Hydraulic Resistance and its Role in Electronics Cooling

In both thermal and fluid sciences, predicting the air and surface temperatures requires an approximate value for the air flow rate. A reasonable estimate for flow rate in any type of enclosure is obtained by accounting for all pressure losses in that system. These pressure drops result from friction generated by fluid flow over the enclosure walls and surfaces, as well as fluid dynamic momentum changes due to sudden expansion or contraction of the enclosure.

To get a sense of these losses, we can apply the first law of thermodynamics, conservation of energy, to a viscous fluid flowing through a duct from point 1 to point 2. Assuming a steady state and incompressible flow, the basic energy equation per unit of mass of the fluid reduces to Equation 1:

$$\frac{\delta Q}{dm} = u_2 - u_1 + \frac{p_2}{\rho} - \frac{p_1}{\rho} + gz_2 - gz_1 + (\frac{\alpha_2 \bar{V}_2^2}{2} - \frac{\alpha_1 \bar{V}_1^2}{2}) \tag{1}$$

Where u, α and V represent internal energy, kinetic energy coefficient, and mean fluid velocity, respectively. Rearranging Equation 1 yields:

$$(\frac{p_1}{\rho} + \frac{\alpha_1 \bar{V}_1^2}{2} + gz_1) - (\frac{p_2}{\rho} + \frac{\alpha_2 \bar{V}_2^2}{2} + gz_2) = (u_2 - u_1) - \frac{\delta Q}{dm} \tag{2}$$

In Equation 2, the terms in the parenthesis

$$(\frac{p}{\rho} + \frac{\alpha \bar{V}^2}{2} + gz)$$

represent the mechanical energy per unit mass at cross sections 1 and 2 of the system being analyzed. The difference between the two is what is irreversibly converted to an undesired increase in internal energy $(u_1 - u_2)$ and the loss of energy in the form of heat $(-\frac{\delta Q}{dm})$. This conversion of mechanical energy is known as the total head loss and is designated by h_{lT} in Equation 3:

$$(\frac{p_1}{\rho} + \frac{\alpha_1 \bar{V}_1^2}{2} + gz_1) - (\frac{p_2}{\rho} + \frac{\alpha_2 \bar{V}_2^2}{2} + gz_2) = h_{lT} \tag{3}$$

Had the fluid been frictionless, the total head loss, h_{lT}, would have been zero and the equation would have been reduced to Bernoulli's equation for incompressible inviscid flow. In this situation, a change in internal energy could only occur through the effect of heat transfer. No conversion of mechanical energy to internal energy would take place.

The reader may now wonder why the term "head loss" is used to describe an energy quantity. During the nineteenth century, when most of the empirical science of hydraulics was developed, it was common practice to express the energy balance in terms of energy per unit weight of the flowing fluid. So, Equation 3 would have been divided by the fluid specific weight, (ρg) rather than fluid density, ρ, as is the routine practice today. The net dimension of the head loss consequently would be $[\frac{L^2}{t^2} * \frac{t^2}{L}] = [L]$, or millimeters of flowing fluid. Even though "head loss" is still in use, its physical meaning in Equation 3 is a loss in mechanical energy expressed per unit mass of flowing fluid.

Total head loss consists of two subcomponents: major (or friction) loss, h_{lf}, and minor (or local) loss, h_{lm}. Major losses are caused by frictional effects in fully developed flow within constant-area enclosures. Minor losses are caused by the fluid flow dynamic changes due to flow acceleration and deceleration in an enclosure with varying cross sectional areas. In the flow's through tubes, the effects of friction predominate the local losses, and thus these are major losses. In electronic enclosures, however, the effect of local losses is as significant as friction losses.

Equation 3 can be used to evaluate friction losses. For fully developed flow through a constant-area enclosure, the term $\frac{\alpha \bar{V}^2}{2}$ is the same at the two sections.

