



ESDU 86002

Issued April 1986

With Amendments A to D

June 2004

Supersedes ESDU 66029

Drag and pressure recovery characteristics of auxiliary air inlets at subsonic speeds

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DRAG AND PRESSURE RECOVERY CHARACTERISTICS OF AUXILIARY AIR INLETS AT SUBSONIC SPEEDS

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DRAG AND PRESSURE RECOVERY CHARACTERISTICS OF AUXILIARY AIR INLETS AT SUBSONIC SPEEDS

1. NOTATION AND UNITS (see Sketch 1.1)

		SI	British
A	cross-sectional area of streamtube	m^2	ft^2
A_d	forward projected area of diverter	m^2	ft^2
A_e	external surface area of scoop inlet	m^2	ft^2
A_p	forward projected area of scoop inlet outside highlight and excluding diverter, $A_m - A_1$	m^2	ft^2
A_t	throat plane area	m^2	ft^2
A_m	maximum outer cross-sectional area of inlet excluding diverter	m^2	ft^2
A_1	inlet highlight capture area	m^2	ft^2
C_D	drag coefficient, $D/\frac{1}{2}\rho_0 V_0^2 A_1$		
C'_D	drag coefficient at zero inlet mass flow, excluding skin friction and diverter drag		
C_{Dd}	diverter drag coefficient		
C_{DF}	external skin friction drag coefficient of scoop inlet, $C_F A_e / A_1$		
C_{Dsp}	spillage drag coefficient		
ΔC_D	incremental correction to drag coefficient for flush inlet		
C_F	mean skin friction coefficient of flat plate based on surface area		
d_{1fl}	flush inlet highlight height measured in inlet plane relative to ramp floor	m	ft
d_{1l}	scoop inlet lower highlight height relative to main surface	m	ft
d_{1sc}	distance between upper and lower highlights for scoop inlet, $d_{1u} - d_{1l}$	m	ft
d_{1u}	scoop inlet upper highlight height relative to main surface	m	ft

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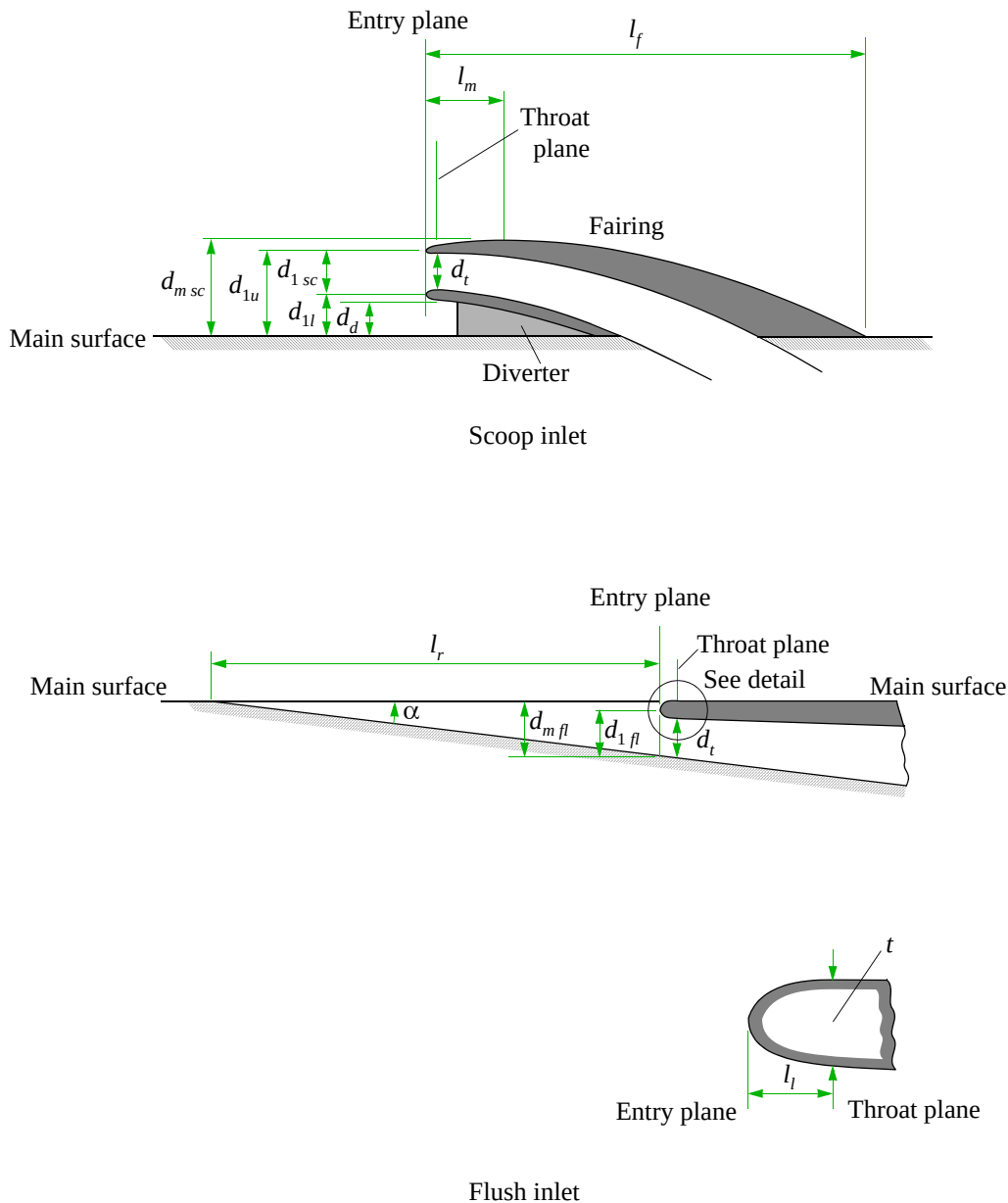
d_d	height of diverter measured from main surface to scoop lower surface	m	ft
d_{msc}	maximum height of scoop inlet relative to main surface	m	ft
d_{mfl}	maximum external height relative to ramp floor of flush inlet measured in inlet plane	m	ft
d_t	distance between upper and lower internal surfaces in throat plane	m	ft
D	drag	N	lbf
F	stream force, $\psi + (p - p_0)A$	N	lbf
h	height above flat plate, see Figures 1 to 4	m	ft
k_f	correction factor allowing for effect of profile of fairing forebody on spillage drag of scoop inlet		
k_M	correction factor allowing for effect of Mach number on C'_D for flush inlet		
k_P	correction factor allowing for variation of $\Delta P_{Ht}/P_{H0}$ with Mach number for scoop inlet		
k_{sp}	correction factor allowing for effect of mass flow on spillage drag		
k_α	correction factor allowing for effect of ramp angle on C'_D flush inlet		
k_ψ	factor applied to momentum flow to allow for ramp planform and lip shape of flush inlet		
K	momentum flow correction factor		
l_f	overall length of fairing of scoop inlet	m	ft
l_l	lip length, distance from entry plane to throat plane	m	ft
l_m	forebody length from lip to maximum height of scoop inlet	m	ft
l_r	length of ramp of flush inlet	m	ft
$\dot{m}$	mass flow in streamtube entering inlet	kg/s	slug/s
$\dot{m}_0$	mass flow in free-stream streamtube of cross-sectional area A_1 , $\rho_0 V_0 A_1$	kg/s	slug/s
$(\dot{m}_0)_t$	mass flow in free-stream streamtube of cross-sectional area A_t , $\rho_0 V_0 A_t$	kg/s	slug/s
M	Mach number		

