Heat Transfer 1.0 – "A Software for Heat Conduction Teaching" Computational Structure and Class-Room Experiences

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Abstract – This paper reports the structure of the Heat Transfer 1.0 educational software and its first classroom experience. The main goal in conceiving Heat Transfer 1.0 was to stimulate the physical reasoning in heat transfer. Therefore, the basic idea behind its conceptual form was to have more than merely a tool to help student to solve the heat conduction equation. The key objective was to create a tool that allows formulating problems, speculating about its physical behavior and exploring the changing of the physics with parameter variations. More, the software should appear attractive and easy-to-use, becoming part of the students toolbox, and not to be seen as another complex application which use is compulsory.

This paper is divided in two parts. The first fully describes the software with its capabilities, pointing out details where it is shown the intimacy between the interface and the notation used in classroom, strongly supported by physics.

The second part addresses the extremely difficult task of evaluating how helpful the software is, how to smoothly introduce the software in a normal course and how to convince students that the software can improve their heat transfer learning without to be painful. With this in mind, during the second semester of 1997 the software was used in the Heat Transfer I course (conduction + radiation) for the mechanical engineering degree at the Federal University of Santa Catarina. The software Heat Transfer 1.0 was made available at the Internet with a collection of exercises covering topics in conduction heat transfer. This collection plays an important role in motivating the students for using the software. A great variety of exercises and a single test, using the computer rooms, were applied during the course and, at the end of the semester, the students filled in a questionnaire where questions about the software itself and the related pedagogic procedure were answered. The findings, revealing the student's view about the software and its impact in their learning, will be also reported in this paper.

Introduction

Engineering education is a topic receiving increasingly attention nowadays, and due to the benefits that the proper use of software can bring to teaching activities, almost every instructor is introducing the use of software in their courses, trying to improve the learning process. While applications in CAD and related areas, where 3D geometry rather than physics is the kernel of the software, are easily introduced in engineering courses, software dealing with physical phenomena require extra care in order to become an efficient partner of the teaching process. In undergraduate heat transfer education, it is common computer packages, originally designed for research studies, to be used as educational software. These packages are usually computationally poorly written, with the graphical user interface created without full compatibility between kernel and interface. This approach for producing educational software may be a disaster because no clear educational goals were established when designing the software. Moreover, the time consumed for students to get used to it may be excessive, overwhelming the benefits.

Heat Transfer 1.0 is a software where all above mentioned preoccupations were taken into account. It was conceived and written, as already stated, with the main task of stimulating the physical reasoning in conduction heat transfer. It is written in C++, using the object oriented programming paradigm (OOP), with full integration between algorithm and graphical interface. Due to the physical appealing intrinsic to the numerical model employed (finite volume), and efforts in constructing a graphical user interface which resembles the usual classroom heat transfer teaching, Heat Transfer 1.0 resulted in a software which can be introduced in undergraduate heat transfer conduction courses with minimal effort.

Heat Transfer 1.0 is a package for solving transient two-dimensional heat conduction problems. The software runs on Windows95/NT, and its entire interface was constructed using the Borland's OWL (Object Windows Library) library.

The equations are solved numerically using a finite volume method with boundary-fitted coordinates, allowing geometries other than the classical Cartesian and cylindrical shapes to be used. Thus, the package permits the solution of very interesting educational problems.

The software is to be used as an auxiliary tool during classroom teaching for the investigation, learning and "visualization" of the heat conduction phenomenon.

The Mathematical Model Embodied In The Software

The software is able to solve two-dimensional transient heat conduction problems with heat generation and variable properties. It also allows solving problems in different geometries other than Cartesian and polar. This permits the instructor to go further, if desired, in analyzing more complex heat conduction problems. Additionally, since numerical methods in heat conduction is a topic itself in a heat conduction course, the software can be used for this purpose, exposing the students to a numerical technique nowadays largely employed for solving engineering problems.

It must be put clear to the students that the software solves a mathematical model given by the following partial differential equation

$$\frac{f}{fx}\left(k\frac{fT}{fx}\right) + \frac{f}{fy}\left(k\frac{fT}{fy}\right) + q''' = c_p\frac{fT}{ft} \qquad (1)$$

