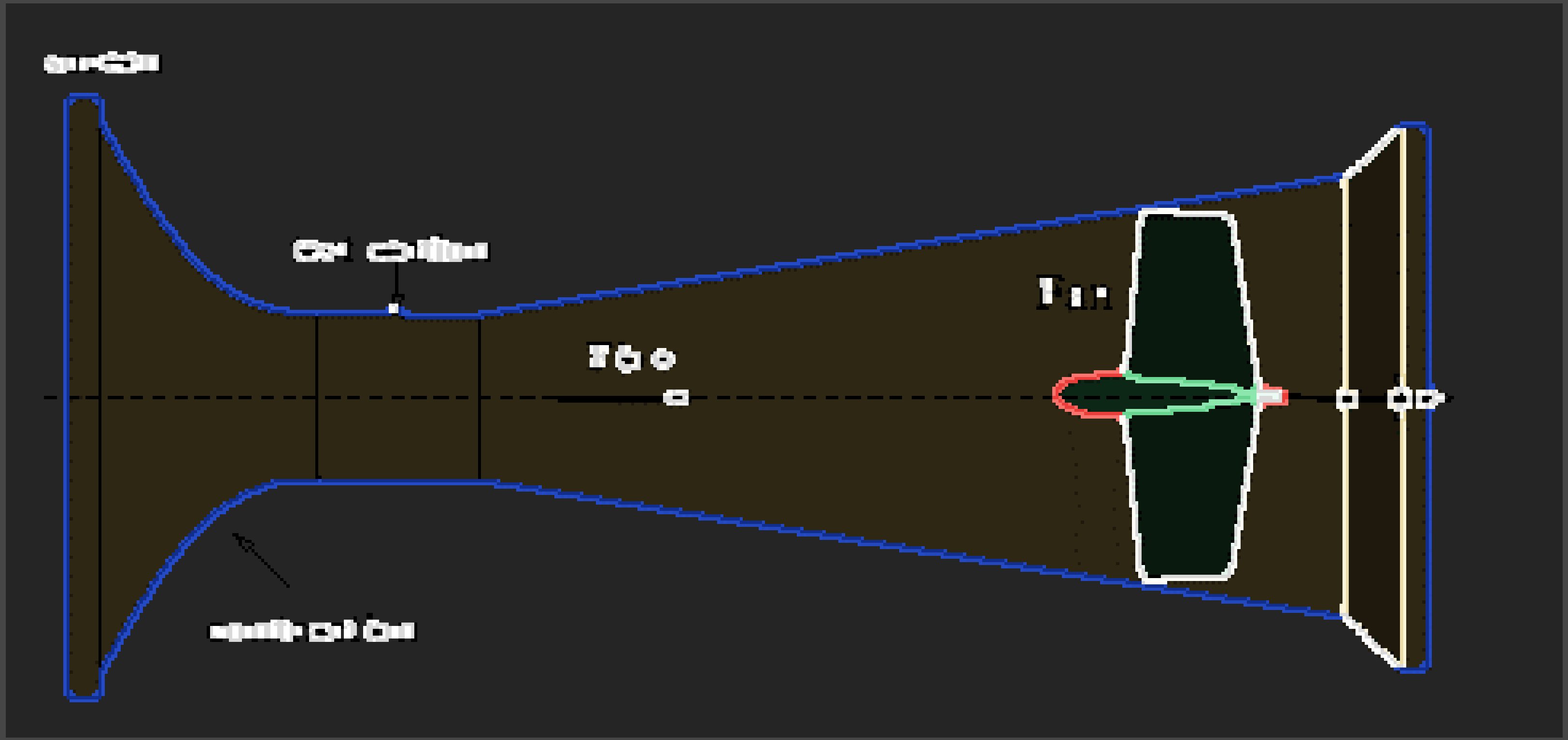


WIND TUNNELS USED IN AERODYNAMICS

TE Automotive- AABE

Wind Tunnel principles

- The loads exerted by static air on a moving body are equal to those exerted by moving air on a static body, as long as the relative velocities between the air and the body are the same in both cases.
- For a truly representative wind tunnel experiment, the body must have its true size and the wind must have the speed that the object would have if it was moving.
- These conditions are not always possible. Several scaling laws can be used in order to render representative experiments where the size or airspeed have been scaled.

Wind tunnels are used to predict the amount of force generated by solid objects.

This helps aerodynamicists choose the proper size for things such as wings, spoilers, and parachutes.

Information obtained in wind tunnels is used to improve the design of anything affected by wind.

Wind-Tunnels come in all shapes and sizes…

History of Wind Tunnels

- 1st attempts at performing aerodynamic testing was Sir George Cayley.
- Langley also used a device to aid in the development of his aerodromes.
- Da Vinci the basics of wind tunnel (fixed position, force air to flow over it)

First Wind Tunnels

- 1st wind tunnel recorded in history was developed by Francis Wenham of England.
  - Simple box with air blown through by a fan
- The 1st American wind tunnel was built at Massachusetts Institute of Technology in 1896.
- The largest in the world was built in Ames Research Center in California with a test section of 40x80

Scale Parameters

- Reynolds Number:

$$Re = \frac{\text{Inertial Forces}}{\text{Viscous Forces}} = \frac{\rho V c}{\mu}$$

- Mach Number:

$$M = \frac{\text{Inertial Forces}}{\text{Elastic Forces}} = \frac{V}{a}$$

- Strouhal Number:

$$Str = \frac{\text{Unsteady Forces}}{\text{Steady Forces}} = \frac{fc}{V}$$

$\rho =$ Air density

$V =$ Airspeed

$c =$ Characteristic length

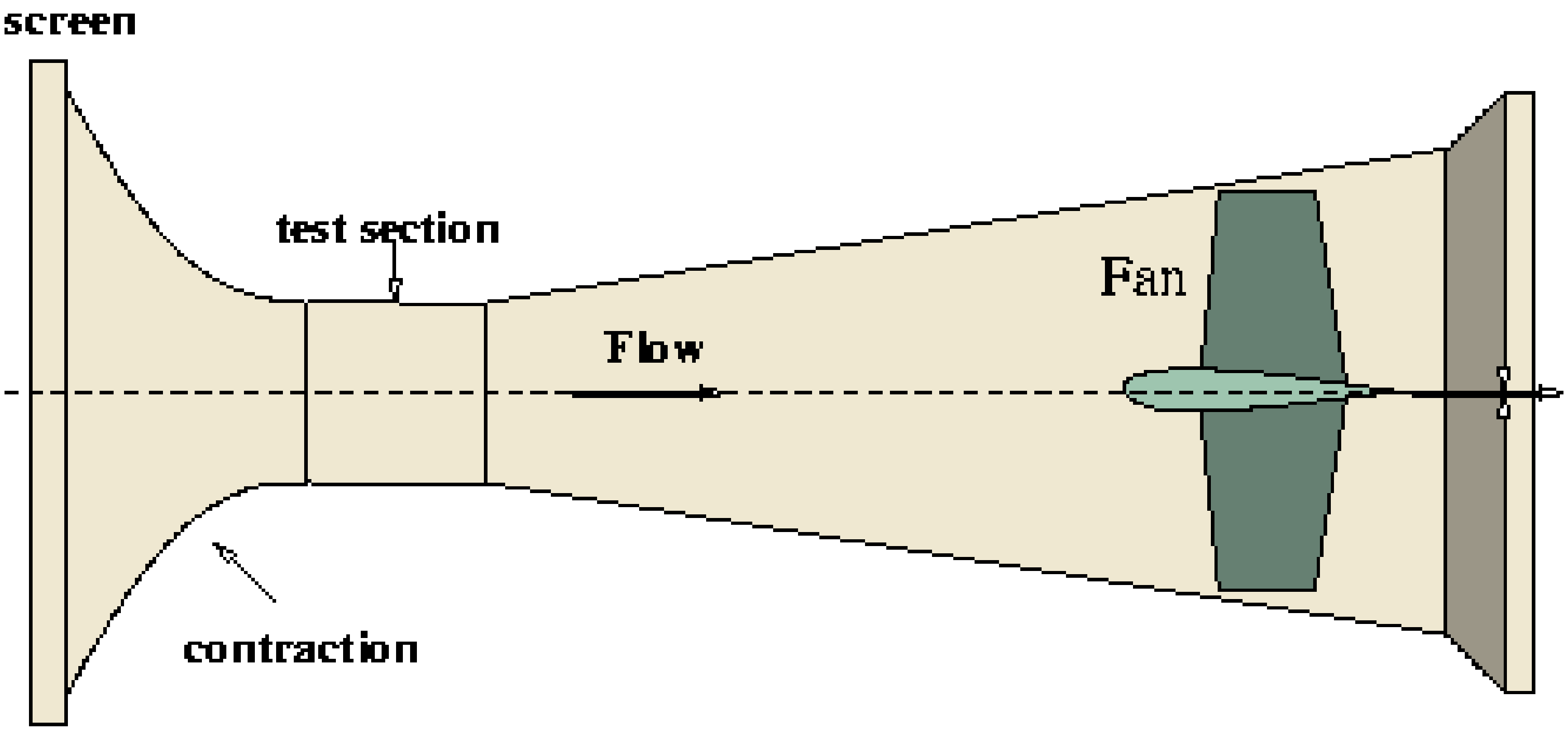
$\mu =$ Air viscosity

$a =$ Speed of sound in air

$f =$ Frequency of unsteady phenomena

- Scaling
  - Two flows are equivalent as long as all the relevant scale parameters are equal.
  - In practice it is nearly impossible to enforce all the scale parameters to be equal
  - Consider the following examples:
    - – Air flow over a real bridge deck with width of 30m and over a model of the bridge deck with width 0.3m.
    - –Air flow over a real fighter plane at $M=1.2$ at sea level and a 1/32 scale model.
  - In very expensive tunnels such problems are sometimes addressed by changing the pressure and density of the air or, even, using a heavy gas instead of air.

- Open type tunnels
- Advantages:
  - Cheaper to build
  - Pollutants are purged (e.g. smoke flow visualization or tests on internal combustion engines)
- Disadvantages:
  - The size of the tunnel must be compatible to the size of the room: the room is the return path for the air
  - Noisy
  - More expensive to run than closed type



Open-Return Type Wind-Tunnel

- Eiffel type

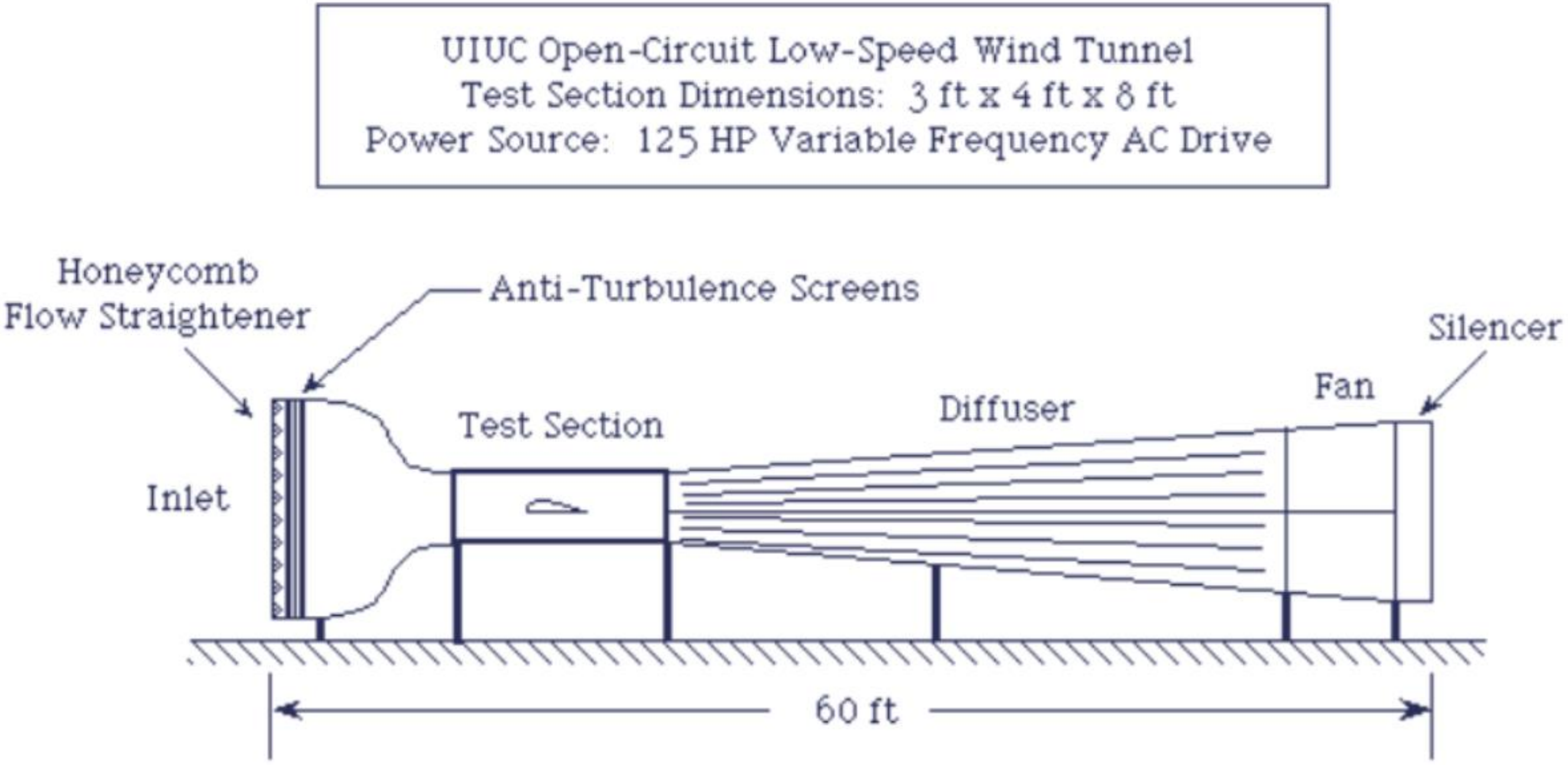
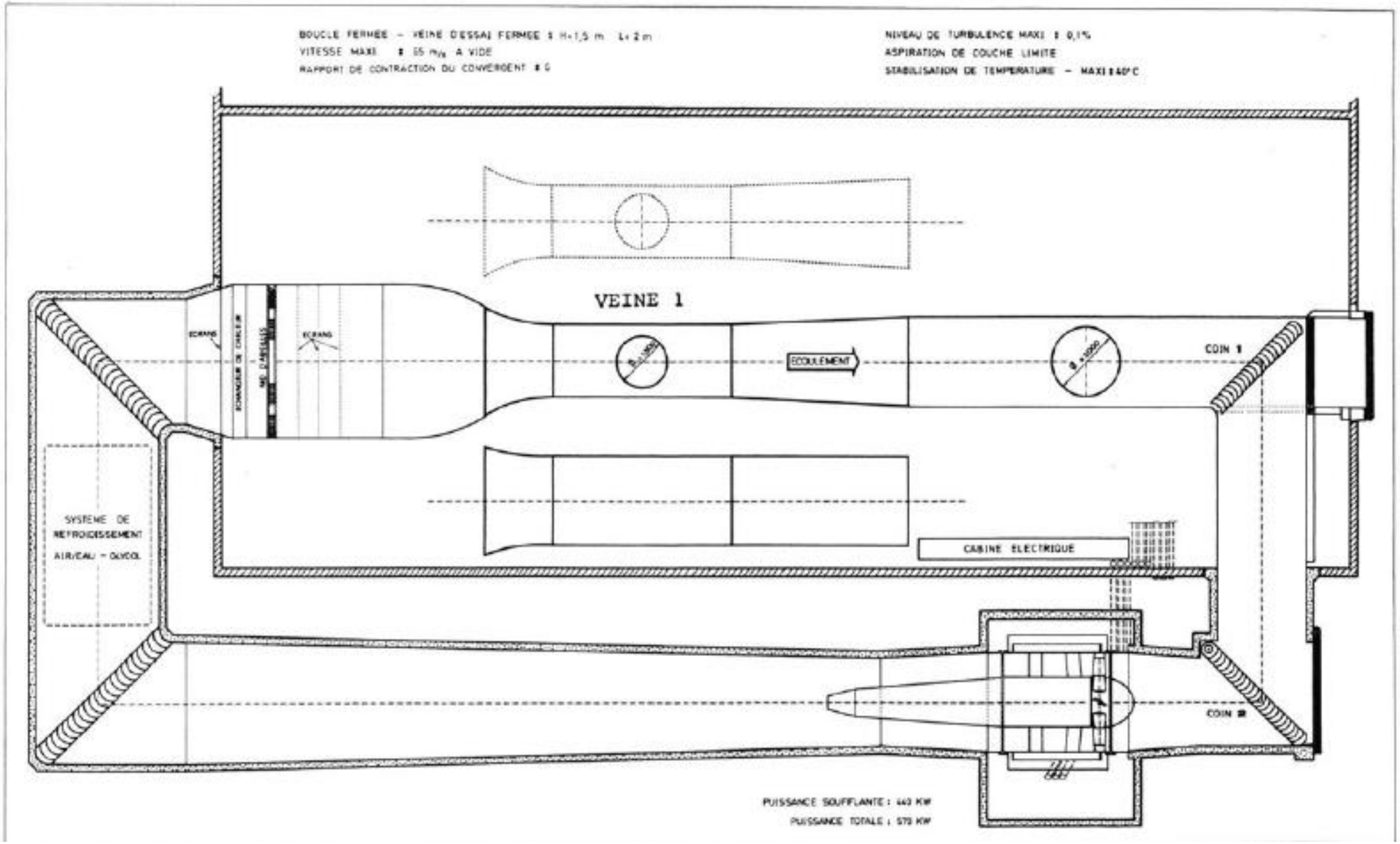
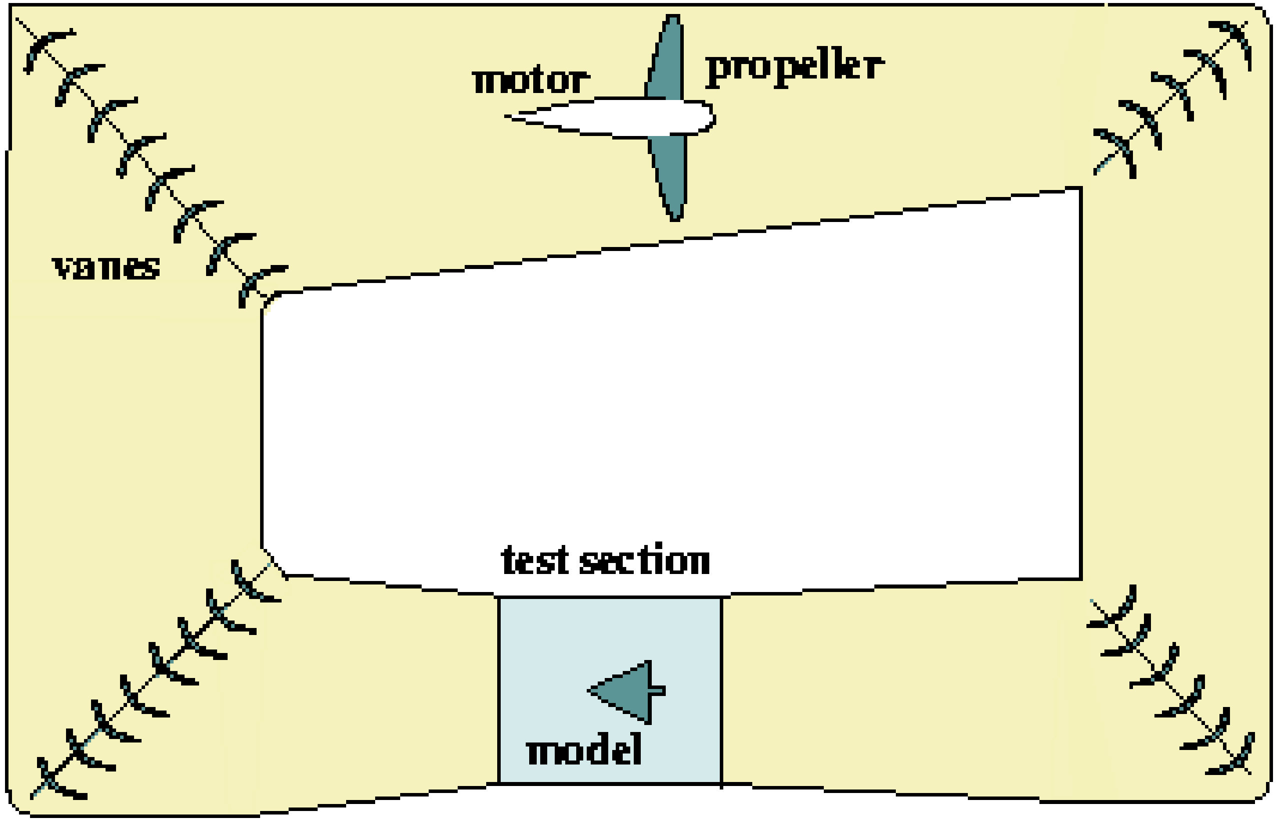


