Lecture Notes in Networks and Systems 965

Angel Moisés Hernández Ponce ·
Khemisset Marcos Escobar ·
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Trends and Challenges in Multidisciplinary Research for Global Sustainable Development

Proceedings of the 3rd International Conference on Applied Science and Advanced Technology

Springer

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Preface

Since around 2010, the postgraduate students from IPN-CICATA Querétaro have been organizing scientific-technological encounters, sometimes in the form of symposia and more recently in academic conferences. Being a rather complicated process, it has suffered several challenges and transformations. However, the enthusiasm and compromise of our students have helped them to overcome all difficulties and put successfully in place the last three occurrences of the event. Additionally, they figured out how to be supported by renowned editorials for the publication of the conference's memories.

ICASAT has two main characteristics, it is mainly organized by postgraduate students, and they must find and convince the keynote speakers to attend, they must coordinate the work with the publisher, the reviewers, the authors, and the sponsors as well as oversee all the necessary logistics. As a result, they develop a great deal of experience in the socialization of science. The second characteristic is the emphasis on the participation of undergraduate students, which in turn provides the opportunity for them to begin their involvement in the process of exposing their findings and ideas to the scientific community.

In the 2023 edition of ICASAT, the keynote speakers were, again, renowned researchers from México and abroad, Joyce Valdovinos, Roberto Manduchi, Beatriz Maruri Aguilar, Reydezel Torres Torres, Jack Reid, Arturo Barba Pingarrón, and Ramón Aguilar Armendariz enriched the conference and allowed the students to see, hear, and learn from scientist who have successfully reach the highest standards on the scientific world. Through this interaction, authors can see how to awaken the interest of an audience even on the densest subjects, a highly valuable ability for young researchers.

With the always valuable support of Consejo de Ciencia y Tecnología del Estado de Querétaro (CONCYTEQ) Continental, the Instituto de Artes y Oficios Querétaro, Joyería Científica and of course the Instituto Politécnico Nacional (IPN). Our community offered a more mature, ever-growing conference in the hope of becoming a key scientific international event in México and maybe, in the future, beyond our borders.

We deeply appreciate all authors for their contributions and wish to see them at the 2025 event, along with new colleagues who may hear from us and decide to help us in making ICASAT more meaningful every time. Thanks to all our students who were involved in the organization and the success of your conference, your dedication and commitment exceeded the expectations, and your contribution will always be appreciated and remembered.

Juan Bautista Hurtado Ramos
Director, IPN-CICATA QRO

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Contents

Thermal Absorption Accumulation Simulator

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Abstract. The work consists of the development of a desktop application developed in the Python programming language, which simulates the thermal absorptance of materials in a solar air heating system based on materials with low environmental impact. In addition, a mathematical verification is carried out through the use of the "Maple" Software on the proposed model that emerges from the energy balance of a thermal reservoir, called Thermal Absorbance Material (TAM). The implemented computational algorithm contributes to facilitating the numerical interpretation of data in a faster and more visual way. Finally, the developed simulator allows to observe not only the temperature curve but also provides the dispersion of a continuum of values, which can help to infer the magnitudes of some variables present in the model, with greater simplicity and effectiveness.

Keywords: Simulation · Sustainable energy · Thermal absorptance · Software

1 Introduction

According to the Secretaría de Energía del Gobierno de México, in the last national energy balance, it is evident that only 14.4% of primary energy at the national level comes from renewable sources [1]. That represents a slightly fluctuating amount in recent years. This shows the dependence on the use of hydrocarbons to satisfy most of the energy demand. The use of renewable energy is also minimal. The sector with the highest consumption of renewable energy sources, in percentage terms by demand, is residential, commercial, and public, where just over 4% of consumption comes from solar energy. Considering this trend, it is necessary to encourage the use of renewable energies at the national level, through concrete actions and through the use of technologies that use these energy resources. Which, also adheres to the 2030 agenda, to meet the objective for sustainable development 7 (ODS-7) [2], "affordable and non-polluting

