DESIGN OF AN ACTIVE THERMAL ELEMENT FOR A SOLAR THERMAL ENERGY MEASUREMENT SYSTEM BY SIMULATING HEAT TRANSFER PROCESSES USING THE FINITE ELEMENT METHOD

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Abstract - The use of solar energy by converting it and using it into thermal energy – for an efficient and correct use – requires knowing exactly the value of the local solar thermal power. The current paper puts forward a method of measuring solar thermal energy and a method of sizing the active elements used in the solar energy meter using open-source software to simulate finite element thermal transfer phenomena.

Keywords: Solar thermal energy, Fresnel concentrator, Finite element simulation, Energy, Solar energy.

1. Introduction

In a world marked by climate change and an increased need for sustainable energy resources, solar energy turns out to be an extremely promising solution. Within this inexhaustible source of energy, solar thermal energy obtained with the help of solar concentrators is an innovative and efficient technology, with significant potential to provide heat in an environmentally friendly way.

Solar concentrators – such as parabolic mirrors or Fresnel lenses – can concentrate solar rays over a small area, generating high temperatures in the process. This technology uses the principle of focusing the sun's rays to produce heat in significant quantities, which can then be used in a variety of thermal applications. By means of parabolic mirrors or Fresnel lenses, solar thermal energy can be captured and channelled into a single point, thus maximizing the efficiency and thermal power obtained.

The advantages of using solar concentrators to obtain solar thermal energy are remarkable. First, the technology of solar concentrators allows to obtain high temperatures, which opens up new possibilities in areas such as steam production for electricity generation or industrial processes that require high temperatures. In addition, solar thermal energy obtained from solar concentrators is a clean and renewable source, thus contributing to the reduction of greenhouse gas emissions and the protection of the environment.

In order to complete a project that uses solar energy by passing rays through solar concentrators, concentrator mirrors or flat lenses, it is necessary first to know the solar thermal power and its distribution over the course of a year in the place where the project will be implemented.

There are a lot of sites that show maps of the solar distribution, such as the one shown in Figure 1. In this figure is presented a map of the solar distribution for Romania, but it features a large scale, which leads to obtaining approximate values of local thermal energy for a certain place. As seen in fig. 1, for Bucharest, solar energy has a daily average value between 3.4-3.8 KWh/m^2, resulting in a power of between 0.94-1.05 KW/m^2.

In order to be able to accurately assess the energy value of solar radiation in a given place, to assess the quality of a concentrator or to assess the absorption capacity of the receptor material, it is necessary to build a system for measuring solar thermal energy.

The measurement system underlying the proposed device for measuring solar thermal energy is shown in Figure 2.

Essentially, the measurement system consists of a metal bar that receives – on one of the sections located at the end – the heat that needs to be measured and which will be dissipated (lost) when reaching the balance point as a consequence of the thermal resistance of the material, by means of radiation and convection.

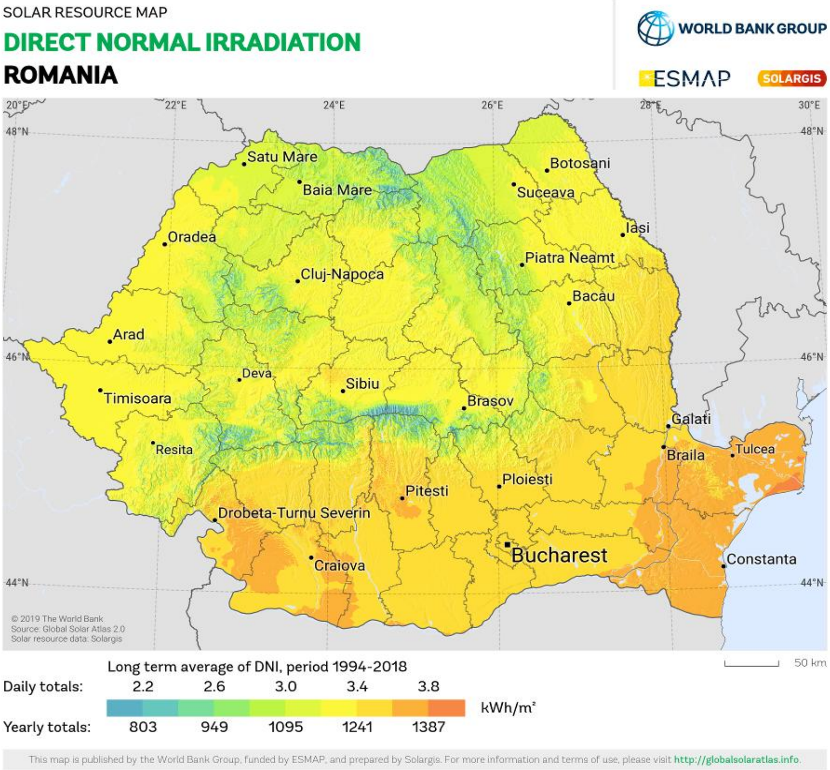

Figure 1: Distribution of normal solar radiation energy in Romania[2]

