AE305 LAB-6 Drag Force (Wake traverse)

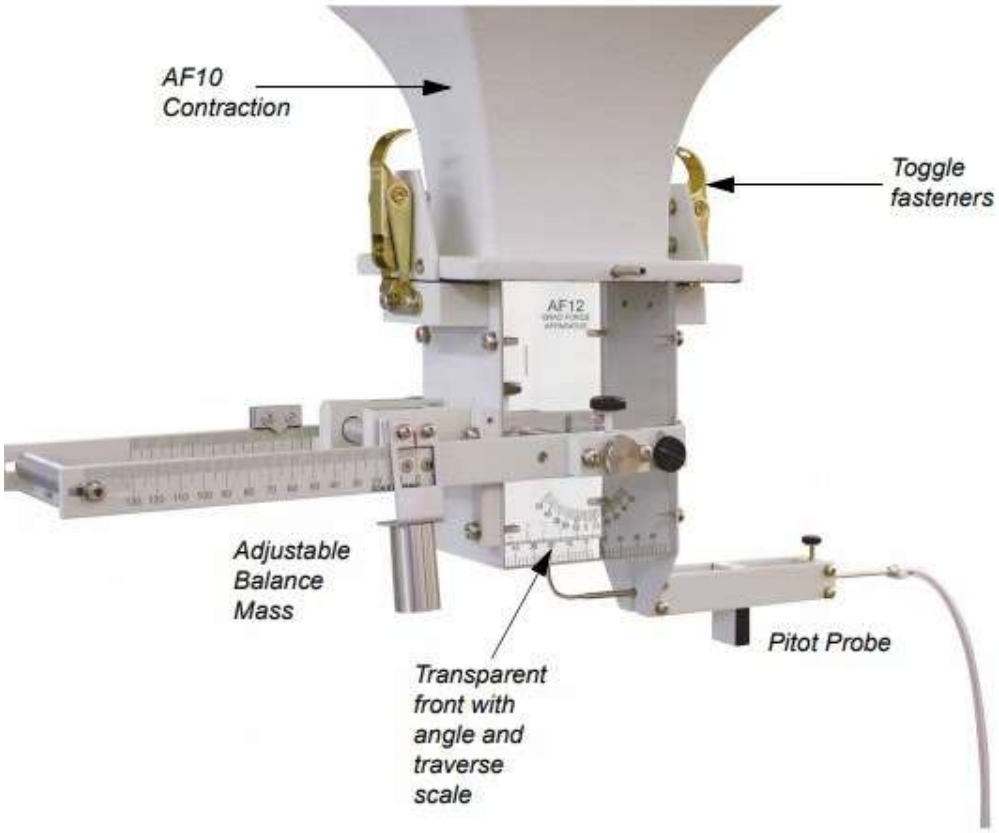


Fig. 1: Drag Force Apparatus

PRINCIPLE AND TASK

The Drag Force Apparatus (AF12) fits to the contraction of the AF10 Modular Air Flow Bench. It has a rectangular section passage with a transparent front and back. Any of three different models fit into the passage for drag tests. These models include a cylinder, a flat plate and a symmetrical-section aerofoil. As the models fit fully from front to back of the passage, the flow is two-dimensional (no air flows over the ends of the models).

A Pitot probe measures air pressure at the outlet of the passage, directly downstream of any fitted models. The probe can traverse across the passage outlet. This helps to measure the pressure profile or 'wake' downstream of the model. The probe connects to the optional manometer (AF10a) to show the measured pressures.

The transparent front and back of the passage include an angle scale to show the angle of the model with respect to the airflow, and linear scales to show the Pitot probe position.

Adjustable masses on parallel balance arms measure the drag force produced by the model. The balance arms have calibrated scales for direct readings of grammes when using the correct masses. A 100 g mass slides along the front balance arm for coarse adjustment of 0 to 130 g. A smaller 10 g mass slides along the back balance arm for more fine adjustment of 0 to 10 g.

