Contents lists available at ScienceDirect

Education for Chemical Engineers

journal homepage: www.elsevier.com/locate/ece

Transient analysis of shell-and-tube heat exchangers using an educational software

*Samuel J.M. Cartaxo, Pedro F.G. Silvino, Fabiano A.N. Fernandes**

Universidade Federal do Ceara, Departamento de Engenharia Química, Campus do Pici, Bloco 709, 60455-760 Fortaleza, CE, Brazil

ABSTRACT

Computer-aided design has become extremely popular and its use in classroom can be very helpful, adding more analysis capabilities to all engineering areas. A free piece of educational software to teach transient analyses of shell-and-tube heat exchanger equipment to undergraduate students is presented. The software was developed to provide unit operation courses with realistic exercises involving dynamic simulation of chemical processes. The use of the program improves the efficiency of the course since it let students practice heat exchanger analysis while relieving them of tedious repetitive calculations.

Keywords: Heat exchanger; Unit operations; Education; Software; Simulation

1. Introduction

Computer-aided design and analysis has leveraged a major shift in the way chemical engineering has been taught in recent years. Any modern and competitive engineering curricula cannot afford the absence of computer/software related courses, just because their students and future engineers would have difficulties to adapt or to match the current professional market demands.

The benefits of using computer-aided tools to improve the learning process of engineering students are broadly recognized. Although the market for process engineering simulators is supplied by a number of vendors, such as Hysys, Pro/II, CHEMCAD, COMSOL, ASPEN Plus, HTRI, HTFS, THERM and CCTherm (Selbaş et al., 2006); such packages are meant for the professional with full understanding of process equipment and are not well suited for didactical purposes when the understanding of the phenomena influencing an equipment functionality is intended.

Shell-and-tube is the most used type of heat exchangers in chemical industries. It consists of a bundle of pipes or tubes enclosed within a cylindrical shell. One fluid flows through the tubes and a second fluid flows within the space between the tubes and the shell. They can operate at high pressures, and their construction facilitates disassembly for periodic maintenance and cleaning (Selbaş et al., 2006; Butterworth, 1987; Cartaxo and Fernandes, 2009; Castier and Amer, 2011). Although the concept is simple, there are a large number of phenomena associated with flow and heat transfer that results in a system that is difficult to master without making in numerous calculations (Dı′az et al., 2001).

Shell-and-tube heat exchangers requires the knowledge and calculation of complicated heat and fluid flow geometries, turbulence in the flow, existence of hydrodynamic and thermal entrance regions, non-uniform local heat transfer rates and fluid temperatures, secondary flow in the tube bends, vortices in the neighborhood of the tube-fin junctions, heat conduction along tube walls, natural convection within the tubes, and temperature dependence of fluid properties. Even steady-state predictions are not easily made from a first principle analysis, therefore dynamic predictions are, of course, harder.

A number of education professionals have found their own pedagogical solutions for teaching heat exchanger design as an analysis. To fill the gap left by third-party packages and commercial vendors, instructors around the world have

* *Corresponding author*. Tel.: +55 85 33669611; fax: +55 8533669610.
E-mail addresses: fabiano@ufc.br, efftech@gmail.com (F.A.N. Fernandes).
Received 2 August 2013; Received in revised form 27 March 2014; Accepted 6 May 2014
http://dx.doi.org/10.1016/j.ece.2014.05.001

developed customized computational applications to fulfill their educational needs (Lona et al., 2000; Ali Kara and Güraras, 2004; Fernandes and Rodrigues, 2004; Cartaxo and Fernandes, 2009; Fernandes and Cartaxo, 2010; Martín and Mato, 2008). Most available software were developed aiming mechanical and thermal engineering after the steady-state operation was reached. Additionally, few software aims toward chemical engineering problems.

Dynamic studies are important to study control strategies, study cooling performance and also to program changes in temperature that may be required by chemical reactors. Many studies depicting several scenarios are reported in the literature showing the importance of dynamic studies in the engineer's life. Control problems and scenarios have been reported by Yan et al. (2014). Shen et al. (2014) and Beier (2014) have studied the cooling performance of heat exchangers using dynamic changes. Dynamic studies can also be used to develop control strategies for reducing the energy consumption (Diaz-Mendez et al., 2014; Ibrahim et al., 2014). The importance of developing heat exchange programming for reactors was presented by Fu and Xu (2013) and Henini et al. (2013).

