HEAT TRANSFER IN ELECTRONIC PACKAGE
SUBMITTED TO TIME-DEPENDANT CLIMATIC
CONDITIONS

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Abstract

The present paper describes the development of a simplified numerical model (SIMFEP\(^1\)) able to simulate heat transfer in an electronic package buried in soil and submitted to climatic conditions. To validate this model, numerical results are compared with experimental results obtained with ESSIC (Experimental Set-up Simulating Climate), a room equipped to simulate climatic conditions.

Nomenclature

\[\begin{align*}
A &\text{ absorptivity} \\
\alpha &\text{ thermal diffusivity} \quad \text{m}^2/\text{s} \\
\beta &\text{ thermal expansion coefficient} \quad \text{l/K} \\
C_p &\text{ specific heat} \quad \text{J/kg.K} \\
d &\text{ height, depth or thickness} \quad \text{m} \\
\sigma &\text{ Boltzmann’s Constant} \quad \text{W/m}^2\text{K}^4 \\
G_{ij} &\text{ conductance between i and j nodes} \quad \text{W/K} \\
g &\text{ gravity} \quad \text{m/s}^2 \\
h_{cv} &\text{ convective heat transfer coefficient} \quad \text{W/K.m}^2 \\
Q &\text{ heat flux} \quad \text{W/m}^2 \\
\lambda &\text{ thermal conductivity} \quad \text{W/m K} \\
L &\text{ width} \quad \text{m} \\
l &\text{ Length} \quad \text{m} \\
Nu_L &\text{ Nusselt number based on the length} \quad - \\
r &\text{ radius coordinate of SIMFEP} \quad \text{m} \\
\rho &\text{ density} \quad \text{kg/m}^3 \\
t &\text{ time} \quad \text{s} \\
t_h &\text{ time} \quad \text{hour} \\
t_d &\text{ time} \quad \text{day} \\
T_a &\text{ ambient temperature} \quad ^\circ\text{C} \\
T_{\text{max}} &\text{ maximal temperature} \quad ^\circ\text{C} \\
T_{\text{min}} &\text{ minimal temperature} \quad ^\circ\text{C} \\
T_{\text{ref}} &\text{ temperature of reference} \quad ^\circ\text{C} \\
\nu &\text{ kinematic viscosity} \quad \text{m}^2/\text{s} \\
s_i &\text{ heats source at node i} \quad \text{W} \\
V &\text{ air velocity} \quad \text{m/s} \\
Z &\text{ vertical coordinate of SIMFEP} \quad \text{m}
\end{align*}\]

1. Introduction

In order to enhance the deployment of xDSL services, France telecom installs outdoor cabinet all over the country. Some cabinets are placed on the sidewalks but another possibility is to use underground telecommunication manholes. These buried connecting rooms have been designed to receive passive equipment. Nevertheless, it remains possible to put inside a watertight box containing electronic cards. The cooling method chosen is natural convection because it is free maintenance. However, this one is not very powerful and the strongly unfavorable thermal conditions (small ground conductivity and solar heat flux on the top) make difficult the respect of ETIS\(^2\) standard temperature.

In order to optimize the cooling effect of natural convection, a simplified numerical model called SIMFEP is developed. This model must simulate the heat transfer in a buried connecting box submitted to climatic conditions.

This study presents the comparison of experimental results obtained with the climatic simulating room ESSIC and the numerical
results obtained with the simplified model SIMFEP. In a first part, this paper describes the principle of a simplified method and the real thermal problem. Next, ESSIC and SIMFEP principles are explained and applied to a specific case. Finally, experimental and numerical results are discussed and compared.

2. Principle of a simplified method
A simplified method is a simulation method situated between correlations and CFD codes. Its advantage is to allow the simulation of a complex case without the time cost of CFD codes.

The most important disadvantages are:
- the low precision in comparison with a CFD code result;
- the need to estimate heat transfer coefficient values.

This method has been used to simulate some complex cases like electronic packages cooling and the thermal response of buildings to climate variations. Our case is situated between these two thermal problems and is very complex for a resolution with a CFD code.

3. Description of the real problem
The real problem of a buried room containing an electronic package involves several kinds of heat transfer (fig.1):
- In the electronic package, the thermal problem is very complex and is a coupling between conduction, radiation and natural convection.
- In the buried room, heat transfer is also due to conduction, radiation and natural convection.
- In the earth, the thermal problem is a simple case of conduction.
- At the surface, the earth and the room lid are submitted to convection and radiation. The solar radiation changes with time and is nil during the night.