NPF	net propulsive force	N	lbf
p	static pressure	N/m ²	lbf/ft ²
P_H	total pressure	N/m ²	lbf/ft ²
P_{Ht}	total pressure in throat plane just aft of inlet lip	N/m ²	lbf/ft ²
ΔP_{Ht}	incremental correction to allow for variation of P_{Ht} with mass flow for scoop inlet	N/m ²	lbf/ft ²
r_{mf}	correction factor allowing for effect of mass flow in calculation of η_{fl}		
t	lip thickness at throat plane	m	ft
V	velocity of flow	m/s	ft/s
w	highlight width of inlet	m	ft
w_d	width of diverter	m	ft
x, y	coordinates of ramp planform	m	ft
α	ramp angle, see Sketch 1.1	degree	degree
δ	boundary layer thickness, where local velocity in boundary layer is $0.999V_0$	m	ft
$\Delta\eta_{mf}$	incremental correction to η to allow for mass flow for flush inlet with curved-divergent ramp		
$\Delta\eta_w$	incremental correction to η to allow for inlet width for flush inlet with curved-divergent ramp		
$\Delta\eta_\alpha$	incremental correction to η to allow for ramp angle for flush inlet with curved-divergent ramp		
η	ram pressure efficiency, $(P_{Ht} - p_0)/(P_{H0} - p_0)$		
η_m	maximum ram pressure efficiency of flush inlet with curved-divergent ramp		
μ	modified mass flow ratio for flush inlet with curved-divergent ramp, $\dot{m}d_{1fl}/\dot{m}_0d_t$		
μ_m	value of modified mass flow ratio for flush inlet with curved-divergent ramp operating at maximum efficiency		
θ	boundary-layer momentum thickness	m	ft
ρ	density	kg/m ³	slug/ft ³
τ	forward component of pressure force on inside of streamtube	N	lbf

ϕ	rearward component of pressure force on outside of streamtube	N	lbf
ψ	momentum flow in streamtube entering inlet	N	lbf
ψ_0	momentum flow in free-stream streamtube of cross-sectional area A_1 , $\dot{m}_0 V_0$	N	lbf

Subscripts

0	denotes free-stream conditions
$0fp$	denotes conditions far upstream on flat plate extending forward of inlet entry plane
1	denotes inlet entry plane
9	denotes inlet exit plane
c	denotes forward suction force
ch	denotes choked flow
f	denotes fairing of scoop inlet
fl	denotes flush inlet
$full$	denotes inlet running full, so that the free-stream boundary of the entering streamtube is unaffected by the inlet lip
int	denotes intrinsic net thrust
pre	denotes pre-entry force
r	denotes ramp of flush inlet
sc	denotes scoop inlet
sh	denotes sharp lips
sp	denotes spillage drag
t	denotes throat plane
T	denotes theoretical values in Figures 1 to 4
Tl	denotes theoretical values in Figures 1 to 4 with $h = d_{1l}$
Tu	denotes theoretical values in Figures 1 to 4 with $h = d_{1u}$



Sketch 1.1 Inlet geometries

2. INTRODUCTION

This Item provides data for the estimation of the drag and pressure recovery of small auxiliary air inlets totally or partially immersed in the boundary layer. The prediction method given is applicable at subsonic speeds and is semi-empirical. In the main, it uses a theoretical calculation of two-dimensional boundary-layer characteristics as a basis and modifies this in the light of the available experimental data.

A qualitative introduction to the drag characteristics of scoop and flush inlets is given in Section 3. The drag quantities to be estimated are identified and the variation of overall drag with mass flow ratio is considered.

The theoretical data that are of use in the prediction of inlet performance are contained in Derivation 13 which gives a two-dimensional analysis of the effect of boundary-layer thickness on the mass and

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momentum flows of a given streamtube along a flat plate. Derivation 13 also gives the pressure recovery just aft of the inlet plane for a thin-lipped inlet running full. Numerical values of the theoretical data have been extracted from Derivation 13 and are reproduced herein, as described in Section 4.

The drag of a scoop inlet protruding from the main surface and having a rectangular, circular or semi-circular entry is considered in Section 5. The pressure recovery in the entry has been obtained from the theoretical calculations in Derivation 13 for full mass flow. A semi-empirical correction to allow for the loss in pressure recovery at lower mass flows has been added from Derivation 19.

This Item provides a means of estimating the pressure recovery and drag characteristics of flush inlets with ramp angles up to 11.5° *. The drag of a flush inlet with a rectangular entry and an inlet ramp planform that is rectangular or of the NACA curved-divergent type is considered in Section 6. A prediction of the pressure recovery in the entry for a rectangular planform ramp has been obtained by making empirical corrections to the data from Derivation 13. A separate method is given for predicting the pressure recovery for inlets with a NACA curved-divergent ramp planform†.

