Numerical and Experimental Analysis of Natural and Mixed Convection Heat Transfer for Vertically Arranged DIMM

Petrone G.*, Cammarata G.

Department of Industrial and Mechanical Engineering, University of Catania
Viale Andrea Doria 6 – 95125 Catania, ITALY

*Corresponding author: gpetrone@diim.unict.it

Abstract: It is commonly recognized that careful thermal design of electronic equipments represents an unavoidable pre-production step in order to ensure reliability and performance of those components during their functioning. This paper mainly concerns a comparison between experimental and numerical results obtained in studying thermal dissipation in natural and mixed convection conditions for RAM modules vertically arranged. Once the numerical model validated, it is exploited in order to produce useful indications for thermal design of those equipments, such as non-dimensional convective heat transfer coefficients.

Keywords: Natural and Mixed Convection, Electronic Equipments, Thermal Design.

1. Introduction

Electronic devices produce a very important rate of specific heat (related to their small dimensions) as a by-product of their normal operation. Exceeding in maximum safe operating temperature specified by the manufacturer means a strong reduction of semiconductors efficiency and functional life [1]. Among the high power components, Random Access Memory modules are one of the more sensitive thermal subsystem of an assembled computer [2]. Cooling of those devices is always performed by mechanical ventilation systems, that assure a forced convection mechanism in order to dissipate thermal energy. However, the forced air flow is often disturbed by many factors. Cables, drive bays and brackets can determinate bypass over the memory components, forcing the subsystem to operate in mixed or natural convection conditions [3]. Therefore, natural convection represents a critical heat transfer mechanism assuring cooling if designed operational conditions, for any reason, partially or totally fall down [4]. Otherwise, the passive character of cooling by natural convection makes it very attractive for possible application in electronic devices [5]. From a theoretical point of view, cooling of electronic packages has furthermore created emphasis on understanding the basic convective fluid flow over discrete heat sources [6-7], which have different characteristics from the traditionally studied convection from a heated whole wall. This article deals with a comparison between numerical and experimental analysis on natural and mixed convection heat transfer for Dual In-line Memory Modules vertically disposed.

2. The technological system

The actually most used Random Access Memories in Personal Computers are the Dual-Inline-Memory-Modules (DIMM). They are made of 4-16 chip of synchrony dynamical memory with random access (SDRAM), type DDR (Double Data Rate) or DDR2. Chips are characterized by very small dimensions and they are mounted on a Printed Circuit Board (PCB). The PCB disposes of a certain number of PIN both on its top and bottom face. These components are object of the Joint Electron Device Engineering Council (JEDEC) standards. According to JEDEC specifications, the mean parameter indicating thermal performance of DIMM is the total thermal resistance θ_{TOT} between miniaturized integrated circuit and surrounding environment. This represents the sum of sequential thermal resistances, such as junction-package resistance, package-heat sink resistance (if a heat sink is present), heat sink-ambient resistance. By knowing θ_{TOT} value, it is possible, for a chosen ambient temperature T_{AMB} and for a standard active power of 1 [W], analytically evaluating the junction temperature T_{JUN} of the chip. In order to guarantee the reliability of the memory modules, it is strictly necessary that chip does not overcome, during its functioning, the maximum temperature recommended in the technical documentations of constructors. These values are commonly comprised in the range 80-110 [°C]. For predictive estimation of operative temperature of DIMM, leading constructors recommend computational modelling in spite of analytical determination of temperature by JEDEC indications. In fact analytical determination of T_{JUN} could be not exhaustive because of the lack of consideration of several significant factors, first of all the proximity of other heat sources.

3. COMSOL Modelling

The considered physical system is outlined by parallel boards (Printed Circuit Board) surrounded by air and arranging on multiple heat sources (Chip), see Figure 1. Governing equations for solving thermal and dynamical fields read as in following:

$$\begin{cases} \rho \dfrac{\partial \vec{U}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{U} \times \vec{U}) = -\vec{\nabla} p + \vec{\nabla}^2 (\eta \vec{U}) + (\rho_0 - \rho)\vec{g} \\ \dfrac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{U}) = 0 \\ \rho C_p \dfrac{\partial T}{\partial t} + \vec{\nabla} \cdot (\rho C_p \vec{U} T) = q + \vec{\nabla}^2 (kT) \end{cases}$$

