AN EXPERIMENTAL AND THEORETICAL INVESTIGATION OF TURBULENT SEPARATED, REATTACHED AND REDEVELOPED FLOWS WITH TRANSVERSE RECTANGULAR CAVITIES.

by

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CERTIFICATE

This is to certify that the thesis entitled 'An Experimental and Theoretical Investigation of Turbulent Separated, Reattached and Redeveloped Flows with Transverse Rectangular Cavities', being submitted by Mr. K.K. Chaudhry to the Indian Institute of Technology, New Delhi, for the award of the Degree of Doctor of Philosophy in the Faculty of Engineering, is a record of bonafide research carried out by him. Mr. K.K. Chaudhry worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge, has reached the requisite standard.

The results contained in this thesis have not been submitted in part or in full, to any other university or institute for the award of any degree or diploma.

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ABSTRACT

An experimental and theoretical study has been conducted on the completely turbulent separated, reattached and redeveloped flows over rectangular tunnel wall cavities with relatively thick approaching boundary layers in the incompressible domain. Detailed measurements of the temporal mean velocities and the mean static pressures with in and aft of the cavities have been made. In these measurements the length to depth ratio (L/D) were varied from 0.5 to ∞ and free stream speeds were varied from 60 ft/sec to 116 ft/sec. Three distinctive flow regimes have been identified and the mean flow characteristics have been evaluated.

A plane free jet analysis proposed by Haugen and Dhanak has been compared with present experimental data on the velocity profiles. Their analysis agrees reasonably well in the outer free shear layer region but shows a considerable mismatch in the inner recirculating cavity flow region.

The wake like mixing region has been analysed using the modified Crocoo-Lees integral method to correlate the base pressure coefficients. It has been found that the ratio of the length of the mixing region to the length of the cavity ($\Delta x_{sh}/L$) is a function of the

L/D-ratio. Also the mixing parameter 'C' on which the base pressure depends is a function of ($\Delta x_{sh}/L$) and the flow parameters, i.e., the Reynolds number of the flow at the separation point (Re_{δ_s}) and the boundary layer thickness at separation δ_s .

The redevelopment region downstream of the cavities has been analysed using the Truckenbrodt energy integral method and the redevelopment lengths for different cavity configurations have been found. The improved Head and Patel entrainment method for the prediction of turbulent boundary layers agrees reasonably well with the experimental data. However, the Bradshaw, Ferriss and Atwell kinetic energy method does not fit the data for the reattaching and redeveloping turbulent boundary layer region well.

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LIST OF SYMBOLS

a	A constant = 0.12 appearing in Haugen and Dhanak deep cavity flow analysis.
C_1, C_2	Haugen and Dhanak constants for the inner recirculating cavity flow velocity profile.
C	Modified Crocco-Lees mixing coefficient.
C_E	Head's Entrainment function = $\frac{1}{U_\infty} \frac{dQ}{dx}$.
C_{D_p}	Pressure drag coefficient.
C_f	Local skin friction coefficient.
C_p	Surface pressure coefficient = $\frac{p - p_o}{\frac{1}{2} \rho U_\infty^2}$.
C_{p_b}	Base pressure coefficient = $\frac{p_b - p_o}{\frac{1}{2} \rho U_\infty^2}$.
$(C_p)_{p.p}$	Coefficient of plateau pressure = $\frac{p_r - p_b}{\frac{1}{2} \rho U_\infty^2}$.
$\bar{d}$	Non-dimensional Truckenbrodt dissipation. integral.
d_1	Bradshaw et.al. Shear stress function.
$\bar{D}$	Shear stress dissipation function.
D	Depth of cavity.
F	Non-dimensional momentum correlation parameter.
$F(r_1)$	Improved Head and Patel correction parameter for non-equilibrium conditions.
G	Bradshaw et.al. diffusion function.
$\bar{G}$	Clauser mean velocity profile defect parameter.
H	Boundary layer shape parameter = $\frac{\delta^*}{\theta}$.

$\bar{H}$	Boundary layer shape parameter = $\frac{\delta^{**}}{\theta}$.
H	Head's entrainment shape parameter = $\frac{\delta - \delta^{*}}{\theta}$.
I	Momentum flux per unit area in the shear layer.
$\mathbf{k}$	Crocco-Lees mixing parameter.
k_1, k_2, k_3	Haugen and Dhanak constants in the outer free shear layer velocity profile.
$\mathbf{K}$	Non-dimensional velocity correlation parameter.
$\bar{K}$	Von Kármán constant = 0.40.
L	Length of the cavity.
$\bar{L}$	Bradshaw et.al. dissipation function.
L_{RD}	Redevelopment length of boundary layer.
M	Mach number.
m	Mass entrained in the boundary layer.
n	Exponent for the power law velocity profile.
N	Recompression coefficient = $\frac{p_r - p_b}{p_o - p_b}$
p	Surface static pressure.
p_o	Free stream static pressure.
p_b	Base pressure.
p_T	Total head pressure.
p_r	Reattachment pressure.
$\overline{q'^2}$	Total turbulence kinetic energy per unit mass = $1/3(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$.
Q	Volume flux entrained in the boundary layer.

r_1	Improved Head and Patel non-equilibrium boundary layer parameter.
R_A	Reattachment point.
R_D	Redevelopment point.
$(Re)_{\delta_s}$	Reynolds number at the separation point $\frac{U_\infty \delta_s}{\nu}$
$\bar{s}$	Shear work integral.
$\overline{u'^2}$	r.m.s. value of turbulence intensity in the longitudinal direction.
$\bar{U}$	Mean velocity at a point in the axial direction.
u_*	Ratio of the dividing streamline velocity to the free stream velocity = $\frac{U_D}{U_\infty}$.
U_D	Dividing streamline velocity.
U_∞	Free stream velocity.
U_{av}	Average velocity in the free-shear layer.
$\bar{V}$	Mean velocity at a point in the transverse direction.
$\overline{v'^2}$	r.m.s. value of turbulence intensity in the transverse direction.
x, y, z	Co-ordinates of the shear layer.
γ	Ratio of specific heats.
$\bar{\gamma}$	Intermittency factor.
δ	Boundary layer thickness($y = \delta$ when $\bar{u} = 0.995\,U_\infty$).
δ_s	Boundary layer thickness at separation.
δ^*	Boundary layer displacement thickness= $\int_0^\infty (1 - \frac{\bar{u}}{U_\infty})\,dy$.

δ^{**}	Boundary layer energy thickness = $\int_0^\infty \frac{\bar{U}}{U_\infty}\left(1-\frac{\bar{U}^2}{U_\infty^2}\right) dy$.
θ	Boundary layer momentum thickness = $\int_0^\infty \frac{\bar{U}}{U_\infty}\left(1-\frac{\bar{U}}{U_\infty}\right) dy$
$\Delta x_{sh.}$	Free shear layer length.
ϵ	Eddy viscosity.
η	Dimensionless co-ordinate of the shear layer = $\sigma \frac{y}{x}$.
η'	Haugen and Dhanak transformed parameter.
ν	Kinematic viscosity.
ρ	Density.
σ	Jet spreading parameter.
τ	Shear stress.
τ_0	Shear stress at the boundary.
ψ	Stream function = $\int \bar{u}\, dy$.
ψ'	Modified stream function = $\int \frac{\bar{u}}{U_\infty} dy$.

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