with boundary conditions of prescribed temperature, prescribed heat flux and convection. The above equation is solved using a boundary-fitted finite-volume method [1], as shown in Figure 1, where the discretization used is also shown. The students should recognize that Eq.(1) could be solved using analytical methods. However, using a numerical method one broad the range of problems to be studied. The numerical method employed is now briefly presented.
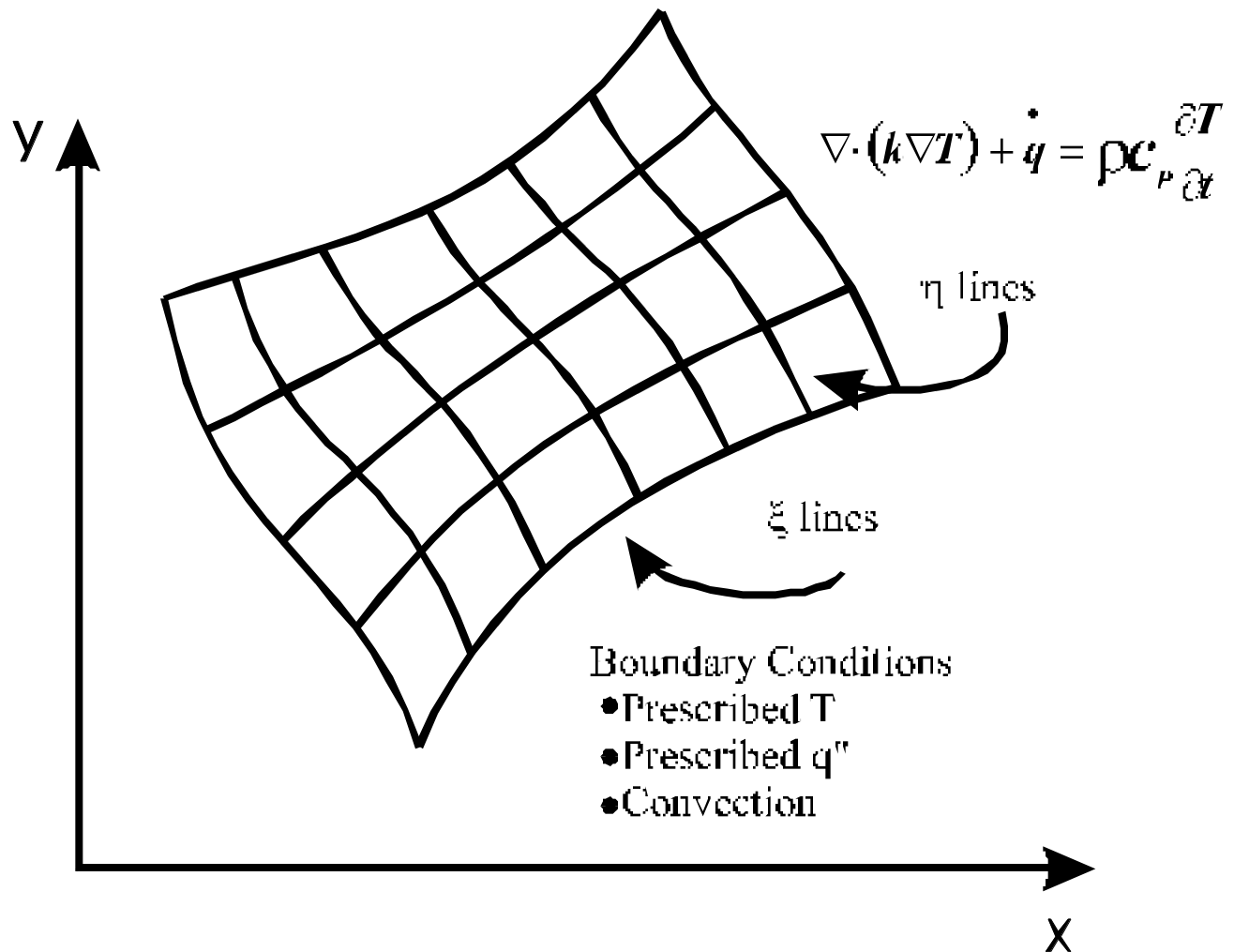

$$\nabla\cdot\left(k\nabla T\right) + \dot{q} = \rho c_p\frac{\partial T}{\partial t}$$

η lines

ξ lines

Boundary Conditions
• Prescribed T
• Prescribed q"
• Convection

Figure 1. Typical geometry used in Heat Transfer 1.0

The Numerical Method

The numerical method employed is the usual finite-volume method, whereby the partial differential equation is integrated in each elemental control volume originating an approximate equation for each control volume. It must be clear that the numerical method can be kept "hidden" to the student without loss of understanding.

If one wants to numerically solve heat conduction problems in geometries other than the usual orthogonal ones, it is necessary to discretize the domain in arbitrary control volumes, as shown in Figure 1, and integrate Eq. (1) over the arbitrary elements in the new system. The integration of the equation, following the basic rules of the numerical methodology, gives a linear system of the type

$$[A]\,[T] \;=\; [B] \tag{2}$$

which can be solved by many existing methods for solving systems of algebraic equations. The solution of Eq. (2) gives the temperature for each control volume. The resulting temperature field can be used in several ways to explain the conduction heat transfer phenomena.