Figure 2: UIUC Open-Circuit Low-Speed Wind Tunnel

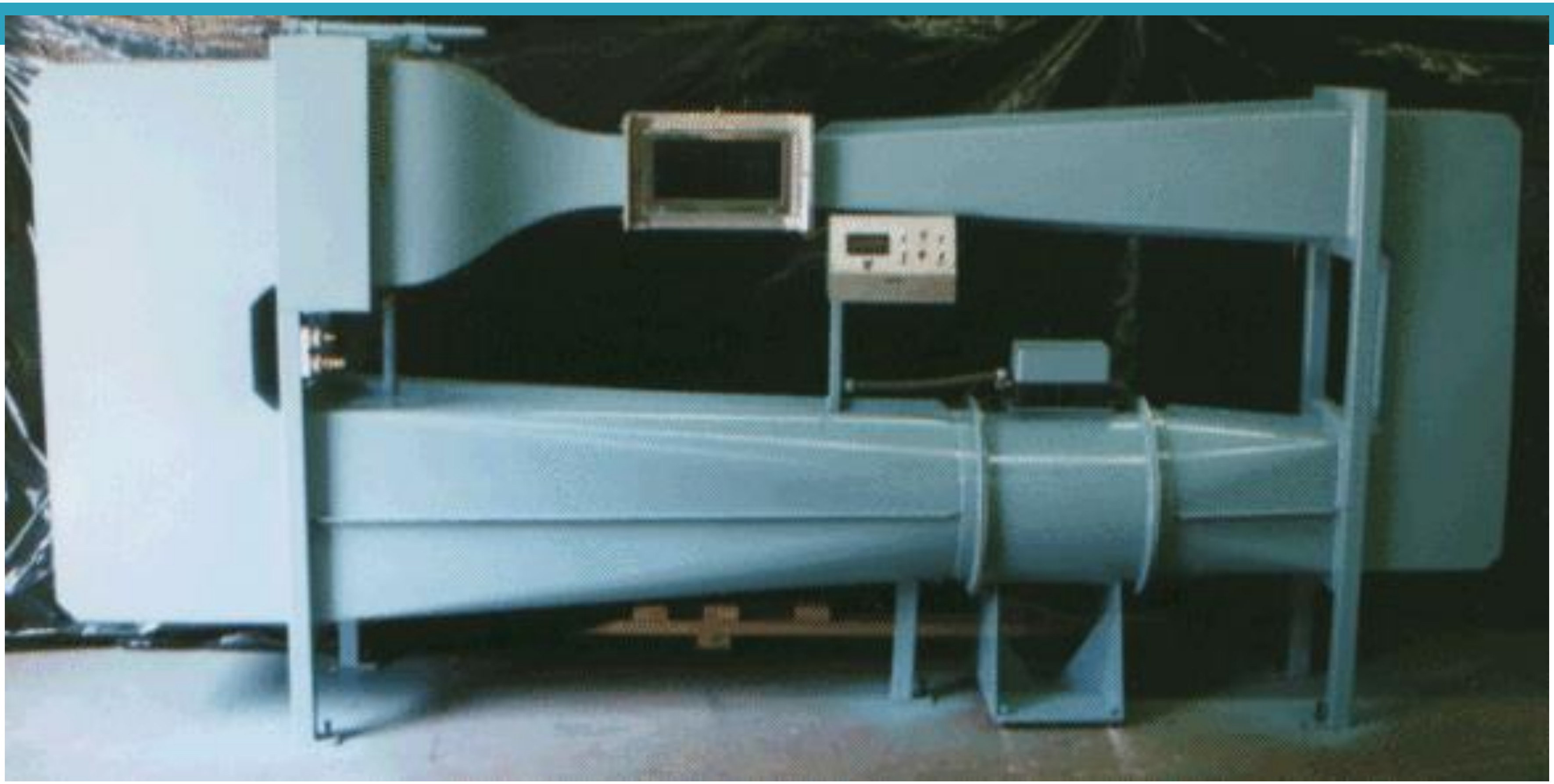
- Closed type tunnels
- Advantages:
  - Cheaper to run: energy is required only to overcome losses.
  - Less noisy than open type.
  - The quality of the flow can be easily controlled.
- Disadvantages:
  - More expensive to build
  - Not easy to purge
  - Continuous losses of energy in the tunnel heat up the air, so the air may need cooling, especially in the summer

- Gottingen type

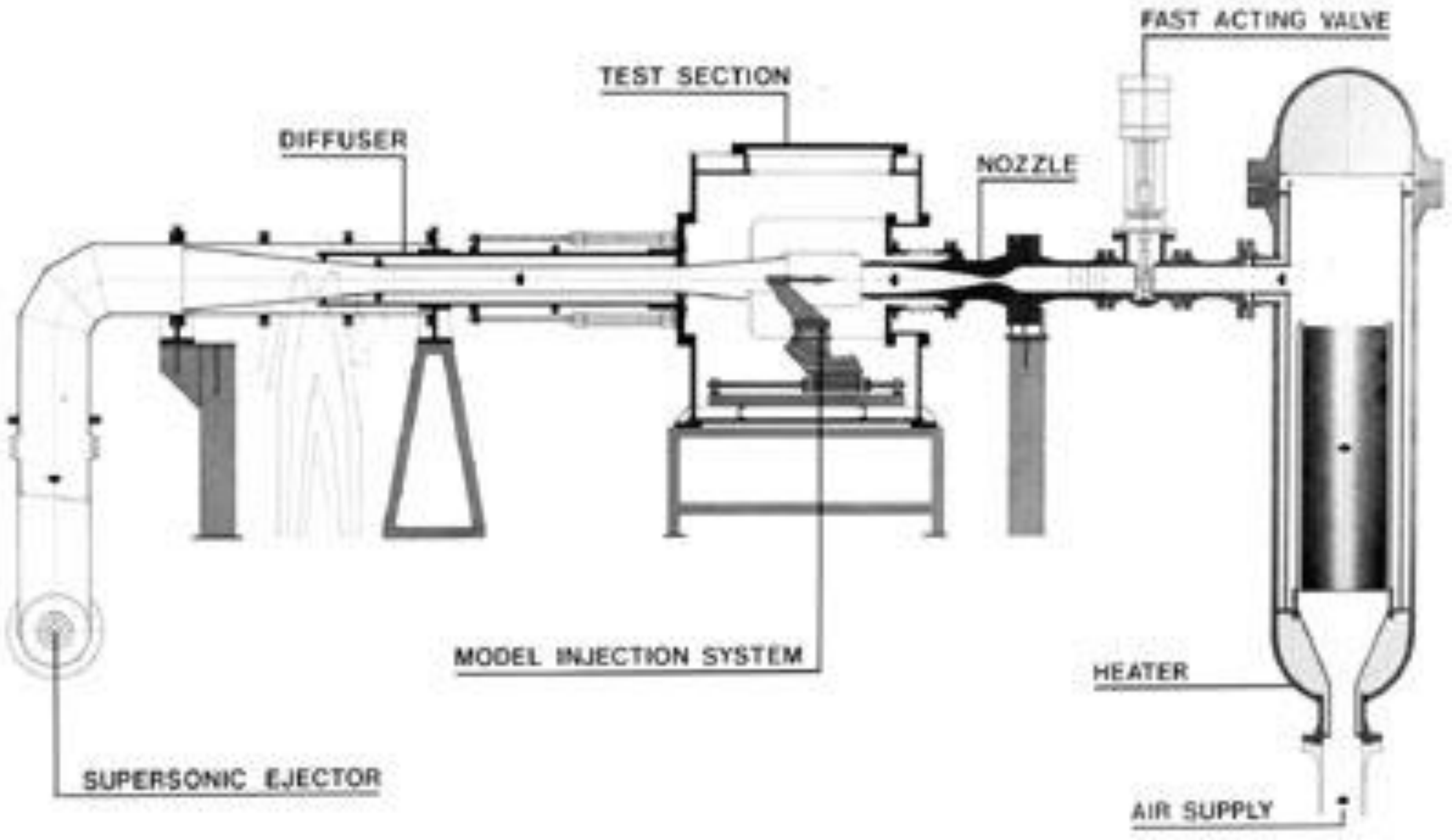




Closed-Return Type Wind-Tunnel

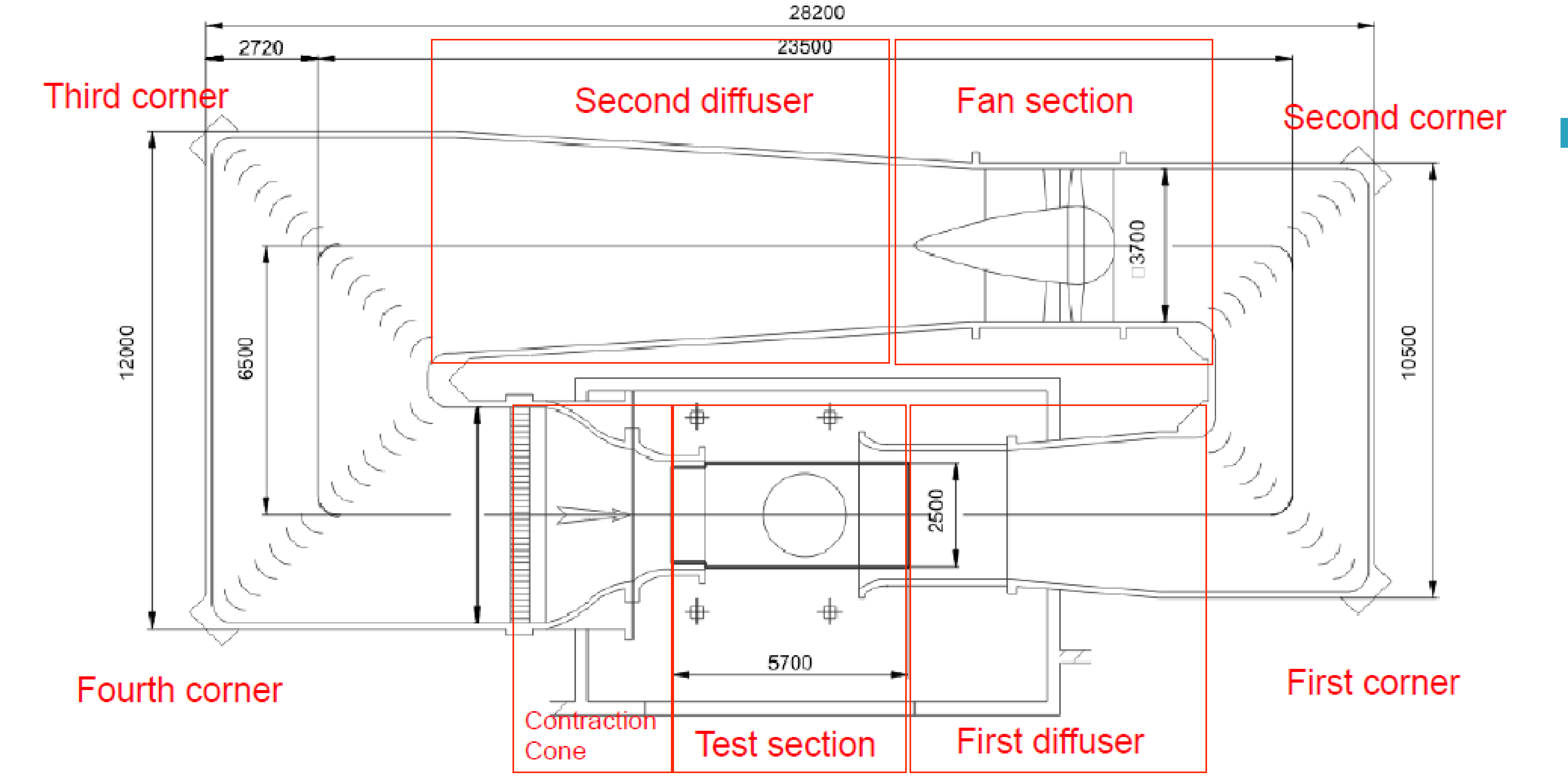


- Special wind tunnels
  - Transonic/Supersonic/Hypersonic
  - Low turbulence tunnels
  - High Reynolds number (pressurized)
  - Transonic dynamics tunnels (for aeroelastic problems, e.g. TDT at NASA Langley or T-128 at TsAGi)
  - Environmental tunnels (simulate the earth's atmospheric boundary layer)
  - Automobile tunnels (e.g. with moving floor)



Blow-Down Type Tunnel

- Wind tunnel dimensions
  - The dimensions of a wind tunnel depend on several factors:
    - Cost and space considerations
    - Speed range
    - Application area (e.g. aerospace, automotive, environmental flows etc)
    - Required Reynolds number, Mach number
    - Other requirements (e.g. STOL tests)


28200
2720
23500
Third corner
Second diffuser
Fan section
Second corner
3700
12000
6500
10500
2500
5700
Fourth corner
Contraction
Cone
Test section
First diffuser
First corner

- Test Section
  - The test (or working) section can have many cross-sectional shapes:
    - Round, elliptical, square, hexagonal, octagonal, rectangular, etc
  - The shape affects directly the cost of building the tunnel and power required to run it.
  - The shape does not affect the aerodynamic losses in the tunnel

Experimental Objectives

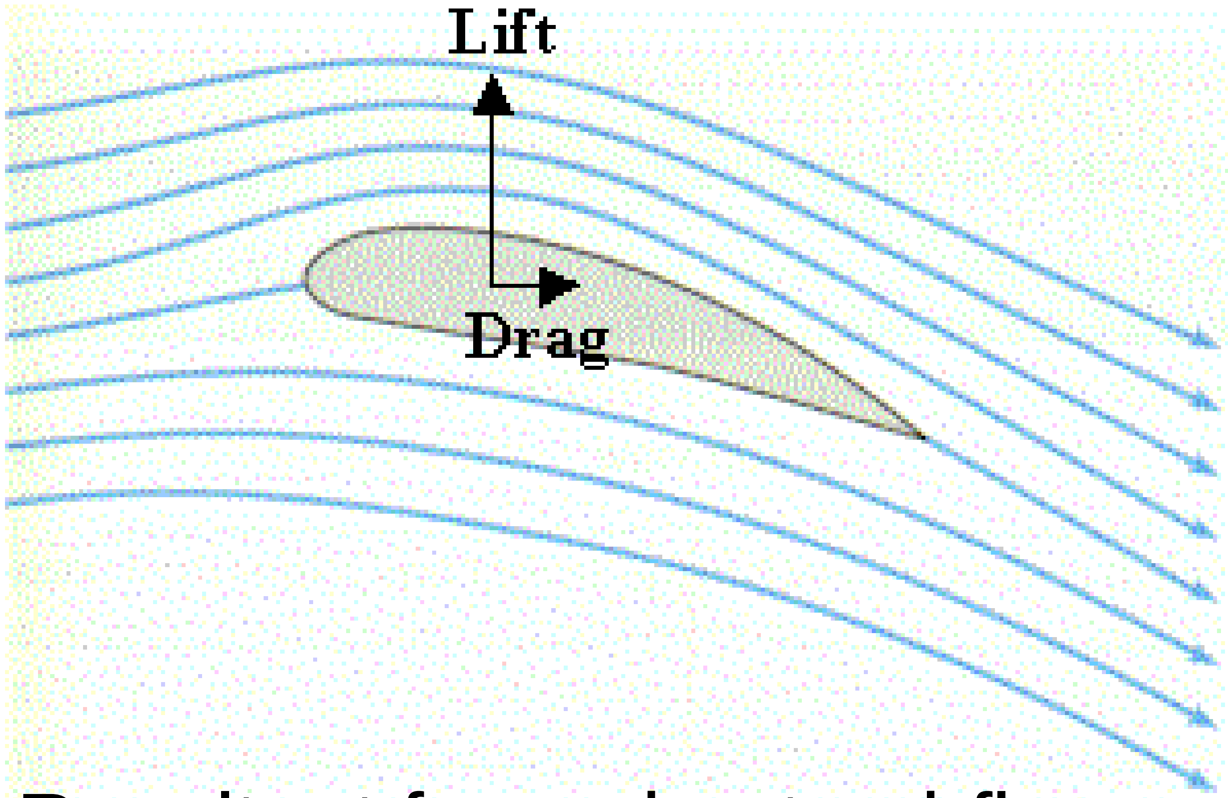
- Measure lift and drag forces
  - NACA 0012 airfoil (National Advisory Committee on Aeronautics)
  - At various angles to air stream
- Determine coefficients of lift and drag and compare to published values
- Determine coefficients of lift and drag at the stall angle

Wind Tunnel Testing

- Allows engineers to predict the amount of lift and drag that airfoils can develop in various flight conditions.