In this case, several aspects make the resolution difficult:
- Two very different heating sources (solar or lights radiation and electronic cards) are coupled.
- This problem is constituted of several kinds of heat transfer depending on the considerate zone.
- Time scales characterizing this problem are very different. Actually, the time scale characterizing radiation effect is very fast whereas the climate periodicity is 24 hours. The effect of the solar radiation is very fast whereas the earth temperature needs several days to converge to a periodic value.

4. Description of the climate imposed
In a first case, this model must be applied to a well known problem in order to be validated. To reach this point, we chose to compare the model to ESSIC measurements in an unfavorable case. This case is a hot climate in the south of France (latitude of Bordeaux) in summer. The solar radiation and the ambient temperature have been measured and an average annual climate with these daily variations has been defined. From these results, the most unfavorable case of a very hot day during summer is chosen to be applied to ESSIC and SIMFEP.
The ambient temperature daily variation and the power of the radiating flux at the surface are defined and imposed both to ESSIC and SIMFEP as a boundary condition during 10 days.

### 4.1 Radiating flux

The climate periodicity is based on a characterizing time of 24 hours. $t$, $t_h$ and $t_d$ represent the time respectively expressed in second, hour and day (Eqn. 1).

$$ t = t_d \times 3600 \times 24 = t_h \times 3600 $$

with:

$$ [t] = s; \ [t_h] = h \ and \ [t_d] = day $$

Equations 2 and 3 define the heat flux simulating the solar effect, nil during the night and reaching a maximal value at 13 hours.

For $5 \leq t_h \leq 21$:

$$ Q = A t_h^4 - B t_h^3 + C t_h^2 - D t_h + E $$

(2)

For $0 \leq t_h < 5$ or $21 < t_h < 24$:

$$ Q = 0 \ W.m^{-2} $$

(3)

With:

$$ A = 0.1141 \ W.m^{-2} h^{-4} $$

$$ B = 5.934 \ W.m^{-2} h^{-3} $$

$$ C = 97.29 \ W.m^{-2} h^{-2} $$

$$ D = 528.85 \ W.m^{-2} h^{-1} $$

$$ E = 847.95 \ W.m^{-2} $$

### 4.2 Ambient temperature

Equations 5 to 7 define the ambient temperature imposed (Fig. 2). The minimal temperature is $T_{min} = 18.5^\circ C$ and the maximal temperature is $T_{max} = 31.5^\circ C$. The temperature of reference is the average of the two extremes temperatures (Eqn. 4).

$$ T_{ref} = (T_{min} + T_{max})/2 $$

(4)

For $0 \leq t_h < 5$:

$$ T_a = T_{ref} \left[ 1 + \cos \left( \frac{2\pi}{28} (t + 9) \right) \right] $$

(5)

For $5 \leq t_h < 15$:

$$ T_a = T_{ref} \left[ 1 - \sin \left( \frac{2\pi}{28} (t - 15) \right) \right] $$

(6)

For $15 \leq t_h < 24$:

$$ T_a = T_{ref} \left[ 1 + \cos \left( \frac{2\pi}{28} (t - 15) \right) \right] $$

(7)

Fig. 2: Heat flux and ambient temperature variations
5. Presentation of ESSIC

ESSIC is an experimental set-up designed to simulate a chosen climate. In a closed room, a France Telecom connecting box is buried and submitted to the simulated climatic conditions. To create a radiation representative of the solar effect, 303 incandescence lights are disposed on the ceiling. To obtain a homogeneous flux, the lights are arranged in row with a space of 33 mm. At the north wall, 4 fans are placed just among the lights to reduce their temperature and keep it inferior to 40°C. Behind the fans, an aperture allows the exterior air to come in and at the opposite wall another aperture allows the hot air to come out. Each light has a variable power with a maximal value of 300 W and the resulting power received at the ground surface is close to the real conditions. The resulting power at the surface (Fig. 2) has been calibrated and is checked during experiments.

The air temperature of the room is controlled and regulated. Four electric heaters allow to increase the mean temperature whereas two fans can fall it.