For both scoop and flush inlets the experimental data available are very restricted in their range of flow conditions and inlet geometries, particularly in regard to lip profile, which is often sharp for the configurations tested. This must be remembered when considering the empirical corrections made to the basic theoretical predictions. Section 7 on accuracy and applicability discusses this point in more detail.

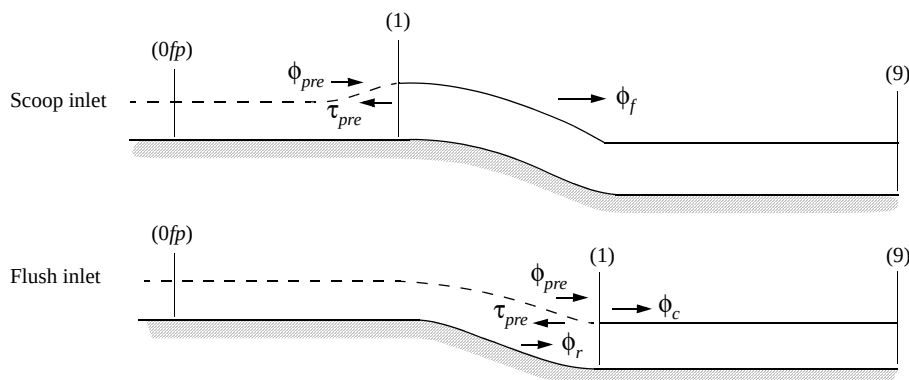
Section 8 lists the Derivation and References that have been used in producing this Item.

Section 9 gives worked examples which compare the drag characteristics of scoop and flush inlets.

3. QUALITATIVE CONSIDERATIONS OF DRAG CHARACTERISTICS

3.1 Basic Model

This section makes a qualitative assessment along the lines set out in Derivation 18 in order to compare the natures of the drag characteristics of scoop and flush inlets. Cross-sectional views of idealised, two-dimensional, scoop and flush inlets are shown in Sketch 3.1. The entry and exit planes are denoted (1) and (9), and station (0fp) is assumed to be far upstream on a flat plate extending forward of the inlet.



Sketch 3.1 Idealised inlets

* Item No. 03006 (Reference 32) extends the pressure recovery and drag prediction methods for rectangular planform flush inlets that turn the flow through angles of up to 90° to the upstream flow direction.

† This method was previously issued in Item No. 66029. That Item has now been withdrawn since it is superseded by the present Item. A description of the basic method in Item No. 66029 in its original form is available in Reference 27.

The streamtube passing through the inlet is bounded by the solid surfaces of the inlet and a free streamline, as shown dashed in the sketches for inlets running less than full. The net force on each inlet arises from the pressures acting internally and externally on the solid surfaces containing the streamtube.

The intrinsic net thrust τ_{int} of the inlets is equal to the difference in the stream force F that occurs between the inlet entry and exit planes, so

$$\tau_{int} = F_9 - F_1 \quad (3.1)$$

where the stream force is given by

$$F = \psi + (p - p_0)A \quad (3.2)$$

with constant velocity across the streamtube.

The net propulsive force, NPF , is equal to the difference between the intrinsic net thrust and the drag forces acting either on the fairing of the scoop inlet, or on the ramp and lip of the flush inlet. Thus

$$NPF_{sc} = \tau_{int} - \phi_f = F_9 - F_1 - \phi_f, \quad (3.3)$$

and

$$NPF_{fl} = \tau_{int} - \phi_r - \phi_c = F_9 - F_1 - \phi_r - \phi_c. \quad (3.4)$$

For the scoop inlet, ϕ_f is the external pressure drag of the scoop fairing, including any lip or forebody suction force (any skin friction drag is ignored at present). For the flush inlet, ϕ_r is the rearward force associated with flow over the entry ramp and $-\phi_c$ represents the forward suction force on the lip.

3.2 Pre-entry Forces

It is convenient and customary to work with the net thrust relative to a plane far upstream ($0fp$), rather than the inlet entry plane (1). To achieve the necessary recasting of Equations (3.3) and (3.4), the change in stream force between stations ($0fp$) and (1) is expressed in terms of forces acting forward of the entry plane. This brings in the concept of the equal and opposing pre-entry forces τ_{pre} and ϕ_{pre} that act on the free streamline that defines the inlet streamtube. The force τ_{pre} acts on the inside of the streamtube and is positive upstream, and ϕ_{pre} acts on the outside of the streamtube and is positive downstream. Therefore,

$$(F_1 - F_{0fp})_{sc} = \tau_{pre} = \phi_{pre} \quad (3.5)$$

and

$$(F_1 - F_{0fp})_{fl} = \tau_{pre} - \phi_r = \phi_{pre} - \phi_r. \quad (3.6)$$

Thus Equations (3.3) and (3.4) become

$$NPF_{sc} = F_9 - F_{0fp} - \phi_{pre} - \phi_f \quad (3.7)$$

and

$$NPF_{fl} = F_9 - F_{0fp} - \phi_{pre} - \phi_c. \quad (3.8)$$

Thus a pre-entry force ϕ_{pre} is present for both types of inlet and this must be included in the drag calculation.

3.3 Drag Accounting

For the purposes of this Item it is assumed that all of the momentum of the air captured by the inlet is lost or is accounted for separately, so F_9 can be set to zero.

(Derivation 16 gives an equation for the maximum possible thrust recovery in terms of the inlet ram pressure efficiency η . This can be written

$$F_9 = \dot{m} V_0 \left\{ \frac{1 - \{1 + \eta[(1 + 0.2M^2)^{7/2} - 1]\}^{-2/7}}{1 - (1 + 0.2M^2)^{-1}} \right\}^{1/2}, \quad (3.9)$$

but in a practical system internal pressure losses greatly reduce the actual thrust recovered.)

