Air Flow Data is Key to Heat Control in Enclosures

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The demand for miniaturization means that devices must provide greater functionality in higher density and lower profile spaces. Hardware for telecom and internetworking continues to pack more processing power into smaller physical packages, whether at the board or the system level. The boards inside are subject to finer spacing and need room for a larger number of unevenly sized components. Shelves have more boards that are slotted at a lower pitch, and frames must pack everything into smaller footprints.

In networking equipment, the power on the boards is similar, but heat concentrations vary per card. Circuit boards present growingly complex and highly three dimensional airflow structures. Their combination of open channel (clearance to the next card on top of the components) and large component protrusions, e.g. BGAs, PQFPs, creates varied pressure distributions that contribute to complex airflows. Common airflow characteristics include laminar (parallel), turbulent, pulsatile (pulsating), and unsteady, along with significant flow reversals co-existing in the volume, i.e., PCB.

Why are airflow characteristics and structure important? All devices in an air-cooled system must be kept within their operating temperature limits. That is their maximum allowed device junction temperature. Device manufacturers provide these specs for the user to perform thermal analyses, along with such data as power dissipation and package thermal characteristics. Some OEMs are also required to report on the heat load dissipated by their electronic boxes. For example, ASHRAE guidelines call for information technology manufacturers to provide heat release values to help plan the thermal management of data centers.

Taking the Air's Temperature and Velocity

The key for determining a system's airflow requirement is to find the temperature and velocity of the approach air for each given device. For rack-based enclosures, critical factors for this analysis range from the physical architecture, to power dissipation, to fan placements. Other elements are venting, spacing from adjacent systems, and environmental issues. Taking all these into consideration, the objective is to develop an understanding of the volumetric flow of air within the system and where the hotspots are found.

Airflow occurs only when there is a difference between pressures. Air follows the path of least resistance and will flow from a region of high pressure to one of low pressure-- the bigger the difference, the faster the flow. An uneven distribution of airflow passageways can deprive devices from the benefits of convective cooling.

In Figure 1, a water tunnel containing dyed fluid reveals flow reversal when the first component encountered is twice the size of the other parts downstream.

A clear picture of airflow distribution across a PCB can be achieved using experimental and computational techniques. Computational fluid dynamics, CFD, is a popular software-driven approach that is ideal in the conceptual design phase for avoiding potential airflow (and other) problems. Direct Numerical Simulation, DNS, is a form of CFD that can provide a more accurate picture at all levels of a design if experimental tools are not readily available, e.g., flow sensors or air or water tunnels for flow visualization.

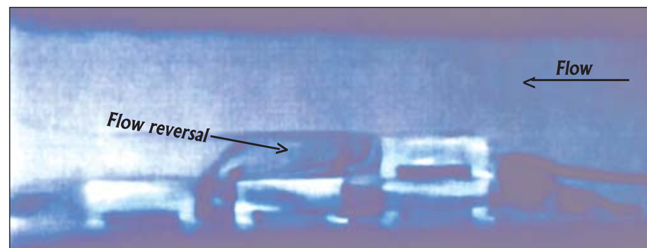

Figure 1 - Water-based visualization of flow in an electronic board with the first component being twice the size of the others down-stream

In Figure 2, a direct numerical simulation model shows a board with both straight and disked fin heat sinks. The air travels in an uneven flow pattern and there is premature egress of the flow form the fin field in both types of heat sinks.

