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Heat Transfer from Impinging Gas Jets on an Enclosed Concave Surface

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Nomenclature

A_j = cross-sectional area of a jet exhaust hole
C_p = gas specific heat
C_D = discharge coefficient
d = jet nozzle diameter
d^* = effective jet nozzle diameter
D = distance from jet nozzle to impinged surface
$f(\theta)$ = influence coefficient of angular displacement on $Nu_s{}^*$
h = heat-transfer coefficient
h_l = local heat-transfer coefficient
h_{ave} = average heat-transfer coefficient
k = gas thermal conductivity
L = the axial peripheral length of the external skin of the model
$Nu_s{}^*$ = Nusselt number for internal heat transfer, $h_{ave}s^*/k$
Pr = hot air Prandtl number evaluated at jet exhaust nozzle manifold tube total conditions, $\mu C_p/k$
$\dot{q}_w$ = wall heat flux
Re_{S^*} = jet nozzle Reynolds number evaluated at manifold tube total conditions, $(\dot{w}/A_jC_D)S^*/\mu$
S^* = effective slot width if jet holes were replaced by a single slot
Sp = jet nozzle hole spacing on manifold tube
T = temperature
T_g = gas temperature
$T_{g,o}$ = total gas temperature in jet exhaust manifold tube
T_w = surface temperature
$\dot{w}$ = mass flowrate per jet
X = surface length from point of impingement
θ = angular displacement of jet
μ = absolute viscosity

Introduction

RESEARCH in heat transfer on surfaces caused by impinging gas jets has been usually limited to open surfaces such as flat plates or rectangular cavities. Little work has been done on problems involving enclosed surfaces. Many applications exist where jets are presently being used in enclosed surfaces. This ranges from conditions of atmospheric icing on wing leading edges and engine inlet cowl lips to stagnation-point cooling of supersonic and hypersonic vehicle leading edges and forward surfaces. It is the intention of this Note to present a more general correlation for the solution of gas jet heat transfer in internal surfaces.

Experiment

A test program was conducted upon an experimental model with a typical enclosed surface shape that would be found in aircraft application (Fig. 1). The test section of the model was 1 ft long with a 0.032-in. aluminum external skin with axial peripheral length of 9.1 in. and a nose radius of 0.62 in. The height of the model at the rear was 2.75 in. The air jet exhaust tube was 0.75 in. inside diameter with 0.0995 in. holes spaced on 0.500 in. centers. The gas exhausted out of the bottom of the model through slots near the rear bulkhead. The pressure inside the plenum of the model was approximately 1 in. of water above atmospheric during experimentation. The model skin was highly instrumented to give dense coverage of data, especially near the point of impingement. The type of test conducted was of the transient-response type where the output of the skin thermocouples was monitored vs time.

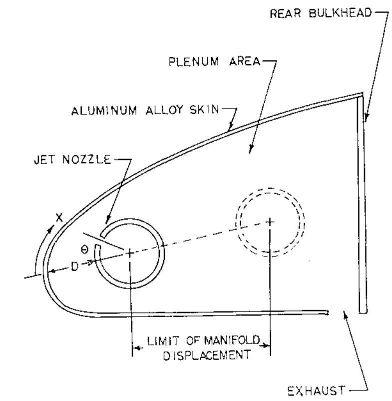

Fig. 1 Experimental model.

Three parameters were varied; the gas flow rate, the distance of the jet exhaust holes from the model skin, and the angle of inclination of the jet exhaust holes. The range of parameters tested included; air mass flow rate from 1.0 to 6.0 lb/min/ft length of jet exhaust tube manifold; distance of jet exhaust holes from model skin from 0.75 to 2.0 in.; angle of jet exhaust hole inclination from $+20°$ to $-20°$.

Results

The resulting correlation from the aforementioned test results for the average heat transfer over the skin surface is

$$Nu_{s^*} = 0.030\,f(\theta)(D/S^*)^{-0.4}Re_{s^*}{}^{0.7}\,Pr^{0.3} \tag{1}$$

The heat-transfer coefficient is defined in terms of the gas total temperature found inside the jet nozzle manifold tube rather than an arrival temperature found near the impinged surface. The total temperature is a more well defined or known quantity while performing analysis and eliminates the error incurred when calculating an arrival temperature. The heat-transfer coefficient is therefore defined as

$$h = \dot{q}_w/(T_{g,o} - T_w) \tag{2}$$

The angular dependence function is given as

$$f(\theta) = 0.087\,(2^{1+\theta/20}) + 0.826 \tag{3}$$

Equation (1) has been cast into such a form that the hole spacing (or slot) and hole diameter on the jet exhaust manifold tube is replaced by an effective two-dimensional slot of width S^*. This eliminates the need for another parameter to take into account hole spacing and hole diameter:

$$S^* = \pi(d^*)^2/4Sp \tag{4}$$

The contraction coefficient is incorporated into the effective hole diameter d^*:

$$d^* = d(C_D)^{1/2} \tag{5}$$

Equation (1) is valid over the range of independent parameters and geometrical variables as shown in Table 1. For symmetrical external surfaces, the author suggests that θ in the angular correction term be replaced by $|\theta|$ in Eq. (3). A comparison with test data is plotted in Fig. 2.