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energy". In this sense, it is urgent for the academy to promote research on the use of clean energy sources, such as solar, which abounds in Mexico and can be used with various technologies that are easy to build and use. For example, solar heating systems, have been documented for years and continue to be the subject of analysis due to their operation and favorable impacts. Regarding these heating technologies, there are different programs for the study of the thermal behavior of materials, however, these are focused on the thermal analysis of buildings, such as ANTESOL, SIMEDIF, and ENERGY [3–5]. There is also software focused on the study of heat transfer through rooms and buildings such as SIMSCALE. The main characteristics of these programs are mentioned below: ANTESOL is a software that simulates the thermal behavior of building envelopes with any inclination and construction composition, rigorously considering the exterior and interior environmental conditions, especially sunlight and infrared radiation [3]; SIMEDIF 2000 is a software that allows thermal simulation of buildings with natural conditioning through passive solar systems, which was developed entirely at INENCO in 1984 [4,5]; ENERGY-10 is a program that allows you to simulate the thermal behavior of buildings with passive, hybrid and/or active air conditioning systems [4]. Finally, SIMSCALE is a simulation platform that offers computer engineering tools on the web [6]. The platform allows various types of simulations to be carried out, from finite element analysis to fluid dynamics. The mentioned software provides thermal analysis, whose applications can be diverse and are based on principles of material and energy balance analysis. However, there is no program that analyzes materials from their thermal absorbency and that particularly considers those with low environmental impact, nor is there free access software applied to the heating of fluids considering these principles. The above motivates this research to generate a strategy for democratizing knowledge affordably, and considering principles of sustainability, designing a digital tool that is easy to use and optimizes the preliminary determination of opto-thermal properties.

The present work focuses on the development of simulation software for the thermal characterization and improvement of low-cost materials and low environmental impact, used as solar thermal accumulators in air heaters. With this, the optimization of material resources, reduction of time, and economic resources is guaranteed. Thus, this work consists of the development of a desktop application made with the Python programming language, to simulate the thermal absorptance of materials in a solar air heating system made from materials with low cost and low environmental impact.

2 Theoretical Framework

We know that a transfer of heat from one body to another is carried out in areas with different temperatures and there are three forms of transfer, which are: conduction, convection, and radiation. By conduction, we refer to the process of heat transmission based on direct contact between two bodies, without the exchange of matter. The conductivity will depend on its microscopic structure:

in a fluid, it is due to the random collisions of its molecules, while in a solid it is due to the exchange of free electrons (metals), or to the vibration modes of its particles (dominant in the non-metallic materials) [7]. For the simplified case of steady heat flow in only one direction, the heat transmitted is proportional to the area perpendicular to the heat flow, to the conductivity of the material and to the temperature difference, and is inversely proportional to the thickness [7,8]:

$$\frac{dQ}{dt} = -kA\frac{dT}{dx} \tag{1}$$

where the term on the left is the rate of heat transfer in an x direction. Here, k is the thermal conductivity and A is the contact surface area.

Convection is the transport of heat through the movement of fluid. In the same way, as in conduction, it requires a material for transfer [9]. This type of energy transfer can be external, where the fluid moves over surfaces. It is said to be internal when the fluid moves inside the surfaces. To calculate the heat transfer by convection, the following formula [7–9] is used:

$$\frac{dQ}{dt} = hA_s(T_s - T_{\text{inf}}) \tag{2}$$

Where h is the convection coefficient, A_s is the area of the body in contact with the fluid. It should be noted that the convective heat transfer coefficient is predicted from empirical formulas that correlate dimensionless numbers. This depends on the type of fluid, the geometry of the system, the flow velocity, and the temperature difference [8]. As for radiation, it refers to electromagnetic radiation that is generated by the thermal movement of charged particles in matter. It is well known that all bodies (with the exception of those that have absolute zero) emit electromagnetic radiation thanks to this effect, and its intensity depends on the temperature and the wavelength considered [9,10]. Thermal radiation is one of the fundamental mechanisms of heat transfer [9,10]. On the other hand, it has been known that the total energy emitted per unit of time and emitting surface is given by the Stefan-Boltzmann law [7,8]:

$$Q_{\text{rad}} = \sigma A T^4 \tag{3}$$

this is for a black body with emissivity of one ($\epsilon = 1$). However, all real bodies have an emissivity less than 1 (grey bodies). Therefore, it emits electromagnetic energy per unit time and area as [7,8]

$$Q_{\text{rad}} = \epsilon\sigma A T^4 \tag{4}$$

where T is the absolute temperature of the surface, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2 K^4) and A is the area of the surface in square meters.

Continuing with the analysis of electromagnetic energy, we can mention that in a closed system, the bodies exchange energy by radiation until their temperature equalizes. The type of surface of a body is important in this exchange. Like any material, when food is exposed to waves, part of them are absorbed and transformed into heat, another part is reflected, and another is transmitted through it [11]. This same phenomenon occurs when solar energy falls on an object, this can be seen in Fig. 1.

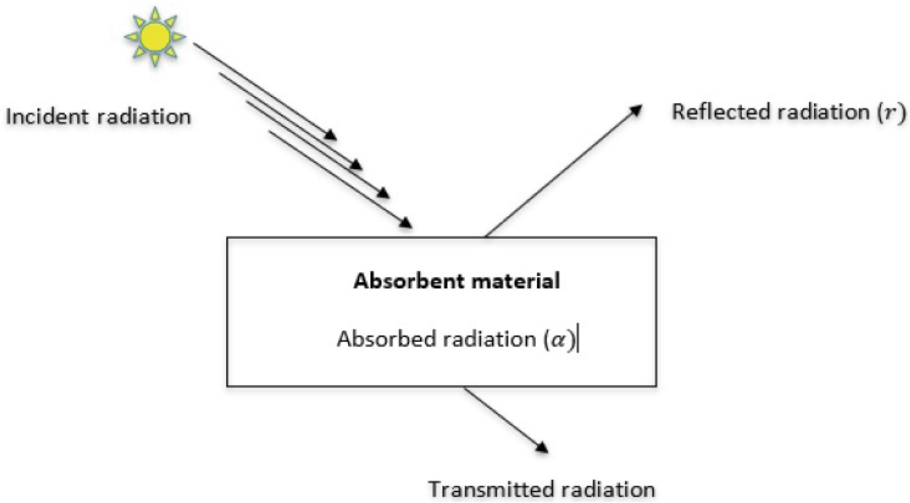

Fig. 1. The behavior of incident electromagnetic energy in a material.

3 Methodology and Procedure

In this section, basic statistical data was obtained such as absorptance, heat capacity, and mass of the materials, which was extracted from [15]. Subsequently, a data analysis tool was used with the Maple software [12], this being the foundation to develop the software that is required for the study of the thermal behavior of the Thermal Accumulation Material (TAM). In this sense, the simulation of the behavior of the temperatures of the TAMs as a function of time has been developed in the Python programming language [13,14]. To do this, data is taken for analysis according to the selected components as follows [15–18]: (a) TAM 1 prototype (T1): 95% gravel'-5% soot (b) TAM 2 prototype (T2): 95% limestone-5% soot (c) TAM 3 (T3) prototype: 50% gravel-50% limestone (d) TAM 4 prototype (T4): 45% gravel-45% limestone-10% soot. The construction of the air heating devices can be seen in detail in [15]. Here, the equations for the analysis of the thermal behavior of the thermo-solar system are proposed through the energy balance in the main components of the prototype. Specifically, the conservation of energy in the TAM leads to a first-degree differential equation [15] given as

