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Blockage corrections for bluff bodies in confined flows

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Item was monitored and guided by the following working party:

Dr D.J. Cockrell	— Leicester University
Dr W. Ewers	— Atkins Research and Development
Mr R.G. Gawthorpe	— British Rail, Derby
Mr R.W. F. Gould	— National Maritime Institute
Mr T. V. Lawson	— Bristol University
Dr A. Moulton	— Atkins Research and Development

appointed by the Wind Engineering Panel which has the following constitution:

Chairman	
Mr T.V. Lawson	— Bristol University
Members	
Mr K.C. Anthony	— Ove Arup and Partners
Dr D.J. Cockrell	— Leicester University
Prof. A.G. Davenport*	— University of Western Ontario, Canada
Dr A.R. Flint	— Flint and Neill
Mr D.H. Freeston*	— Auckland University, New Zealand
Mr R.I. Harris	— Cranfield Institute of Technology
Mr R.A. Lyons	— Atkins Research and Development
Mr J.R. Mayne	— Building Research Establishment
Mr R.J. Melling	— Post Office Telecommunications
Dr G.A. Mowatt	— CJB—Earl and Wright Ltd
Mr J.R.C. Pedersen	— Independent
Mr D.J.W. Richards	— Central Electricity Research Laboratories
Mr C. Scruton	— Independent
Mr R.E. Whitbread	— National Maritime Institute.

* Corresponding Member

The work on this Item was carried out in the Wind Engineering Group of ESDU under the supervision of Mr N. Thompson. The member of staff who undertook the technical work involved in the initial assessment of the available information and the construction and subsequent development of the Item was

Mr B.C. Freeman — Senior Engineer.

BLOCKAGE CORRECTIONS FOR BLUFF BODIES IN CONFINED FLOWS

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BLOCKAGE CORRECTIONS FOR BLUFF BODIES IN CONFINED FLOWS

1. NOTATION AND UNITS

		SI Unit
A	cross-sectional area of wind tunnel or duct at reference plane	m^2
a, b	cross-sectional dimensions of prismatic or similar body (see Sketch 1.1 and Section 10)	m
B	maximum cross-sectional area of separation bubble	m^2
b, c	cross-sectional dimensions of ellipse or similar body (see Sketch 1.1 and Section 10)	m
b_d, H_d	cross-sectional dimensions of wind tunnel or duct at reference plane (see Sketch 1.1 and Section 10)	m
C_C	across-flow, lift, or side, force coefficient; lift force/ $(\frac{1}{2}\rho V_\infty^2 S)$	
C_D	drag coefficient; drag force/ $(\frac{1}{2}\rho V_\infty^2 S)$	
C_{Di}	lift-induced drag coefficient (see Section 4.4)	
C_F	force coefficient*; force/ $(\frac{1}{2}\rho V_\infty^2 S)$	
C_p	pressure coefficient; $(p - p_\infty)/(\frac{1}{2}\rho V_\infty^2)$	
d	diameter of circular cylinder	m
H	larger across-flow dimension of isolated body, dimension between walls or normal to surface for surface-mounted bodies (see Sketch 1.1 and Section 10)	m
K_s	net static-pressure loss coefficient for obstruction in duct (see Equation (8.3))	
m	wake expansion factor, B/S_s (see Appendix A2)	
n	vortex-shedding frequency	Hz
p	static pressure	Pa or N/m^2
p_∞	reference static pressure (corresponding to V_∞)	Pa or N/m^2
Re	Reynolds number, $V_\infty a/\nu, V_\infty c/\nu$ or $V_\infty d/\nu$	
Re_f	Reynolds number based on effective flow velocity (see Section 6.2)	
Re_e	effective Reynolds number (see Section 6.2)	
S	reference [†] cross-sectional area of body, bH	m^2

For Footnotes see end of Notation Section.

St	Strouhal number, nb/V_∞ or nd/V_∞	
V	local mean axial flow velocity	m/s
V_H	mean flow velocity at distance H from wall or surface	m/s
V_m	area-averaged flow velocity in duct, (volume flow rate)/ A	m/s
V_∞	reference mean flow velocity (see Section 6.1)	m/s
w	body width projected normal to flow, for bodies at incidence (see Sketch 1.1)	m
x, y, z	distances along Cartesian-coordinate body-axes, defined such that Ox is in the flow direction for $\alpha = \pi/2 (=90^\circ)$ (see Sketch 1.1)	m
α	angle of incidence [†] of approaching flow (see Sketch 1.1)	rad
$\bar{\alpha}$	power-law exponent for mean wind speed (see Section 6.1)	
δ	boundary layer thickness, value of z at maximum velocity in shear flow	m
ε	Maskell's ¹² blockage correction parameter, $-1/C_{psf}$ (see Equation (4.1))	
λ_1, λ_2 λ_3, λ_4	shape factors for quasi-streamlined flow blockage corrections (see Equations (4.4) to (4.9))	
ν	kinematic viscosity of fluid	m ² /s
ρ	density of fluid	kg/m ³
ϕ	lift-dependent drag factor (see Equation (4.11))	