The Software Heat Transfer 1.0

General

Heat Transfer 1.0 takes advantage of the modern computational resources to provide an exciting and intelligent learning environment. This section is devoted to explain the functionality of the software.

The software is based on the construction of an organized structure of the internal data and on its powerful graphical user interface. The data organization and the user interface were based on steps that describe the usual approach in the solution of a heat conduction problem. These steps are the definition of the geometry and boundary conditions, the setting of the numerical parameters, the solution of the problem and the visualization of the results.

Interface Objects Organization

The software takes advantage of the Windows95/NT platform, using the best facilities offered by the system, namely the friendly graphical user interface and its intuitive easy-to-use capability.
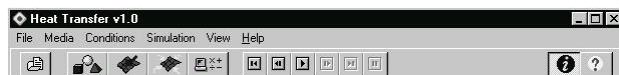

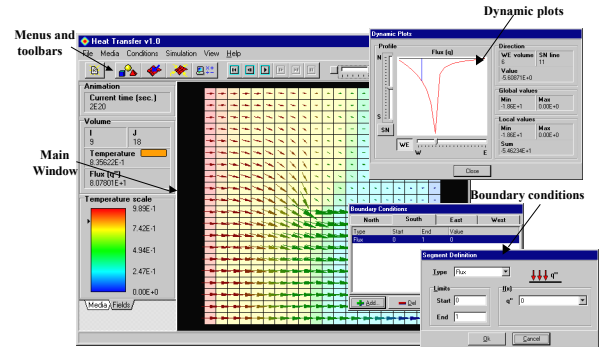*Figure 2. Heat Transfer 1.0 toolbar zoom*

Figure 3. Heat Transfer 1.0 environment

The definition of the domain, the setting of the parameters, the simulation (solution of the problem) and the visualization of the results are accessed by menus. The procedures frequently used have a correspondent shortcut on the toolbar (Figure 2) available in the software main window, shown in Figure 3, which depicts the graphical interface environment of Heat Transfer 1.0. As an example, the heat flux profile across the domain can be seen in the insert of Figure 3. The main window also shows the color map used in the visualization of the temperature fields or any other scalar quantity. It is also seen that it is possible, using a slider, to select plots of temperature along the coordinate lines.

Menu Items Description

It is now provided a brief explanation of all menu items modules and its potentialities, with the main goal of furnishing a deeper view of the software capabilities.

File: This module allows the user to import from other programs the geometry and its grid, to be used in Heat Transfer 1.0. There is a specified file format to be obeyed.

Media/Geometry: This is a module responsible for the domain definition and its grid. In this module the user has the possibility to generate three different types of domains [rectangular, radial and mixed (rectangular + radial)] changing its dimensions. Just clicking on the desired geometry and giving the parameters which defines it, the user will have its domain and the grid created. If other geometries, than the default ones, are required, the user can generate them in any grid generator and employ the module *file* to input the grid in Heat Transfer 1.0.

After the definition of the geometry and its discretization (grid), the user needs to define which will be the problem to be solved. This operation is executed by setting the physical properties, the initial and boundary conditions and the simulation parameters. These modules are now presented.

Media/Physical Properties: In this module the user defines the physical properties of the medium, such as

thermal conductivity, density, specific heat and sources or sinks of heat.

Variable properties are handled by setting their values for groups of cells. Therefore, heat transfer in heterogeneous domains can be simulated. Adding this characteristic to the possibility of prescribing mixed boundary conditions, the Heat Transfer 1.0 can cover a large class of problems, allowing the student to speculate and check his (her) physical feelings.

Conditions/Boundary: In defining boundary conditions, the user can have prescribed temperature (a constant value, a linear and a sinusoidal distribution $T(x) = To + \sin(p\ x)/L$), prescribed heat flux or convection. These conditions are applied in each boundary (north, south, east and west), and they can be of different type at the same boundary. For example, the user can prescribe, at the north face, a convection boundary condition along one part of the boundary and prescribed temperature in the remaining.

Conditions/Initial: If a transient problem is being solved, there is the need of specifying the initial conditions (initial temperature field). If the interest is only on the steady state solution, the initial conditions works as initial guess for the iterative procedure.

Simulation: After the definition of the boundary conditions and physical properties of the problem, the user has the possibility of manipulating the numerical parameters of the simulator embodied in Heat Transfer 1.0. Among them, the user can modify the maximum number of iterations (in space and time), the value of the maximum error allowed in the solution for each time level, and the criterion for defining when the steady state has been reached.

During the simulation the software gives information about errors, iteration number (in space and time) and other details of the solution. The user can also set the time levels he wants to have the results printed or visualized.