This work presents a non-commercial educational software developed to introduce the transient study of heat exchanger equipments (shell and tube heat exchangers, from 1–1 to 1–4 flows configurations) to undergraduate students. Special care was taken in the design of the software interface to allow the students to concentrate their efforts in learning how to analyze the transient behavior of shell-and-tube heat exchangers and not in learning how to use the program. Several exercises and also stand alone simulations can be performed with the software, so the students can have a permanent tool to be used when needed.

The development of the program started in 2009 and since then the program has been tested in undergrad courses on heat exchangers and simulation of our university. The program has also been available through the Internet during most of this time. The information gathered from this experience has been used to optimize the capabilities and interface of the program. *DHXA* is distributed without charges on the web page www.deq.ufc.br and it can be installed by the students on their personal computers.

2. Learn through doing concept

The philosophy used to develop the software is the "learning through doing", where the exercises are presented in a way to involve the student in the assignment. The software was developed to be complementary to the teaching of the fundamentals and mathematical methods of the technical phenomena. The software is used to stress the engineering practice, not only the textbook design procedure, so that students do not have the wrong idea that an isolated analysis is complete. They need a perspective that the practice is much more than the fundamentals.

Showing some applications examples, the graduate will enter engineering with an awareness of how fundamentals can be connected to practice, and there will be less of a tendency to resort to pure empiricism. Furthermore, this will build an awareness of the complexity and scope of engineering practice, and will combat any impression that the isolated and simplified school day's design is sufficient (Rhinehart, 1991).

Specifically for the case of teaching heat exchangers, the example applications are to be carefully planned. Although, in practical terms, the operation and control of these equipments are relatively simple, their analysis and design is complex due to the large amount of equations that needs to be solved and due to the iterative nature of the solving technique (Cartaxo and Fernandes, 2009). The design of shell-and-tube heat exchangers including thermodynamic and fluid dynamic design, cost estimation and optimization represents a rather complex engineering task involving a variety of design rules, judgment considerations, calculating methods and empirical knowledge of various fields.

Some industrial cases were reviewed and common examples were transformed into exercises to be used with the software (Shreve and Austin, 1984; Kirk et al., 1992). The exercises present the problem that should be solved, where the equipment is placed inside the process and asks for the student to find a solution for that particular problem. The exercises bring several concepts into the student's attention, such as: industrial applications of the heat exchangers, influence of major design parameters, influence of the operating conditions and environmental concerns. The student can feel themselves as an engineer making the course more interesting than the ones in which the student only solves exercises without having an idea about the process they are working with.

The *DHXA* software was built to be a pathway to understand the heat exchanger dynamic behavior. We have focused on the overall comprehension of the cause–effect relation governing the equipment operation. Details about the design method, the numerical solution scheme and other important concepts are considered a prerequisite at this time, and in our university it is ministered in the unit operations course.

3. Software

The software code was implemented in Delphi v7 and is available for PC's running Windows system (XP or higher). The use of Delphi v7 allowed the software to be fully visual and avoided any kind of link with external DLLs that could require installing third party software. A set-up was built for easy installation of the software that can be run in any PC.

The software was divided into modules comprising the typical workflow of analyzing a heat exchanger, i.e., input the project parameters, equipment specification, equipment operation and the transient analysis.

The simulator built in the software implements a solver for the numerical solution of the mathematical model. The mathematical model is comprised essentially by a set of partial differential equations, combined with some constitutive relations for estimation of physical properties, heat transfer coefficients, among others model parameters. Several design options can be assessed and modified by the user, such as the number of passes in the tubes, number of tubes, internal and external tube diameter, shell diameter, tube length, tube pitch, pitch type (squared or triangular), baffle spacing, and allocation of the cold and hot fluids (shell or tube side).