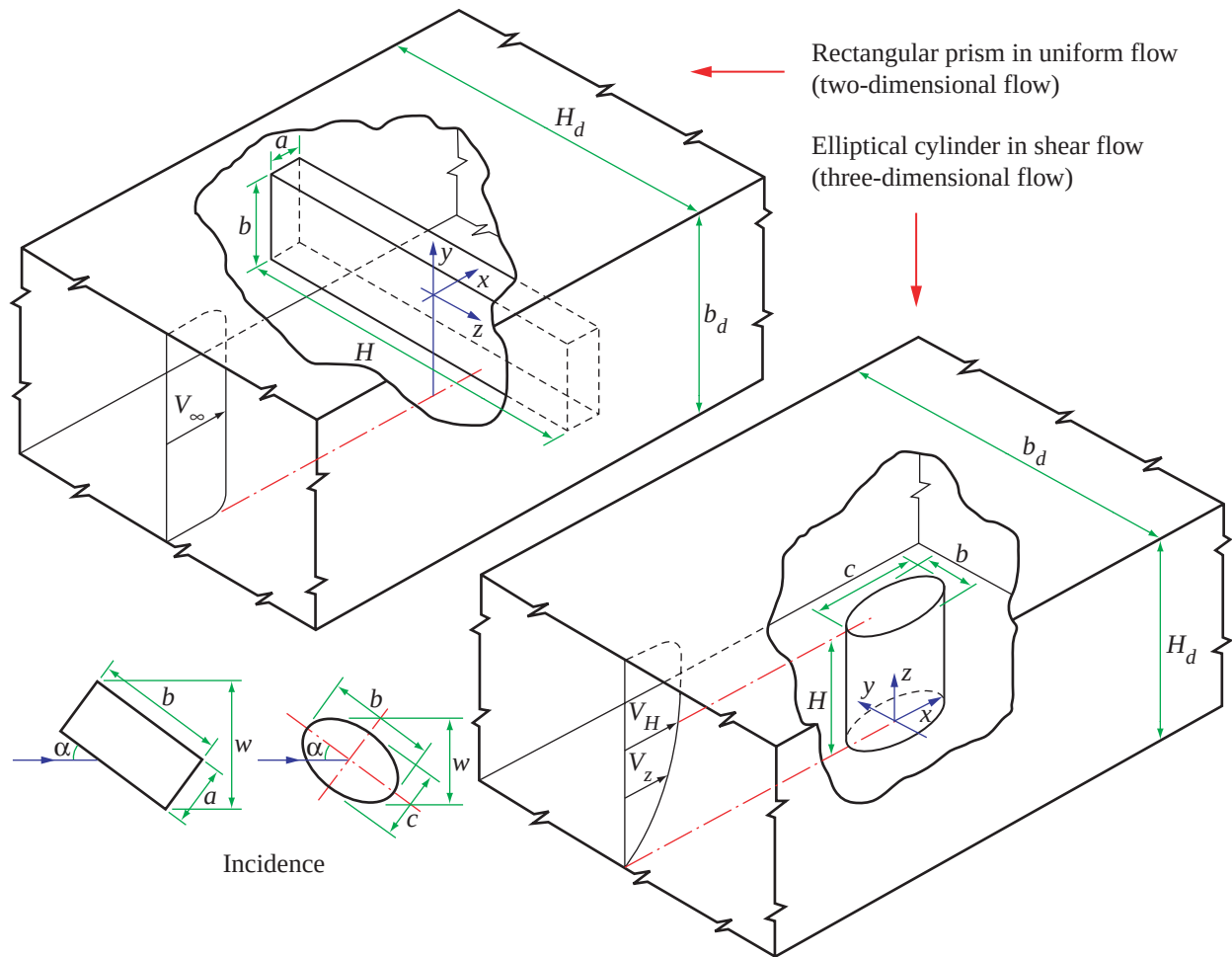
Subscripts

b	value on base [‡] of body (<i>i.e.</i> on surface downstream of separation points of body, particularly at furthest downstream point on body)
f	value corrected to, or appertaining to, 'free air' or unconfined flow conditions
s	value at the separation position (except in Equation (8.3), see K_s)
z	value at position z on body

* The suffix F is used as a general notation and represents the appropriate suffix for the force component considered: D (drag), C (lift or side force), X, Y, Z , (in Ox, Oy, Oz directions respectively).

† Care should be taken when using data from other sources in conjunction with this Item since the reference area used and incidence definition may differ from those here.

‡ The term "base" originated with its usage in description of the drag of artillery shells in supersonic flow which arises predominantly from pressure forces on the downstream face.



