

DETERMINATION OF TEMPERATURE FIELDS IN A LOUDSPEAKER

Édison Pereira Dachi
Eletrônica Selenium S.A .- Department of Product Engineering
BR 386 km, 435, 92480-000 - Nova Santa Rita, RS, Brazil
edison@selenium.com.br

Horácio Antonio Vielmo
Federal University of Rio Grande do Sul – Mechanical Engineering Department – GESTE
R. Sarmento Leite 425, 90050-170 - Porto Alegre, RS, Brazil
vielmoh@mecanica.ufrgs.br

Abstract. This work describes the experimental and simulation procedures used to evaluate the temperature field of a loudspeaker, with cylindrical geometry and operating in transient and steady state conditions. The simulation results were obtained by solving the equations that describe the system behavior through the Finite Volume Method. Boundary conditions of the third kind were assumed. Both the temporal and spatial meshes were optimized in order to guarantee accurate results. The simulation and experimental results are presented, compared and discussed.

1. Introduction

The electrodynamic loudspeaker is an electroacoustic transducer, that is, it transforms electrical energy into acoustic energy. However a large part of this electric energy is transformed into thermal energy (heat). The electric current that circulates in the voice coil wire, which has an electric resistance to the passage of the current, generates heat due to the Joule effect. The efficiency of the loudspeakers is commonly low, of about 2-3%, and therefore, approximately 97-98% of the electric energy applied to the terminal is transformed into heat by the Joule effect. This heat is mostly generated by the loudspeaker voice coil, and must be dissipated, as excessive heat can cause the voice coil to reach its maximal operation temperature, and thus be destroyed.

Besides the voice coil, other essential parts for the functioning of the loudspeaker, such as adhesives, cannot reach maximal operation temperature as they can also be destroyed. In addition, the increase in the voice coil wire temperature also increases the electric resistivity of the wire. The functioning of the loudspeaker shows that the higher the resistance of the voice coil wire, the lower its sensitivity. This effect is known as power compression.

The factor of total quality of the loudspeaker, designated as Qts, which aids the description of the natural response to an excitation of the input terminals, either in the domain of time or in the domain of frequency, depends on the ohmic resistance of the voice coil, and therefore, it is also influenced by temperature. In the specific case of this parameter, Qts is inversely proportional to the electric resistance of the voice coil wire. If the voice coil wire temperature increases, its electric resistance increases, thus decreasing the Qts value.

Due to the influences of temperature on the performance of loudspeakers, the knowledge of the distribution field of temperatures is essential to increase the degree of optimization, performance and reliability of this device.

Design techniques using trial and error are currently widely used to determine the maximal operation power of loudspeakers, but they do not determine the maximal operation temperature of the components, compromising their thermal optimization.

Hence, the knowledge of the temperature fields in loudspeakers can be used to optimize and to enhance thermal reliability, either in steady or in transient state, of their design.

2. Problem formulation

The knowledge of the transient and the steady state of temperature distribution is critical for design purposes. First, the transient regime is determined from the moment in which the electric tension is applied to the loudspeaker terminals until the steady state is established.

A more accurate formulation of the problem can be expressed as follows: to determine the temperature fields, both in transient and steady state, of the loudspeaker, based on known values of the heat generated in the loudspeaker E_g, the environmental temperature T_∞, the coefficient of convective heat transfer h, the dimensions of its components, and the thermophysical properties of its materials (specific mass ρ, specific heat c_p and thermal conductivity k). The domain of calculation consists of the voice coil, the magnetic assembly, and the atmospheric air inside the magnetic assembly.

3. Physical modeling

The physical system to be solved in shown in Figure 1, where can be identified the domain, the control surface, the different regions and its respective materials, as well as the dimensions referring to each region. The relative position of the coordinate axis (x, r) is used for reference. The energies used for (effluent, generated, and stored) balance are indicated. Measures are given in “mm”.

1. Copper (pole piece)
2. Fiberglass (voice coil former)
3. Aluminum (voice coil wire)
4. Atmospheric air: external to the volume control and internal to the magnetic assembly
5. Steel (pole piece, upper and lower washers)
6. Barium ferrite (magnet)

