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Simul-Therm: A MATLAB/Simulink Blockset of Thermal Modelling and Simulation for Engineering Education*

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In this work, an intuitive computer-based system to model and simulate heat transfers is presented. This software application can be used for processes with unidirectional and multidirectional heat exchanges and it permits the user to model and simulate them quickly and with a reduced computing load. This is possible thanks to a simple generic model library or blockset implemented in the MATLAB/Simulink environment. The models included in this library can be easily linked in order to build holistic structures. In addition, the dimensions and features of the objects modelled can be simply defined. The simulations run by means of this library are fast and they do not need a wide range of computer resources in comparison to those based on discrete finite element models (FEM). Thanks to all these characteristics, this blockset can be considered a useful tool to didactic purposes and to multi-physic simulation applications.

Keywords: thermal model; thermal simulation; holistic modelling; multi-physic simulation; co-simulation; object-oriented interface; didactic application; engineering education

1. INTRODUCTION

A MOST IMPORTANT PROBLEM concerning circuits and modern electronic devices is the evacuation and management of the heat generated by their components [1]. In practice, heat energy is transmitted by means of three different thermodynamic phenomena, namely: conduction, convection (natural or forced) and radiation [2].

In order to analyse these phenomena, different mathematical formulations can be used, such as ordinary differential equation (ODE) resolution, which can only be used in unidirectional transfer studies, or partial differential equations for multi-directional or 3D transfer processes. This kind of calculation, implemented with FEM tools, requires a computer with high and powerful facilities and long learning time, which is a great disadvantage when using them as a starting point for holistic modelling or for computer-assisted multi-physic simulation.

Other authors have analysed mathematical methods that do not require a great computational cost, such as, Laplace Direct Transform (LDT) [3], Green's Functions [4] or State Space representation [5]. Due to the low computer resource charge of these methods, it is possible to simulate heat transfers almost instantaneously. Besides, the object-oriented interface (implemented with Simulink) simplifies and reduces the user's work related to the modelling and simulation environment [6].

These features make this blockset, which has been called Simul-Therm, a thermal modelling and simulation tool quite useful for didactic purposes, especially in higher education [7]. Furthermore, it is also very useful in engineering projects and scientific applications in which 3D thermal maps are not essential and the top priority is to get a fast and accurate solution. Moreover, Simul-Therm could serve as starting point for the development of future holistic modelling and multi-physical simulation environments. In that way, Simul-Therm could be used in co-simulation processes that, from our point of view, might be the main objective of the research in the field of scientific and technologic simulation [8].

2. SIMUL-THERM PRESENTATION

The thermal modelling and simulation blockset presented in this paper has been implemented with Simulink, environment powered by the mathematical engine of MATLAB. This choice is based on

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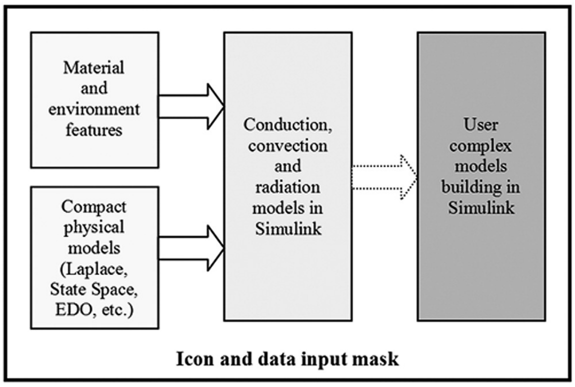

Fig. 1. Structure of heat transfer library.

the fact that this programming language enables the user to group different models together and, consequently, to implement systems and subsystems with different hierarchical levels [9]. In addition, it is possible to create data masks with parameters related to the models and edit icons as user interface, making the personalization, identification and use of the model easier (Fig. 1).

On the other hand, working with Simulink, the models developed can be joined together in libraries. These libraries or blocksets (SimulTherm) are totally open and they can be updated by any other user working with this methodology. Accordingly, it is possible to link models with the same operative and functional base in order to build more complicated ones in the future [10].

In order to make user's work easier, the blocks of the heat transfer library are divided into four groups or sublibraries, namely: convection, conduction, radiation and multi-directional heat distribution links.

2.1 Thermal unidirectional conduction library

The thermal behaviour of the simple models included in the thermal unidirectional conduction library is based on thermal transfer functions [3], which come from the application of the LDT to the Fourier's law in ODE format [2]. According to this approach, low computer load and simulation time are achieved. The transfer function defining the physical-mathematical model is [11]:

$$\frac{\Delta T(s)}{P_{th}(s)} = \frac{1}{C_{th} \cdot s + G_{th}} \tag{1}$$

In (1), G_{th} is the thermal conductance, C_{th} the specific heat capacity, T represents the temperature difference and $P_{th}(s)$ stands for the heat power.

Once the model has been implemented by means of block algebra, it is possible to generate an easier structured subsystem for the user by grouping different blocks.

