Development of an Educational Environment by Using Graphical User Interfaces Applied to Heat Transfer Problems

EDVCATIO PHYSICORVM
QVO NON ASCENDAM?

ISSN 1870-9095

Fran Sérgio Lobato[1], Fábio de Oliveira Arouca[2], Gustavo Barbosa Libotte[3,4]
[1,2]School of Chemical Engineering, Federal University of Uberlândia, Brazil.
[3]National Laboratory for Scientific Computing, Petrópolis, Brazil.
[4]Polytechnique Institute, Rio de Janeiro State University, Nova Friburgo, Brazil.

E-mail: fslobato@ufu.br

(Recibido el 12 de diciembre de 2020, aceptado el 15 de febrero de 2021)

Abstract

In the last few decades, the development of computational tools has made the approach of more complex case studies in chemical engineering classrooms more accessible, such as the simulation of nonlinear problems, assessment of the sensitivity of input parameters in certain models and analysis of physical behavior considering different operating conditions in a system. In this context, the use of graphical user interfaces represents a typical example of this type of computational tool that makes classes more dynamic and allows for greater understanding by students, even in more complex problems. In this work, it is proposed to use graphical user interfaces, developed in Scilab, to improve learning and engagement in the analysis of heat transfer problems in chemical engineering classrooms. For this purpose, two classical case studies are simulated and analyzed using the proposed tools. The first considers the heat transfer in solids and the second considers the Gurney-Lurie charts. The results obtained demonstrate that the use of graphical user interfaces allows some difficulties to be avoided, such as the understanding and implementation of numerical methods necessary to solve some problems, besides facilitating the understanding of different physical aspects, since it provides a visually simplified environment for carrying out different simulations with varied parameter values and easy access to graphical results.

Keywords: Educational Environment, Graphical User Interface, Scilab, Heat Transfer.

Resumo

Nas últimas décadas, o desenvolvimento de ferramentas computacionais têm permitido a abordagem de estudos de caso mais complexos em salas de aula nos cursos de graduação em engenharia química, como por exemplo a simulação de problemas não lineares, a avaliação da sensibilidade dos parâmetros de entrada em determinados modelos e a análise do comportamento físico considerando diferentes condições de operação no sistema em análise. Nesse contexto, o uso de interfaces gráficas representa um exemplo típico desse tipo de ferramenta computacional que torna as aulas mais dinâmicas, permitindo uma maior compreensão dos alunos, mesmo em problemas mais complexos. Neste trabalho, propõe-se a utilização de interfaces gráficas, desenvolvidas em Scilab, para aprimorar o aprendizado e o engajamento na análise de problemas de transferência de calor em salas de aula do curso de graduação em engenharia química. Para essa finalidade, dois estudos de caso clássicos são simulados e analisados a partir das ferramentas propostas. O primeiro avalia a transferência de calor em sólidos e o segundo considera a análise dos diagramas de Gurney-Lurie. Os resultados obtidos demonstram que o uso de interfaces gráficas permite que algumas dificuldades sejam minimizadas, tais como a compreensão e implementação de métodos numéricos necessários à resolução de alguns problemas, além de facilitar o entendimento de diversos aspectos físicos, uma vez que a metodologia proposta apresenta um ambiente visualmente simplificado onde podem ser realizadas inúmeras simulações e de fácil acesso aos resultados gráficos.

Palavras-chave: Ambiente Educacional, Interface Gráfica, Scilab, Transferência de Calor.

I. INTRODUCTION

The study of transport phenomena encompasses several areas in chemical engineering with many applications in different fields of science. In the context of heat transfer phenomenon, a profusion of applications can be found in the literature, such as heat transfer in reactors, distillation columns, dryers, among others [1, 2, 3]. The mathematical formulation of problems of this type depends on certain hypotheses and requires, in general, the application of numerical methods due to the different levels of complexity (system of algebraic equations, system of differential equations, differential-integral system and algebraic-differential system). As demonstrated by Cartaxo and co-workers [4] and Golman [5], computer simulations can be employed to understand chemical models and to produce knowledge in the teaching of chemical engineering. In this case, considering certain chemical engineering simulations, the cost related to laboratory analysis can be reduced. In addition, the number of experiments needed to understand a particular process can be optimized [6].

In the academic context, analyzing such problems, which make use of various mathematical tools, in different disciplines of undergraduate courses may be not a trivial task. This is due to the structure provided by some universities and the difficulty inherent in working with analytical and numerical methods. For this reason, in many of these courses, a large number of student failures can be observed. Thus, the development of methodological tools that help the student to understand the different concepts involved in these disciplines without the need to implement computational codes represents an area of study with great importance and applicability.

In the specialized literature, a wide variety of software to simulate different phenomena can be found. In chemical engineering, one of the main representatives is the EMSO simulator (Environment for Modeling, Simulation and Optimization) [7]. EMSO is a graphical environment that allows the mathematical modeling of complex systems under steady state or transient conditions, based on the selection and coupling of different models. The software also allows the development of new models using the simulator's modeling language or using models from the EMSO Model Library (EML). Despite the great applicability of EMSO, the need to manipulate source code and dependence on programming logic is still an obstacle to its employment in many disciplines. In view of these possible limitations, we can also mention ANSYS, FLUENT, COMSOL and MATLAB, which also has great processing capacity but, in general, depends on programming skills, despite the fact that these softwares still require a license for use in certain applications, which does not guarantee access to the source code. In this case, possible changes in case studies previously incorporated into these softwares, in general, cannot be made. Alternatively, Scilab was developed by the French Institute for Research in Computer Science and Automation (INRIA). It is a high-level programming language and a cross-platform computing environment that provides powerful tools for scientific applications.

