



## HEAT CONDUCTION TEACHING *HEAT TRANSFER 1.1* SOFTWARE + NEW COURSE PROGRAM

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**Abstract.** *This paper presents a general overview of the educational software Heat Transfer 1.1, developed to be used as an auxiliary tool in heat conduction teaching. It is also addressed a new proposed structure for a heat conduction course that differs significantly from the ones adopted in classical heat conduction textbooks. In these books very little attention is devoted to 2D/3D problems, concentrating the analysis in 1D problems, what precludes a full understanding of the vector nature of the heat flux. In addition, teaching steady state and transient regimes in separated chapters, suggesting that they are different physical phenomena, inhibits a clear understanding of the physics of heat conduction. Therefore, it is proposed that the software Heat Transfer 1.1 be used in conjunction with a new course program to enhance the learning process. In this new course program the software plays the role of a virtual laboratory, helping students to "see" the phenomenon of the heat flow what stimulate the physical reasoning. Heat Transfer 1.1 was chosen as the "best educational software" of 1998, in a contest between Brazilian universities for the development of educational software.*

**Key words:** *Educational heat transfer, Educational engineering, Heat transfer software, Heat conduction virtual laboratory.*

### 1. INTRODUCTION

The use of software is becoming more and more frequent in modern education. The design of such tools to deal with the learning of physical phenomena requires extra care in order to become an efficient partner of the teaching process. Unfortunately, in undergraduate heat transfer education it is common computer packages, originally designed for research studies and usually computationally poorly written, be used as educational software. This

approach for improving the teaching process may be a disaster because no educational goals were established when designing such packages. Moreover, the time consumed by students learning to use the program may be excessive, overwhelming the benefits. Therefore, educational software should be specially designed for attaining the course objectives and to contribute for creating a better learning environment. This type of development is not a trivial task, demanding specialists of several areas and a constant feedback from the students. In the development of *Heat Transfer 1.1* great effort was made to take these subjects into account. During the last three semesters the students' opinions were taken through questionnaires and their suggestions played a fundamental role in the improvement of the software. Opinions from faculty members from other universities, which have used the software in early versions, were also helpful.

The project called *Heat Transfer* began four years ago, involving students in the second year of the mechanical engineering course. These students entered a careful training process, involving concepts of advanced programming, numerical methodologies and software ergonomics. Several versions of the software were released to absorb new ideas from students and faculty members. The software was conceived and written with the main task of stimulating the physical reasoning in conduction heat transfer. Computational resources play an even more important role in heat transfer teaching, since the flow of heat inside a solid can not be "seen". In this case, the software can be viewed as a virtual heat conduction laboratory, where the heat front and the path of the heat flow can be seen in the computer screen for different physical situations.

Due to the physical appealing, intrinsic to the numerical model employed (finite volume), and to the graphical user interface, which resembles the usual heat transfer classroom, *Heat Transfer 1.1* resulted in a software which can be introduced in undergraduate heat transfer conduction courses with minimal effort.

During the last three semesters the software *Heat Transfer 1.0* (and *Heat Transfer 1.1*) were used in the Heat Transfer I course for the mechanical engineering degree at the Federal University of Santa Catarina. *Heat Transfer 1.1* was made available to the students at the Internet with a collection of exercises covering the topics in conduction heat transfer. These exercises play an important role in motivating the students to use the software. At the end of each semester the students filled in a questionnaire where questions about the software itself and related pedagogic procedures were asked. The findings, revealing the student view about the software and its impact in their learning can be found in Maliska et al (1998).

This paper is divided in three parts. The first one briefly describes the software with its capabilities. The second part suggests a new program for Heat Conduction which suits better to the use of the software during the course and, in the author's opinion, is physically more consistent than the classical program encountered in almost all available textbooks. Finally, an example of the software capability is shown.