Considering that the only losses are friction losses, and assuming the effect of elevation is negligible, Equation 3 will reduce to Equation 4:

$$(\frac{p_1}{\rho} - \frac{p_2}{\rho}) = h_{lf} \tag{4}$$

Therefore, friction head loss is calculated from the static pressures at the two sections. When the flow is laminar the static pressure drop is given as:

$$\Delta p = p_1 - p_2 = 32\frac{L\mu\bar{V}}{D_h^{\,2}} \tag{5}$$

Substituting Equation 5 into Equation 4 will yield the friction head loss in terms of a friction factor that, for a given length and hydraulic diameter, is only dependant on the fluid velocity or Reynolds number:

$$h_{lf} = (\frac{64}{\mathrm{Re}})\frac{L}{D_h}\frac{\bar{V}^2}{2} = f_{laminar}\frac{L}{D_h}\frac{\bar{V}^2}{2} \tag{6}$$

For turbulent flow, however, such analytical correlation is not available. The value of the friction factor for circular tubes can be extracted from Moody's diagram, given that the Reynolds number, $\frac{e}{D}$, the ratio of the pipe inside surface roughness and diameter, are known. Even though the Moody diagram has been developed for circular tubes, it can also be used for non-circular ducts when the tube diameter is replaced with hydraulic diameter, $D_h = \frac{4 \times A}{P_{wetted}}$. The use of rectangular cross section ducts are valid only if the ratio of height to width is less than about 3 or 4 [1].

For turbulent flow in smooth pipes with Reynolds numbers less than 10^5, Blasius' correlation is used to estimate the friction factor:

$$f = \frac{0.3164}{\mathrm{Re}^{0.25}} \tag{7}$$

The most common formula used to estimate turbulent friction factor is Colebrook's Equation:

$$\frac{1}{f^{0.5}} = -2.0\log(\frac{e/D_h}{3.7} + \frac{2.51}{\mathrm{Re}\,f^{0.5}}) \tag{8}$$

This equation is transcendental and iterations are needed to evaluate the friction factor. After estimating the friction factor, the friction head loss in turbulent flow can be calculated using the following equation:

$$h_{lf} = f\frac{L}{D_h}\frac{\bar{V}^2}{2} \tag{9}$$

Local, or minor, losses are the types that occur whenever the dynamic momentum of the flow alters due to an abrupt change in the cross sectional area. In fluid flow through tubes, for example, these losses are seen in fittings, bends, valves, reducers, etc. The losses are the result of energy dissipation due to mixing of fluid in the separated regions. Figure 1 depicts the flow vortices in the separated regions when a fluid flow encounters a sudden contraction.

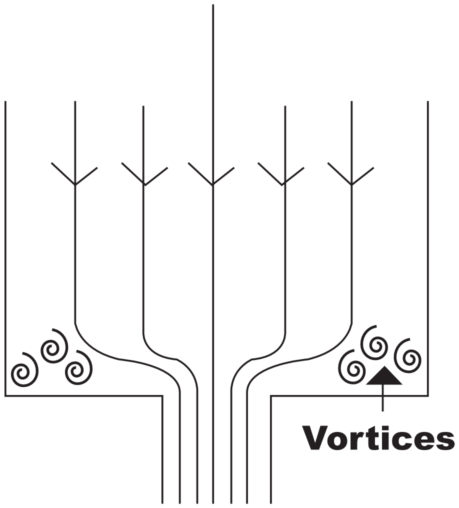

Figure 1. Flow Vortices in Separated Regions.

Local losses can be estimated using Equation 10, where K represents the loss coefficient. The K values are published in hydraulic resistance handbooks for a variety of situations that could be encountered in practical applications. These include sudden expansion and contraction, flow over barriers, orifices, etc. In some cases, values of K are provided by manufacturers of the devices that cause the head loss. If the value of the loss coefficient is not available in literature or provided by the supplier it can be determined by a simple differential pressure measurement across the device:

$$h_{lm} = K\frac{\bar{V}^2}{2} \tag{10}$$

Adding the friction and local losses, Equations 9 and 10, will give the expression for the total pressure loss. Please note that the summation in Equation 11 indicates that all discrete local head loss coefficients must be evaluated and accounted for in determining the total head loss.

$$h_l = h_{lf} + h_{lm} = \frac{\bar{V}^2}{2}\left(\frac{fL}{D_h} + \Sigma K\right) \qquad (11)$$

The concept of hydraulic losses explained in the preceding sections is now extended to electronic enclosures. A simple forced air cooled cabinet for an electronic system, shown in Figure 2, is one in which air enters an inlet panel at the bottom, is drawn through the chassis to the fan tray on the rear, and is exhausted out into the room.