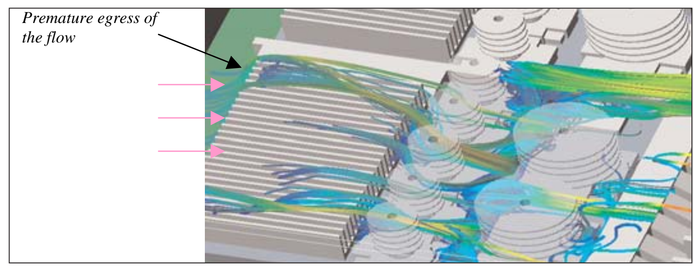

Figure 2 - Computational Fluid Dynamics (CFD) simulation of PCB having straight and disked fin heat sinks

Where these complex and unpredictable flows present problems is when it comes to determining the channel temperature rise or a device's junction temperature. Because most analysis tools fail to accurately predict such complicated flows, it's necessary to take actual airflow measurements. The key is to take enough measurements to be able to pinpoint the problem regions. Some of these spots are not readily detectable but can be discovered with non- to least-intrusive devices such as thin, low-profile sensors that won't alter the airflow characteristics.

With a good understanding of the airflow profile, individual components should be reviewed for their thermal condition. Problem components can often be addressed by optimizing the fan system or by adding an off-the-shelf heat sink. In severe cases a high performance, custom sink is needed to work with the available airflow, but this will cost less than redesigning board layouts.

The Role of Fluid Velocity

Fluid velocity plays a significant role in maintaining or determining the junction temperature. Let's take a simple and first order approach, i.e., junction-to-ambient thermal resistance.

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

Where Ta is the approach air temperature and is obtained for the change of enthalpy across the board upstream of the component.

$$Q = mC_p\,(T_a - T_{amb})$$

Where Q is the power dissipated on the board, upstream of the component of interest, m is the mass flow rate and is equal to:

$$m = \tilde{n}VA$$

Where? is the air density, V is air velocity and A the cross sectional area of the channel, with Cp being the specific heat at constant pressure.

A simple calculation shows the following:

$$T_j = P \cdot R_{ja} + Q/(\tilde{n}VA\;C_p\,) + T_{amb}$$

Where Tamb, is the temperature of free ambient. Equation (2) clearly shows the role fluid velocity plays in the magnitude of the junction temperature, which is the most important parameter in electronics cooling.

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Measuring Fluid Velocity

There are many techniques for measuring airflow. Here are some of the methods that are well-suited for use in electronic systems:

- Hot-film and hot-wire anemometry (most common). Measures fluid temperature based on heat transfer.
- Pitot tube velocimetry (not accurate for low flows). Uses Bernoulli equation to relate the pressure difference to the velocity
- Laser Doppler velocimetry (LDV). Requires optical access and seeding of the flow. Measures the speed of micron-sized seeding particles that flow through a pair focused beams.
- Particle image velocimetry (PIV). Requires optical access and seeding of the flow. It is basically LDV in a plane.

Note: LDV and PIV, though accurate, require line of sight and do not measure air temperature.

Hot Wire Anemometry (HWA)

Of the aforementioned airflow measurement techniques, hot wire anemometry (HWA) is by far the most suitable method for electronics cooling applications. By maintaining the wire temperature at a constant level, i.e. between 150-250°C, you can correlate the rate of heat loss to the air velocity passing across the sensor. To accurately measure the air velocity, it is necessary to know the temperature of the air approaching the sensor, where the velocity sensor is located, and the temperature of the sensor itself.

There are two basic sensor types: single and dual. See Figures 3 and 4. Single sensors measure both air temperature and air velocity at the same location. Dual models include a second sensor for measuring the approach air temperature, but at a distance away from the velocity sensor.

Figure 3 - Single sensor technology **Figure 4 - Dual sensor technology**

While physically less invasive, dual sensors have certain features that may become sources of error. The following are the most common issues.

T_a	T_{TC}
17.4	20
21.4	24
25.4	28
27.4	30

Fluid Temperature Gradient

Due to the non-isothermal nature of airflow in electronic enclosures, dual sensors used for measuring temperature and air velocity at two different points can cause significant errors, particularly as values increase.

Radiated Heat Transfer

Dual sensors contain both hot (velocity) and cold (temperature) areas. Radiation coupling between the two will cause the temperature sensor to report a Ta value that is substantially larger than the actual. As a result, the measurement system will produce significant errors in air velocity magnitude.