## **2. THE SOFTWARE HEAT TRANSFER 1.1**

### **2.1 General**

*Heat Transfer 1.1* takes advantage of the modern computational resources to provide an exciting and intelligent learning environment. The software is based on the construction of an organized structure of the internal data and on its powerful graphical user interface resembling the notation used in classroom. 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, medium and boundary conditions, the setting of the numerical parameters, the solution of the problem and the visualization of the results.

## 2.2 The mathematical model and the numerical method embodied in the software

The *Heat Transfer 1.1* is able to solve two-dimensional transient heat conduction problems with heat generation and variable properties. It also allows solving problems in 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 which is nowadays largely employed for solving engineering problems.

Performing a heat balance in the control volume in the right part of Fig.1, one obtains

$$q_w + q_s - q_e - q_n = \frac{\Delta E}{\Delta t} \Big|_{v.c.} \quad (1)$$

Making  $\Delta z$ ,  $\Delta y$  and  $\Delta t$  approach zero and using Fourier's law, one obtains the energy conservation principle at infinitesimal level, given by

$$\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t} \quad (2)$$

where all three types of boundary conditions can be applied: prescribed temperature, prescribed heat flux and convection. For the purposes of the software, it does not matter how the equation is solved, unless the software is used for teaching numerical methods in heat conduction. Although *Heat Transfer 1.1* has been designed such that the numerical method embodied in the could be kept hidden to the student, without loss of understanding, the numerical method employed is now briefly presented for the shake of completeness.

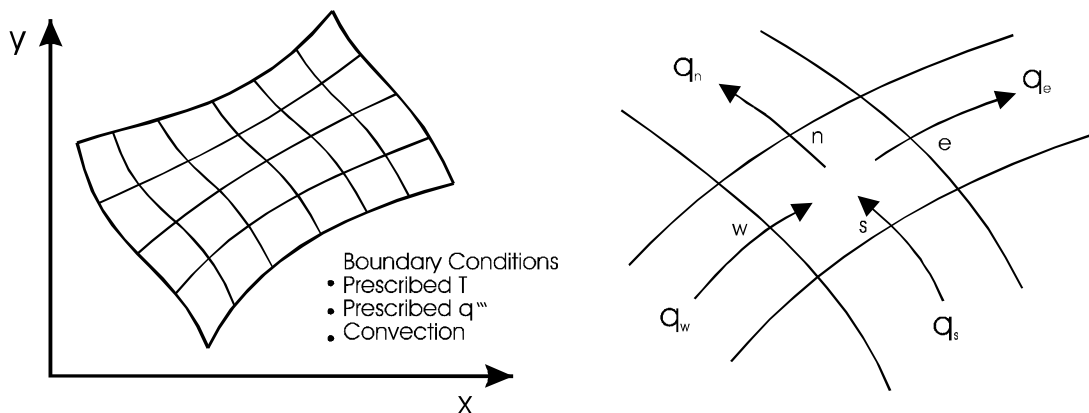


Figure 1 - Coordinate system used in *Heat Transfer 1.1* and the heat balance

The usual finite-volume method, using boundary-fitted coordinates is employed. The domain is discretized in small control volumes as shown in the left part of Fig. 1. The algebraic equation for each control volume is obtained performing a heat balance, as shown in the right part of Fig.1. Details of the methodology for obtaining the approximate equations for can be found in Maliska (1995). Recall that the procedure for obtaining the algebraic equation for each finite-volume is the very same procedure used for deriving the heat conduction

equation. The difference is that in the numerical method the finite size of the control volume ( $\Delta x, \Delta y, \Delta z$ ) does not suffer the zero limiting process. This demonstrates how physically strong is to solve the heat conduction equation by a finite-volume numerical method.

After performing a heat balance for all control volumes one obtains a linear system of equations given by

$$[A] [T] = [B] \quad (3)$$

where  $[A]$  is the matrix of the coefficients,  $[B]$  is the independent vector and  $[T]$  is the vector, which contains the temperature field to be determined. The solution of Eq. (3) gives the discrete temperature field, that is a value of the temperature for each finite control volume. The temperature field can be, then, used in several ways to explain the conduction heat transfer phenomena.