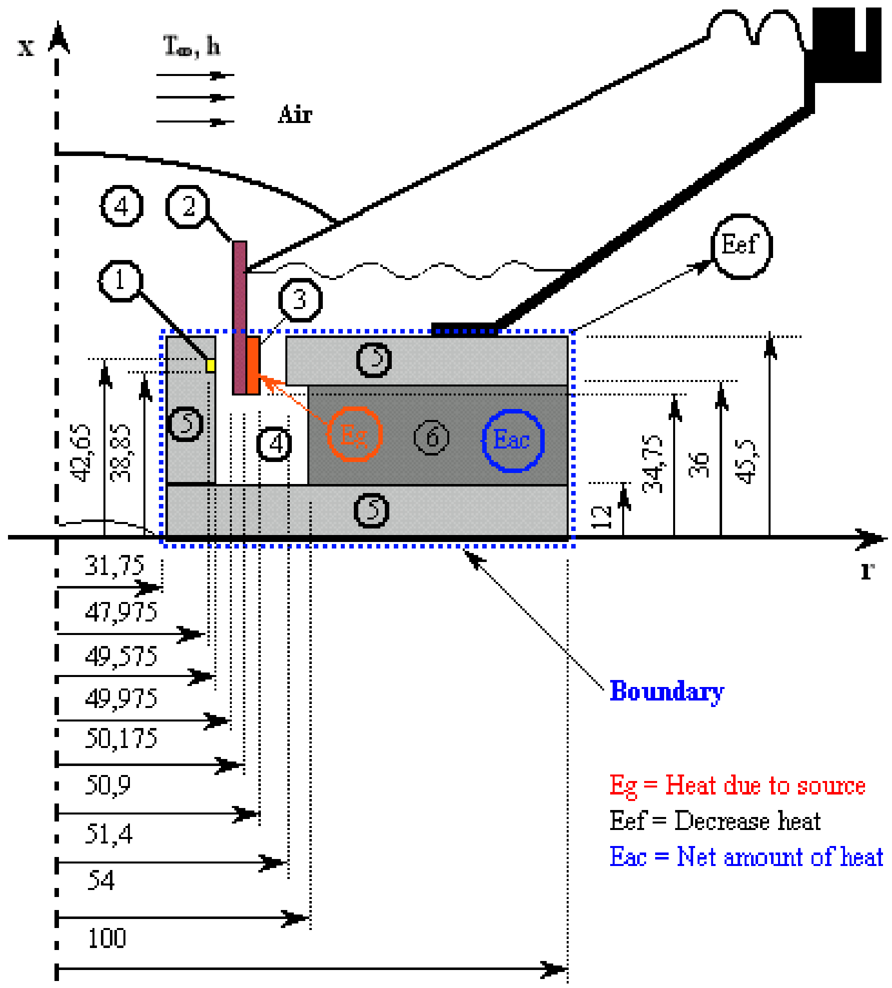


Figure 1 – The physical system.

4. Mathematical modeling and solution

It is a bidimensional heat diffusion problem, in transient regime, containing a heat source.

The following differential equation describes the problem, in cylindrical coordinates, assuming a symmetry [T (r, x, t)]:

$$\frac{\partial}{\partial t}\left(\rho c_p T\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + S \qquad (1)$$

Where ρ is the specific mass, c_p is the specific heat at constant pressure, T is the temperature, k is the thermal conductivity, r is the direction of the cylindrical system of the coordinates, radius, S is the heat source term, t is the time, x is the direction of the cylindrical system of the coordinates, length.

The boundary condition is assumed as the third kind (convective heat transfer coeficient on the surface and T_∞), given as

$$-k\left(\frac{\partial T}{\partial x}\right)=h\left(T_{s(x)}-T_{\infty}\right) \quad \text{and} \quad -k\left(\frac{\partial T}{\partial r}\right)=h\left(T_{s(r)}-T_{\infty}\right) \tag{2}$$

where h is the convective heat transfer coefficient, T_s is the temperature on the surface and T_∞ is the surrounding temperature.

Following several independence mesh tests, an equally spaced mesh of 32x100 volumes was used for the discretization of solution domain. The mesh is shown in Figure 2. The time interval used was 1 s.

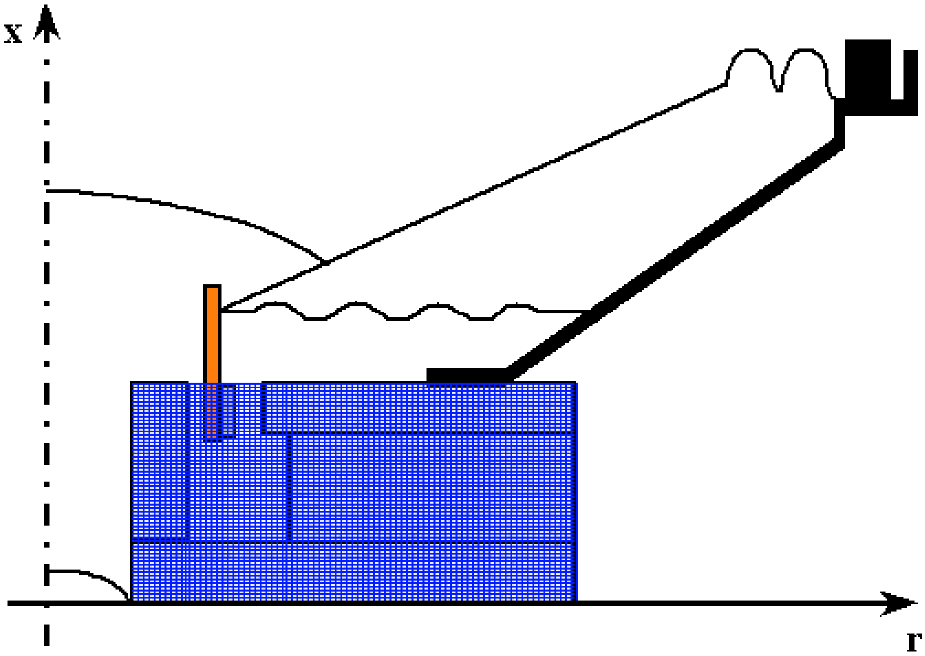


Figure 2 – Finite volumes mesh, with angular symmetry.

