



Supersonic base and boat-tail pressure drag of cylindrical bodies with a conical boat-tail and a central propulsive jet

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SUPERSONIC BASE AND BOAT-TAIL PRESSURE DRAG OF CYLINDRICAL BODIES WITH A CONICAL BOAT-TAIL AND A CENTRAL PROPULSIVE JET

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	3
3. METHOD	3
3.1 Base Drag	3
3.2 Boat-tail Pressure Drag	4
3.3 Total Afterbody Pressure Drag	6
4. ACCURACY AND APPLICABILITY	6
5. DERIVATION AND REFERENCES	9
5.1 Derivation	9
5.2 References	9
6. EXAMPLES	11
6.1 Example 1	11
6.2 Example 2	13
Figures 1a to 2e	17 to 21

SUPERSONIC BASE AND BOAT-TAIL PRESSURE DRAG OF CYLINDRICAL BODIES WITH A CONICAL BOAT-TAIL AND A CENTRAL PROPULSIVE JET

1. NOTATION AND UNITS (see Sketch 1.1)

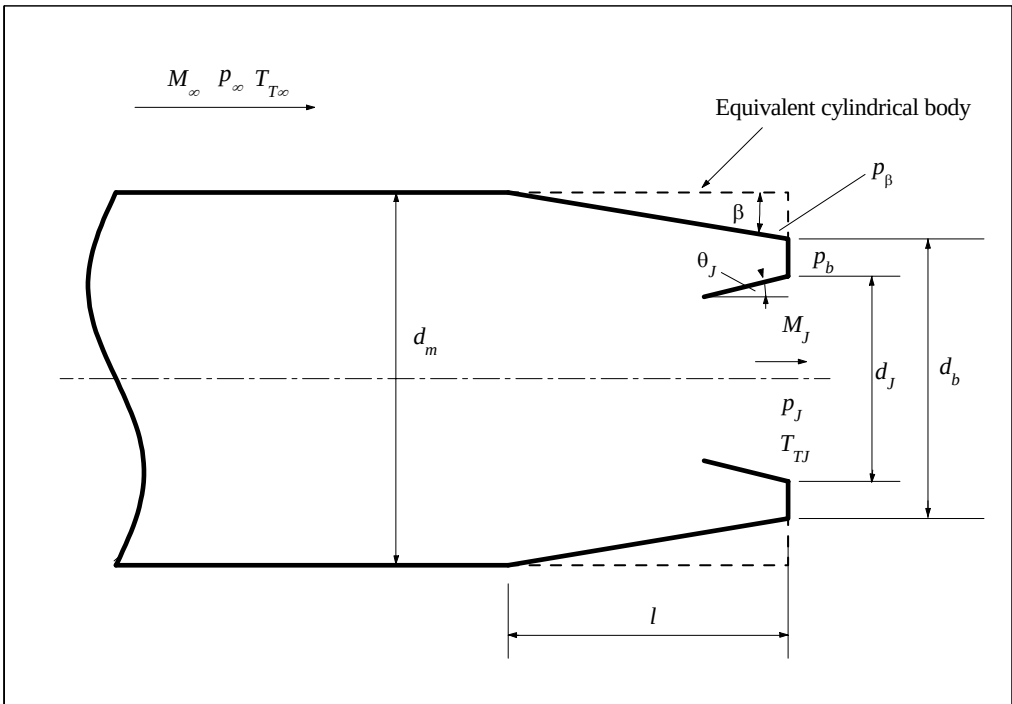
		SI	British
C_{Da}	total afterbody pressure-drag coefficient, $C_{Db} + C_{D\beta}$		
C_{Db}	base drag coefficient based on S , $-C_{pb}[(d_b/d_m)^2 - (d_J/d_m)^2]$		
$C_{D\beta}$	boat-tail pressure-drag coefficient based on S		
$\Delta C_{D\beta}$	change in boat-tail pressure drag coefficient due to jet, see Equation (3.7)		
C_p	pressure coefficient, $(p - p_\infty) / (\frac{1}{2}\gamma_\infty p_\infty M_\infty^2)$		
C_{pb}	base pressure coefficient, $(p_b - p_\infty) / (\frac{1}{2}\gamma_\infty p_\infty M_\infty^2)$		
$C_{p\beta}$	pressure coefficient at end of boat-tail in absence of jet effects, $(p_\beta - p_\infty) / (\frac{1}{2}\gamma_\infty p_\infty M_\infty^2)$		
C_T	thrust coefficient, $(\text{thrust}) / (\frac{1}{2}\gamma_\infty p_\infty M_\infty^2 S)$		
d_b	base diameter	m	ft
d_J	jet diameter at nozzle exit plane	m	ft
d_m	body maximum diameter	m	ft
l	boat-tail length	m	ft
M_J	jet Mach number at nozzle exit plane		
M_∞	freestream Mach number		
p_b	base pressure	N/m ²	lbf/ft ²
p_J	jet static pressure at nozzle exit plane	N/m ²	lbf/ft ²
p_β	pressure at end of boat-tail in absence of jet effects	N/m ²	lbf/ft ²
p_∞	freestream static pressure	N/m ²	lbf/ft ²
R_g	gas constant	N m/kg K	ft lbf/slug K
S	reference area, $\pi d_m^2/4$	m ²	ft ²