The energy equation is solved in fluid as well as in solid sub-domains of system, by considering appropriate values for thermal conductivity ($k_{CHIP} = 163\ [Wm^{-1}K^{-1}]$, $k_{PCB} = 0.3\ [Wm^{-1}K^{-1}]$).
Only in chip sub-domains the heat source term is different from zero and its value is $q = Q_{DIMM} / (n_{CHIP} \Omega_{CHIP})$. Adopted properties and conditions for fluid in this study are reported in Table 1. Both transient and steady formulation of Navier-Stokes and energy equations are numerically solved by using COMSOL Multiphysics. Time integration of the governing equations lies on a backward Euler method. An implicit time-stepping scheme solves a nonlinear system of equations at each time step [8]. The steady solution is instead iteratively approached by applying a modified Newton-Raphson method for directly solving the nonlinear system [9]. Algebraic systems coming from differential operators discretization are solved by using a direct unsymmetrical multi-frontal method based on the LU decomposition. Computations are carried-out on a 64 bit calculator disposing of 16 GB of RAM.

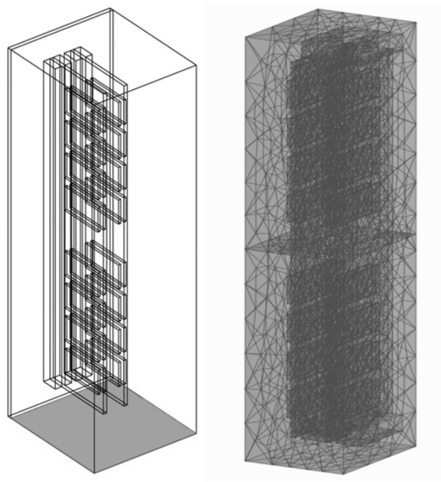

Figure 1. Geometry of the DIMM and computational mesh.

Parameter	Unit
$M = 0.0288$	$[kg\ mol^{-1}]$
$R = 8.134$	$[J\ mole^{-1}kg^{-1}]$
$p_a = 101325$	$[Pa]$
$\rho \equiv p_0 M/(RT)$	$[kg\ m^{-3}]$
$\eta \equiv 6,0 \cdot 10^{-6} + 4,0 \cdot 10^{-8} T$	$[Pa\ s]$
$k \equiv \exp(-3,723 + 0,865 \log T)$	$[W\ m^{-1}K^{-1}]$
$C_p = 1100$	$[J\ kg^{-1}K^{-1}]$

Table 1: Physical properties assumed for fluid.

Influence of computational grid has been preliminary studied in order to assure mesh-independent results. In Table 2 we report a summary of the mesh studying. Relative gaps of maximum of temperature and velocity values over all the domains with respect to reference ones (evaluated for the finest tested grid) indicate that a mesh made of 24611 nodes (139857 degrees of freedom, d.o.f.) can be adopted assuring very small sensitivity of results with spatial discretisation. Saturation of error with increasing in mesh refinement is otherwise well testified by Figure 2, where maximum of velocity is reported as function of the number of elements of the computational grid. Further increasing in mesh refinement does not correspond to substantial benefit in precision justifying much more higher computational time.

d. o. f.	T_{max} [°C]	gap (%)	U_{max} [m/s]	gap (%)
38791	85.61	2.60	0.159	13.14
55108	86.24	1.87	0.153	9.08
79140	87.13	0.86	0.147	4.85
139857	87.74	0.17	0.142	1.34
225600	87.89	-	0.140	-

Table 2: Maximum values of temperature and velocity as function of d.o.f. and relative gap with respect to reference values (finest grid tested).

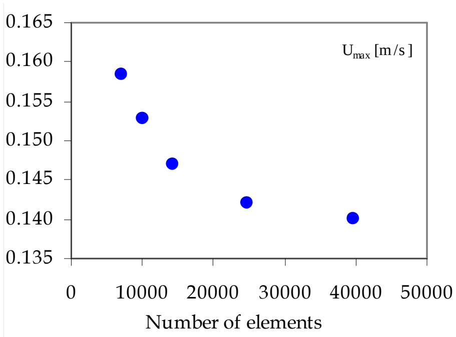

Figure 2. Maximum velocity values reported as function of mesh elements.

4. Experimental set-up

The experimental technique chosen to produce comparing data for numerical results lies on a thermo-graphic investigation on surfaces thermal distribution of Dual In-line Memory Modules during operative conditions. The experimental apparatus mainly consists in a test PC where two 16-chip memory modules (DDR - 512 MB - 266 MHz) were arranged on, an infrared camera (ThermaCAM Flir SC 3000) for detection of surface thermal fields and a laptop PC used for acquisition. In order to reproduce the most critical heat transfer condition of functioning for the electronic devices, some black panels (see red arrows in Figure 3) were employed in order to shield the memory modules by the forced air-flow produced by ventilators. The power-pack was put outside the case (blue arrow in Figure 3).

