MATHEMATICAL MODELING OF THERMAL MANAGEMENT AT DIFFERENT ATMOSPHERIC PRESSURE CONDITIONS

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Abstract

Cooling process is an important element in the correct functioning of all electronic devices. While some components can resist high temperatures, others are damaged during overheating conditions. We performed numerical simulation to study the temperature variation during cooling process of electronic devices that are subject to the effect of different pressures. Commonly the correct functioning of instruments is tested under specific conditions given by the location of the manufacturer but generally the consumer uses the device in a different region. Cooling process performed by convection uses the air provided by a fan. Fluid properties such as kinematic viscosity are influenced by pressure and the effect in cooling is demonstrated by analyzing the variation of surface temperature at different pressures. This study allows us to understand the importance of fluid flow speed in controlling the heating rate. We performed numerical simulation at different air speed (10 – 20 m/s) and pressure (77 – 100 kPa) which corresponds to the elevation of cities that are located between 31 m and 2240 m., additionally we studied the maximum amount of power dissipation as a function of air velocity with radiation contribution and without radiation effect.

Keywords: Air flow velocity; Nusselt parameter; atmospheric pressure; kinematic viscosity; power dissipation

1. Introduction

Forced convection is a process in which heat transfer occurs due to simultaneous conduction and fluid flow. During the process of cooling caused by high velocities of flow, laminar regime is present in the interphase of the surface and the fluid while turbulent flow is present far from the surface. The mathematical model of cooling process is frequently expressed by differential equations. In some cases, analytical solutions exist but frequently numerical methods are required. One of the most common cases of cooling is caused by air flowing in parallel direction of a hot solid plate [1]. As the air flows, the temperature profile changes at different cross sections normal to the plate surface. The direction of heat flows is always from regions of higher to regions of lower temperature. Energy is transferred through an area in the form of heat at a rate proportional to the temperature gradient normal to the area. [2]

Intensive research has been performed about cooling systems. Heating and cooling experiments were performed by Vogel and coworkers, who studied heat transfer in a rectangular enclosure with different widths and heights [3]. Earlier studies by Bareiss and Beer described the observation of two-regime models, a conduction regime was observed firstly, followed by a quasi-steady convection regime [4]. Studies on heat transfer of fluids in cylinders by convection at different heat generation rates and temperatures were performed by Shibahara et al., [5]. Experiments were also performed using different Rayleigh numbers according to the numerical value of heat flux input, rectangular box length and initial properties of the fluid and defined Prandtl number identifying three different stages, namely conduction through the fluid layer, Rayleigh-Bénard convection and formation of longitudinal rolls [6]. Other studies were aimed to validate theoretical correlations that take part in fluid flow and heat transfer characteristics in microchannels (i.e. Nusselt number) [7, 8]

Cooling system on computers is normally unnoticed by the user while using the device but it is a key element for reliable operation and correct functioning of the device. Without the presence of a cooling system, the heat generated while operating the instrument would cause overheating, damage and not only the breakdown of the system but also could represent a risk to users' health [9]. The proper design of the cooling system has to be compact and also efficient. During the operation of a computer, the temperature of some parts of the component could reach up to 100 °C. Heat transfer plays an important role in controlling the temperature by distributing the heat generated to fins located in the electronic device. A fan is used to circulate the air which adsorbs and release the heat. There exist several alternatives to cool a system, among the most common are by air and by water (watercooling). Tubes containing copper filaments and water in liquid state are in continuous contact with the electronic parts where heat is generated. Transfer of heat occurs from the computer microprocessors and heated components of the device to the tubes due to conduction. Inside the cavity of the tube, the temperature increases as water adsorbs the heat, evaporates and changes the gaseous state. Heated water vapor fills the cavity of the tube surrounding the filaments and the heat starts to be distributed to the fins due to the continuous air flow provided by a near fan. When the water vapor reaches the extreme of the tubes, the heat is adsorbed and the vapor condensates in the copper filaments and changes its state to liquid. The space between the filaments is filled gradually until reaching again the hot area of the device to repeat the cooling process. Therefore, the heated vapor is continuously replaced with cooled water and the cycle continues. A gradient of temperature exists due to the difference in temperature between the solid surface and the fluid surrounding it [10–12]. Recent publications on heat transfer states the importance of simulation and modeling of thermal processes in several research fields of study [13–16].Often, the influence of parameters such as atmospheric pressure on convection process is not taken into account. In the present paper, we aim to model the variation of kinematic viscosity of cooling air and surface temperature of a transistor at different pressures. The different values of corresponding pressures depend on the elevation of the cities which were randomly selected for numerical simulation purposes. Mathematical description of air flow variation is presented to account for the regulation of surface temperature. This information would be helpful to assist in the design of new cooling devices of electronics as the control of temperature in the surface of transistors is a key element in troubleshooting thermocouple failures. Furthermore, we studied the effect of air flow in the theoretical maximum value of power dissipation that could be achieved.