The buried room is a concrete box of L5T model (179 × 88 × 120 mm). Electronic cards power (100W) is simulated by three heating resistances. The estimation of natural convection between the electronic cards and package walls is very complex. Thus, to simplify the simulated problem, a fan is placed in the electronic package under the electronic cards. By this way, the forced convection induced allows to homogenize the temperature and the electronic package can be introduced as a simple node in the simulation. The electronic package used is small in comparison with the buried room in order to permit the full development of the fluid flow by natural convection.

There are 126 thermocouples disposed on the room wall, in the air, in the ground and in the buried box. The thermocouples placed outside of the buried box are protected from the light radiation with an aluminum paper. Figure 3 is a simplified scheme of ESSIC configuration whereas figure 4 shows the box geometry and thermocouples positions.

Table 1 describes the geometry dimensions. The first and second column present respectively the width and the length. The third column is the vertical component and can be the height, the depth or the thickness depending of the element considered.

<table>
<thead>
<tr>
<th></th>
<th>L (m)</th>
<th>l(m)</th>
<th>d(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESSIC Room</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Buried room</td>
<td>1.79</td>
<td>0.88</td>
<td>1.2</td>
</tr>
<tr>
<td>L5T model</td>
<td>1.79</td>
<td>0.88</td>
<td>0.01</td>
</tr>
<tr>
<td>Room lid</td>
<td>0.66</td>
<td>0.55</td>
<td>0.38</td>
</tr>
</tbody>
</table>

6. Presentation of SIMFEP

In this numerical model, the geometry is simplified to be supposed cylindrical in order to use a cylindrical symmetry.

6.1 Boundary Conditions

This problem has 4 different boundary conditions:
- The box containing electronic cards is supposed to be homogeneous in temperature.
At the earth and lid surfaces, the heat transfer is due to convection and radiation.

The boundary condition in depth \((z = -2\text{m})\) is a constant temperature measured with ESSIC \((T = 17.5 \, ^\circ\text{C})\).

The vertical boundary condition is supposed to be remote enough to be independent of the buried heated source. In this case, the heat transfer direction is only vertical and it is possible to introduce an adiabatic boundary condition.

### 6.2 Equations resolved

The problem considers several kinds of heat transfer: radiation and convection at the surface, convection in the box, conduction in the walls and in the earth.

The model is based on the finite volume concept. For each node \(i\), the thermal balance equation is solved:

\[
s_i + \sum_{j=1}^{K} G_{ij} (T_i - T_j) = \rho V_i C_p \frac{dT_i}{dt}
\]

\((8)\)

\(G_{ij}\) is the admittance of the heat transfer mode and \(s_i\) is a heat flux source at the node \(i\). In this case there is one heat flux source:

The electronic package: \(s_i = 100\text{W}\)

**Conduction:**

\[
G_{ij} = \frac{\lambda_i S_{ij}}{D_{ij}}
\]

\((9)\)

**Convection:**

\[
G_{ij} = h_i S_{ij}
\]

\((10)\)

**Radiation:**

\[
G_{ij} = \sigma e S_{ij} \left( T_i^4 + T_j^4 - T_i^2 - T_j^2 \right)
\]

\((11)\)

The equation 11 is solved using an implicit scheme:

\[
\frac{s_i^{n+1} - s_i^n}{\Delta t} + \frac{1}{2} \sum_{j=1}^{K} \frac{G_{ij}(T_i^{n+1} - T_j^{n+1}) + \frac{1}{2} \sum_{j=1}^{K} G_{ij}(T_i^n - T_j^n)}{2}
\]

\((12)\)

\[
\rho_i V_i C_p \frac{T_i^{n+1} - T_i^n}{\Delta t}
\]

The grid used for the resolution is a \(27 \times 55\) grid nodes horizontally refined close to the buried room (Fig. 5).

