Application of Experimental Airflow Visualization Techniques to Aid the Numerical Modeling of Electronic Component Convective Heat Transfer

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Abstract

This study advocates the use of experimental flow visualization to aid the numerical modeling of electronic component convective heat transfer in air-cooled Printed Circuit Boards (PCBs) applications. A detailed characterization of the airflow patterns around PCB-mounted electronic components is undertaken using different, but complimentary flow visualization techniques, for uniform 2 m/s airflows. The methods consist of traditional smoke-flow and a novel paint-film evaporation technique, which combined provide a detailed description of the flow phenomena and their effects on the heat transfer processes. A range of PCB topologies is considered, the complexity of which is gradually increased to generate different airflow phenomena. Apart from uniform free-stream conditions, the impact of upstream aerodynamic disturbance, mimicking more realistic system level flow conditions, is also studied both on component convective heat transfer and numerical predictive accuracy. These qualitative descriptions of the flow fields are used to help explain instances of prediction errors in component operating temperature, obtained using Computational Fluid Dynamics (CFD) analysis. Flow visualization is shown to be an efficient means of identifying aerodynamically sensitive regions on populated boards, where temperature prediction accuracy must be viewed with caution. It can also help with the selection of a numerical flow modeling strategy, and should be considered as a valuable design tool early in the thermal design phase.
Key Words

Experimental characterization, flow visualization, airflow phenomena, smoke wire, paint film evaporation, component heat transfer, electronics cooling, thermal management, numerical analysis, computational fluid dynamics (CFD).

1. Introduction

The thermal design of electronic equipment relies significantly on the use of Computational Fluid Dynamics (CFD) software for the prediction of component operational temperature. Its application to electronics cooling has been motivated by the drastic reduction of product development cycle times, preventing the use of extensive prototyping, and enabled by computational advances. In the early to intermediate product design phase, CFD analysis is used to select a cooling strategy and refine a thermal design by parametric analysis. In the final design phase, detailed analysis of product thermal performance is performed to provide boundary conditions for electrical performance analysis and reliability assessment. While CFD is still a computationally expensive design method, the productivity of design analysis has become a primary concern [1-3], and methods to improve CFD-based design efficiency are being actively pursued [4-7]. Responding to the demand for improved productivity, vendors of CFD codes dedicated to the thermal analysis of electronics have focused on improving code pre- and postprocessing capabilities, with turbulence flow modeling generally constrained to low-order models. These are generally algebraic or standard high-Reynolds k-e eddy viscosity models, with the turbulent exchange of heat and momentum between solid surfaces and the fluid solved using “law-of-the-wall” wall functions. Unfortunately, this approach is not entirely satisfactory for modeling the thermal and kinematic complexity of thermofluid problems in forced air-cooled electronic systems. Such systems contain complex geometries, numerous length scales, buoyancy forces and the fluid flow is often transitional [8,9] with complex flow phenomena [10]. Such phenomena are generated by cooling fans or intricate geometries such as EMC screens, vents, and populated circuit boards [11]. Fan-generated flows contain swirling flow patterns [12], while screen holes will produce jets downstream [13]. Such flow disturbances can generate unsteady or transitional flow conditions over electronic circuit boards, with attaching, separating and recirculating flow features [14]. In addition, the component topology often generates multi-dimensional flow phenomena that include pulsating and vortical structures [14,15]. All these flow features are typically present at different locations within real systems. Airflows over populated boards are usually classified as low-Reynolds number flows, on account of the low velocities and small length scales encountered [16,17], that contain pockets of turbulence generated by the component geometry [16]. Therefore, the flow modeling employed in CFD codes dedicated to the thermal analysis of electronics is not specific for these types of flow [18,19]. This limitation has been highlighted in two independent case studies that have assessed numerical predictive accuracy for PCB heat transfer. Rodgers et al. [18] analyzed a double-sided multi-component PCB topology incorporating four different component types, while Eveloy et al. [19] considered a symmetrical in-line array of fifteen Plastic Quad Flat Packs (PQFPs). In forced convection conditions, both studies showed that the operating temperature of all components could not be accurately predicted using either the laminar or turbulent flow models employed, and concluded with the need for a flow model capable of modeling
transition. Errors in predicted component junction temperature ranged from -10ºC to +22ºC (up to 35%), with discrepancies of up to 10ºC between flow models in aerodynamically sensitive regions.

These difficulties are compounded by the fact that in an early design phase, the CFD user generally has little or no a priori knowledge of the flow regime over the board, whether laminar, transitional, turbulent, and whether steady or unsteady. Such an uncertainty arises from both the absence of a physical prototype for experimental characterization, and the difficulty in defining a characteristic dimension, hence transition Reynolds number, that adequately describes the heat transfer characteristic over the PCB [18]. In spite of this difficulty, the onus is on the CFD user to select an appropriate flow modeling strategy [18,19]. Until improved flow modeling is employed, this study seeks to advocate the use of experimental flow visualization early in the design phase, to both guide the modeling strategy and enable cautious interpretation of numerical predictions in aerodynamically sensitive regions of the PCB.