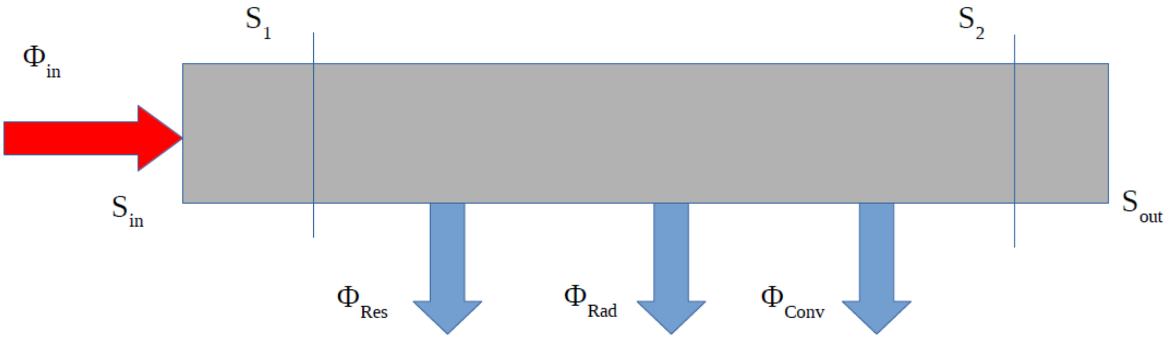

Figure 2: Distribution of heat received by a lateral face of a metal bar

2. Analysis based on Classic Thermal Transfer Methods

In this scenario

$$\Phi_{in}=\Phi_{Res}+\Phi_{Rad}+\Phi_{Conv} \qquad (1)$$

where

Φ_{in} is the heat flow received by the metal bar

Φ_{Res} is the heat flow lost by conduction (thermal resistance of the metal bar)

Φ_{Rad} is the flow of heat lost through radiation

Φ_{Conv} is flow of heat lost through convection

Of these

Φ_{res} is the heat of thermal conduction and it is given by the relationship proposed by Fourier:

$$\Phi_{Res}=-\lambda\cdot S\cdot grad\,T \qquad (2)$$

where:

Φ[W] is the flow of heat transmitted by conduction;

λ[W/mK] is the thermal conductivity of the material;

S[m^2] is the transfer area of heat - measured perpendicular to the direction of the propagation of the heat;

grad T [grd/m] is the temperature gradient.

For homogeneous solid materials, the thermal conductivity is roughly linearly dependent on the temperature

$$\lambda=\lambda_0\cdot[1\pm\beta\cdot(t-t_0)] \qquad (3)$$

where:

λ_0 is the thermal conductivity at the reference temperature t_0;

β is a constant (+ or -) determined experimentally, depending on the nature of the material.

Φ_{Rad} – heat emitted by the body by thermal radiation.

Thermal radiation is the result of the transformation of the internal energy of bodies into an electromagnetic energy, whose waves feature a wavelength λ = (0.1... 100) µm, encompassing the field of visible and infrared radiation. The intensity of radiation is given by Planck's law:

$$I_{\lambda,0}=\frac{C_1}{\lambda\cdot\left(e^{\frac{C_2}{\lambda T}}-1\right)} \tag{4}$$

where:

C_1 is the first Planck constant with the value 0.374×10^{-15} [W/m^2];

C_2 is the second Planck constant, with the value of 1.4388×10^{-2} [mK]

λ is the wavelength of radiation emitted by the body λ= (0.1…100) µm

According to [1] the energy emitted by radiation for heat transfer phenomena is neglected for temperatures below 350°C, and we shall ignore it in the follow analyses.