- A 747 aircraft can weigh over 200,000 lbs.

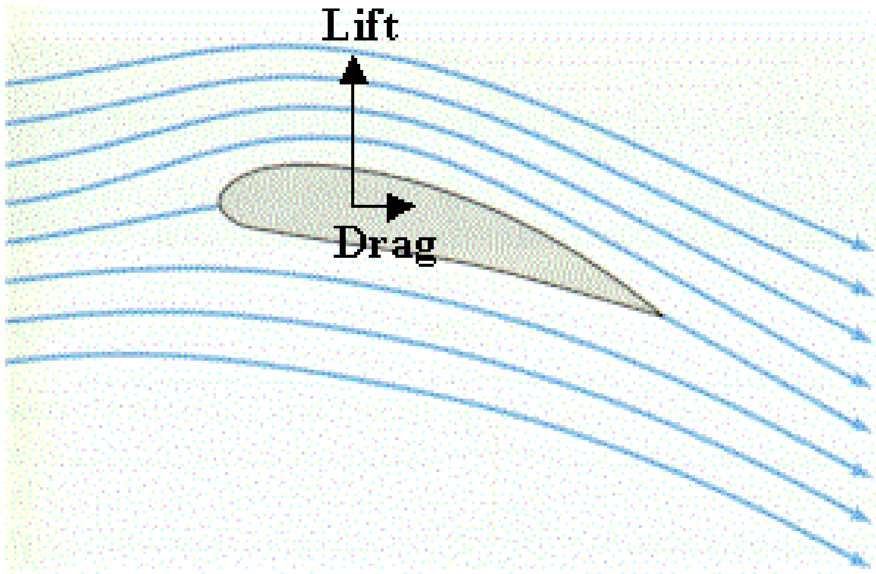
2D Components of Lift and Drag



- Resultant force due to airflow across an asymmetric body is not in the direction of the airflow

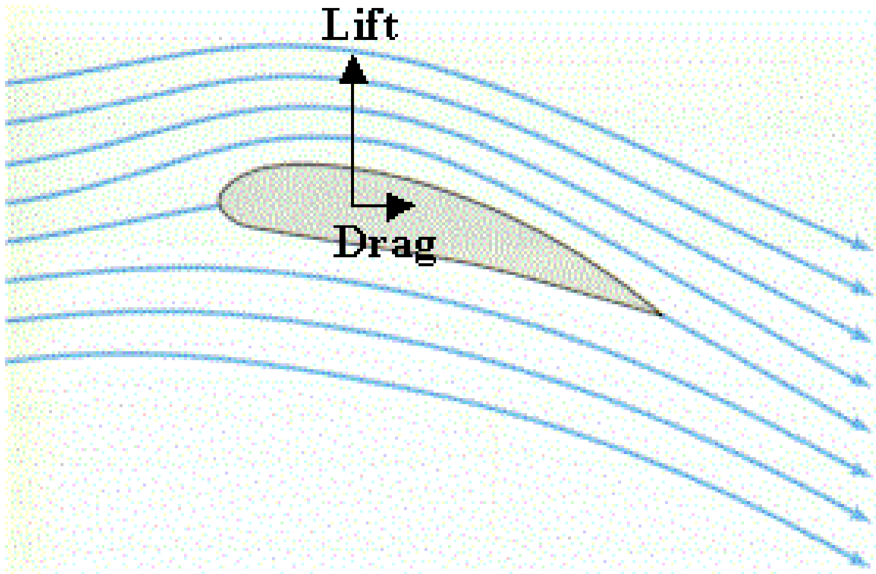
Lift

- Generated by pressure difference over the airfoil when the air moving over the body takes a different path to reach the same point



Drag

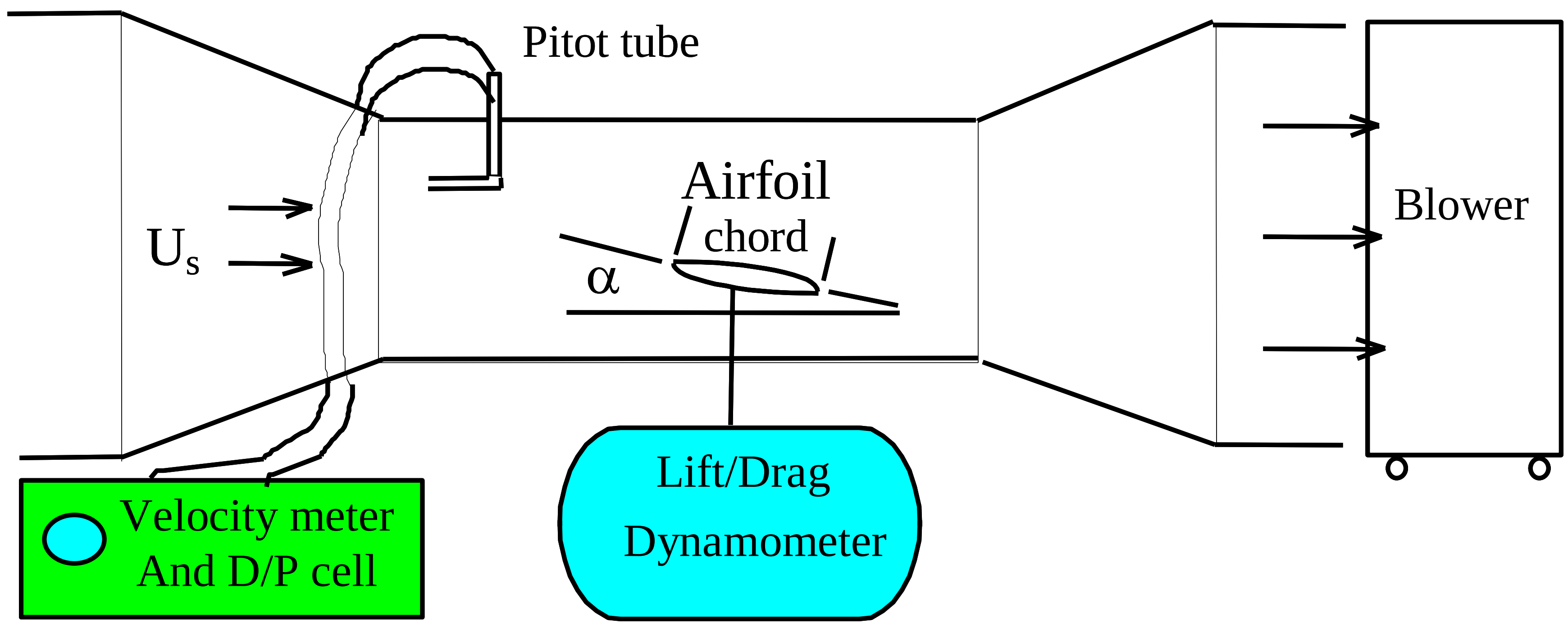
- Result of fluid friction
- Opposes body motion



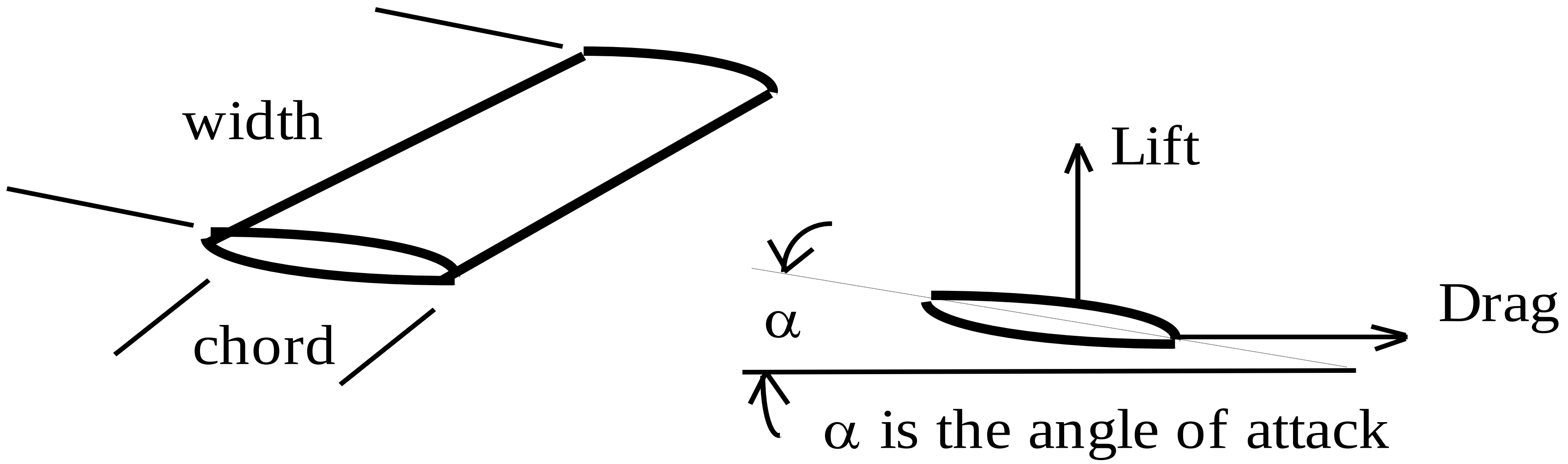
Lift and Drag Dependence

- Size
- Shape
- Fluid flow
- Principle of Similitude allows us to “non-dimensionalize”these parameters

Wind Tunnel and Instrumentation



NACA 0012 Air Foil



Scaled-down Physical Modeling

- Consider size for a given shape

$$C_{drag} = \frac{Drag\ Force}{(Dynamic\ Pressure)(Area)}$$

$$C_{lift} = \frac{Lift\ Force}{(Dynamic\ Pressure)(Area)}$$

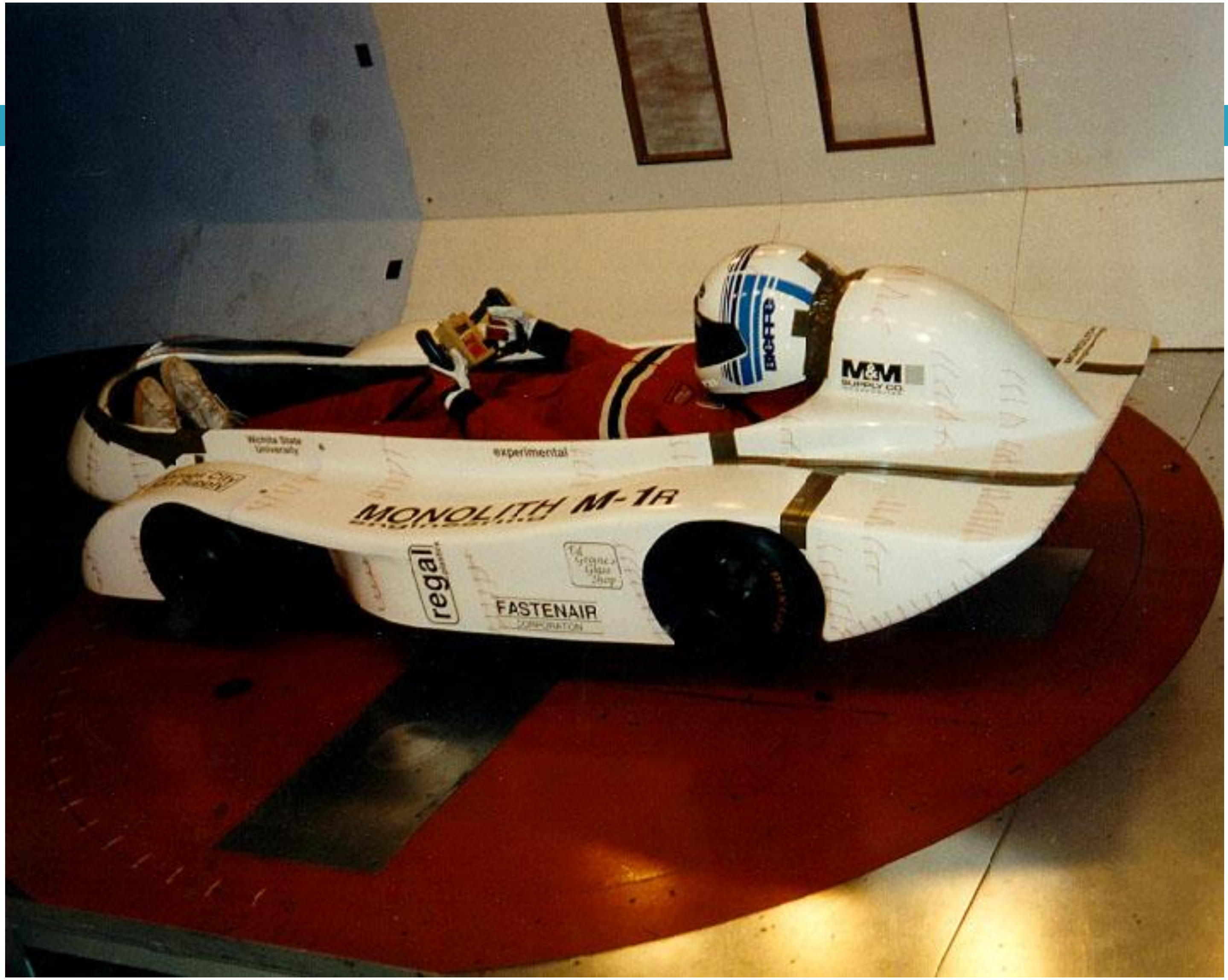
$$Area = (Chord\ Length)(Foil\ Width)$$

$$Dynamic\,Pressure = \frac{\rho_{air} u^2}{2}$$

$$\rho_{air} = 1.18 \frac{kg}{m^3}$$

$$C_{drag} = \frac{2F_{drag}}{\rho_{air} u^2 A}$$

$$C_{lift} = \frac{2F_{lift}}{\rho_{air} u^2 A}$$


MONOLITH M-1R
experimental
regal
FASTENAIR
M&M

Increase in Area :

For subsonic flow ($M < 1$)

velocity decreases & pressure increases

For supersonic flow ($M > 1$)

velocity increases & pressure decreases

M = Mach
V = velocity
p = pressure
A = area

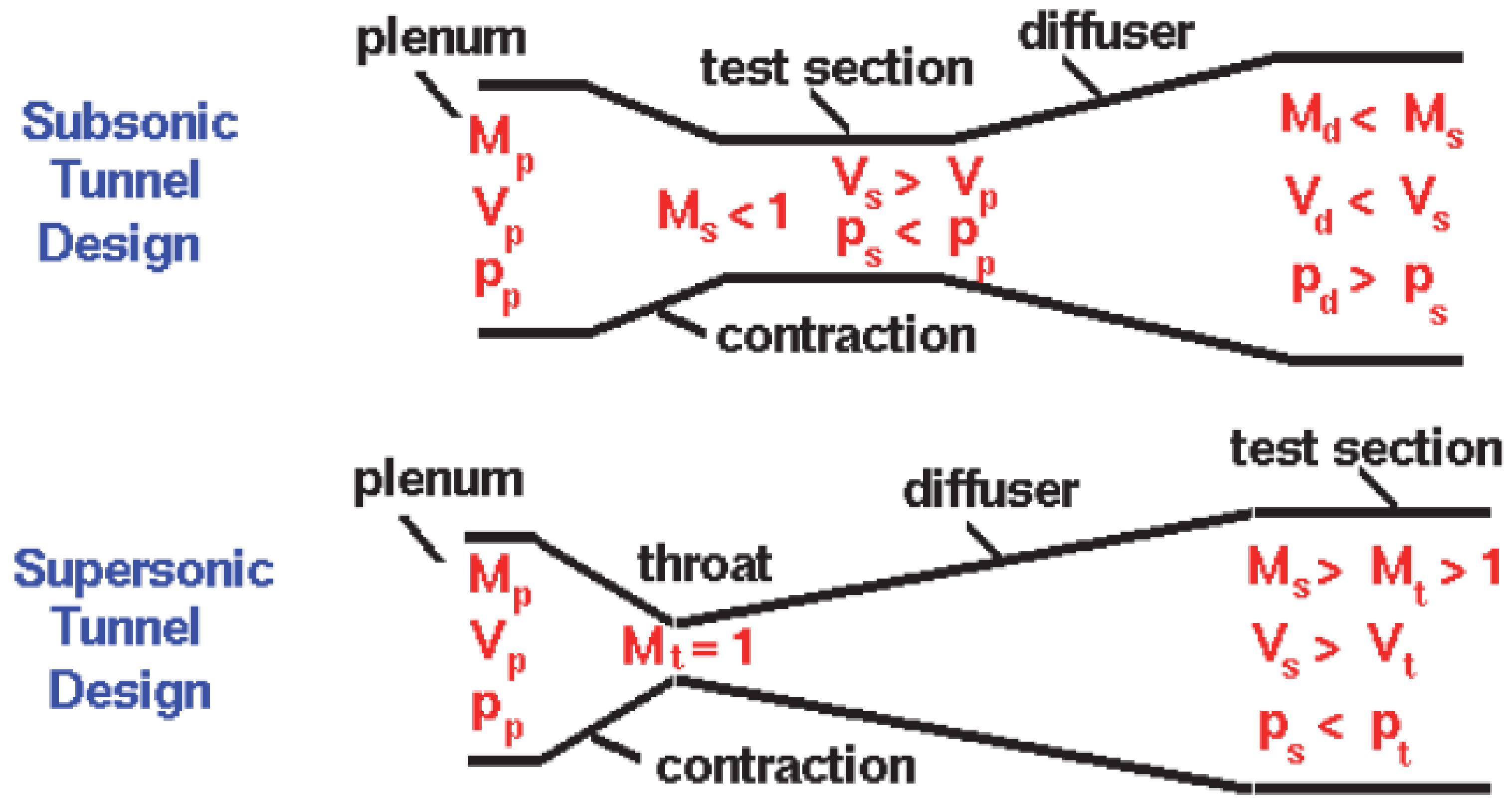


Fig. 3. Schematic designs of subsonic and supersonic wind tunnels (NASA).