Issued July 2000 – 21 pages

T_{TJ}	jet total temperature at nozzle exit plane	K	K
$T_{T\infty}$	freestream total temperature	K	K
β	boat-tail angle	degree	degree
γ_J	ratio of specific heat capacities for jet		
γ_∞	ratio of specific heat capacities for freestream		
θ_J	nozzle exit angle (positive for divergent nozzle), see Sketch 1.1	degree	degree

Subscripts

<i>BT</i>	denotes value for boat-tailed body
<i>cyl</i>	denotes value for cylindrical body
<i>Th</i>	denotes theoretical value



Sketch 1.1 Body geometry and flow conditions

2. INTRODUCTION

This Item provides a means of estimating the base drag and boat-tail pressure-drag coefficients of cylindrical bodies with conical boat-tailing at supersonic speeds at zero angle of attack in the presence of a central propulsive jet. The method for base drag requires either an estimate or test data for the base drag coefficient of the cylindrical body without boat-tail but with identical nozzle geometry (see Sketch 1.1) under the same freestream and internal flow conditions. Item No. 99010 (Reference 12) provides such a prediction method for the supersonic base drag of cylindrical bodies with jet flows. That Item also includes a general discussion of jet flow phenomena and should be referred to for background information when using the present Item. The method for boat-tail pressure drag is based on empirical modification of theoretical data.

The method is described in Section 3 and its accuracy and applicability are discussed in Section 4. Section 6 provides worked examples which illustrate the use of the method and demonstrate the benefits of boat-tailing in reducing afterbody drag.

Item No. 79022 (Reference 9) provides data for base drag at supersonic speeds for the jet-off situation.

3. METHOD

The method for base drag coefficient is given in Section 3.1 and is based on a simple adaptation of the prediction method of Item No. 99010 for cylindrical bodies. Section 3.2 deals with boat-tail pressure drag and utilises theoretical data obtained by the method of characteristics. Section 3.3 considers the total afterbody pressure drag coefficient.

3.1 Base Drag

An analysis of test data in Derivations 1 and 3 to 8, which describe parametric studies where bodies of identical nozzle geometry and with identical flow conditions were tested with varying degrees of boat-tailing, shows that the effect of boat-tailing on the base pressure of an axisymmetric body, expressed as the ratio $(p_b)_{BT}/(p_b)_{cyl}$, may be represented by a simple factor depending solely on the base closure ratio, d_b/d_m . The boat-tail length and angle are found to be of relatively minor significance. The ratio $(p_b)_{BT}/(p_b)_{cyl}$ is substantially independent of jet pressure ratio, provided that the pressure acting on the base is below freestream pressure (see Section 4).