In order to recognize the different models in the blockset, an icon representative of each body and kind of transfer is created. Figure 2 depicts, as an example, the different parts of a unidirectional thermal conduction model of a rectangular sheet and how to access to each of them [10].

The kind of material, the object dimensions and the maximum number of simulation iterations are defined as local variables and supplied by a data entry mask (Fig. 2). The material characteristic parameters (thermal conductivity, density and specific heat) are automatically uploaded from a database linked to this mask [12].

All the unidirectional conduction models can be easily specified so that the user should just update new data in the mask to run different simulations [3].

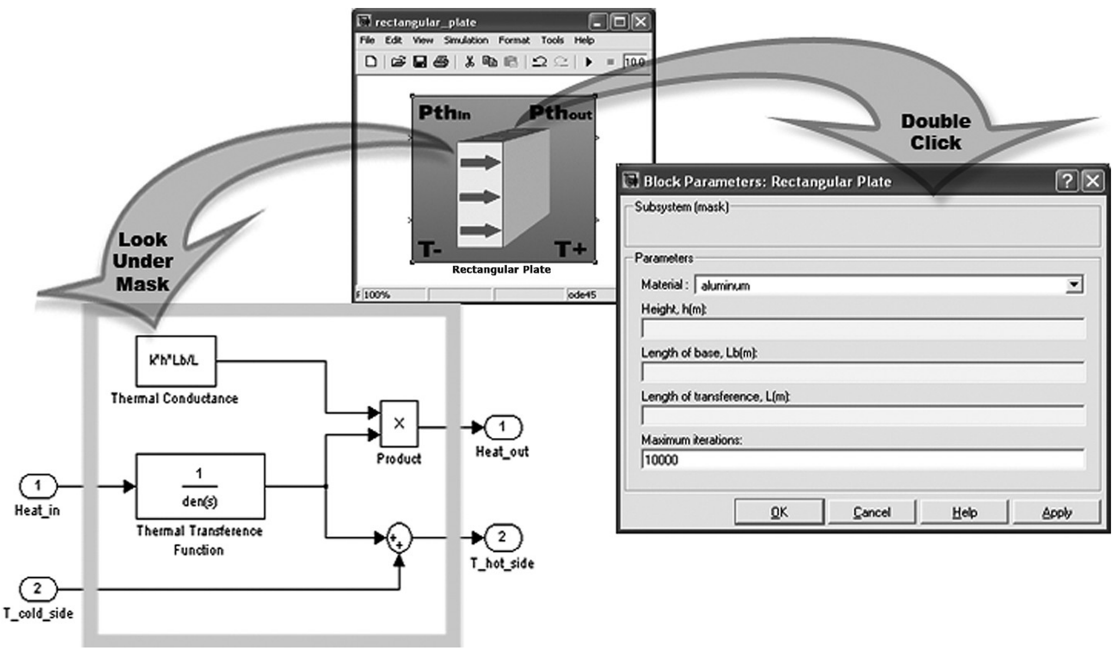

Fig. 2. Icon, Parameter Data Mask and Block Diagram of a rectangular sheet model.

2.2 Thermal convection library

There are two different kinds of thermal convection: natural and forced convection. Forced convection is based on the movement of a fluid due to external agents. To the contrary of natural convection, this movement is due to density differences between the fluid layers [13].

The physical-mathematical conduction model obeys the following expression:

$$P_{th} = h_c \cdot A \cdot \Delta T \quad (2)$$

In (2), h_c is the thermal transfer coefficient, A is the area of convection, and T stands for the temperature difference between the hot surface and the fluid with which is exchanging the heat [2].

The thermal transfer coefficient (h_c) depends on the heat transfer phenomenon. In the following two sections, the calculations of each case are explained.

2.2.1 Natural convection

The coefficient of natural convection heat transfer is calculated from the boundary layer temperatures at each integration step. Other features, such as the hot object position (horizontal or vertical) and whether the flow is laminar or turbulent, must be considered [13]. The natural convection coefficient is calculated according to the following expression:

$$h_c = \frac{1}{L} \cdot \left[\int_0^{x_{tr}} C \cdot (\Delta T/x)^{\frac{1}{4}} \cdot dx + \int_{x_{tr}}^{L} C \cdot (\Delta T)^{\frac{1}{3}} \cdot dx \right] = \frac{1}{L} \cdot \left[C \cdot \left(\frac{4}{3}\right) \cdot \Delta T^{\frac{1}{4}} \cdot x_{tr}^{\frac{3}{4}} + C \cdot \Delta T^{\frac{1}{3}} \cdot (L - x_{tr}) \right] \quad (3)$$

Table 1. Laminar and turbulent flow constants

	Horizontal	Vertical
Laminar flow	0.9962	1.07
Turbular flow	1.51	1.3

In (3), x_{tr} stands for the distance from the laminar layer to the transition to the turbulent area, L is the convection calorific transfer length and C represents the dimensionless constant associated to laminar and turbulent flows, whose values are presented in Table 1 [14].