© 2024

SETUP (ASSEMBLY & INSTALLATION)

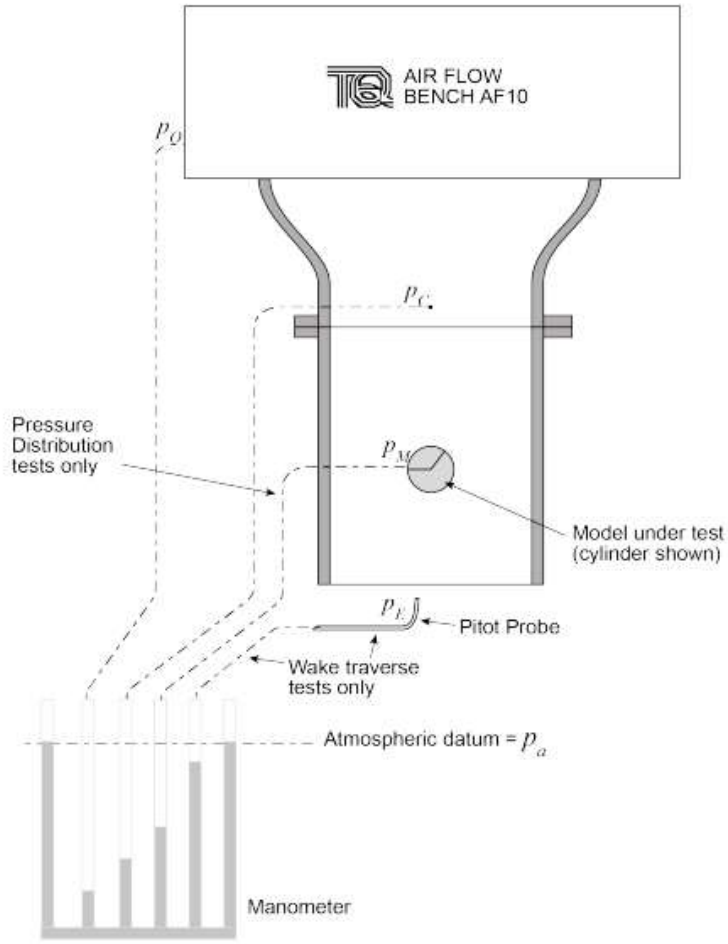
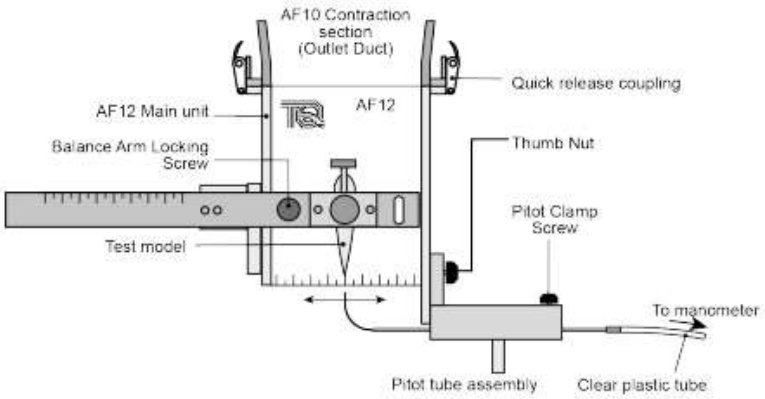


Figure 4 Arrangement of the Apparatus

Wake Traverse Assembly



1. Slide the model inside the passage and fit the model clamp screws to hold it in position.
2. Fit the Balance arm Locking Screw to hold the model in a fixed position.
3. Fit the Pitot Assembly.
4. Do not fit the Retaining Screw.
5. Connect the manometer to the Pitot, the Air Box and the contraction.

PROCEDURE

. Fit the standard circular cylinder model into the passage.

. Fit the Pitot traverse assembly.