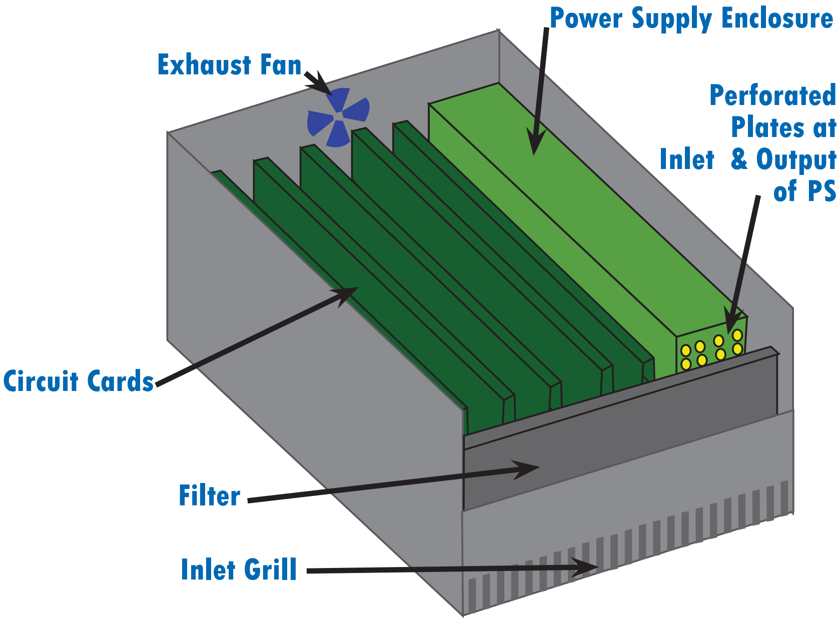

Figure 2. A Simple Electronic Enclosure.

The air inlet and outlet panels and the internal mechanical structure of the chassis (air filters, perforated plates, honeycomb, circuit cards, component blockade, fan tray plenum, etc.) resist the airflow and cause the system pressure loss. The total pressure drop of the system can be calculated from the net resistance, R_t including all the aforementioned resistances and the air volumetric flow rate, G.

$$h_l = R_t * G^2 \qquad (12)$$

In a graphical presentation of Equation 12, the flow rate versus the pressure drop would produce a system curve for the electronic chassis. When the system curve is drawn with the same scale on the fan curve provided by the fan manufacturer, the point where these curves intersect will be considered the operating point from which the system airflow is determined. Such a graph is shown in Figure 3. A system should be designed so that its operating point falls below the stall range of the fan curve. In Figure 3, the stall range of the fan is the intermediate section of the fan curve where it becomes fairly flat before its sharp final descent.

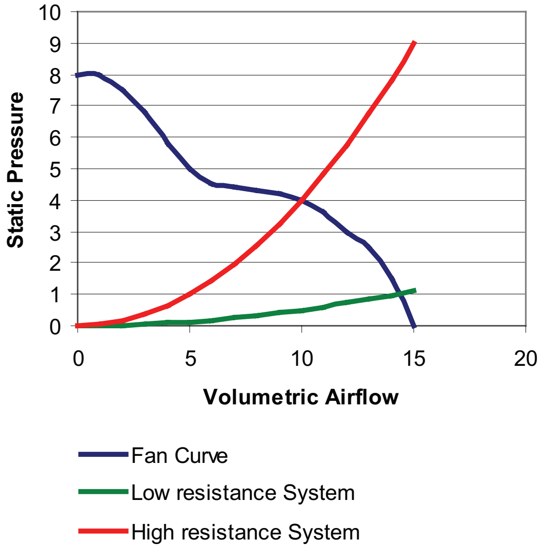

Figure 3. System and Fan Characteristic Curves.