2. Visualization of Airflows over Populated Boards

The three-dimensional shape and irregular nature of electronic component topologies on air-cooled Printed Circuit Boards (PCBs) give rise to complex airflow patterns that have been well documented [10,11,20]. Even laminar flows over relatively simple component shapes often exhibit multi-dimensional flow phenomena. To understand the underlying convective heat transfer processes, it is vital that the impact of such flow phenomena on heat dissipation be examined. This can be achieved by experimental flow visualization, which has the potential to yield significant insight into a fluid flow or convection problem, and thus can be an efficient approach to studying a new flow situation [20]. The literature abounds in flow visualization methods and their application to a very large range of situations, and Azar and Rodgers [11] summarize those most applicable for visualizing airflows in electronic systems. Flow visualization methods can be grouped into two categories; those suited to investigate the complexity of the streamlines just above a surface, or those suited to characterize the surface heat transfer properties. These analyses combined, can provide a detailed description of the flow phenomena and their effects on the heat transfer processes [21,22].

Numerous flow visualization studies have been undertaken to help develop an understanding of the flow phenomena about component-PCB topologies, and these have been well summarized by Garimella [20]. These studies provide excellent descriptions of the flow phenomena about classical geometries such as two-dimensional ribs [23] and cubical elements [16,24-26], or the flat pack geometries considered in this study [15,27,28]. The link between flow phenomena and convective heat transfer has also been investigated using various techniques, including mass transfer techniques such as naphthalene sublimation [29,30], interferometry [23,31,32], Particle Image Velocimetry (PIV) [31,33-36], heat flux sensors [37], and surface temperature contour maps measured using infrared thermography [10,16,33,34,38]. While it is recognized that detailed fluid flow and heat transfer measurements provide a more accurate assessment of the flow phenomena than qualitative methods, such measurements generally require access to expensive and specialized equipment more suited to the research environment, and their use may only act to prolong the design cycle. Consequently, this paper is aimed at industrial thermal
designers who may seek guidance on the selection of an appropriate numerical flow model early in the design stage, and a means of interpreting the accuracy of predicted operating temperatures before undertaking a full thermal design or system reliability calculation. To this end, qualitative techniques are most applicable.

The use of smoke-flow visualization combined with a novel paint-film evaporation method has been presented by Eveloy et al. [22] to qualitatively interpret component junction temperature prediction discrepancies between flow models on a multi-component board, and in some instances, prediction errors. The smoke-flow method permitted aerodynamically sensitive regions on the PCB to be identified, while the evaporation method provided qualitative descriptions of the PCB surface heat transfer properties. The application of both flow visualization techniques, which was confined to one PCB topology, is extended in this study to a range of PCB test vehicles, generating different airflow phenomena and varying degrees of component thermal interaction. Apart from uniform free-stream conditions, the impact of upstream aerodynamic disturbance, mimicking more realistic flow conditions such as encountered in an electronic system, is also studied on component convective heat transfer and CFD predictive accuracy.

The test vehicles employed are the double-sided multi-component PCB thermally characterized by Rodgers et al. [18], referred to as PCB A, Figure 1, and PCB topologies thermally characterized by Lohan and Davies [39]. These topologies are based on the PCB shown in Figure 2, denoted as PCB B, which is populated in incremental steps with one, seven and fifteen components. Numerical predictive accuracy for component heat transfer in free and forced convection was previously assessed for these test configurations using a CFD code dedicated to the thermal analysis of electronics [18,19]. The benchmark strategy employed was based on both component junction temperature and component-board surface temperature distributions, measured using thermal test dies and infrared thermography respectively. In the absence of a dominant length scale for describing the fluid flow regime in non-dimensional form, the fluid domain was solved using both laminar and turbulent flow models. This paper establishes the link between numerical predictions and the flow phenomena visualized herein. These visualizations are used as qualitative supporting data to help explain instances of predictive errors.

The objectives of this study, therefore are to (i) demonstrate how two complimentary flow visualization techniques consisting of smoke-flow and a novel paint-film evaporation method can easily be applied to visualize forced airflows over PCBs; (ii) highlight the relationship between flow phenomena, PCB topology and convective heat transfer; and in doing so, (iii) propose that flow visualization be considered as a valuable tool in the early design stage to both guide designers towards the selection of an appropriate flow modeling strategy, and enable cautious interpretation of the temperature predictions in PCB regions exposed to complex flows. This defines a novel approach to optimize the use of CFD codes for the thermal analysis of electronic boards. While acknowledging the fact that water flows offer better resolution of the primary flow features than air [11,15], this flow visualization study was performed using airflows due to the availability of wind tunnels and the lower cost involved.
Figure 1. Test PCB A, showing component locations and airflow direction.

Note: The lettering A to O identifies component location.