. Set up an air speed to give an upstream pressure difference $p_o - p_c$ of approximately 450 N.m^{-2}. Keep this constant throughout the experiment.

. Note the air temperature and ambient pressure.

. Traverse the Pitot tube across the section, in increments of 2 mm near the centre, increasing to 5 mm towards the sides, where the total pressure becomes fairly constant. The table shows the positions as the Pitot extends outwards from centre as negative for clarity. Note that due to the Pitot curvature, it can extend this way slightly further than it can retract.

. Record the downstream pressure difference of p_e and p_a. The readings in the wake may be unsteady because of the high level of turbulence. To help damp these oscillations, use a pipe clamp on the pipe connecting the Pitot to the manometer. Take care not to damp the oscillations too much. Less damping is better than too much damping.

. Repeat the experiment with the other two models.

DATA SHEET

Model:					Air Temperature: Ambient Pressure:			
y mm	y/d	$p_a - p_E$ (= 1/2ρu^2) mmH_2O	 $N.m^{-2}$	$p_a - p_c$ (= 1/2ρU^2) mmH_2O	 $N.m^{-2}$	u/U	$1-\frac{u}{U}$	$\frac{u}{U}\left(1-\frac{u}{U}\right)$
45								
40								
35								
30								
25								
23								
21								
19								
17								
15								
13								
11								
9								
7								
5								
3								
1								
0								
-1								
-3								
-5								
-7								
-9								
-11								
-13								
-15								
-17								
-19								
-21								
-23								
-25								
-30								
-35								
-40								
-45								
-49								
Average $p_o - p_c$								

RESULTS ANALYSIS

Using d as 12.5 mm, calculate y/d for each position.

The difference between Air Box and contraction pressure give the upstream dynamic pressure which should be reasonably constant during the experiment. Find its average value, then use this as the value for $p_o - p_c$ in the next calculations.

Assuming incompressible conditions, as the air temperature and therefore density remain reasonably constant throughout the experiment, the value of 1/2ρ should remain constant. This means that the pressure difference ratio should be the same as the velocity ratio:

$$\frac{p_a - p_e}{p_o - p_c} = \frac{1/2\rho u^2}{1/2\rho U^2} = \frac{u^2}{U^2}$$

and therefore:

$$\frac{\sqrt{p_a - p_e}}{\sqrt{p_o - p_c}} = \frac{u}{U}$$

Use these equations to find the velocity ratios, then use them to complete the table.

Plot a chart of $\frac{u}{U}\left(1 - \frac{u}{U}\right)$ (vertical axis) against y/d.

Note the upturned ends of the curve where the boundary layer of the duct walls affects the results. Also note that because the model in the duct creates a reduction in duct area, then velocity in the wake either side of the model can be slightly higher than the free stream velocity. This gives a chart with a negative vertical offset.

Ignore the negative offset (use absolute values of y axis) and to avoid boundary conditions, only use that part of the curve for the wake traverse of 25 mm each side of centre (y/d = -2 to +2). Use drawing skills, a spreadsheet program or other suitable method, find the area under this curve and double it to find the drag coefficient.

If all three methods to find the drag coefficient have been completed, compare them in terms of complexity, ease of use, and what has been learned from them.

APPENDIX

Theory

Notation

Symbol	Term	Units
A	A position on a model	
A	Area	m^2
c	Chord	m
C_d *and* C_p	Coefficient of drag and pressure	- (dimensionless)
d	Dimension	m
l	Length	m
p, p_a , p_c *and* p_o	Pressure, ambient pressure, pressure at the contraction and pressure in the Air Box	Pa or $N.m^{-2}$
p_E, p_M, p_s *and* p_t	Press at the duct exit, at the model, static pressure and total pressure	Pa or $N.m^{-2}$
R	Gas Constant	287 $J.kg^{-1}.K$ for air
T *and* T_a	Temperature and ambient temperature	K or °C where shown
u *and* U	Air velocity	$m.s^{-1}$
ρ	Density	$kg.m^{-3}$

Conversions - Pressure and mmH_2O

The optional manometer shows pressure in mm of water (mmH_2O), but water density changes slightly with temperature, so this normally has to be allowed for. However, if the equipment is used at around room temperature, its density can be assumed to remain at around 1000 $kg.m^{-3}$ or 1 $kg.L^{-1}$.

