/m K]
L	characteristic length of sample [m]
m	gradient of logNu/Pr^n vs log Re
M_{ave}	average gas molar mass [kg/mol]
Ma	local Mach number
n	$n = 0.33$ for air
P_o	local total pressure [Pa]

P_s	local static pressure [Pa]
Pr	Prandtl number
q	heat rate [W]
q''_{gas_rad}	gas infrared irradiance on plate [W/m^2]
q''_{net_rad}	net infrared radiation heat flux [W/m^2]
q''_{plate_rad}	plate surface infrared radiosity [W/m^2]
q''_{total}	total average heat flux without radiation [W/m^2]
q_{cond}	conduction heat transfer rate [W]
q_{conv}	convection heat transfer rate [W]
R	radius of the plume [m]
r	local radius of the plume [m]
R_g	gas constant [J/mol K]
Re_L	Reynolds number
S	swirl number
T_f	film temperature [K]
T_o	local total temperature [K]
T_s	local static temperature [K]
T_∞	bulk flow temperature at infinity [K]
T_{noz}	temperature of flow at nozzle exit [K]
T_{surf}	maximum local surface temperature of sample [K]
U	local axial flow velocity [m/s]
U_∞	bulk flow velocity at infinity [m/s]
U_{le}	mean flow velocity at leading edge of sample [m/s]
V	local radial flow velocity [m/s]
W	local azimuthal flow velocity [m/s]
Δx	lateral distance between nodes [m]
Δy	longitudinal distance between nodes [m]

the resulting interaction with airframe elements. This paper presents the use of a few selected micro jet turbine plume conditions to simulate airframe surface heating phenomenon and the determination of empirical convection heat transfer correlations based on the experimental results.

2. Experimental setup

For the experiment, a thin 7075-T6 aluminium alloy flat plate with the dimension $8D$ (360 mm) × $2D$ (90 mm) × $0.03D$ (1.27 mm) was chosen to be placed in a developed plume region downstream of the 45 mm diameter (D) nozzle of a micro jet engine which can produce up to 80 N thrust. The plate was placed at two locations: (1) $X = 7D$ and $Z = 0D$; (2) $X = 7D$ and $Z = -1D$, referenced to the leading edge of the plate as shown in Fig. 1. The plate was painted with a black paint with a measured average emissivity ε of 0.94. A 384 × 288 pixel thermal imaging camera with spectral range 7.5–14 µm and temperature measurement range −40 °C to 1200 °C, mounted on a rail over the top of the engine, was used to capture the infrared images of the samples for surface heating experiments. The thermal imaging results were checked using the thermocouples installed on the surface of the plate [12].

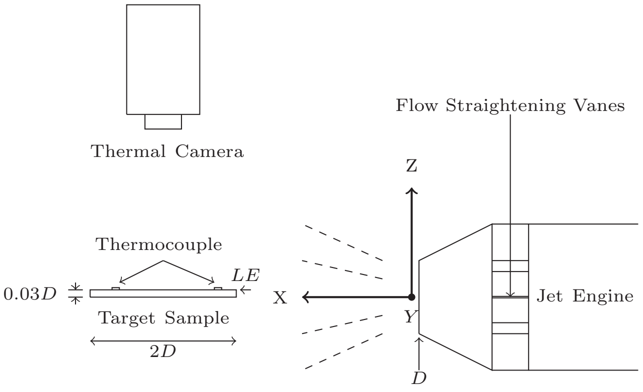

Fig. 1. Experiment schematic layout.

3. Characterisation

3.1. Plume characterisation

3.1.1. Flow velocity and temperature magnitude

The plume conditions were measured using various probes with the aid of a 3-axis stepper motor, which moved the probes incrementally in a precise three dimensional space frame. An open-ended type-K thermocouple with tip size 0.45 mm diameter × 2.15 mm length was aligned so that it measured the exhaust gas stagnation temperature, T_o at different points in the exhaust gas stream. The steady-state temperature at each designated point was acquired by a thermocouple data logger. Since the thermocouple sensor size was small, it was assumed that the variation of flow velocity around the sensor was negligible. Therefore, the recovery factor of the kinetic energy at the sensor tip can be approximated to be unity [20].

A 1.2 mm stagnation hole pitot-static tube and a differential pressure transducer were used to measure the pressure difference between the stagnation and static pressure of the exhaust gas stream to acquire the velocity magnitude profile of the exhaust gas. Details on post-processing temperature and velocity