Sketch 1.1

2. INTRODUCTION

Most wind-tunnel tests are aimed at predicting some of the forces, pressures, moments and other parameters that will be experienced by a full-scale structure in an unconfined or 'free air' situation. The wind-tunnel boundaries impose constraints on the flow around the model so that the measured values of these parameters differ from the required free-air values and need correction to obtain the free-air values. Conversely, if the free-air drag coefficient of a body is known, inverse application of the correction allows estimation of the corresponding drag coefficient for the body in the confined flow of a duct, from which the resultant pressure loss may also be estimated.

The flow boundaries in a wind tunnel may be, (a) solid walls, which impose a condition of zero transverse velocity on the flow at the wall or, (b) the jet boundary in an open-jet wind tunnel which imposes a condition of approximately constant static pressure (equal to ambient pressure) along the boundary. Blockage corrections for closed-wall and open-jet boundaries are essentially of opposite sign and this has led to the use in aeronautical wind tunnels of slotted or perforated walls to minimise blockage corrections^{*}. Movable, flexible walls (usually the roof when atmospheric winds are simulated) can, in principle, be contoured to match the shape of a stream-line in the unconfined flow to minimise blockage effects. In practice the exact required shape varies for each model and the shape used may then be estimated from other considerations.

2.1 Scope of the Data Item

This Data Item provides information on blockage effects on the forces and pressures on, and flow around, bluff bodies[†] in flows confined by straight, solid-wall[‡] boundaries.

Bluff bodies can be regarded as those for which the flow is dominated by large regions of separated flow, such as flat plates or rectangular prisms normal to the flow. Bodies such as circular or elliptical cylinders may behave as bluff bodies or as quasi-streamlined bodies according to the operating flow-regime^{**} and the Item therefore includes appropriate corrections for this latter case. Bodies such as aerofoils or streamlined-section struts may behave as bluff bodies at high incidence, *i.e.* in stalled flow.

Blockage correction methods may be needed for one of three requirements:

- (i) for correction of existing wind-tunnel data (or to assess corrections already applied),
- (ii) for correction of wind-tunnel measurements yet to be made,
- (iii) for estimation of forces on, or pressure drop across, obstructions sited in ducts.

* There are also special reasons for the use of perforated-wall or slotted-wall wind tunnels for transonic flow, see Derivation 16, Chapter VI for a brief discussion.

† Wind-tunnel corrections for streamlined bodies, such as aerofoils, are given in Reference 5 and Derivation 16.

‡ Some information for open jet wind tunnels, for which blockage corrections may be equally important but generally of opposite sign, is given in Reference 2 and Derivations 16 and 47. Because of the relatively short working section length of the jet, speed measurement errors, resulting from blockage effects propagated upstream from the model to the speed measuring pressure tapping in the nozzle, may be important. The corresponding effect in closed wind tunnels is discussed in Appendix C1.

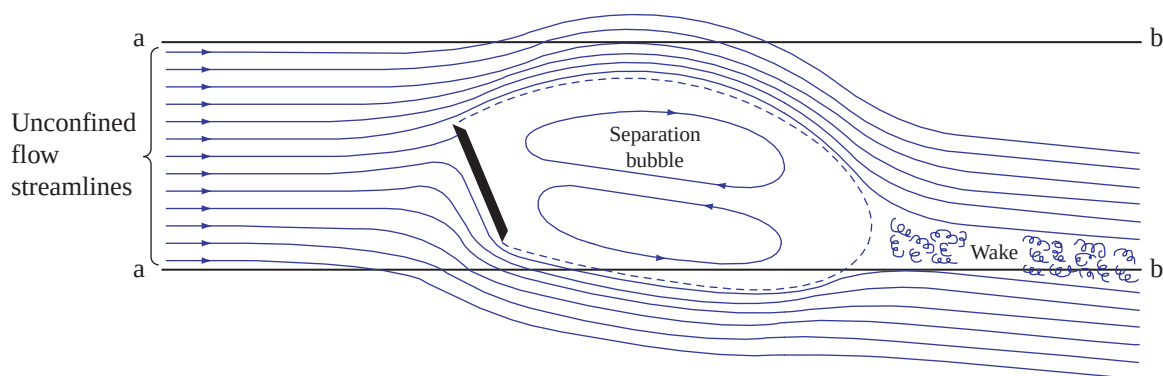
** See Section 6 and References 7 and 8 for information on flow regimes for such shapes.

Blockage effects can be neglected only if the model is very small in relation to the wind tunnel or duct, (less than, say 1 per cent* of the cross-sectional area). In wind-engineering studies, this requirement is in direct conflict with the need to test large models in order to achieve adequate Reynolds numbers, allow representation of small details of structural shape and generate forces large enough to allow their accurate measurement. Consequently blockage area ratios, S/A , of 5 per cent are common and even up to 10 to 15 per cent are used, requiring appreciable correction to measured results.