In the educational context, these softwares are used to solve problems with different levels of complexity in a classroom environment. Edgar and co-workers [8] assessed the simulation in control education of classical process in chemical engineering (distillation columns, chemical reactors, pH processes, microelectronics, and biological processes). Bordeianu and co-workers [9] developed a Scilab code for the study of turbulent flows and maps considering chaotic systems defined by ordinary differential equations. Domingues and co-workers [10] described the design and implementation of two virtual labs (by using internet) for biochemical engineering education. The first virtual lab consists of the determination of correlation between oxygen transfer rate, aeration rate and agitation power in a reactor. The second virtual lab consists of the determination of residence time distribution in continuous tanks series. According to these authors, the advantages in this kind of implementation are: reduced costs, reduced experience time, and improved data with no loss of education efficiency. Komulainen and co-workers [11] developed a dynamic simulation software based on D-Spice and K-Spice to solve three different chemical engineering problems. For this purpose, the following topics were assessed: basic chemical engineering; operability and safety analysis; and process control. The experiences of both teachers and students were analyzed. According to these authors, the experiences confirm that dynamic simulators provide realistic training and can be successfully integrated into undergraduate and graduate teaching, laboratory courses and research. Rahman and co-workers [12] developed a MATLAB code involving chemical and biochemical engineering education. Llanos and co-workers [13] describes a laboratory routine designed to help chemical engineering students understand the basic concepts of corrosion. For this purpose, the corrosion rates of six different materials have been calculated to assess the effects of the corrosion environment and to apply corrosion prevention methods.

To make the interaction between user and source code more accessible, graphical user interfaces (GUIs) have been increasingly used in the classroom. Thus, tasks such as implementation and choosing a methodology to solve certain problems can be avoided. Taking into account simple commands, the user can define parameters, model and simulation characteristics, and perform sensitivity analysis. In addition, a visual illustration of how results change due to various variables reinforces the lessons [14].

In literature, various works considering the use of GUIs and other similar approaches can be found. Wilson and Marcotte [15] developed a graphical interface by using LabVIEW 4.0 to analyze the gas-phase reaction kinetics of cyclopentene vapor pyrolysis. This code was used to produce a graphical interface with the same look and feel as a physical data station with all its switches, digital readouts, and strip chart recorders. Tsai [16] developed a post-processor by using GUI tools in Scilab to visualize fuel rod burnup analysis data. This code associates a GUI (numerical results with 2-D and 3-D graphs) with animations regarding the fuel temperature distribution. Depcik and Assanis [14] developed several GUIs in an educational engineering environment, considering different software options and programming languages (FORTRAN, C, JAVA, MATLAB and VISUAL BASIC) to solve a cavity flow problem. In this problem, the flow inside the box is driven by a plate moving at a constant velocity. The governing equations of motion for the flow within the box are the incompressible two-dimensional Navier-Stokes equations.

Kaddouri and co-workers [17] proposed a novel software called NLSoft, developed for the design of nonlinear controllers based on the well-known feedback linearization technique. This software package contains several symbolic manipulation modules, which includes differential geometric tools for the design and simulation of control systems. In addition, the NLSoft package presents a user-friendly GUI that incorporates the calculation time of linearizing control laws considering several digital signal processors characteristics. Andreatos and Zagorianos [18] developed a GUI tool for teaching and learning automatic control systems by using MATLAB. The proposed tool was applied to the control of a rigid supersonic aircraft with linear dynamics described by a simple single-input singleoutput transfer function that depends on the airplane structure and flight parameters. Magyar and Zakova [19] proposed a Scilab-based Remote Control applied to two experiments: the thermo-optical and the hydraulic plant.

The implemented code is based on open technologies whereby the kernel of the application is built using XCOS (control-oriented toolbox).

Vieira and co-workers [20] also applied the XCOS package in Scilab to study two case studies---stirred tank with heating and continuous stirred tank reactor with van de Vusse kinetic. For this purpose, they focused on the development of control loops block diagrams, PID control tuning, and process response analysis. He and Li [21] proposed a MATLAB-based GUI to evaluate the Hydrogeochemical Diagram. In this project, the different diagrams can be obtained by user (Piper diagram, Gibbs diagram, Wilcox diagram and PI classification diagram). As mentioned by the authors, all the codes of the graphical interface can be freely accessed and adjusted by users according to their needs. Molina and co-workers [22] developed the KBR (Kinetics in Batch Reactors) code. This is a MATLAB-based application with a friendly GUI for chemical kinetic model simulation and parameter estimation.

The School of Chemical Engineering at the Federal University of Uberlândia (Brazil) has been promoting a pilot project that concerns the development of GUIs, using Scilab, for classroom assistance in the discipline of Heat Transfer. Each GUI developed addresses a specific case study in chemical engineering and aims to complement the work of students in the classroom, as well as to promote new educational activities in e-Learning, that is, these platforms allow better preparation of students in relation to physical concepts learned during classes.

In this work, our objective is to present the structure of two graphical environments for the treatment of heat transfer problems. For this purpose, we use Scilab to analyze two classical case studies. The first one concerns the simulation of heat transfer in solids and the second one considers the determination of Gurney-Lurie Charts. This work is structured as follows. Section II presents the general characteristics about Scilab and its use for creating GUIs. Section III presents a mathematical description for the two case studies analyzed. Section IV describes the schematic representation of the GUIs proposed. The applications regarding the above mentioned case studies are presented in Section V. Finally, the conclusions are presented in the last section.

