Thermal state of electronic assemblies applied to smart building equipped with QFN64 device subjected to natural convection

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1. Introduction

The performance and reliability of electronic components and assemblies strongly depend on their thermal state. The knowledge of the temperature distribution throughout the assembly is therefore an essential element to ensure their correct operation. This is the main objective of this work that examines the case of a conventional assembly equipped with a quad flat non-lead QFN64 subjected to free convection. This active electronic package is welded on a PCB which may be inclined by an angle varying between 0° and 90° (horizontal and vertical positions respectively) and generates during its operation a high power ranging from 0.1 to 1 W. Thermoregulation of the assembly is ensured by natural convection, given its many well known advantages in this engineering field. Accurate relationships are proposed to determine the temperature on different areas of the device and the PCB. They are determined by means of a 3D numerical approach based on the finite volume method confirmed by measurements on an actual installation. These relationships allow reliability improvement of these electronic assemblies that are widely used in many engineering fields such as computing industry, mobile telephony, home automation, automotive, embodied electronics and the smart building applications considered in this work. The present survey complements a recent study which quantifies the natural convective heat transfer on the considered electronic assembly equipped with the QFN64 device, for the same power range and angle of inclination.

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Please cite this article as: A. Baïri, et al., Thermal state of electronic assemblies applied to smart building equipped with QFN64 device subjected to natural convection, Microelectronics Reliability (2017), http://dx.doi.org/10.1016/j.microrel.2017.01.002

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This applies to the passive parts as the Printed Circuit Board (PCB) which support components, in order to avoid the separation of the copper layer from the substrate (epoxy resin) or desoldering the components. The junction temperature of the QFN64 device considered in this present work must be maintained below a maximal value recommended by the manufacturers. This criterion has to be respected under the most unfavorable thermal and geometric conditions. The thermal design and management of the electronic assemblies are highly dependent on several physical parameters and the environment in which they are installed [20-21]. The effects of the molding compound which they are installed [20] on the QFN64 device welded on a PCB installed in an air-filled cavity (35 mm × 20 mm × 8 mm) whose walls are maintained isothermal at temperature \( T_{e} = 293.15 \, \text{K} \). The thermal conductivity \( \lambda \) of the materials constituting the assembly are of 120, 260, 260, 2.1, 0.66 for the die, the diepad, the leads, and the molding compound (resin) respectively. These values have been measured within ±3% by means of the Hot Disk TPS 2500 model [24], based on the transient plane source (TPS) method [25], with parallelepipedic samples (square side 12 mm, 4 mm thick) provided by a QFN's manufacturer. The copper network density corresponds to a Copper ratio of 5.26% (see [18]). The resulting thermal conductivity of the PCB according to its plane is of 4 mm thick) provided by a QFN's manufacturer.

### 3. Numerical procedure

Calculations are processed for the (QT), (QS), (BB), (BS) and (BB) areas by means of a 3D numerical survey based on the finite volume method. Details of the calculating procedure are available in [17]. To simplify the presentation of the results in the continuation of this work, the two surfaces (BS) and (BB) are grouped as (BB+BS). Furthermore, an fictitious surface denoted as (QB) is designed to facilitate the direct modeling of the package without the PCB. However, the results concerning this area take into account the convective heat transfer that occur on the PCB. They were obtained by means of a thermal balance performed on the entire assembly. The temperature gradient \( \partial T / \partial n \), concerning any k element of the surface all around the assembly determines the corresponding local convective heat transfer coefficient \( h_{i} = [\lambda_{A}(\partial T / \partial n)/\partial T]_{i} \), whose integration weighted by the surfaces \( S_{i} \) allows determination of the average convective heat transfer coefficient \( \bar{h}_{i} = (\sum_{k} h_{i} S_{i}) / (\sum_{k} S_{i}) \) concerning a given i area. Its association with the power \( P_{i} \) exchanged by convection provides then the average difference temperature \( T_{i} \) of every area by means of the Newton's law \( P_{i} = \bar{h}_{i} A_{i}(T_{i} - T_{e}) \), being \( A_{i} \) the surface of the considered i area. This operation was performed for all the configurations obtained by varying the high power generated by the QFN64 between 0.1 and 1.0 W, and the tilt angle \( \alpha \) between 0° and 90° by steps of 15°.

Evolution of the temperature difference \( \Delta T = T - T_{e} \) presented in Figs. 2 and 3 versus \( \alpha \) and \( P \) respectively shows that \( \Delta T \) decreases as the PCB inclination angle increases between the horizontal position (\( \alpha = 0° \)) and the vertical one (\( \alpha = 90° \)), on all areas.

The decrease is however less significant on (QB). The change is more pronounced for large \( P \) values, almost zero for the lowest value (\( P = 0.1 W \)). The highest values of \( \Delta T \) are observed on the QFN sides (QS). In this region, the conductive resistance is greater according to the reduced exchange surface. Fig. 3 shows a significant \( \Delta T \) difference between (QS) and (Qr). The lowest values of the mean temperature concern the PCB which acts as a fin. The heating of the board is limited to the immediate vicinity of the device, the rest being almost at the environment temperature.