Lack of Calibration at Elevated Temperature

Because HWA is a heat transfer sensor, and is exposed to high temperature air during actual testing, calibration must include the impact of air temperature at different levels. Not having such calibration, there will be measurement errors.

Sensor Size 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 can be seen in the figures below, large blocks alter the flow dramatically and cause errors in measurement.

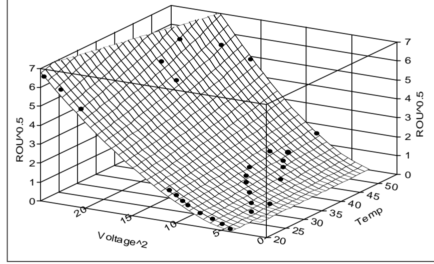


Figure 5 - Required calibration surface that contains the effect of elevated temperature.

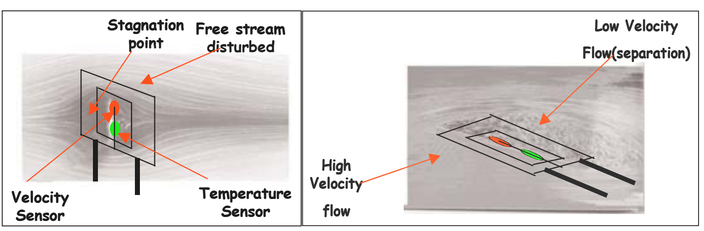
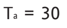


Figure 6 **Figure 7**

Here is an example of the magnitude of error that can be introduced when a velocity sensor is not designed to address the complexity of the airflow and temperature seen in electronics applications.



T_a = 30

P = 7 W

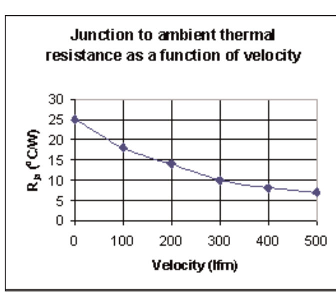
T_j = Ta + RjaP

T_j (at 200 lfm) = 30 + 15 by 7

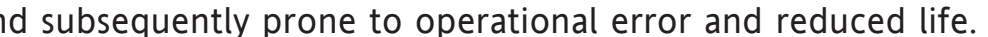
= 135°C at V = 200, actual

T_j (at 270 lfm) = 30 + 11 by 7

= 107°C at V = 270, measured using an improper



The use of improper sensors resulted in an error of 28°C in calculation of junction temperature. Certainly at 107°C, the design is a go, but in a real application, its temperature will be in excess of 135oC and subsequently prone to operational error and reduced life.



Conclusion

A variety of thermal management issues have been solved using multipoint air velocity measurement. Typical uses include evaluating the performance of fans and heat sinks. Another use is verification of CFD software modeling. It is an accepted industry practice to verify software models with lab tests and replicas. Similarly, multipoint measurements have been used to profile printed circuit boards to determine critical component placement and to monitor quality. The best place to address thermal problems is in the concept stage where they are relatively cheap to fix. Unfortunately, this doesn't happen often enough. Then, the cost for failing the eventual thermal tests will be much higher in terms of price and time.

Advanced Thermal Solutions, Inc (ATS) is a leading-edge engineering/manufacturing company focused on the thermal management of electronics. Founded in 1989 as a consulting company, ATS has evolved to a complete thermal solutions provider and is world renown for its portfolio of more than 450 high- and ultra performance heat sinks, research-quality test equipment, and leading-edge R&D.

In the interval of three years, ATS has established its own manufacturing center in the U.S., developed strategic partnerships with Asian manufacturers and opened ATS-Europe, its sales and engineering office in Holland. As ATS has significantly increased its customer base, its product offerings have also expanded to include Advanced Fan Trays, Liquid Cooling Systems, Advanced Cooling Systems and Next-Generation Thermal Test Instruments. For more information about Advanced Thermal Solutions please contact them at www.qats.com, 781-769-2800, or ats@qats.com.

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