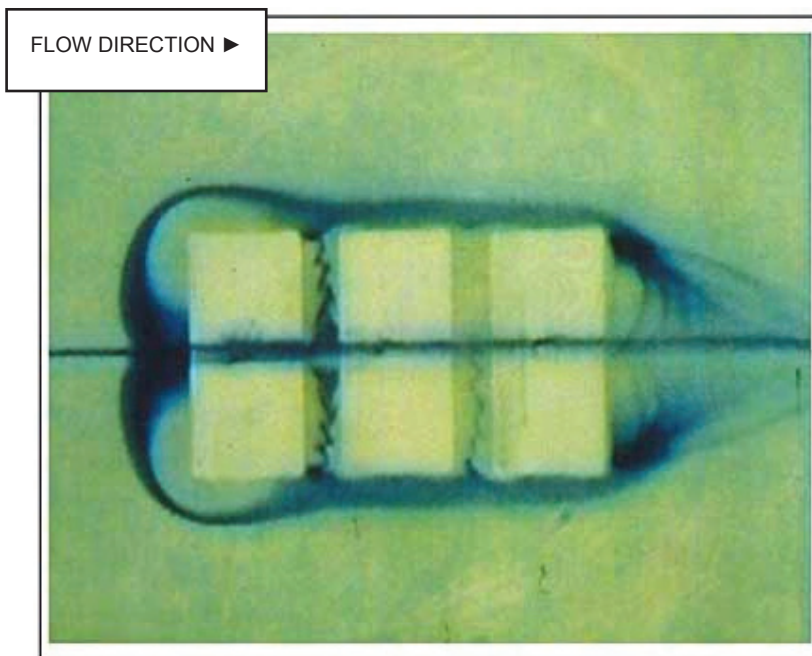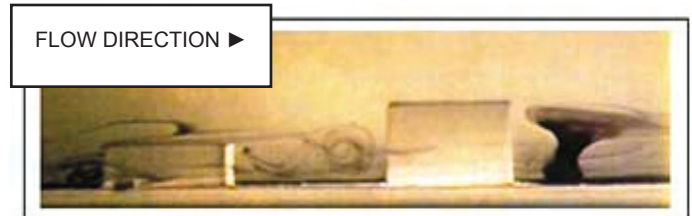# Using Flow Visualization for PCB Thermal Design and Optimization

FLOW DIRECTION ►

◄ Figure 1. Top View of Flow Around Equal Sized Components, Depicting Reversed Flow in the Wake of the Component and Rotational Flow on the Outer Periphery and in Between Components [2].

FLOW DIRECTION ►

▲ Figure 2. Flow Around Two Components of Varying Heights and the Same Planar Area. The Flow Between the Components Exhibits Oscillation and Reversal. the Wake Shows a Near Stagnant Rotating Flow.

PCBs support a multitude of components with varied geometries, electrical functions, power dissipation and thermal performance needs. For a PCB to work properly, a component's thermal requirements must be met locally or at the system level. Regardless of the type of housing that surrounds a PCB, its cooling system must be designed so that diverse components are electrically functional and run at temperatures that help them reach their expected life spans.

Much effort is needed to meet a component's thermal requirements, whether by enhanced fluid flow (liquid or air) or by adding a cooling solution, e.g., heat sink, onto the component. Except for a conduction cooled PCB, where a coldplate extracts heat from the board, electronics are typically in contact with some sort of cooling fluid. In many cases, the PCB is in direct contact with the coolant. This creates a very complex problem along with a unique opportunity.

The problem stems from the intricate topology of the PCB. Highly complex flows are observed on PCBs due to their three dimensional protrusions, i.e., components. A typical PCB sees every imaginable flow structure [1]. These include laminar, turbulent, separated flow, reversed flow, pulsating, locally transient and others. Figures 1 and 2 show examples of these complex PCB flow structures [2].

These flow visualizations were made in a laboratory water tunnel at Advanced Thermal Solutions, Inc. Because the flows are very complex, water flow visualization using colored dyes captures the flow details more accurately than air flow visualization. These flow structures are identical whether in air or water as long as the Reynolds number is the same for both conditions.