2. Description of the mathematical model

For the analysis of the problem, we consider steady state conditions, assuming that the surface of the transistor is isothermal. Air is used to cool the upper layer of the chip surface entering at 25°C and flowing in parallel over the surface of the chip with length (l). The remaining layers of the chip are well insulated from the surrounding. The average convection coefficient for the external flat surface of the chip located at distance (L) from the leading edge is related to the local value according to equation $\bar{h} = \frac{1}{L}\int_0^L h \cdot dx$ [17]. Additionally, we suppose that the system can be confined to two dimensions if the transistor dimensions of length are assumed to be considerably greater than the thickness. This system can be represented as described in Figure 1. Considering the Newton's law of cooling, the rate of convection ($\dot{q}$) is proportional to the temperature difference as expressed in (1). The heat transfer from the solid to the stagnant fluid layer is by conduction, following Fourier's law (2)

$$\dot{q} = h(T_S - T_\infty) \tag{1}$$

$$\dot{q} = -k_f \frac{\partial(T - T_S)}{\partial y}\bigg|_{y=0} \tag{2}$$

Where h is the convective heat transfer coefficient (W/m²·K), T_S is the chip surface temperature (K), T_∞ is the fluid temperature (K), k_f represents the thermal conductivity of the fluid, and T is the temperature at distance (y) [18]. Combining (1) and (2) leads to (3) and to determine the value of h we derive expression (4)

$$h(T_S - T_\infty) = -k_f \frac{\partial T}{\partial y}\bigg|_{y=0} \tag{3}$$

$$h = \frac{k_f}{(T_S - T_\infty)} \cdot \frac{\partial(T_S - T)}{\partial y}\bigg|_{y=0} \tag{4}$$

Fluid properties are normally evaluated at the film temperature, which is given by expression (5) representing the average value between the transistor surface and the surrounding fluid temperatures [19].

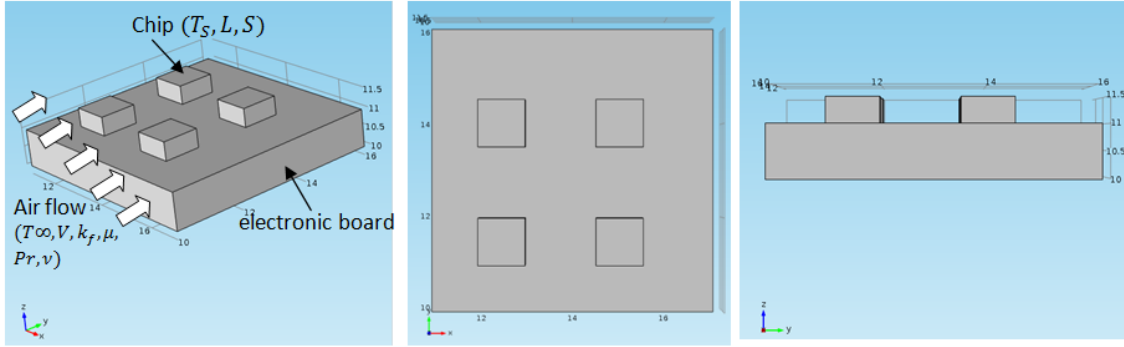$$T_F = \frac{(T_S + T_\infty)}{2} \tag{5}$$

Fig. 1. Graphical representation of the system under study showing the electronic board, direction of air flow, location of transistor and geometrical parameters.