The thermodynamic model is implemented with Simulink by a block diagram and a structured subsystem is created by grouping different simple blocks, so that the user works with it. In order to distinguish each model saved in the blockset, a representative icon for each body is created (geometric model). Figure 3 shows the block diagram, the subsystem created by grouping and the data input mask for a unidirectional natural convection model of a rectangular sheet [10].

Geometric data of the objects integrated in the natural convection blockset are defined as local variables. All the Simul-Therm models have a data input mask so that the user does not need to handle the block diagram (Fig. 3).

The natural convection blockset can be used as a standard Simulink library, just copying (clicking and dragging) its models and building with them more complicated holistic structures [15].

2.2.2 Forced convection

The coefficient of forced convection heat transfer (h_c) is calculated as the average value of this

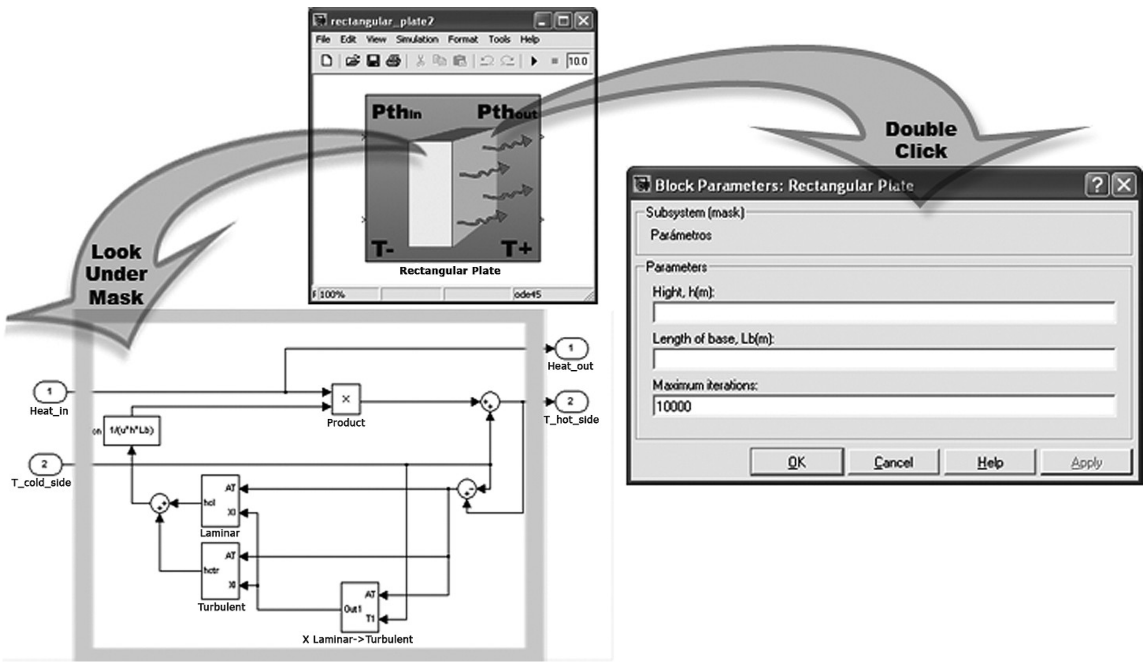

Fig. 3. Icon, Parameter Data Mask and Block Diagram for natural convection model of rectangular sheet.

coefficient when the flow is laminar and when it is turbulent, at each integration step. The forced convection coefficient responds to the following expression [2]:

$$h_c = {}^{k}/_{L} \cdot \overline{Nu} \tag{4}$$

In (4), k is the fluid conductivity, L represents the boundary layer length and $\overline{Nu}$ is the average Nusselt number, which is calculated as follows:

$$\overline{Nu} = 0.664 \cdot Re_{tr}^{1/2} \cdot Pr^{1/3} + 0.036 \cdot Re_l^{0.8} \cdot Pr^{0.43} \cdot \left[1 - \left(\frac{Re_{tr}}{Re_l} \right)^{0.8} \right] \tag{5}$$

In (5), Pr is the Prandtl number for the fluid. The Re_{tr} and Re_l coefficients are the Reynolds numbers at the turbulent flow starting point and the boundary layer final point, respectively [14].

The block algebra implementation, characteristic of the Simulink environment, is similar to the natural convection one. In order to differentiate forced convection from other models in the blockset, a representative icon for this thermal process has also been created. Figure 4 shows, as an example, the different parts of a unidirectional forced conduction model of a rectangular sheet and how to access to them.

The forced convection characteristic parameters (fluid velocity and conductivity) and the body dimensions are input by the user by means of a data mask (Fig. 4).

In order to be used in other simulations, the forced convection models saved in this blockset can be easily specified [10].

2.3 Thermal radiation library

The physical-mathematical model implemented for the thermal radiation is based on Stefan-Boltzmann law and the thermal radiant emittance correction factor. According to that, the thermal power responds to the following expression:

$$P_{th} = \varepsilon \cdot A \cdot \sigma \cdot \left(T_2^4 - T_1^4 \right) \tag{6}$$

In (6), A is the radiant surface, ε the emittance, σ the Stefan-Boltzmann constant ($\sigma \approx 5.67 \cdot 10^{-8}$ W/m^{2}K^4) and T_2 and T_1 the temperatures of the radiant and irradiated surfaces respectively [13].