Pressure in scientific calculations is normally in Pa (pascals) or $N.m^{-2}$ (Newton per square metre). Assuming the equipment is used at room temperature, then:

$$1\ mmH_2O\ (at\ room\ temperature) = 9.81\ Pa = 9.81\ N.m^{-2}$$

Atmospheric pressure is often measured in bar, where 1 bar = 100000 Pa = 100000 $N.m^{-2}$

Gauge and Absolute Pressures

Many scientific experiments use pressures measured with respect to absolute zero (a perfect vacuum). These are termed ***absolute*** pressures. The pressures used in the experiments with this equipment are all based on the pressures measured by the manometer and relative to atmospheric. These are termed ***gauge*** pressures and are acceptable for use in the associated theory provided they are consistent.

However, ambient (atmospheric) pressure is always absolute.

Air Density (ρ)

As with most fluids, the density of air changes with pressure and temperature. To accurately compare results of fluid experiments, it is always useful to know the density of the fluid being used.

$$\rho = \frac{p_a}{RT_a}$$

For these air flow experiments, the ambient temperature and pressure can be used to find the ambient air density around the experiment.

Force

The drag force measurement by weighing gives a force in units of grammes or gramme force (gmf). This is not a standard SI unit, so for correct use it must be converted into the correct unit of force due to gravity- the Newton.

$$1\ gmf = 0.00981\ N$$

Dynamic Pressure and Velocity

From Bernoulli's simple equation and assuming inviscid incompressible flow, velocity can be found using the air pressures in the duct and its density. The difference between the total and static pressure (p_t - p_s) is the ***dynamic pressure***. The upstream dynamic pressure is the difference between the Air Box and contraction pressure. The downstream dynamic pressure is the difference between the Pitot traverse pressure (exhaust) and atmospheric.

Upstream

$$p_o - p_c = \frac{1}{2}\rho U^2 \ so\ U = \sqrt{\frac{2(p_o - p_c)}{\rho}}$$

Downstream

$$p_E - p_a = \frac{1}{2}\rho u^2 \ so\ u = \sqrt{\frac{2(p_E - p_a)}{\rho}}$$

Consider the non-circular cylindrical body shown in cross-section in (Figure 9). For this theory, the word 'cylinder' describes a body generated by a straight line moving round a plane closed curve, its direction being always normal to the plane of the curve. For example, even a pencil of hexagonal cross-section can be considered a cylinder.