Φ_{Conv} represents the energy lost by the warm body through convection per unit of time; is given by the formula:

$$\phi_{Conv}=\alpha\cdot S\cdot\left(t_{body}-t_{fluid}\right) \tag{5}$$

where:

α is the coefficient of convection heat exchange (convection coefficient), expressed in W/m^2°C;

S is the surface of heat exchange, in m2;

t_{body}, t_{fluid} – warm body temperature, respectively of the fluid, expressed in °C;

By defining the convection heat exchange this way makes all the factors that determine the convection process to be included in the convection coefficient: the type of movement, the flow regime, the physical properties of the fluid, the shape and orientation of the heat exchange surface. Convection is characterized by four dimensionless invariants, namely:

1. Nusselt number:

$$Nu=\frac{\alpha d}{\lambda} \tag{6}$$

2. Prandtl number:

$$Pr=3600\frac{\upsilon}{\alpha} \tag{7}$$

3. Reynolds number:

$$R_e=\frac{wd\rho}{\eta g}=\frac{wd}{\upsilon} \tag{8}$$

4. Grashof number:

$$Gr=\frac{d^{3g}\beta\Delta T}{\upsilon^2} \tag{9}$$

where:

α is the heat transfer coefficient, (W/m^2 K);

d is a characteristic size, (m);

a is the thermal diffusivity $a=\frac{\lambda}{\rho c}$;

c is the specific heat, (J /kg K);

ρ is the density, (kg/m^3);

λ is the thermal conductivity, (W/m K);

w is the speed, (m/s);

υ is the dynamic viscosity, (Ns/m^2);

η is the kinematic viscosity, (m^2/s) $\upsilon=\frac{\eta g}{\rho}$;

β is the coefficient of thermal expansion, $\beta=\frac{1}{T}$ (for gases), (1/K);

g is the gravitational acceleration, (m/s^2)

Δt is the temperature difference between the gas and the wall, (K).

In the above formulas, for λ, for thermal conduction, and α, for thermal convection, the coefficients vary with temperature and other physical characteristics of the material that needs to be checked which makes their value difficult to obtain.

These impediments can be easily overcome by using a software for the analysis of thermal phenomena via the finite element method. From this point on, the thermal analysis processing presented in this paper was carried out with the help of Salome-Meca open-source software [3].

3. Experimental Heat Transmission

The first stage in the realization of a device for obtaining solar thermal power is the determination of the parameters of λ in equation (3) and of α in equation (6) for the material used to build the experimental radiator (stainless steel).

To this end, an experimental model was built. It is depicted in the Figure. 3.

Through the heating element (1) with a known thermal heating power, the right side of the metallic circular element is heated (2) and the temperature variation along the metal bar is read out using thermal sensors 3 and 4. Thanks to the thermal conductivity and convection cooling effect, there will be a temperature difference between sensors 3 and 4.

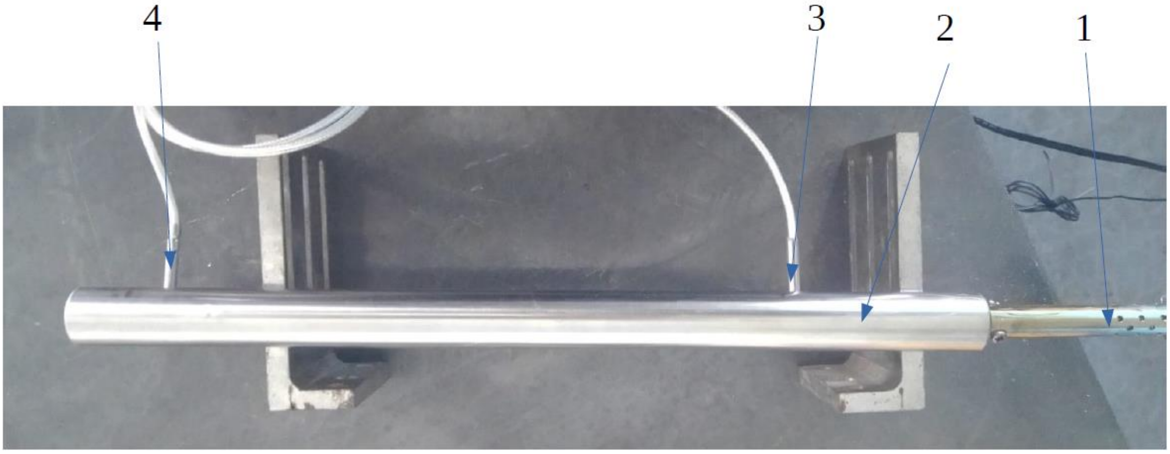

Figure 3: Experimental heat transmission installation components: 1 – heat source, 2 – metal bar, 3, 4 temperature sensors

In order to determine the thermal conductivity (λ) and the convection coefficient (α) of the material used for the construction of the metal bar, we will make a thermal transfer simulation – with the help of the Salome-Meca software – in which the dimensional parameters of the metal element will be introduced, along with the source of heating located on one of the sides of the cylinder, and with a known value (15.6 W), and various parameters for thermal conductivity (λ) and the convection coefficient (α), so that the simulation values coincide with the values used in the actual experiment (Figure 4).