II. SCILAB AND THE CREATION OF GUIS

Scilab is a free and open source platform, based on the well-known MATLAB, which provides powerful tools for numerical computing and a high-level numerically oriented programming language. The software allows the definition of different types of operations, with an extensive range of built-in mathematical functions. In addition, it presents the possibility of interaction with other programming languages, 2-D and 3-D graphics library, functions for integration of ordinary differential equations and algebraic-differential equations, tools for handling classic and robust control, packages for optimization, signal and image processing, parallel architecture, among other features.

Recently, a toolbox designed to provide the interactive creation of GUIs, called *GuiBuilder*, has been incorporated into Scilab. The toolbox can be easily installed (through a single command) using ATOMS (AuTomatic mOdules Management for Scilab), which is the Scilab's repository for packaged extension modules. The GUI development environment provided by the GuiBuilder package can be seen in Fig. 1.

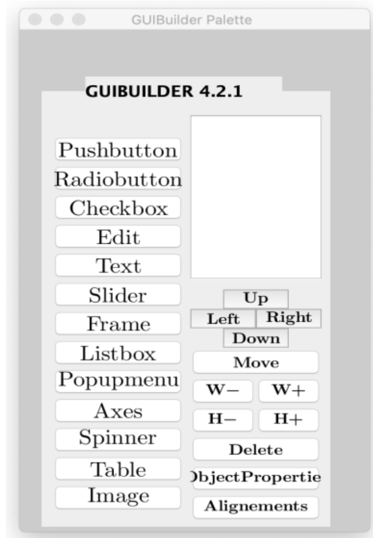


FIGURE 1. GUI Builder environment composed of the palette of widgets.

In the window shown in Fig. 2, all the essential widgets (graphic objects) for creating a graphical interface are available, as well as some options for handling the properties of such objects. The creation is simple and intuitive, and can be mostly driven by drag-and-drop tasks. The combination between these two figures represents the window in which the graphic objects can be inserted. The toolbox provides the possibility of immediate visual inspection, as the graphical interface is created, which makes easier the achievement of the expected result. After creating the GUI, the toolbox generates the corresponding source code, in Scilab language, which can be manipulated by the user.

In fact, the creation of GUIs itself is not the focus of this work, but the discussion on its use and importance in the field of teaching, especially in chemical engineering courses. Therefore, we are not going to detail its creation procedure, but focus our discussion on the advantages that the use of graphical interfaces can bring to the dynamics of classes and to the understanding of students about analyzes that can hardly be carried out effectively without the use of computational resources. The case studies discussed in this work are presented below, which are further included in the proposed GUIs.

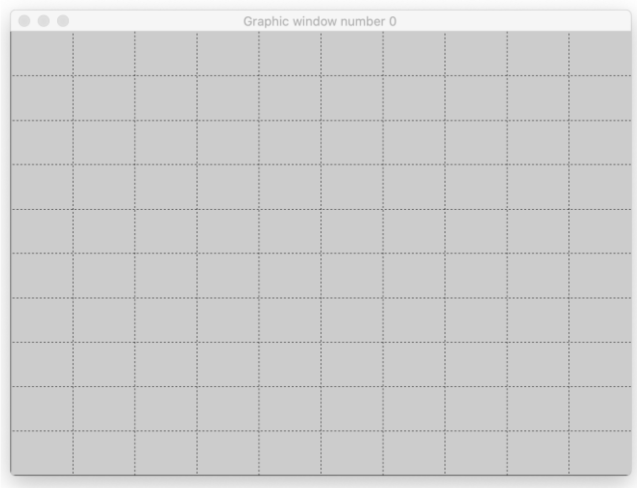


FIGURE 2. GUI Builder environment composed of the graphical window.

III. CASE STUDIES: HEAT TRANSFER IN A SOLID BODY AND GURNEY-LURIE CHARTS

In this section, the mathematical descriptions of two case studies are presented. The first case study considers the simulation of heat transfer in a solid body, which is initially at a temperature T_0 and is suddenly exposed to the environment (air) at a temperature T_∞. In this model, the following simplifications and assumptions are considered [23]: *i*) the rate of heat transfer by convection is much higher than the rate of heat transfer by radiation to other surfaces or to open spaces; *ii*) surrounding air has a mass such that its temperature - at least for positions far from the body surface - remains constant and equal to T_∞; *iii*) no chemical reaction or any other form of energy source is present in the body; *iv*) within the range of temperatures involved in the process, no phase change is verified; *v*) volume of the body is small and its thermal conductivity is relatively high, and does not change too much within the range of temperature of the process.

Mathematically, this heat transfer process can be represented by:

$$\frac{dT}{dt} = -\frac{\alpha A}{\rho V C_p}\left(T - T_\infty\right), \tag{1}$$

$$T(0) = T_0, \tag{2}$$

where t is the time (and t_∞ is the final time), T is the temperature, ρ is the density, C_p is the specific heat, A is the heat exchange area, V is the volume and α is the heat transfer coefficient. In order to simulate the results of this ordinary differential equation on the graphical interface, we employ the classic fourth-order Runge-Kutta method (referred to here as RK4). However, note that the analysis of these numerical results must be an extension of the analytical solution developed during the classes, which can be obtained using the method of separation of variables (more details on this solution can be seen in [23]).

The second case study considers the determination of Gurney-Lurie charts [24]. These charts can be used to represent solutions of mathematical models designed to describe non-steady state heat conduction in prototype geometries such as a flat plate, infinite length cylinder or sphere. In general, the use of these charts is restricted to the following conditions [25]: *i*) the solid is homogeneous; *ii*) the thermal diffusivity is constant; *iii*) there is no source of heat generation; *iv*) the initial temperature is uniform; *v*) the system is forced by a change in ambient temperature; *vi*) the heat transfer process is one-dimensional and; *vii*) the process is transient.