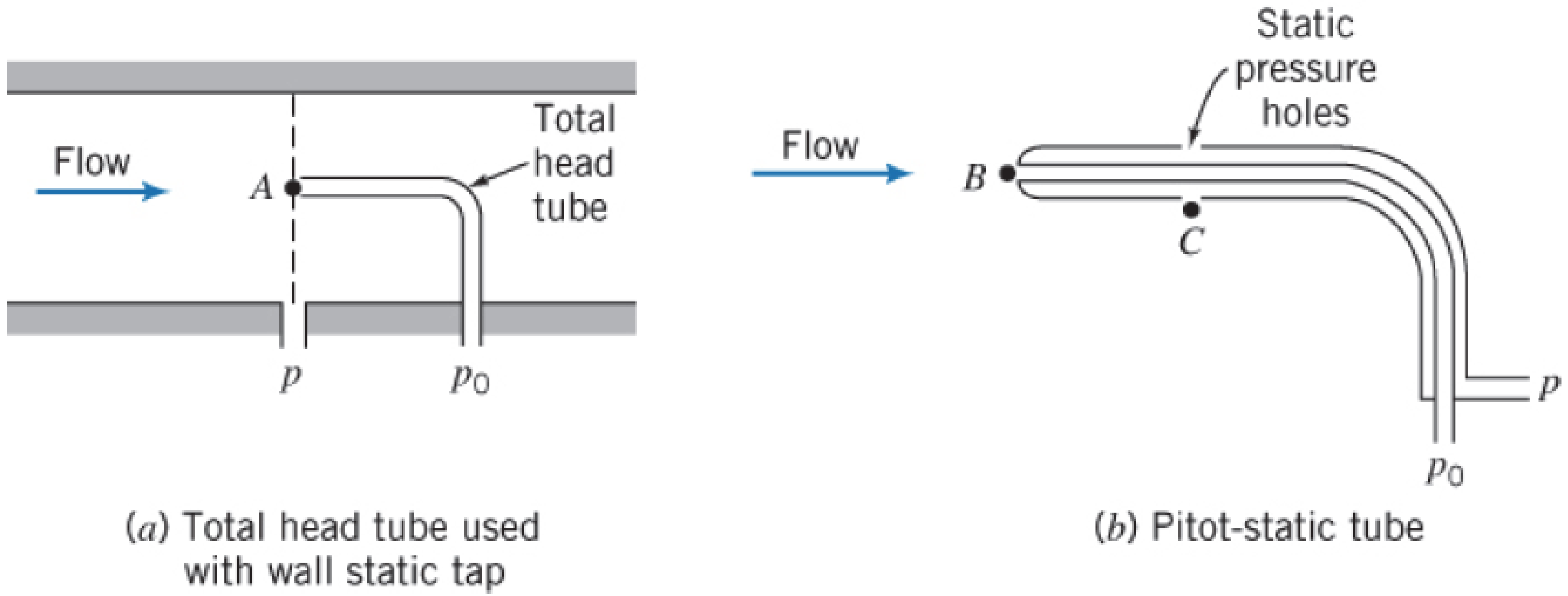


Fig. 6. Two different ways to measure the total and static pressures inside the test section (Pritchard, 2011).

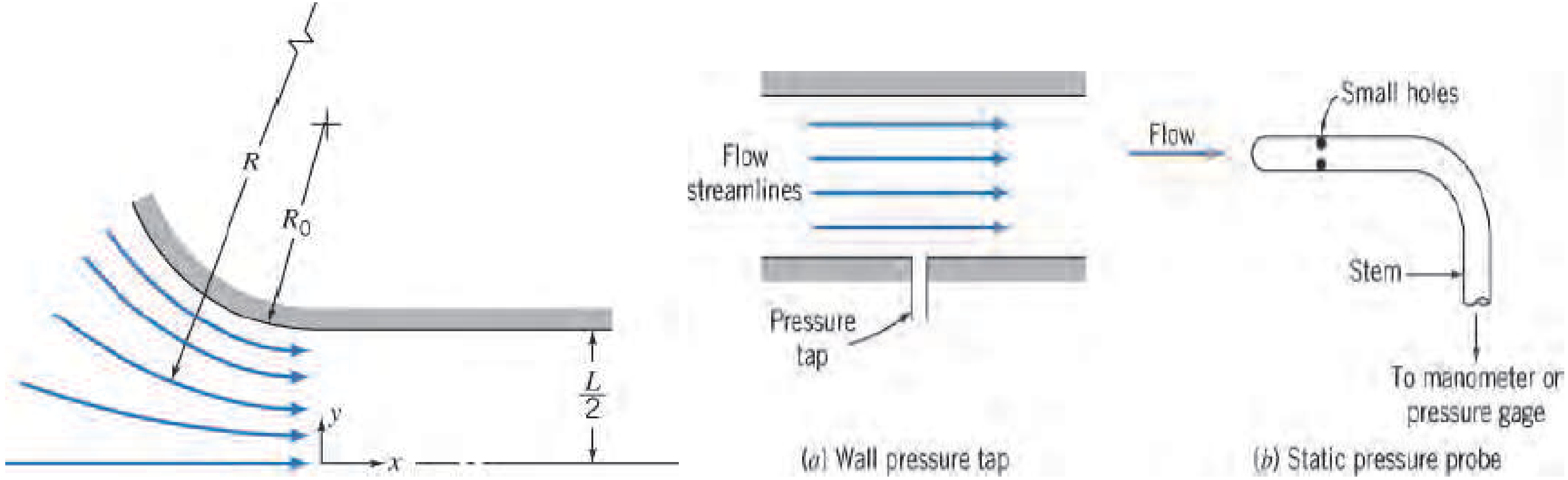


Fig. 7. Illustration showing that the radius of curvature becomes very large inside the test section (Pritchard, 2011).

$$\rho\left(\frac{V^2}{R}\right)=\frac{\partial p}{\partial n}\Rightarrow\frac{1}{\rho}\frac{\partial p}{\partial n}=\frac{V^2}{R};. \qquad (2)$$

$$Parallel-flow:\Rightarrow R\to\infty,\frac{\partial p}{\partial n}\to 0$$

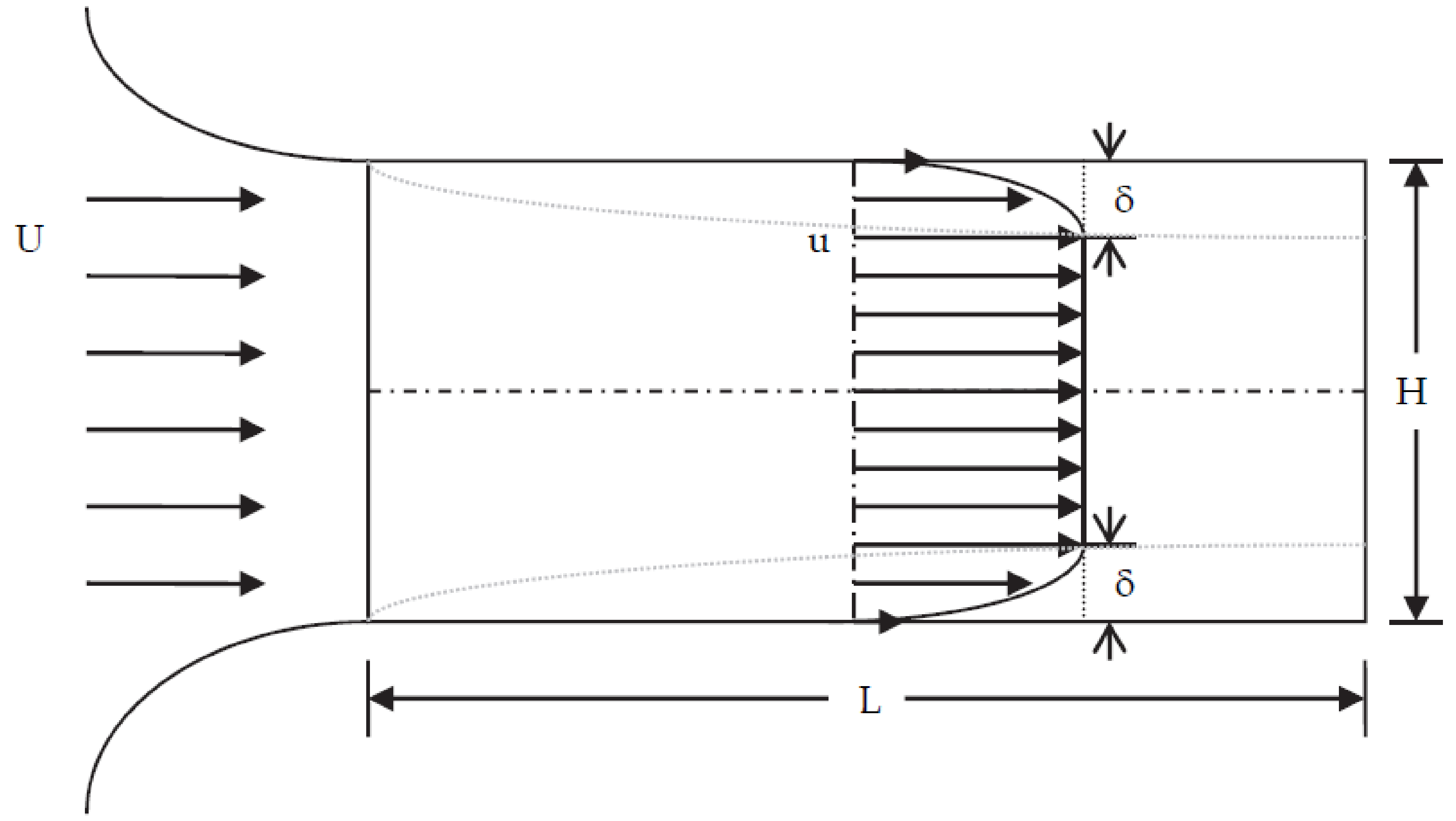


Fig. 9. Graphical Representation of Boundary Layer Theory in Wind Tunnel Test Section

4.2.3 Experimental procedure

- The experimental procedure consists of the following steps:
  - 1. Choose a vertical plane in the test section.
  - 2. Choose a vertical line within that vertical plane.
  - 3. Select a series of points along that vertical line where the velocity of the air will be determined.
  - 4. Read the temperature and the pressure inside the lab, or inside the wind tunnel, or both.
  - 5. Use these values to compute the mass density of air inside the lab using the ideal gas law. Or Use these values to look up the mass density of air on a Table.
  - 6. Select a wind speed and set the wind tunnel to generate that wind speed inside the test section.
  - 7. Use the wind tunnel at that set speed to measure the pressure difference, $p0 - p$, at each point that was identified along the preselected vertical line. This process is known as traversing a cross section of the flow space.
  - 8. Use Energy Eq. to compute the speed of the air at each such point.

- **Experimental determination of lift and drag forces on an airfoil**
  - **Purpose**
    - To measure the lift and drag of several different airfoils using a force balance and a subsonic wind tunnel, and compare the results to published data and theoretical expectations.
  - **Key equations**
    - The lift coefficient, CL, is given by
    - Where FL is the lift force, V is the average speed, and A is the reference area.
    - The drag coefficient, CD , is given by

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \qquad C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}$$

Irregularities of flow in low speed tunnels

1) Spatial non uniformity ® Mean velocity not be uniform over a cross section. This is overcome by transferring excess total head from regions of high velocity to those of low velocity.

2) Swirl ® Flow may rotate about an axis resulting in variation of direction of flow. Flow straightness and honey combs are used to reduce swirl.

3) Low frequency pulsation ® These are surges of mean velocity. Under their influence, time taken for steady conditions becomes excessive. It is difficult to locate the source of such pulsations.

4) Turbulence ® Turbulence generates small eddies of varying size and intensity and results in time variations of velocity. Turbulence may be defined as irregular fluctuations of velocity superimposed on mean flow.

- In order to quantify turbulence:
- Take components of mean velocity as U, V, W
- Those of turbulent velocity u, v, w

RMS values $\sqrt{(\overline{u})^2}, \sqrt{(\overline{v})^2}$ and $\sqrt{(\overline{w})^2}$ are denoted as u', v', w'

Intensity of turbulence = $\frac{u'}{V_0}$ or $\frac{v'}{V_0}$ or $\frac{w'}{V_0}$ where, V_0 is the mean of U, V, W

Scale of turbulence $L = \int_0^\infty R_y \, d_y$

where R is the coefficient of co-relation between the longitudinal component of turbulent velocity at A and that at another point B distant y from it.

$$R_y = \frac{\overline{u_A u_B}}{u'_A u'_B}$$

- **The diffuser**
- The diffuser in the wind tunnel serves the purpose of recovering the kinetic energy of flow in the test section as pressure energy. A well designed diffuser does this efficiently. In subsonic wind tunnels, the diffusers are diverging passages with a semi divergence angle of about 7.5 to 8.0 degrees. The Bernoulli's equation written in differential form in the context of a diffuser is as follows:

$$d\left(\frac{V^2}{2}\right) + \frac{dp}{\rho} = 0$$

- This implies that for a decrease of kinetic energy per unit mass, there is a corresponding increase in pressure energy. The pressure gradient in a subsonic diverging passage is adverse. It is difficult to avoid boundary layer thickening and flow separation. Hence, the conversion of kinetic energy into pressure energy is never fully efficient.

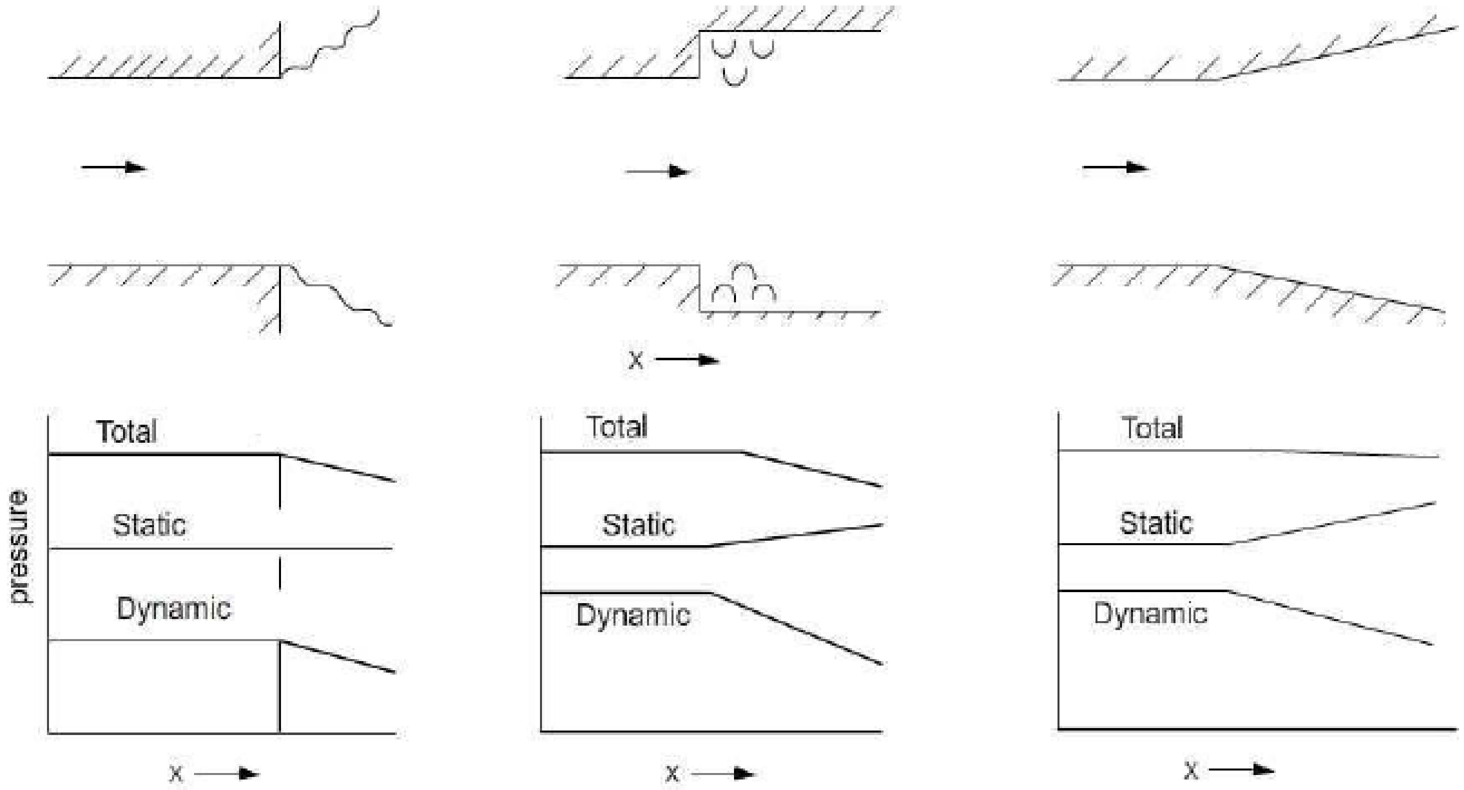


Fig.1.6 Exit pressure profile of jet through different passages

There are two definitions of diffuser efficiency

(a) Polytrophic efficiency (η_D)

$$\eta_D = \frac{p_2 - p_1}{\frac{1}{2}\rho v_1^2 - \frac{1}{2}\rho v_2^2}$$

Use continuity equation to write the above equation as

$$\eta_D = \frac{p_2 - p_1}{\frac{1}{2}\rho v_1^2\left[1-\left(\frac{A_1}{A_2}\right)^2\right]}$$

where subscripts '1' and '2' refer to conditions at the entry and exit of the diffuser.