The complexity and structure of fluid flow in PCB topologies creates a unique thermal problem. Despite many

attempts to improve flow at the inlet of a PCB, the board layout diverts the flow to the path of least resistance. This generates regions of stagnation and creates high pressure areas. The components are deprived of cooling air or liquid. Figures 3a and 3b show one such example.
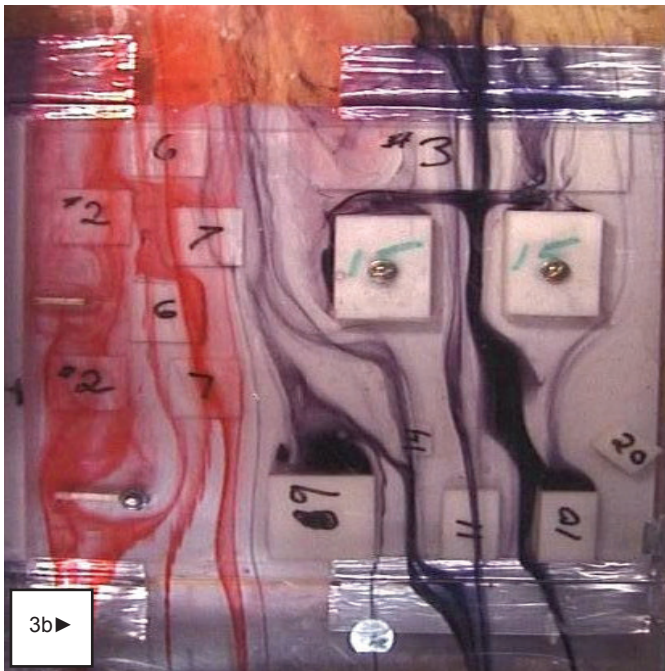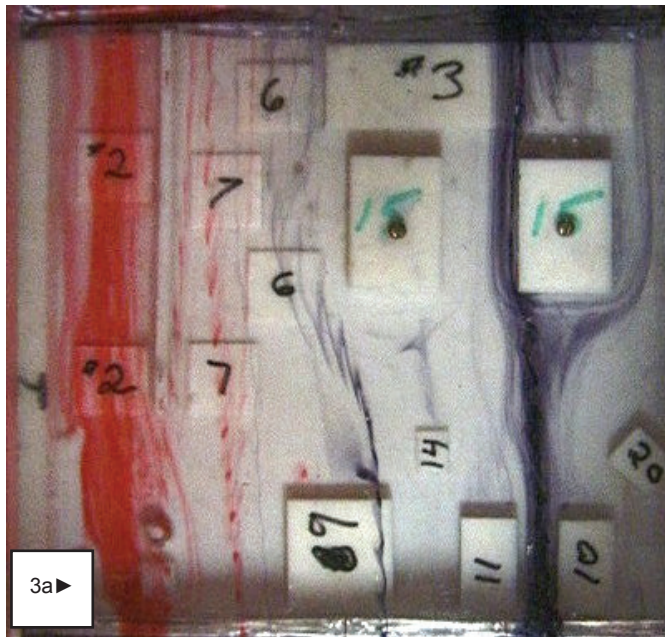

3a ▶

3b ▶

Figure 3a. Original Layout, Components.
Figure 3b. Optimized Layout.
Note: Components 6, 7 and 9 are Deprived of the Flow.

In Figure 3a, visualization lets the engineer see the fluid flow pattern on the PCB and identify those areas and components where flow exposure is at a minimum. By reconfiguring the board (note the location of components 6, 7 and 9 which is rotated 90°), as shown in Figure 3b, the pressure distribution on the PCB was balanced and subsequently the flow distribution improved significantly.

Another significant advantage of flow visualization is the measurement of local velocity. Simple videography (30 FPS) on a scaled distance can provide the approach air velocity to each component on the PCB. This gives the designer local knowledge of the flow magnitude and type for help when choosing the cooling system.

Considering the complexity of fluid flow in a PCB, predicting flow patterns is not reliably achieved with numerical modeling. In some instances, the result has been significant prediction errors in component junction temperature [3, 4]. Flow visualization has the potential to yield more insight into a fluid flow or convection cooling problem than any other single method. Many misconceptions can usually be cleared up by flow visualization. However, it is important to use the technique most suited to a given problem.