Considering such conditions, the process described by one-dimensional variables can be modeled by the following partial differential equation, together with the initial and boundary conditions [25]:

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial\varphi^2} + \frac{\Phi}{\varphi}\frac{\partial\theta}{\partial\varphi}, \tag{3}$$

$$\frac{\partial\theta}{\partial\varphi} = 0, \quad \varphi = 0, \quad \forall\,\tau > 0, \tag{4}$$

$$-\frac{\partial\theta}{\partial\varphi} = \mathrm{Bi}\,\theta, \quad \varphi = 1, \quad \forall\,\tau > 0, \tag{5}$$

$$\theta = 1, \quad \tau = 0, \quad 0 \le \varphi \le 1, \tag{6}$$

where θ, φ and τ represents temperature, geometric coordinates and time, respectively, Bi is the Biot Number, and Φ is a parameter that defines the type of geometry (Φ = 0 stands for flat plate, Φ = 1 for cylinder and Φ = 2 for sphere).

To solve this model, the well-known Method of Lines is used [26]. This approach consists in transforming the original model (partial differential equation) into a system of ordinary differential equations by using, for instance, the finite difference formulas. Thus, by defining the number of discretization points for φ, using approximations for first and second order derivatives, and evaluating the boundary conditions, the original model can be converted into a system of ordinary differential equations. The resulting system can be solved using RK4, as employed here.

IV. STRUCTURE AND FEATURES OF THE PROPOSED GUIS

In this section, a brief description of the GUIs proposed in this work is presented, mainly in relation to their features. For the sake of didactic and previous experiences, it is convenient to organize both case studies in two separate GUIs, in order to make the use simplified. Naturally, it is possible to develop a platform that brings together these and several other problems of the same nature. However, one surmises that encompassing several functionalities in a single GUI may represent an increase in its complexity, which is not desirable from the point of view of usability.

A. Heat Transfer in a Solid

Figure 3 shows the GUI proposed in this work for the heat transfer problem in a solid. Initially, one may note that the structure of the application is simple: the upper left frame (*Model*) shows fundamental information about the model, referring to equation (1) and equation (2). Model parameters (T_∞, T_0, ρ, C_p, A, V, α and t_∞) are listed in the frame below, followed by the respective units of measurement, and a field to input the desired value for a simulation. The same goes for the only adjustable parameter of the RK4 method, the number of points for discretization N. In turn, the empty frame, which covers most of the visible area of the GUI, is intended for the graphical display of the results. Finally, the *Simulate* and *Clear* buttons are responsible for starting a simulation and clearing existing results, respectively.

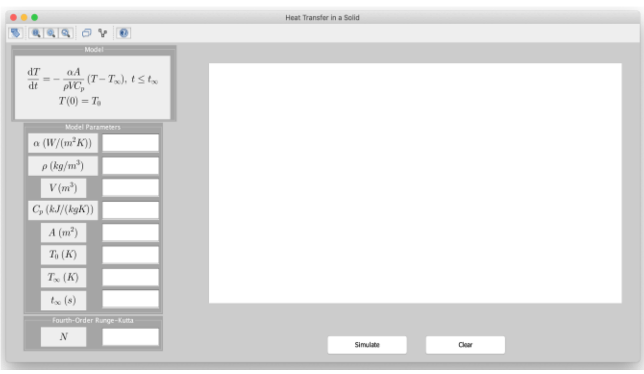


FIGURE 3. Graphical interface for the Heat Transfer in a Solid problem.

In the menu bar, the option *Problem Description* shows, in a new window, an essential description of the simulated model in the GUI, as can be seen in Fig. 4.

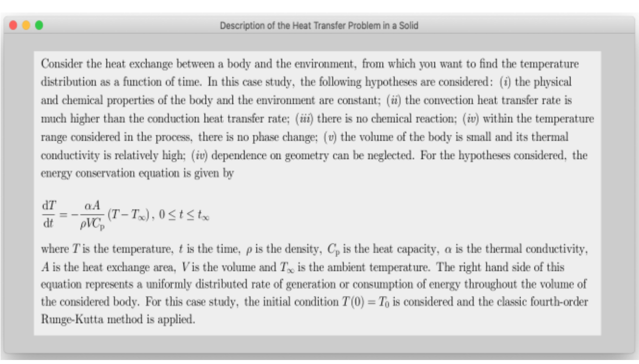


FIGURE 4. Brief description of the heat transfer problem in a solid.

In order to execute a simulation, the operation of the GUI is very intuitive: the user must only input all the values of the parameters listed in the *Model Parameters* and *Fourth-Order Runge-Kutta* frames, and click on the *Simulate* button. Then the entered values are used in the simulation of the heat transfer problem in a solid, showing the temperature profile as a function of time.

Also, in the menu bar, it is possible to select a parameter, within all the adjustable ones, on which a sensitivity analysis is carried out, that is, a set of results is generated for different values of an arbitrary parameter (with the others fixed), with the objective of assessing the impact of such a parameter on the profile that relates temperature and time. When a parameter is selected in the menu bar for sensitivity analysis, the graphical interface prompts the user to input the values that will be part of the analysis (Fig. 5 shows an example when T_0 is selected). The set of values entered determines the number of profiles calculated, all of which are plotted on the same set of axes, in order to make easier the visualization and favor comparisons between them.

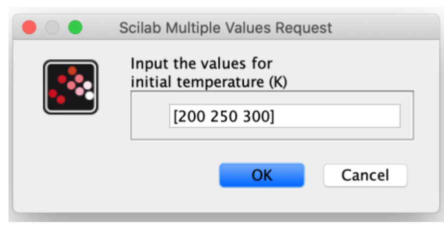


FIGURE 5. Graphical window for entering multiple values required for sensitivity analysis of parameters (in this case, the initial temperature).