By Equation (3.2), $F_{0fp} = \psi_{0fp}$, so that with $F_9 = 0$

$$NPF_{sc} = -\psi_{0fp} - \phi_{pre} - \phi_f \quad (3.10)$$

and

$$NPF_{fl} = -\psi_{0fp} - \phi_{pre} - \phi_c. \quad (3.11)$$

If the momentum flow $-\psi_{0fp}$ is taken as a ram drag forming part of the total inlet drag, then

$$D_{sc} = \psi_{0fp} + \phi_{pre} + \phi_f \quad (3.12)$$

and

$$D_{fl} = \psi_{0fp} + \phi_{pre} + \phi_c. \quad (3.13)$$

Because of the presence of a boundary layer the ram drag in the entering streamtube is less than it would be if free-stream conditions prevailed upstream of the entry. If a factor K represents this loss, then

$$\psi_{0fp} = K V_0 \dot{m}, \quad (3.14)$$

where $\dot{m}$ is the mass flow along the streamtube and V_0 is the free-stream velocity.

3.4 Spillage Drag

Scoop inlet

For the scoop inlet a forward suction force may develop on the lip or forepart of the fairing when the inlet is not running full, see Item No. 81004 (Reference 28). This suction force can cause a total or partial cancellation of the pre-entry force ϕ_{pre} . For inviscid flow over the fairing $\phi_f = -\phi_{pre}$. For viscous flows, boundary layer growth reduces the suction force and causes a corresponding rise in the net force $\phi_{pre} + \phi_f$. As the mass flow is reduced from its full value the pressure gradients around the lip become more serious until separation of the flow causes a very rapid decay of the suction force and a corresponding rise in $\phi_{pre} + \phi_f$. The mass flow at which separation occurs depends on the lip geometry and Mach number, see for example the data for free axisymmetric cowls in Item Nos 81024 and 84004 (Reference 29 and Derivation 24) which give information on this, together with theoretical values of ϕ_{pre} in coefficient form. For ideal, sharp-lip inlets the flow is separated at all mass flows and there is no cancellation of the pre-entry force.

If $\phi_{f\ full}$ is the pressure drag on the fairing at full mass flow, then the drag due to the flow that spills at lower mass flows can be defined using this as a datum value,

$$D_{sp} = \phi_{pre} + \phi_f - \phi_{f\ full}. \quad (3.15)$$

Variations in D_{sp} with mass flow will then represent the large changes in $\phi_{pre} + \phi_f$.

Therefore, by Equations (3.12), (3.14) and (3.15)

$$D_{sc} = KV_0 \dot{m} + D_{sp} + \phi_{f\ full}. \quad (3.16)$$

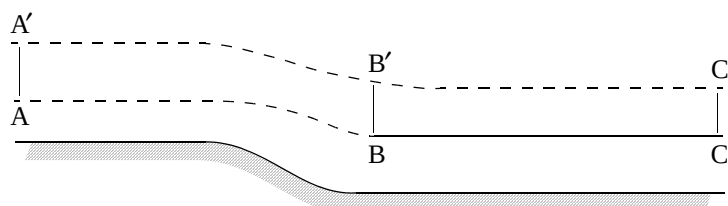
This can be expressed in coefficient form by dividing by $\frac{1}{2}\rho_0 V_0^2 A_1$ or its equivalent $\frac{1}{2}\dot{m}_0 V_0$, where $\dot{m}_0$ is the free-stream mass flow through the inlet capture area A_1 , giving

$$C_{Dsc} = 2K\left(\frac{\dot{m}}{\dot{m}_0}\right) + C_{Dsp} + C_{Df\ full}. \quad (3.17)$$

For an ideal, sharp-lip inlet $C_{D\ sp}$ will rise from zero for an inlet running full to a bluff-body value near unity for zero mass flow. For a round-lip inlet the value will not rise until the mass flow has fallen to some intermediate value and will not rise to so high a value at zero mass flow. The variation of C_{Dsp} against mass flow will change with Mach number. The datum coefficient $C_{Df\ full}$ is constant with mass flow.

Flush inlet

For the flush inlet, Derivation 18 considers an external streamtube that is defined by the streamline bounding the flow entering the inlet, the aft surface of the inlet, and a streamline well above, as shown in Sketch 3.2.



Sketch 3.2 Idealised flush inlet

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If free-stream conditions exist at AA' and CC' and the flow between them is isentropic, then there is no change in stream force and no net force on the streamtube. If the external streamline A'B'C' is well out in the free stream and at ambient pressure there is no force on it, and consequently no force on the lower boundary of the streamtube, ABC. Since the inlet after-surface is flush with the main surface and parallel to the free stream there is no force on the surface BC and so none on the surface AB.

Thus for the flush inlet ϕ_{pre} will be small. For a round-lip inlet a suction force ϕ_c may also exist to oppose ϕ_{pre} , as discussed above for scoop inlets. As there is no force on the inlet after-surface the net drag due to spillage flow is $\phi_{pre} + \phi_c$ which is zero for full mass flow. Using Equations (3.13) and (3.14) the flush inlet drag can then be written in coefficient form as

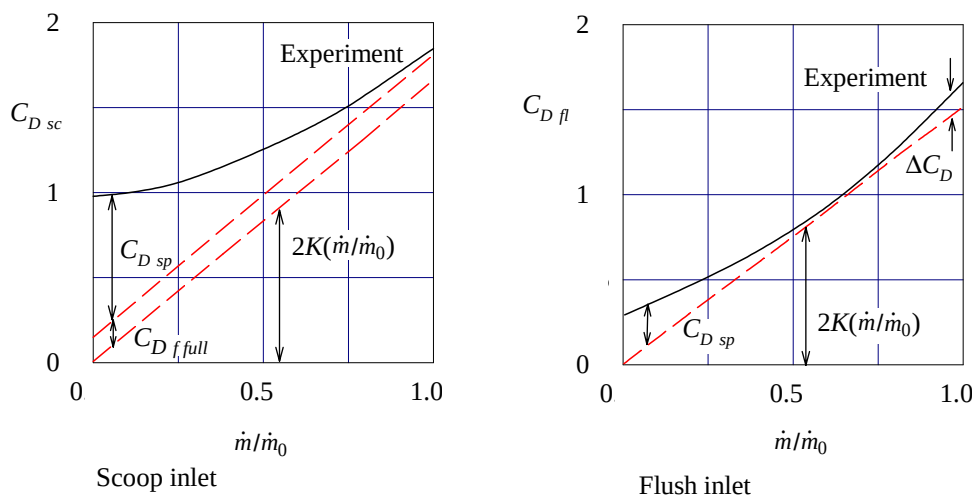
$$C_{Dfl} = 2K\left(\frac{\dot{m}}{\dot{m}_0}\right) + C_{Dsp}, \quad (3.18)$$

where C_{Dsp} provides a small positive contribution at zero mass flow that decays as the mass flow increases.