4.1. Heat source

The voice coil is the existing heat source because the electric current circulating in the voice coil wire, which has an electric resistance to the passage of this current, generates heat by Joule effect. The electric power generated by the voice coil is determined by the following equations:

$$P_{rms} = V_{rms}.I_{rms} \tag{3}$$
$$P_{rms} = V^2_{rms}/R_E \tag{4}$$

Where P_{rms} is the rms value or the mean efficient value of the electric power generated by the voice coil, I_{rms} is the rms value or the mean efficient value of the electric power in the voice coil; V_{rms} is the rms value or the mean efficient value of the electric tension in the voice coil, R_E is the value of the voice coil electric resistance.

However, as the voice coil resistance directly varies with temperature, this behavior is indicated by the coefficient of linear temperature of resistance α, by the following equation:

$$\alpha = (R - R_0) / R_0 (T - T_0) \tag{5}$$

Where R_0 is the reference resistance; T_0 is the reference temperature, R is the resistance at the measurement point; T is the temperature at the measurement point.

For the case of aluminum, $\alpha = 0{,}004\ {}^{o}C^{-1}$ (the loudspeaker voice coil wire chosen for this study is made of aluminum). Taking into consideration equations 4 and 5, equation 6 was obtained:

$$P_{rms} = V^2_{rms} / (R_0 + R_0.\ \alpha.\ (T-T_0)) \tag{6}$$

This equation is used to implement the heat source term. This equation is important as it shows that the electric power applied to the loudspeaker decreases as the voice coil temperature increases, and its use is essential for the adopted numerical method.

4.2. Simplifying hypotheses

The following hypotheses were considered for the solution of the proposed problem:

1) Except for α, the other thermophysic properties are temperature independent.
2) Coefficients of convective heat transfer (h) were initially assumed due to natural external convection.

However, due to the high complexity of the loudspeaker geometry, which renders the determination of the h value very difficult, we decided to perform some adjustments in these coefficients. A mean temperature of approximately 48 °C in the polar part and of 41 °C in the other parts were observed. Based on this, a h value of 5 W/m^2.K, and of 20 W/m^2.K for all the other parts were designated to the upper and internal faces.

3) Net exchange of radiation between surfaces.

The net exchange of radiation between any two diffusive gray surfaces can be expressed by the following equation (Bejan, 1984; Incropera, 1996)

$$q_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}} \tag{7}$$

where q_{12} is the net exchange of radiation between two diffusive gray surfaces; σ is the constant of Stefan-Boltzmann = 5.67x10^{-8} W/ m^2 K^4, ε_1, ε_2 are the emmissivities of surfaces 1 and 2, respectively; A_1, A_2 are the areas of surfaces 1 and 2, respectively; F_{12} the black body shape factor. In addition, in the specific case of any small convex body inside a large cavity, the net exchange of radiation between these two surfaces, under the hypothesis that $A_1 / A_2 \approx 0$ and $F_{12} = 1$, can be expressed by the equation:

$$q_{12} = \sigma A \varepsilon_1 \left(T_1^4 - T_2^4\right) \tag{8}$$

The experiments were carried out in a 1.85m wide, 3.35m deep, and 2.25m high testing chamber, resulting in a total surface area of 31.6325m^2. Due to the complexity of the loudspeaker, the total surface area, which exchanges heat by radiation with the environment, was determined by the 3-D modeling software SolidEdge as 0.226m^2. The ratio between the total area of the loudspeaker and the testing room surface was A1/A2 = 0.00082. The net exchange of radiation transfer for each considered surface was determined by equation (8), resulting in a total value of 0.57W. Hence, the hypothesis of net exchange of radiation between the loudspeaker and the environment was considered negligible.

4) The frame is considered as a heat dissipator. The implementation of the frame is described according to the equations to determine heat dissipation through a ring fin, and its coupling in the mesh.

4.1) Modeling of the ring fin. The frame is considered as a ring fin, as shown in Figure 3. The heat transfer through a ring fin can be calculated as follows:

$$q_f = \eta_f A_f h\left(T_b - T_\infty\right) \tag{9}$$

where η_f is the fin efficiency; A_f is the surface area of the ring fin and T_b is the temperature in the fin base. The surface area of the ring fin is calculated by the equation:

$$A_f = 2\pi\left(r_{2c}^2 - r_1^2\right) \tag{10}$$

where r_{2c} is the corrected external radius of the fin; r_1 is the corrected internal radius of the fin, where r_{2c} is determined by the equation

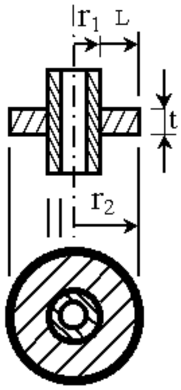
$$r_{2c} = r_2 + t/2 \tag{11}$$

where r_2 is the external radius of the fin, given in [m], t is the fin width, given in [m].