Multiple fans in a fan tray can be represented by a single fan curve. Theoretically, the volumetric flow rate of multiple fans coupled in parallel is the sum of the individual flow rates, while the static pressure will not differ much compared to that of a single fan. However, in practice the available rate will be about 20 to 30% less. In contrast, fans configured in series (push-pull) would have a higher static pressure while the volumetric flow rate nearly stays unchanged. Fan tray characteristics must be determined experimentally if accurate results are needed.

In estimating the total system resistance of an electronic chassis, all individual resistances must be considered. Unfortunately, very limited resistance data is available for the devices typically used in electronic enclosures. Some of the published data for the common chassis elements is presented in Table 1.

Chassis Element	Resistance	Comment
Perforated plate	$\frac{0.828}{A^2}$	A - open area
Filter	$\frac{L \times 510.79}{A^2}$	A - filter exposed area L - filter loss coefficient provided by the manufacturer
Circuit board	$\frac{4.2 * L}{A^2}$	L - circuit board length A - effective free area of the channel between two circuit boards
Fan Tray- Sudden Expansion	$0.46 \times [\frac{1}{A_1} \times (1 - \frac{A_1}{A_2})]^2$	A_1 - small area A_2 - large area
Fan Tray- Sudden Contraction	$\frac{0.321}{A^2}$	A - small area

Table 1. Resistance of Common Elements in Electronic Chassis [2].

When obtaining the total pressure drop and the system curve of an electronic enclosure, the equivalent resistance must be calculated from the individual resistances. The procedure is analogous to finding equivalent resistance in an electrical network. However, the simple linear relation of the Ohm's Law does not apply to the fluid flow system. Instead, the flow pressure drop is approximately proportional to the square of the flow rate. This nonlinearity makes iterative solutions necessary, and the resulting calculations can be quite lengthy and tedious. Table 2 shows how equivalent resistance is calculated when the enclosure elements are in series and parallel.

Series	$R_{eq} = R_1 + R_2 + ...R_n$
Parallel	$\frac{1}{\sqrt{R_{eq}}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + ... \frac{1}{\sqrt{R_n}}$

Table 2. Equivalent Resistance Calculation.

To illustrate how the equivalent resistance is calculated from individual resistances, refer again to the electronic enclosure depicted in Figure 2. Air enters the enclosure through the inlet grill at the bottom, passes through a filter and reaches a section with two adjacent chambers. In the left chamber, there are 5 evenly spaced circuit cards. The chamber to the right contains the power supply enclosure that is entirely sealed except for its perforated inlet and outlet. Air is exhausted to a room by a fan in the back.

The air flow in the enclosure can be modeled according to the electrical circuit shown in Figure 4. In this network, pressure losses due to expansions and contractions are not considered.

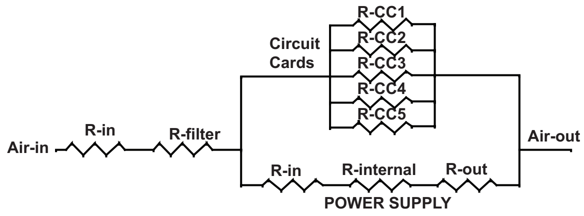

Figure 4. Forced Air Flow Circuit for the Enclosure Shown in Figure 2.

As shown in Figure 4, the flow is in series going through the inlet grill and filter. However, it would have to divide when it reaches the card cage and power supply chambers. In the card cage chamber, the flow is distributed among the cards before reaching the exhaust fan. In the power supply chamber, the equivalent resistance will include the inlet and outlet perforated sections and the internal resistance in the power supply chamber.