View: This is done using available visualization tools which consist in the presentation of a color interpolation of the temperature (or any other scalar, like thermal conductivity) field, and the heat flux vectors simultaneously. In addition, the software also offers a visualization of the results in dynamic plots of the temperature and heat flux profiles along the coordinate lines. It is possible to visualize the results in any specified time and to compose the color fields, or the plots, for having an animation of the transient process. Just by clicking Simulation/Play Animation in the menu, all the color interpolated temperature or heat flux fields are shown, allowing the student to "see" the movement of the heat front.

About: This module brings specific information about the program, such as the developer team, institution and current version.

To accomplish the software package, the development team is now working on a help guide, the Heat Transfer 1.0 Tutorial, divided in three parts:

Heat Transfer 1.0 **step-by-step teaching**, contains all basic information about the use of the software.

Basic Heat Conduction: contains information about the heat conduction phenomena and a large group of examples witch analytical solutions can be used for comparisons with the results obtained by the software. It contains also some suggested problems for analysis.

Basic Numerical Methods: contains basic notions about the numerical methods used in the solution of the heat conduction problems, emphasizing the finite volume methodology and the other techniques used in implementing the program. This part is used only if the student wants to know how the conduction problem is solved.

The help guide is being built using the Windows Help Format, which allows the user to navigate through it and to use it simultaneously to the program.

Classroom Experiences Using The Software

Introduction

When new tools and new teaching methodologies are introduced in undergraduate engineering courses, the difficult task is to clearly measure the rewards of using it. The experience of using Heat Transfer 1.0 in the Heat Transfer I course is now described. The Heat Transfer I course is offered in the sixth semester of the Mechanical Engineering degree at Federal University of Santa Catarina (UFSC). It has a workload of 3 class-hour per week. In general, one of the weak points of heat transfer courses is to little explore the analysis of 2D heat conduction problems. In fact, textbooks in heat conduction for undergraduate students carries in its contents only the method of separation of variables and 2D and 3D solutions using graphical charts[2]. Of course, this is because textbooks, usually, deal only with topics that allow mathematical treatment. To fill this gap in heat transfer teaching may be one of the most important rewarding of the software Heat Transfer 1.0.

The introduction of the software was done in the second semester of 1997. During this period, a full professor and an assistant were in charge of the course. At this stage of the graduation course, the students already have good knowledge of Calculus, Physics, Thermodynamics and Fluid Mechanics. Classes using the software were realized in the Microcomputers Lab of the Technological Center. PC 486-66MHz with 16 Mb RAM satisfies the needs.

In the classes the students were exposed to several simple physical problems, having as main goal stimulating their physical heat conduction feeling. One and two-dimensional problems in permanent or transient regime were analyzed.

The software was available to the students for downloading from the course homepage, so that they could easily install and use it at their own home. In the

Internet, Heat Transfer 1.0 is available at the following address: http://www.sinmec.ufsc.br/transcal. In the site there is also a great variety of exercises specially proposed for using the software.

Software Introduction Methodology

In the Heat Transfer I course of the Mechanical Engineering degree at Federal University of Santa Catarina, the use of an educational software with such characteristics was a pioneer initiative. In its first application the main objective was to verify the viability of its definitive implementation as an auxiliary teaching tool. In the stage of testing the pedagogic innovation, several exercises were proposed to the students. It was not compulsory to solve them. In the case the student opted in solving the exercises with the software, an extra mark was assigned which could only benefit him, never harm. This procedure was adopted because we would want to have students using the software because it is helpful and not because it is compulsory.

During the software introduction, the main goal was to verify the student evolution in thinking about the physics of heat conduction. Aspects such as the behavior of isotherms and flow vectors related to the boundary conditions, symmetry and transient regimes for a great variety of geometries were abundantly explored. Also, the validity of simplification hypothesis adopted in some physical and mathematical models (lumped capacity and analogy with electronic circuits) were thoroughly discussed.

For the evaluation, exercises were idealized, involving most of the concepts approached during the classroom.

Detailed reports were always asked as a tool for the interpretation of the results.

During the semester the students were periodically submitted to these exercises. Assignments and a single test formed the evaluation system. As mentioned above, detailed reports, describing the steps and simplifications adopted during the solution, were asked. In the end of the semester, the students had two hours for the resolution of a final test, which included all the topics approached by the use of the software.

Typical Example On How To Use The Software

To illustrate the investigative potential available through the use of the software, it's now provided an example that was applied during the course. Other examples can be found in [3].

Calculating The Conduction Shape Factor "Learning To Apply The Symmetry Concept"

As already mentioned, Heat Transfer 1.0 supports reading files created by several others grid generators.