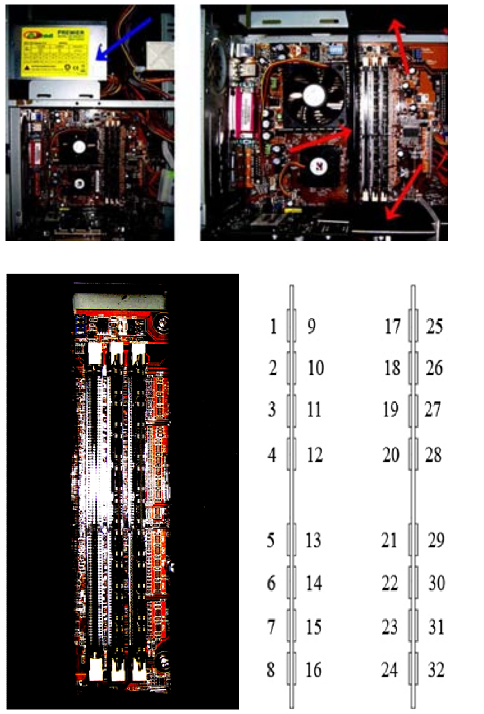

Figure 3. Experimental set-up and assigned labels for the IC mounted on the DIMM.

The black box built around the investigated devices also resulted helpful for thermo-graphical acquisition. In fact other hot electronic components mounted on the mainboard were hindered by the black panels, allowing to set temperature range of the acquisition system with thermal values characteristic of the memory modules we were interested to record. During experimental running specific applications were launched on the test PC in order to load memories by a known electrical power (0.3-0.4 [W]). The experimental acquisitions were recorded each 5 seconds, during a transient time of 3-4 hours. Exceeded this time a stationary thermal behaviour was reached by the dissipating components.

5. Results

Once the test section built-up under the laboratory facility, numerical models were implemented exactly corresponding to geometrical dimensions and applied thermal load of the test section. Then numerical simulations were carried-out both in transient and in steady conditions for comparing results with the experimental ones. In running transient simulations, the imposed temperature value at the bottom boundary of the air volume surrounding the memory modules (T_{AMB}) was assigned as a time-dependent function, approximating, by two linear functions, the temporal evolution of temperature, experimentally detected by a thermometer arranged at the bottom of the slots of the test set-up in the time-range 0-2400 [s]. Then it was considered constant.

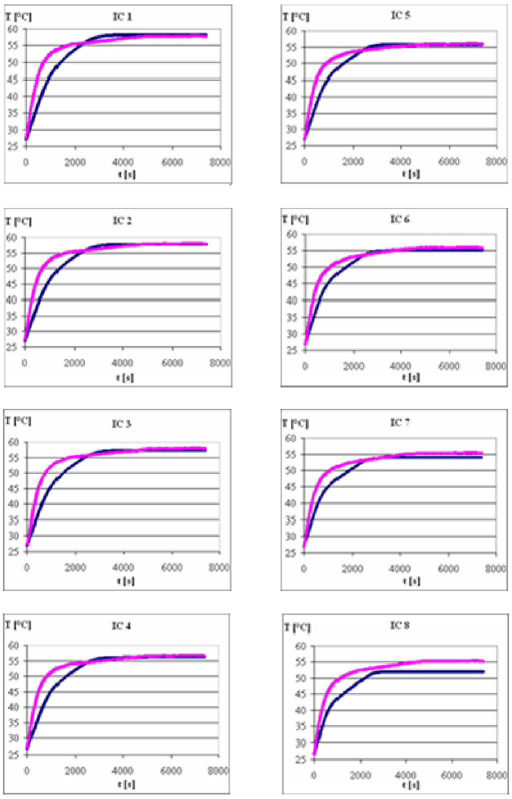

Figure 4. Time evolution of temperature values detected on experimental (pink line) and numerical (blue line) frontal surfaces of the chip (IC 1-8 according to numeration of Figure 3)

Numerical results were then compared with experimental data obtained by the infrared thermo-graphical investigation. In Figure 4 time evolution of the mean temperature values detected on 8 experimental and numerical frontal surfaces of the chip arranged on one of the two memory modules are reported. From comparison a very good agreement in transient evolution is clearly observable. Special attention was paid to investigate on comparison between experimental and numerical thermal fields in the time range during which the wider difference was pointed-out. In Figure 5 we report thermal fields obtained by experimental (on the right side) and numerical (on the left side) analysis at time steps t=180 s (A), t=300 s (B), t=600 s (C), t=1200 s (D). It is to notice that pictures presented in Figure 5 underline the most unfavourable detected conditions in comparing results coming from experimental and numerical investigation.