B. Gurney-Lurie Charts

Following an arrangement similar to the structure presented above, Fig. 6 shows the proposed GUI for the Gurney-Lurie problem. The *Model* frame, positioned in the upper left corner, shows the essential elements of the analyzed model. Below, one can select the geometry of the problem to be solved (plate, cylinder or sphere), according to the value of Φ selected in the corresponding *radio button*. Next, the *Parameters* frame is shown, which has two widgets that assist in choosing the model parameters: in the first, the Bi button opens a new window for the user to input the set of values for the Biot Numbers employed in the simulation. In the second, the user enters a value for τ_∞ (the final time) in the blank field. When all parameters are defined (Φ, τ_∞ and Bi), a simulation can be executed by pressing the *Simulate* button.

As in the GUI presented in Section III, the user can review essential information on the model, according to equations (3)-(6), by clicking on *Problem Description*, located in the menu bar, and then on the option *Model*. A new window opens, like the one presented in Fig. 7, showing the main information of the model incorporated in the GUI. In addition, it is also possible to see information about the numerical method used in the simulation. Also in the menu bar, the user must click on the *Method of Lines* option to see information about the numerical method used to solve the problem. The information shown is as in Fig. 8.

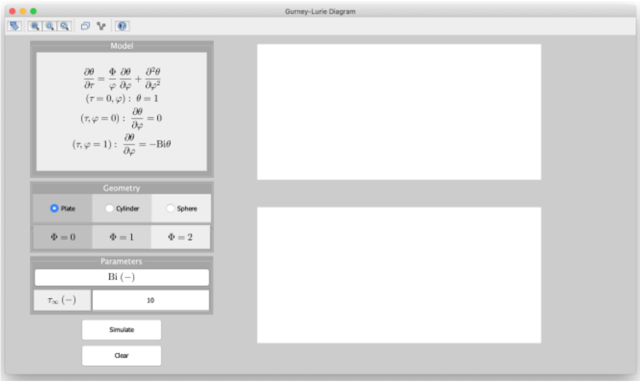


FIGURE 6. Graphical interface for the Gurney-Lurie problem.

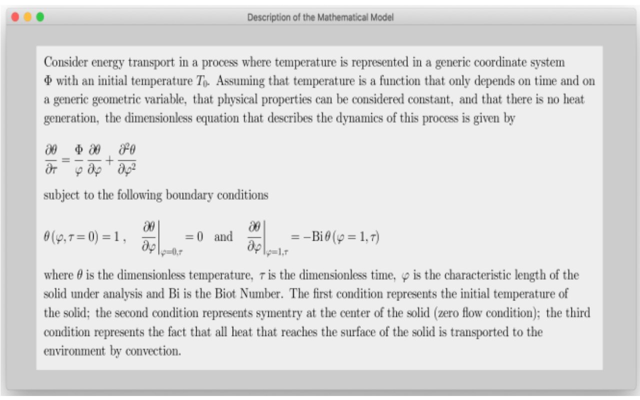


FIGURE 7. Mathematical description of the Gurney-Lurie problem.

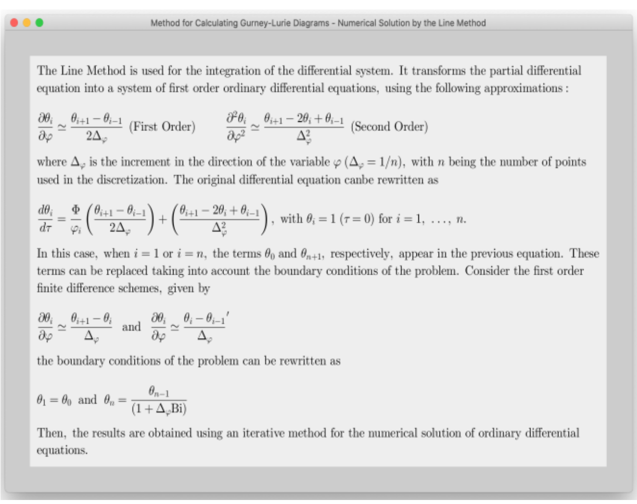
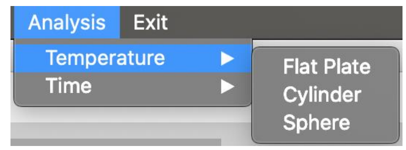


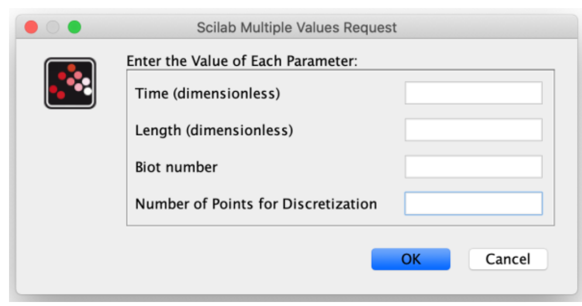
FIGURE 8. Methodology applied to solve the Gurney-Lurie problem.

Finally, the graphical interface also offers the possibility of analyzing Gurney-Lurie Charts for specific input data. This functionality may be very important during classes because, in many cases, printed Gurney-Lurie charts are used, where students make approximate visual inspections. This approach, although widely used, may not be adequate, as it favors possible errors of approximation in calculations in which the verified data are employed. In the proposed GUI it is possible to make an accurate analysis, in relation to specific data. To do this, in the menu bar, just click on *Analysis* and then select the type of analysis to be performed, which can be in relation to temperature or time, for each of the available geometries, as shown in Fig. 9.