### 4. Experimental approach

Experimental measurements were performed with the assembly presented in Fig. 1(d) to check the numerical results. The QFN64 (1 in Fig. 1(d)) is welded on a rectangular (30 mm × 13 mm) single side conventional PCB (35 μm of copper on an 1.6 mm width epoxy base, (2 in Fig. 1(d)). The device is connected to the other components of the

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{i} )</td>
<td>surface of a given i area (m²)</td>
</tr>
<tr>
<td>( g )</td>
<td>gravity acceleration (m s⁻²)</td>
</tr>
<tr>
<td>( \bar{h}_{i} )</td>
<td>average convective heat transfer coefficient of a given i area (W m⁻² K⁻¹)</td>
</tr>
<tr>
<td>( P )</td>
<td>generated power (W)</td>
</tr>
<tr>
<td>( P_{i} )</td>
<td>convective heat power exchanged by a given i area (W)</td>
</tr>
<tr>
<td>( T_{m} )</td>
<td>measured average temperature of a given i area (K)</td>
</tr>
<tr>
<td>( T_{c} )</td>
<td>temperature of the cavity's walls; initial temperature of the whole system (°C)</td>
</tr>
</tbody>
</table>

#### Greek symbols

- \( \alpha \): inclination angle of the PCB with respect to the horizontal plane (°)
- \( \Delta T \): calculated temperature difference; \( \Delta T = (T - T_{e}) \) (K)
- \( \Delta T_{m} \): measured temperature difference; \( \Delta T_{m} = (T_{m} - T_{e}) \) (K)
- \( \Delta T_{\text{max}} \): maximum \( \Delta T_{m} \) value (K)
- \( \Delta T_{m}^{i} \): ratio defined by \( \Delta T_{m}^{i} = \Delta T_{m} / \Delta T_{\text{max}} \) (K)
- \( \lambda_{A} \): air thermal conductivity (Wm⁻¹ K⁻¹)
- \( \lambda \): thermal conductivity of the materials (Wm⁻¹ K⁻¹)

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assembly by a standard copper network. The board is linked to a USB type plug (3, Fig. 1(d)) which is used to power-on the QFN and to measure all the electronic assembly parameters. The assembly is installed in the center of a parallelepiped box (35 mm long × 20 mm wide × 8 mm thick; (1) in Fig. 1(d)). The USB plug is connected to a computer (2, Fig. 1(d)) equipped with a fast data acquisition system and a conventional resistor assembly including a resistance calibrated previously. An internal multimeter-multiplexer of high resolution (3 × 10^6 points) allows the measurement of the intensity of the current \( I \) and \( U \) voltage of the device’s active source with an accuracy of 0.1% and 0.08% respectively in the ranges concerned by the tests. The power generated by the \( P = UI \) is so determined with a maximum error of 0.2% (\( \Delta P/P = \Delta U/U + \Delta I/I \approx 0.2\% \)).

The thermal state of the whole system is measured by means of 24 K-type calibrated thermocouples of 0.04 mm diameter. They are welded by laser technique on the surfaces of assembly: 5 on the diagonals of (QT) allows the measurement of the intensity of the current \( I \) and \( U \) voltage of the device’s active source with an accuracy of 0.1% and 0.08% respectively in the ranges concerned by the tests. The power generated by the \( P = UI \) is so determined with a maximum error of 0.2% (\( \Delta P/P = \Delta U/U + \Delta I/I \approx 0.2\% \)).

Fig. 1. (a) The considered QFN64 with its (QT), (QS) and (QB) areas; (b) The PCB with its (BT), (BS) and (BB) areas; (c) the PCB inclination angle \( \alpha \); (d) The considered assembly.

Fig. 2. Evolution of \( \Delta T \) versus \( \alpha \) on (QT), (QS), (QB), (BT) and (BB + BS) areas.

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and \((Q_b)\), 1 on each of the 4 \((Q_b)\) sides, 4 on the center axis of \((B_T)\) and 6 on the center axis of \((B_B)\). Thermocouples are welded simultaneously with the other components of the assembly to avoid wire tangling. They are connected to specific plugs located on the back area \((B_B)\) electrically insulating, and communicate with the mother card which is connected to the computer. The 5 thermocouples of \((Q_T)\) are protected by a 10 \(\mu m\) resin layer deposited with the pressurized spray technique. The temperature uncertainty is estimated at \(\pm 0.5%\) in the considered thermal range, following an in-situ calibration. The electronic assembly inclined to the angle \(\alpha\) considered for the test is installed in a room whose temperature is maintained at temperature \(T_c(\pm 0.1 \text{ K})\). All the measurements (temperatures and electrical data) are made at steady state with a sampling time of 100 ms. The measurements are taken for 10 min after the start of the steady-state regime which is characterized by a relative variance for all temperatures less than \(0.3\%.\) The average measured temperature difference \(\Delta T_m = (T_m - T_c)\) for each area is determined with the average value of the measured temperatures weighted by the corresponding surfaces. Direct measurement of the temperature difference allows limiting the uncertainty measurement of the thermal state to \(\pm 0.5\%.\) All combinations of \(0.1 \leq P \leq 1.0 \text{W} \) step 0.1W with \(0 \leq \alpha \leq 90^\circ\) step \(15^\circ\) were tested. Comparison between measured \(\Delta T_m\) and calculated \(\Delta T\) temperature differences for \(\alpha = 0\) and \(90^\circ\) on \((Q_T)\) and \((Q_s)\) areas shows a very good agreement: 3\% and 4\% for the average and maximum deviation respectively.

