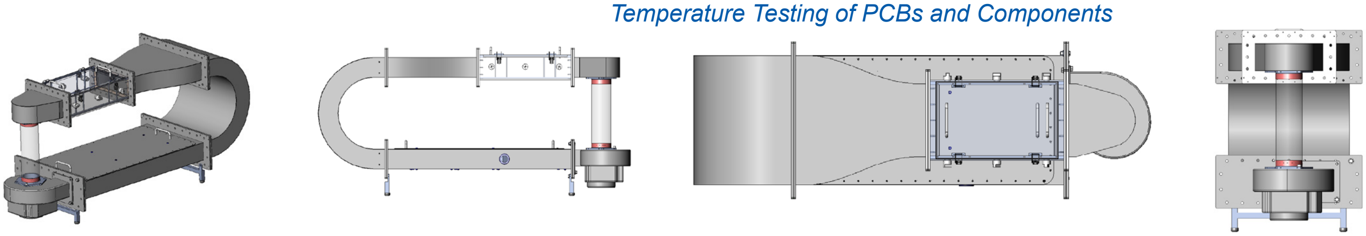
Basic Principles of

Wind Tunnel Design

Below: Views of ATS' new CLWT-067 Closed Loop Wind Tunnel for Elevated Temperature Testing of PCBs and Components



Wind tunnels generate uniform air flows, with low turbulence intensity, for thermal and hydraulic testing. These devices have been around for more than a century, and are used in many industries, including aerospace, automotive, and defense. They also play a key role in electronics thermal management. Wind tunnels are made in different shapes and sizes, from just 30 cm long to large enough to contain a passenger airplane. But the basic idea behind all wind tunnels is universal.

There are two basic kinds of wind tunnels. One is the open type, which draws its air from the ambient and exits it back to the ambient. This kind of wind tunnel provides no cost effective temperature control. The air follows the ambient temperature when there is no heating element at the intake. The second type of wind tunnel is the closed loop wind tunnel, whose internal air circulates in a loop, separating it from outside ambient air. The temperature in a closed loop wind tunnel can be controlled using a combination of heaters and heat exchangers. Air temperatures can be varied from sub-ambient to over 100^{o}C. Figure 1 shows a schematic of a closed loop wind tunnel.

In general, closed loop wind tunnels are made with the following sections:

1- Test section
2- Settling chamber
3- Contraction area
4- Diffuser
5- Blower assembly
6- Heater/heat exchanger assembly

A good quality wind tunnel will have a flow uniformity of 0.5-2% and turbulence intensity of 0.5-2%. It should provide temperature uniformity within 0.1-0.5^{o}C at the inlet of the test section [1].

To achieve uniform, high quality flow in the test section, the settling chamber and the contraction area are used to smooth the flow. The role of the settling chamber, which is upstream of the contraction area, is to eliminate swirl and unsteadiness from the flow. The settling chamber includes