### 2.3 Software characteristics

The source code of *Heat Transfer 1.1* was written in C++, using Object Oriented Programming - OOP. The use of the OWL (Object Windows Library) developed by Borland allowed total integration between the algorithm and the graphic interface. The program runs on Windows95/NT, with a minimal configuration of a PC 486 100MHz, with 16 MB of RAM.

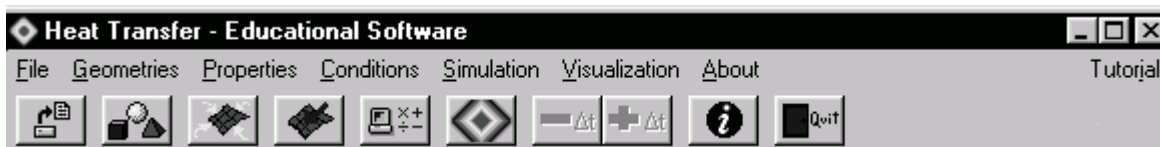


Figure 2 - *Heat Transfer 1.1* toolbar zoom

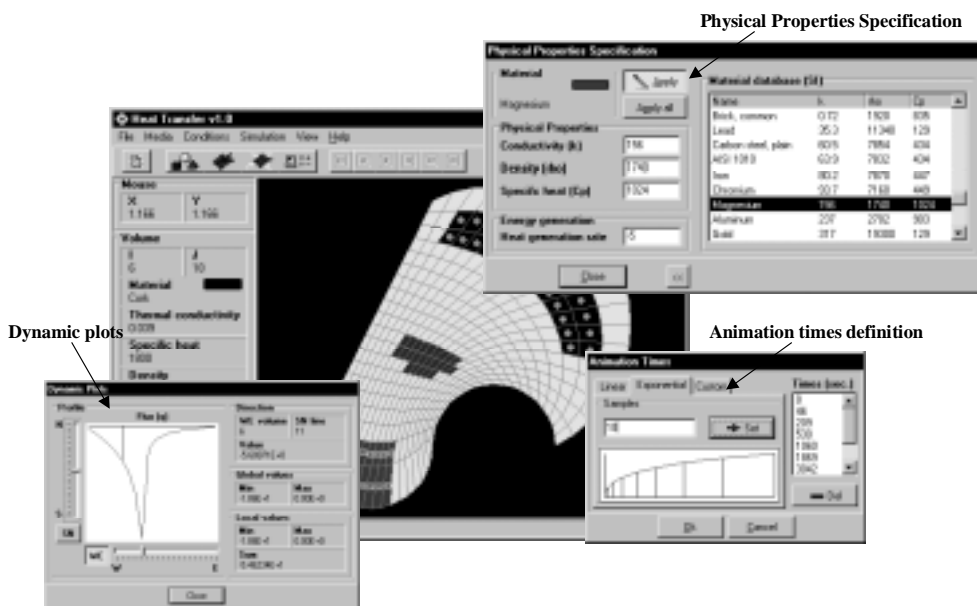


Figure 3 - *Heat Transfer 1.1* environment

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 (Fig. 2) available in the software main window, shown in Fig. 3, which depicts the graphical interface environment of *Heat Transfer 1.1*.

*Heat Transfer 1.1* supports reading files created by several others grid generators. However, to facilitate its use some geometries are easily created. The default geometries available in *Heat Transfer 1.1* are shown in Fig. 4.

