DESIGN AND DEVELOPMENT OF A DRAG REDUCTION EXPERIMENT FOR PARTICLE-GAS FLOW IN THE TURBULENT BOUNDARY LAYER ON A FLAT PLATE

BY

WALTER ALLEN LOUNSBERY, 1955-

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ABSTRACT

This study describes design and development of experimental hardware for tests of turbulent boundary layer drag reduction with particle-gas flow. During the course of development, alternative calibration functions for constant temperature hot wire anemometers were evaluated. The best static calibration function related a third order polynomial in the square root of velocity to the square of the voltage applied to a constant-temperature anemometer. A flat plate test article was designed that incorporated air bearings for a drag-sensitive surface. A nearly constant static pressure was obtained along the test article with two wind tunnel test section wall contour modifications (false walls), and small flow obstructions. Leading edge separation was eliminated by use of a rounded leading edge constructed according to the geometric recommendations of Davis, and application of the false walls nearly symmetrically about the test plate. Test data from the plate boundary layer showed that an equilibrium, self-similar two-dimensional turbulent boundary layer was achieved on a test plate of finite aspect ratio, with a heavily conditioned boundary layer, in the presence of a nozzle upstream of the plate.

PREFACE

Although the scope of this work is large, I would like to emphasize at least one item. The geometry of plate tests has been worked out in other installations, other investigators have applied roughness to obtain thickened self-similar turbulent boundary layers, but apparently only a few really attempt to examine the calibration of their instruments. Each scientist would like to think their work worthwhile, and I think that if someone reads this and retains some hint of caution in using sensing instruments, then I will be satisfied with this piece of work.

I would like to thank everyone that kept me on the path to completion. Of course, the Committee itself was very helpful, most of all Dr. Robert Oetting. My wife put up with the long hours at school as well as later. My special thanks go to Joe Lefebvre, wherever he is, for providing most of the design insight and machining expertise for a very amazing traverse mechanism. And certainly, my employers at the Boeing company have helped provide a readable form for this text.

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NOMENCLATURE

c - specific heat per unit volume of fluid surrounding hot-wire, $c = s\sigma$

c_f - local fluid friction coefficient

c_p - fluid pressure coefficient,

$$c_p = \frac{P_s}{q_{ref}} \qquad (1)$$

E - instantaneous voltage across a hot-wire anemometer

G - Clauser's universal turbulent boundary layer form factor (nondimensional),

$$G = (1 - \frac{1}{H})\left[\frac{2}{c_f}\right]^{\frac{1}{2}} \qquad (2)$$

H - form factor of boundary layer (nondimensional),

$$H = \frac{\delta^*}{\Theta} \qquad (3)$$

or heat flux per unit length of a hot-wire.

n - constant in Boussinesq's equation for heat transfer from a cylinder, defined by,

$$2\,n = \frac{c\,V}{\kappa} \qquad (4)$$

P_b - barometric pressure (inches mercury)

P_s - fluid static pressure (pounds force/feet^2)

q_{ref} - fluid reference dynamic pressure for test plate (pounds force/foot^2)

Re_l - Reynolds number per foot,

$$Re_l = \frac{U_\infty \rho}{\mu} \qquad (5)$$

Re_x - local Reynolds number referenced to free stream and distance along plate from leading edge

$$Re_x = \frac{U_\infty \rho x}{\mu} \qquad (6)$$

Re_{δ^*} - boundary layer displacement thickness Reynolds number

$$Re_{\delta^*} = \frac{U_\infty \rho \delta^*}{\mu} \qquad (7)$$

T - temperature (degrees Fahrenheit)

u - local velocity (feet/second)

u^* - friction velocity (feet/second),

$$u^* = \frac{U_\infty}{\left[\frac{2}{c_f}\right]^{\frac{1}{2}}} \qquad (8)$$

u' - local to free stream velocity ratio,

$$u' = \frac{u}{U_\infty} \qquad (9)$$

u^+ - local velocity to friction velocity ratio,

$$u^+ = \frac{u}{u^*} \qquad (10)$$

u^- - velocity defect to friction velocity ratio,

$$u^- = \frac{u - U_\infty}{u^*} \qquad (11)$$

U_s - flow velocity tangential to surface (feet/second)

U_∞ - free stream velocity (feet/second)

V - free stream velocity at a large distance from a hot-wire

x - axial distance along plate from leading edge (feet)

x_s - surface arc length distance (feet)

y - height above surface of plate (feet or inches)

y^+ - friction height (feet or inches),

$$y^+ = \frac{y u^*}{\nu} \qquad (12)$$

y^- - Clauser's universal height coordinate for turbulent boundary layers (nondimensional),

$$y^- = \frac{y}{\Delta} \qquad (13)$$

β_0 - aft equipotential coordinate of cylinder

δ - boundary layer thickness, y, such that $u = 0.99 * U_\infty$ (feet or inches)

δ^* - momentum thickness (feet or inches),

$$\delta^* = \int_0^\infty \left(1 - \frac{u}{U_\infty}\right) dy \qquad (14)$$

Δ - Clauser's universal turbulent boundary layer thickness (feet or inches),

$$\Delta = \delta^* \left[\frac{2}{c_f}\right]^{\frac{1}{2}} \qquad (15)$$

η - Blasius normalized height coordinate for flat plate laminar boundary layers,

$$\eta = \frac{1}{2} y \left(\frac{U_\infty}{\nu x}\right)^{\frac{1}{2}} \qquad (16)$$

Θ - displacement thickness of boundary layer (feet or inches),

$$\Theta = \int_0^\infty \frac{u}{U_\infty}\left(1 - \frac{u}{U_\infty}\right) dy \qquad (17)$$

Θ_0 - ratio of the hot-wire temperature to the temperature of the fluid at infinite distance from the wire

κ - thermal conductivity of fluid surrounding hot wire

λ - Pohlhausen boundary layer velocity distribution parameter,

$$\lambda = \left(\frac{\delta^2}{\nu}\right)\left(\frac{dU_s}{dx_s}\right) \qquad (18)$$

μ - viscosity, according to Sutherland's relation for air,

$$\mu = (2.2137 \times 10^{-8}) \frac{(460 + T)^3 2}{658 + T} \qquad (19)$$

ν - kinematic viscosity ($feet^2$/second),

$$\nu = \frac{\mu}{\rho} \qquad (20)$$

ρ - density (pounds force-$second^2$/$feet^4$), for air approximately,

$$\rho = 0.0412 \frac{P_b}{(460 + T)} \qquad (21)$$

σ - Density of fluid surrounding hot-wire