The main fluid properties that are important to consider are the thermal conductivity (k_f;W/m·K), the viscosity (μ; N·s/m²), Prandtl number (Pr), kinematic viscosity (v;m²/s) which can be obtained from Thermodynamic tables available in literature after linear regression as described through (6) to (9) for a temperature range of $100 \leq T,(K) \leq 550$

$$v = \left[-2.072 + 0.0276T_F + 1.078 \times 10^{-4}T_F{}^2\right] \times 10^{-6} \tag{6}$$

$$\mu = \left[6.109 + 0.6945T_F - 3.323 \times 10^{-4}T_F{}^2\right] \times 10^{-7} \tag{7}$$

$$k_f = \left[-0.0386 + 0.097T_F - 3.1 \times 10^{-5}T_F{}^2\right] \times 10^{-3} \tag{8}$$

$$Pr = \left[0.8396 - 6.2857 \times 10^{-4}T_F + 6.32 \times 10^{-7}T_F{}^2\right] \tag{9}$$

Then, for the case of air at 25°C at sea level (P=1 atm), the parameters are $v = 1.5726 \times 10^{-5}\ m^2/s$, $\mu = 1.8356 \times 10^{-5}\ N \cdot s/m^2$, $k = 0.0261\ W/m \cdot K$, $Pr = 0.7084$

Reordering equation and multiplying both sides by length (L) we obtain

$$\frac{hL}{k_f} = \frac{L}{(T_S - T_\infty)} \frac{\partial(T - T_S)}{\partial y}\bigg|_{y=0} \tag{10}$$

were the term hL/k_f represents the dimensionless Nusselt parameter which expresses the relationship between the heat transfer by convection and the heat transfer by conduction across the boundary[20]. This parameter is function of Reynolds and Prandtl numbers. For Reynolds number in the range $10^4 \leq Re \leq 5\times10^4$, the Nusselt number can be evaluated from the expression $Nu = aRe^bPr^c$, were *a, b, c* are defined constant values depending on the geometry of the solid and Reynolds number. Particularly, for turbulent flow, the Nusselt number takes the form of $Nu = 0.023Re^{4/5}Pr^{1/3}$ for 0.6 $\leq Pr \leq 60$ based on Chilton-Colburn analogy [21]. Moreover, from the definition of Reynolds number: *Re=Vx/v*, and evaluating when *x=L* leads to $Re = VL/v$. Thus

$$\frac{hL}{k_f} = 0.023\left[\frac{VL}{v}\right]^{4/5} Pr^{1/3} \tag{11}$$

Following from expression (11), we can obtain the value of the local heat transfer coefficient

$$h = \frac{k_f}{L^{1/5}} \cdot 0.023\left[\frac{V}{v}\right]^{4/5} Pr^{1/3} \tag{12}$$
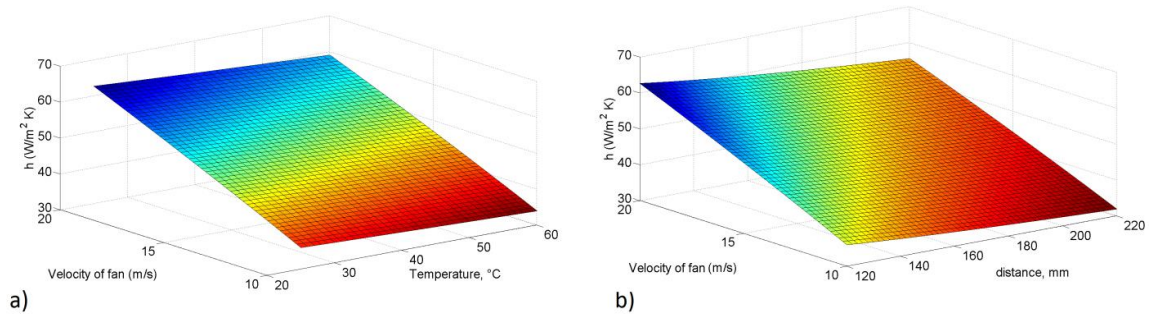
Fig. 2. Local heat transfer coefficient profile as function of velocity of input air (m/s), Temperature (°C) and distance (mm)