The efficiency of the ring fin with convection at the tip, η_f, can be determined by Eq. (13), which contains the approximation of the adiabatic tip. In this equation, $m^2 \equiv hP/kA_c$; L_c is the corrected fin length; k is the thermal conductivity of the fin material; A_c is the area of the straight section of the fin. Under conditions where (ht/k) > 0.0625, the error associated to approximation are negligible. If w >> t, where w is the fin width, then P = 2w, and the mL_c can be calculated by the equation

$$mL_c = \left(2h / kA_p\right)^{1/2} \cdot \left(L_c\right)^{3/2} \tag{12}$$

where, $A_p = L_c\, t$, and $L_c = L + t/2$, L is the fin length, t is the fin thickness, $L = (r_1 - r_2)$. Therefore, the efficiency of the fin is:



$$\eta_f = \frac{\mathrm{tgh}\left(\left(\frac{2h}{k A_p}\right)^{1/2} L_c^{3/2}\right)}{\left(\frac{2h}{k A_p}\right)^{1/2} L_c^{3/2}} \qquad (13)$$

Figure 3: Dissipator with a ring fin.

4.2) The boundary condition of the third kind is applied thought an additional source term in the boundary volumes, according Patankar (1980).

5) Atmospheric air is not quiescent within the magnetic assembly, but rather moving, and its thermal conductivity, k, is increased to 0.035 W/mK inside the magnetic assembly in order to simulate this movement. This value was fit based on comparisons with the experiments described below.

6) The heat source is not moving. A continuous and constant electric current was applied at the loudspeaker terminals. Therefore, the electric current circulating in the voice coil conducer wire is continuous. Then, the magnetic field generated in the voice coil interacts with the magnetic field of the permanent magnet, moving the voice coil as a function of the magnetic force, until it stops in a determined position. This position is limited in its maximal value by the maximal displacement of the spider. This is the position used in the control volumes for the implementation of this heat source.

5. Experimental approach – temperature field measurements

This study used a 12” “mid-bass” commercial loudspeaker. After being tested, the chosen model was placed in a power testing room, which dimensions are according to norm NBR5308/1982.

The part was initially fixed in a horizontal position, in order to ensure the axial-symmetry of the problem. The part was fixed using circular metal hooks, with an approximate diameter of 5mm, insulated from the part by a low thermal conductivity adhesive tape in order to avoid heat loss through the hooks.

Tests were carried out at an environmental room temperature of 24°C, where the air was initially still, and started to move after the experiment started due to natural convective currents. Precautions were taken to avoid external disturbances of temperature and air movement variations to the internal environment. The adhesive was used only around the sensors, and care was taken to prevent that it from being placed between the sensor and its respective temperature measurement surface. A thermal paste was used between the sensors and these surfaces, and the sensors were firmly pressed against the surfaces, aiming at reducing the contact thermal resistance. Care was also taken to place sensors of the same quota (coordinate x) or of the neighboring quotas in different angular quotas (coordinate ϕ) in order to reduce the influence of the proximity among sensors on the measurements as much as possible. All sensors were previously tested. The connection between the sensors and the Field Logger was made with three wires, thus decreasing the error of temperature measurement. The 26 AWG wire was used. In addition, the connecting wires, the sensors and the loudspeaker itself were not exposed to variable magnetic fields as a function of time, thus avoiding induced tensions and the introduction of this type of measurement errors.

5.1. Data collection

Sensor data were collected by a Field Logger Novus (system for acquisition and recording of analogical variables, with 8 channels) connected to a personal computer. The computer recorded and stored the data received form the Field Logger. PT100 sensors, manufactured with “thin film” technology on flat clay substrate, recommended for –200ºC to 650ºC high precision temperature measurements, were used. The sensors measured 1.6 x 3.2 mm, with and uncertainty of measurement of 0.2% in the maximum range and one tenth of degree resolution, and were fixed with instant adhesive.

Data acquisition rate was a measurement every 5 s, during a total period of 4 h of data acquisition, in order to ensure that the steady state was reached. Due to the thermal inertia of the system under analysis, this rate was considered as an excellent sampling number.