While the software allows the student to quickly run several test cases to gain insight about sensitive parameters in the design process, it does not do the entire job. The student should learn how to read standard tables like IPS or BWG pipe specifications to input the required pipe dimensions into the software (Kern, 2001). This approach enhances the learning

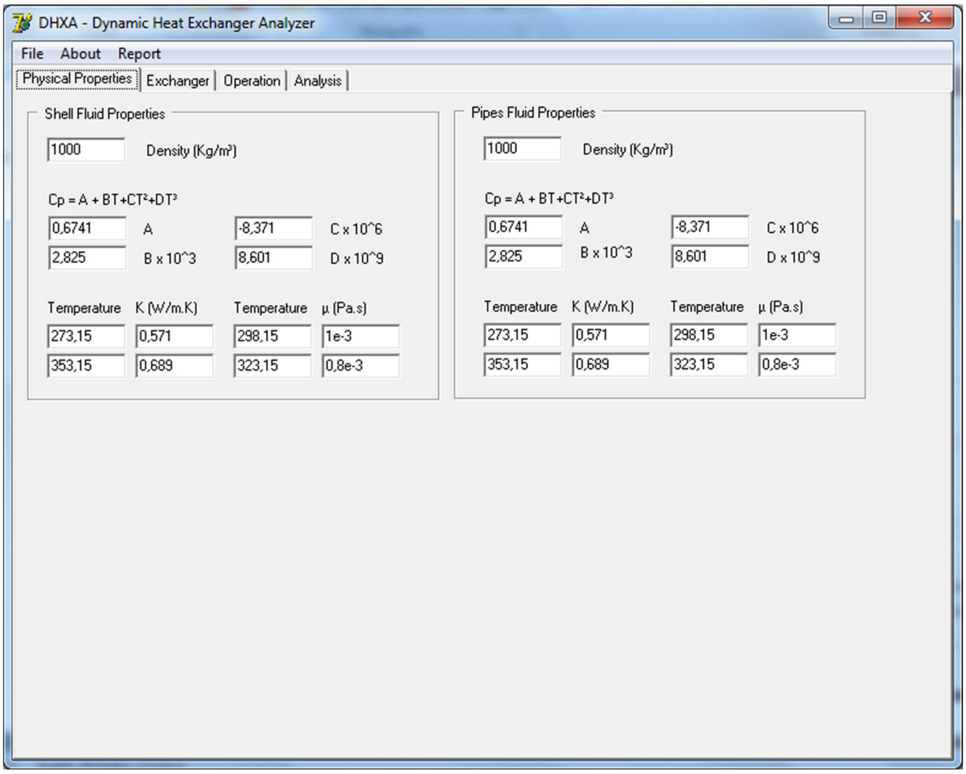

Fig. 1 – Input screen for physical–chemical properties of the shell-side and tube-side fluids.

process, because the students will not use the software like a "black box" and become aware of the procedures performed underneath the thermal design or analysis of heat exchanger equipment.

Fig. 1 presents the main screen for setting the physical properties of shell and tubes fluid streams. Students are able to learn the practical importance of the physical properties by experimenting with this module. In general terms, physical properties of the substances have a direct significance on the behavior of the physical system. This assertion is invariably true for heat exchanger devices. It is desirable that the students develop a "feeling" about this impact on the operating conditions of a certain piece of equipment. They should recognize which are the more relevant variables, the ones that have greater sensitivity in the model calculations.

The student is compelled to look for the fluid properties (density, heat capacity, thermal conductivity, and viscosity) to use the software. The option not to have a built in physical properties data bank was purely didactical so the student has to search the literature before using the software. In the process, the student will be learning where to find the needed data when necessary. The students are enforced to search through tables, treat the physical data and obtain the physical properties equation parameters that fit the data at the temperature range they will be working with. Consequently, a marginal didactic benefit to the learning process is that the student faces the fact that sometimes the available data are not presented in the form they need and some adaptations should be made.

Nowadays, the availability of physical properties sources is huge. Aside of the traditional sources like classical text books, there are a number of online ones, some of them for free and other for a subscription price. Additionally, a conscious educator cannot close their eyes to the so-called "non-scientific" sources, just because they already are in widespread use by our students; a remarkable example is Wikipedia. The use of such "open source" resources cannot be practically prevented and, for that reason, cannot be ignored and the students should be advised accordingly. Especially for the professionals certified from the last decade on, those engineers who spent their academic times using Google, Wikipedia and so forth, they believe for sure that much of the information from these sources is dependable for preliminary engineering calculations, however some confirmation is needed, just because a non insignificant part of that information is potentially misleading.

Viscosity and specific heat are more sensible to temperature changes and require proper evaluation. Depending on the temperature range of the fluid streams, the calculation of viscosity and calorific capacities may introduce a significant variation during the solution of the differential equations. Thus, students should learn that these properties are correlated through temperature functions in the simulation algorithm, and what mathematical relation is appropriate for each property. For example, the specific heat is well represented by a fourth degree polynomial for a large temperature range. On the other hand, because of its greater sensitivity, viscosity is more adequately correlated by a logarithmic-inverse or logarithmic-polynomial function of absolute temperature. With this background, the students are encouraged to fit their own numerical coefficients for the properties correlations. Through experimenting with these values, they are able to develop engineering insight about physical properties sensitivity and relative relevance.