As has been previously done with conduction and convection, a general model for the radiation has been implemented with block diagrams and a structured subsystem has been defined, by grouping different blocks. In addition, a representative icon has been created for each body. Figure 5 shows, as an example, the unidirectional thermal radiation model for a rectangular sheet.

In order to define the intrinsic emittance of the material/body modelled, a pull-down menu has been programmed and associated to a database previously created. In that way, once the material has been specified by means of a tab, MATLAB extracts the emittance magnitude from the database in order to use it in the model [12].

As with the convection and conduction models, this blockset can be used as a standard Simulink library, so that the models implemented can be used to rebuild different real cases, provided the user can define them.

2.4 Multidirectional transfer library

In many real cases, unidirectional simplifications are not possible or not advisable. In those

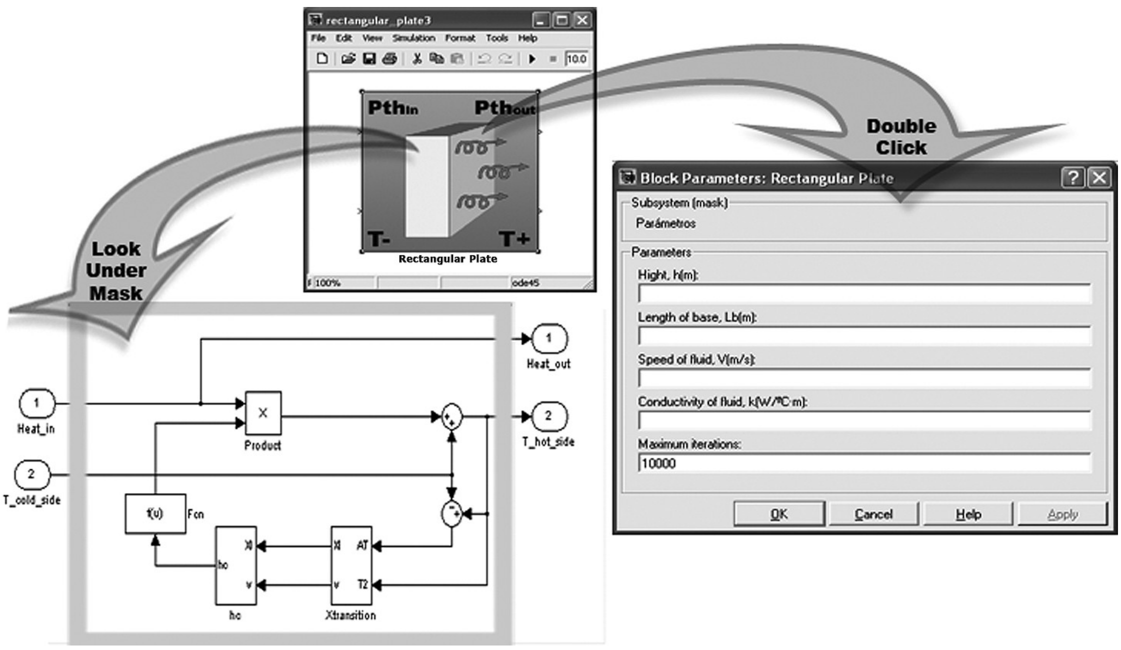

Fig. 4. Icon, Parameter Data Mask and Block Diagram for forced convection model of rectangular sheet.