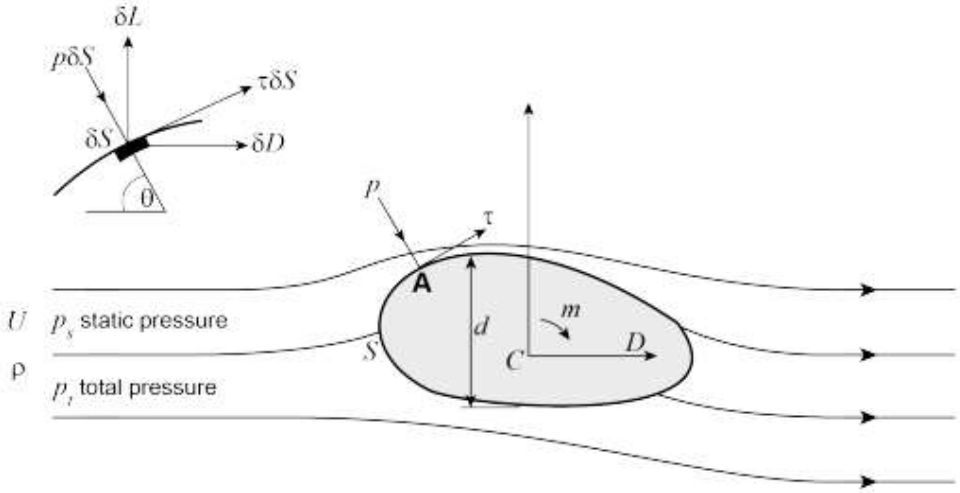


Figure 9 Flow Around a Cylinder

The curve shown in (Figure 9) represents a section of an non-circular cylinder. An essential property of a cylinder is that its geometry is two-dimensional; each cross-section is exactly the same as every other cross-section, so that its shape may be described without reference to the dimension along the cylinder axis. A 'circular cylinder' describes the particular and important case of a cylinder with circular cross section.

Motion of the cylinder through stationary fluid (or fluid moving over a stationary cylinder) produces actions on the cylinder surface which create a resultant force. Textbooks usually analyse these actions as an observer moving with the cylinder. The fluid appears to be approaching as a uniform stream. At any chosen point (**A**) of the surface of the cylinder, the effect of the fluid may be resolved into two components, pressure (p) normal to the surface and shear stress (τ) along the surface. The static pressure (p_s) is always with respect to the absolute ambient pressure datum so p is then a gauge pressure found from:

$$p = p_a - p_s$$

From Bernoulli's simple equation, the dynamic pressure in the undisturbed (upstream) is:

$$1/2\rho U^2 = p_t - p_s$$

From this, engineers can quantify the non dimensional coefficients for the example shown (assuming incompressible inviscid flow):

$$\textit{Pressure Coefficient } C_p = \frac{p}{1/2\rho U^2}$$

$$\textit{Skin Friction Coefficient } C_f = \frac{\tau}{1/2\rho U^2}$$

The combined effect of pressure and shear stress (sometimes called skin friction) creates a resultant force on the cylinder. As shown in (Figure 9), this resultant force can be resolved into three components acting at any chosen origin C of the section:

1. A component in the direction of U, called the ***drag force***, of intensity D per unit length of cylinder.
2. A component normal to the direction of U, called the ***lift force***, of intensity L per unit length of cylinder.
3. A moment about the origin C, called the ***pitching moment***, of intensity M per unit length of cylinder.

These components may be expressed as important non-dimensional terms of drag, lift, and pitching moment coefficients for quantifying aerodynamic force measurement:

Drag coefficient (C_D)

$$C_D = \frac{D}{1/2\rho U^2 d} \qquad (1)$$

Lift coefficient (C_L)

$$C_L = \frac{L}{1/2\rho U^2 d} \qquad (2)$$

Pitching moment coefficient (C_M)

$$C_M = \frac{M}{1/2\rho U^2 d} \qquad (3)$$

In these equations, d is a suitable dimension that characterises the size of the cylinder. In (Figure 9) this is shown as the dimension measured ***across*** the cylinder, normal to U, which is the usual convention.