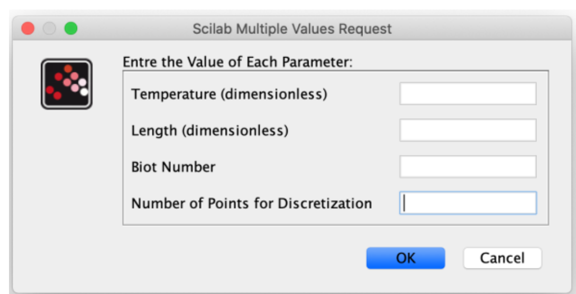


(a)

(b)



(c)



(d)

FIGURE 9. Options for analysis of (a) temperature and (b) time; Input parameters required for (c) temperature and (d) time analysis.

It is important to note that, in both GUIs proposed here, it is possible to use all the graphical tools available in Scilab, such as zoom, insertion and manipulation of data tips (which are boxes that show the exact value of the coordinates of a point belonging to a curve), modification of axes names and figure exportation. This favors an even more accurate analysis of the results.

V. RESULTS AND DISCUSSION

This section presents the results and discussions on both GUIs presented previously.

A. Heat Transfer in a Solid

Figure 10 shows an example simulation of the proposed GUI for the heat transfer problem in a solid, considering the parameters α = 100 W/(m^{2}K), ρ = 1000 kg/m^3, V = 1 m^3, C_p = 4.2 kJ/(kg K), A = 10 m^2, T_0 = 290 K, T_∞ = 500 K, t_∞ = 30 s and N = 100. Under such conditions, the process reaches the steady state condition, that is, the temperature gradient over time is equal to zero when $T = T_\infty$. If t_∞ is much less than 30 s, this condition cannot be seen on the temperature distribution curve presented. Taking into account the dynamics of a classroom, this GUI provides the possibility to perform successive simulations, with little programmatic effort, obtaining instant results and providing students different perspectives on the behavior of the problem and its results for several input parameters. This favors the understanding of the mathematical model and reinforces the behavior of the analytical solution.

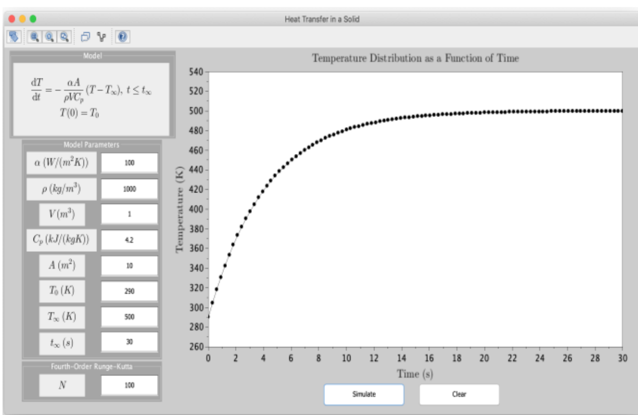


FIGURE 10. Typical execution of the heat transfer problem in a solid, showing the curve that describes the temperature distribution as a function of time.

Providing a comparative view on the behavior of the curve that describes temperature as a function of time when varying a given model parameter can be more convenient using the *Sensitivity Analysis* tool. Figure 11 presents the results of the sensitivity analysis of the model when the area of the solid varies, keeping the other parameters of the model fixed. In these results, the temperature profiles are shown when A = [10 20 30 40 50] (m^2). Using this tool, it is clear that the increase in the heat exchange area implies less time to obtain the steady state, that is, smaller areas imply smaller volumes of the solid, which is being heated or cooled. Physically, increasing the heat exchange area causes a decrease in convective resistance but, on the other hand, leads to an increase in conductive resistance. Concepts like these, when shown through examples and numerical simulations, can be more easily understood by students.

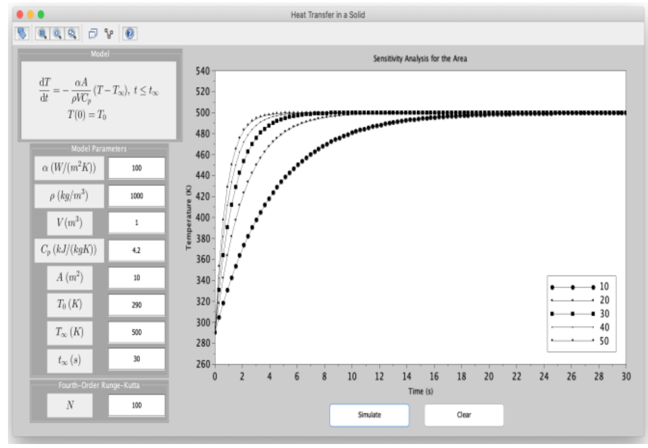


FIGURE 11. Results for the sensitivity analysis of the area considered in the model of the heat transfer problem in a solid.

B. Gurney-Lurie Charts

Gurney-Lurie Charts obtained from a typical simulation considering Bi = [0.1 0.2 0.5 1 2], τ_∞ = 10 and Φ = 0 are presented in Fig 12. Note that the colors of the curves, the types of markers and the legends are automatically inserted, which provides a clear reading of the results obtained. For this application, a fixed number of points for discretization (N = 100) is programmatically determined, in order to transform the original partial differential equation into a system of ordinary differential equations. When clicking on the *Simulate* button, the graphical interface also provides the possibility to perform the simulation with Bi → ∞, as can be seen in Fig. 12.