Figure 2. Multi-component thermal test PCB mounted vertically within wind tunnel test section for smoke-flow visualization.
3. Experimentation

3.1 Test Vehicles

PCB A. This topology incorporated four package types, namely PQFP 208, TSOP 48 and SO16, Figure 1. The PCB had both the same copper tracking- and component layouts, and component powering configurations on both sides. This design permitted numerical modeling to be confined to one PCB side, with an adiabatic plane applied along the PCB central in-plane axis. This topology was analyzed in two opposite airflow directions parallel to the PCB surface, Figure 1, to assess the impact of the flow phenomena on predictive accuracy. Perspex block obstructions were mounted on the PCB to introduce different degrees of aerodynamic disturbance in either flow direction. The placement of two SO16 devices at different locations permitted the combined effects of local thermal and flow interaction to be further assessed. The thermal characterization and benchmark analyses for this test vehicle are detailed in Rodgers et al. [18,21]. The three package types were firstly analyzed individually on JEDEC standard boards [40] to validate the component and board modeling methodologies. These simple PCB topologies generated less complex flow phenomena and eliminated component thermal interaction. Component junction predictions were on average within ±3ºC of measurement, with laminar and turbulent flow model predictions within 0.5ºC of each other.

PCB B. This vehicle, shown in Figure 2 for the fifteen-component population, was a single-sided board supporting an in-line array of 160-lead PQFPs. Nylon flatpacks were used to represent the functional components for flow visualization purposes. The position of each component on the PCB is identified by the lettering A to O, with A, F, K being leading edge components, Figure 2. The complexity of this PCB topology was increased in controlled stages from one centrally placed component at location H, to seven components, consisting of component H plus components A, F and K on the PCB’s leading edge and components E, J and O on the trailing edge, and finally the full population consisting of all fifteen components. These different topologies are referred to as Stages 1, 2 and 3 respectively. To mimic system level effects, flow disturbance was further increased by attaching a 50 mm-thick layer of Styrofoam thermal insulation on the board non-component side for Stage 3. While for thermal characterization [39] the primary purpose of this insulating layer was to generate a high degree of component thermal interaction, such as that present on double-side PCBs that do not permit heat loss from the non-component side, in this instance it also acted as a controlled flow disturbance having a similar influence on the flow and heat transfer as that generated by structural supports and ancillary electronic equipment, such as power supplies and transformers, in real systems. The extent of flow separation was controlled, however, by having this insulating block contoured with an elliptical profile at its leading edge.

3.2 Flow Visualization Techniques

Flow visualizations were performed for 2 m/s free-stream air velocity. This velocity is representative of those encountered in industrial applications, which are confined to the 0 to 5 m/s range, both to minimize acoustic emissions and due to component thermal resistance reaching an asymptotic limit at higher velocities. 2 m/s was found to exceed the region where PCB heat transfer was buoyancy-aided.

Smoke-Flow Visualization. The flow streamlines over the test PCBs were visualized using the smoke-wire technique [21,41].
Smoke was introduced into the flow using a 0.18 mm diameter, heated nichrome wire, placed upstream of the PCB’s leading edge and flush with its surface, as illustrated in Figure 2. This wire had a resistance of 19 Ohm/m and a 10V power pulse was used to combust tiny oil droplets on the wire to give strands of bright white smoke that illuminated the downstream flow fields. The oil used was Dantec’s Safex ‘Standard’ fog fluid [42]. The test environment used for PCBs A and B were wind tunnels having 200 and 300 mm square test sections respectively, generating uniform velocities. As indicated in Figure 2 for PCB B, the test boards were located centrally and vertically within the respective test sections. The visualized flows were recorded using a digital video camera.

**Paint-Film Evaporation.** This method was used to highlight the impact of the flow features visualized using the smoke-wire technique, on the surface heat transfer. The principles of the method, which is a mass transfer process, are outlined in [22], where it was applied to PCB A. Heat transfer rates are indicated by monitoring the rate at which a thin, evenly applied layer or film of paint, initially wet, evaporates from the PCB surface. The application of this technique was further developed in this study for PCB B.

For this test vehicle, the paint-film applied consisted of an ethanol - talc powder mixture, in the approximate ratio 30:1. The use of this mixture enabled a faster drying sequence than with the isopropanol – talc powder mixture used for PCB A [22]. Consequently, contrary to [22], PCB B was not pre-heated prior to applying the paint-film to accelerate the evaporation process. Pre-heating could result in non-uniformity of the board surface temperature during board cooling. Such a transient heat transfer process could adversely impact on the adiabatic drying, hence evaporation sequence. Although this factor was not found to be a significant issue in [22], it was eliminated here considering the greater complexity of the PCB topologies and associated flow fields. As in [22], the PCB was horizontally orientated within the wind tunnel test section to facilitate the application of the paint mixture, but without airflow. Contained within a sealed bottle, the ethanol - talc powder liquid mixture is pressurized by a small hand pump and forced through a nozzle located approximately 250 mm above and downstream of the horizontal PCB surface. Access to the PCB is achieved by removing a window on the wind tunnel test section’s top wall, Figure 2. As the jet of fine mist emerges it is directed towards the PCB at an angle of 30° and allowed to descend onto the PCB surface. The jet is removed once the entire PCB surface has been wetted. Note that this paint-film is so thin that it only acts to dampen the PCB surface and excess paint build-up or droplets in certain regions should be avoided. At this stage the test section is resealed, airflow applied and the visualization results are obtained by recording the evaporation process for up to five minutes. The contrast between the dry regions, indicative of high heat transfer, and the wet regions, is enhanced through the use of the talc powder that leaves a gray finish when dry. The transient evaporation process was recorded using a digital video camera. The accuracy of this qualitative method is dependant upon applying a thin, evenly distributed film of paint across the entire surface. As this condition is difficult to achieve, several evaporation sequences of the same PCB topology were visualized and while some variation existed, the images presented in this paper reflect the dominant features always present.
4. Results and Discussion