To evaluate total flow resistance, the equations for the appropriate enclosure elements given in Table 1 must be used in calculating the individual resistances. In analyzing the modeled electrical circuit, the equations in Table 2 also must be implemented to find equivalent resistance in series and parallel connections.

Once the total equivalent resistance of the system is obtained, it must be substituted in Equation 12, and a curve of the system pressure versus the volumetric flow rate must be constructed. Given that this curve is drawn with the same scale on the fan curve, the point where the system and fan curves intersect will be the operating point from which the amount of available air flow for the system is found.

References:

1. Fox, R., McDonald, A, Introduction to Fluid Mechanics, Wiley, 1985.

2. Ellison, G., Thermal Computations for Electronic Equipment, Van Nostrand Reinhold, 1984.

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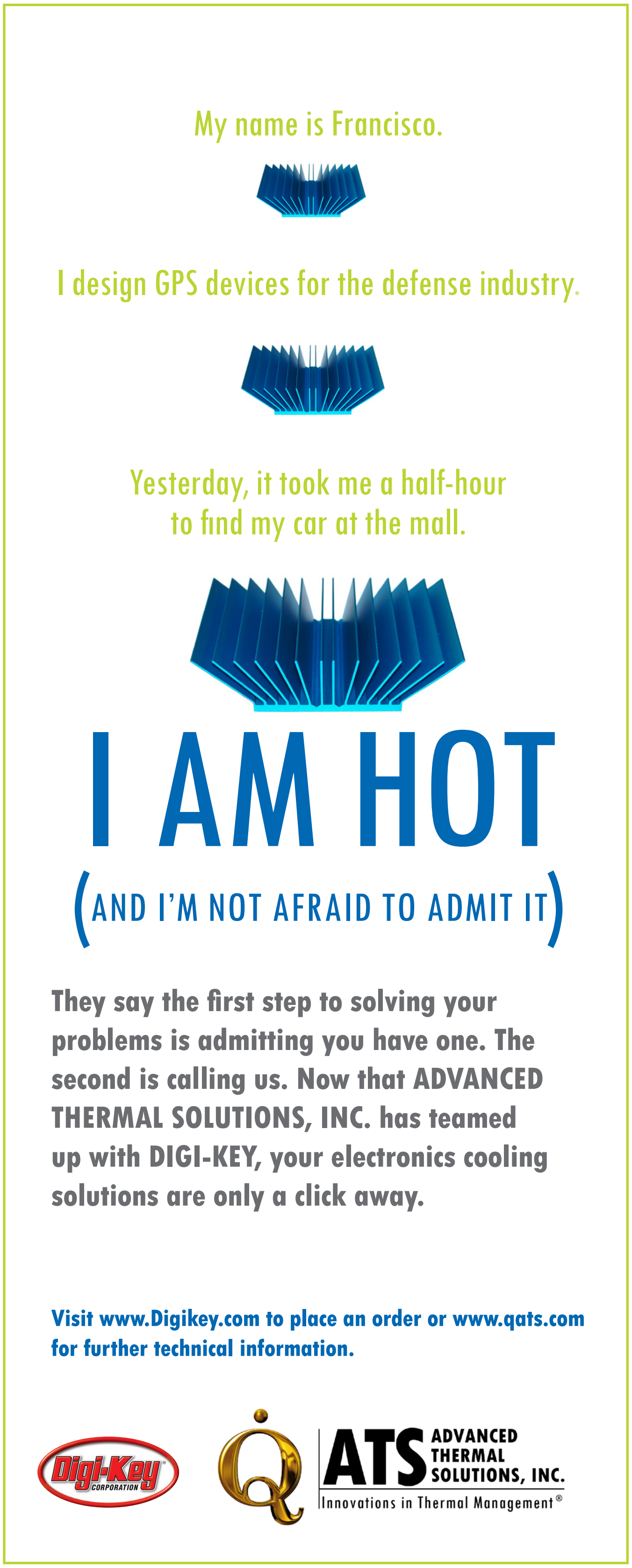
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