A good fit to the test data is found to be given by the equation

$$\frac{(p_b)_{BT}}{(p_b)_{cyl}} = \left(\frac{d_b}{d_m} \right)^{-1.9} \quad (3.1)$$

The equation relating base drag coefficient to base pressure ratio for a boat-tailed body is

$$(C_{Db})_{BT} = \frac{1}{\frac{1}{2}\gamma_\infty M_\infty^2} \left[1 - \frac{(p_b)_{BT}}{p_\infty} \right] \left[\left(\frac{d_b}{d_m} \right)^2 - \left(\frac{d_J}{d_m} \right)^2 \right] \quad (3.2)$$

Substitution of Equation (3.1) into (3.2) gives

$$(C_{Db})_{BT} = \frac{1}{\frac{1}{2}\gamma_{\infty}M_{\infty}^2} \left[1 - \frac{(p_b)_{cyl}}{p_{\infty}} \left(\frac{d_b}{d_m} \right)^{-1.9} \right] \left[\left(\frac{d_b}{d_m} \right)^2 - \left(\frac{d_J}{d_m} \right)^2 \right]. \quad (3.3)$$

The value of $(p_b)_{cyl}/p_{\infty}$ may be obtained either from test data or derived from the predicted value of base drag coefficient, based on maximum cross-sectional area, from Item No. 99010. The required equation is

$$\frac{(p_b)_{cyl}}{p_{\infty}} = 1 - \frac{1}{2}\gamma_{\infty}M_{\infty}^2 \left[(C_{Db})_{cyl} / [1 - (d_J/d_m)^2] \right]. \quad (3.4)$$

3.2 Boat-tail Pressure Drag

At low jet pressure ratios the base pressure is usually below that prevailing at the end of the boat-tail. This results in an expansion fan at the point of flow separation at the base. The flow on the boat-tail is isolated from the influence of the jet and the boat-tail pressure drag remains independent of jet pressure ratio. In this regime the boat-tail pressure drag may be estimated by

$$C_{D\beta} = 0.85(C_{D\beta})_{Th} \quad \text{for } (C_{pb})_{BT} < C_{p\beta}. \quad (3.5)$$

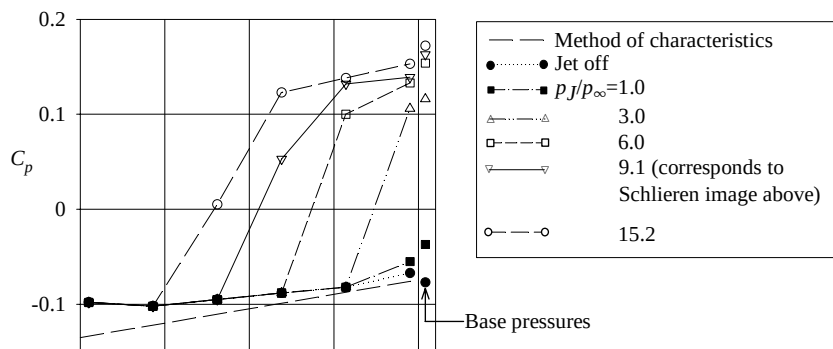
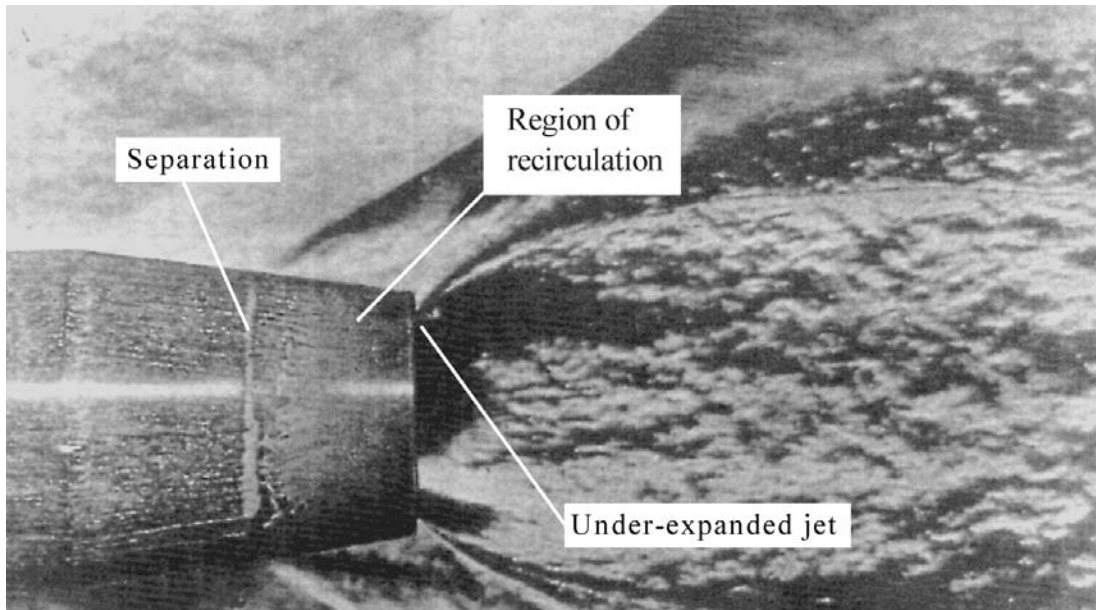
The theoretical value, $(C_{D\beta})_{Th}$, is given in Figures 1a to 1e for boat-tail angles, β , of 2, 4, 6, 8 and 10 degrees. The factor of 0.85 is empirical and improves agreement with experiment. In order to check whether the base pressure is below that at the end of the boat-tail, the base drag coefficient calculated in Section 3.1 can be used to derive a base pressure coefficient using