$$m_{\mathrm{TAM}} \cdot C_{\mathrm{TAM}} \cdot \frac{dT_{\mathrm{TAM}}}{dt} = \alpha_{\mathrm{TAM}} \cdot \tau_{\mathrm{g}} \cdot I \cdot A_{\mathrm{TAM}} - h_{1\mathrm{TAM}} \cdot A_{\mathrm{TAM}} \cdot (T_{\mathrm{TAM}} - T_{\mathrm{gi}}) - Q_{k\mathrm{TAM}-b} \quad (5)$$

where $\alpha_{\text{TAM}} \cdot \tau_{\text{g}} \cdot I \cdot A_{\text{TAM}}$ is the energy gain due to incident radiation, $-h_{1\text{TAM}} \cdot A_{\text{TAM}} \cdot (T_{\text{TAM}} - T_{\text{gi}})$ is the energy loss originating from the surface of the TAM to the glass by natural convection of the air and by radiant heat transfer between the surface of the TAM towards the glass. Finally, $Q_{k\text{TAM}-b}$ is the energy loss due to conductive heat transfer from the TAM to the base of the tray. It should be mentioned that energy conservation at the outer surface of the cover glass and energy conservation at the inner surface of the cover glass are obtained in [15,19–21].

The solution of the differential equation is as follows:

$$T_{\text{TAM}} = e^{-\beta t} f_1(t) + T_{\text{TAM0}} e^{-\beta t} \tag{6}$$

with $f_1(t) = \int_0^t f(t)\, e^{\beta t}\, dt$ and $T_{\text{TAM0}} = T_{\text{TAM}}(0)$ which is the initial temperature of the TAM. The parameter $\beta = \frac{h_{1\text{TAM}} \cdot h_{g0} \cdot A_{\text{TAM}} \cdot t_h}{m_{\text{TAM}} \cdot C_{\text{TAM}} \cdot (h_{\text{TAM}} + h_{g0})}$ and $f(t) = \frac{A_{\text{TAM}} \cdot t_h}{m_{\text{TAM}} \cdot C_{\text{TAM}}} \left[(\alpha_{\text{TAM}} \tau_g - \alpha'_b) \cdot I + \frac{h_{1\text{TAM}}}{h_{1\text{TAM}} + h_{g0}} \cdot (\alpha_g I + h_{g0} T_e) + h_{cbe} \cdot (T_b - T_e) \right]$.

Here, $\alpha_{b'} = \alpha_b \alpha_{\text{MAT}} \tau_g$ is the fraction of absorptance experienced by the base of the tray and $t_h = 3600 s/h$. This result is also related to other parameters, such as ambient temperature as a function of time, thermal irradiance, absorptance, among others; these parameters can be found in references [15,22–26]. In particular, the values of the absorptance and the initial temperature of the different computed TAMs are given in Table 1 [15]. The solutions of the aforementioned equations were included in a code in the *Python* programming language, which can be seen in Appendix I.

Table 1. Absortance of the TAMs.

	TAM1	TAM2	TAM3	TAM4
Absorptance	0.935	0.437	0.341	0.725
$T_{TAM}(0)$ [°C]	12.3	12.1	12.4	12.2

3.1 Program Operation

Considering the principles of the energy balance of the previous section, the program has the behavior of the ambient temperature, as well as the thermal irradiance, these depend on the maximum and minimum temperature of the study region (the first two buttons shown in Fig. 2). In the same way, it provides the thermal behavior of thermal absorptance materials, which is the main objective of the Software. Therefore, we can access the TAM thermal simulator through the button, called "Material Temperature (TAM)" to enter the data as shown in Fig. 3. These data correspond to the heat capacity of the TAM (CTAM), the

TAM mass (MTAM), TAM area (TAM), TAM initial temperature ($T0_{TAM}$) and TAM absorptance (AlphaTAM). In turn, you must enter the initial conditions of the environment, which correspond to the maximum temperature (T_{max}), minimum temperature (T_{min}), total daily solar radiation on the horizontal surface (W_0), initial irradiance (I_0), respectively.