3.5 Comparison of Drag Characteristics

Sketch 3.3 gives typical experimental drag characteristics from Derivation 16 for a sharp-lip scoop inlet and a sharp-lip flush inlet of the same entrance area and a width to height ratio of 4. A tentative division into component contributions, as suggested by Equations (3.17) and (3.18), is shown by dashed lines.

The scoop inlet has a much higher drag at low and intermediate mass flows, mainly due to its spillage drag component. But for the flush inlet the ram drag contribution $2K(\dot{m}/\dot{m}_0)$ provides a reasonable first approximation to the total drag coefficient for all mass flows.



Sketch 3.3 Examples of typical drag characteristics of scoop and flush inlets

4. TWO-DIMENSIONAL BOUNDARY LAYER DATA

The two-dimensional theoretical analysis in Derivation 13 provides data that are required in the prediction of inlet drag and pressure recovery to account for the effect of boundary-layer thickness, δ , and velocity profile on the flow properties of a streamtube of given height, h , passing along a flat plate. Of special interest for the methods of this Item are the effects on mass and momentum flows. These properties can be expressed as a proportion of the values in streamtubes of equal thickness h with and without a boundary layer. For a $1/7$ th power-law velocity profile, Figures 1 and 2 present $(\dot{m}_T/\dot{m}_0)$ and ψ_T/ψ_0 as functions of δ/h and M . The data in Figure 1 are of use in making an estimate of the size of an inlet required to capture a specified mass flow when running full. The data in Figure 2 are used in estimating the ram drag.

Information for calculating the total pressure recovery and the associated ram pressure efficiency for an inlet running full is also given in Derivation 13. Based on this, Figure 3 shows P_{HtT}/P_{H0} and Figure 4 shows η_T as functions of δ/h and M for an inlet of height h .

Estimates of the boundary layer thickness δ may be made using Item No. 68020 (Derivation 20).

5. SCOOP INLETS

Section 5.1 describes a general method for predicting the drag of scoop inlets, which has been developed by using Equation (3.17) as a model. Experimental data for comparison are available for only a small number of scoop geometries. Derivation 1 deals with inlets with a circular or a semicircular entry in low-speed flow. Derivations 14 and 16 cover inlets with a high aspect-ratio, rectangular entry ($w^2/A_1 \geq 4$) or a circular entry, in high-speed subsonic flow, $0.55 \leq M \leq 0.9$. All of these inlets have sharp lips and no boundary-layer diverter. Sketches 5.1a to 5.1d illustrate typical geometries.

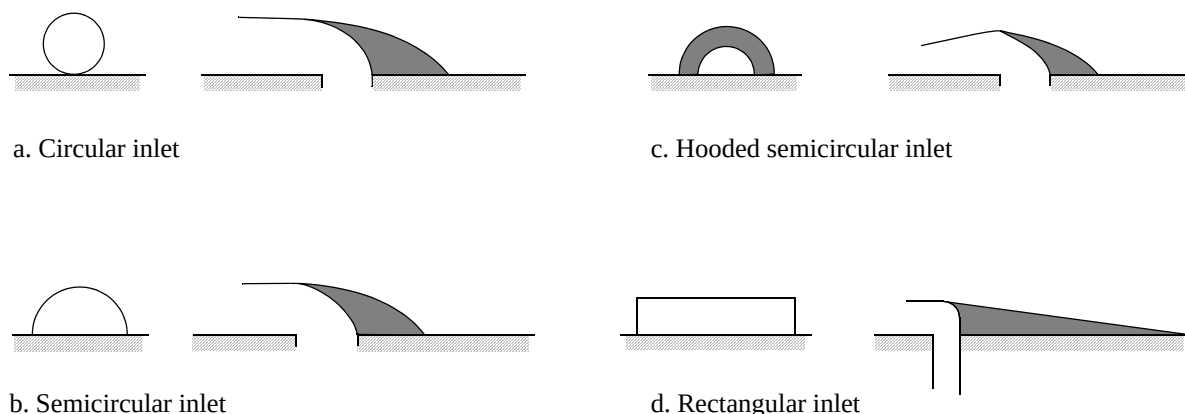
There is a tentative extension of the method, partly based on data from Item No. 84004 (Derivation 24), to deal with round-lip inlets for a range of fairing forebody shapes that include elliptical, NACA-1 series and linear profiles. The comparative sketches in Item No. 84004 show that the first two profiles are fairly similar. A definition of the NACA-1 series profiles and a description of their performance advantages for isolated, axisymmetric cowls are given in Reference 25. For auxiliary inlets the simpler profiles may often be chosen.

Many of the correlating parameters in the method are presented separately for the particular cases of rectangular inlets with $w^2/A_1 \geq 4$, circular or semicircular inlets. To provide guidance for other entry shapes such as rectangular inlets of low aspect-ratio a cross-plot against w^2/A_1 is also provided, but must be used with more caution than the individual data.

The method also covers the possible presence of a wedge-shaped boundary-layer diverter which, as an aid to pressure recovery, may be present to redirect all or the lower part of the boundary layer so that it is not captured by the inlet. The drag of the diverter is estimated as suggested in Derivation 21.

Section 5.2 describes the method for predicting the pressure recovery. This is based on theoretical data from Derivation 13 and a semi-empirical correction provided by Derivation 19.

Section 5.3 explains how the size of the inlet may be determined once the mass flow to be captured has been specified.



Sketch 5.1 Example of inlet types tested

5.1 Drag

In Equation (3.17) the drag of a scoop inlet is divided into a ram drag, a spillage drag and a datum drag for an inlet running full. To these must be added the skin friction drag of the external surface of the scoop and the drag of any diverter.