5.2. Description of the experiment

After all the above precautions and procedures were taken, the experiment itself consisted in applying a constant and continuous electric tension sign with an amplitude of 13.55 VDC at the entry of the entry of the loudspeaker. This tension was maintained constant throughout the experiment, and was monitored by a voltmeter permanently linked to the loudspeaker entry terminals. The electric current values circulating through the electric resistance of the voice coil, were measured and monitored by a current meter, and were collected and stored in a personal computer. The value of the initial electric current was 2.35 ADC, which resulted in an initial electric power applied to the loudspeaker of 31.8425 Wrms. It is designated as initial because the electric resistance of the voice coil wire as a function of temperature, which caused the power applied to the loudspeaker to decrease as the temperature increases, was considered. This variation was also taken into consideration in the simulations. After 4 hours, the power source was switched off as it was observed that the temperature was stabilized, therefore ensuring that the steady state was obtained. Another indication that the temperature reached its maximal value was the constant value of the electric current circulating in the voice coil (value read in the current meter that monitored this current), as this indicated that the electric resistance no longer varied.

Finally, the total displacement of the voice coil (heat source) was measured using a pachymeter. This measurement was made on the previous day in order to ensure that the voice coil would be completely cooled at the moment the experiment was carried out. The tension to be used in the experiment was applied to the voice coil, and its displacement from the center of the cap was measured. This was considered as the value of the voice coil displacement.

This measurement is necessary to determine the coordinated to be used in the simulation (position of the heat source).

The equation used to determine the electric power rms, considering here a power factor equal to 1, is given by equation 3. The figure 4 shows the equipment used in the experiment.

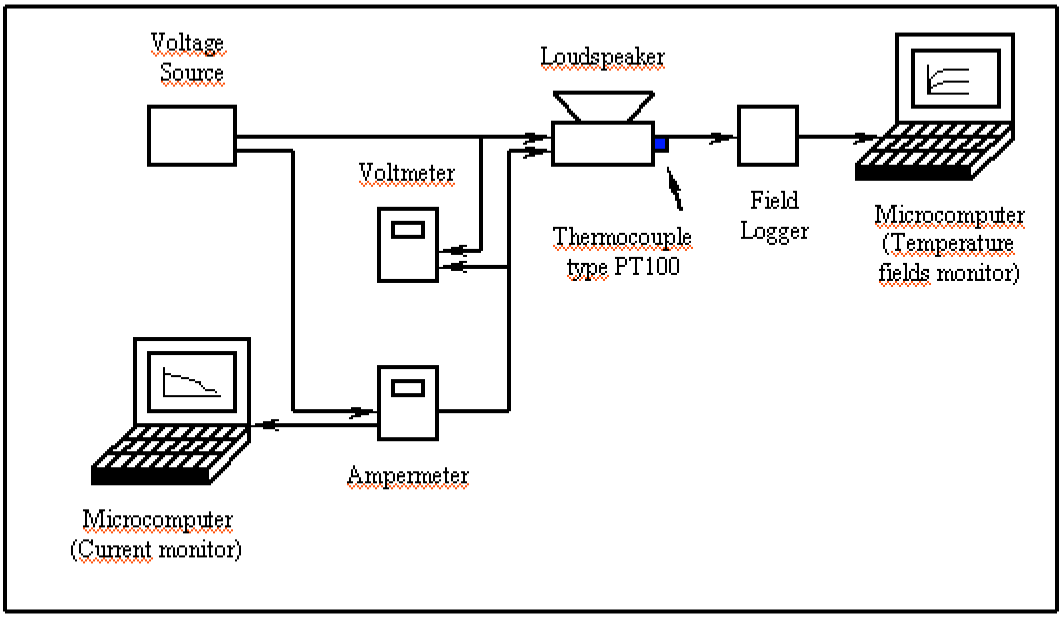


Figure 4 – Equipment used for measuring temperature fields in the loudspeaker.

The following instruments were used in this experiment:

a) Desktop computer: Pentium 200 MMX, 32 MB RAM, HD 2.1 GB
b) Laptop computer: Pentium II, 300 MHz, 64MB RAM, HD 2.1 GB
c) Field Logger: Novus System for analogical variables acquisition and recording
d) Electric tension source: Audio Authority Model 2 / 77 Hybrid 12-Volt Power System 50 A continuous, 300 A peak
e) Multimeter: Fluke 867B Graphical
f) Multimeter: Mastech Model M890G
g) Pt 100 sensors
h) Fixation stand for the loudspeaker
i) 12” loudspeaker: Selenium
j) Interconnection cables
k) Pachymeter

6. Comparison between experimental and numerical results

The experimental and numerical results of the temperature fields of the loudspeaker, as well as the coordinates of these points, are shown for comparison purposes. Figure 5 shows the loudspeaker design, indicating the temperature sensors with numbers. Figures 6 to 8 show the experimental and numerical results obtained in points 3, 6, and 15, which coordinates are (30.75; 0.9; 90°), (41; 95; 225°), and (0; 92.5; 225°), respectively. Figure 9 shows isothermal in the steady state.

