Air Flow Measurement in Electronic Systems

Electronic circuit boards create some of the most complex and highly three dimensional fluid flows in both air and liquid. The combination of open channel (clearance to the next card above the components) and large protrusions (components, e.g., BGAs, PQFBs, etc.) creates varied pressure distributions that contribute to such flow complexities. These distributions include highly three dimensional flows with all modes of fluid flow structures (laminar, turbulent, pulsating, unsteady, etc.) and significant flow reversals, see Figures 1 and 2.

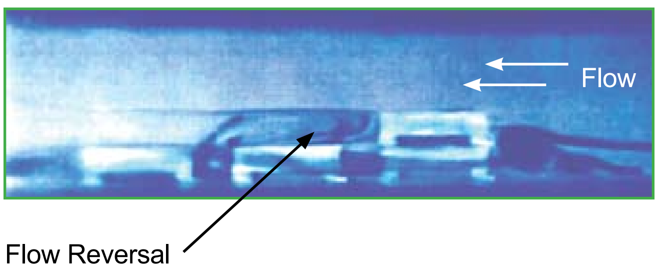


Figure 1. Visualization of Water Flow over an Electronic Board. The First Component is Twice the Size of the Others Down-Stream.

Figure 2 shows a Direct Numerical Simulation (DNS) of a PCB with straight and disked fin heat sinks. Note the complex flow structure with premature egress of the flow from the fin field in both types of heat sinks.

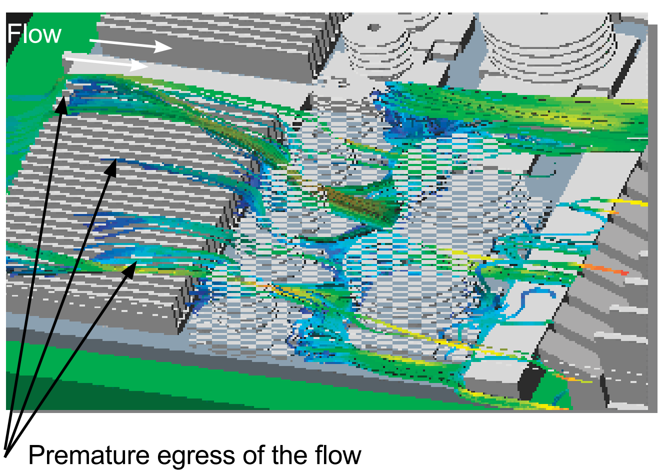


Figure 2. Computational Fluid Dynamics (CFD) Simulation of a PCB with Straight and Disked Fin Heat Sinks.

The complexity and unpredictability of these flows present problems when one needs to determine the temperature rise in a channel or a device's junction temperature. Because most analysis tools fail to accurately predict such complex flows, direct measurements are often needed.

The Role of Fluid Velocity

Fluid velocity has a significant role in maintaining or determining a component's junction temperature

Figure 3 shows the value of R_{ja} as a function of the air velocity for a typical component.

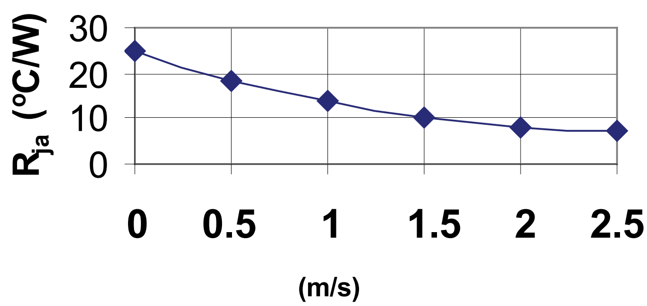


Figure 3. Junction-to-Ambient Thermal Resistance as a Function of Air Velocity.

Let's take a simple and first order approach, i.e., junction-to-ambient thermal resistance, as shown in Figure 3,

$$R_{ja} = (T_j - T_a)/P \qquad (1)$$

Where T_a is the approach air temperature obtained from the change of enthalpy across the board, upstream of the component.

$$Q = \dot{m}Cp\,(T_a - T_{amb}) \qquad (2)$$

Where Q is the power dissipated on the board, upstream of the component of interest, T_{amb} is the temperature of free ambient, and is the mass flow rate defined by the following:

$$\dot{m} = \rho VA \qquad (3)$$

Where ρ is the air density, V is air velocity, and A is the cross-sectional area of the channel. C_P is the specific heat at constant pressure.

Substituting equations 2 and 3 into 1 and solve for T_j,

$$T_j = P \cdot R_{ja} + Q/(\rho VA\ Cp) + T_{amb} \qquad (4)$$

Considering that the junction temperature, T_j, is the most important parameter in electronics cooling, Equation 4 clearly shows the role that fluid velocity plays in the magnitude of T_j.