4. Finite Element Method Analyses

The simulation parameters are presented in Figure 5.

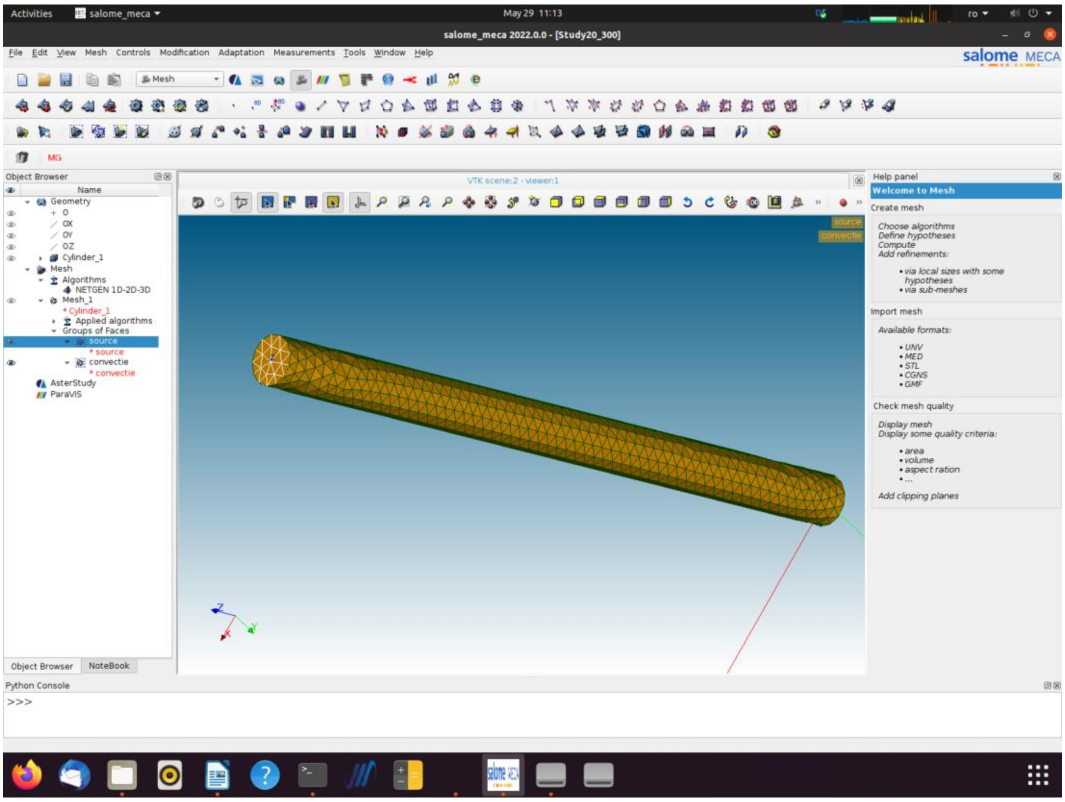

Figure 4: Screen capture from the finite element heat transfer software used in the simulation: the electronic equivalent of the physical experimental assembly

```
mesh = LIRE_MAILLAGE(UNITE=20)

model = AFFE_MODELE(AFFE=_F(MODELISATION='3D',
                            PHENOMENE='THERMIQUE',
                            TOUT='OUI'),
                    MAILLAGE=mesh)

otelinox = DEFI_MATERIAU(THER=_F(LAMBDA=40.0))

fieldmat = AFFE_MATERIAU(AFFE=_F(MATER=(otelinox, ),
                                 TOUT='OUI'),
                         MODELE=model)

source = AFFE_CHAR_THER(FLUX_REP=_F(FLUN=49657.0,
                                    GROUP_MA=('source', )),
                        MODELE=model)

load = AFFE_CHAR_THER(ECHANGE=_F(COEF_H=20,
                                 GROUP_MA=('convectie', ),
                                 TEMP_EXT=24.8),
                      MODELE=model)

resther0 = THER_LINEAIRE(CHAM_MATER=fieldmat,
                         EXCIT=(_F(CHARGE=source),
                                _F(CHARGE=load)),
                         MODELE=model)

resther0 = CALC_CHAMP(reuse=resther0,
                      RESULTAT=resther0,
                      THERMIQUE=('TEMP_ELGA', ))

IMPR_RESU(RESU=_F(RESULTAT=resther0),
          UNITE=80)
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Figure 5: Simulation parameters of the heat transfer for the experimental assembly