As explained before, the equation is indicative that from kinetic energy to pressure energy it is not fully converted. Loss of total head in the diffuser action:

$$\Delta H = \left(\frac{1}{2}\rho v_1^2 - \frac{1}{2}\rho v_2^2\right) - (p_2 - p_1)$$

$$\eta_D = 1 - \frac{\Delta H}{\frac{1}{2}\rho v_1^2\left[1-\left(\frac{A_1}{A_2}\right)^2\right]}$$

(b) Isentropic efficiency

Isentropic Efficiency (η_σ) is defined as the ratio of

$$\eta_\sigma = \frac{\text{Kinetic energy which would have to be transformed to produce the observed pressure recovery}}{\text{Kinetic energy actually transformed}}$$

$$\left(\frac{p}{\rho^\gamma}\right) = \text{constant for an isentropic process}$$

KE to be transformed to raise pressure from p_1 to p_2 $= \int_{P_1}^{P_2} \frac{dp}{\rho}$

$$\int_{P_1}^{P_2} \frac{dp}{\rho} = \frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}-1\right]$$

$$\eta_\sigma = \frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}-1\right]$$

$$\frac{p_2}{p_1} = \left[\frac{(\gamma-1)M_1^2}{2}\eta_\sigma+1\right]^{\gamma/\gamma-1}$$

$$\frac{p_1}{H} = \frac{p_1}{p_{01}} = \left[\frac{2}{2+(\gamma-1)M_1^2}\right]^{\gamma/\gamma-1}$$

Overall pressure ratio $\frac{p_{01}}{p_2} = \frac{H}{p_2}$. Here p_2 corresponds to the pressure at the exit of the diffuser and H represents the stagnation pressure p_{01} at the entry to the wind tunnel.

$$\frac{H}{p_1} \times \frac{p_1}{p_2} = \left[\frac{2+(\gamma-1)M_1^2}{2+(\gamma-1)M_1^2 \eta_\sigma} \right]^{\gamma/\gamma-1}$$

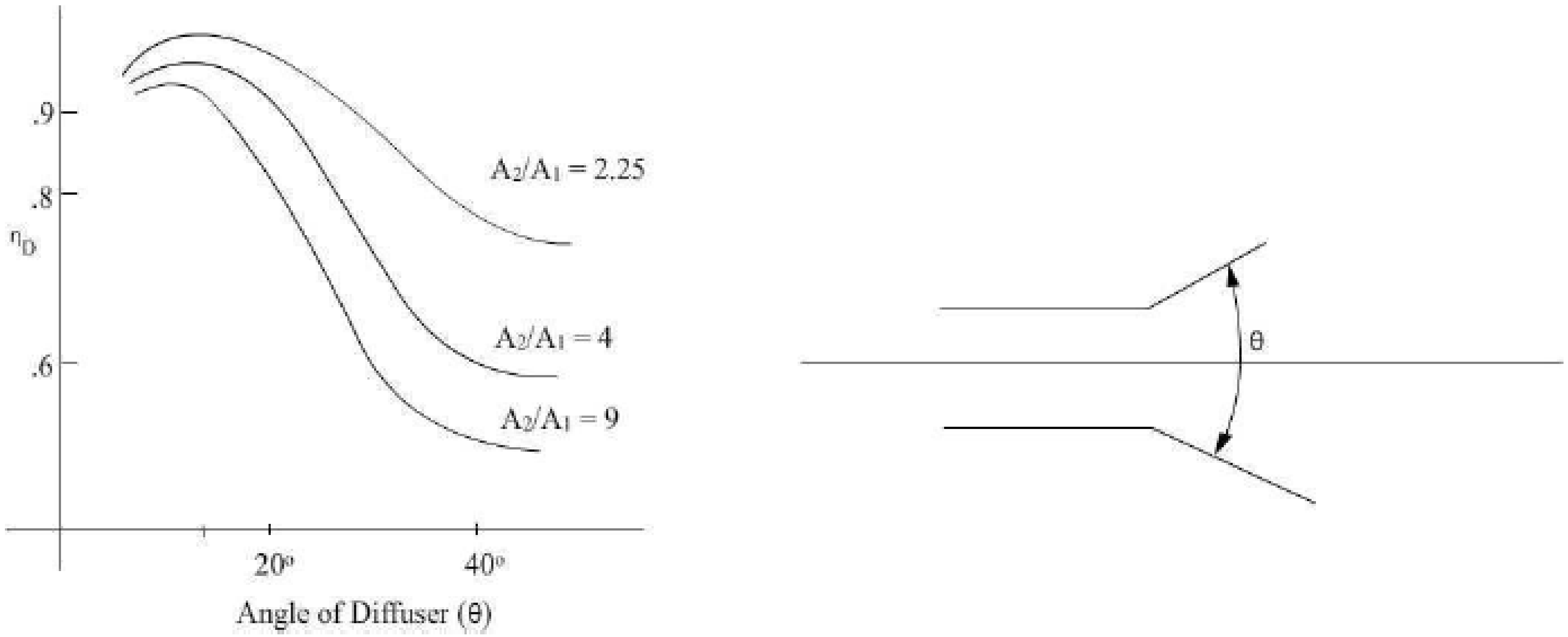


Fig.1.7 Diffuser efficiency as a function of diffuser angle

1.5 Losses in the wind tunnel circuit

- Losses are due to:
  - Inefficiency of drive unit
  - Skin friction, separation etc
  - Loss of kinetic energy at the diffuser exit
  - Shocks in the case of supersonic wind -tunnels

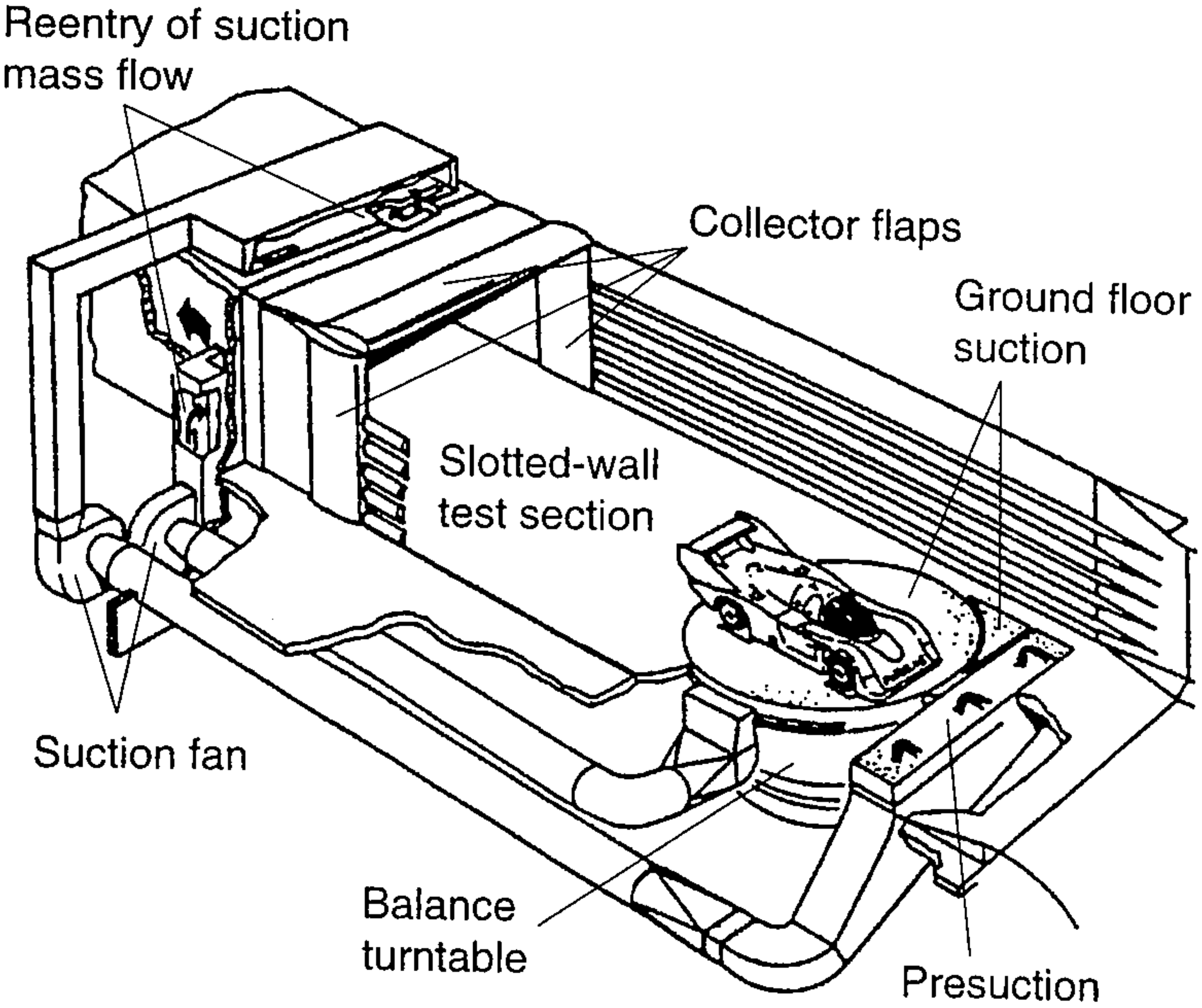
Losses due to skin friction

$$\text{Local coefficient of skin friction} = \frac{\text{Frictional force}}{\frac{1}{2}\rho v^2 A'}$$

where, A' is the surface area of the solid boundary which is subjected to frictional force.

$$\Delta H = \int C_f \frac{1}{2}\rho v^2 \frac{L}{A} dS$$

Fig. 3-19. *Three-quarter view of the slotted-wall test section in the Porsche wind tunnel (Weissach, Germany). Reprinted with permission from SAE Paper 920346 Copyright ©1992 SAE, Inc.*



Example for Wind Tunnel Corrections Wind tunnel wall corrections are used to modify the data so that it will be closer to the open air condition. Most of these wall correction methods are based on the ratio between the model frontal area A and the wind-tunnel test-section (or open jet) cross-section area C. For example, one of the simplest formulas for the blockage correction in a closed test section is (from Ref. 3.6, p. 371):

Eq. 3.3

$$\frac{(1/2\rho V_\infty^2)_c}{(1/2\rho V_\infty^2)_m} = \left(1 + \frac{1}{4}\cdot\frac{A}{C}\right)^2$$

Here the correction is applied to the dynamic pressure $1/2\rho V_\infty^2$ (defined in Eq. 2.7) and the subscript c stands for *corrected* and m for *measured*, respectively. This correction can be applied to any aerodynamic coefficient and, for example, when applied to the lift coefficient (Eq. 2.14) we can write that

Eq. 3.4

$$C_{L_c} = C_{L_m}\left[\frac{1}{\left(1 + \frac{1}{4}\cdot\frac{A}{C}\right)^2}\right]$$

Table 3.1 Typical Frontal Area of Some Sports and Race Cars

Vehicle Type	Frontal Area A
Open Wheel (F-1, Indy)	1.5 m^2
Sports Cars (IMSA GTO)	1.7 m^2
Prototype (IMSA GTP)	1.8 m^2
Production (Porsche 928s)	1.9 m^2

B

Vehicle in wind tunnel

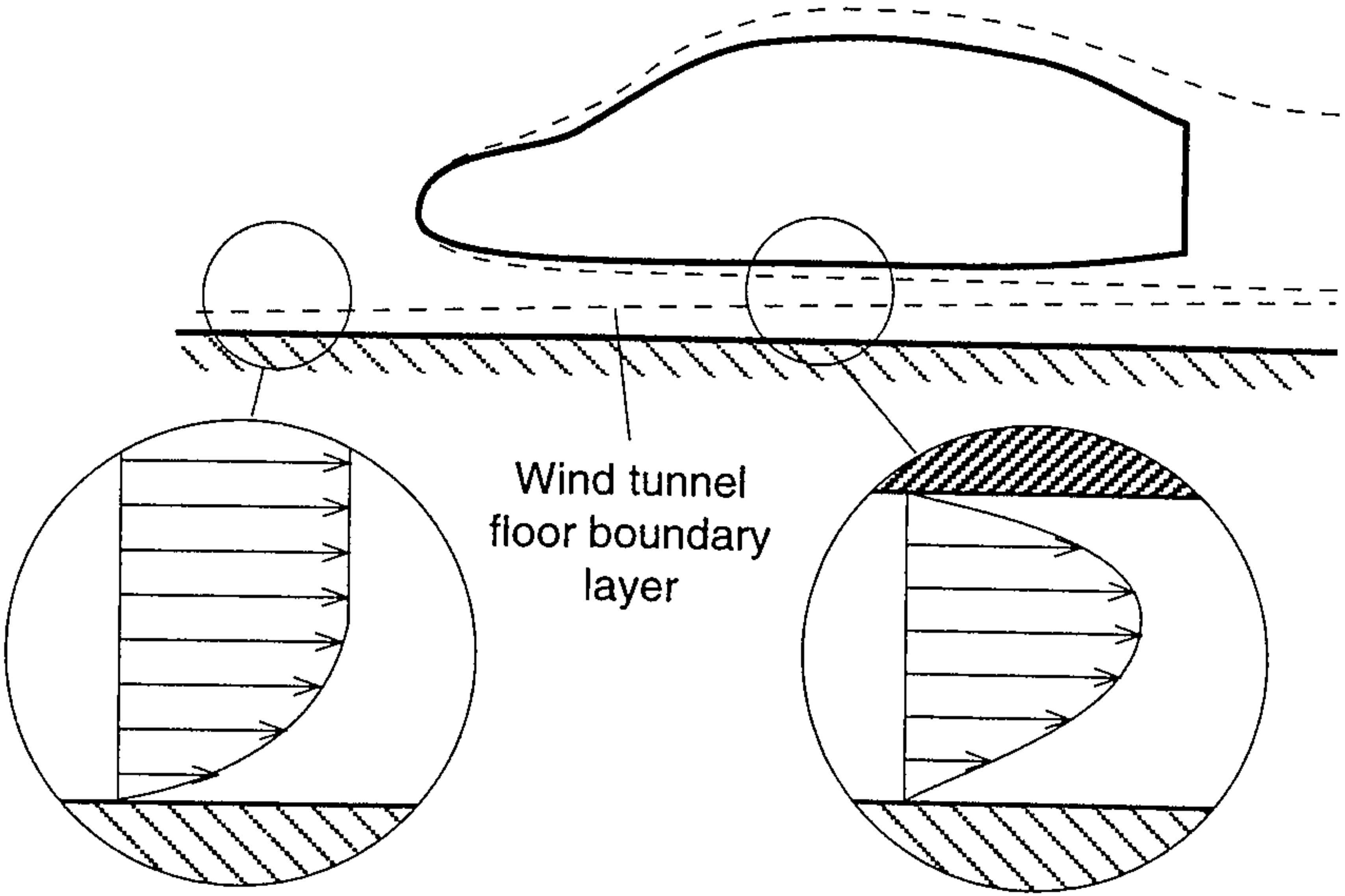
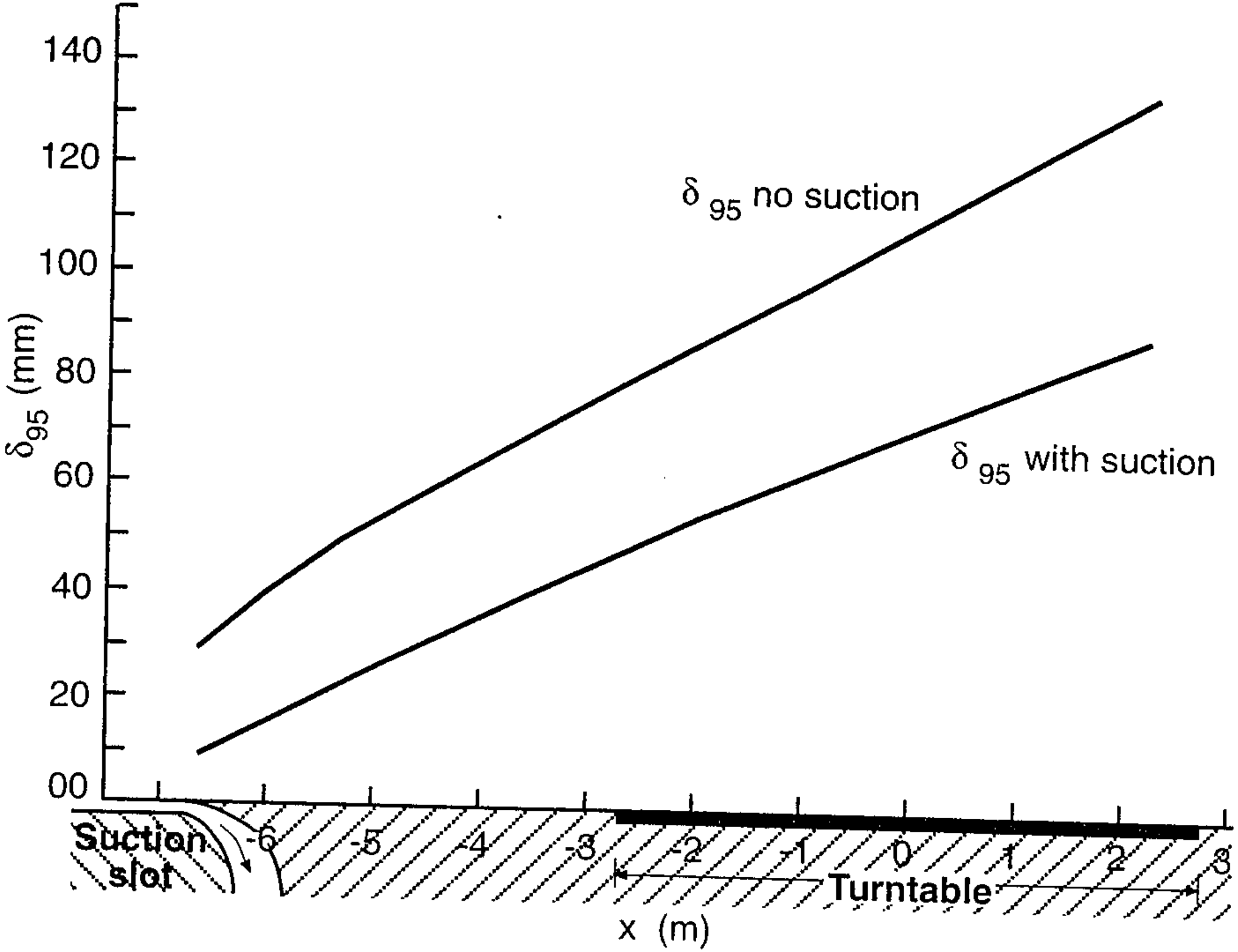