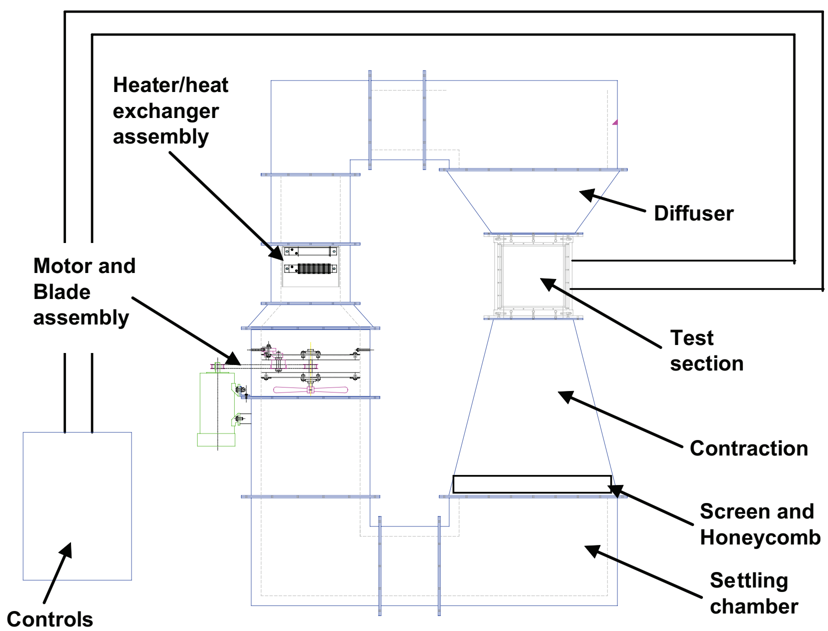


Figure 1. Schematic of an ATS Closed Loop Wind Tunnel.

a special honeycomb and a series of screens. As long as a flow's yaw angles are not greater than about 10°, a honeycomb is the most efficient device for removing swirl and lateral velocity variations and to make the flow more parallel to the axial axis [2]. Large yaw angles will cause honeycomb cells to stall, which increases the pressure drop and causes non-uniformity in the flow. For large swirl angles, screen meshes should be placed before the honeycomb. For swirl angles of 40°, a screen with a loss factor of 1.45 will reduce yaw and swirl angles by a factor of 0.7. Several screens are needed upstream of the honeycomb to bring the swirl down to 10°.

Using a honeycomb will also suppress the lateral components of turbulence. Complete turbulence annihilation can be achieved in a length of 5-10 cell diameters [2]. Honeycombs are also known to remove the small scale turbulence caused by the instability of the shear layer in front of them. This instability is proportional to the shear layer thickness, which implies a short honeycomb has a better ratio of suppressed turbulence to that generated.

Screens break up large eddies into smaller ones which decay faster. They lower turbulence drastically when several screens are placed in a row. Screens also make flow more uniform by imposing a static pressure drop which is proportional to velocity squared. A screen with a pressure drop coefficient of 2 removes nearly all variations of longitudinal mean velocity. Low open area screens usually create instabilities. In general, screens should have openings larger than 57%, with wire diameters about 0.14 to 0.19 mm. Sufficient distance is needed between multiple screens to stabilize static pressure from perturbation. This distance is typically a percentage of the settling chamber diameter.

The contraction area is perhaps the most important part of a wind tunnel's design. Its main purpose is to make the flow more uniform. It also increases the flow at the test section, which allows flow conditioning devices to be at lower flow section with less pressure drop. Batchelor used the rapid distortion theory and estimated the variation in mean velocity and turbulence intensity [3]:

1- u component of mean velocity, U: $1/c$

2 - v or w component of mean velocity V, W: $\sqrt{1/c}$

3 – u component r.m.s intensity, u': $\frac{1}{2c}\left[3(\ln 4c^3 - 1)\right]^{1/2}$

4 – v or w component r.m.s intensity, v', w': $(3c)^{1/2}/2$

Where c is the contraction ratio.

The above equations show that honeycomb is less efficient in suppressing longitudinal turbulence than mean velocity variations. It also shows that the lateral turbulence intensity v' or w' actually increases, but the stream-wise intensity u' is reduced.

A considerable number of shapes have been investigated for contraction, including 2-D, 3-D and axisymmetric shapes with various side profiles.

The shape of the contraction can be found using potential flow analysis. Consider the axisymmetric contraction shown in Figure 2 [4]

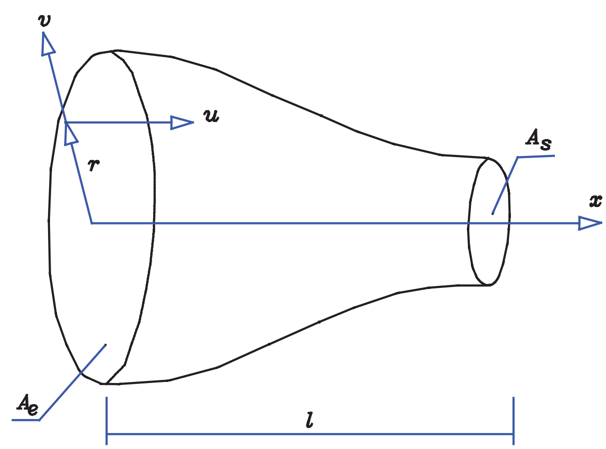


Figure 2.-Schematic of an Axisymmetric Contraction [4].