Drag by Wake Traverse

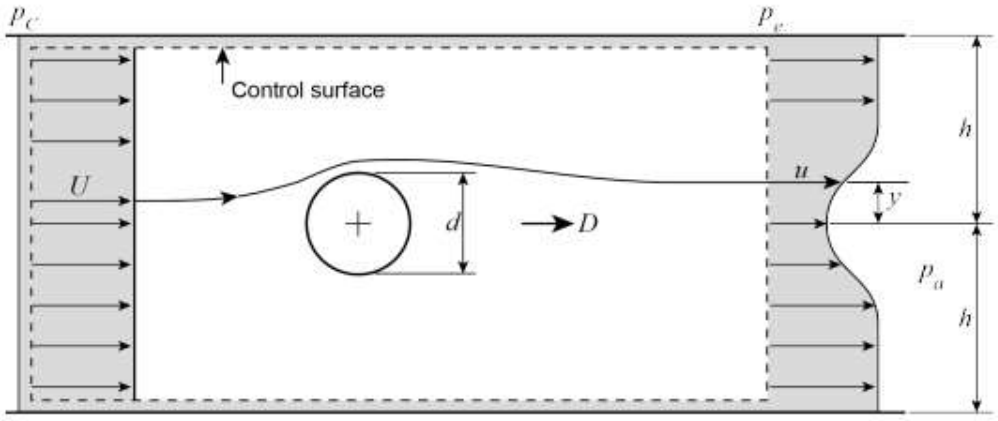


Figure 16 Flow Past a Cylinder in a Duct

A different method of finding the drag on a cylinder depends on the application of the momentum equation to the airflow. Most fluid dynamics textbooks show the standard derivation, so this guide shows a simple summary.

Consider the flow of a fluid along a duct of width $2h$ past a cylindrical body which spans the duct, so that the motion is two-dimensional as indicated in (Figure 16). The upstream velocity is U and the upstream pressure is p_C (at the contraction of the wind tunnel). Downstream of the cylinder, the velocity is no longer uniform, being slightly less directly behind the cylinder and maximum elsewhere. Let the velocity be u at distance y from the duct centre line. The pressure across the downstream section is assumed to be uniform and has the value p_E (exhaust pressure). When referring to parts of the duct, the space bounded by the upstream section, downstream section and duct walls (dotted line in (Figure 16)) is the ***control volume***. The surface formed by these boundaries is the ***control surface***.

NOTE  *Remember that when testing aerofoils, substitute the diameter of the cylinder for the chord (c) of the aerofoil.*

The forces in the direction of flow, acting on the fluid in the control volume are, per unit length of cylinder:

$2h\,p_c$ (at the upstream section)

- $2h\,p_E$ (at the downstream section)*

- D (at the cylinder)

*note the minus sign for the force exerted by the cylinder on the fluid, which is equal and opposite to the force exerted by the fluid on the cylinder. Forces due to shear stress on the wall of the duct and due to the fluid weight are neglected.

The momentum flux per unit width over the downstream section is:

$$\int_{-h}^{h} \rho u^2 dy$$

and over the upstream section is:

$$\int_{-h}^{h} \rho U^2 dy$$

Equating the net force in the direction of flow to the momentum flux out of the control volume:

$$2hp_c - 2hp_E - D = \int_{-h}^{h} \rho u^2 dy - \int_{-h}^{h} \rho U^2 dy$$

Rearranging and making dimensionless, gives the result:

$$C_D = \frac{D}{1/2\rho U^2 d} = \frac{2h}{d} \cdot \frac{p_c - p_E}{1/2\rho U^2} + \frac{2}{d}\int_{-h}^{h} \left(1 - \frac{u^2}{U^2}\right) dy$$

The integral may also be made non-dimensional by the substitution:

$$y = \eta h$$

so that:

$$\int_{-h}^{h} \left(1 - \frac{u^2}{U^2}\right) dy = h\int_{-1}^{1} \left(1 - \frac{u^2}{U^2}\right) d\eta$$

and the final result is:

$$C_D = \frac{2h}{d} \cdot \frac{p_c - p_E}{1/2\rho U^2} + \frac{2h}{d}\int_{-1}^{1} \left(1 - \frac{u^2}{U^2}\right) d\eta \qquad (10)$$

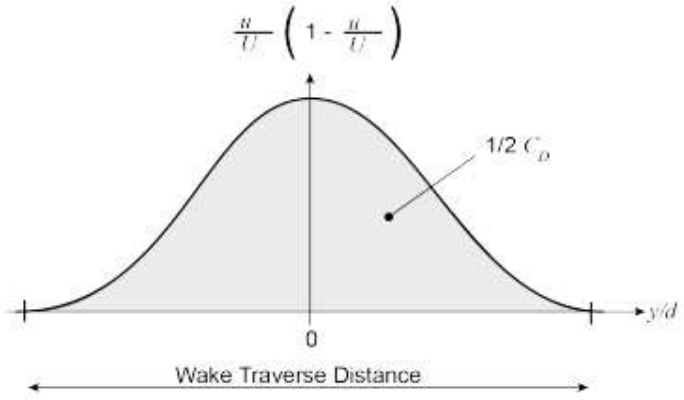


Figure 17 Wake Traverse Curve

Alternatively, as shown in (Figure 17), the area under a curve of $\left(\frac{u^2}{U^2}\left(1-\frac{u^2}{U^2}\right)\right)$ against y/d gives ***half*** the drag coefficient, so:

$$C_D = 2\int_{-y/d}^{y/d}\left(\frac{u^2}{U^2}\left(1-\frac{u^2}{U^2}\right)\right)d\frac{y}{d} \qquad (11)$$

Equation 10 allows C_D to be calculated using the pressure drop along the duct and the velocity distribution in the wake. Note that the derivation does not restrict the result to pressure drag only; the contributions of both pressure and skin friction forces are contained in the force D which comes into the momentum equation. The skin friction drag on the walls also contributes to the momentum change and is also included in D. Note that Equation 10 applies only to the case of flow along a duct where the flow is confined between parallel walls.

Equation 11 allows C_D to be calculated using the velocity ratios and the frontal diameter of the model.

Errors Caused by the Duct

In an ideal test, the wake traverse is done in a very large wind tunnel, with a large duct width-to-model ratio. This reduces any problems with boundary layers caused by the air flow along the duct walls and ensures that the area reduction caused by the model has no effect on pressures and therefore wake velocity. The models and duct in this equipment are large enough to do tests with reasonable accuracy, but their ratio is small enough to show these problems, so they can be allowed for.

The boundary effect will be noted as a slight upturn at the ends of the traverse curve. The duct area reduction caused by the model gives an overall pressure drop from the contraction (p_c) compared with the exit pressure (p_E). This gives an overall offset to the entire curve.

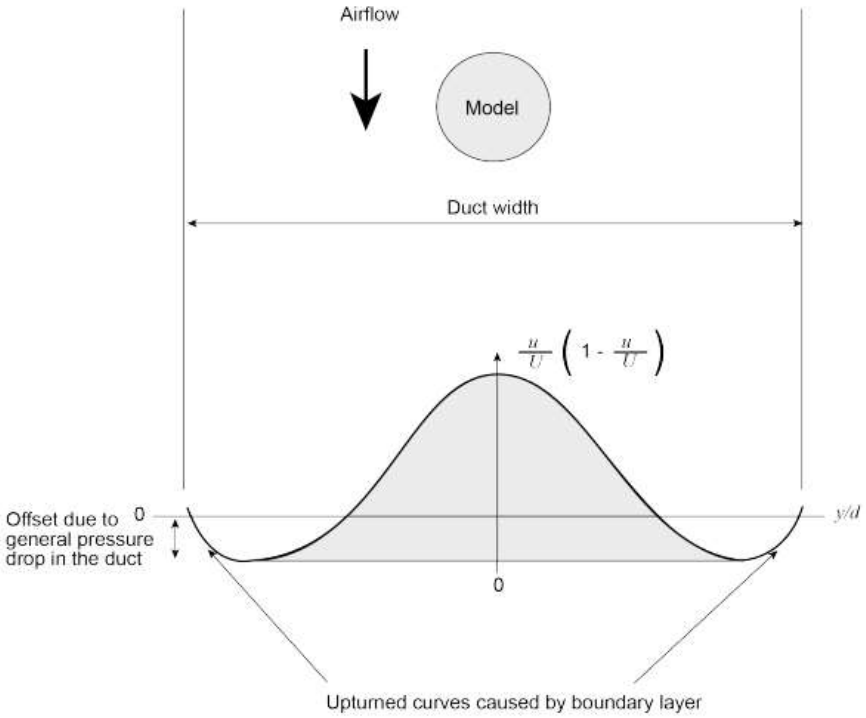


Figure 18 Errors Caused by a Duct