Measuring Fluid Velocity

There are numerous techniques for measuring fluid flow liquid or gas [1]. The following methods are the most suitable for use in electronic systems:

- Hot-film and hot-wire anemometry (most common) measure fluid temperature based on heat transfer.
- Pitot tube velocimetry (not accurate for low flows). This method uses Bernoulli's equation to relate the pressure difference to the velocity
- Laser Doppler velocimetry (LDV). This technique measures the speed of micron-sized seeding particles that flow through a pair of focused laser beams. Optical access to measurement area and seeding of the flow are required.
- Particle image velocimetry (PIV). Requires optical access and seeding of the flow. It is basically LDV in a plane.

LDV and PIV, though accurate, require line of sight to the measurement area and do not measure air temperature. They are not commonly used in electronics systems, although they are effective tools in a wind tunnel setting.

Hot-Wire Anemometry (HWA)

From the methods listed above, hot-wire anemometry (HWA) is by far the most suitable method for electronics cooling applications. Hot-wire anemometers are heat transfer elements. By maintaining the wire or bead temperature at a constant level (150-250 °C) one can correlate the rate of heat required to maintain the wire temperature constant to that of the air velocity passing across the sensor. Thus, to accurately measure the velocity, one must know the temperature of the air approaching the sensor, where the velocity sensor is, and the sensor temperature itself.

The governing equation for HWA is given by 5,

$$V = \left(\frac{Q}{\alpha A_{sensor}(T_{sensor} - T_{approach})} \right)^{\frac{1}{ß}} \qquad (5)$$

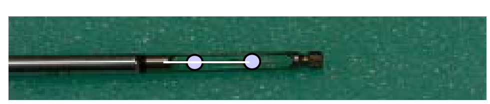
Where Q is the power to the sensor supplied by the HWA electronics, A_{sensor} is the surface area of the sensor, T_{sensor} and $T_{approach}$ are the Sensor and the Approach air temperatures, respectively, and, α and ß are deduced from the calibration of the HWA. Two points are note worthy,

1. the $T_{approach}$ plays a pivotal role in the magnitude of the velocity reported by the sensor. Therefore, in non-isothermal flows, it is imperative that the air temperature is measured at the same location as the velocity sensor.
2. α and ß are calibration dependent. If the HWA is not calibrated properly, the data reported by the system will be erroneous.

There are two sensor types in the market: single and dual. With the single type, the same sensor measures both air temperature and velocity at the same location. In the dual type, two independent sensors are used for temperature and velocity measurements, and are placed apart from each other, as shown in Figures 3 and 4.

Figure 3. Single Sensor Technology (Product of Advanced Thermal Solutions, Inc.)

Figure 4. Dual Sensor Technology



These technologies have some unique advantages. Yet, both also have design disadvantages that may affect measurement results.

In single sensor technology, there is a brief lag time between the temperature and velocity measurements during which the temperature might slightly change. While this difference, if any, is typically miniscule, the results are not based on perfectly simultaneous measurements.

There are four key possible sources of error in dual sensor technology:

1. Fluid temperature gradient.
2. Radiation heat transfer between the velocity sensor and the temperature one.
3. Lack of calibration at elevated temperatures.
4. Sensor size and its support body.

1 - Fluid Temperature Gradient

Dual sensors measure temperature and velocity at two different points. This can cause significant errors if the air flow is non-isothermal – which is the case with the air flow over most PCBs. Using Equation 5, the table below shows the magnitude of such errors:

Table 1. Induced Errors Resulting from Non-Isothermal Flow in a PCB Channel.

Velocity (m/s)	Fluid Temp T_a (°C)	Error in velocity (%)
1	30	0
1.21	35	21
1.35	38	35
1.45	40	45
2.1	50	110

2 - Effect of Radiation Heat Transfer

Dual sensors feature the hot (velocity) and cold (temperature) elements working in close proximity. Radiation coupling between them causes the temperature sensor to report a $T_{approach}$ that is substantially larger than the actual. As a result, the measurement system will produce significant errors in air velocity magnitude.

Table 2. Effects of Radiation Heat Transfer on Dual Sensor HWA Temperature Measuring Probe.

Actual Temperature	Reported by Thermocouple (T_{TC})
17.4	20
21.4	24
25.4	28
27.4	30

By referring to Table 1, one can see what the error in velocity measurement will be as the result of radiation heat transfer to the temperature sensor.

3 - Lack of Calibration at Elevated Temperature

Because a HWA is a heat transfer sensor, and is exposed to high temperature air during actual testing, its calibration must include the impact of air temperature at different levels. Without elevated temperature calibration the results will be riddled with measurement errors. Figure 5 shows the typical calibration surface that is required for elevated temperature testing.

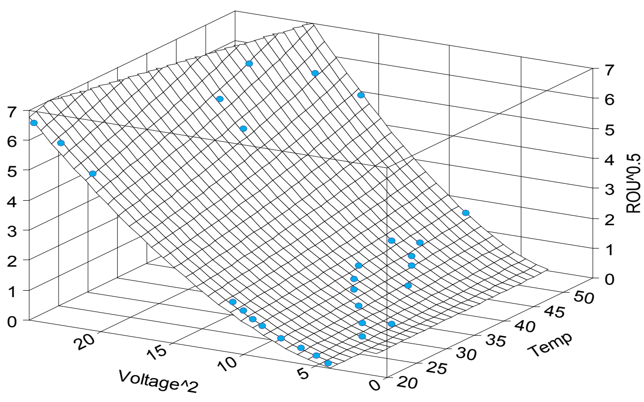


Figure 5. Required Calibration Surface Including the Effects of Elevated Temperatures.