As described in figure 2, the value of convective heat transfer coefficient does not vary with the temperature. However, the distance of the transistor from the leading edge has an impact in increasing the value of *h*. From expression (1), it is clear that the local surface temperature (*Ts*) can be calculated as expressed in (13) and depicted in Figure 3 where the variation of chip temperature is described as function of chip dimensions and convective coefficient. Accordingly, Figure 3b) shows the influence of air velocity and chip dimensions in temperature profile.

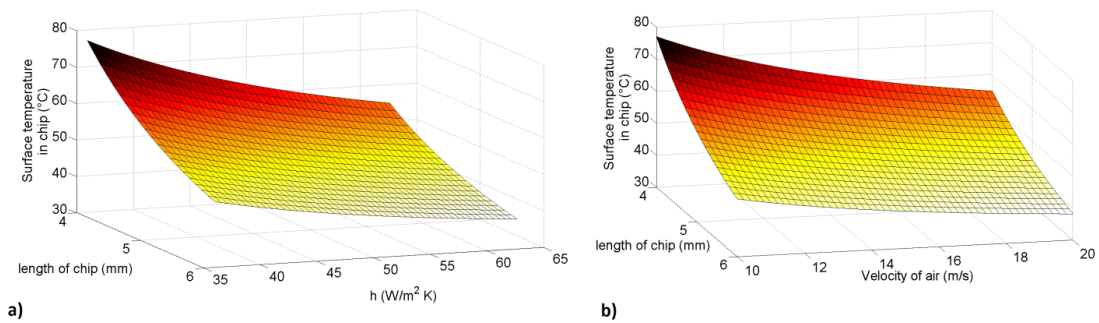$$T_S = \frac{\dot{q}}{h} + T_\infty = \frac{q}{A \cdot h} + T_\infty \tag{13}$$

Fig. 3. Temperature on the surface of the chip variation (°C) as function of length (mm), h (W/m2·K) and input air velocity (m/s).

We proceed to calculate the influence of atmospheric pressure on the cooling performance of the electronic device. We select a diversity of cities with an altitude between 31m and 2240 m as described in Table 1. Pressure is determined as described in (14)

$$P = 101.325[1 - 2.25577 \times 10^{-5} \cdot h]^{5.25588} \tag{14}$$

were *h* is the altitude of the city (*m*) and Pressure is given in *kPa*

Altitude (m)	Pressure (kPa)
2240	77.15
2147	78.05
1804	81.45
1537	84.17
1137	88.39
530	95.12
31	100.95

Table 1. Variation of pressure from selected cities around a country with corresponding values of altitude

In case of ideal gases we have $\rho = P/RT$, in which ρ is constant for incompressible liquids. As the kinematic viscosity is $\nu = \mu/\rho$, then $\mu = \nu P/RT$. Considering case 1 the conditions at atmospheric pressure (*P1*) and case 2 the pressure at different city (*P2*), the value of viscosity does not change with pressure, then

$$\mu_1 = \mu_2 \tag{15}$$

$$\frac{v_1 P_1}{\mu_1 R T_1} = \frac{v_2 P_2}{R T_2} \tag{16}$$

$$v_2 = \frac{v_1 P_1}{P_2} \tag{17}$$

$$v_2 = \frac{(1.5726 \times 10^{-5} \ m^2/s)(101.325 \ kPa)}{P_2} = \frac{0.001593}{P_2} \tag{18}$$

