Accurate Air Flow Measurement in Electronics Cooling
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Air is the most commonly used medium to remove heat from electronics enclosures. Knowledge of the air velocity plays an important role, as it provides information on the heat removal rate and the thermal characteristics of the entire electronics system. Measuring the speed of airflow has always presented a challenge since air is invisible. This paper discusses airflow measurement in electronics cooling, and how to get best results when using thermal anemometer sensors including technical information and factors affecting airflow measurement.

Topics include: thermal anemometer basics, calibration, compensation, acceptance angle, sensor placement, and interpreting results.

Why measure airflow in electronics cooling?
When air is used to remove heat from electronics enclosures, it is important to know the flow rate. The goal is to achieve the most cooling effect with as little air as possible. Pumping enough air through the system to ensure an acceptable temperature even under the worst conditions, but at the same time keeping flow rates down to avoid acoustic noise requires careful planning. Space is at a premium, causing fan placement and fan size to be critical decisions in the design process. Knowing flow rates is essential for gathering required parameters for CFD (Computational Fluid Dynamics) software, as well as validating the results from the CFD software.

Types of Anemometers
Anemometers are instruments for measuring the force and velocity of the wind. There are different technologies of Anemometers:
• Rotating Vane Anemometers
• Heated Anemometers
• Ultrasonic Anemometers
• Laser-Doppler-Anemometers (LDA)
• Pitot Tube Anemometers

Not all of these instruments are useful in Electronics Cooling. E.g., Rotating Vanes and Pitot Tubes are generally too big in size and produce signals too small at typical electronics cooling flow rates. Most importantly, different technologies have different characteristics, and can lead to different results. Improper matching of sample intervals with the 'time constant' of the flow, or insufficient measuring period length may result in systematic errors.

Measuring airflow means chasing an invisible and compressible moving medium, which shows different characteristics depending on the conditions. According to theory, in a laminar flow all particles move in parallel tracks (layers) and in the same direction. Particles exchange energy and impulse irregularly. In turbulent flows the exchange is macroscopic and detectable, because the main current is superimposed by additional components in x, y, and z direction (eddy-currents). The change from laminar to turbulent flow happens when the Reynolds Number reaches critical levels, which depends on a number of parameters like shape and cross section of flow. Airflow in Electronics Cooling is usually very turbulent due to fans, obstacles, and heat sources. Therefore measuring these velocities requires sensors that are capable of sensing under these conditions, while minimizing disturbance of the flow.
**Why thermal anemometers?**

For multiple reasons, thermal anemometers are the best tools available for measuring airflow in electronics cooling. Thermal sensors can be built small in size, minimizing obstructions in a crowded enclosure. They have a fast response time and high sensitivity, allowing measurement of turbulence intensity. Thermal sensors are available with most standard interfaces, they are very reliable and are available at relatively low cost.

**Thermal Anemometer Technology**

Thermal anemometry is a method of determining fluid velocities by measuring the heat transfer rate from a heated small object like a wire, film, or thermistor, located in the flow. The rate at which heat is removed from the sensor is directly related to the velocity of the fluid flowing past the sensor. Constant Temperature Thermal anemometers (CTA) work like a finger held up in the wind. Kept at a constant temperature above ambient, the device is cooled by passing air. The power required to maintain a constant temperature is then used to calculate the air speed. Other methods are also used.

Thermal anemometry is a flexible, accurate, and almost entirely automated way of flow measurement. It can be applied to nearly any flow, where the physical presence of a sensor does not adversely affect the current, or where contaminants in the flow do not damage the sensor. It is especially appropriate for applications requiring very fast response to flow changes (turbulence measurements), and where cost limitations are a factor.

Heated anemometers are best characterized by the heat transfer rate, which describes the heat loss dependence on multiple factors: temperature, pressure, content of gas, nature of flow. Not all of the above have the same influence on measurement, but each one should be considered to achieve accurate readings.

**Temperature:** Thermal anemometers require temperature compensation because the heat transfer rate depends on the temperature differential between the heated sensor and ambient air. The greater the temperature differential, the greater the heat loss and, consequently, the greater the signal. However, a hot device can also alter the nature of the flow by adding heat, or causing warm air to rise.

**Pressure:** Molecules carry heat. Below standard pressure (760mm Hg, 101.3kPa), e.g. at high altitude or in a vacuum chamber, a lower number of molecules is available to carry away heat from the heated sensor, which will then read low. Above standard pressure, additional cooling is provided due to an increased number of molecules, and the heated sensor would read high. Heated anemometers therefore need to be pressure compensated.

**Content of gas:** Thermal anemometers are usually calibrated for air in human environments. In case such a sensor is used with gases different from room air, the calibration might no longer be accurate due to different heat capacity and heat transfer rate depending on content of the medium. Secondly, aggressive chemicals might damage the probe. Also, deposits on the probe head might alter aerodynamics and affect the accuracy of readings. Humidity does not necessarily change heat transfer rates significantly. Studies show that there is less than a 3% change in the velocity reading while relative humidity changes from 5 to 95% in air at room temperature. However, water condensing on the sensor can cause calibration errors.
**Nature of Flow:** Air forced through tight openings or nozzles shows different characteristics than a current moving along a straight duct. Fans can generate heavily turbulent flows in a corkscrew-like pattern even far downstream. Components on a circuit board or obstacles in ducts are likely to redirect flow, as fluids always follow the path of least resistance. Rapid pressure changes are likely where gases are forced through nozzles, tight openings or close to fast-turning fans. Air is a compressible medium, and due to its invisibility may show unforeseeable behavior that might affect readings of thermal anemometers. It is therefore advisable to always verify results.