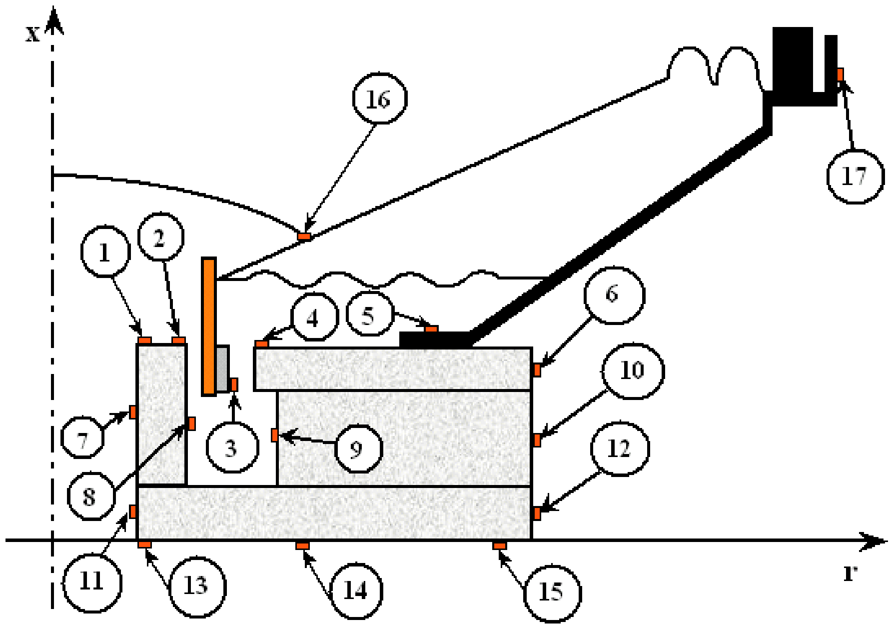


Figure 5 – Experimental and numerical points.

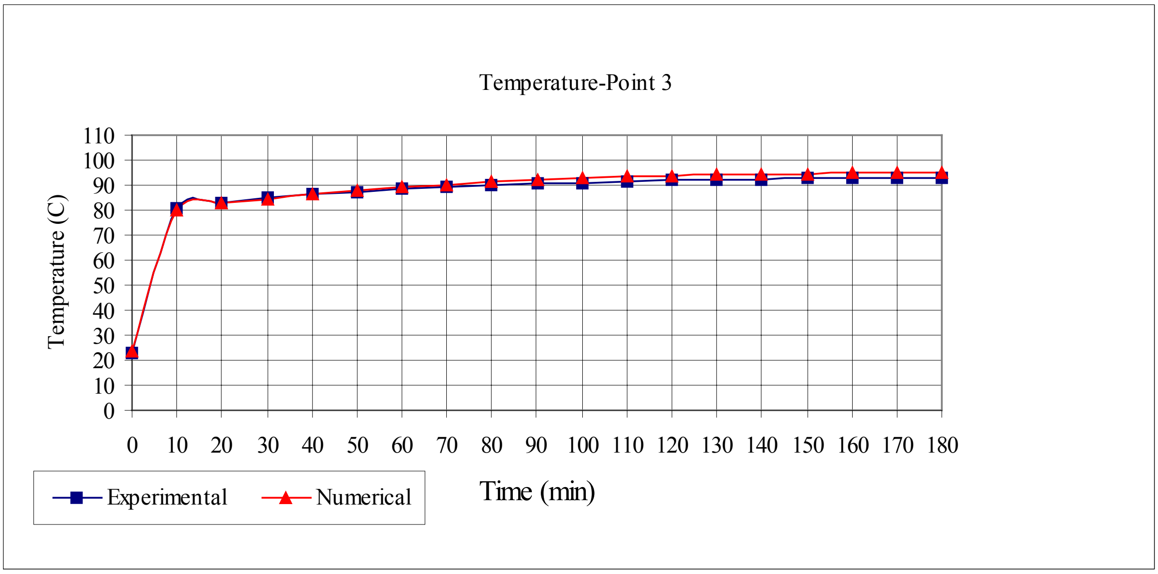


Figure 6 - Experimental and numerical values of temperatures in point 3.