Kinematic viscosity relates the ability to transmit momentum disturbance with the ability to sustain momentum disturbance. As a result, the value of convective heat transfer coefficient and the temperature at the chip surface at different pressure can be calculated from expressions (19) and (20) respectively

$$h_2 = \frac{k_f}{L^{1/5}} \cdot 0.023 \left[\frac{P_2 V}{0.001593}\right]^{4/5} Pr^{1/3} \tag{19}$$

$$T_S = \frac{q}{A \cdot h_2} + T_\infty \tag{20}$$

Pressure (kPa)	υ (m²/s)	Vf=10 m/s		Vf=20 m/s	
		h (W/m²·K)	T (°C)	h (W/m²·K)	T (°C)
77.15	21×10⁻⁶	28.9	89.73	69.59	51.79
78.05	20.4×10⁻⁶	29.16	89.13	70.24	51.54
81.45	19.5×10⁻⁶	30.17	86.97	72.67	50.64
84.17	18.92×10⁻⁶	30.98	85.36	74.61	49.97
88.39	18×10⁻⁶	32.21	83.04	77.59	49
95.12	16.7×10⁻⁶	34.16	79.72	82.28	47.63
100.95	15.78×10⁻⁶	35.83	77.15	86.29	46.57

Table 2. Corresponding values of *h* and chip Temperature at given values of air flow speed and Pressure

This data is represented in Figure 4 for the limit of air velocity flow studied (10m/s - 20 m/s). As pressure decreases (higher altitude) the temperature on the transistor surface is higher. Using A speed of 10m/s the maximum chip temperature at normal pressure is 77 °C but in a city with different altitude, the temperature could reach 89.73 °C which is a significant variation and should not be considered irrelevant. In order to reduce the temperature, air speed should be increased. This can be calculated from expression (21)

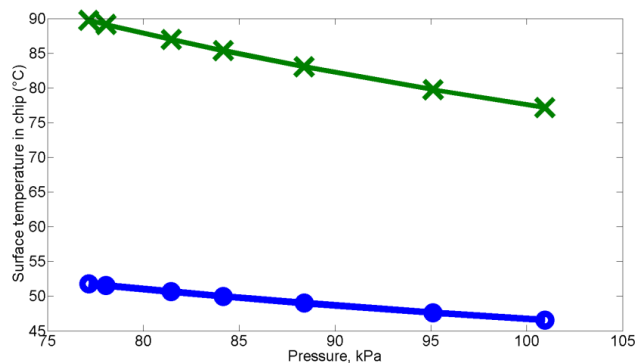$$V = v \left[\frac{h L^{1/5}}{k_f 0.023 Pr^{1/3}}\right]^{5/4} \tag{21}$$

Fig. 4. Chip surface temperature range for selected values of input air flow (10 m/s ×; 20 m/s •).

Pressure (kPa)	υ (m²/s)	$\nu = 1.57 \times 10^{-5}\, m^2/s$, $h = 35.93\ W/m^2 \cdot K$		$\nu = 1.57 \times 10^{-5}\, m^2/s$, $h = 62.57\ W/m^2 \cdot K$	
		T	Vf	T	Vf
77.15	21×10⁻⁶	89.73	13.3	51.79	26.26
78.05	20.4×10⁻⁶	89.13	12.98	51.54	25.96
81.45	19.5×10⁻⁶	86.97	12.44	50.64	24.88
84.17	18.92×10⁻⁶	85.36	12.03	49.97	24.07
88.39	18×10⁻⁶	83.04	11.46	49	22.92
95.12	16.7×10⁻⁶	79.72	10.65	47.63	21.3
100.95	15.78×10⁻⁶	77.15	10.03	46.57	20.07

Table 3. Readjustment of air velocity to cool the temperature on the surface of the transistor at same levels as tested at 1 atm