The comparison experience-calculation presented in Fig. 4(a) for \(\alpha = 0\) and \(90^\circ\) on \((Q_T)\) and \((Q_s)\) areas illustrates the low deviation and confirms the validity of the calculated values. Furthermore, an IR thermography of the assembly was made by means of a high-resolution infrared camera (Flir Systems ThermoVision A40M type) equipped with a Focal Plane Array detector [27]. Calibration of the overall assembly was made with a Class 1 black body. The Fig. 4(b) presents the distribution of the dimensionless temperature difference \(\Delta T_m = \Delta T_m / \Delta T_{\text{max}}\) on the upper face of the QFN64 for the combination \((\alpha = 0, P = 0.5\text{W})\), \(\Delta T_{\text{max}}\) being the maximum \(\Delta T_m\) value corresponding to a given generated power.

Many tests were also performed in order to check the reliability, durability, aging and robustness of the assembly. Several cycles of powering up and disconnection of the package have been carried out, thus subjecting it to variable thermal stresses. The tests done according to the envisaged applications were carried out for many \((0 \leq \alpha \leq 90^\circ, 0.1 \leq P \leq 1.0 \text{W}\)\).
combinations. The results of the tests are satisfactory, ascertained by reproducible, consistent and stable responses of the assembly.

5. Relationships

The least squares optimization technique was used to develop relationships allowing calculation of the average temperature difference $\Delta T$ of all the assembly’s areas according to the generated power $P$ and inclination angle $\alpha$. In a first step, the optimization has quantified the influence of $\alpha$ on $\Delta T$ by means of correlations minimizing the sum of squared residuals between the value calculated with the numerical approach and the fitted value obtained with the function which best models evolution of $\Delta T$ versus $\alpha$. The same work was done in a second step to determine the influence of $P$ on $\Delta T$, by using the results obtained in the first step. Both steps are based on a coefficient of determination greater than 0.998.

Finally, the average temperature difference can be calculated in any area of the assembly by means of the following relationships of $(\Delta T_i - P - \alpha)$ type:

$$\Delta T_{Q=QF} = \left( 19.5 - 0.031\alpha \right)P + 0.2$$
$$\Delta T_{Q=QB} = \left( 42.9 - 0.042\alpha \right)P + 0.2$$
$$\Delta T_{QB} = \left( 12.4 - 0.017\alpha + 1 \times 10^{-4}\alpha^2 \right)P$$
$$\Delta T_{B} = \left( 4.07 - 0.010\alpha \right)P$$
$$\Delta T_{B_i} = \left( 4.2 - 0.013\alpha \right)P$$

Valid for:

- $0.5 \leq \alpha \leq 90 \degree$
- $0.1 \leq P \leq 1$ W

The associated coefficient of determination are higher than 0.998, which confirms their validity. They allow sizing the QFN64 device, while controlling its temperature according to manufacturers’ recommendations.

6. Discussion and conclusion

The results of this numerical and experimental work clearly confirm different temperatures on every area of the considered electronic assembly equipped with QFN64. The influence of the power generated by this device and its inclination relative to the gravitational field on the surface temperature is highlighted. The part of power generated by the source is predominantly (around 94%) exchanged by natural convection through its back face. The results clearly show that on all the areas of the considered electronic assembly, the surface temperature decreases as the PCB inclination angle increases from the horizontal to the vertical position. This trend is more pronounced for the large powerers generated by the device. The study also shows that the PCB is the coldest part of the assembly, and that the maximum average surface temperature is observed on the QFN sides, which is due to a high conductive resistance. These observations are useful for the thermal design of these assemblies. The relationships proposed in this work facilitate the calculation of the average temperature on each surface. They can be applied in different engineering fields such smart buildings and home automation, the focus of the current work. They constitute an important tool for the thermal design of these electronic assemblies, to increase their reliability and contribute to improving their performance. The present paper complements a recent study which quantifies the natural convective heat transfer on the considered electronic assembly equipped with the QFN64 device, for the same power range and angle of inclination.

References

[10] Assembly Guidelines for QFN (Quad Flat No-lead) and DFN (Dual Flat No-lead) Packages, Freescale Semiconductor, Inc., Application Note, Document Number: AN1902, Rev. 7.0, 10.2014.