Interpretations of the flow fields visualized about the PCBs are presented and used as supporting qualitative data to provide an insight into instances of numerical component junction temperature prediction errors.

Study A

The visualized smoke-flow and paint-film flow fields over PCB A are presented in Figures 3 and 4 respectively. Component junction temperature prediction accuracy on PCB A, in both the forward and reversed airflow directions, is presented in Table 1.

Smoke-Wire Flow Visualization. Figures 3(a) and 3(b) present qualitative descriptions of the fluid flow fields in the forward and reversed airflow directions respectively. In this instance, the heated nichrome wire was placed 25 mm upstream of the board leading edge and flush with its surface. Figure 3(a) shows a good example of the classic horseshoe vortex wrapping around the leading face of the Block 1 obstruction, identified by Boyle and Asante [15] and Azar and Russell [27]. Its presence is clearly represented by the shape of the smoke streamlines. Also in this figure, the horseshoe vortex that wraps inwardly around the PQFP back vertical face is shown by the two smoke trails which act to cool the PCB locally. Similar flow features are evident in the reversed flow direction, Figure 3(b).

Paint-film Evaporation. The visualised evaporation sequence for the forward airflow direction is presented in Figure 4. Despite the reservations previously expressed about the use of pre-heating in [22], the drying rate observed in Figure 4 seems to be proportional to heat transfer rate. Thus the drying sequence shows that regions closest to the leading edge dry first, followed by the component top surfaces and regions of high flow disturbance. The impact of the horseshoe vortex wrapping around the leading face of the Block 1 obstruction in Figure 3(a), on heat transfer is reflected by the light coloured/dry regions in Figure 4(a). Obviously the intensity of the re-circulating flow upstream of the front face of obstacles creates high shear stress and in turn, heat transfer rates. This is also evident for both the PQFP and even the low-profile TSOP in Figures 4(b) and 4(c). The similarity between the smoke streamlines both immediately upstream of the PQFP and towards the downstream face of the TSOP, and the shape of the dried regions in Figures 4(b) and 4(c) is striking. Similar observations can be made between Figures 3(a) and 4(d) immediately downstream of the PQFP, with the flow stream sweeping in from the right-hand side drying a similar shape portion of the PCB surface.

A comparison of the drying sequence for both SO16’s in Figure 4 is particularly insightful. Figures 4(c) and 4(d) show the action of the jet presented in Figure 3(a), which impacts on the PCB between the PQFP and SO16-m as it acts to dry firstly the board in this region, Figure 4(c), and secondly the top surface of the SO16-e component. Note that this occurs before any drying of SO16-m top surface, as shown in Figures 4(b) to 4(d), signifying higher heat transfer rates in the SO16-e region and in particular from the component top surface. The predicted energy balance analyses of component heat transfer for both SO16’s were shown to correlate with this observation [22]. The measured operating temperature of SO16-e individually powered was approximately 12°C lower than that for SO16-m, further supporting this point. This was attributed to a combination of lower heat transfer rates in the vicinity of SO16-m, associated with weak flow fields downstream of Block 1, and component orientation in the stream-wise direction.
Figure 3. Experimentally visualized flow fields on PCB A at 2m/s, with the smoke introduced 25mm upstream and flush with the PCB surface: (a) Forward airflow direction, (b) Reversed airflow direction.
Figure 4. Surface paint flow visualization time sequence on PCB A at 2 m/s, for the forward airflow direction. Brighter regions indicate high heat transfer: (a) PCB exposed to airflow for 10 seconds, (b) PCB exposed to airflow for 15 seconds, (c) PCB exposed to airflow for 25 seconds, (d) PCB exposed to airflow for 35 seconds.
Table 1. Component junction temperature prediction accuracy on PCB A in a 2 m/s airflow.