4 – Size of Sensor, and Its Support Body

Good measurement practices mandate that the best sensor is the one that introduces the least disturbance in the flow field. As seen in Figure 6, large blocks alter the flow dramatically and cause errors in measurement.

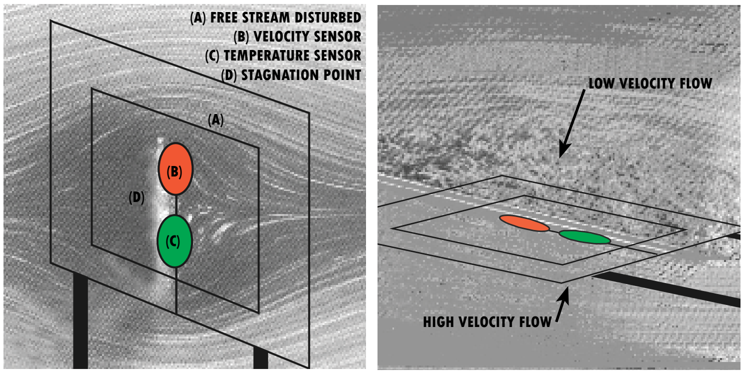


Figure 6. Effect of Large Sensors in Flow Dispersion.

The following example shows the magnitude and impact that such sensors have on the final design or operation of a system.

Example - Measuring Air Velocity in Telecom Equipment

Extreme temperature gradients are commonly observed in typical electronic cabinets. An improperly designed HWA can give false readings when used in these environments. Figures 7a and 7b show temperature and velocity distribution in a telecom cabinet, where:

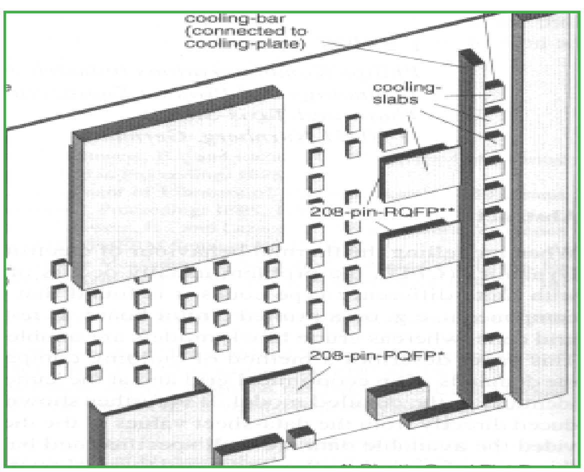


Figure 7a. Typical Telecom Cabinet.
(Philips Kommunications Industrie AG)

T_a=30

P=7 W

$T_j=T_a+R_{ja}P$

T_j =30+15x7 =135 °C at 1 m/s, actual.

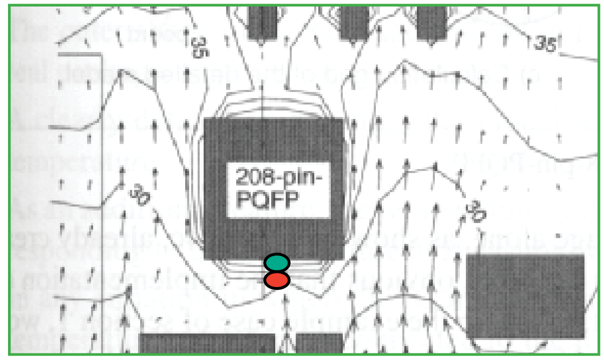


Figure 7b. Dual Sensor HWA Used to Measure V_a and T_a for Calculating Junction Temperature

By using Equation 5 and the data from Figure 7b, had we used a dual sensor, the resulting velocity would have been 1.35 m/s vs 1 m/s. Subsequently, the device junction temperature would have been

T_j = 30+11x7 =107 °C at V=1.35 m/s.

Considering that for a typical ASIC the set limit, i.e., critical junction temperature, is 125 °C, any temperature at least 10% below the set limit is acceptable. In this application, had the engineer used a properly designed sensor, where the air temperature and velocity were measured at the same point, the resulting junction temperature would have been 135 °C. This is substantially above the critical temperature of 125 °C. Now, the use of dual air velocity sensor resulted in junction temperature of 107 °C, substantially below the critical temperature, and thus rendering the design acceptable. But in reality, the ASIC will be operating at an unacceptable temperature of 135 °C that will adversely impact its electrical operations and reduce its expected life.

Examples like these show that accurate air flow measurement is an essential component of successful product design. Since device temperature impacts system life and is a direct function of air velocity, choosing a properly designed flow sensor will be instrumental in the success of the product in the market place.

Reference:

Azar, K., Thermal Measurements in Electronics Cooling, CRS Press, 1997.