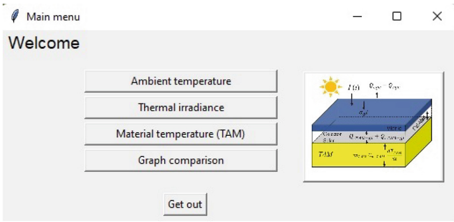

Fig. 2. Components of the Main menu.

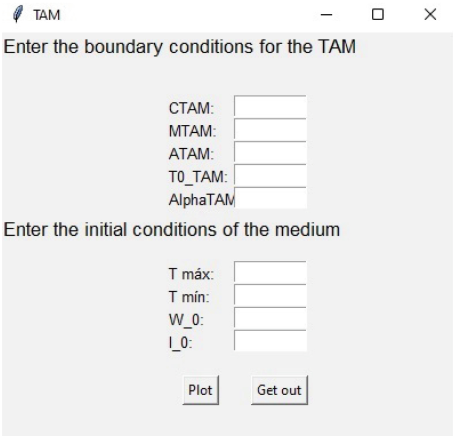

Fig. 3. Characteristics for data entry.

The button, called "Graph comparison", is made up of five modules, the first four refer to the boundary conditions of the TAM and the fifth is for the initial conditions of the environment (see Fig. 4). It allows you to enter five values of the TAMs parameters and generates four graphs for a simple, dynamic, and comparative analysis of each TAM. It should be added that Figs. 3 and 4 show that there are two buttons: the "Plot" button to generate the graphs of the different TAMs and the "Get out" button to leave the System.

4 Discussion and Results

The purpose of this section is to present the results obtained through two programs, which are Maple [12] and *Python* [13,14]. It should be noted that the main objective is to develop a simulation through computer programming developed in *Python*, this is to obtain the thermal behavior of low-cost materials as a function of time. In addition to its usefulness in the scientific field, the graphic structure allows us to make a simple and precise analysis of the statistical data, allowing us to understand the complex numerical matter in the context of the study of opto-thermal materials that have similar characteristics to the one considered in this work.

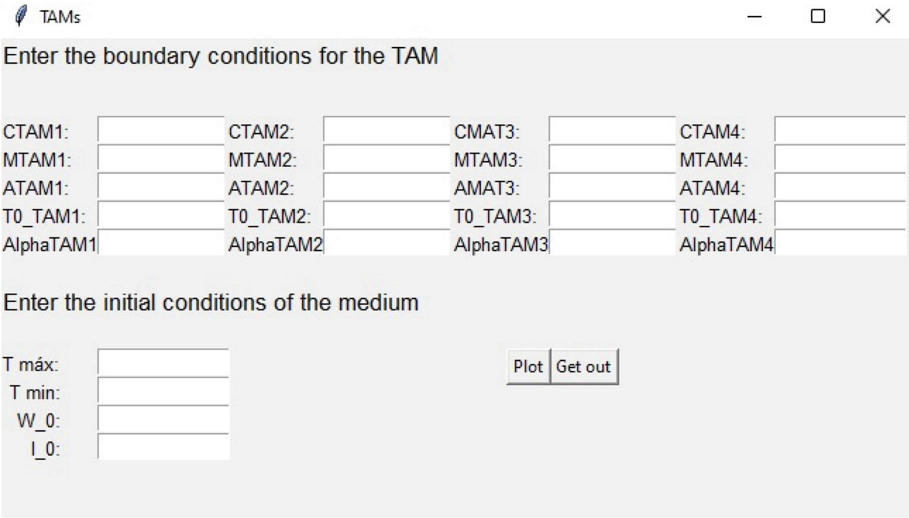

Fig. 4. Value entry for different TAMs.