Although the supporting experimental data were derived largely from wind tunnel tests, the methods apply generally for incompressible flow of gases and for liquid flows provided that cavitation does not occur in the wake. Some information on the effects of confinement on cavitating flows is given in Reference 44.

Section 3 of the Item provides an introduction to blockage effects and methods of determining them (Appendix C notes some problems and uncertainties in using wind tunnel data for this purpose). Three recommended methods are introduced in Section 4 which considers their application to mean force coefficients while Section 5 extends the application to mean pressures (Appendix A gives additional background information on the recommended methods and Appendix B briefly describes a number of other correction methods which have been applied to bluff bodies). Section 6 considers the appropriate reference flow conditions and Section 7 considers fluctuating quantities. The application of blockage corrections to duct-flow situations is considered in Section 8.

3. BACKGROUND DISCUSSION OF BLOCKAGE EFFECTS



Sketch 3.1

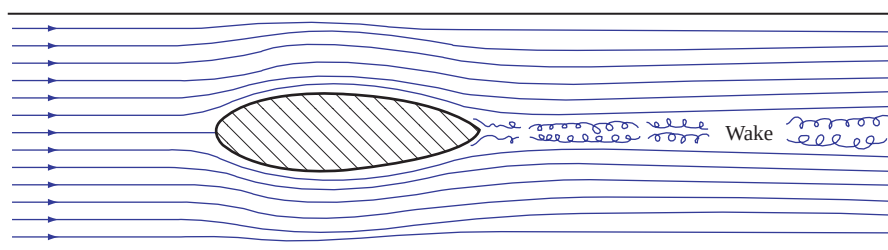
The general nature of the effects of confinement on the flow past a body may be appreciated from Sketch 3.1. If the solid walls indicated by the heavy lines a-b are imposed on the flow originating across section a-a it is evident that the flow pattern shown by the unconfined-flow streamlines must be modified in order that this flow is contained within the walls. Firstly, the expansion of the streamlines around the body and its wake is restricted by walls and secondly, the inclination of the streamlines is modified to become parallel to the wall downstream of the body.

* The value adopted here will depend on the accuracy required in the final results. A blockage area ratio of one per cent probably results in blockage corrections of less than three per cent.

The first effect, usually termed “blockage”, results in increased velocities in the flow around the body and its wake. For reasonable blockage area ratios^{*} it has been demonstrated that the principle of “invariance under constraint”[†] can be applied to both streamlined-body attached flows and bluff-body separated flows. The principle implies that the form of the pressure distribution on a body (and its separation bubble) does not vary with the degree of constraint and allows the blockage effect to be equated to a uniform increase in reference velocity. Blockage affects both along-flow (drag) and across-flow (lift or side) forces and is important for all bodies of blockage area ratio greater than about one per cent.

The second effect influences primarily the across-flow or lift force and is consequently termed “lift interference”. Lift interference[‡] is most important for streamlined bodies designed to generate lift, such as aerofoils. Most bluff bodies are inefficient generators of lift (the ratio lift/drag is small) and lift interference can generally be neglected^{**} in comparison with blockage effects. For three-dimensional flow there is, however, an additional effect of lift since the total measured drag will include the lift-dependent or lift-induced drag which does not contribute to blockage effects (Section 4.4).

3.1 Streamlined Body Flow



Sketch 3.2 Streamlined body flow

Sketch 3.2 shows the time-averaged flow around a non-lifting streamlined body in a confining channel. The flow remains attached to the body surface over most of the body with a surface boundary-layer growing in thickness towards the rear. This boundary layer separates from the surface near the rear and forms the viscous wake, a low velocity region of flow extending downstream from the body. The cross-sectional area of the wake continues to increase downstream as a result of viscous mixing at its boundary.

For such a body the blockage effect is usually considered in terms of ‘solid-body blockage’ and ‘wake blockage’. Closely associated with the wake blockage is a correction to the drag force that is conventionally called the ‘longitudinal-buoyancy drag’. These effects are discussed in the following paragraphs.

- (i) Solid-body blockage is a function of the volume and shape of the body. Continuity of mass flow through the channel requires increases in the flow velocities near the body compared with the velocities in unconfined flow; downstream the flow is assumed to revert to the undisturbed upstream flow conditions. The increases in velocity from the unconfined flow situation vary across the channel, being largest near the walls and extend for some distance upstream and downstream of the body location, as shown in Sketch 3.3. Solid-body blockage for a streamlined body is independent of the body drag except insofar as the body shape may be assumed to include the displacement thickness of the body boundary-layer.