However, to facilitate its use some geometries are easily created and discretized. Therefore, simulations of problems defined in the default geometries module are ready executed. The default geometries available by Heat Transfer 1.0 are shown in Figure 4.
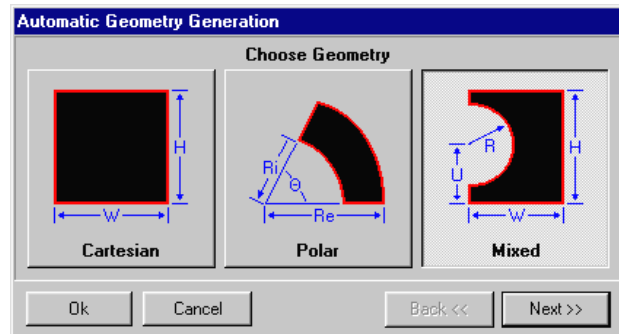

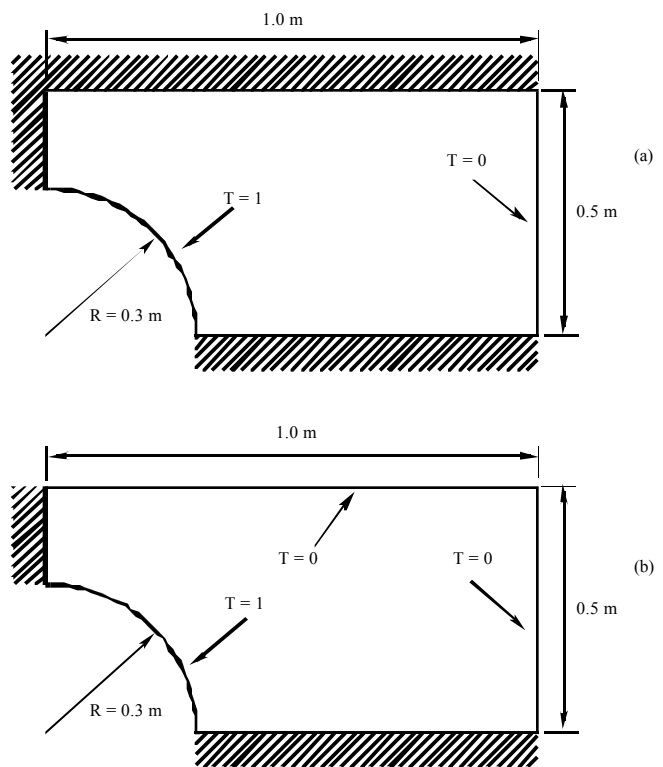*Figure 4. Automatic geometry generation dialog box*

Figure 5. Proposed exercises

One of the proposed exercise for evaluating how capable were the students in using the software, had the objective of calculating the conduction shape factor for two situations shown in Figure 5. For that, it was only allowed to use the default grid generator embedded in the software. To perform the task, the student needed also describe, in details, all the steps adopted, make

comparisons of the results obtained for the two situations and explain the physical phenomena involved.

It can be seen in the Figure 4, that Heat Transfer 1.0, in the option of automatic grid generation, presents the possibility of building a geometry called "Mixed", varying the parameters (U, R, W, H). However, there are some geometry generation restrictions. For U=0 and U=H, the geometry can not be generated, a limitation already known by the students.

However, inspecting Figure 7 one conclude that such a problem involves a symmetry line, which means that the geometry of Figure 7 can be used for solving the problem proposed in Figure 5.

Therefore, for the solution of this exercise using the "Mixed" geometry, the student need to know the meaning of the symmetry concept, so that he will have the possibility to apply the correct boundary conditions. For this case, the resulting grid would have the form presented in Figure 6.
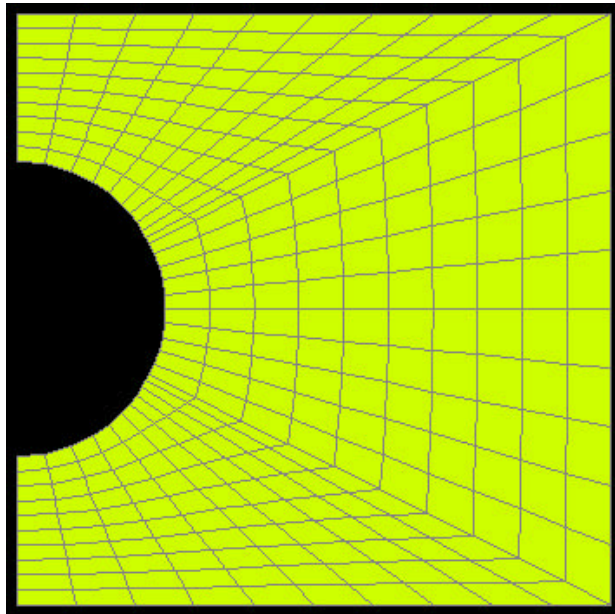