Figure 5 shows the behavior of the TAM1 temperature during the day. This type of graph is very useful for phenomenological analysis since it clearly reflects the produced points of ambient temperature as a function of time. Regarding Fig. 6, the behavior of the TAMs is shown depending on the hours of the day generated with the developed program. Here, it is clearly appreciated that the graph facilitates a much faster and visual numerical interpretation.

It should be noted that the developed computer program provides an interactive and dynamic graph, since it can provide the data by placing itself in the coordinate to be analyzed with the use of the cursor. It also makes investigation easier by using the zoom button for closer and more assertive observation. In this sense, it has been possible to obtain an efficient and functional result, where the relevant information can be extracted using visual elements of easy numerical interpretation. In addition, with this program we guarantee to obtain results that are easier to interpret, which can be used as a reference or as a point of contrast before carrying out new investigations. Finally, as a comparison of the results obtained from the two methods used, the following is mentioned: The behavior of the temperature of the TAMs depending on the hours of the day generated with Maple, can be seen in Fig. 7. In this case, we can only appreciate the behavior of the curve without obtaining other information about it. However, *Python* is a tool that allows codifying and simplifying the way of approaching the aforementioned phenomenology. In addition, it allows to observe not only the curve but also provides the dispersion of a continuum of values, which can help to infer the data of an investigation with greater simplicity and effectiveness.

The developed software, compared to some conventional software used in fluid dynamics analysis [3–6], is a simple tool to use, it is free and open access to

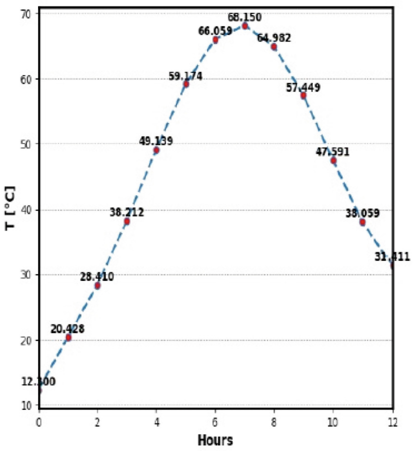

Fig. 5. TAM1 temperature as a function of time.

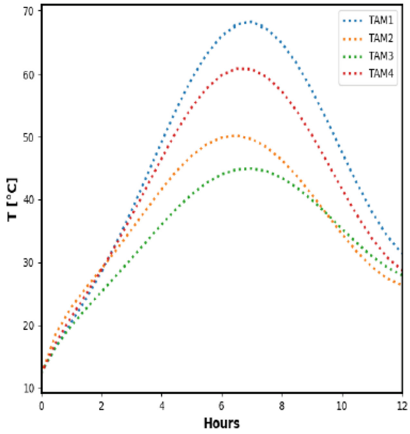

Fig. 6. The TAMs as a function of time.

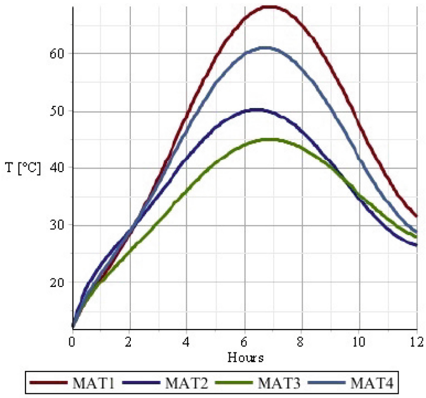

Fig. 7. Temperature of the MATs with Maple

improve its operation. It is useful to predict the maximum temperature of materials that accumulate thermal energy from the absorption of solar energy, and to know comparatively under controlled conditions the materials with the best opto-thermal efficiency, without the need to use costly laboratory analyzes or build high-cost prototypes. It also allows estimating solar absorption properties through the maximum temperature reached in experiments with thermal accumulators exposed to solar energy. Therefore, it is software that has applications in the study of photo-thermal materials and energy accumulation.