A result of a finite element heat transfer simulation is depicted in Figure 6.

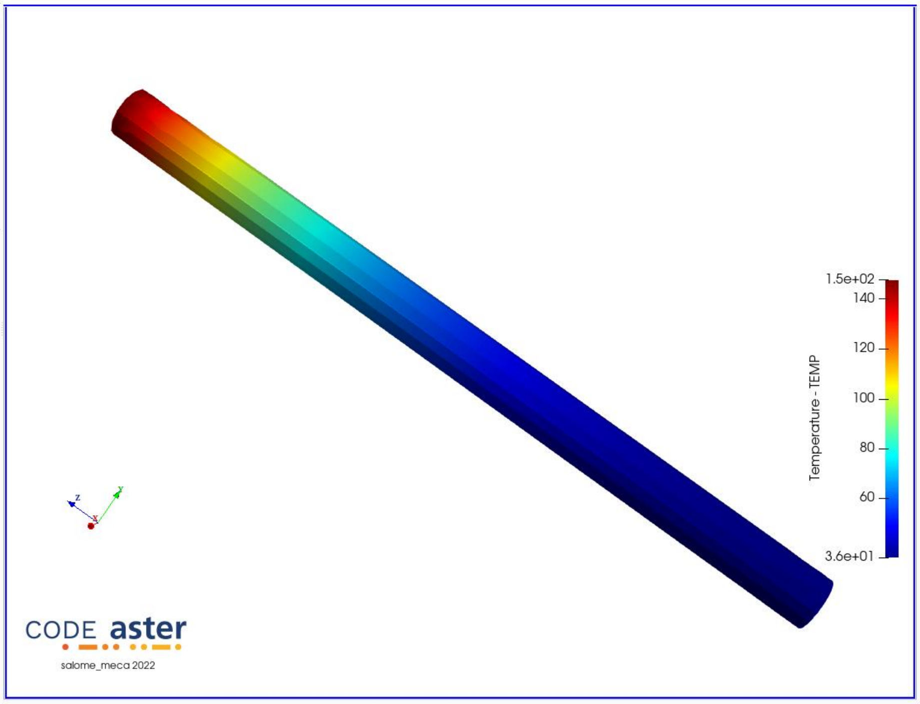


Figure 6: The result of the temperature distribution for the metal bar used in the practical experiment

In order to obtain the temperature value in the measurement positions of the temperature sensors 3 and 4 (fig. 3), the way of displaying the temperature in the section corresponding to each of the 2 sensors will be used. An example of the temperature display in a section is shown in Figure 7.

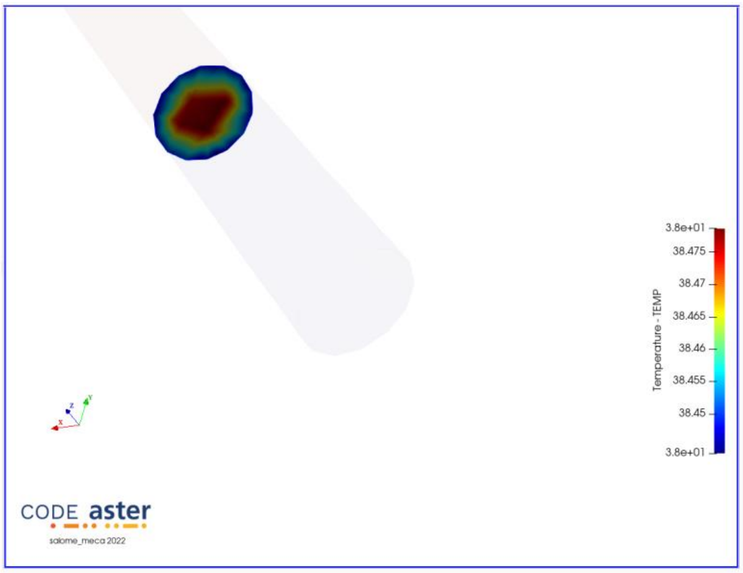


Figure 7: Temperature display in a section of the metal element used in the simulation

The result of simulations with different parameters for λ (thermal conductivity) and α (convection coefficient) are given in Table 1.

Table 1. Result simulations for the determination of λ and α parameters

Experiment	Temperature sensor 3[1] (°C)	Temperature sensor 4[2] (°C)	Thermal conduction coefficient(λ) [W/mK]	Convection coefficient (α) [W/m^2 °C]
Practical results	**92.3**	**36.1**	**-**	**-**
1	78.5	34	47	25.3
2	77	34.9	55	25.3
3	80	32	40	25.3
4	81	31	35	25.3
5	93	35	35	20
6	73	28.9	35	30
7	88	33	35	27
8	**91.9**	**36.6**	**40**	**20**
9	97	40	42	18
10	94	42	52	18
11	109	45	40	15
12	98	39	40	18

[1]) located at 10% of the length of the metal from the cold end
[2]) located at 80% of the length of the metal bar from the cold end