The ram drag term is obtained by replacing K in the first term of Equation (3.17) by

$$K_{sc} = \left\{ \frac{\psi_{Tu}}{\psi_0} d_{1u} - \frac{\psi_{Tl}}{\psi_0} d_{1l} \right\} \frac{1}{(d_{1u} - d_{1l})}, \quad (5.1)$$

where the theoretical momentum flow ratios ψ_{Tu}/ψ_0 and ψ_{Tl}/ψ_0 are obtained from Figure 2 with respective heights $h = d_{1u}$ and d_{1l} corresponding to the upper and lower highlights of the entry. Equation (5.1) is strictly valid only for rectangular inlets, but numerical checks have shown that it can be used directly for circular and semicircular inlets without any significant loss of accuracy.

The datum drag coefficient at full mass flow has been determined from the data in Derivations 1, 14 and 16. This is shown as $C_{Df\ full}$ in Figure 5. The data for circular, semicircular and rectangular inlets are indicated individually. For interpolation or extrapolation the data have been plotted against w^2/A_1 . In all cases a smooth rear fairing is assumed with an overall fairing length $l_f \geq 2.0d_{msc}$. The experimental scatter shown by the broken curves is large because the effects of Mach number and the detailed design of the fairing have not been eliminated. Data in Derivation 16 show an apparently random variation with Mach number between the limits indicated. In the absence of additional data $C_{Df\ full}$ is assumed to apply to both sharp-lip and round-lip inlets.

The spillage drag term in Equation (3.17) is written as

$$C_{Dsp} = k_f k_{sp\ sc} (C'_D - C_{Df\ full})_{sh}, \quad (5.2)$$

and has been derived from experimental results in Derivations 1 and 16.

The quantity $(C'_D - C_{Df\ full})_{sh}$ is the difference between the drag coefficients at full and zero mass flow for sharp-lip inlets and depends on Mach number. It is defined by the solid curves in Figure 6a for circular and for semicircular or rectangular inlets, with broken lines indicating the experimental scatter. The generalised trend with w^2/A_1 and M is shown in Figure 6b.

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The factor $k_{sp\ sc}$ allows for the variation of the spillage drag with mass flow ratio. Figure 7a gives $k_{sp\ sc}$ for circular inlets and Figure 7b gives $k_{sp\ sc}$ for semicircular or rectangular inlets. In both cases solid curves define the factor and broken lines indicate the experimental scatter. The scatter includes the effect of variations with Mach number for $M \leq 0.9$, for which no systematic behaviour could be identified. Figure 7c gives the generalised trend of $k_{sp\ sc}$ with w^2/A_1 and $(\dot{m}/\dot{m}_0)$. In view of the small data base available for defining $k_{sp\ sc}$ the precise shape of these curves is tentative but they show typical experimental behaviour.

The factor k_f in Equation (5.2) models the significant reduction in spillage drag to be expected for inlets with a fairing forebody that has a smoothly shaped profile that allows the development of a forward suction force. The only experimental data for auxiliary inlets that permit this matter to be examined directly are those in Derivation 1 for semicircular inlets with hooded forebodies and sharp lips, see Sketch 5.1c. Therefore, supplementary information at zero mass flow has been inferred from Item No. 84004 which predicts the spillage drag for free, axisymmetric cowls. Figure 8 gives values of k_f that correspond to the reduction in spillage drag at zero mass flow for typical types of forebody. The factor depends on the parameters A_p/A_m and l_m/w , where A_m is the maximum cross-sectional area of the inlet, $A_p = A_m - A_1$, l_m is the forebody length from the lip to the maximum height and w is the highlight width. Figures 8a and 8b deal with elliptical and NACA-1 series forebody profiles for $M \geq 0.6$ and $M = 0.2$, respectively, and Figure 8c deals with sharp-lip inlets where the forebody profile is linear. These data are a simple approximation to those in Item No. 84004 and they should be quite accurate for circular auxiliary inlets. The experimental data of Derivation 1 suggest that they also provide a good estimate for semicircular inlets. There are no data to verify the values of k_f for rectangular or other inlet shapes but Figure 8 should give a reasonable guide to the benefits of shaping the fairing forebody and rounding the inlet lips.

The skin friction drag of the scoop fairing is given by

$$C_{DF} = C_F A_e / A_1, \quad (5.3)$$

where C_F is the mean skin friction coefficient of a flat plate based on surface area, and may be obtained from Item No. 68020 (Derivation 20) as a function of Reynolds number based on the fairing length l_f .

Following the suggestion of Derivation 21 for two-dimensional wedge-shaped diverters it is assumed that the diverter drag coefficient is 0.25 based on its forward projected area, A_d , so that

$$C_{Dd} = 0.25 A_d / A_1. \quad (5.4)$$

In some cases, for example circular inlets, the diverter may not be two-dimensional because of the lower surface curvature of the fairing. For calculation purposes it is then sufficient to take $A_d = w_d d_d$.

The overall drag coefficient is thus

$$C_{Dsc} = 2K_{sc} \left(\frac{\dot{m}}{\dot{m}_0} \right) + k_f k_{sp\ sc} (C'_D - C_{Df\ full})_{sh} + C_{Df\ full} + C_{DF} + C_{Dd}, \quad (5.5)$$

where

- K_{sc} is from Equation (5.1),
- k_f is from Figure 8,
- $k_{sp\ sc}$ is from Figure 7,
- $(C'_D - C_{Df\ full})_{sp}$ is from Figure 6,
- $C_{Df\ full}$ is from Figure 5,
- C_{DF} is from Equation (5.3)

and C_{Dd} is from Equation (5.4).

5.2 Pressure Recovery

For a scoop inlet that is running full or nearly full, with no boundary-layer diverter, the pressure recovery ratio and the ram pressure efficiency in a throat plane just aft of the lip can be obtained from Figure 3 as

$$\left(\frac{P_{Ht}}{P_{H0}}\right)_{sc \text{ full}} = \frac{P_{Ht} T_u}{P_{H0}}, \quad (5.6)$$

and from Figure 4 as

$$\eta_{sc \text{ full}} = \eta_{Tu}, \quad (5.7)$$

where in each case $h = d_{1u}$, the height of the upper highlight of the entry.