Fig. 3-24. *Test-section boundary layer thickness in the GM wind tunnel (after Ref. 3.8). δ_{95} is the boundary layer thickness at which 95% of the velocity outside this boundary was obtained. Reprinted with permission from SAE Paper 820371 Copyright ©1982 SAE, Inc.*



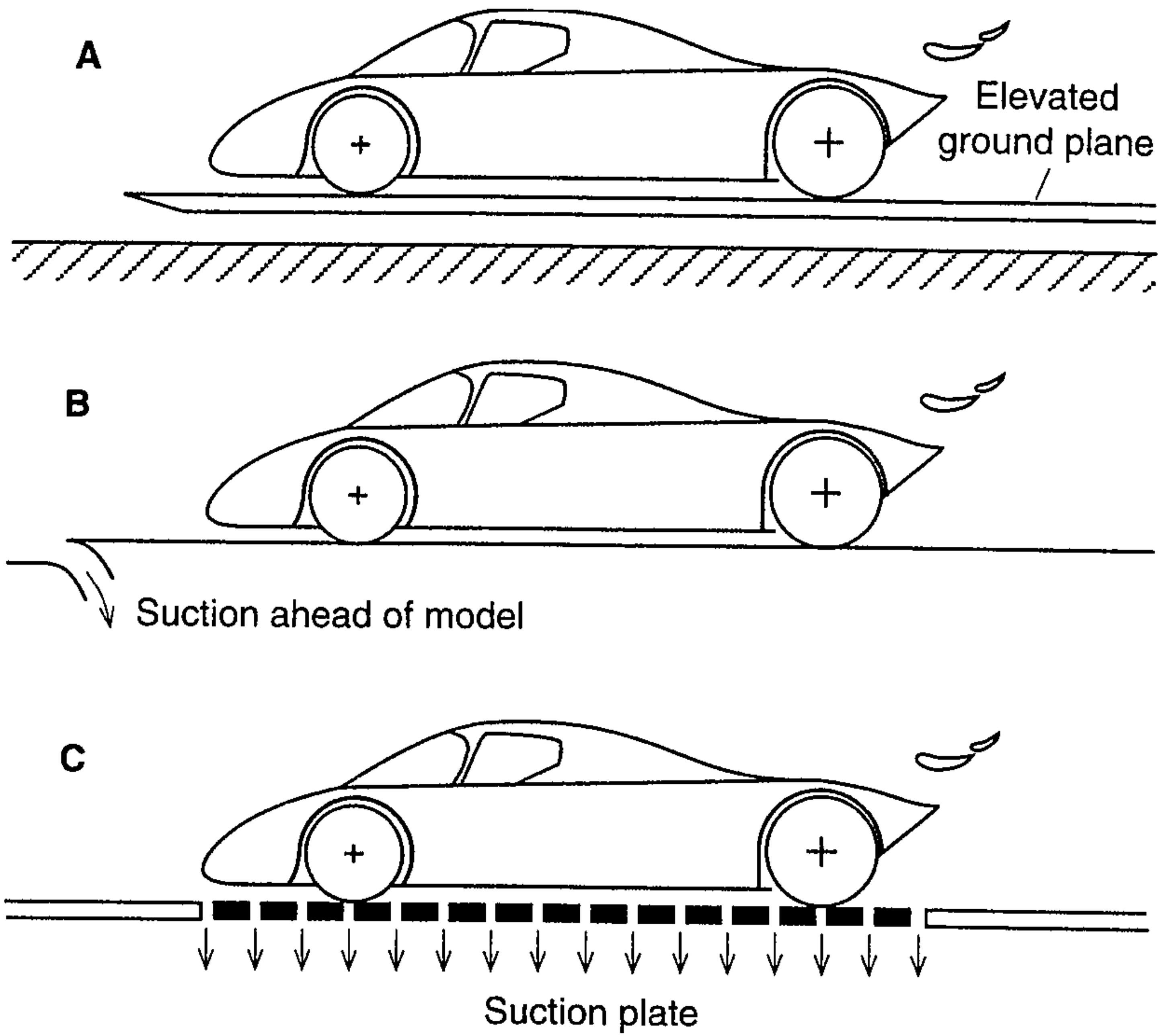


Fig. 3-25. *Various methods for simulating moving ground in a wind tunnel.*

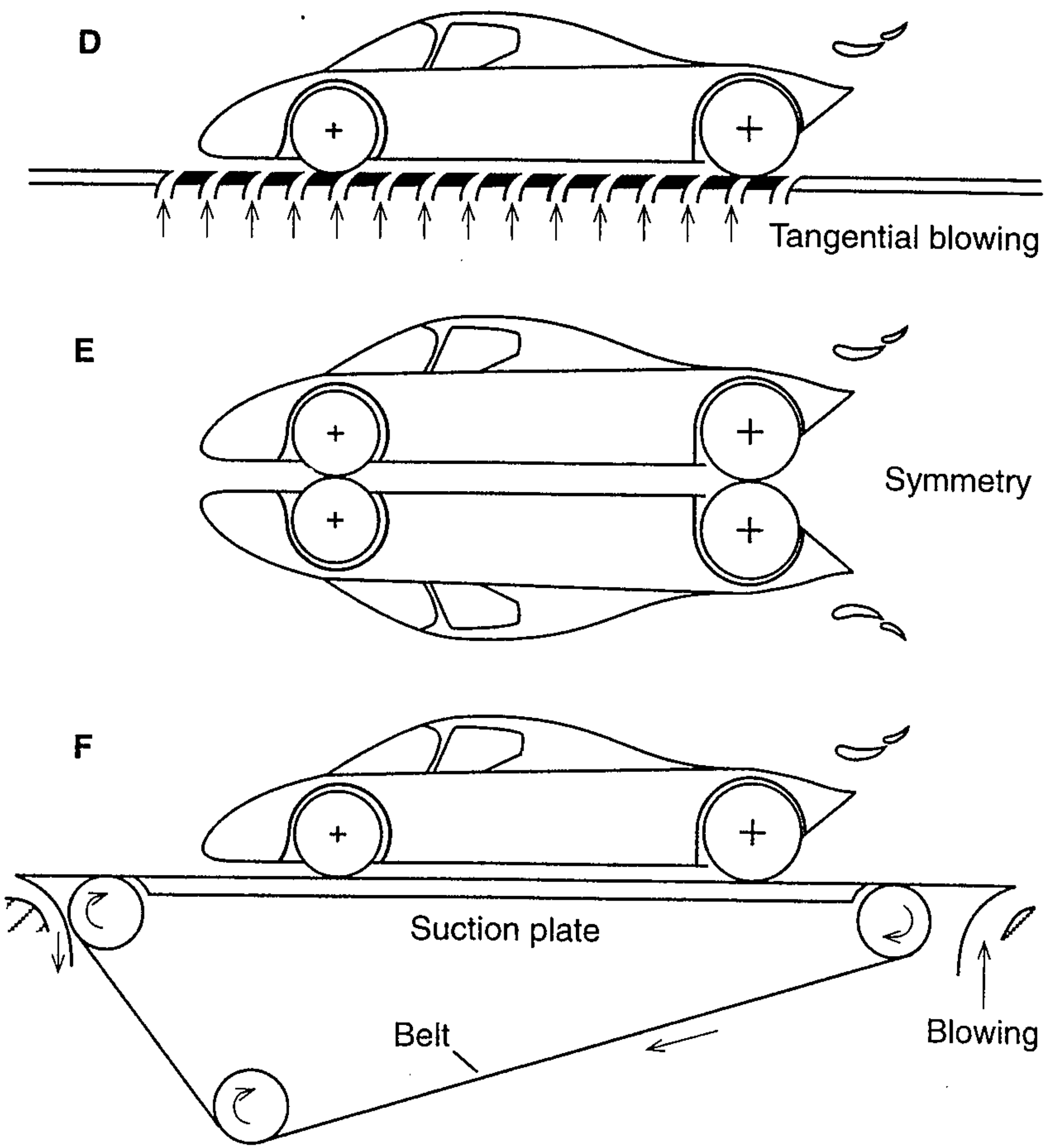

D
Tangential blowing
E
Symmetry
F
Suction plate
Belt
Blowing

Fig. 3-27. *One approach for mounting a wind tunnel model using an elevated ground plane technique. The aerodynamic loads are measured by the scale mounted under the tunnel.*

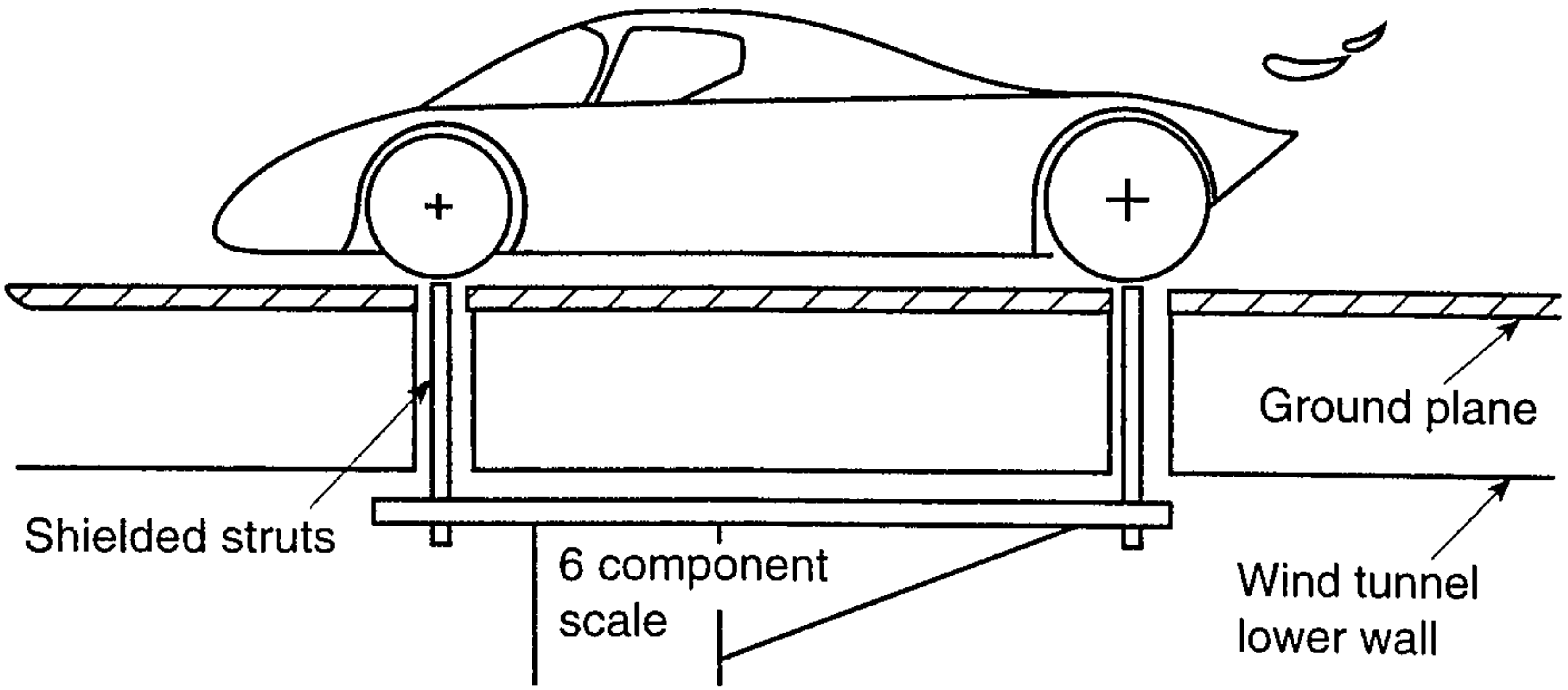


Fig. 3-28. *Schematic view of the various turntables used to mount the vehicle on the balance (of a "drive-in" full-scale wind tunnel). Reprinted with permission from SAE Paper 820371 Copyright ©1982 SAE, Inc.*

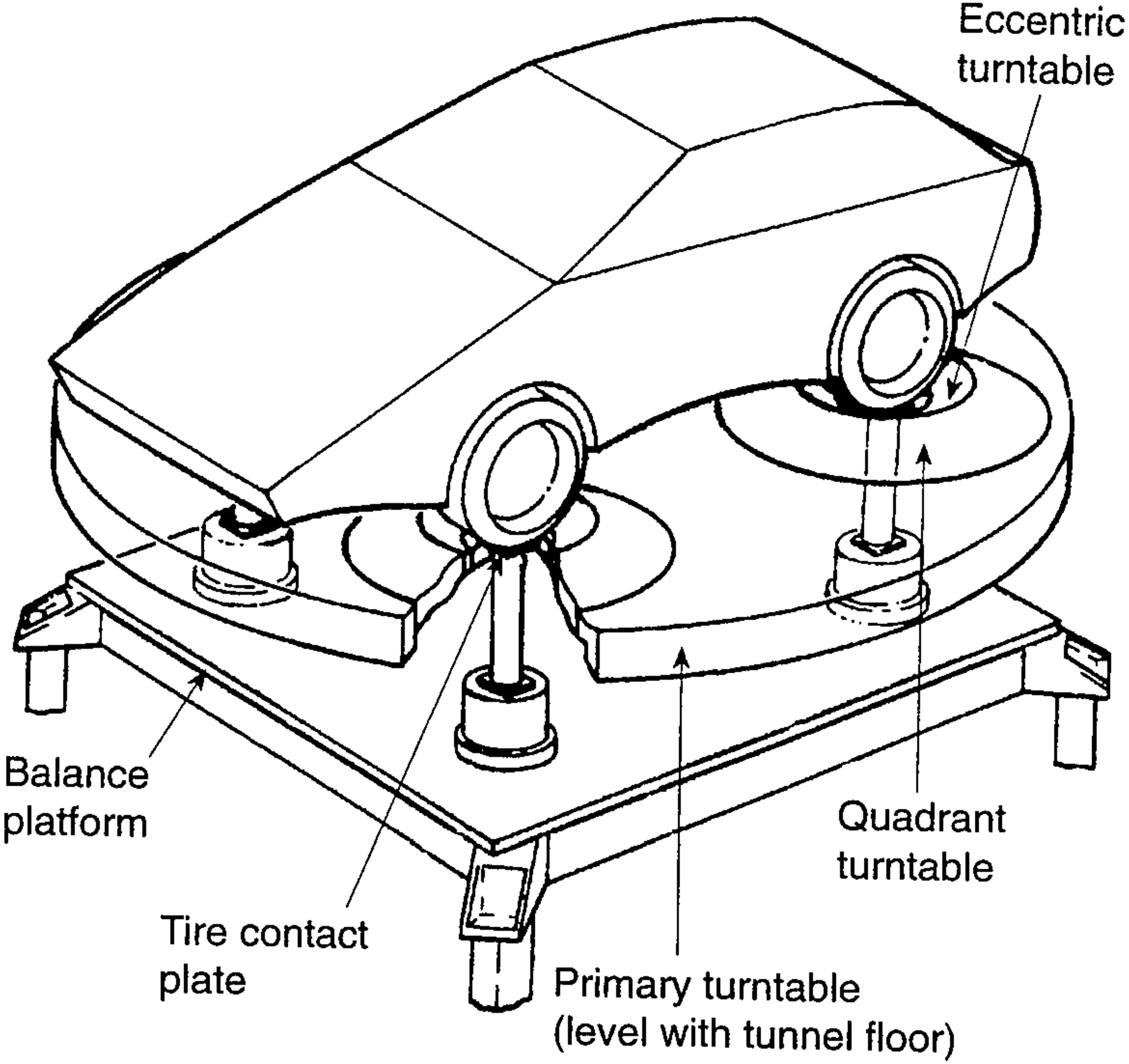


Fig. 3-29. *Typical method for mounting a model with rotating wheels on a fixed ground plane.*