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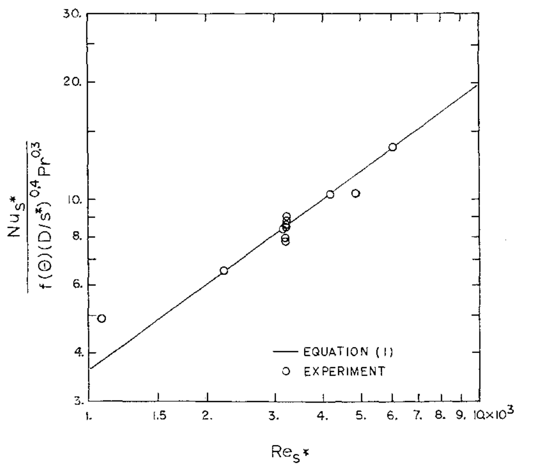

Fig. 2 Correlation of test results.

The local heat-transfer coefficient may be obtained approximately by the following procedure. It was found that the local heat-transfer coefficient distribution follows a Gaussian probability density distribution curve. The results may be expressed as

$$h_l = h_{min} + (h_{max} - h_{min})e^{-\eta^2/2} \quad (6)$$

For air it was found that over all the tests the maximum and minimum heat-transfer coefficients could be approximately expressed as

$$h_{max} = 1.40 \, h_{ave} \quad (7)$$

$$h_{min} = 0.70 \, h_{ave} \quad (8)$$

h_{max} is the heat-transfer coefficient found at the point of impingement. h_{min} is found at extreme end of the surface furthest removed from point of impingement. h_{ave} is obtained from Eq. (1). The exponent may be expressed as

$$\eta = 2.4 \, X/L \quad (9)$$

X is measured from the point of impingement along the surface.

Conclusion

This series of tests has provided a usable correlation for the design of systems using impinging air jets on concave enclosed surfaces. The empirical correlation, Eq. (1) suggests a Nusselt number dependency on the Reynolds number to a 0.7 power. This compares quite well to the available literature, which is almost solely for flat plate surface geometries. References 1 and 3–7 give Reynolds number exponents in the range from 0.6 to 0.8. This seems to imply that if the surface geometry is concave, so long as it is smooth and continuous, the jet air mass flow rate affects the heat-transfer coefficient in the same manner as in the flat plate case. The distance from jet exit to surface spacing affects the Nusselt number to a −0.4 power. This compares to a −0.6 power as found in literature.[7] This result shows that the jet impingement heat transfer in a closed cavity is affected to a lesser degree by the distance between surface and jet exit than for a flat plate surface case. This implies that the gas jet tends to reentrain more of its own mass, thus causing recirculation currents within the cavity. This effect tends to dampen the effect of jet nozzle distance from the surface. The angular effect is related by $f(\theta)$. This parameter tends to give a lesser degree of effect in concave surfaces than in flat plate geometries. The reason for this behavior is again due to the existence of recirculation currents within enclosed cavities and the fact that the distance from the jet nozzle to the surface does not change to the same degree in an enclosed concave cavity as in the flat plate case.

Table 1 Range of applicability of correlation, Eq. (1)

Variable	Range
Re_s*	1000–8000
$D/S*$	50–120
θ	−20°–20°
$Sp/d*$	2.5–10
$L/S*$	500–700

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TACTICS—a Three-Body Simulation Program

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Introduction

TACTICS is a computer program for use in simulating the kinematics and dynamics of motion of three vehicles in three-dimensional space. Care has been taken to make the program versatile so that it may be used in studing a wide variety of problems; but, in keeping with the program's initial purpose, the most important capabilities relate to interceptor-target guidance and to intercept trajectories in general. Since the flights of three separate vehicles may be represented simultaneously, the program can be used to simulate aerial combat between aircraft (e.g., a two-on-one engagement or a one-on-one with missile launching). On the other hand, there are a number of other possibilities, such as 1) using one or more of the vehicles to represent an ASM, SAM, or SS, 2) having the target represent an ICBM reentry vehicle, 3) using vehicles 1 and 2 to represent first- and second-stage boosters, or 4) having one vehicle represent an orbiting satellite.

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