From table 1 it turns out that for the material used in practical experiment (stainless steel) has the thermal transfer coefficient λ = 40 [W/mK] and the natural convection coefficient α = 20 [W/m2 °C] with these values and by using the same material for the construction of the active element that will be used to build the thermal energy measurement device.

To cut down dimensions (the metal bar used in the experiments has a length of 300 mm and a diameter of 20 mm), an active element was designed as in Figure 8.

In order to be able to achieve a conversion of the values picked up by the temperature transducers into power, it is necessary to perform a series of thermal test simulations in which the values of the thermal conductivity and the convection coefficient will formerly be introduced and different values of the thermal power introduced at different temperatures of ambient air (which will influence the phenomenon of convection). The obtained results will then be used to convert the temperature values read by the temperature transducers into the values of the thermal power received (by interpolation or extrapolation, starting from the data obtained via the simulation).

An example of simulation based on the active elements shown in Figure 8 is presented in Figure 9.

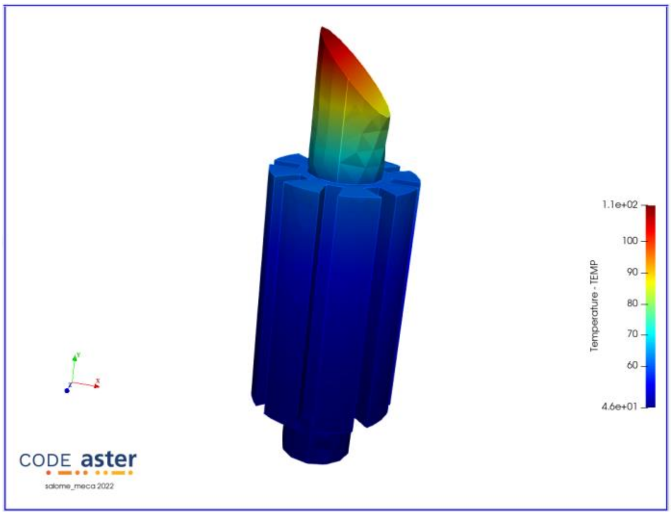
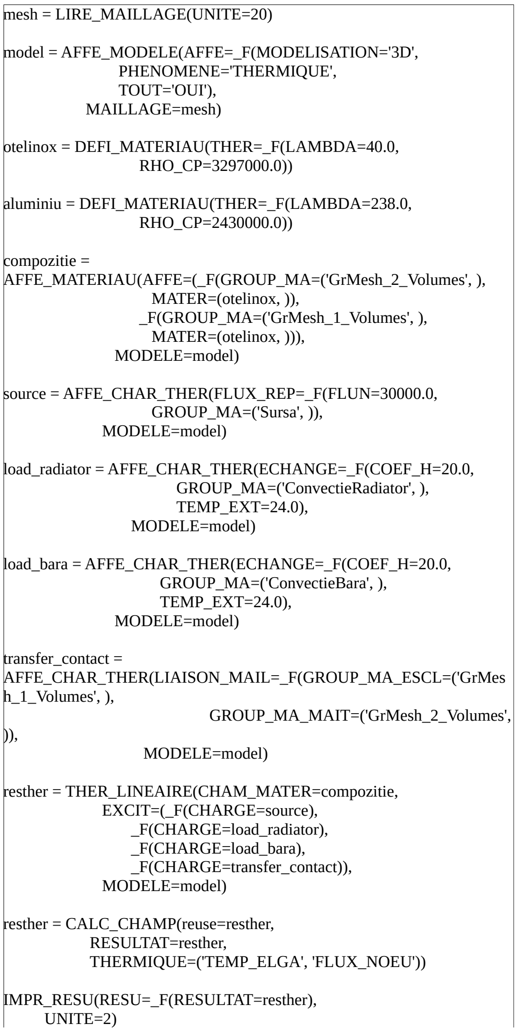


Figure 9: Thermal simulation display for the item that will be used as an active element in the solar thermal energy measurement device

The configuration of the Salome-Meca Software simulation is presented in the following figure:



```
mesh = LIRE_MAILLAGE(UNITE=20)

model = AFFE_MODELE(AFFE=_F(MODELISATION='3D',
                     PHENOMENE='THERMIQUE',
                     TOUT='OUI'),
               MAILLAGE=mesh)

otelinox = DEFI_MATERIAU(THER=_F(LAMBDA=40.0,
                         RHO_CP=3297000.0))

aluminiu = DEFI_MATERIAU(THER=_F(LAMBDA=238.0,
                         RHO_CP=2430000.0))

compozitie =
AFFE_MATERIAU(AFFE=(_F(GROUP_MA=('GrMesh_2_Volumes', ),
                        MATER=(otelinox, )),
                      _F(GROUP_MA=('GrMesh_1_Volumes', ),
                        MATER=(otelinox, ))),
                 MODELE=model)

source = AFFE_CHAR_THER(FLUX_REP=_F(FLUN=30000.0,
                        GROUP_MA=('Sursa', )),
                  MODELE=model)

load_radiator = AFFE_CHAR_THER(ECHANGE=_F(COEF_H=20.0,
                               GROUP_MA=('ConvectieRadiator', ),
                               TEMP_EXT=24.0),
                       MODELE=model)

load_bara = AFFE_CHAR_THER(ECHANGE=_F(COEF_H=20.0,
                           GROUP_MA=('ConvectieBara', ),
                           TEMP_EXT=24.0),
                   MODELE=model)

transfer_contact =
AFFE_CHAR_THER(LIAISON_MAIL=_F(GROUP_MA_ESCL=('GrMes
h_1_Volumes', ),
                                GROUP_MA_MAIT=('GrMesh_2_Volumes',
)),
                          MODELE=model)

resther = THER_LINEAIRE(CHAM_MATER=compozitie,
                  EXCIT=(_F(CHARGE=source),
                        _F(CHARGE=load_radiator),
                        _F(CHARGE=load_bara),
                        _F(CHARGE=transfer_contact)),
                  MODELE=model)

resther = CALC_CHAMP(reuse=resther,
                RESULTAT=resther,
                THERMIQUE=('TEMP_ELGA', 'FLUX_NOEU'))