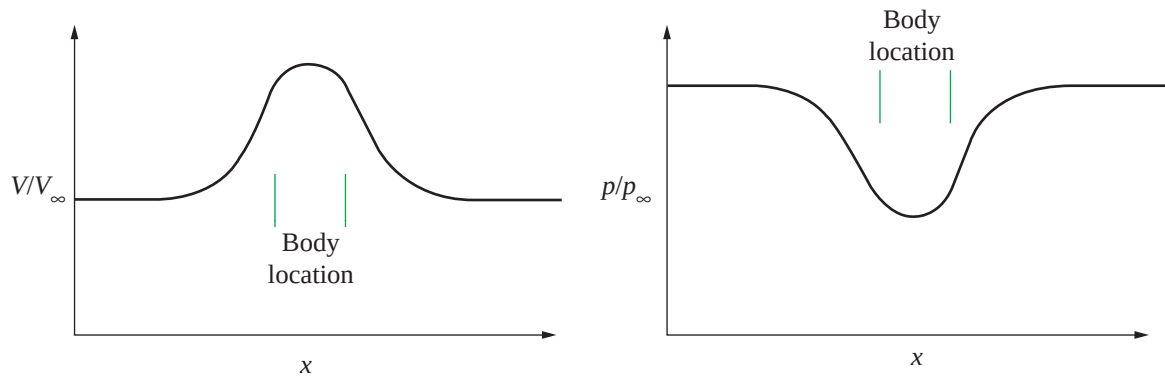
^{*} Typically for blockage area ratios, S/A , up to about 10 to 15 per cent.

[†] See Appendix A.

[‡] Lift interference, and blockage, corrections for streamlined bodies are given in, for example, Reference 5 and Derivation 16.

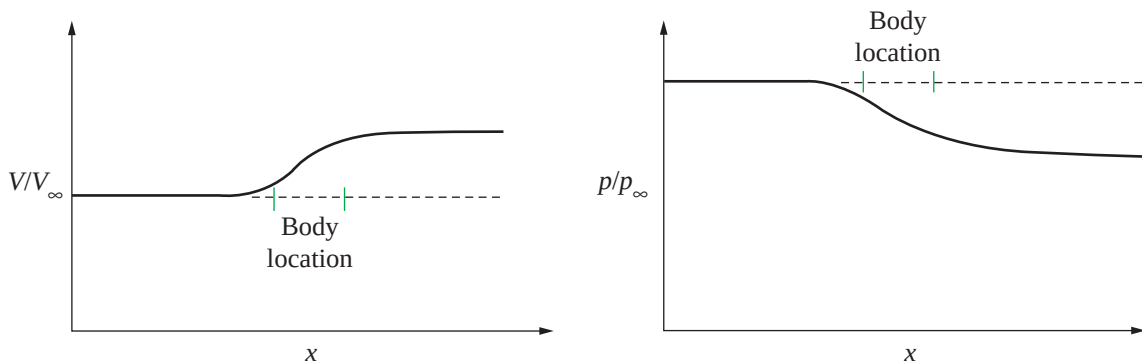
^{**} An approximate guide can be obtained from the lift interference predicted for a two-dimensional aerofoil for which Reference 5 gives (using present notation)

$$\Delta C_C \approx -0.2 \left(\frac{S_C}{A_b} \right)^2 C_C$$



Sketch 3.3 Solid body blockage effect

- (ii) Wake blockage is a function of the drag of a body. As noted, the wake is an expanding low velocity region of flow extending downstream from the body. Continuity of mass flow therefore requires that the velocity outside the wake increases along the channel as a result of wake blockage, as shown in Sketch 3.4, so that the effective velocity past the body location increases. This increase is uniform across the section and, because the momentum deficit in the wake is a measure of the body drag, is proportional to the drag per unit cross-sectional area of channel.



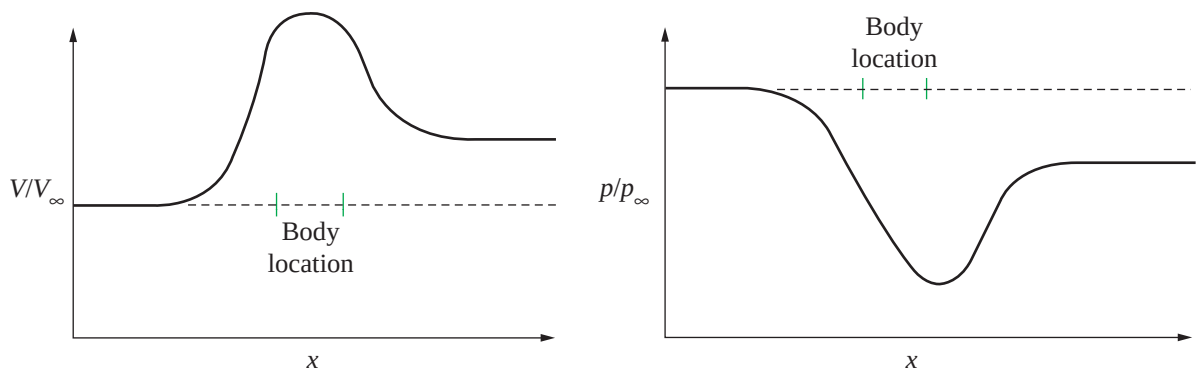
Sketch 3.4 Wake blockage effect (V and p outside the wake)

Associated with the increasing axial velocity caused by wake blockage is a decreasing static pressure. This pressure gradient along the body causes an additional drag, conventionally termed 'longitudinal-buoyancy drag^{*}', which does not occur in unconfined flow. The overall drag measured by a wake traverse method does not include the buoyancy drag but the overall drag measured by a balance or by integration of body pressure measurements must be corrected for buoyancy drag.