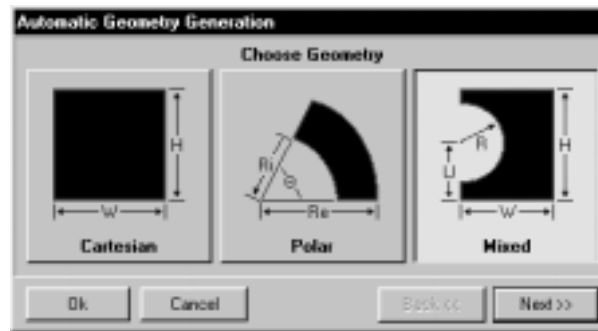


Figure 4 – Default geometries available in *Heat Transfer 1.1*

There are several modules that are used for defining a heat conduction problem. A brief explanation of each one is described below (following the menu items available in the software).

**File:** This module allows importing the geometry and the correspondent grid that has been generated by other programs. There is a specified file format to be obeyed.

**Media/Geometry:** In this module the domain and the correspondent grid are defined. It is possible to the user to generate three different types of domains [rectangular, radial and mixed (rectangular + radial)] (Fig. 4) and change its dimensions. Just clicking on the desired geometry and giving the parameters the geometry is created. If other geometries are required than the default ones, the user can generate them in any grid generator and employ the module file to input the grid in *Heat Transfer 1.1*.

**Media/Physical Properties:** In this module the user chooses 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 these 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 1.1* 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 may apply prescribed temperature (a constant value, a linear and a sinusoidal distribution  $T(x) = T_0 + \sin(p x)/L$ ), 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, it is possible to prescribe a convection boundary condition along one fraction of the north face boundary and prescribed temperature in the remaining of the boundary.

**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 a guess for the iterative procedure.

**Simulation:** In this module the numerical parameters of the simulator embodied in *Heat Transfer 1.1* can be adjusted. It can be modified 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 and other details of the solution. The user can also define the time levels he wants to save the results for printing or visualizing.

**View:** It consists of the presentation of a field of colors related to the interpolation of the field of a property (any scalar value, like temperature, thermal conductivity), and the heat flux vectors simultaneously. The isotherms can be plotted too. Each one of the four visualization modes (borders, media, temperature field and isotherms) can be analyzed jointly with the field of vectors. The software also offers a visualization of the results in dynamic plots of the temperature and heat flux profiles along the coordinate lines. During the transient process, the results can be saved at any specified time. Thus, it is possible to compose the color fields or the plots, to having an animation of the phenomenon. Just by clicking Simulation/Play Animation in the menu, all the interpolated temperature or heat flux colored fields are shown, allowing the student to "see" the movement of the heat front.

**Help:** This module contains a complete like-Windows help-on-line:

**Contents:** It allows fast access to a specific topic of each one of the three available books (Introduction, Heat Transfer step-by-step and Tutorial);

**Help Topics:** It allows the location of a topic that contains a specific key word.

**Help on Help:** It presents a brief description on the operation of the help-on-line.

**Tutorial:** Direct access to the text that composes the Tutorial book.

**About:** 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 the *Heat Transfer 1.1* Tutorial, divided in two parts:

*Basic Heat Conduction* contains information about the heat conduction phenomena and a large group of examples which analytical solutions can be used for comparisons with the results obtained by the software. It also contains 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.

### **3. PEDAGOGIC RESOURCES – THE VIRTUAL LABORATORY**

Heat Transfer is classically a course defined as difficult by the students. It is not clear if the difficulty comes from the fact that the heat transfer phenomenon can be described mathematically, through partial differential equations, and the students do not feel comfortable with the mathematics involved, or if the heat transfer is, by itself, a physical phenomenon difficult to be understood. It is reasonable to ask why a phenomenon that accompanies all of us since we were born and to which we are frequently exposed, can pose difficulties when we need to be successful in facing it as an university course. Who has taught us to blow the tip of the finger when we get a burn? Did our parents tell us that forced convection is more efficient in removing heat than natural convection? Due to the fact that heat transfer "lives with us", it would be natural that learning heat transfer would be more a joy than a pain. One possible explanation for not being that is because human being likes to see and experimenting things. And the flow of heat can not be seen, but only its results can be felt through temperature. Without feeling the physics, heat transfer courses rely too much in mathematics what may not motivate the students enough. Aiming to create motivation by

approximating the student to the physics of heat conduction, is why the software was construct. It works as a virtual laboratory, allowing the student to perform computational experiments involving the heat flow phenomena in solids. Of course, it is not supposed to substitute the experimental laboratory, but to fill the gap that even the laboratory can not easily provide: to " see" the flow of heat and its relation to the medium.