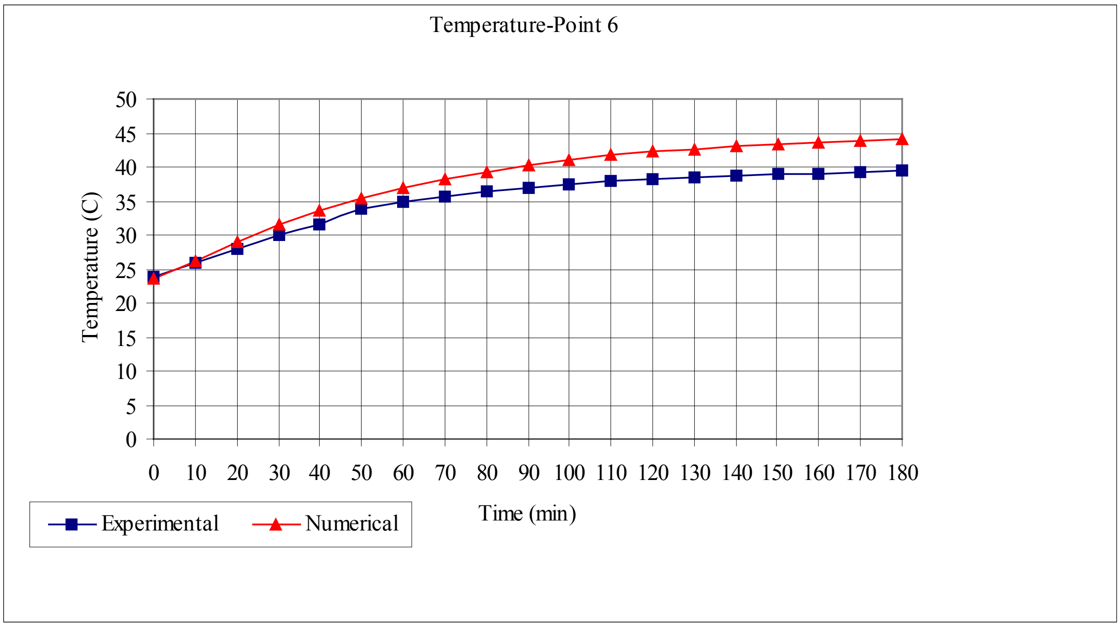


Figure 7 - Experimental and numerical values of temperatures in point 6.