IMPR_RESU(RESU=_F(RESULTAT=resther),
        UNITE=2)
```

Figure 10: Configuring the simulation for the Salome-Meca software

In order to obtain the temperature-power conversion table, a series of simulations have been carried out based on the values for the thermal conductivity and the convection coefficient.

The numerical values obtained in the simulations are presented in Table 2

Table 2. Values obtained in the numerical simulations

Outside Temperature (°C)	Applied thermal power (W)	Value measured by the cold temperature sensor (°C)(T4)	Value measured by the hot temperature sensor (°C)(T3)
18	5	23	27
	10	27	34
	20	34	50
	30	42	65
24	5	27.7	32
	10	32	39
	20	39	54
	30	46.7	70
30	5	33	36
	10	37	44
	20	44	59
	30	52	74
36	5	37.6	41.2
	10	41	49
	20	49	64
	30	57	79.25

The graphical representation of the change in the lower temperature (cold) is given in Figure 11 and the variation in the upper temperature is given in Figure 12.

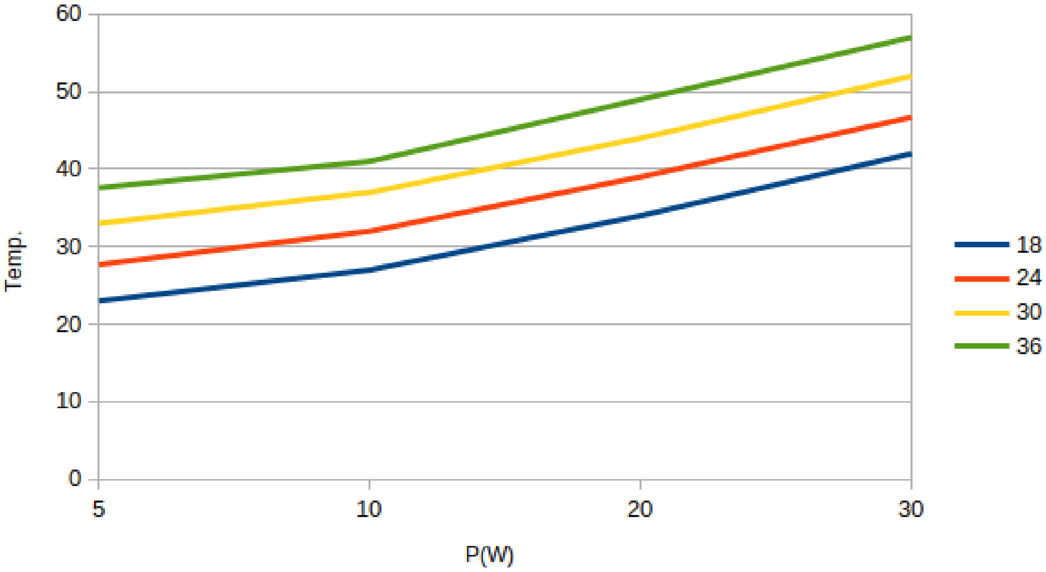


Figure 11: Variation in the lower temperature correlated with the outside ambient temperature

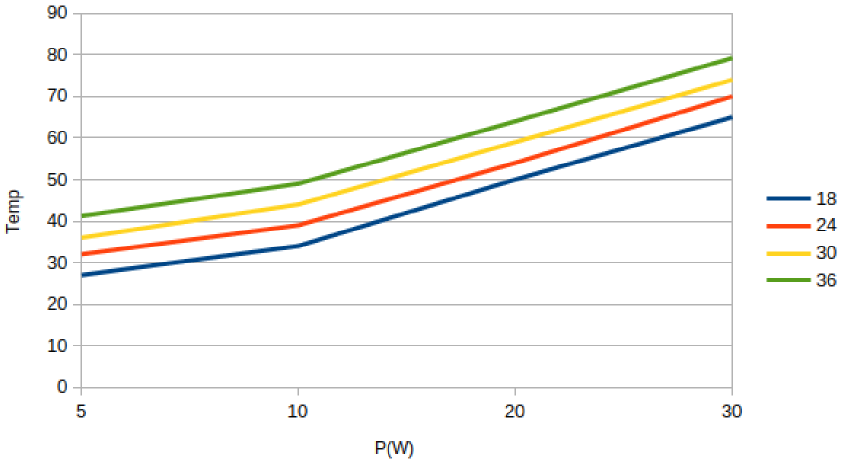


Figure 12: Lower temperature variation correlated with ambient outer temperature

The values stored in the table following the experiments will be processed as follows:

1. The ambient temperature is not found in Table:

We generate a new table with interpolated values based on temperatures close to the current temperatures, as follows:

We define T_{amb} as the current ambient temperature; thus, the values of temperature for the new interpolated table, according to the new ambient temperature, are calculated as follows:

if $T_{amb} < 18$ degrees then i-1=18, i=24

if $T_{amb} > 36$ degrees then i-i=30, i=36

2. The ambient temperature is found in Table:

if $T_{amb} > 18$ degrees and $T_{amb} < 36$ degrees then i is determined so that

$T_{amb,i-1} < T_{amb} <= T_{amb,i}$

where i represents the index of the simulated data set for a given temperature.

Then

$$T_p = \frac{T_{amb} - T_{amb,i-1}}{T_{amb,i} - T_{amb,i-1}} * (T_{i,p} - T_{i-1,p}) + T_{i,p}$$

for p= 5,10,20,30 W.

In the newly interpolated table, for an ambient temperature that is not found in the simulated data set, we will have the distribution of the (lower or upper) temperature depending on the solar thermal power.

For each of the temperatures, the equivalent solar power is obtained by linear interpolation and the final result will be the average between the two powers

$$P_{\text{final}} = \frac{P_{Temp_{\text{inferioara}}} + P_{Temp_{\text{superioara}}}}{2}$$

where:

$P_{Temp_{\text{inferioara}}}$ stands for the value of the interpolated solar power corresponding to the temperature of the cold area (minimum temperature values) and $P_{Temp_{\text{superioara}}}$ stands for the value of the interpolated solar power corresponding to the temperature of the hot area (maximum temperatures values).

Using the calculation methodology presented above, a microcontroller system that will directly provide the value of the solar power measured by the device can be easily implemented.

5. Conclusions

The use of the simulation software thermal transfer with a finite element is a handy solution for the engineers in the thermal-mechanical field. With the help of the Open Source Salome-Meca (for thermal simulations) software, all the practical elements specific to the active element used to achieve the disposition of solar energy measurement has been easily obtained. Next follows the mechanical and electronic design of the other component elements of the system.

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