Figure 6. Illustration of the mixed grid

According to the boundary conditions given in Figure 5 the boundary conditions for the geometry of Figure 7 would result, according to its location in Figure 7:

Table 1. Boundary Conditions

Boundary	Problem (a)	Problem (b)
East	0% to 33% (q" = 0) 33% to 66% (T = 0) 66% to 100% (q" =	0% to 100% (T =0)

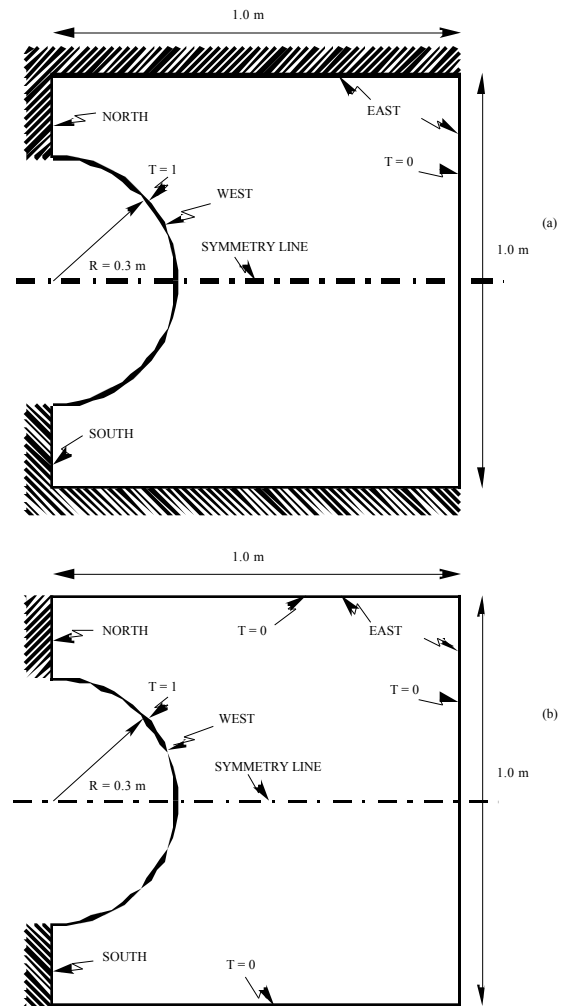|		0)
West	0% to 100% (T = 1)	0% to 100% (T = 1)
South	0% to 100% (q" = 0)	0% to 100% (q" = 0)
North	0% to 100% (q" = 0)	0% to 100% (q" = 0)

Figure 7. Problem boundary conditions

The conduction shape factor is given by

$$S = \frac{q_{half\ geometry}}{k\ T} \qquad (3)$$

where

$$q_{half\ geometry} = \frac{q_{complete\ geometry}}{2} \qquad (4)$$

which comes from the adoption of the geometry of Fig 7, after the recognition of the symmetry boundary.

When the simulation reach the steady state, the available output resources allow visualizing the calculated variable in each elemental control volume. For both examples, to obtain the total heat flux, the student needs to sum up the heat flux for each elemental volume of the north face. Figure 8 illustrates the way that these outputs are supplied.
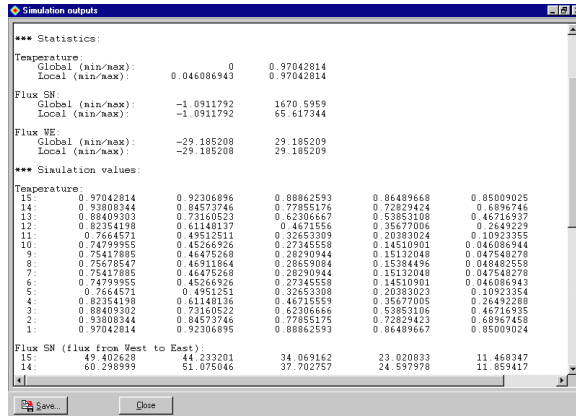

Figure 8. Simulation outputs

Therefore, the results for the shape factor for each geometry, would be, for the grid shown in Figure 6