<table>
<thead>
<tr>
<th>Component</th>
<th>Forward flow</th>
<th>Reversed flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Individually powered</td>
<td>Simultaneously powered</td>
</tr>
<tr>
<td></td>
<td>Lam</td>
<td>k-e</td>
</tr>
<tr>
<td>TSOP 48</td>
<td>-9.7 (18%)</td>
<td>-10.2 (19%)</td>
</tr>
<tr>
<td>PQFP208</td>
<td>+3.1 (6.3%)</td>
<td>-0.2 (0.4%)</td>
</tr>
<tr>
<td>SO16-m</td>
<td>-2.8 (3.5%)</td>
<td>-10.3 (13%)</td>
</tr>
<tr>
<td>SO16-e</td>
<td>+4.2 (6.1%)</td>
<td>-2.6 (3.8%)</td>
</tr>
</tbody>
</table>

Note: Airflow directions defined in Figure 1. Lam (laminar) and k-e refer to the flow model. The Percentage prediction error in parenthesis ( ) is calculated based on measured component junction temperature rise above ambient air temperature, 20°C. Component power dissipation = 0.5W for both TSOP 48 and SO16's, 2W for PQFP 208. Measurement uncertainty for component junction temperature, ±0.5°C.

Numerical Predictive Accuracy.

Interpretations of the flow visualizations in Figures 3 and 4 are used to provide insights into sources of component junction temperature discrepancies in Table 1. As greatest prediction errors and discrepancies between flow models occurred for the SO16 components, discussion focuses on these predictions.

In both airflow directions on the simultaneously powered multi-component PCB, using either the laminar or k-e flow model, predictive accuracy is overall within ±10% of measurement for the SO16 and PQFP 208 components, when accounting for experimental uncertainty. Based on structural analysis and numerical parametric studies [21], the lower accuracy for the TSOP 48...
component was primarily attributed to an uncertainty in encapsulant thermal conductivity value. While the TSOP model predictions must therefore be considered with some skepticism, the good agreement between measured and predicted PCB surface temperature in vicinity of this component [18,21], indicated that the component-PCB thermal interaction was correctly captured, both on the single- and multi-component PCBs.

While in the forward airflow direction, the laminar and k-e flow models yield comparable predictions for the TSOP and PQFP components, significant differences exist between flow model predictions for the SO16 devices. This has nothing to do with the component type, which is only used to define the location on the board. The greatest deviation between flow model predictions occurs in the SO16-m region, which experimental measurements showed to be the most sensitive to aerodynamic disturbance [19,21]. As revealed by smoke-flow visualization in Figure 3, the flow separates upstream of the Block 1 obstruction and reattaches in a region located between PQFP and SO16-m. This suggests that the k-e flow model discrepancy for SO16-m individually powered, Table 1, could be related to the limited applicability of the wall functions used to predict wall shear stress, hence heat transfer in re-attaching flow conditions [43]. This limitation will be more evident for the analysis of PCB B exposed to upstream flow disturbance. By contrast, the laminar flow model, which does not rely on the use of wall functions, displays better accuracy at this board location, Table 1. Therefore, neither flow model is found to be accurate for all components, indicating that the rules governing the application of a laminar or turbulence model are not clear.

By contrast, junction temperature predictions on single-component PCBs were found to be flow model insensitive, [18], with greater prediction error on the populated PCB being therefore attributable to a weakness of the flow models used to predict the more complex flows visualized in Figure 3.

Numerical energy balance analyses of component heat transfer provided an additional link between junction temperature and flow field prediction errors [18,21]. While the laminar and k-e predictions differed by 10ºC and 8ºC for SO16-m and SO16-e respectively in the forward flow direction, the predicted energy balances were very similar for both components. This clearly indicated that the component internal conductive domain is only weakly sensitive to flow model. Hence, prediction error for these components was related to the representation of the convective domain.

Table 1 highlights that aerodynamic factors significantly influence flow model predictive accuracy in both airflow directions on the multi-component PCB. Differences between flow model predictions increase with distance from the PCB leading edge. These differences are more pronounced in the forward flow direction, indicating proportionality to the amount of flow disturbance introduced in the flow field upstream of the component. Note that the leading edge obstruction in the forward flow direction was significantly wider and taller than in the reversed flow direction. In this flow direction, the laminar model produces better predictive accuracy for all components, possibly reflecting the effect of milder flow disturbance being generated upstream. The results suggest that ultimately a transitional flow model may be required to predict the complete flow field over populated PCBs, hence yield best predictive accuracy for all components. This will be confirmed in Study B.
Study B

Results obtained for PCB B are presented in order of increasing flow complexity, beginning with Stage 1, then Stage 2, followed by Stage 3. The airflow direction is from left-to-right in all flow visualization images.

Stage 1 PCB Topology. The smoke-flow and paint-film flow visualizations are presented in Figures 5 and 6 respectively.

Smoke-Flow Visualization. In this instance, the smoke was introduced 2 mm upstream of the PCB’s leading edge and flush with its front surface. The streamlines in Figure 5 display characteristics of steady, laminar flow at all locations on the PCB, except in the vicinity of the component and its downstream wake region. The development of a horseshoe vortex upstream of the component and its tails sweeping inwards immediately downstream of the component are identified in the Figure 5(a) inset, comparable to those observed on PCB A. The impact of the reattaching flow after one component-length downstream of the component’s trailing edge is also striking.