The flow of a fluid may be characterized by one of the following four terms, which must be carefully defined:

Streamline: a curve that is tangent everywhere to the instantaneous velocity vectors.

Streakline: the locus of all fluid particles that have passed through a prescribed fixed point during a specific interval of time. An example of a streakline is a line traced by the continuous injection at a certain point of dye, smoke or bubbles.

Pathline: the curve traversed by a particular fluid particle during a specified time interval, such as that produced by time-exposure photography of a tracer particle moving in a flow.

Timeline: a set of fluid particles that form a line at a given instant, such as would be obtained in a short-time exposure photograph of a line of hydrogen bubbles released from a wire to trace the velocity profile in a fluid.

While a streamline is mathematically the most tractable, the others are easier to generate experimentally. Streamlines and timelines are instantaneous entities, while streaklines and pathlines are generated over a period of time [5].

Azar, et al., [5] report that the literature abounds in flow visualization methods and their use in a wide range of situations. Flow visualization methods can be grouped into two categories: those suited to investigate the complexity of streamlines just above a surface, and those suited to characterizing surface heat transfer properties. When combined, these analyses can provide a detailed description of the flow phenomena and their effects on heat transfer processes.

This article is confined to the methods the authors consider most applicable for visualizing air flows in electronic systems. These techniques appear in Table 1 and can be reviewed more thoroughly and in greater detail by reading Garimella [6]. The principle for each technique is described in addition to general implementation details, with examples of visualizations also given. Unlike shadowgraph and Schlieren, HI (holographic) is especially easier to implement, with less expensive optical components, and affords high resolution as well as transient mapping. PIV (particle image velocimetry) is perhaps the most expensive of the techniques discussed, but yields accurate measurements over entire planes in the flow field.

Air Flow Visualization Methods

As reported by Azar, et al. [5], air flows can be qualitatively visualized using smoke entrainment techniques or quantitatively measured using optical methods.

Smoke entrainment is the most common visualization technique for laminar air flows. But it has somewhat limited use in turbulent flows due to its rapid diffusion by turbulent mixing. Smoke can be produced from many sources, but essentially it is made by either smoke-tube or smoke-wire.

In the smoke-tube method, vaporized oil is used to form a visible whitish cloud of small particles as the hot oil vapor condenses. Consideration must be given to the vortices shed by the smoke probe itself, since the most visible small-scale features often arise from the probe's own wake. This effect is important for probe diameter-based

Technique	Fluid	Remarks
Smoke entrainment		Inexpensive.
Smoke-wire	Air	Easy to implement.
Smoke-tube	Air	Stabilization of smoke filaments and photography need care. Results harder to interpret than in dye entrainment in liquids due to the greater extent of diffusion of smoke in air.
Dye Entrainment Neutral dye (e.g., ink)	Liquid	Inexpensive. Relatively easy to implement (injection easier than entrainment, but the latter more accurate since spurious injection velocities avoided). Good contrast is easy to obtain. Neutral buoyancy of dye must be ensured. Closed-loop systems contaminate in a short period. Interpretation and photography are straightforward.
Tracers for core flows		Relatively inexpensive.
Dye injection	Liquid	Recommended wherever practicable,
Tufts	Air, Liquid	especially in liquid-flow facilities. Excellent contrast can be obtained with a good source of illumination.
Wall traces		Relatively inexpensive but can be labor-intensive.
Oil film/powder	Air	Good for specialized applications where
Oil film/ink dot	Air, Liquid	wall shear stresses and near-wall velocity fields need to be mapped, e.g. three-dimensional corner regions which are less accessible to other methods.
Tufts probes	Air, Liquid	
Sublimation/Evaporation	Air	
Optical methods Shadowgraph Schlieren Interferometry Holographic	Air, Liquid	electronics applications, unlike shadow graph and Schlieren; HI (holographic) especially easier to implement, with less expensive optical components, and affords high resolution as well as transient mapping. PIV (particle image velocimetry) is perhaps the most expensive of the techniques discussed, but yields accurate measurements over entire planes in the flow field.

Table 1. Flow Visualization Techniques for Electronic Systems [6].