Now we proceed to determine the influence of air velocity at 25°C on the maximum amount of power dissipation as a function of air velocity. Considering that the maximum recommended temperature in the transistor surface should not be more than 85°C for reliable operation over prolonged periods of time, the properties of air at the film temperature, which is given by $T_F = (85 + 25)/2 = 55°C$ are $\nu = 1.86 \times 10^{-5}\, m^2/s$, $\mu = 1.98 \times 10^{-5}\, N \cdot s/m^2$, $k = 0.0285\, W/m \cdot K$, $Pr = 0.7014$. We considering an emissivity of 0.8 and performing an energy balance on the chip which is stagnant in a dielectric board with a surrounding temperature of 25°C. The graphical description of power dissipation can be observed in Figure 5.

$$P_c = \dot{q} + \dot{q}_r = hS(T_S - T_\infty) + h_r S(T_S - T_{sur}) \tag{22}$$

$$h_r = \varepsilon\sigma(T_S + T_{sur})\left(T_S^2 - T_{sur}^2\right) \tag{23}$$

$$P_c = hS(T_S - T_\infty) + \varepsilon\sigma S(T_S + T_{surrounding})\left(T_S^2 - T_{surrounding}^2\right)(T_S - T_{surrounding}) \tag{24}$$

$$P_c = S\left[\frac{k_f}{L^{1/5}} \cdot 0.023\left[\frac{V}{\nu}\right]^{4/5} Pr^{1/3}\right](T_S - T_\infty) + \varepsilon\sigma S(T_S + T_{sur})\left(T_S^2 - T_{sur}^2\right)(T_S - T_{sur}) \tag{25}$$
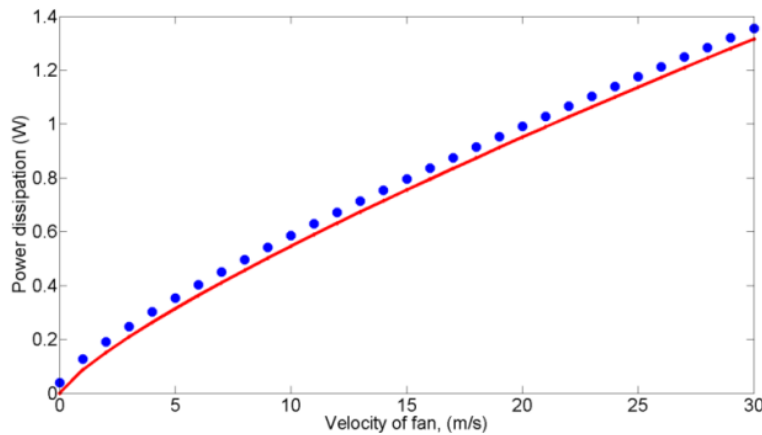

Fig. 5. Power dissipation profile as function of velocity of inlet air considering a maximum of 30 m/s with radiation contribution (dotted) and without radiation effect (continuous).

The convective heat transfer coefficient increases with the velocity of air in the same proportion as the power of dissipation. This can be seen in Figure 6 were it is plotted the value of *h* at different values of inlet air speed. Power dissipation increases with the velocity of air. The effect of radiation increases at a constant rate the dissipation of heat (0.04W) while the convective heat transfer coefficient reaches a maximum value of 82.2 at 30 m/s. Accordingly, it is also possible to evaluate an average convection coefficient according to the integral over a range of the leading edge distance.
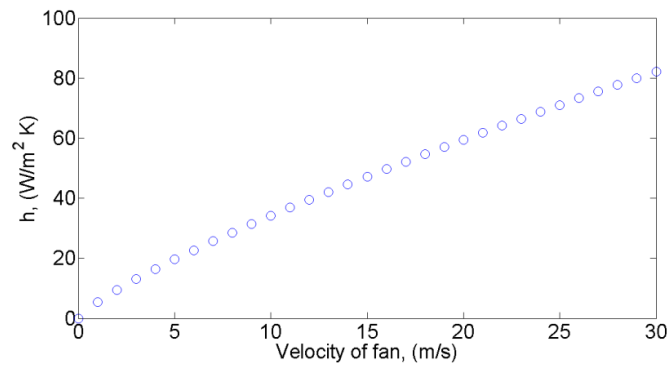
Fig. 6. Influence of air cooling velocity speed (0-30m/s) in heat transfer coefficient.

