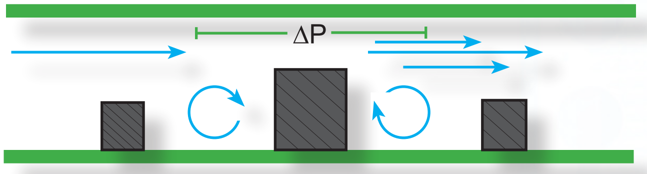
Correlations of Pressure Drop in Electronics Packaging

Calculating pressure drop is one of the most basic and important aspects of any thermal analysis. Knowing the pressure drop in a system is key to determining how much fluid is available for the cooling process. This is true for heat sinks, heat exchangers, telecom chassis or any other device using some form of liquid or gas.



Pressure drop can be divided into two fundamental categories: frictional and dynamic. The pressure drop from frictional effects is the dominant part of the overall pressure drop. Dynamic pressure drop owing to momentum changes is typically small, unless the fluid velocity reaches Mach 0.2. Dynamical changes can be attributed to entrance effects, sudden expansion or contraction, elbows, valves, etc.

A fundamental formula for pressure drop is the Darcy-Weisbach equation. This correlates head loss due to friction in a pipe of any cross section, factoring in velocity and pipe dimensions for either laminar or turbulent flow. Head loss is simply the pressure drop divided by the density, which is equivalent to a column of that fluid exerting the same pressure as the pressure drop.

This equation is stated as:

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

Where f is the Darcy friction factor, L is the length of the pipe, D is the diameter of the pipe and V is the velocity. The friction factor can be taken from the Moody Chart, which plots the friction coefficient as a function of the Reynolds number for both laminar and turbulent flow, and for smooth and rough pipes.

In 1839, experiments by Hagen showed that pressure drop in laminar flow was proportional to flow rate, but for turbulent flow it is roughly proportional to the square of the flow velocity.

The pressure drop for a laminar flow in a tube was found by Hagen to be:

$$\Delta P = \frac{8\mu L G}{\pi R^4}$$

Where G is the volumetric flow rate, and μ is the dynamic viscosity.

The Darcy-Weisbach equation for turbulent flow pressure drop in a tube can be shown as:

$$\Delta P = 0.241 L \rho^{3/4} \mu^{1/4} D^{-4.75} G^{1.75}$$

This relation shows that pressure drop in turbulent flow varies by the power of 1.75 of velocity. L is the length of the pipe.

For noncircular pipes an equivalent diameter, called the hydraulic diameter, D_h, can be defined as:

$$D_h = \frac{4A}{P}$$

Where A is the cross section and P is the wetted perimeter.

For dynamical pressure drop, a loss coefficient, K, is defined as:

$$K = \frac{\Delta P}{\rho V^2/2g}$$

Where ρ is the fluid density and g is the gravitational constant.

The total head loss of a complicated system can be calculated as:

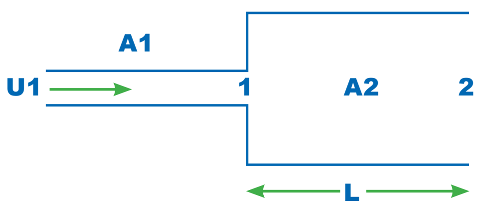
$$\Delta h_{loss} = \frac{V^2}{2g}\left(\frac{f1}{D} + \Sigma K\right)$$

Where V is the fluid velocity.

In the following, we show the pressure drop for some simple geometries:

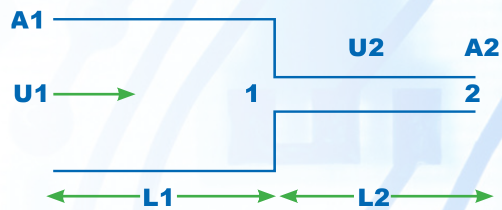
Sudden expansion [2]

$$\frac{\Delta P}{\frac{1}{2}\rho U1^2} = \left(\frac{A2}{A1}\right)^2 - 1 + \left(1 - \frac{A1}{A2}\right)^2 + \frac{f^1}{D}$$



Sudden Contraction [2]

$$\frac{\Delta P}{\frac{1}{2}\rho U1^2} = 1 - \left(\frac{A2}{A1}\right)^2 + \frac{1}{2}\left(1 - \frac{A1}{A2}\right) + \frac{f1L1}{D1} + \frac{f2L2}{D2}$$



K value in circuit board channels [3]

$$K=0.2065+0.1549 \times C_V^{-0.4224}$$

Where the volume fraction coefficient is defined by:

$$C_V = \frac{V_{comp}}{V_{channel}},$$

Here, V_{comp} is the total volume occupied by the components and $V_{channel}$ is the total volume of the circuit board forming the channel.

K value for a sharp corner turn

$$K = 1.4$$

Pressure drop for a heat sink [4]

$$\alpha = \frac{S}{H}$$

$$\Delta P_{friction} = f\left(L\frac{10^{-3}}{D_h(S)}\right)0.5\left(\rho U^2\right)$$

$$f = \left(\frac{96}{Re}\right)\left(1-\frac{1.3553}{\alpha}+\frac{1.9467}{\alpha^2}-\frac{1.7012}{\alpha^3}+\frac{0.9564}{\alpha^4}-\frac{0.2537}{\alpha^5}\right)$$

$$\Delta P_{friction} = f\left(L\frac{10^{-3}}{D_h(S)}\right)0.5\left(\rho U^2\right)$$

$$\Delta P_{expansion} = \left(\rho\frac{Uapp^2}{2}\right)\left(1-\sigma^2-1.0257\sigma^2+2.029\sigma-1.0058\right)$$

$$\Delta P_{contraction} = \left(\rho\frac{Uapp^2}{2}\right)\left(1-\sigma^2-0.4405\sigma^2+0.039\sigma-0.4011\right)$$

$$\Delta P_{total} = \Delta P_{friction} + \Delta P_{contraction} + \Delta P_{expansion}$$

σ = Open channel area / Total frontage area

Where S is channel spacing, H is the fin height, U is velocity between fins, U_{app} is the approach velocity, and $D_{h(s)}$ is the channel hydraulic diameter.

Readers should note that the literature contains many correlations for pressure drop that should be used with caution. While these correlations can provide good first order approximations for quick analyses, they may break down in cases that do not fall into their range of applicability. For example, some correlations will reasonably predict the pressure drop across a heat sink in a bypass flow when the fin density is moderate. But they may fail if the heat sink has 3-4 mm tall, closely packed, thick fins.

References:

1. White, F., Fluid Mechanics, McGraw-Hill, 1979.
2. Blevins, R., Applied Fluid Dynamics Handbook, Van Nostrand Reinhold, 1984.
3. Azar, K., Electronic Cooling Theory and Application, Lucent Technologies, 1994.
4. Kays, M. and London, A., Compact Heat Exchangers, Third Edition, McGraw-Hill, 1984.