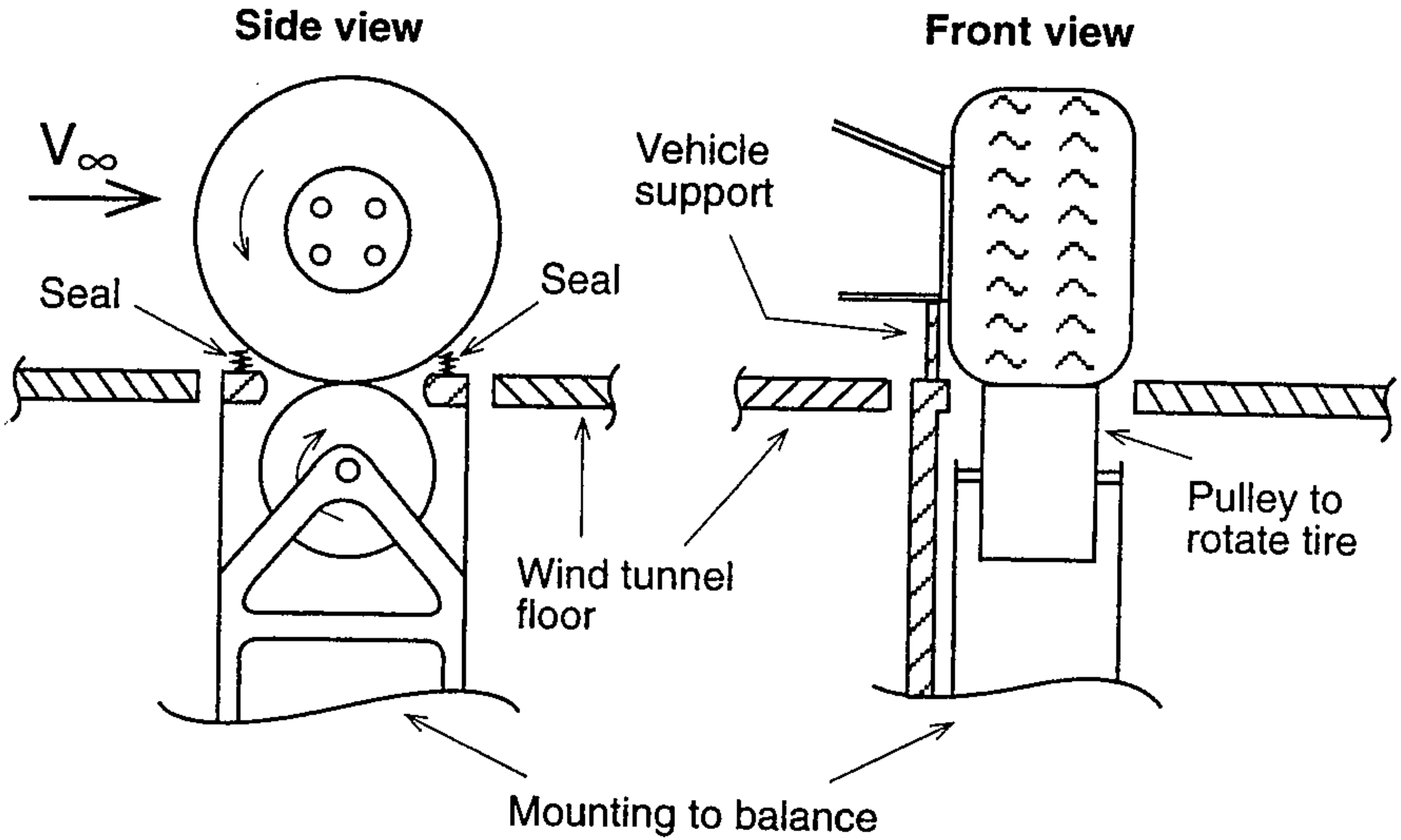


Fig. 3-30. Typical rear sting mounting for suspending a model with rotating wheels above a moving belt system.

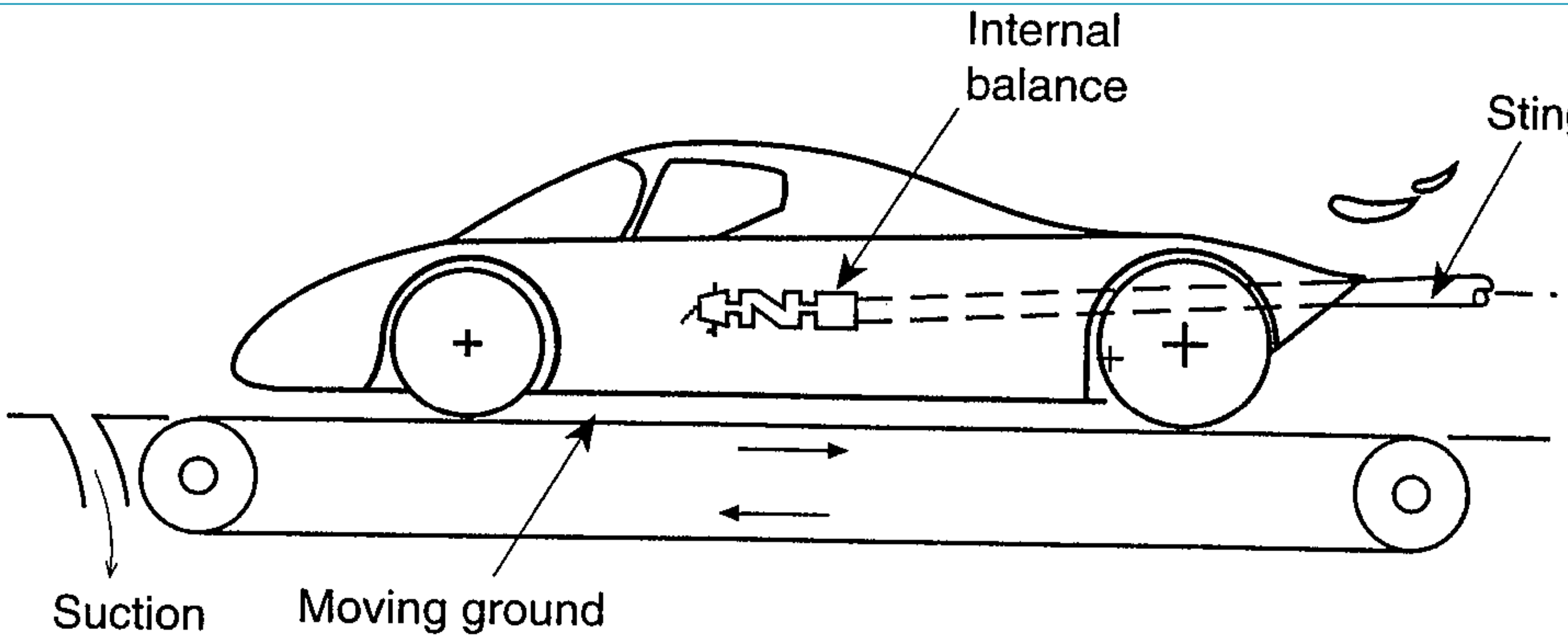
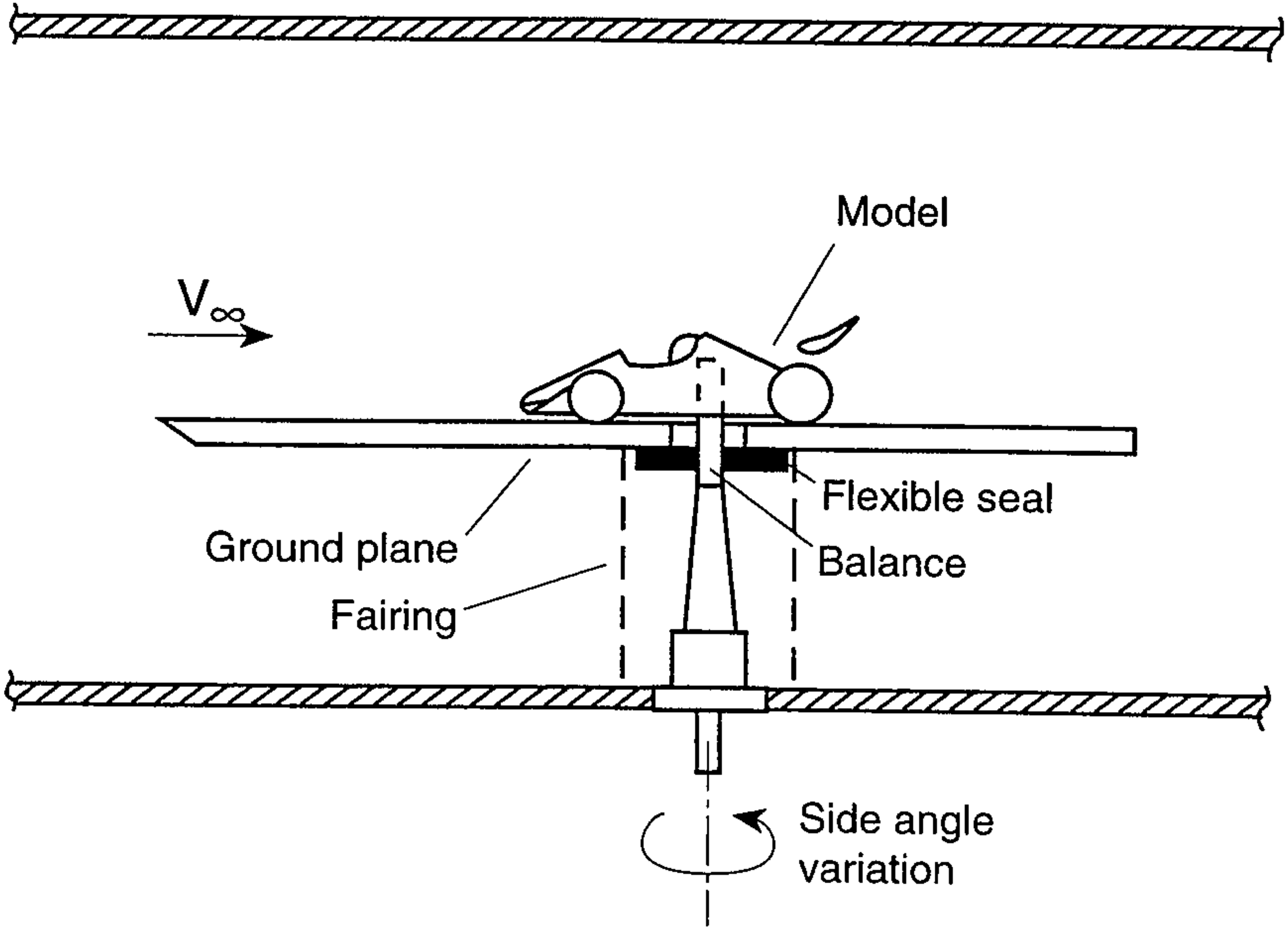


Fig. 3-35. *Small-scale model mounted above a fixed ground plane. The load measuring balance is attached below the model. Reprinted with permission from SAE Paper 850283 Copyright ©1985 SAE, Inc.*



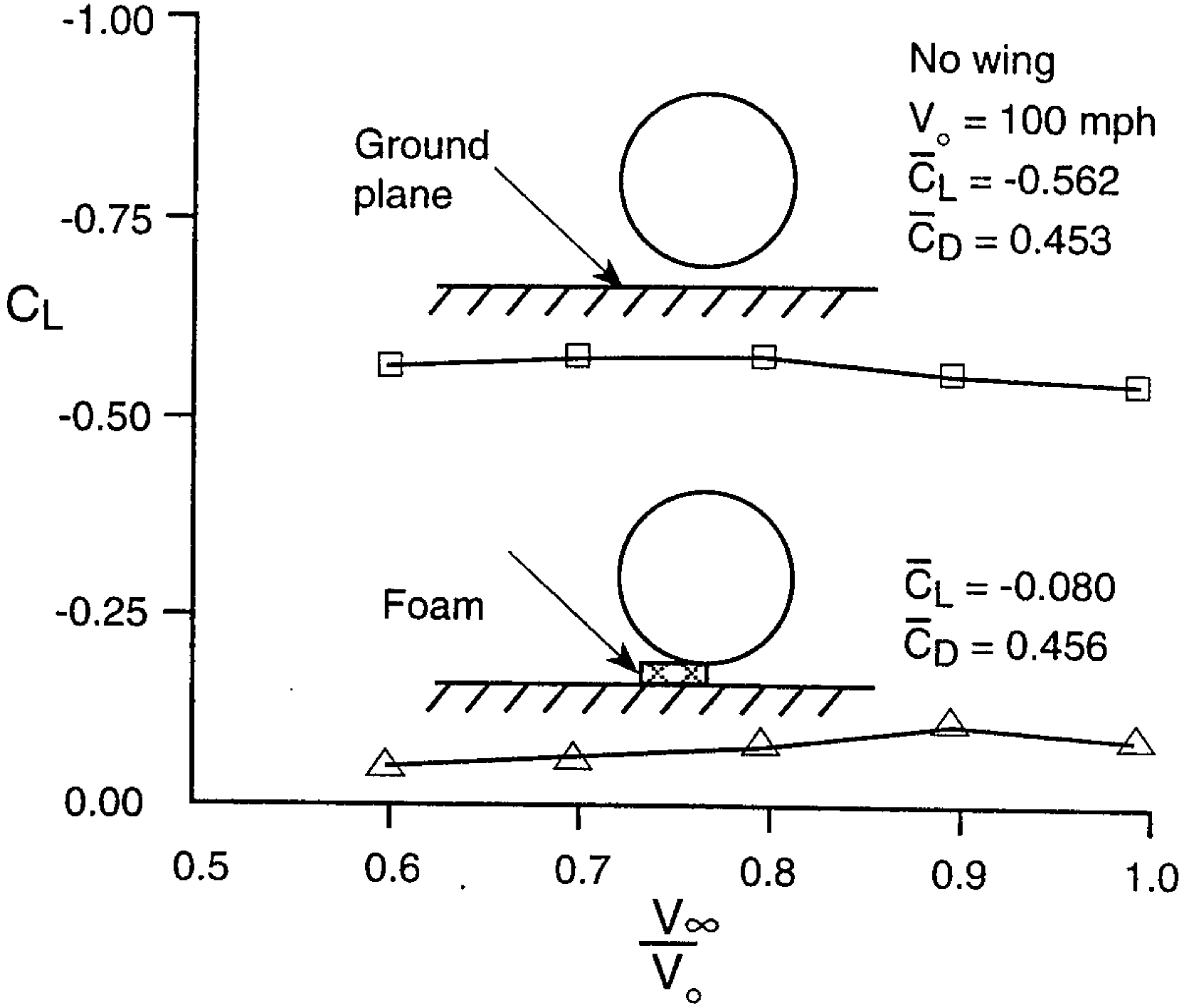


Fig. 3-36. *Effect of gap between the stationary wheels and the ground on a prototype race car model lift coefficient (Reynolds number based on model length,* $Re_L = 3.3 \times 10^6$*). Reprinted with permission from Ref. 2.9.*

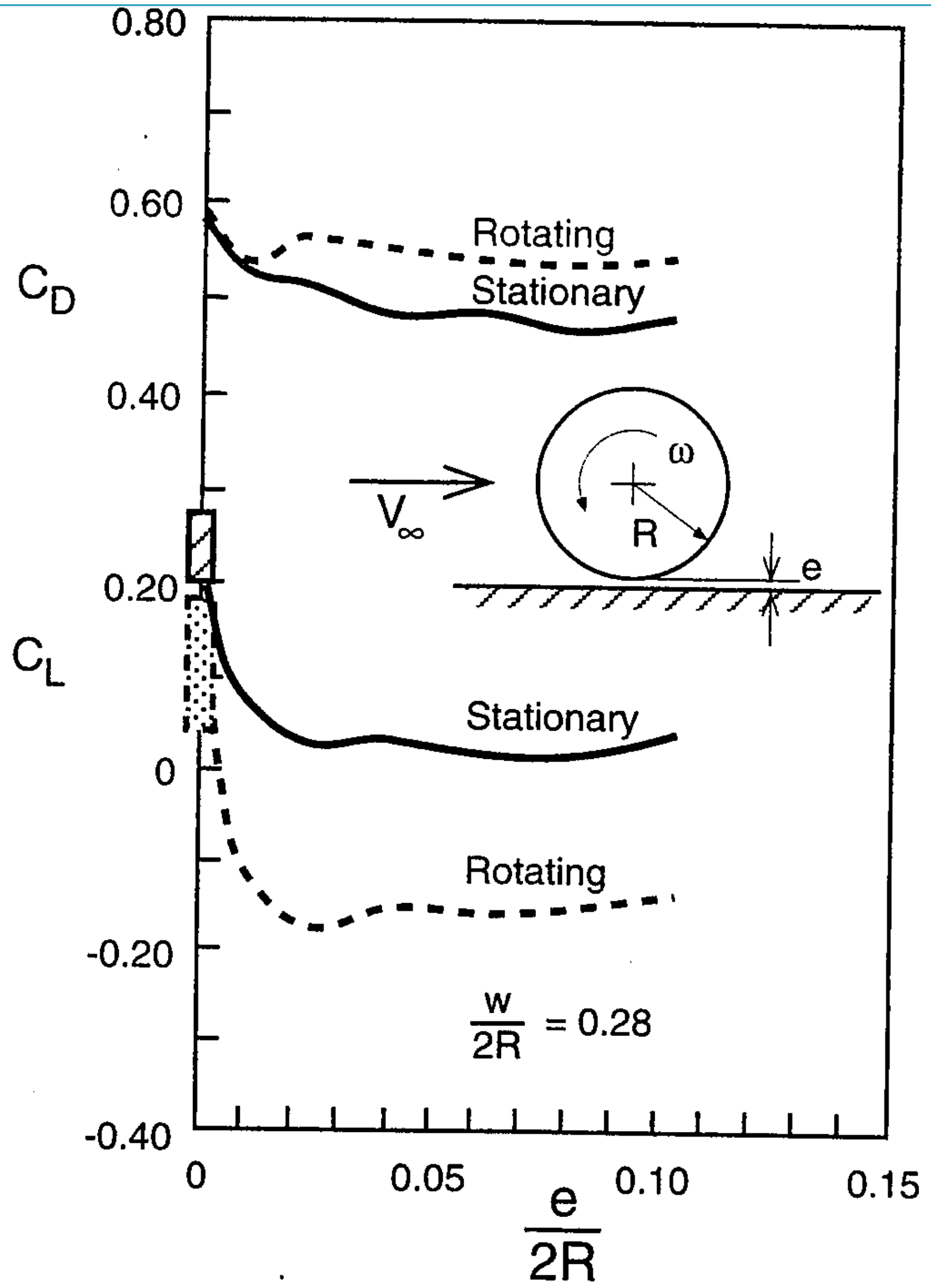


Fig. 3-37. *Drag and lift of isolated stationary and rotating wheels versus ground clearance. Coefficients based on wheel frontal area (after Ref. 3.9). The range of C_L shown for zero ground clearance indicates the range of results obtained with a variety of ground-to-wheel seals.*