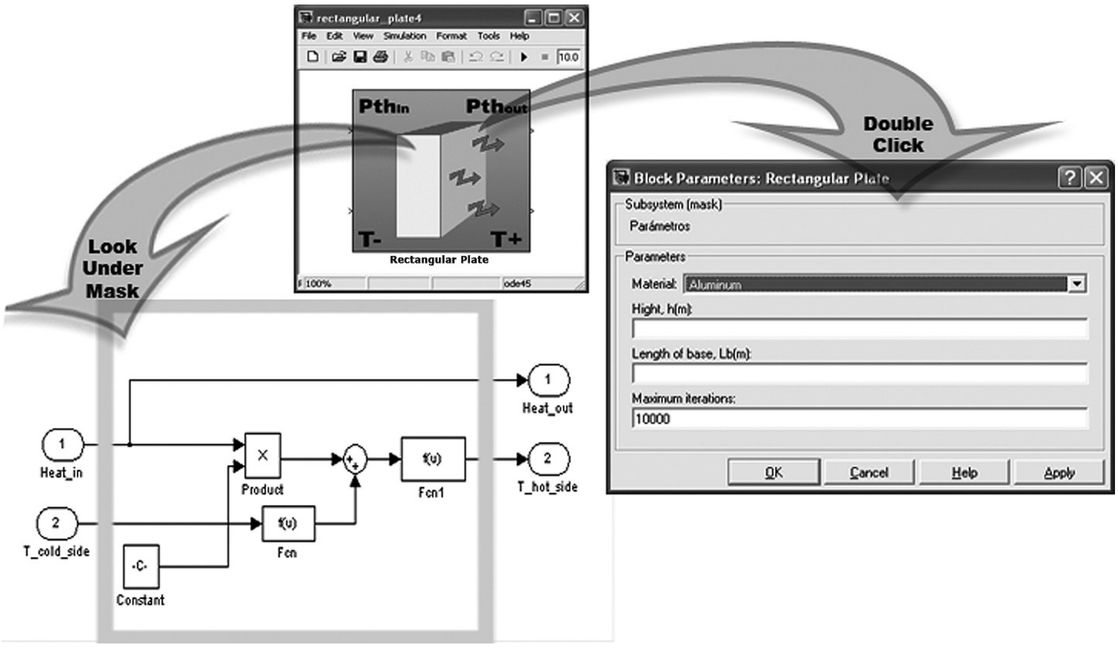

Fig. 5. Icon, Parameter Data Mask and Block Diagram for unidirectional radiation model of rectangular sheet.

situations, multidirectional heat transfer must be considered. However, since the data input/output structure of the blocks of this library, Simul-Therm, is standardized and it is possible to link its blocks directly 'in series', any multidirectional transfer can be modelled just implementing the connection nodes 'in parallel' [3].

Contrary to the FEM approach (physic constructions), in this environment (whose modelling is based on symbolic construction) the engineer must interpret the real physic phenomena and adapted it to the model. In that sense, the simulation will be less or more accurate depending on the user's skill and knowledge. That could be very interesting for its application to the teaching but a disadvantage in other fields.

According to the first law of thermodynamics, as a result of the energy conservation in the node,

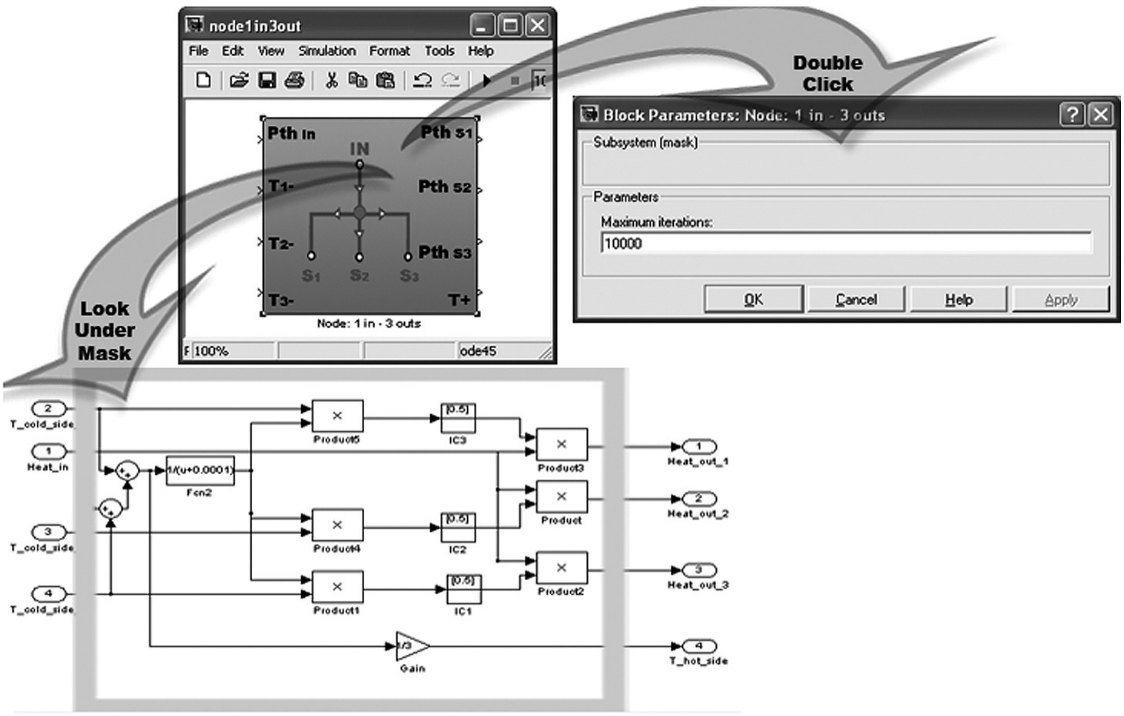

Fig. 6. Icon, Parameter Data Mask and Block Diagram for model of multi-directional heat transfer.

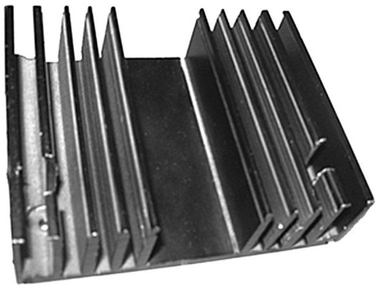

Fig. 7. Heat sink.

the 'superposition principle' must be observed in it. This can be mathematically expressed according to (7).

$$\sum P_{thE} = \sum P_{thS} \tag{7}$$

Calorific contributions in each node will be distributed among all the lines (outputs) to the node, depending on the thermal impedance of the blocks connected in each one. Therefore, the heat flow will be inversely proportional to the thermal resistances connected to the node [16].