Variation of elevation affects several thermodynamic properties. The air is less dense at higher elevation, which decreases the atmospheric pressure value. Boiling point is other property that is affected as it decreases with the increment in elevation due to the effect of vapor pressure. In the case of convective heat transfer, there are several dimensional parameters that are important, namely Nusselt number, Reynolds number Prandtl number, and Rayleigh number. After Rayleigh number reaches certain values, the dominant mechanism is convection, rather than conduction. These values are strongly dependent on the characteristics of the system like the shape of the solid, fluid state (gas or liquid), viscosity and kinematic viscosity of the fluid, heat capacity of the air that is used for cooling, as well as the thermal conductivity, among others. Cooling process is affected considerably when the process is performed at different altitudes as it has been demonstrated by the different value of surface temperature (12.58 °C difference) achieved when the device is used in cities above 2240 m. Adjustments in the input air flow have to be made in order to compensate for this difference. This has a big impact in the design of new types of electronic devices which should take into consideration whether or not some changes have to me made according to the maximum allowed temperatures recommended for the components to maintain or improve their performance.

3. Conclusion

Mathematical modeling and simulation is an important element in several applications in many different fields of sciences such as chemistry, physics, mechanics, biology, and electronics among others. The study of fluid flow through a hot surface that allows the distribution of heat due to a temperature gradient is a practical problem that faces many challenging problems. Numerical simulation and modeling are tools that are frequently used to understand many processes and be applied to real cases to improve the design and its performance. In this paper we have used numerical simulation to study the variation of temperature on a transistor that is heated on an electronic device and is subject to the effect of different pressures. This is the case of using the device in different cities as the pressure changes with altitude and more important the density of the air since this parameter increases proportionally to the increment in pressure. Accordingly, at constant mass flow rate a decline in density causes a linear drop in the pressure. Many fans that are manufactured conventionally cool at constant speed even with the change of pressure or flow rate due to the design of blades which run at constant speed. The pressure output of the fan is strongly connected with the density of the air. Even at constant volumetric flow rate values a drop in mass flow rate with density is observed. Other type of fans is called slip fans, which allows the use of different speeds from the motor driving. This is extremely important from the point of view of electronic and mechanical cooling design for the control of temperature. In this type of fans, changes in altitude do not causes a drastic variation in the pressure flow rate curves in comparison to the use of conventional fans. One of the most important parameters to take into consideration for the effect of cooling through convection is the mass flow of fluid. When the air flow mass in the system is increased, the rise in temperature is lower. For example, using a flow of 10 m/s, a temperature near 77 °C can be achieved in the surface of the chip but this temperature decreases up to 46 °C when the speed is doubled. In the numerical study range of elevation (31-2240 m) the temperature values achieved using fans with 10 m/s leads to temperatures between 77.15 °C and 89.73 °C while in the case of doubling the air mass flow the temperature range is between 46.57 °C and 51.79. This decrement of temperature is a key element in the correct functioning and maintenance of devices that generates heat such as the case of electronics. Selection of fans appropriate for cooling of electronic devices should be base on the proper interpretation of fan supply curve and system pressure drop, particularly in the identification of stable operating points with enough flow rates. At higher altitudes, is important to take into account the influence of low density and temperature on pressure drop. Variation of volumetric flow rate is related to the type of fan used. This study allows us to evaluate the variation of temperature and to understand the importance of fluid flow speed in controlling the heating rate. The value of heat flux is restricted to the maximum temperature that the chip can resist after technical and thermal characteristics of design. Additionally, we studied the maximum amount of power dissipation as a function of air velocity considering a maximum of 30 m/s with radiation contribution and without radiation effect. Other consideration that could be incorporated in further studies is the influence of temperature in the surroundings (i.e. temperatures during winter and summer seasons), particularly the hot days in summer which would characterize the design for critical and worst conditions.

4. Acknowledgments

5. References

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