### 6.3 Thermophysical properties

The thermal conductivity, the density and the heat capacity of each material used are presented in the table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (\lambda) (W/m.K)</th>
<th>Density (\rho) (kg/m(^3))</th>
<th>Specific heat (C_p) (J/kg.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>0.4</td>
<td>1200</td>
<td>975</td>
</tr>
<tr>
<td>Concrete (buried room walls)</td>
<td>1.4</td>
<td>2300</td>
<td>920</td>
</tr>
<tr>
<td>Cast iron (buried room lid)</td>
<td>50</td>
<td>7000</td>
<td>500</td>
</tr>
<tr>
<td>Electronic package</td>
<td>15</td>
<td>2300</td>
<td>500</td>
</tr>
</tbody>
</table>

**Tab. 2: Physical properties of each material**

Emissivity \(\varepsilon\) and absorptivity \(a\) of the lid and the earth are presented in the table 3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity (\varepsilon)</th>
<th>Absorptivity (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Lid</td>
<td>0.9</td>
<td>1</td>
</tr>
</tbody>
</table>

**Tab. 3: Emissivity and absorptivity used in SIMFEP**
6.4 Estimation of convective heat transfer coefficients

This problem involves the definition of several unknowns: the convection coefficients at the earth and lid surfaces and at box walls.

6.4.1 Convective heat transfer at the surface

At the surface, the convective heat transfer coefficient is issued from correlations. According to the experimental results, there are 3 different cases:

- During the night, the ground temperature is close to the ambient temperature and the convective heat transfer tends to zero.
- In contrary, during the day the buried room lid is heated by the source. Thus, the convective heat transfer coefficient can be estimated using the correlation of natural convection due to a horizontal hot plate.
- During the day, a cooling air flow due to fans induce a forced convective heat transfer at lid and earth surfaces. Thus, the convective coefficient is estimated using a correlation of forced convection.

Natural convection case (lid during night):

The characterizing Rayleigh number value based on the lid width $L$ is large enough to obtain a turbulent state. Thus, the Nusselt number can be expressed as a function of the Rayleigh number following the correlation of Fishenden and Saunders [1]:

\[ Nu_L = 0.14 Ra_L^{1/3} \]  \hspace{1cm} (13)

\[ h_{cv} = 0.14 \left( \frac{g \beta \Delta T \lambda^{1/3}}{\nu \alpha} \right) \]  \hspace{1cm} (14)

The $h_{cv}$ value obtained and introduce in the code is:

\[ h_{cv} = 3 \text{ W/m}^2\text{.K} \]

Forced convection case (Day):

During the day, the $h_{cv}$ coefficient is estimated using the correlations of Cole and Sturrock [2]. These correlations are based on experimental results obtained outside and during the night in order to avoid the solar radiation. Two cases are defined, depending of the air direction.

- Air direction parallel to the wall:
  \[ h_{cv} = F v = V^{1/3} \]  \hspace{1cm} (15)

- Air direction perpendicular to the wall:
  \[ h_{cv} = G + F V^{1/3} \]  \hspace{1cm} (16)

With $F=5.7 \text{ W.s}^{1/3}/\text{m}^{7/3}.\text{K}$ and $G=11.4\text{ W/m}^2.\text{K}$ and $V$ is the air velocity.

In our case, the air velocity due to fans has not a constant direction. Thus, the correlation chosen is an average of the two correlations:

\[ h_{cv} = \frac{G}{2} + F V^{1/3} \]  \hspace{1cm} (17)

This relation is applied using a velocity $v_i$ equal to the average of the velocity measured during the day. The $h_{cv}$ value obtained is:

\[ h_{cv} \approx 9 \text{ W/m}^2\text{.K} \]

In the present study, the convective heat transfer coefficient at the lid surface used is the average between the coefficients estimated during the night and during the day ($h_{cv} \approx 6 \text{ W/m}^2\text{.K}$).

6.4.2 Convective heat transfer in the buried room

In the buried room, convective heat transfer coefficients are obtained by CFD simulations. Actually, the CFD commercial fluid mechanics code FLUENT is used to simulate a
bidimensional square box containing a hot square source with a small aspect ratio. Based on the experimental information several temperature differences between the hot source and the box walls are tested. Actually, during the day, temperatures measurements at the lid and near the electronic package are close whereas during the day the temperature difference is about 20°C (Fig 6).

Flow structures obtained describe two large recirculation cells. Actually the fluid is heated going up along each vertical wall of the hot source before being cooled down by the box walls. Cells development depends of the temperature difference between the top wall and the hot source compared to the temperature difference between the top wall and the vertical walls. Actually, when the hot source and the top wall are at the same temperature, the ascending flow does not reach the top wall and the heated flow is cooled along the vertical walls. These results prove that during the night the flux due to the electronic package is essentially dissipated by the top wall whereas during the day, the heat transfer at the vertical wall is more important. Moreover the case with a cold top wall is much more effective because it allows the full development of the flow. In all the cases the heat transfer at the bottom is very low.