Table 2. Results

Problem (a)	Problem (b)
S = 0,658	S = 2,147

The program still offers the visualization of the heat flux vectors. This interesting characteristic allows the student to recognize how the heat travels through the media. The student can also calculate the conduction shape factor using the graphical method and compare the results with the one obtained with the software. It must be recalled that the graphical method is a tentative of solving the mathematical model of the 2D conduction problem, task which is done precisely (depending only on the grid size) by the software. Figure 9 and 10 shows the heat flux plots for both situations.
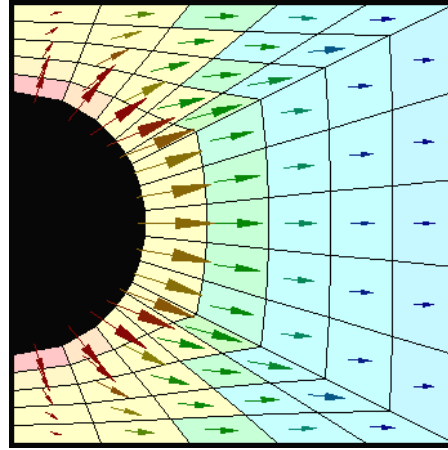

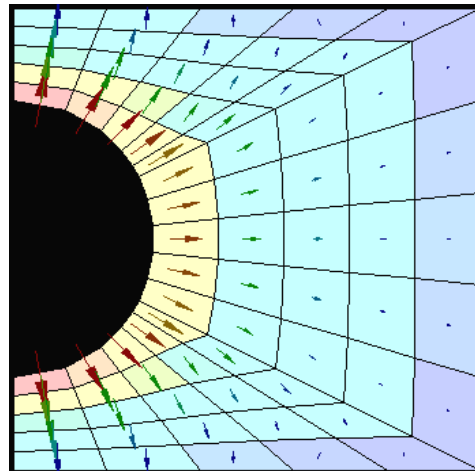Figure 9. Heat flux vectors for problem (a)

Figure 10. Heat flux vectors for problem (b)

Impact Evaluation Of The Use Of Heat Transfer 1.0 In Learning Heat Conduction

Trying to measure the impact of using the software, at the end of the semester, a questionnaire was filled in by each student. The main goal was to have opinions about the use of Heat Transfer 1.0 as a learning tool. The questions aimed to obtain information on aspects such as the improvements to the learning, usability and the viability of definitively implement the software in the Heat Transfer I course.

In the amount of 39 students, 28 of them (72%) answered the proposed questionnaire and 27 (69%) attended the test about the use of the software (which was optional). In a scale from 0 to 100, the student could express their relative agreement to the questions. Non-answered questions were considered as invalid.

The questionnaire contained the following questions:

1) Did you use the software to do the recommended exercises, or other exercises?

2) Did you have easy access to personal computers to use the software (at home, in the laboratories,…)?

3) If you didn't use, was it because lack of computational resources?

4) Did you try or did you use the PC computer rooms available at the university to solve the exercises using Heat Transfer 1.0?

5) Do you think the use of software in undergraduate disciplines contributes to the learning?

6) Did you feel more stimulated to study because the software Heat Transfer 1.0?

7) Do you agree with the non-obligation of the use of the software during the course?

8) Do you think that the tests of software must has the same weight as the written tests in the final mark, valorizing the use of this type of application?

9) Did the software help you to better understand the physics of heat transfer? Did its use enlarged you vision on the topics?
:

10) Do you think that the use of Heat Transfer 1.0 enhanced your discussion level about heat conduction subjects?

11) Would you recommend the continuity of the use of Heat Transfer 1.0 in the Heat Transfer I discipline?

12) Do you feel familiarized with the use of commercial software (Word, AutoCAD, CorelDraw,…) or with other educational packages?

13) Compared with other commercial packages, known by you (technical applications,…), and considering that Heat Transfer 1.0 is an educational software, did you find it easy to use?

14) The friendly graphical user interface called your attention?

15) Do you think the software is adapted for educational purposes?

16) Were you motivated to solve some different problems with Heat Transfer 1.0?

The following table shows the results for the above questions

Table 3 - Questionnaire results

STATISTICS

	100	80	60	40	20	0	A	I	V
q.1	50	25	14	7	4	0	82.1	0	100
q.2	75	11	7	4	4	0	90.0	0	100
q.3	0	6	19	0	0	75	16.3	43	57
q.4	18	4	7	4	0	68	26.4	43	57
q.5	75	18	4	4	0	0	92.9	0	100
q.6	39	29	21	7	4	0	78.6	0	100
q.7	57	29	14	0	0	0	88.6	0	100
q.8	58	15	12	4	4	8	79.2	7	93
q.9	52	30	11	4	4	0	84.4	4	96
q.10	22	19	22	15	7	15	57.8	4	96
q.11	92	8	0	0	0	0	98.5	7	93
q.12	81	7	7	4	0	0	93.3	4	96
q.13	63	30	4	4	0	0	90.4	4	96
q.14	56	33	11	0	0	0	88.9	4	96
q.15	65	31	4	0	0	0	92.3	7	93
q.16	52	30	11	0	4	4	83.0	4	96

A – Average   I – Invalid answers   V – Valid answers

From the 28 students that answered the questionnaire, a greater number (90%) has an easy access to computers of the PC type. A still larger portion (93,3%) is well familiarized in using commercial software, such as text editors, graphic editors and worksheets. These characteristics demonstrate that the student's profile that used the software is up-to-date regarding the current state of the art of the available commercial software.