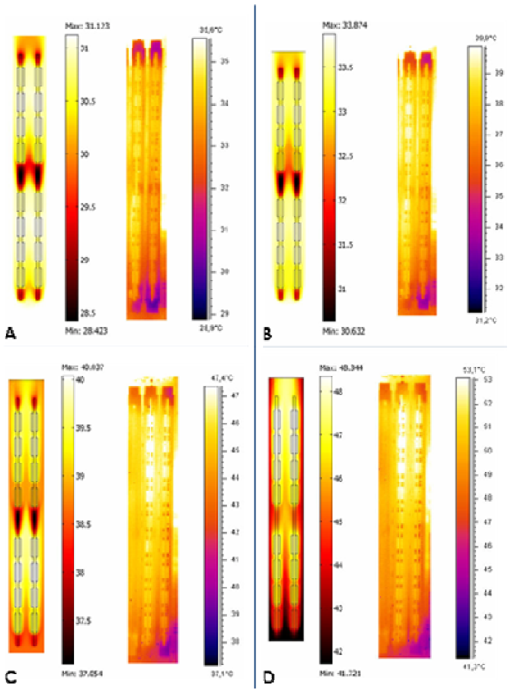

Figure 5. Comparison between numerical and experimental thermal distribution at time steps t=180 s (A), t=300 s (B), t=600 s (C), t=1200 s (D).

The experimental thermal values are generally higher than the numerical ones during the initial portion of the transitory. This item could be explained by considering that during PC starting-up several other electronic components, very close arranged to memory modules, dissipate an high rate of thermal energy. This heating contribution is not considered in the numerical model, so that it underestimates thermal level of the memory modules during the first range of the transitory.

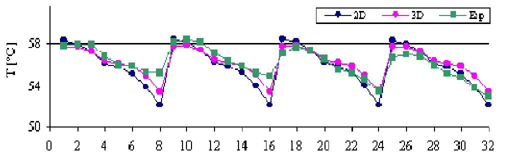

Figure 6. Comparison between steady mean temperature on each chip surface detected by experiments (green square) and computed by 2D (blue dots) and 3D (pink dots) models.

Otherwise, Figure 6 shows distribution of the mean temperature computed on each chip frontal surface once achieved a thermal steady state. Comparison between experimental and numerical results highlights a very good agreement. The best correspondence is obtained for the three-dimensional model of the physical system (maximum relative gap with respect to experimental results less than 3.5%).

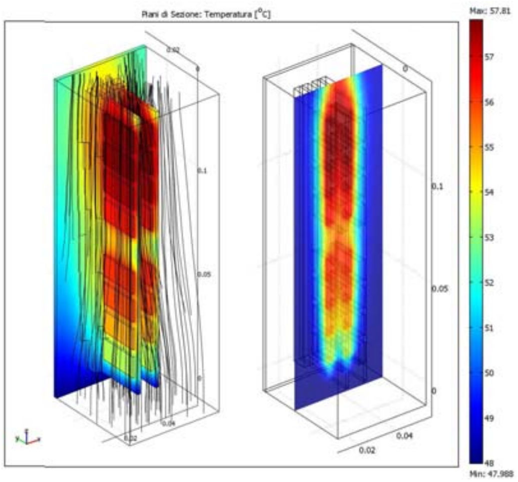

Figure 7. Thermal distribution at fluid-solid interfaces, streamlines of flow and temperature field on a longitudinal section.

From Figure 7 it can be deduced as fluid-dynamical fields for vertical disposition result less complex than those highlighted for the horizontal configuration in previous studies [2]. Fluid is propelled by buoyancy force to flow up without encountering obstacles in its path. Heat is vertically transported and for that reason the integrated circuits arranged in the top portion of the modules manifest higher thermal levels (Figures 7-8). From results analysis it globally appears that vertical disposition is preferable from a thermal point of view with respect to the horizontal one. For a fixed value of imposed thermal load, the vertical configuration assures lower thermal levels on the package. However, the interest in studying this configuration was motivated to investigate on convective heat transfer not only in natural convection condition, but in mixed convection condition also.