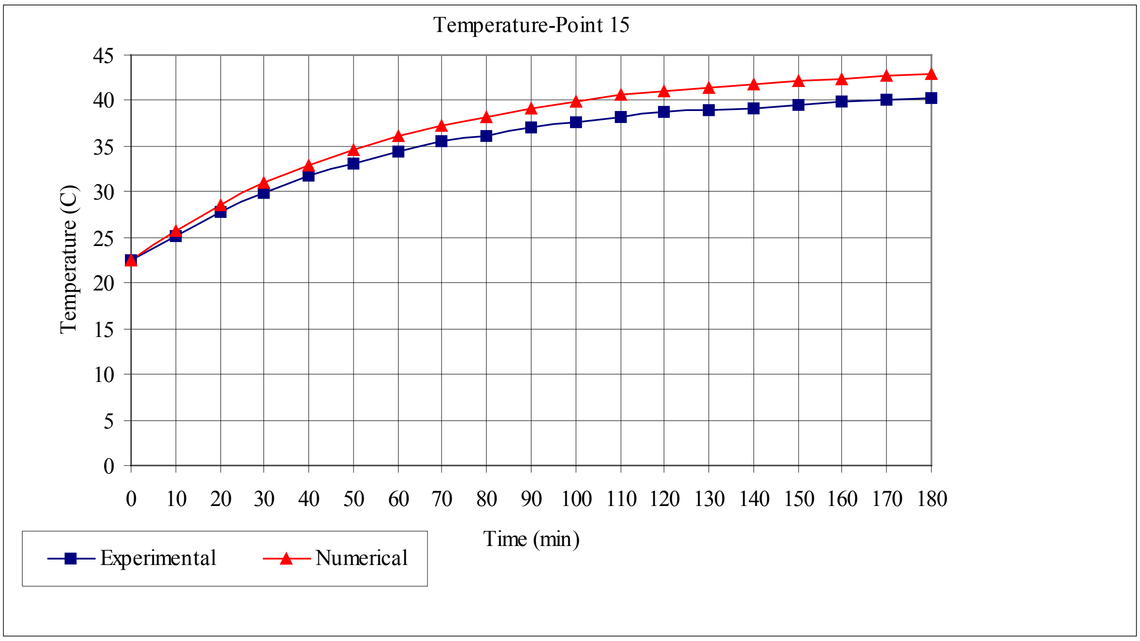


Figure 8 - Experimental and numerical values of temperatures in point 15

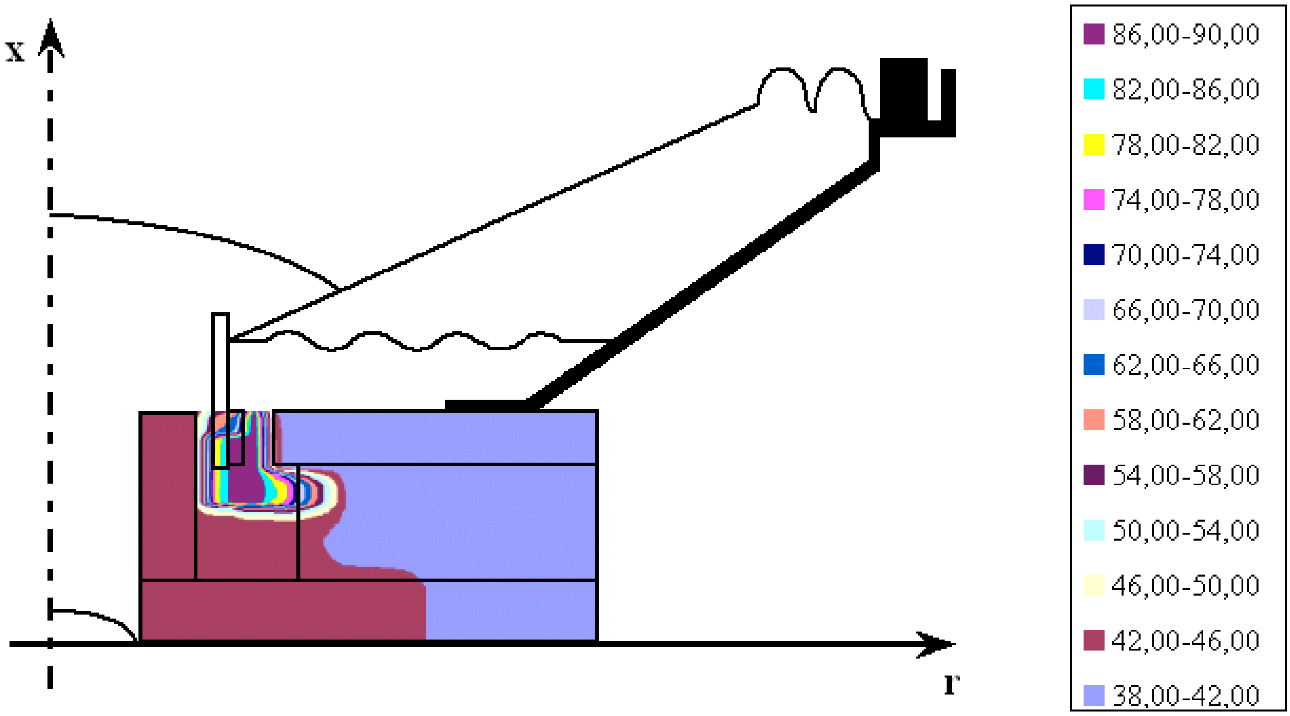


Figure 9 – Temperature map in the steady state [^oC].

It is observed that the average deviation between the experimental value and the numerical value is approximately 5%, what seems to be a very good result, considering this kind of coupled phenomenon. These deviations may be due to the following factors:

1. Sources of errors derived from data acquisition due to the contact resistance between the sensors and measurement points;
2. Measurement errors derived from the used voltmeter and current meter while monitoring tension and current, respectively. It must be pointed out that the determination of the applied electric power value was based on these values;
3. Initial values of temperatures read by different sensors because the sensors were place in different positions, and also because these sensors, despite being of the same type (PT100), having the same size (1.6 mm x 3.2 mm), and provided by the same manufacturer, presented differences derived from variations in their manufacturing process;
4. Non-linearities and uncertainties inherent to thermophysical properties;
5. The high complexity of the geometry of the loudspeaker made it difficult to determined the value of the coefficient of convective transfer.
6. A slight disturbance in the temperature field surrounding each sensor as a function of the heat removed by the wires and the applied adhesive, in spite of the precautions taken.

7. Conclusions

The experimental and numerical results of this study presented excellent agreement. Deviations were very low, which can be assumed as perfectly acceptable, considering the complexity of the investigated situation.

It may be asserted that the experimental results demonstrated that the number of measured points were sufficient to perform the analysis, as the differences among temperature values in points on the same face were small. This means that a higher number of points would not result in expressive benefits.

From the numerical standpoint, the refinement of the mesh, either spatial or temporal, was considered sufficient, that is, the solutions are independent from the mesh, and that the required computational effort is relatively small.

Finally, it is concluded that the developed modeling was successful, thus providing a new tool for the analysis of loudspeakers using this manufacturing technique.

8. References

Bejan, A., 1984. "Convection Heat Transfer", John Wiley & Sons, New York.

Ferziger, J.H. & Peric, M., 1997. “Computational Methods for Fluid Dynamics”, Springer.
Fox, W.R. & McDonald, A.T., 1995. “Introduction to Fluid Mechanics”, John Wiley & Sons.
Hayt, W.H.Jr. & Kemmerly, J.E., 1975. “Análise de Circuitos em Engenharia,” McGraw-Hill do Brasil,
Incropera, F.P., DeWitt, D.P., 1996. “Fundamentos de Transferência de Calor e Massa”, LTC, Rio de Janeiro,RJ. Brasil.
Maliska, C.R., 1995. “Transferência de Calor e Mecânica dos Fluidos Computacional”, LTC, Rio de Janeiro, RJ, Brasil.
Manual de Operação Field Logger Novus.
Norma NBR 5308 ABR/1982 - Alto-Falantes – Medição de Características - Método de Ensaio.
Patankar, S.V., 1980. “Numerical Heat Transfer and Fluid Flow”, McGraw-Hill, New York.
TDK Products Catalogue BME9Y-012B, TDK Electronics CO, LTD, 1979, Japan.
Users Manual Fluke 867B Graphical Multimeter.
Users Manual Mastech Model M890G.
Versteeg, H.K. and Malalasekera, W., 1996. “An Introduction to Computational Fluid Dynamics”, Harlow, England.