Paint-Film Evaporation. Notable features in the paint-film evaporation sequence presented in Figure 6 indicate that, as expected, the highest heat transfer rates exist close to the PCB’s leading edge and component top surface, Figure 6(a). These high heat transfer rates are revealed as the wet paint-film, represented by the black surface, slowly evaporates from these regions first, leaving a dry, gray surface. The impact of the weaker flows that reattach directly downstream of the component, are also apparent in Figure 6(a), but it is clearly shown in Figure 6(b) however that the highest heat transfer rates downstream of the component lie at the reattachment point. These observations are reinforced as time elapses in Figures 6(b) and 6(c), with the paint film completely evaporating after 220 s. The wake region immediately downstream of the component displayed the weakest heat transfer, drying after 210 s.

As highlighted in the description of this technique, the application of a thin, evenly distributed film of paint across the entire board surface is a condition difficult to achieve, which necessitated that several evaporation sequences of the same PCB topology were visualized to identify the dominant features always present. Evidence of a slightly uneven paint-film is shown in Figure 6, where the upper right corner of the PCB in Figures 6(b) and 6(c) remains wetter than the lower right corner. However, repetition of this test showed that both regions dry at the same rate, but in all cases the distinguishing features of the flow about and immediately downstream of the component were always present.

Comparison of the results obtained from both flow visualization methods in Figures 5 and 6, highlights how these methods compliment each other. Each method helps to identify important features of both the flow phenomena and the heat transfer, and when combined they can form a clear impression of the flow condition.

Numerical Predictive Accuracy. In line with the predictions for and other single-component PCB topologies [18,44], predictive accuracy for Stage 1 was within ±2°C (3%) of measurement, Table 2. The laminar and k-e flow model predictions were within 1°C of each other, indicating that the k-e model predicted a low level of turbulent viscosity in the flow. The laminar prediction was slightly more accurate, which may not be surprising considering the laminar nature of the flow upstream of the component in Figure 5(a).
Figure 5. Smoke-flow visualization over the Stage 1 PCB at 2 m/s. Smoke introduced 2 mm upstream and flush with the PCB surface: (a) PCB front view (inset also at 2 m/s), (b) PCB plan view inclined at 4° to horizontal.
Figure 6. Paint-film evaporation sequence from the Stage 1 PCB at 2 m/s using an ethanol paint film: (a) Degree of evaporation after 50 s, (b) Degree of evaporation after 105 s, (c) Degree of evaporation after 220 s.

Table 2. Comparison of measured and predicted junction temperatures for component H individually powered on the Stage 1 and Stage 2 PCBs in a 2 m/s airflow.

<table>
<thead>
<tr>
<th>Test configuration</th>
<th>Measured (°C)</th>
<th>Prediction discrepancy (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Laminar</td>
</tr>
<tr>
<td>Stage 1</td>
<td>66.0</td>
<td>+0.7 (1.5%)</td>
</tr>
<tr>
<td>Stage 2</td>
<td>63.0</td>
<td>+5.1 (12%)</td>
</tr>
</tbody>
</table>

Note: Measurement uncertainty, ±0.4°C. Percentage prediction error in parenthesis (%) is calculated based on the measured component junction temperature rise above ambient air temperature. Component power dissipation = 3W. Ambient air temperature = 20°C.
Stage 2 PCB Topology. Discussion is confined to the smoke-flow visualizations, presented in Figure 7, to highlight the impact of aerodynamic disturbance generated by the leading edge components AFK, upstream of component H.

Smoke-Flow Visualization. Figure 7 shows that the complexity of the flow field increased significantly from that shown for the single-component PCB in Figure 5(a). In Figure 7(a), the flow field over the majority of the PCB is dominated by two features that emanate from each component on the leading edge: the reattachment of the flow over the component top surface and its interaction with the tails of the horseshoe vortex that flow around each component. Resulting from their closer proximity to the PCB's leading edge, shorter reattachment lengths are recorded for the leading edge components, in Figure 7(a) than for component H in Figure 5(a). This is clearly evident when Figure 7(b) is compared with Figure 5(b).

Numerical Predictive Accuracy. Comparison of component H's junction temperature measurements in Stages 1 and 2, Table 2, reveals the sensitivity of its operating temperature to the upstream flow disturbance generated by the passive leading edge components. Based on the metrics of both measured junction temperatures, Table 2, and component-board surface temperature [19], this sensitivity was not captured by numerical prediction. While H's measured operating temperature decreased by approximately 3°C from Stage 1 to 2, corresponding predictions remain similar. This invariance indicates that the flow models fail to capture the enhanced heat transfer resulting from upstream aerodynamic disturbance generated by the passive leading row devices (A, F, K), visualized in Figure 7. The decay in junction temperature accuracy from Stages 1 to 2, Table 2, is therefore linked to the increased complexity of the flow phenomena in Figure 7.

Stage 3 PCB Topology. The smoke-flow visualizations and paint-film evaporation results are presented in Figures 8-9 and 10 respectively.