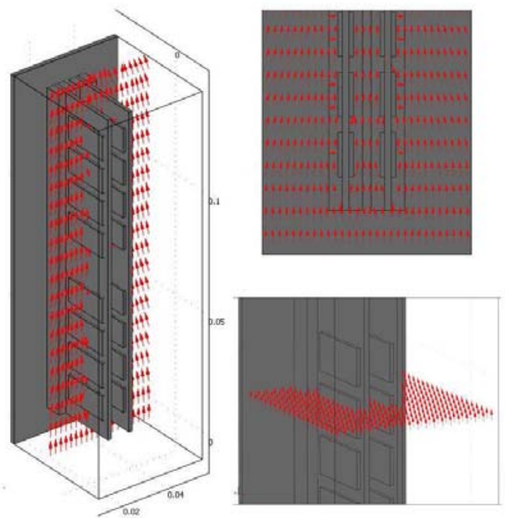

Figure 8. Velocity vectors in longitudinal and transversal sections of the air volume surrounding the electronic devices

Models considering imposed air flow rate coming from the bottom surface of the outlined air volume have been built and convective heat transfer coefficient have been computed for several values of fixed velocity for air. The non-dimensional parameter chosen in order to quantify the convective heat transfer rate is the local Nusselt number evaluated on chip top surfaces, defined as:

$$Nu = \frac{\dfrac{1}{H_{CHIP}\cdot L_{CHIP}}\displaystyle\int_{z_1}^{z_2}\int_{y_1}^{y_2}\frac{\partial T}{\partial x}dydz}{(T_{CHIP}-T_{AMB})\big/L}$$

The range of fixed values for velocity inlet flow (0.1÷0.2 [m/s]) has been limited to maximum velocity values characteristics of fluid-dynamical motion fields observed in natural convection condition. This procedure allows to reproduce physical systems where natural and forced convection effects in heat transfer could be considered comparable. In Table 3 natural and mixed convection configuration are compared from a thermal point of view. The relative gap, concerning the main temperature evaluated on each chip surface of one memory module (IC 1-16, see Figure 3) and the computed local Nusselt number, between natural and mixed convection conditions are listed. Relative gaps are evaluated both for minimum (v=0.1 [m/s]) and maximum (v=0.2 [m/s]) velocity values chosen for the inlet forced flow.

IC	$\frac{T_{nat}-T_{v=0.1}}{T_{nat}}\%$	$\frac{T_{nat}-T_{v=0.2}}{T_{nat}}\%$	$\frac{Nu_{v=0.1}-Nu_{nat}}{Nu_{nat}}\%$	$\frac{Nu_{v=0.2}-Nu_{nat}}{Nu_{nat}}\%$
1	1.59	3.25	12.52	32.32
2	1.68	3.34	13.52	35.54
3	1.75	3.59	15.59	39.81
4	1.83	3.89	20.48	48.80
5	2.53	5.27	25.79	47.04
6	3.20	5.81	26.76	47.38
7	3.89	5.86	30.20	54.42
8	4.02	5.30	50.81	85.19
9	1.58	3.23	17.42	34.74
10	1.67	3.38	26.84	53.77
11	1.73	3.56	34.96	70.68
12	1.81	3.86	45.88	115.72
13	2.52	5.24	80.97	228.95
14	3.24	5.93	101.31	291.41
15	3.99	6.06	192.06	311.35
16	4.11	5.46	197.02	327.19

Table 2: Relative gaps in temperature and local Nusselt number between natural and mixed convection conditions.

From analysis of results it appears that benefit of forced flow mainly concerns IC arranged at the bottom position and on external surfaces of the PCB. It is to notice as decreasing in thermal levels on IC surfaces is comprised in the thin range 1-6%, while increasing in heat transfer coefficient results very fluctuant and, depending on IC position, achieves values up to 300%. This item can be explained: the IC standing on the top positions are in natural convection subject to air flow at the higher velocity, while IC standing on the bottom position are plunged in fluid almost at rest conditions. In mixed convection configuration air flow is quantitatively distributed homogeneously, so that the best advantage in heat transfer coefficient is related to those IC arranged in the most unfavourable position when any forced flow is imposed.

6. Conclusions

This study highlights the opportunity to exploit a numerical approach in order to simulate thermal and fluid-dynamical behaviour of electronic devices. The goal mainly consists in disposing of a predictive and flexible tool for characterising those equipments during several functioning conditions avoiding expensive experimentations. On the other hand, the paper also underlines the unquestionable importance of a validation step for the numerical model, strictly needed in order to assure effectiveness and reliability of the results carried-out. As applications of the proposed approach, Dual Inline Memory Module dissipation is studied for vertical arrangement in natural and mixed convection heat transfer mechanism. Detected temperature values are in good accordance with data obtained by an experimental test set-up. Non-dimensional parameters, such as local Nusselt number, are computed in order to quantify the heat transfer coefficients for the studied application.

7. References

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