Reynolds numbers exceeding about 15. Because it is impractical to reduce the probe diameter beyond a point and still get a reasonable amount of smoke flow, the smoke can be injected upstream of a convergence section to eliminate wake effects. A key disadvantage to the smoke-tube method is that the smoke is produced hot and rises due to its own buoyancy, thus it doesn't follow the local flow faithfully. To reduce buoyance effects, the smoke can be cooled in a long length of tubing from the point of generation before its introduction into the flow.

In the smoke-wire method, smoke is generated as a sheet by coating a thin wire with oil, stretching it across the flow, and heating it with a pulse of current. Almost any wire and power supply can be used in this technique. The oil should be chosen carefully to have a broad boiling plateau, rather than a single temperature, in order to generate good smoke. Model train oil is suitable for this method.

Wire diameters of about 0.1 mm work well. Stripped chromel or alumel thermocouple wires are readily available choices. Once the wire is coated and allowed to sit, the oil draws up into regularly spaced droplets on the wire in less than a minute. Upon being pulsed with current, the droplets produce discrete parallel streaks of white smoke.

Type 1964 fog juice, with a boiling temperature of 276ºC, has also been recommended in the literature for producing dense smoke that is non-toxic and non-corrosive. An example of flow visualization obtained over a multi-component PCB using the smoke-wire method is shown in Figure 4.
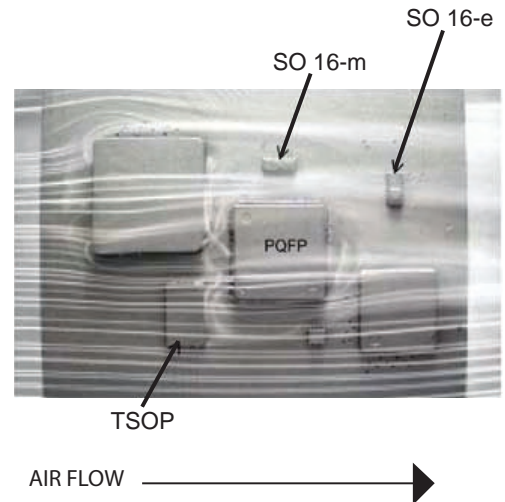

Figure 4. Experimentally Visualized Flow Fields On a Multi-Component PCB in a 2 m/s Air Flow, Using a Smoke-Wire Method [5].

While the smoke-tube method uses large quantities of smoke and produces a limited number of streaks that are rather thick (10 mm or more in diameter), the smoke-wire method can produce very thin smoke streaks (about 1 mm).

Liquid Flow Visualization

Flow visualization is usually easier to perform in water than air and yields results of better quality. As with smoke visualization, dye entrainment is successful mostly in laminar flow. The enhanced mixing in turbulent flow causes the smoke streaks to diffuse too rapidly to be of value as tracers. Compared to smoke visualization in air, dye entrainment in liquids is helped by the fact that the mixing between most dyes and water is less intense than between smoke and air [5]. As a result, water-flow tunnels are frequently used to study air flows by testing scaled models at lower velocity. This often provides a better description of the flow.

A liquid flow model is scaled with a different working fluid than air using dimensional analysis. For a treatment of the principals of dimensional analysis and similitude that should be used in applying flow visualization in model experiments, reference can be made to any standard textbook on fluid mechanics. For the flow conditions around a model to be completely similar to those of the prototype, all relevant dimensionless parameters must have the same corresponding values: the model and prototype are then said to possess geometric, kinematic, dynamic and thermal similarity.

To visualize the flow, water-soluble dyes such as food coloring, potassium permanganate, methylene blue, ink and fluorescent ink may be injected using hypodermic needles or entrained from holes or slots in the walls of a test section. It is important that the velocity and density of the injected dye equal those of the surrounding fluid to maintain a stable dye filament and reduce disturbance of the surrounding flow.

In summary, fluid flow visualization is a powerful and unique technique for quickly identifying the flow distribution and approach air velocity to thermally challenging components in a complex PCB structure. By using this technique, one can attain the following:

• Examine the PCB layout at the design stage for expected thermal performance, e.g., determine flow stagnation areas.

• Make component layout recommendations that provide a thermally optimum board.

• Identify approach air velocities necessary for component thermal management and the choice of cooling system.

The end result of board level flow visualization is PCBs that are thermally optimized and require no re-spin because of thermal constraints. If the board is thermally laid out, heat sinks and other cooling solutions are often not required.

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