Figure 7 is an example of the flow streamlines structure obtained with a cold top wall.

Thanks to these results some average values of the convective heat transfer coefficient can be estimated for each wall and introduced in SIMFEP:

- Electronic package: $h_{cv} = 8 \text{ W/m}^2\cdot\text{K}$
- Top wall: $h_{cv} = 8 \text{ W/m}^2\cdot\text{K}$
- Vertical walls: $h_{cv} = 5 \text{ W/m}^2\cdot\text{K}$
- Bottom wall: $h_{cv} = 1 \text{ W/m}^2\cdot\text{K}$

7. Results

7.1 Experimental results

The results present two kinds of behaviors. Actually, during the night, the box is essentially cooled by the lid that is very conductive. But, during the day, the box lid is strongly heated by the lights radiation and most of the heated flux coming from electronic cards is dissipated by the vertical and the bottom walls.

Figure 8 shows the time variations of temperature measurements at the lid room and at the earth surface compared to the ambient temperature imposed. The earth surface temperature measurement noise is more important than at the other place because of the lights radiation.

At the earth surface, the temperatures measured in the distance of the buried room increase at 5h to reach a maximal value of about 45°C at 14h and decrease to 20°C. For a deeper point this variation amplitude decreases and becomes nil for depth of 2m.

Figure 9 shows the temperature daily variation in the buried room:
in the electronic package (thermocouple 26),
- in the air between the lid and the top of the electronic package (thermocouple 84),
- between the electronic package and the north vertical wall (thermocouple 94),
- at the bottom of the buried room (thermocouple 52).
The temperature measurements above the electronic package is larger than in the other air zones of the buried room. All the zones of the buried room have a temperature varying with the daily periodicity, but the zone under the electronic package have a temperature variation amplitude very low.

7.2 Numerical results
The numerical results provide the evolution of the temperature field with time. Fig. 10 shows the temperature fields obtained at 0h, 10h and 16h. On the left these fields show two hot zones: the lid and the electronic package. In the middle zone, the earth is heated by the buried room and by its surface. On the right side the temperature field of the earth is independent of the buried room temperature and the temperature variations are only due to climatic conditions.

7.3 Comparison of the numerical and experimental results
To compare the numerical and experimental results, we choose several points of reference corresponding to measurement points in ESSIC:
- lid temperature: thermocouple 95,
- electronic package: thermocouple 26,
- earth surface: thermocouple 14,
- earth at deep of 50 cm: thermocouple 32.

Figure 11 allows to compare the numerical results to the experimental measurements averaged on 3 days. All the points of reference present a same level for experimental and numerical results. This figure shows that the comparison between experimental and numerical results is in relative agreement. The temperature levels have the same between ESSC and SIMFEP, except for the earth surface temperature. This point could be improved taking a different heat transfer coefficient for night and day.

8. Conclusion
This paper has presented the development of SIMFEP, a simplified model simulating the heat transfer in an electronic package submitted to climate variation. To be validated, SIMFEP was applied to a specific unfavorable case and its results were compared with experimental results. The experimental part was realized with ESSIC, a room able to simulate a chosen climate. The first results show a good agreement between the simplified model and experimental results. The further development of ESSIC must allow the variation of the admittances with time to take into account the convective heat transfer variations.

References

Acknowledgement
The authors thank J. Gautier for his technical assistance during the experimental investigation with ESSIC.
- Velocity measurement points
- Temperature measurement points

**Fig. 4: Buried room and thermocouple position**

**Fig. 5: Grid used for the simulation with SIMFEP**
Fig. 6: Lid and Electronic package temperatures measured with ESSIC during a day

Fig. 8: Lid and earth surfaces temperature measurements with ESSIC and ambient temperature imposed
HEAT TRANSFER IN AN ELECTRONIC PACKAGE SUBMITTED TO TIME-DEPENDANT CLIMATIC CONDITIONS

Fig. 9: Temperature measurements of thermocouples 25, 55, 84 and 94 with ESSIC

Fig. 10: Temperature field obtained with SIMFEP at 10h, 16h and 0h
Fig. 11: Comparison of ESSIC and SIMFEP results