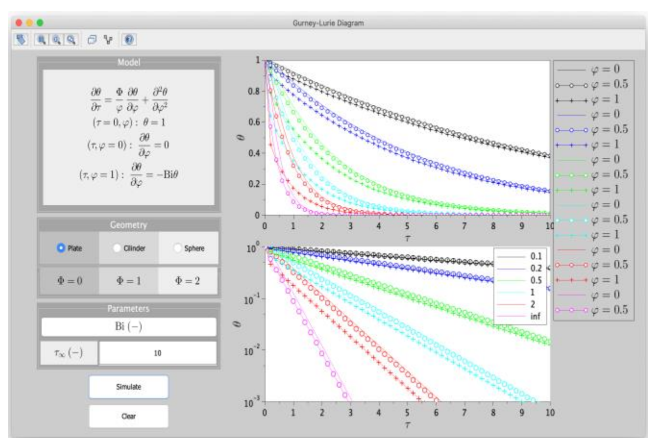


FIGURE 12. Typical graphic window for the Gurney-Lurie problem.

In both sets of results presented in Fig. 12, the temperature profiles considering the arithmetic and logarithmic scales for different values of the parameter referring to the Biot Number are presented. In general, as expected, the temperature profile is equal to 1 when τ is equal to zero. For these profiles, the steady state is not reached. In this case, the parameter τ_∞ should be increase.

If we look at transient problems of heat transfer in a dimensionless form, we have dimensionless temperature and time, in addition to the Biot Number. If we have a problem in which Bi is big enough, we also obtain a dimensionless position, since the spatial gradients do not disappear. One of the most practical reasons for making our results dimensionless is their generalization. Since the same dimensionless equation holds for many different systems, we can use the same dimensionless response for all of them. A particularly useful fact of this is that one can tabulate results from dimensionless solutions to transient problems.

Despite this, tabulated results restrict analyzes to the existing values and, in addition, do not favor the verification of the behavior of the results as a whole. Therefore, it is important to take account of the results more accurately, given arbitrary input parameters. In this context, Fig. 13 presents a specific simulation, performed using the *Sensitivity Analysis* tool shown in Fig. 9, for the system temperature in a flat plate, considering the other parameters defined with the values shown in Fig. 13.

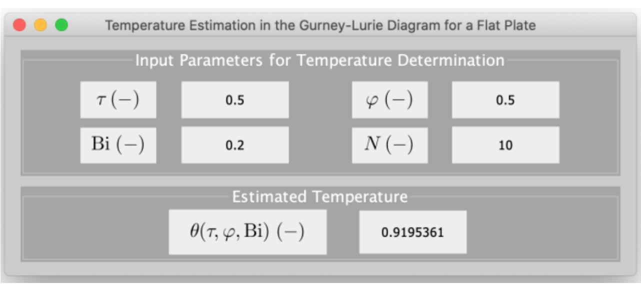


FIGURE 13. Graphical window for estimating the temperature of the Gurney-Lurie problem for a flat plate.

Indeed, the same analysis can be carried out over time, taking into account each of the geometries (flat plate, cylinder or sphere) of the problem.

VI. CONCLUSIONS

In this work, two graphical tools have been proposed, aiming to solve two heat transfer problems in undergraduate chemical engineering courses. The main steps of the proposed methodology are: *i*) describe the mathematical modeling of each case study; *ii*) present the GUIs considering each case study and a specific numerical methodology; *iii*) assess the sensitivity of the parameters inherent to the model and; *iv*) insert a description page to help understand each application.

From the proposed GUIs and the discussion presented, it is clear that the development of this type of platform helps teachers in relation to the physical analysis of chemical problems, especially considering the fact that the development of computational routines to simulate ordinary and partial differential equations is avoided. This graphical tool allows the simulation in a simplified way of mathematical models which are very common in undergraduate courses in chemical engineering, as well as the input of parameters and the generation of graphical results in a simplified way. As the aspects related to the implementation and the choice of numerical methodologies for each application are avoided, access to information becomes simplified. From the didactic point of view, it is highlighted that this tool can help teachers in the classroom, as more complicated case studies can be worked on without teacher and students having to worry about the methodologies used to solve these problems.

It is important to mention that, although the problems considered in this work are relatively simple, the main objective is the development of an interface that helps the user in understanding the chemical model, as well as in physical analysis. Thus, more sophisticated applications can be developed from this approach. In future works, we aim to explore other heat transfer models of interest in undergraduate and graduate courses in chemical engineering and related areas, such as: *i*) determining the critical radius in pipes; *ii*) the study of extended surface heat transfer and; *iii*) Laplace Equation (transient and three-dimensional), among others.

ACKNOWLEDGEMENTS

The authors are thankful for the financial support provided to the present research effort by CNPq, FAPEMIG, CAPES and FAPERJ. Gustavo Libotte is supported by a postdoctoral fellowship from the Institutional Training Program (PCI) of the Brazilian National Council for Scientific and Technological Development (CNPq), grant number 303185/2020-1, and Carlos Chagas Filho Foundation for Supporting Research in the State of Rio de Janeiro, grant number E-26/200.560/2018.

SOFTWARE AVAILABILITY

The source codes of the GUIs proposed in this work can be requested by contacting Dr. Fran Sérgio Lobato (fslobato@ufu.br).

REFERENCES

[1] Towler, G. and Sinnott, R., *Chemical Engineering Design*, Second Edition (Butterworth-Heinemann, Boston, 2013).

[2] Finlayson, B. A, *Introduction to Chemical Engineering Computing*, Second Edition (John Wiley & Sons, Hoboken, 2012).

[3] Duncan T. M. and Reimer, J. A., *Chemical Engineering Design and Analysis: An Introduction*, Second Edition (Cambridge University Press, Cambridge, UK, 2019).