**Theory of Operation of Thermal Anemometer Sensors**

*Thermal anemometer sensors* use the cooling effect of air passing by a heated device for determining the air speed. The amount of electrical power required to maintain the device at a constant temperature (Constant Temperature Thermal Anemometer CTA), is equivalent to the heat carried away by airflow past the device.

**Temperature Compensation**

The calibration of all thermal anemometers is profoundly affected by the ambient temperature of the air flowing past them. Unless an anemometer is compensated for this, it will be correct only at the temperature at which it was calibrated. Therefore, temperature compensation is essential, and normally part of all such products. To do this, the ambient temperature of the flowing air is measured and used as part of the compensation algorithm, to provide a compensated air velocity measurement.

There are two ways to do this. The first method uses two separate sensors for airflow and temperature, e.g. the AccuSense sensors that use two thermistors (*Fig. 1*).

![Sensors on the AccuSense CAFS series.](image)
The temperature sensing thermistor and the airflow sensing thermistor are mounted in close proximity to one another. Airflow and temperature signals are sampled virtually simultaneously (Fig. 2), and read into the system. The small displacement in position (5 mm / 0.2” on AccuSense sensors) between the two is immaterial for most purposes, since flow inside cooling systems is typically quite turbulent and is not markedly isothermal in most cases.

The second method (Fig. 3) uses a single sensor for both the temperature and airflow reading. The same sensor is time-shared between airflow and temperature measurements. It is first heated up and then sampled for airflow. A cooling down period follows this, and the sensor is then sampled for temperature. The limiting factor however is the time of 1 to 2 seconds it typically takes to cycle through this consecutive measurement process, which is determined by the thermal time constants of the sensor.

This does not yield a real-time, simultaneous reading. The reality is that the segment of air that is sampled for airflow is physically separated from the segment in which the temperature is sampled by the air velocity times the cycle time. At 3 m/s (600 fpm), it is between 3-6 m (10 and 20 feet)! (Fig. 3)

In other words, the segment of air, which is used for temperature compensation, may be as much as 6 m (20 feet) away from the segment in which the airflow is measured. The time separation of 1 to 2 seconds between the airflow and temperature readings is converted to a large physical separation.

If changes in air velocity or temperature are recorded over time, it is usually essential to take readings uninterruptedly over a longer period of time.
Fig. 4 and Fig. 5 show how valuable information might be lost while alternating between airflow and temperature measurement using method 2, while method 1 provides information on both parameters simultaneously.

![Simultaneous sampling of airflow and temperature](image1)

Fig. 4: Simultaneous sampling of airflow and temperature

![Alternated sampling of airflow and temperature](image2)

Fig. 5: Alternated sampling of airflow and temperature

Clearly, Method 1 is preferable, because it provides the most precise compensation and lowest temperature reading errors.

**Acceptance angle of anemometer sensors**

Anemometer sensors are typically not uniformly shaped, which causes them to be direction sensitive. It is therefore important to know the orientation at which a sensor was calibrated, and what errors to expect if certain acceptance angles are exceeded. In the following, we are using the AccuSense AFS and CAFS Airflow Sensor Series as an example.

For calibration, the sensors are installed in the AccuSense wind tunnel perpendicular to the oncoming air stream. The air moves through the two holes in the sensor head *(Fig. 1)*, across the sensor beads. Due to the aerodynamics of the sensor head,
misalignment can cause the airflow to go around the sensor head rather than across the beads, which can lead to errors. To learn about the limits of the technology, and to find the influence that the acceptance angle had on airflow sensor readings, AccuSense performed the following experiment. Both a Clip-On and Low-Profile Sensor were inserted into the airflow of AccuSense’s wind tunnel at room temperature. Readings were then recorded with the sensors turned in increments of 5° from the original perpendicular position. This experiment was performed multiple times and at different speeds to ensure repeatability.

Figure 6: Accuracy sensors vs. angle from perpendicular of oncoming airflow.

Figure 6 shows the results for Clip-On (AFS) and Low-Profile (CAFS) Sensors. The horizontal axis represents the angle in degrees from perpendicular, at which the sensor head was facing the oncoming airflow. On the vertical axis the error in percent compared to the sensor in ideal (perpendicular) position to the flow is displayed. This example shows how important it is to know the characteristics of a sensor, which should be considered when interpreting results. It also shows, that thermal anemometers are well suited for electronics cooling applications, where the air moves irregularly and it is difficult to predict the angle at which it approaches a sensor. As long as this angle lies within an imaginary cone with a 90° angle at the tip (Fig. 7), the error from the acceptance angle will not exceed 2% compared to a reading taken perpendicular to the airflow, making the sensor angle tolerance ±45°.
Fig. 7: Airflow acceptance angle as recommended by AccuSense

Fig. 8: Heated sensors may cause convection at very low flows.

**Low Velocities**

There is one limitation to thermal anemometers. At low velocities, below 0.15 m/s (30 fpm), hot air rises upwards from the heated sensor (convection). This might be detected and cause a higher reading than the airflow is actually moving. This problem is typical of all heated anemometer sensors, and users should question accuracy claims to 0 m/s (0 fpm).

**Sensor placement**

When mounting thermal anemometer sensors in electronics enclosures, on circuit boards, heat sinks and close to fans, it is advisable to keep the following issues in mind to avoid inaccurate readings:

1. Air always takes the path of least resistance. That's usually the widest opening.
2. Sensors might block or redirect flow if placed close to tight openings or obstacles.
3. Close to fans the airflow is usually extremely turbulent and eddies might cause a reversed airflow.
4. Always use sensors within their specified calibration range only, and have sensors recalibrated as recommended by the manufacturer.

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