As a consequence, it is possible to determine the heat power absorbed by each line with (8).

$$P_{thS(i)} = \sum_{i=1}^{n} P_{thE} \cdot \left(\frac{T_i}{T_1 + T_2 + \ldots + T_n} \right) \tag{8}$$

Figure 6 shows the block diagram corresponding to the implementation of a thermal node with a heat entry and three outputs [10].

The nodes of multi-directional heat transfer connection can be easily linked to the blockset since all of them share the same input/output variable structure.

3. SIMUL-THERM APPLICATION

As an application example, an aluminium heat sink (Fig. 7), frequently used in electrical and electronic engineering, has been modelled and used for scientific and technical validation of Simul-Therm (next epigraph).

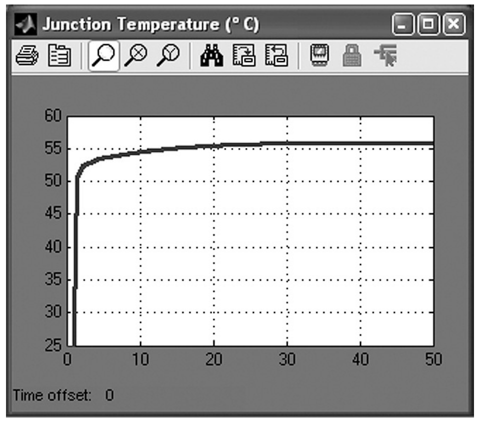

Fig. 9. Joint temperature.

In order to model the heat sink of Fig. 7, the user only has to connect the simple models available in Simul-Therm in an organized way. As a result, a complex structure like the one shown in Fig. 8 is obtained.

Each body in the right side of Fig. 8 represents a part of the heat sink and the connections are the results of the interpretation of its thermal behaviour, including conduction, natural convection and radiation processes [17].

A 10W thermal power heat source is connected to the heat sink perpendicularly to its base. Environmental temperature will be 25°C. Placing adequately a SCOPE block (Fig. 9), the dynamic heating curve in the base of the heat sink can be easily obtained.

This example shows clearly that relatively complex models can be easily and quickly simulated with this blockset. Moreover, the body modelling is intuitive not only because the block interface of the blockset is simple, but also since the user does not need to deal with the mathematical expressions defining the body behaviour.

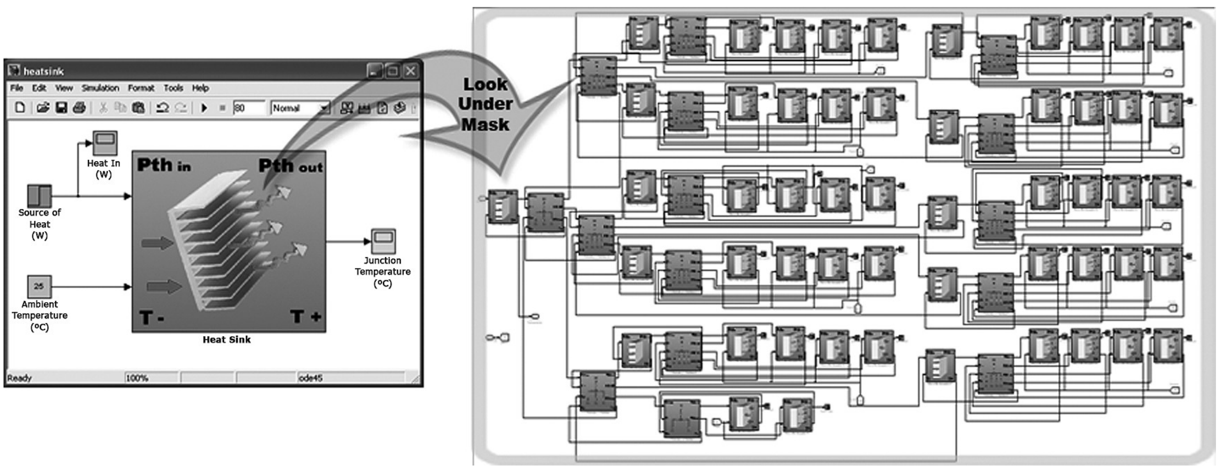

Fig. 8. Heat sink model implemented in thermal transfer blockset.

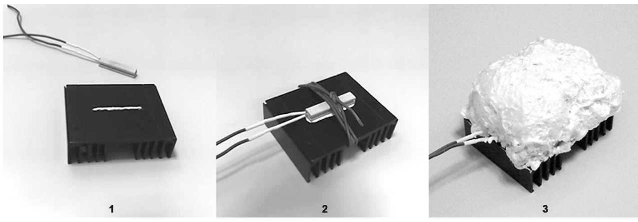

Fig. 10. Image sequence of assembly of heat sink tested.

Furthermore, the simulations require a low computing load.