Smoke-Flow Visualization, non-insulated PCB. In Figure 8, the smoke-flow patterns at the PCB leading edge reveal similar flow features to those for the Stage 2 configuration, Figure 7. The tightly packed streamlines tend to flow closely to the component-PCB surfaces near the leading edge. This is particularly evident both in the regions between the components, and for the streamlines that impact close to the front face corners of the leading edge components and sweep inwards over their top surface as they flow downstream.

Insulated PCB. For the same wire position in the insulated case, Figure 9(a), the leading edge streamlines no longer follow the component-PCB contours. Instead, the flow field is now dominated by a strong reattaching flow that sweeps inwards from the PCBs left-hand-side leading edge corner, and the mainstream flow that reattaches in a region just downstream of the leading row components A, F, K. The magnitude of the separation zone beneath this reattaching mainstream flow is best viewed in plan view, with Figures 9(b) and 9(c) showing the flow over the central F component. This clearly shows a larger separation zone than that generated by the non-insulated PCB. The extent of this separation zone over component A was similar. Since the impact angle of the re-attaching flow is much greater for the insulated PCB in Figures 9(b) and 9(c) than in the non-insulated case, it is not surprising that the smoke streak lines break down much more in Figure 9(a) than in Figure 8, indicating a
Figure 7. Smoke-flow visualization over the non-insulated Stage 2 PCB at 2 m/s. Smoke introduced 4 mm upstream and flush with the PCB surface: (a) Front view, (b) Plan view with smoke flow over component A.
Figure 8. Smoke-flow visualization over the non-insulated Stage 3 PCB at 2 m/s. Smoke introduced 4 mm upstream and flush with the PCB surface.

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Figure 9. Experimentally visualized flow field on the insulated Stage 3 PCB at 2 m/s: (a) Front view, (b) Plan view – still 1, (c) Plan view – still 2.

Note: Time lapse between stills 1 and 2 is approximately 230 ms. Smoke introduced 4 mm upstream and flush with the PCB surface, and in plan view, aligned with the central stream-wise axis of component F.

higher degree of flow mixing and turbulence downstream of the leading row. Inspection of a single streamline over the central F component in Figures 9(b) and 9(c) highlights the unsteady nature of this separating/reattaching flow. As both these images were taken from the same image sequence, but 230 ms apart, it is obvious that the location of the re-attachment point varies, indicating unsteady flow characteristics. Analysis of many such image sequences revealed that this flow phenomenon was non-periodic and fluctuated randomly at frequencies between 3 and 9 Hertz. It was concluded therefore that localized characteristics of the flow over the insulated PCB were unsteady, and that the strong re-attachment zone immediately downstream of the leading row components could pose problems for modeling heat transfer in this region.
Figure 10. Paint-film evaporation from the insulated Stage 3 PCB at 2 m/s using Ethanol: (a) Evaporation status after 15 seconds, (b) Evaporation status after 35 seconds, (c) Evaporation status after 60 seconds.

Paint-Film Evaporation. To highlight the impact of the smoke-flow patterns presented for the insulated PCB in Figure 9, an impression of the heat transfer characteristics associated with this flow was obtained using the paint-film evaporation technique, presented in Figure 10. The impact of the vortices that sweep inwards over the PCB from the leading edge, left corner is evident in Figure 10(a), as the paint-film begins to dry first at this point. Figure 10(b) highlights the impact of the separation and reattachment zones downstream of the leading edge. Note in Figure 10(b) that the heat transfer rate is less over the leading edge of component F, signifying the impact of the separation zone identified in Figure 9(b), and that the trailing edge of the first row components and the leading edge of the second row components begin to dry first, signifying the higher heat transfer associated with the reattaching flow in this region.

Note: The bright regions in (a) represent reflections from the overhead lighting.
From an inspection of the smoke-flow images in Figures 5 and 9, it is clear that there is a significant increase in the flow complexity as a result of the combined effects of including more components on the PCB and also by including system level effects, generated in this case using the insulating block on the PCB non-component side. It must also be concluded, however, that these system level effects generated the greatest level of flow disturbance and should therefore not be ignored when such studies, either experimental or numerical, are undertaken.

**Numerical Predictive Accuracy.**

i) Individually powered components on the non-insulated PCB. In Table 3, the laminar and k-e flow models predictions are similar, with greatest prediction errors occurring at the first two leading edge component rows. This indicates a weakness of the code to predict the leading edge flows visualized in Figure 8. In this region, the k-e model displays slightly better accuracy. In free convection conditions, however, the operating temperature of the leading edge, individually powered components was accurately predicted, to on average within 3°C (5%) of measurement [45].