In this aspect the software plays an extremely important role in motivating students, since many problems, with different materials and boundary conditions can be " experimented" using the virtual laboratory. Also important is the fact that the laboratory is mobile and can be used anytime, anywhere. But the most significant contribution of the software is changing the way heat transfer is taught nowadays. Since analytical treatment of two-dimensional problems with non-homogeneous boundary conditions would require tedious mathematical manipulations of the equations, classical textbooks carries few pages dedicated to two-dimensional problems. Therefore, heat conduction courses deal massively with one-dimensional problems, what precludes the full understanding of the vector characteristics of the heat flux quantity. In the author's opinion this is the weakest point in the approach nowadays used for teaching heat conduction. The proposed software, associated with a well-chosen collection of exercises allows sharing the classroom with independent studies, reducing, therefore, the time spent by students as a passive partner of the learning process.

To reach the full benefits of using the software described in this paper it is necessary to modify the course program. This issue is addressed in the coming section.

#### **4. PROPOSAL FOR A NEW HEAT CONDUCTION COURSE PROGRAM**

It is classical in almost all heat transfer textbooks to start a heat conduction course by deriving the heat conduction equation in three dimensions. After this point this equation is forgotten for few months and the course starts, approximately with the following structure:

1. 1D steady-state with no heat generation
2. 1D steady-state with heat generation
3. 2D steady-state- analytical and numerical methods
4. 1D transient (lumped capacity analysis), 1D transient (spatial variation), 1D/2D numerical methods for transient heat conduction.

There are two main problems with this organization:

1. When teaching heat conduction it is impossible to explain steady-state regime without to follow, first, the transient. Besides the fact that is not possible to separate the physics of the phenomenon, you duplicate efforts teaching a little bit of transient, to support item 1, and then talking again about transient regime when giving the equations in item 4.
2. Even less didactic is to teach numerical methods for steady state separated from numerical methods for transient problems, as recommended in most textbooks. In this approach the students fail to recognize that it is only necessary to make the time step very large to reach steady-state. This pitfall can be easily resolved by just updating the numerical issues of the textbook with the modern numerical approaches available in the literature.

Recognizing that a problem always appears with the full physics involved, the two above cited pitfalls can be resolved if a change in the course structure is done helped by a tool which facilitates to easily analyze the phenomenon as a whole. Therefore, the following structure is proposed in conjunction to the use of the virtual laboratory *Heat Transfer 1.1*.

1. Introduction
2. Derivation of the Heat Conduction Equation
3. Alternatives for solving the Heat Conduction equations
  - Analytical procedures.
  - Numerical Methods for transient problems. Steady state is attained by merely making the time step infinity. Use this part of the course for teaching the method used in the software. The finite-volume method is preferred due to its physical appeal (balances in control volumes is what is done to derive the Heat Conduction equation in item 2). At this point of the course the software is introduced to the students. From now on they will explore the heat conduction problems. It is now a matter of each teacher to choose the problems he (or she) wants to examine.
4. Choose now a collection of exercises to explore the physics of heat conduction. Since the software will be used, problems will be always 2D and transient. Through boundary conditions it will be possible to solve 1D problems and following the transient according to the time step chosen. The exercises can grow in complexity trying to examine several important points normally taken by grant by students, like:
  1. When the electrical resistance analogy concept is valid?
  2. What means Biot number less than 0,1? May I use the lumped analysis when the Biot is less than 0,2?
  3. And so on.