If a diverter is present, so that the height of the entry lower highlight $d_{1l} \geq 0$, the total pressure recovery at full mass flow is obtained by using the data in Figure 3 and the equation

$$\left(\frac{P_{Ht}}{P_{H0}}\right)_{sc \text{ full}} = \left\{ \frac{P_{Ht} T_u}{P_{H0}} d_{1u} - \frac{P_{Ht} T_l}{P_{H0}} d_{1l} \right\} \frac{1}{(d_{1u} - d_{1l})}, \quad (5.8)$$

where the theoretical pressure ratios $P_{Ht Tu}/P_{H0}$ and $P_{Ht Tl}/P_{H0}$ are obtained from Figure 3 with respective heights $h = d_{1u}$ and d_{1l} .

For mass flows less than full there is an adverse interaction between the pre-entry pressure gradient and the boundary layer. This distorts the boundary-layer profile and may cause separation. As a consequence, the pressure recovery in the throat is decreased by an amount $-\Delta P_{Ht}$. More importantly, the disturbed nature of the entry flow reduces the efficiency of any diffuser downstream of the throat.

It is not possible to give a general quantitative prediction of these effects but for inlets without a boundary-layer diverter a limited amount of information is contained in Derivation 19. That Derivation reports a series of tests in which sharp-lip inlets, with $d_{1l} = 0$, were mounted on a flat plate and the pressure loss due to the boundary-layer disturbance was measured at the end of diffusers of differing contours and lengths. Included in the test programme was a rectangular inlet followed by a straight, constant cross-section duct of length $4.5d_{1u}$. Derivation 19 contains a semi-empirical prediction for the pressure loss at the downstream end of that duct and if it is assumed that the loss ΔP_{Ht} has the same form but a lower magnitude, then

$$\frac{\Delta P_{Ht}}{P_{H0}} \leq -k_p \frac{\theta}{d_{1u}} \left\{ 1 - \left(\frac{\dot{m}}{\dot{m}_0} \right)^3 \right\}, \quad (5.9)$$

where θ is the boundary-layer momentum thickness, which can be estimated from Item No. 68020 (Derivation 20), and k_p is a function of Mach number given in Figure 9.

If a boundary-layer diverter is present the interaction between the pressure gradient and the boundary layer becomes unimportant and

$$\frac{\Delta P_{Ht}}{P_{H0}} = 0. \quad (5.10)$$

The total pressure recovery ratio is

$$\left(\frac{P_{Ht}}{P_{H0}}\right)_{sc} = \left(\frac{P_{Ht}}{P_{H0}}\right)_{sc \text{ full}} + \frac{\Delta P_{Ht}}{P_{H0}}. \quad (5.11)$$

This is converted to a ram pressure efficiency through the equation

$$\eta_{sc} = \frac{(1 + 0.2M^2)^{7/2}(P_{Ht}/P_{H0})_{sc} - 1}{(1 + 0.2M^2)^{7/2} - 1}. \quad (5.12)$$

The data available to verify these equations from pressure measurements made in the inlet throat are very limited. In Derivation 18 a few data are collected for rectangular inlets, without diverters, operating at full mass flow. Those data are in good agreement with the predictions of Equation (5.6).

5.3 Captured Mass Flow

The mass flow ratios in Figure 1 allow the effect of boundary-layer thickness to be considered when estimating the size of an inlet that at full mass flow captures air at a specified mass flow.

For a scoop inlet running full

$$\dot{m} = \rho_0 V_0 A_1 \left\{ \frac{\dot{m}_{Tu}}{\dot{m}_0} d_{1u} - \frac{\dot{m}_{Tl}}{\dot{m}_0} d_{1l} \right\} \frac{1}{(d_{1u} - d_{1l})}, \quad (5.13)$$

where $\dot{m}_{Tu}/\dot{m}_0$ and $\dot{m}_{Tl}/\dot{m}_0$ are calculated for $h = d_{1u}$ and d_{1l} respectively. Although strictly valid only for rectangular inlets numerical checks have shown that Equation (5.13) can be used for circular and semicircular inlets without any significant loss of accuracy.

Equation (5.13) is used to calculate d_{1u} once $\dot{m}$ and the free-stream conditions are known, the cross-sectional shape of the entry specified, and d_{1l} chosen, say, as a fixed proportion of the boundary-layer thickness. This is accomplished by first setting $A_1 = \dot{m}/\rho_0 V_0$ and obtaining a first estimate of d_{1u} in the implied absence of a boundary layer. Equation (5.13) can then be used to establish the shortfall in captured mass flow that will be occasioned by the boundary layer. The necessary increase in A_1 and hence d_{1u} , that is needed to offset this can then be estimated. This procedure is demonstrated in Section 9.1.1 of the example for a circular scoop.

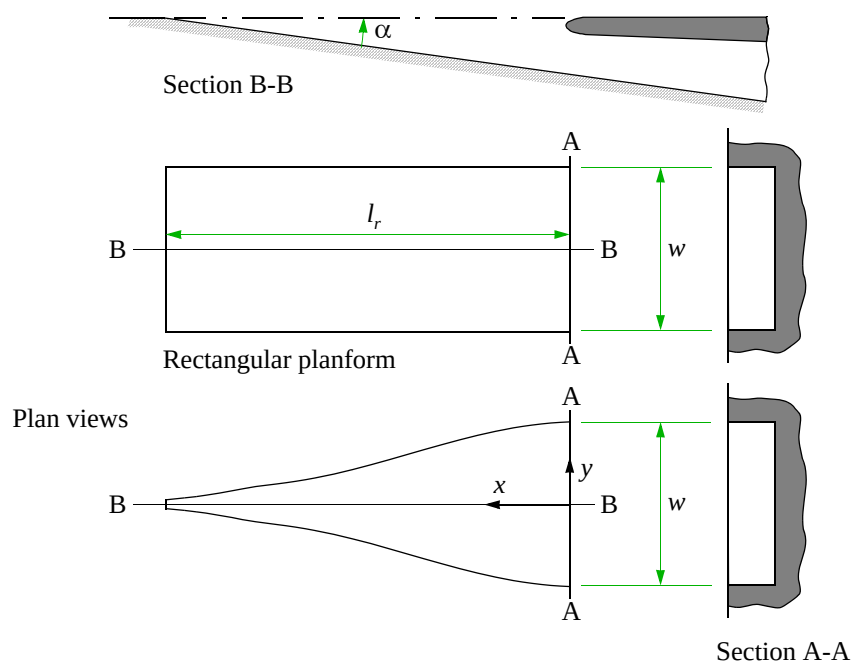
Assuming the cross-sectional area of the inlet is least in the throat plane just aft of the lip, Derivation 22 with Reference 28 gives the theoretical mass flow for a choked inlet,