4. SIMUL-THERM DISCUSSION

4.1 Scientific and technical discussion

In order to validate the results of the heat sink simulation previously described, an experiment with a real heat sink totally analogous to the modelled one was designed. A brief sequence of the assembly of the heat sink used in the validation experiment is illustrated in Fig. 10.

As shown in Fig. 10, the heat sink was connected to a resistor (33 Ω; 15 W) by means of a contact of silicone paste, with high thermal conductivity, and it was bound by a non-conductive PVC fixing wire. In addition, in order to assure the thermal insulation of the back of the heat sink (as this side has not been included in the model shown in Fig. 8), high density polyurethane foam was poured onto it.

Subsequently, the resistor was connected to a c.c. adjustable power supply and its current and voltage were measured by means of the respective accurate measurement instruments, as well as the environment temperature. Besides, under these conditions, a thermographic picture was taken with an infrared camera (IR) which is shown in Fig. 11 together with a picture of the trial device.

As illustrated in the image on the left, the power supply voltage was adjusted to 18.552 V and the current through the resistor is 539.9 mA. Thus, the electric power supplied to the 33 Ω resistor is P = $18.552 \cdot 539.9 \cdot 10^{-3} = 10.016$ W which will have been totally transformed into heat power according to Joule's law. The environment temperature registered is 24.8°C with a relative humidity in the lab of 40%.

The figure on the right corresponds to the thermographic picture of the heat sink obtained by means of the IR FLUKE Ti-45 camera, equipped with a 54 mm telephoto. The picture was taken from 1m distance so that the corresponding spot size is 1×1 mm^2 approximately. The maximum temperature point can be observed in the middle of the heat sink and reaches 55.8°C which is in good agreement with the 55.85°C derived from the simulation of the Simul-Therm model.

4.2 Didactic discussion

Moreover, Simul-Therm has important benefits for its application to the educational area. Particularly, the modelling with Simul-Therm is very intuitive since the user does not need to deal with the mathematical expressions defining the phenomenon and the block interface of the blockset is simple. On the other hand, the user must interpret the real physic phenomenon and adapt it to the model, so that the simulation will be less or more accurate depending on the individual's skill and knowledge. For that reason, Simul-Therm is an appropriate didactic tool to check whether the students have understood heat transfer phenomena or not. Furthermore, as has been mentioned before, the simulations with Simul-Therm require a low computing load so no specific and very

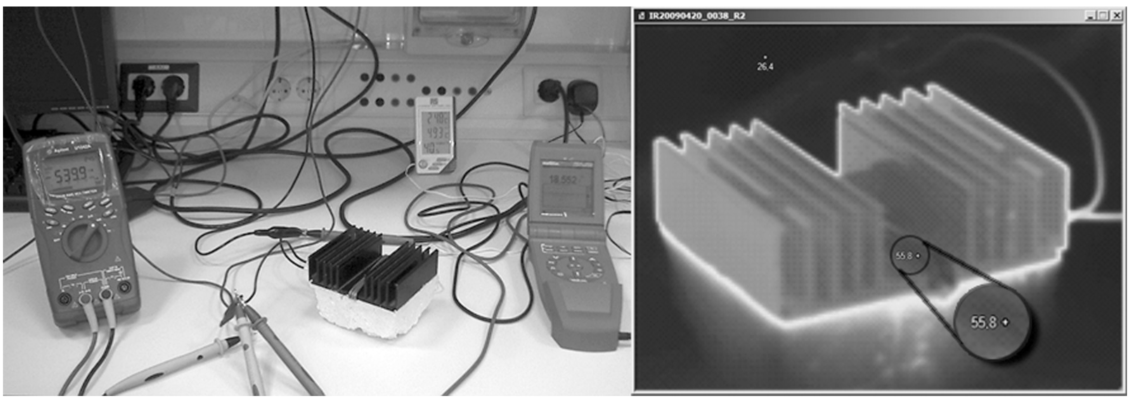

Fig. 11. Trial test and thermographic pictures obtained during validation experiment.

Table 2. Qualification data of students (scale: 0–100%).

	2005/2006	2006/2007	2007/2008
Number of students who did not attend the exam	7	3	2
Number of Fail (0–49%)	2	1	2
Number of Pass (50–69%)	11	15	14
Number of Good or Very Good (70–89%)	18	15	21
Number of Excellent or Outstanding (90–100%)	3	2	6
Average Values of the Califications	59.4%	64.3%	69.8%

Table 3. Data and standard deviation(s) from opinion polls of students (scale: 0–5).