## 5. EXAMPLE PROBLEM

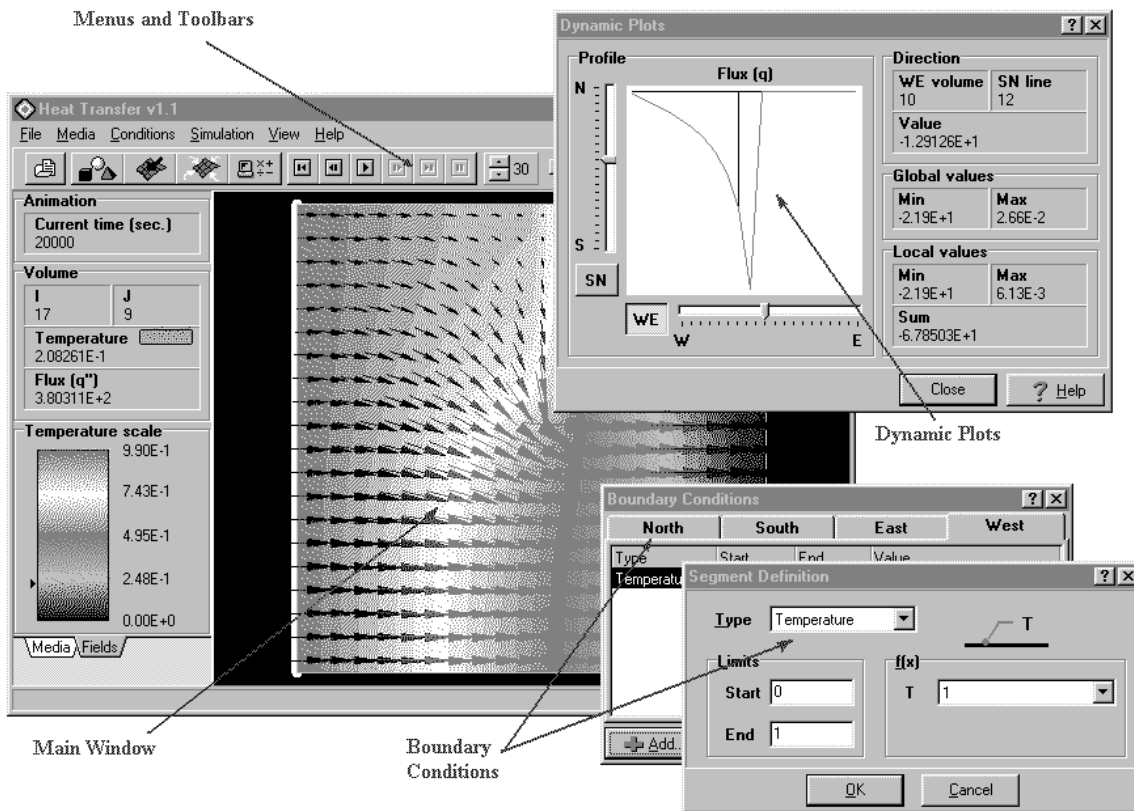


Figure 5 – Example of a simulation using *Heat Transfer 1.1*.



As an example, Fig. 5 presents the heat flux profile across a rectangular domain. The main window also shows the color map used for the visualization of the temperature field (here prepared in black and white). It can be seen that it is possible, using a slider, to select plots of temperature along the coordinate lines. There are also shown the boxes for inserting the boundary conditions.

## 6. CONCLUSIONS

This paper presented an auxiliary tool to be used in heat conduction teaching. The construction of the software obeyed clear pedagogic objectives to be attained with its use. The software has been used in the last three semesters in an heat conduction course and the evaluation, reported in another paper, reveal that the software helped the students to enlarge their vision about the heat conduction phenomenon. The role of a virtual laboratory played by the software increases significantly the feeling of the heat flow physics. The paper also advanced a proposition for changing the usual course program adopted by the majority of the textbooks, emphasizing the learning of transient and steady state regimes in an integrated approach.

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