$$(C_{pb})_{BT} = -(C_{Db})_{BT} / \left[(d_b/d_m)^2 - (d_J/d_m)^2 \right], \quad (3.6)$$

which can be compared with the boat-tail pressure data in Figure 2. Figures 2a to 2e present the pressure coefficient at the end of conical boat-tails for boat-tail angles, β , of 2, 4, 6, 8, and 10 degrees, as calculated by the method of characteristics. Estimates of $(C_{D\beta})_{Th}$ for intermediate values of β may be obtained by cross-plotting.

At higher jet pressure ratios the base pressure can exceed that on the boat-tail so that the expansion fan is replaced by a shock wave. The base pressure then feeds onto the boat-tail via the subsonic portion of the boundary layer causing a reduction in drag. Further increases in jet pressure ratio, and thus base pressure, lead to the formation of a shock wave of increasing strength, which eventually provokes separation and moves upstream of the base, further reducing the boat-tail pressure drag*. This phenomenon is known as 'plumage' or 'plume-induced' separation. Base pressure continues to increase until reaching a plateau at some point where it exceeds the freestream pressure. Plume-induced separation is illustrated in the photo-montage in Sketch 3.1, taken from Derivation 3, which shows composite results of Schlieren and oil flow investigations. The sketch includes a plot of the experimental pressure distribution along the boat-tail and the base pressure for the same freestream and jet flow conditions as the photograph, together with the results observed at both higher and lower jet pressure ratios, and the case of no jet flow.

* Although, strictly, the method of Item No. 99010 is invalid for cases where separation occurs upstream of the base, its application to boat-tailed bodies, via the method of Section 3.1, still appears to model successfully the monotonic increase in base pressure demonstrated by the test data, at least until the base pressure equals the freestream pressure.



Sketch 3.1 Plume-induced separation

A simple method (Derivation 2) of allowing for jet influence on $C_{D\beta}$ when $(C_{pb})_{BT}$ exceeds $C_{p\beta}$ is based on the assumption that the effect on the boat-tail drag may be represented solely as a function of the difference between the base pressure and the pressure at the end of the boat-tail in the absence of jet effects, i.e. $(C_{pb})_{BT} - C_{p\beta}$.

An analysis of the test data for $(C_{pb})_{BT} > C_{p\beta}$ shows that the change in boat-tail pressure-drag, $\Delta C_{D\beta}$, is represented adequately by

$$\Delta C_{D\beta} = 0.010 \left([(C_{pb})_{BT} - C_{p\beta}] M_\infty^2 \right)^3 - 0.018 \left([(C_{pb})_{BT} - C_{p\beta}] M_\infty^2 \right)^2. \quad (3.7)$$

In Equation (3.7) the parameter $[(C_{pb})_{BT} - C_{p\beta}]$ is modified by M_∞^2 to cater for the effect of external Mach number.

The boat-tail pressure-drag coefficient is then given by

$$C_{D\beta} = 0.85(C_{D\beta})_{Th} + \Delta C_{D\beta} \quad \text{for } (C_{pb})_{BT} > C_{p\beta}. \quad (3.8)$$