	2005/2006	2006/2007	2007/2008
Number of students enrolled/polled.	41/27	36/25	45/37
Item 4: Facilitate learning and promote student participation.	4.12 ($s = 0.78$)	4.77 ($s = 0.60$)	4.86 ($s = 0.38$)
Item 8: Teaching resources used increase the understanding of the subject.	3.41 ($s = 0.87$)	4.23 ($s = 0.73$)	4.71 ($s = 0.49$)
Item 14: Learning has proved affordable.	3.47 ($s = 0.87$)	4.08 ($s = 0.86$)	4.43 ($s = 0.79$)
Item 17: The practical activities help understanding the subject.	3.94 ($s = 0.97$)	4.31 ($s = 1.03$)	4.86 ($s = 0.38$)
Item 26: Overall evaluation.	4.31 ($s = 0.79$)	4.85 ($s = 0.38$)	4.86 ($s = 0.38$)

expensive computers are needed. Finally, complex models are easy and quickly simulated so that the teacher does not need to spend very much extra time on that activity.

In order to show the positive impact of Simul-Therm on teaching and learning, a brief report of the last three years experience in the subject of Engineering of Electronic Equipment is presented. This is an optional subject (4.5 credits) of the second semester in the 3rd year of Industrial Electronics Technical Engineering degree, which is offered by the Polytechnic High School in the University of Cordoba (Spain). The syllabus for this subject includes, among others, the issue of thermal analysis and design of electric and electronic equipment, discussed both theoretically and practically [18].

The first years that this subject was held, its experimental contents were taught by means of problems and exercises that might be solved on paper with pen and calculator. This activity follows a classical methodology poorly motivating for students. In that way, Simul-Therm arises from the necessity of a new didactic and encouraging tool. It was used for the first time during 2006/2007 academic year, trying to give a more experimental approach to the subject. This change not only improved student's motivation but also the level of knowledge they acquired at the end of the semester.

In that sense, the teachers could check that students understood much better heat transfer phenomena and their influence in electronic devices. In fact, it has been checked that the student's qalifications have improved from 59.4% to 69.8% on average (Table 2).

In addition, students showed great satisfaction with the new methodology. Particularly, this approval was reflected in the polls that the teaching quality department of the University of Cordoba conducts every year among students. In that sense, Table 3 shows the results of these surveys related to the subject Engineering of Electronic Equipment. Specifically, the results form the academic year 2005/2006 in which the traditional methodology was followed are compared with those of the years 2006/2007 and 2007/2008 in which Simul-Therm was already used as a teaching tool.

Accordingly, it is possible to state that students find that this application promote their active participation in the teaching-learning process favouring the understanding of the contents of the subject, so that, they feel that the subject is more easily affordable with this tool. Finally, the increase in students assessment in item 17 (The practical activities help understanding of the subject) is particularly meaningful, rising from 3.94 in the course 2005/2006 (without Simul-Therm) to 4.86 in 2007/2008 (with Simul-Therm), on a scale of 0 to 5.

For all these reasons, it is possible to conclude that this application is very useful as an educational tool while teaching heat transfer phenomena in engineering degrees.

6. CONCLUSIONS

In this paper, a set of simple object libraries is presented, called Simul-Therm. The bodies are classified into different libraries according to the heat transfer process they experiment. Thus, as has been previously described, different libraries have been implemented for each unidirectional energy transfer process, such as conduction, convection (natural and forced) and radiation. In addition, multidirectional connectors have been defined in order to model and simulate multidirectional processes by linking the blocks of the unidirectional transfer libraries mentioned.

Thanks to this classification, the libraries are structured and, consequently, the modelling and simulation become easier. Each simple body modelled in the libraries has an icon that is representative of the body modelled itself and the thermal phenomenon experimented. In that way, it is possible to get an object-oriented interface. Furthermore, a parameter mask for each body is created in order to define its dimensions and the materials it is made of (in those cases it influences the thermal processes). The materials parameters are extracted from a database created and linked to the mask. Thanks to all these features described, and the great possibility of grouping models offered by Simulink, this computer application stands out because of its simplicity and the great reduction of work in the modelling and simulation.

Another advantage of this modelling and simulation tool is the low computer resources needed. Thanks to that, thermal processes can be easily and quickly simulated and holistic structures can be implemented from simple and homogeneous structures.

The models included in this library, called Simul-Therm, have been validated against an example based on an aluminium heat sink typical for electrical and electronic power devices. In that way, firstly, it has been implemented into the blockset, updating the characteristic parameters of the real heat sink, and lately, an experiment has been developed reproducing these simulation conditions. The difference between the results obtained by both methods is smaller than 0.1%.

These features described make this application very useful for didactic purposes (especially in Higher Education)) as has been possible to check in the subject of Engineering of Electronic Equipment, an optional subject of the Industrial Electronics Technical Engineering degree, held in the Polytechnic High School in the University of Cordoba (Spain). In this subject, the use of Simul-Therm not only has improved student motivation but also the level of knowledge on heat transfer phenomena they acquired. In fact, student qualifications have risen since Simul-Therm has been used, by 10.4%. Besides, as opinion polls show, students find that this application promotes their active participation in the teaching learning process favouring the understanding of the contents of the subject.

Furthermore, it is also very helpful in engineering projects and scientific applications in which 3D thermal maps are not essential and the top priority is to get a fast and accurate solution. Moreover, this modelling and simulation tool could become a starting point for both the development of real holistic modelling environments, which could be defined by the user and the multi-physical simulation in an integrated environment.

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