According to Table 1, 82% of the students frequently used Heat Transfer 1.0. The 16.3% ones that had difficulties in the use or that didn't used the application, alleged deficiencies or lack in computational resources access.

A quarter of them (26.4%) used or tried to use the available microcomputer laboratories besides the normal class schedule. It can also be concluded that Heat Transfer 1.0 had been used predominantly in student's home.

For 78.6% of the students, the software was a motivation factor to enhance their studies and 83%

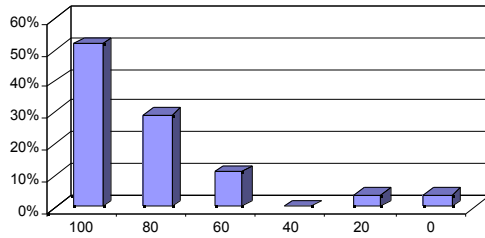(Figure 11) feel more motivated to simulate some different problems created by themselves.

igure 11 - Were you motivated to solve some different problem with Heat Transfer 1.0?

The majority (92.9%) thinks that the use of computational applications in undergraduate courses represents a great pedagogic progress. An amount of 79.2% think that the test using the software should have the same weight as the conventional written tests in the final mark. However, according to 88.5%, its optional use should continue. This clearly shows that the students do not want to take the risk.

As shown in Figure 12, 84.4% of the students reported to have enlarged their vision of the course subjects and that Heat Transfer 1.0 has facilitated the understanding and visualization of heat conduction phenomena. Very interesting is the fact that 55.8% think to be better prepared to discuss related subjects.
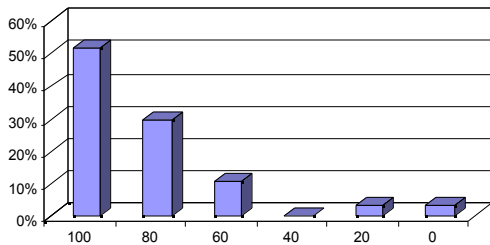

gure 12 - Did the software help you to better understand the physics of heat transfer? Did its use enlarge your vision on the topic?

When compared with available applications in the market, the software was considered easy-to-use by 90.4% (Figure 13). About 88.9% found the interface attractive and friendly.
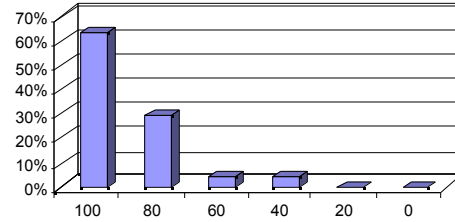

ure 13 - Compared with other commercial packages, known by you (technical applications, games…) and considering that Heat Transfer 1.0 is a educational software, do you find it easy to use?

Finally, the majority (92.3%) considered that the software resources are appropriated to the use as a teaching tool. Most (98.5%), as shown in Figure 14, of the students recommended the continuity use of Heat Transfer 1.0 in the Heat Transfer I course.
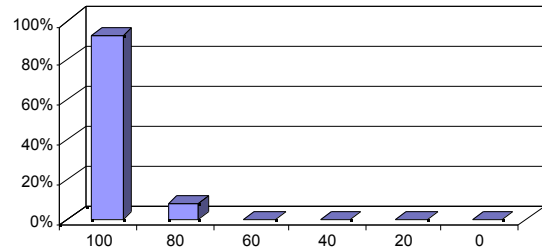

Figure 14 - Would you recommend the continuity of the use of Heat Transfer 1.0 in the Heat Transfer I course?

Conclusions

The use of Heat Transfer 1.0, besides its application during only one semester, demonstrated that use of computers in teaching represents a great progress to the current used teaching methodologies. The reduction in price, size, and the growing CPU capacity of computers, allows the simulation of more realistic complex problems and can now be taken into the classroom. This represents an enormous step towards the preparation of the engineers for facing the modern technological world. It is imperative, however, that packages be specially designed for educational purposes.

The results obtained in the questionnaire shows evidences of efficiency and effectiveness of the Heat Transfer 1.0 use in the teaching of the Heat Transfer I course. The curiosity and the student's critical feeling were motivated through the variety of exercises that can be solved using the software.

The use of well conceived educational packages, supported by strong visualization tools, together with the knowledge by the students of the physics of the phenomenon and of the limitation of the mathematical

models is, certainly, the route for reaching the "virtual laboratory".

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