[4] Cartaxo, S. J. M., Silvino, P. F.G. and Fernandes, F. A. N., *Transient Analysis of Shell-and-tube Heat Exchangers Using an Educational Software*, Education for Chemical Engineers **9**, e77-e84 (2014).

[5] Golman, B., *Transient Kinetic Analysis of Multipath Reactions: An Educational Module Using the IPython Software Package*, Education for Chemical Engineers **15**, 1-18 (2016).

[6] Skorzinski, E., Shacham, M. and Brauner, N., *A Simulation Program for Modelling Pollutant Dispersion for Educational Applications*, 19th European Symposium on Computer Aided Process Engineering, Computer Aided Chemical Engineering Series, Jacek Jezowski and Jan Thullie (Editors), Elsevier **26**, 1233-1238 (2009).

[7] Soares, R. P. and Secchi, A. R. *EMSO: A New Environment for Modelling, Simulation and Optimisation*, European Symposium on Computer Aided Process Engineering-13, Andrzej Kraslawski and Ilkka Turunen (Editors), Computer Aided Chemical Engineering Series, Elsevier **14**, 947-952 (2003).

[8] Edgar, T. F., Ogunnaike, B. A. and Muske, K. R., *A Global View of Graduate Process Control Education*, Computers & Chemical Engineering **30**, 1763-1774 Papers form Chemical Process Control VII, (2006).

[9] Bordeianu, C. C., Felea, D., Besliu, C., Jipa, Al., Grossu, I. V. *A New Version of Scilab Software Package for the Study of Dynamical Systems*, Computer Physics Communications **180**, 2398-2399 (2009).

[10] Domingues, L., Rocha, I., Dourado, F., Alves, M. and Ferreira, E. C., *Virtual Laboratories in (bio)Chemical Engineering Education*, Education for Chemical Engineers, **5**, e22-e27 (2010).

[11] Komulainen, T. M., Enemark-Rasmussen, R., Sin, G., Fletcher, J. P. and Cameron, D.", *Experiences on Dynamic Simulation Software in Chemical Engineering Education*, Education for Chemical Engineers **7**, e153-e162 (2012).

[12] Rahman, N. A., Hussain, M. A., Jahim, J. M., Kamaruddin, S. K., Abdullah, S. R. S. and Kamaruddin, M. Z. F., *Integrating Computer Applications Into Undergraduate Courses: Process Control and Utility Design*, Education for Chemical Engineers **8**, e45-e57 (2013).

[13] Llanos, J., Perez, A. and Lucas-Consuegra, A., *Enhancing the Teaching of Corrosion to Chemical-Engineering Students through Laboratory Experiments*, Journal of Chemical Education **96**, 1029-1032 (2019).

[14] Depcik, C. and Assanis, D. N., *Graphical User Interfaces in an Engineering Educational Environment*, *Computer Applications in Engineering Education* **13**, 48-59 (2005).

[15] Wilson, L. D. and Marcotte, R. E., *Graphical Interface for the Study of Gas-Phase Reaction Kinetics: Cyclopentene Vapor Pyrolysis*, Journal of Chemical Education **78**, 799 (2001).

[16] Tsai, C. W., *Visualization of Fuel Rod Burnup Analysis by Scilab*, Nuclear Engineering and Design **265**, 341-347 (2013).

[17] Kaddouri, A., Blais, S., Ghribi, M. and Akhrif, O. *NLSOFT: An Interactive Graphical Software for Designing Nonlinear Controllers*, Mathematics and Computers in Simulation **71**, 377-384 (2006).

[18] Andreatos, A. S. and Zagorianos, A. D., *Matlab GUI Application for Teaching Control Systems*, World Scientific and Engineering Academy and Society (WSEAS), Proceedings of the 6th WSEAS International Conference on Engineering Education of the 6th WSEAS International Conference on Engineering Education, 208-211, Rodos Island, Greece, (2009).

[19] Magyar, Z. and Zakova, K., *SciLab Based Remote Control of Experiments*, IFAC Proceedings Volumes, **45**, 206-211, 9th IFAC Symposium Advances in Control Education, (2012).

[20] Vieira, E. B., Busch, W. F., Prata, D. M. and Santos, L. S., *Application of Scilab/Xcos for Process Control Applied to Chemical Engineering Educational Projects*, Computer Applications in Engineering Education **27**, 154-165 (2019).

[21] He, S. and Li P., *A MATLAB Based Graphical User Interface (GUI) for Quickly Producing Widely Used Hydrogeochemical Diagrams*, Geochemistry, 125550, (2019).

[22] Molina, R., Orcajo, G. and Martinez, F. *KBR (Kinetics in Batch Reactors): a MATLAB-based Application with a Friendly Graphical User Interface for Chemical Kinetic Model Simulation and Parameter Estimation*, Education for Chemical Engineers **28**, 80-89 (2019).

[23] Souza-Santos, M. L., *Analytical and Approximate Methods in Transport Phenomena*, First Edition (CRC Press, Mechanical Engineering Series, Boca Raton, 2007).

[24] Gurney, H. P. and Lurie, J., *Charts for Estimating Temperature Distributions in Heating or Cooling Solid Shapes*, Industrial & Engineering Chemistry **15**, 1170-1172 (1923).

[25] Pandharipande, S. L. and Badhe, Y., *Artificial Neural Networks for Gurney-Lurie and Heisler Charts*, Journal of the Institution of Engineers (India): Chemical Engineering Division **84**, 65-70 (2004).

[26] Schiesser, W. E., *The Numerical Method of Lines: Integration of Partial Differential Equations*, First Edition, (Academic Press, San Diego, 1991).