$$\frac{\dot{m}_{ch}}{(\dot{m}_0)_t} = \frac{\dot{m}_{ch}}{(A_t/A_1)\dot{m}_0} = \frac{0.579}{M} \left(\frac{P_{Ht}}{P_{H0}}\right)_{sc} (1 + 0.2M^2)^3. \quad (5.14)$$

6. FLUSH INLETS

Section 6.1 describes how a general method for predicting the drag of certain types of flush inlets has been developed by taking Equation (3.18) as an initial model. Empirical corrections are based on the available experimental data, but it has only been possible to produce a method for a limited range of inlet geometries. The method in Section 6.1 is applicable for ramp angles $\alpha \leq 11.5^\circ$. Item No. 03006 (Reference 32) may be used to predict the drag of rectangular planform flush inlets with geometries that turn the flow through larger angles (up to 90° to the upstream flow direction).

The two basic types of inlet considered are shown in Sketch 6.1. The first has a ramp of rectangular planform, which has the advantage of ease of manufacture. The second has a NACA curved-divergent ramp with a highly swept planform that causes strong vortices to develop along the ramp sides. These thin the boundary layer in the centre of the ramp and so reduce the pressure loss due to the boundary layer. Although there are additional losses due to the vortices themselves, the net result is a pressure recovery superior to that of other flush inlets and which exceeds the theoretical two-dimensional pressure recovery. See Derivations 2 to 9, 11, 12, 17 and 23 and References 26 and 30. For best pressure recovery an inlet width to depth ratio of about 4 and a ramp angle α of 7° are desirable.



Ramp coordinates for NACA curved-divergent planform

x/l_r	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$2y/w$	1.0	0.996	0.916	0.766	0.614	0.466	0.388	0.312	0.236	0.158	0.085

Sketch 6.1 Flush inlets

Equation (3.18) has been used to analyse the two sets of data that are provided by the parametric test programmes reported in Derivations 3 and 16. Derivation 3 treats inlets of aspect ratio 2, 4 or 6 with rounded lips in low-speed flow with $l_l/t \approx 1$ and $d_t/t \approx 2$, and Derivation 16 treats inlets of aspect ratio 4 with sharp lips in high-speed subsonic flows, $0.55 \leq M \leq 0.9$. No other collections of systematic data are available, although there are a few isolated data from particular tests.

Section 6.2 describes how the pressure recovery is calculated for the two types of flush inlet. For the rectangular ramp inlet pressure recovery is obtained to a first approximation. The method uses the theoretical predictions of Derivation 13 together with an empirical correction to allow for the variation with mass flow based on data from Derivation 3. For the curved-divergent ramp inlet a separate method is given (see footnote in Section 2).

Section 6.3 presents a comparison of the drag and pressure recovery characteristics of inlets with differing ramp planforms.

Section 6.4 describes how the size of a flush inlet is designed to accommodate a specified mass flow. A special method is given for inlets with a curved-divergent ramp operating at maximum efficiency.

6.1 Drag

Following Equation (3.18) the drag of a flush inlet is divided into a ram drag term and a spillage drag term, the former dominating at moderate to high mass flows.

The ram drag term is obtained by replacing K in the first term in Equation (3.18) by

$$K_{fl} = k_{\psi} \left(\frac{\psi_T}{\psi_0} \right), \quad (6.1)$$

where ψ_T/ψ_0 is the theoretical momentum flow ratio from Figure 2 for a height $h = d_{1fl}$, corresponding to the inlet highlight height.

The factor k_{ψ} is an empirical constant that has been deduced from the experimental data for inlets running full or near to their maximum mass flow. For inlets with round lips, and regardless of ramp profile, the data in Derivation 3 suggest that for low-speed flow and ramp angles $\alpha \leq 9^\circ$

$$k_{\psi} = 1, \quad (6.2)$$

but there is evidence that k_{ψ} decreases by about 10 per cent for $\alpha = 11.5^\circ$. The data in Derivation 16 suggest that for sharp-lip inlets with rectangular ramps, with $\alpha = 7^\circ$, Equation (6.2) is valid for $M \leq 0.9$. Figure 10a summarises the general behaviour of k_{ψ} that has been inferred by combining these data. For sharp lip inlets with a curved-divergent ramp, however, data in Derivation 16 show that k_{ψ} increases with Mach number from a value of 0.8 at $M = 0.55$ to a value of 1.0 at $M = 0.9$, as shown in Figure 10b. For high ramp angles a reduction in k_{ψ} similar to that shown in Figure 10a has been applied. Although determined at high mass flows, these values of k_{ψ} should provide a good approximation to the boundary-layer loss for all mass flows.

The spillage drag coefficient has been determined empirically from data in Derivations 3 and 16 by correlating a drag coefficient, C'_{Dfl} , at zero mass flow and low Mach number in terms of lip shape for a 7° ramp, as shown in Figure 11. Because there is only one set of experimental data available for inlets with round lips, the parameter defining the lip shape, $(d_{mfl} - d_{1fl})/l_f$, is simple and carries the assumption that the profile is approximately elliptical. An interpolation between the experimental results for round-lip and sharp-lip inlets and an extrapolation to circular-profile lips are shown dashed. Two factors, k_{α} and k_M given in Figures 12 and 13, are applied to C'_{Dfl} , to allow for ramp angles $\alpha \geq 7^\circ$ and Mach numbers $M \geq 0.55$. The factors k_{α} and k_M have been derived solely from data on round-lip and sharp-lip inlets, respectively. Moreover, only data for curved-divergent ramp planforms are available for defining k_{α} .