Boundary layer growth on the duct walls may contribute to the wake blockage and longitudinal buoyancy effects by partially blocking the flow. In wind tunnels it is common practice to prevent this by allowing a gradual increase in tunnel cross-sectional area along the working section.

The total effect of solid-body blockage plus wake blockage, assuming that they can be superimposed, is therefore to produce velocity and static-pressure variations along the wind tunnel of the form shown in Sketch 3.5.

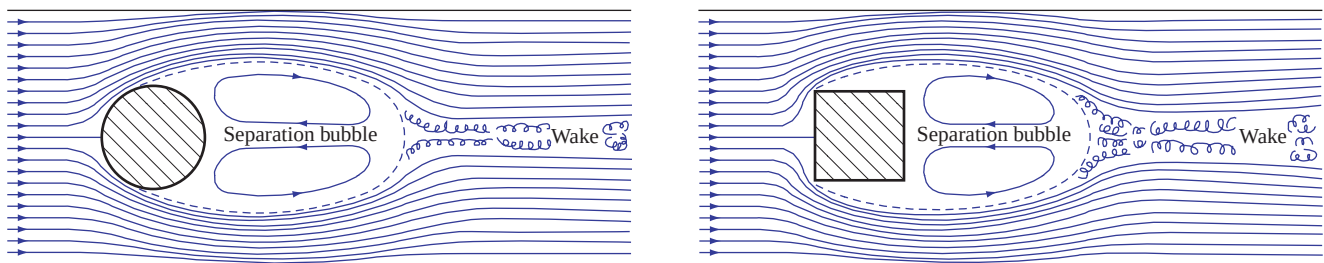
* The term buoyancy should strictly be applied only to forces arising from density differences but its usage in this context is widespread.



Sketch 3.5 Total blockage effect (V and p outside the wake)

3.2 Bluff-body Flow (Flow separation occurs at or ahead of maximum cross-sectional area of body.)

Sketch 3.6 shows the time-averaged flow around two bluff bodies in confined flow. The main difference from the streamlined body flow of Sketch 3.2 is that although the flow is attached over the front face of the body it separates at a position at or before the maximum cross-sectional area of the body. The static pressure at the separation position depends on the body shape. The separated flow initially diverges from the body at an angle determined by the separation pressure and then curves to form the boundary of a region of low speed, recirculating flow behind the body known as the separation bubble. Outside the bubble the separated boundary layer (usually termed the free shear-layer) follows the bubble surface, growing in thickness, and closes around the rear of the separation bubble to form a viscous wake similar to that for a streamlined body flow.



(a) Circular cylinder, two-dimensional subcritical flow

(b) Square prism, two-dimensional flow

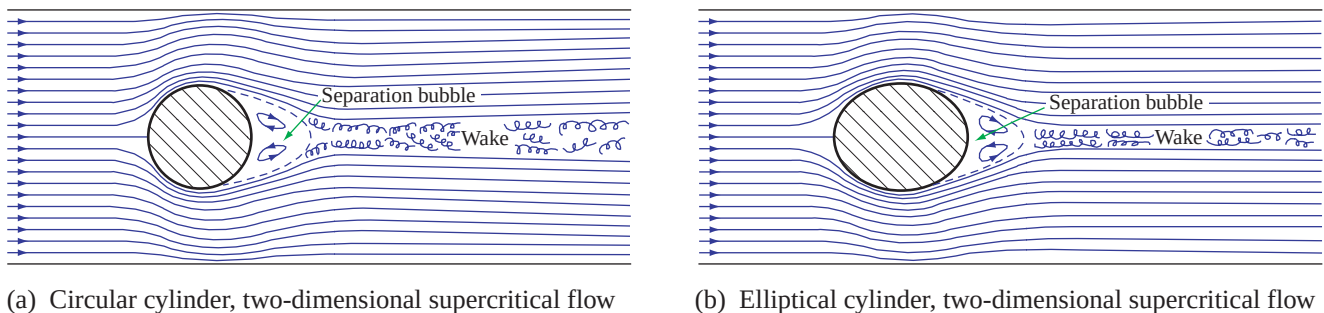
Sketch 3.6 Bluff-body flow

Along the boundary of the separation bubble the static pressure remains substantially constant and equal to the separation pressure¹² at least as far as the maximum cross-sectional area of the bubble. This boundary together with the front face of the body behaves much as an effective 'body' as far as blockage effects are concerned.