For forced convection, the predictive discrepancies at the leading edge are therefore not related to component sample, but its location on the board.

ii) Individually powered components on the insulated PCB. The greatest prediction errors occur for component G using the k-e flow model, Table 3, which is located in a region identified as aerodynamically sensitive by flow visualization, Figure 9. As previously described, the flow separates upstream of the insulated PCB leading edge and re-attaches in a region just downstream of the leading row components A, F and K, with unsteady characteristics. The flow models therefore display different sensitivities to the aerodynamic conditions on the insulated PCB, with the laminar model being more accurate. The poor accuracy of the k-e model for component G is again attributed to the limited applicability of the wall functions used for the prediction of wall shear stress, hence heat transfer in re-attaching flow conditions. It should also be noted that the k-e model is not suited to the analysis of the unsteady flow over the insulated board, as it does not capture flow unsteadiness. This is due in this instance to an overprediction of the turbulent viscosity damping out any transient flow features [45]. However, the k-e model was assessed to reflect normal design scenarios, where there is no *à priori* knowledge of the flow regime, and whether it is steady or unsteady. Though the k-e predictions should therefore be considered with skepticism, this model yields accuracy similar to that of the laminar model for the downstream components H to J.

iii) Simultaneously powered components on the insulated PCB. In Table 4, predictive accuracy for both flow models decays for the downstream components H to J, relative to the corresponding individually powered configurations in Table 3. This is attributed to inaccurate prediction of the downstream component temperature rise between the individually- and simultaneously powered configurations. This rise is solely due to component thermal interaction. These errors are more pronounced for the laminar flow model, and result in junction temperature errors increasing with distance from the PCB leading edge. Therefore, the predictive accuracy obtained for the simultaneously powered PCB in Table 4 are only net values, and a function of component power dissipation.
Table 3. Comparison of measured and predicted component junction temperatures for individually powered components on the Stage 3 PCB in a 2 m/s airflow.

<table>
<thead>
<tr>
<th>Component</th>
<th>Measured (ºC)</th>
<th>Non-insulated PCB</th>
<th>Laminar</th>
<th>k-e</th>
<th>Insulated PCB</th>
<th>Laminar</th>
<th>k-e</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>61.2</td>
<td>+7.3 (18%)</td>
<td>+6.1 (15%)</td>
<td>+2.6 (4.7%)</td>
<td>+4.1 (7.4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>62.6</td>
<td>+7.1 (17%)</td>
<td>+6.6 (15%)</td>
<td>+4.1 (7.7%)</td>
<td>+11.9 (22%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>64.4</td>
<td>+4.8 (11%)</td>
<td>+5.1 (12%)</td>
<td>+2.9 (5.2%)</td>
<td>+5.9 (11%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>64.3</td>
<td>+4.3 (9.7%)</td>
<td>+4.3 (9.7%)</td>
<td>+1.5 (2.7%)</td>
<td>+3.0 (5.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>64.9</td>
<td>-0.9 (2.0%)</td>
<td>-0.8 (1.8%)</td>
<td>-2.1 (3.8%)</td>
<td>-2.0 (3.6%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: F and J are leading and trailing edge components respectively, Figure 2. Measurement uncertainty, ±0.4ºC and ±0.5ºC on the non-insulated and insulated PCBs respectively. Percentage prediction error in parenthesis () is calculated based on the measured component junction temperature rise above ambient air temperature. Component power dissipation = 3W. Ambient air temperature = 20ºC.

Table 4. Comparison of measured and predicted component junction temperatures for simultaneously powered components on the insulated Stage 3 PCB in a 2 m/s airflow.

<table>
<thead>
<tr>
<th>Component</th>
<th>Measured (ºC)</th>
<th>Laminar</th>
<th>k-e</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>81.2</td>
<td>+6.5 (11%)</td>
<td>+11.0 (18%)</td>
</tr>
<tr>
<td>G</td>
<td>84.0</td>
<td>+12.2 (19%)</td>
<td>+22.4 (35%)</td>
</tr>
<tr>
<td>H</td>
<td>92.1</td>
<td>+13.2 (18%)</td>
<td>+15.6 (22%)</td>
</tr>
<tr>
<td>I</td>
<td>95.7</td>
<td>+15.5 (21%)</td>
<td>+12.4 (16%)</td>
</tr>
<tr>
<td>J</td>
<td>94.9</td>
<td>+12.8 (17%)</td>
<td>+5.5 (7.3%)</td>
</tr>
</tbody>
</table>

Note: F and J are leading and trailing edge components respectively, Figure 2. Measurement uncertainty, ±0.6ºC. Percentage prediction error in parenthesis () is calculated based on the measured component junction temperature rise above ambient air temperature. Component power dissipation = 3W. Ambient air temperature = 20ºC.
5. Conclusions and Recommendations

This study has demonstrated the application of two complimentary flow visualization techniques to help identify the complex flow phenomena that develop over forced air-cooled Printed Circuit Boards (PCBs). This included the application of a novel paint-film evaporation technique that highlighted the sensitivity of convective heat transfer to the airflow phenomena.

Combined and individually, the flow visualization methods enabled the location of aerodynamically sensitive regions on the boards to be identified and associated with significant prediction errors in component operating temperature, highlighting that any predictions in such regions must be viewed with caution. Flow visualization, which is an efficient means of identifying these regions, should therefore be considered as a valuable design tool early in the design phase. Flow visualization can also help with the selection of a numerical flow modeling strategy.

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References


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