The equation describing an ideal flow in an axisymmetric coordinate is:

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} = 0$$

Where $\psi(r, x)$ is a stream function.

The solution to the above partial differential equation is subject to the boundary conditions. Assuming a value for the stream function on the boundary, and using a fixed contraction ratio, will give the shape of the contraction. Figure 3 shows the shape of the stream function for values of $\psi(r,x)$ from 0.5 to 4. The figure shows r as a function of x for different values of stream function. The value of ψ = 4 is unacceptable because at x = -3 there is a boundary layer separation. Even though we solved the potential flow by assuming that the bulk of the fluid is ideal, the flow near the surface is affected by viscosity, and the mathematical change in stream function near -3 implies that viscosity will separate the flow from the surface. Physically ideal flow cannot exhibit this behavior. The stream functions 0.5 and 1 show a very long length for the stream function and hence the velocity to stabilize. The ψ =2 gives the best result of short length and smooth stream function behavior. Most designers have used 5th, 6th and higher order polynomials. The shape and size of this contraction depends on the geometric constraints, cost, and the quality level of the wind tunnel.

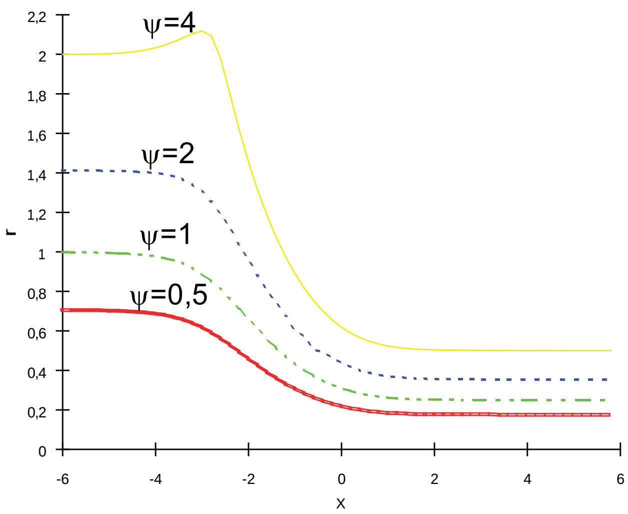


Figure 3. Contraction Shapes For Different Values of Stream Function [4].

The diffuser section is used for pressure recovery, but caution should be taken not to have flow separation at the exit. Some of the guidelines for design purposes can be outlined briefly as the following [1]:

Contraction:

- 5th degree polynomial wall shape
- Contraction ratio: depending on the application, a range of 2-14

Diffuser:

- Design for minimal pressure recovery
- Use screens or perforated plates at inlet and exit
- 80% open mesh, 5-20 mm openings

Ducting and corner design:

- Use guide vanes to reduce the sharp angle variations at turns

Settling chamber:

- Precondition the flow using coarse mesh or perforated plates (80% open, 5-20 mm openings)
- Use honeycomb after the preconditioning with a 4/8 length/diameter ratio, cell diameter 2-5 mm, open area > 90%
- Use 2-5 screens after the honeycomb. First one touches the honeycomb and gradually finer mesh, 80% open , 0.1-0.2 mm diameter wire mesh

The design of a wind tunnel is a lengthy process and, as shown above, it requires extensive knowledge and experience in both theory and construction. A novice might attempt to construct a tunnel, but considering the time spent, it might not be justified economically. Wind tunnel design also depends on economic and space constraints. Larger wind tunnels allow more space to have all the conditioning elements in place. A space-constrained wind tunnel must compromise some features at the cost of reduced flow quality, but can still be acceptable for practical engineering purposes.

References

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