Blockage effects could in principle, be considered in terms of solid-body and wake blockage with the 'solid body' including the separation bubble. The total blockage effect would be similar to that in Sketch 3.5. However the size and shape of the effective body is not generally known* and it is usually more convenient to use other approaches (see Appendix A2 and Section 4.1). Since the bubble shape and the pressure is a function of the body drag, both the bubble blockage and the wake blockage are functions of the drag of the body and can be evaluated as a single correction. Unless a substantial proportion of the body extends ahead of the separation position, solid-body blockage will be negligible and, similarly, 'longitudinal buoyancy drag' will be small because most of the body is enclosed in the nearly constant-pressure separation bubble.

3.3 Quasi-streamlined Flow (Flow separation occurs behind maximum cross-sectional area of body.)

The flow around bluff bodies such as circular or elliptical cylinders and rounded-edged polygonal sections behaves in a manner intermediate between streamlined-body flow and bluff-body flow in the condition known as supercritical flow†. Examples are shown in Sketch 3.7. In such cases the flow remains attached past the maximum cross-sectional area and the separation pressure and separation angle are such that the separation-bubble boundary converges and forms a smaller bubble than for bluff-body flow. Consequently the effective body shape differs less from the actual body shape and the streamlined body corrections can be applied approximately (with appropriate body shape parameters and drag coefficients).



Sketch 3.7 Quasi-streamlined flow

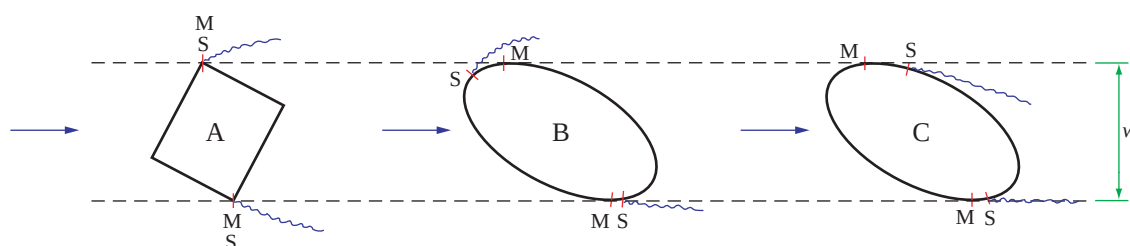
3.4 Lifting Bodies

Assuming that lift-interference corrections can be neglected (as discussed in the introduction to Section 3), two other considerations must be taken into account for lifting bodies.

Firstly, separation no longer occurs symmetrically around the body. In this case the flow will be defined as bluff-body flow if separation occurs at or ahead of the maximum lateral extent on one side of a two-dimensional body as shown in Sketch 3.8. A similar criterion can be established for three-dimensional flow.

* But see Section 4.3 and Appendix A4.

† The principal determining parameter is the effective Reynolds number of the flow. Ranges of effective Reynolds number for supercritical flow for various body shapes are given in References 7 and 8.



Sketch 3.8 Lifting bodies: M denotes maximum lateral extent of body, S denotes separation position (schematic only). A and B in Bluff-body flow, C in Quasi-streamlined flow

Secondly, in defining the drag coefficient to be used in the blockage correction equations, allowance must be made for lift-dependent or lift-induced drag, incurred on three-dimensional lifting bodies, which does not contribute to blockage effects. Some guidance is given in Section 4.4.

3.5 Methods of Obtaining Corrections

It might appear that blockage effects could be estimated easily by measuring the required parameters (say, drag coefficients) of a series of different sized models in one wind tunnel or of one model in different sized channels, and extrapolating the results to zero blockage^{*}. However, although an apparently simple technique with application to complex flow situations, the method has a number of disadvantages. In the absence of a theoretical or semi-empirical blockage model the results can only be applied to the configuration tested; testing time (and cost) will be greatly increased by the need to repeat tests for each model/channel combination; flow and model scaling problems may arise with size changes and measurement accuracy over a wide range of magnitudes may make trends in data uncertain. Despite such uncertainties,[†] which make the technique impractical as a general approach, such data[‡] are required in order to confirm theoretical or semi-empirical methods.

The classical method of deriving blockage effects (outlined in Appendix A3) is to represent the confinement by a series of images (of the flow around the body in unconfined flow) reflected in the channel walls. For streamlined bodies, linearised potential-flow[‡] models of the flow around the body have been used successfully (see Derivation 16 and References B1 and B3 for example). The solid body is represented by a 'doublet' (a source and sink pair of equal strength at an infinitesimal distance apart) or by a distribution of sources and sinks and the wake by a source and sink pair an infinite distance apart with the source located at the body position.

