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Computational Simulation of Cylindrical Film Hole with Jet Pulsation on Flat Plates

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Film cooling of flat plates with pulsation were simulated using FLUENT$^{\mathrm{TM}}$ commercial code with realizable k-ε turbulence model. The simulations were done for nominal blowing ratios 0.5 and 1.5, duty cycle = 50%, and Strouhal number ranging from 0.0119 to 1.0. Pulsation helps to lower the amount of cool air from the compressor, which is desirable for film-cooling applications. Pulsed jets performance significantly depends on geometry and blowing ratio. From the cases studied and for steady flow with attached jets, pulsation considerably decreases the film-cooling effectiveness. On the other hand, for steady flow cases where jet liftoff occurs (e.g., higher blowing ratios), pulsation helps to increase the film-cooling effectiveness.

Nomenclature

B = blowing ratio $= \rho_c V_c / \rho_\infty V_\infty$
D = film hole diameter, m
f = frequency, Hz
L = Length of film-cooling hole channel, m
Re = Reynolds number $= V_\infty D/\nu$
St = Strouhal number $= fD/V_\infty$
T = local fluid temperature, K
t = time/(cycle time)
V = local fluid velocity magnitude, m/s
x = streamwise distance along the test plate, m
y = vertical distance above the test plate, m
y^+ = dimensionless wall distance $= y(\tau_w/\rho_w)^{1/2}/V_w$
z = spanwise coordinate, distance from centerline of the hole, m
η = adiabatic film cooling effectiveness $=(T_{\mathrm{aw}} - T_\infty)/(T_{\mathrm{jet}} - T_\infty)$
θ = dimensionless temperature, $(T - T_\infty)/(T_{\mathrm{jet}} - T_\infty)$
ν = kinematic viscosity, m^2/s
ρ = density, kg/m^3

Subscripts

aw = adiabatic wall
c = coolant flow characteristics
fh = film hole
jet = film-cooling jet characteristics
∞ = mainstream

I. Introduction

FILM cooling has been used in modern gas turbines to protect the surface of turbine blades from failing at high temperatures. Much research has been done in film cooling to achieve better cooling of gas turbine blades and thus increase performance of turbine engines by allowing higher inlet temperatures. About 20–25% of compressor air is used for cooling high-performance turbine engines (Ekkad et al. [1]). Higher engine efficiency may be obtained by minimizing coolant mass flow with the same or higher film-cooling effectiveness. Experimental studies found in the literature showed that coolant flow pulsation might help to improve film cooling while reducing the actual film flow rate. There are very few studies published that consider the effect of jet pulsation on the film-cooling characteristics.

Ekkad et al. [1] experimentally investigated the effect of jet pulsation and duty cycle on film cooling from a single jet located on the circular leading edge of a blunt body. Film-cooling characteristics were examined for duty cycles (DC) (from 0.1 to 1) at nominal pulse blowing ratios (B) (from 0.5 to 2) and pulse frequencies of 5 and 10 Hz. This study reported that higher film-cooling effectiveness was obtained at the reduced blowing ratios, and the effect of varying the pulsing frequency was negligible. The conclusion of this work was that pulsed jets resulted in relatively better film-cooling effectiveness compared to continuously blown jets.

Coulthard et al. [2] conducted an experimental study of a row of film-cooling jets in crossflow on a flat plate. Jets were inclined 35 deg to the surface in a streamwise direction. Various blowing ratios (from 0.25 to 1.5), duty cycles (from 0.25 to 0.75), and Strouhal numbers St (from 0.0119 to 0.1905) were considered. The authors reported that the highest film-cooling effectiveness was achieved at blowing ratio 0.5 with steady blowing. With increasing blowing ratio, effectiveness decreased due to jet liftoff. In their work the authors observed that higher pulsation frequencies resulted in lower effectiveness with the exception of the highest frequency tested, where the trend was reversed. The overall conclusion was that pulsing does not provide benefits to the film-cooling applications for the studied geometry and flow characteristics. Comparing the results of the two experiments (Ekkad et al. [1] and Coulthard et al. [2]) is rather difficult because the two cases had different geometry (both jet and plenum) and free-stream pressure gradients, in addition to other differences.

Muldoon and Acharya [3] were the first to conduct a computational direct numerical simulation (DNS) study of pulsed jet film cooling. The geometry in their work consisted of a cylindrical jet, inclined at 35 deg in the streamwise direction, in a crossflow. Jets were pulsed with various duty cycles (from 0.25 to 1), blowing ratios (from 0.375 to 1.5), and Strouhal numbers (0.08 and 0.32). The coolant delivery tube was modeled in baseline DNS calculations to obtain jet-exit conditions. A conclusion of their study was that pulsing, with higher frequency DC = 50% and peak B of 1.5, helped

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