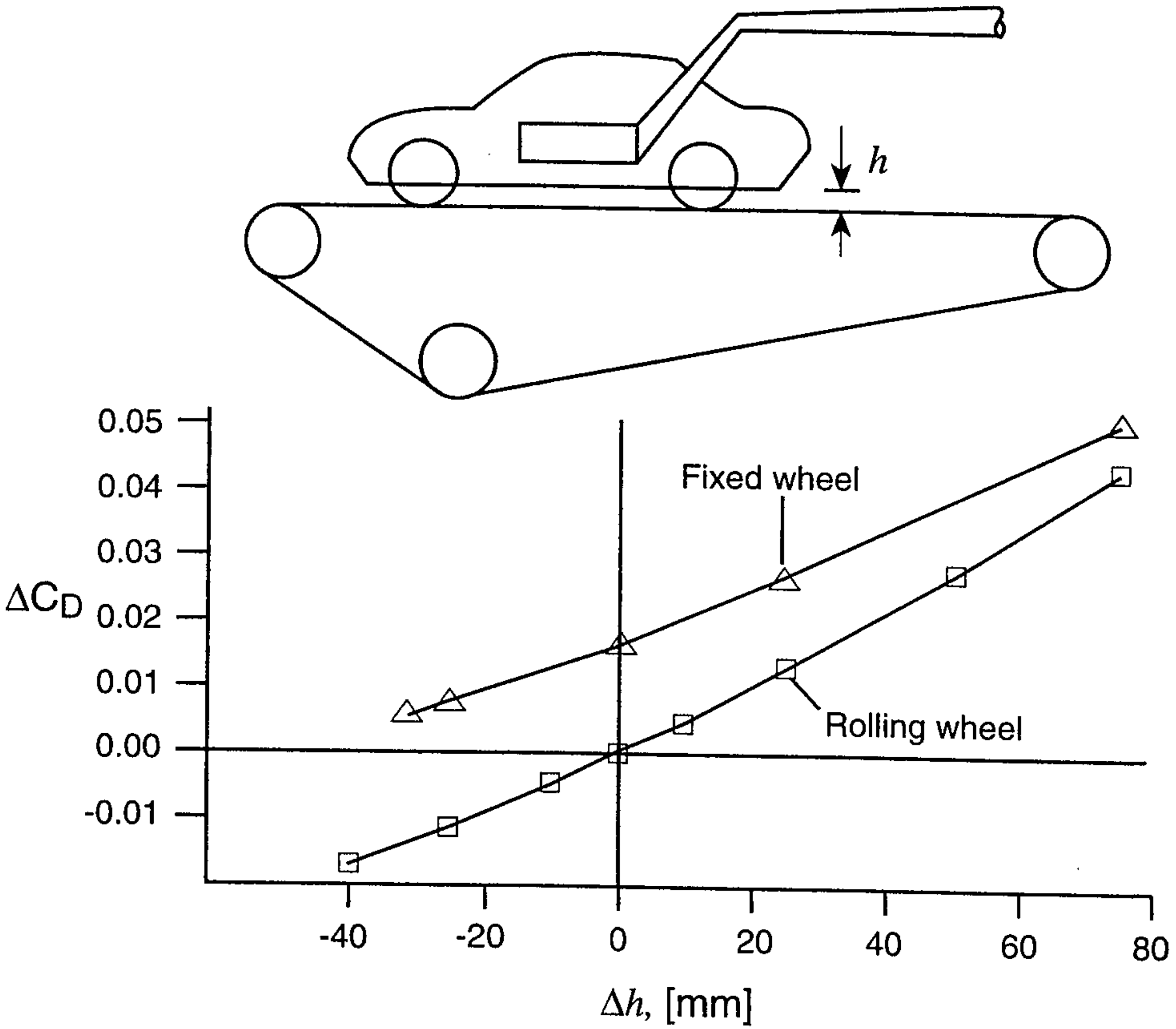
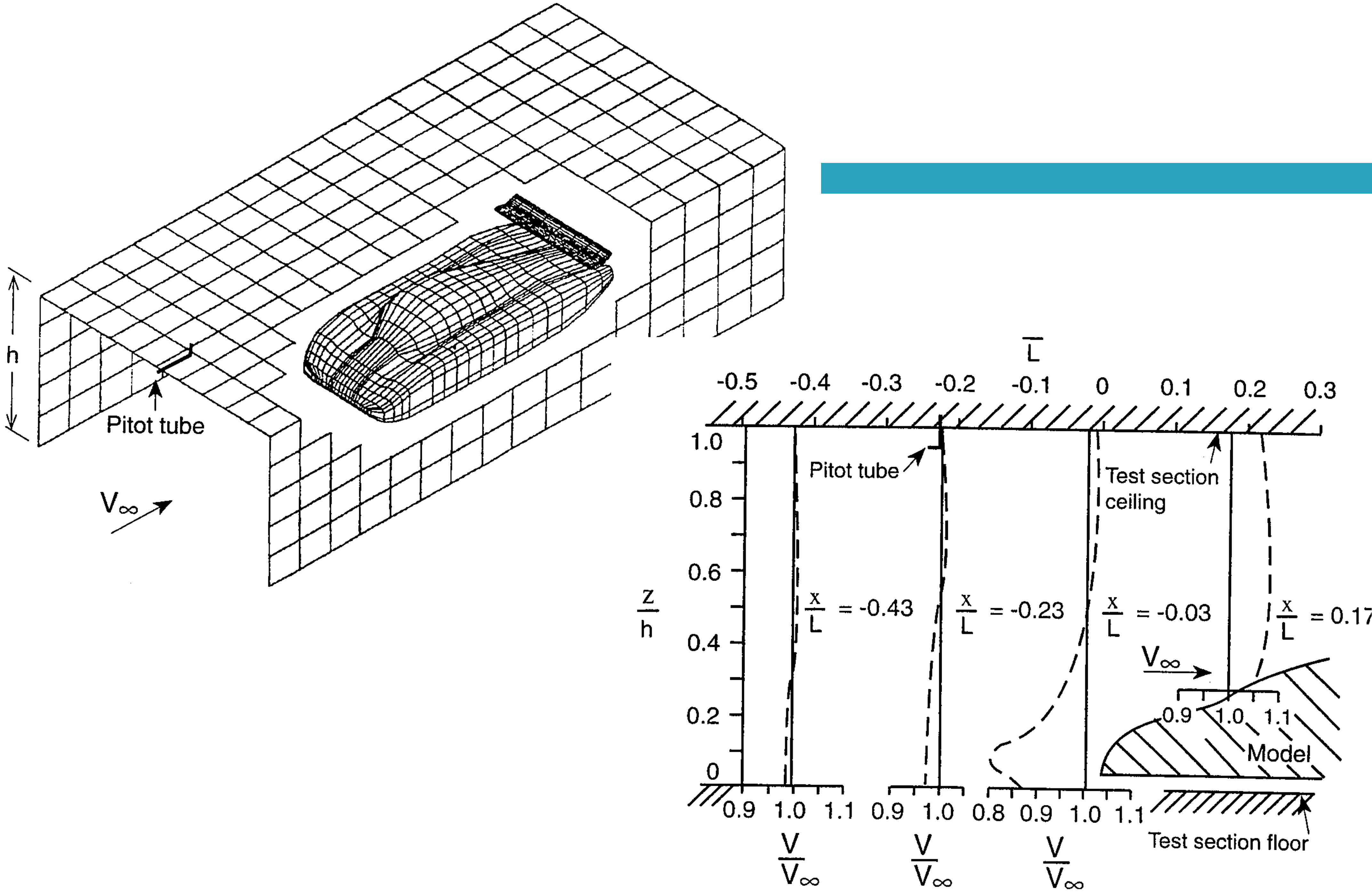


Fig. 3-38. *Influence of wheel rotation and ground clearance on the drag coefficient of an automobile (referenced to the production vehicle with ~180 mm ground clearance). Reprinted with permission from SAE Paper 910311 Copyright ©1991 SAE, Inc.*

Fig. 3-40. *Distortion of the velocity profile ahead and near the vehicle, when placed in a wind tunnel test section. Reprinted with permission from SAE Paper 890601 Copyright ©1989 SAE, Inc.*



Conclusions on Wind Tunnel Methods

While it may seem as if wind tunnels can never exactly simulate actual road conditions (due to ground effect, wheel rotation, Reynolds number, etc.), the wind tunnel is, in fact, the primary tool used to study automotive and race car aerodynamics.

In regard to the accuracy of the data, many wind tunnel operators proudly advertize the microscopic accuracy of their balance system, but in reality some of the problems mentioned earlier refute this claim of high fidelity. And measuring lift coefficients with more than 2 digits behind the decimal point may not be necessary. The bottom line is:

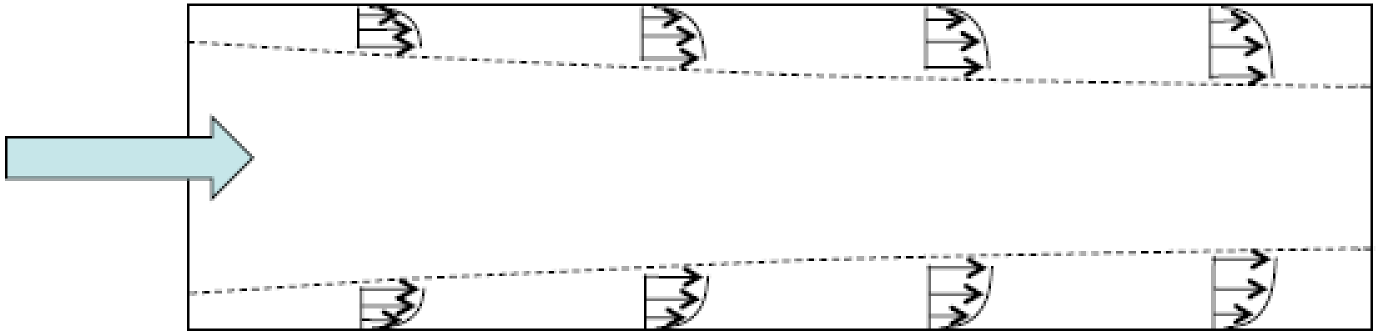
- Understanding the aerodynamic problem is more important than having too sensitive equipment. Since vehicle improvement requires only incremental data (to judge if an idea is good), productive vehicle improvements can be achieved with minimum resources (good results have been achieved with 14% blockage in a wind tunnel with no moving ground belt)
- Whatever works satisfactorily in the wind tunnel, will usually work on the track (or on the road)
- A design optimized in a small-scale wind tunnel will be too conservative on the actual road, and the vehicle can be further improved

- Cross-sectional shape
- •! The most usual shapes are rectangular
- and octagonal.
- •! The octagonal shape is chosen to
- minimize secondary flow problems in
- the corners of a rectangular section

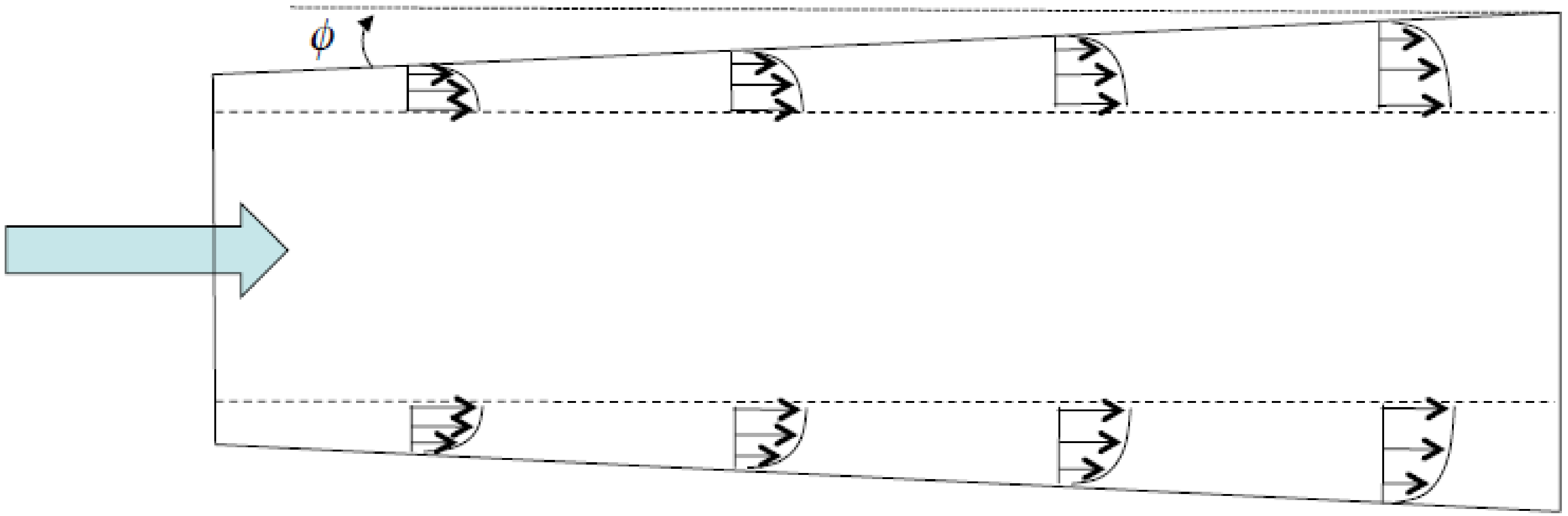
Side view

•! The test section is not completely straight

•! The boundary layer grows in the test section, reducing its effective area, increasing the velocity and decreasing the static pressure



- To overcome this problem, most test sections feature a small geometric increase of their cross-sectional area.



- There is no magic value for the angle ϕ. It is often chosen as ϕ=0.5°.

- More about the test section
  - The length of a test section is usually chosen as one or two times the size of the major dimension of the cross section. E.g. for a 3mx2m cross section, the length would be 3m-6m.
  - There are significant losses in the test section so it should be kept as short as possible
  - There must be adequate windows in the test section
  - There must be good lighting in the test section
  - There must be holes for passing cables, tubes, shafts,

- The diffuser
  - A wind tunnel could have the same cross-sectional area throughout.
  - However, power losses depend on the cube of airspeed.
  - So, it pays to reduce the airspeed in the sections of the tunnel that are not used for experiments.
  - That's the job of the diffuser. As the diffuser decreases airspeed, it increases static pressure, causing an adverse pressure gradient.
  - This can cause separation at the wall. Separated flow can cause vibrations, increased losses, oscillating airspeed in the test section (surging), oscillating fan loading etc.
  - The two diffusers usually increase the area by a total maximum factor of 5 or 6 to avoid separation.

- Corners
  - Most corners are 90o bends(180o bends have also been used)
  - They are connected by short constant area ducts.
  - To avoid big losses, the corners are equipped with turning vanes:
  - Highly cambered plates
  - Highly cambered airfoils
  - The turning vanes should be adjustable to ensure good quality flow

- Purpose of the fan
  - The fan operates in a constant area duct; due to continuity, the airspeed is constant across the fan.
  - Therefore, the fan does not accelerate the flow. It creates a difference in static pressure across its two sides.
  - This static pressure difference can be high in order to set the flow in motion.
  - It can also be equal to the losses in static pressure in the tunnel in order to keep the flow speed constant

- Fan section
  - Fans develop their highest efficiency when in a relatively high speed flow.
  - Therefore, they are not positioned in the section of the tunnel with the largest area.
  - They are not positioned in the first diffuser because of the fear of broken parts from models or loose tools etc.
  - Therefore, they are usually placed after the second corner, before the second diffuser.

- More about the fan section
  - The area ratio between the fan section and the test section is usually 2/1 or 3/1.
  - The fan motor is usually mounted inside a nacelle. This usually requires cooling for the motor.
  - The nacelle has a length to diameter ratio of about 3. 30-40% of its length has constant diameter.
  - The closing cone angle is around 5°.

- Contraction cone
  - The object of the contraction cone is to accelerate the flow from the low power loss speed to the test section speed.
  - There are two problems with their design:
    - Adverse pressure gradients in the entrance and exit of the contraction cone can cause boundary layer separation
    - Secondary flow in the corners of rectangular cross-section cones

- Contraction design
  - The secondary flow problem is solved by making the contraction cone octagonal
  - The adverse pressure gradient problem is solved by carefully designing the geometry
  - Until the advent of digital computers and CFD these modifications were very difficult to design
  - Nowadays, contraction ratios of 8 can be designed with very small losses.

- Cooling of wind tunnels
  - •! Energy is lost from the flow in the form of heat.
  - •! This energy is constantly replaced by the fan.
  - •! Therefore the temperature of the flow increases until the heat gain is balanced by heat loss to the environment
  - •! Sometimes the equilibrium temperature can be too high for the required experiments.
  - Running water on the tunnel exterior
    - •! Water-cooled turning vanes
    - •! A water-cooled radiator in the largest tunnel section
    - •! An air exchanger continuously replacing heated tunnel air with cool external air.

- Steadiness
  - •! Steadiness refers to temporal fluctuations.
  - •! Time-dependent velocity variations should be of small magnitude and at low frequency.
  - •! This type of unsteadiness results from separated flow.
  - •! The cause of separated flow must be located and eliminated

- Turbulence
  - •! Turbulence is unsteadiness at much higher frequency caused by wakes, noise, roughness etc.
  - •! Turbulence can be reduced by installing honeycombs and screens upstream of the contraction cone.
  - –!Screens reduce axial turbulence more than lateral turbulence
  - –!Honeycombs reduce lateral velocities