Application of the streamlined-body model to bluff body flows is not generally successful however because the solid body in this case now effectively includes the separation bubble. A number of 'free-streamline' methods have been proposed to define the bluff-body flow model (References 3 and 4 for example) but they are restricted in practice to relatively simple body shapes and to bodies with zero or small lift or cross-flow force in order to permit evaluation of the methods and require an empirical input for defining separation position. In the method of Hackett *et al.*^{39,51} the necessary experimental data to define the flow model is obtained from wall-pressure measurements along the channel (see Section 4.3 and Appendix A4).

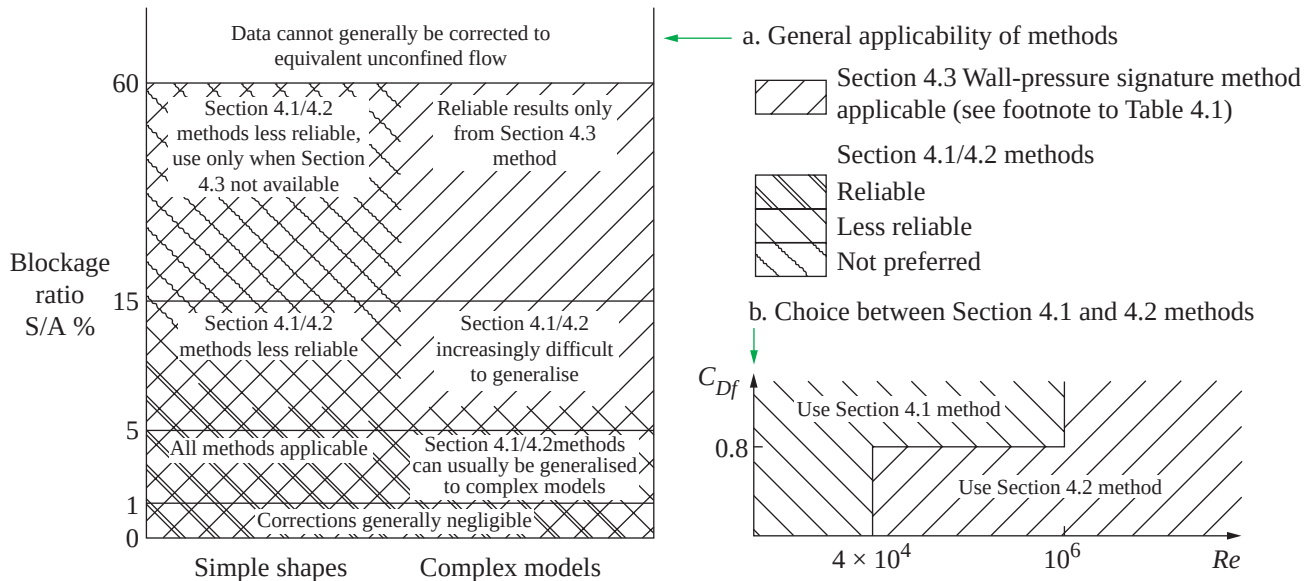
The capabilities of modern computational methods offer the possibility of a numerical solution of the Navier-Stokes equations governing the flow around a bluff body and the addition of boundary conditions representing the channel walls could then allow direct computation of confined flows. Because of their complexity these methods do not yet represent a practical method for general calculation of blockage effects.

^{*} Since for small blockages the correction is proportional to $C_D S/A$, extrapolation on that basis might be preferable.

[†] See Appendix C for discussion of some other considerations in obtaining and interpreting such wind-tunnel data.

[‡] A basic discussion of potential flow theory may be found in text books on aerodynamics or fluid mechanics, for example Reference 1.

4. BLOCKAGE CORRECTIONS FOR MEAN FORCE MEASUREMENTS



Sketch 4.1

Three recommended methods are given in this Section. The choice of method depends on a number of factors and guidance on various aspects of the choice is given in Table 4.1 and Sketch 4.1. The wall-pressure signature methods of Section 4.3 are universal in application but the theoretical/empirical methods of Sections 4.1 and 4.2 require a decision as to the position of flow separation. For sharp-edged bodies this is often obvious but for rounded-edged bodies it may not be. If tests over a reasonable range of Reynolds number are feasible it may be possible to deduce when the flow is supercritical since C_D generally drops when supercritical flow is reached. Wall pressure measurements as described in Section 4.3.2 can give an indication of changes between bluff-body flow and quasi-streamlined flow. In the absence of any other criterion it is suggested that for rounded bodies the method of Section 4.1 be used if $Re_f \leq 4 \times 10^4$ or $C_{Df} \geq 0.8$ and the method of Section 4.2 if $Re_f \geq 5 \times 10^5$ or $C_{Df} < 0.8$, see Sketch 4.1(b).