Several equations have been proposed in the literature (books and articles) for the changes in viscosity as a function of temperature and pressure; and sometimes we have limited amount of equation parameters for a given fluid. During the development of the project we decided that the student should look for some physical and chemical properties of the fluids (also to learn how to look for these information). Thus, a linear behavior for viscosity was implemented in the software. Although the results will not be too accurate, it is possible

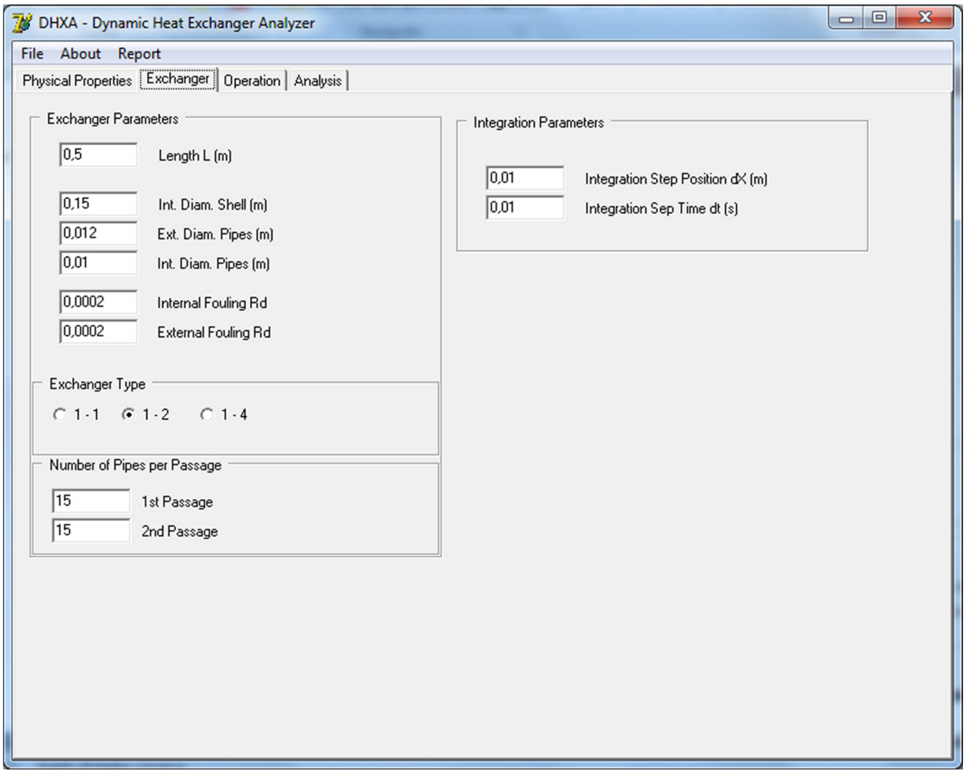

Fig. 2 – Module for definition of heat exchanger geometric design and other parameters for the mathematical model solver.

to get good simulation results using this formula, especially because the temperature changes during simulations will not be too large.

After setting up the proper fluids and their properties, the student needs to specify the geometric and design features of the studied heat exchanger. The students interact with the software through the dialogs presented in Fig. 2, where they define the length and internal diameter of the exchanger shell, the internal and external diameters of tubes in the bundle and fouling factor for hot and cold sides.

The heat exchanger design module allows exploring creatively the dynamic operation of three types of heat exchanger: 1–1, 1–2 and 1–4 fluid passages, where the first figure refers to the number of fluid passes on the shell-side, while the last one regards the passes count on the tube-side of the bundle. Increasing the tube passes requires the specification of the quantity of tubes contained in each one. This setting is directly related to the bundle internal cross section, to the fluid velocity and, consequently, to the tube-side heat transfer coefficient. Such design–parameter–performance relations are strongly reinforced through the exercises in this software module.

The selection of the fluid tube passes automatically reconfigures the software screen for the proper tube-count input. No provision is made for defining this specification, so the student is expected to be able to gather the information from reference sources. The same is true for the internal/external diameters for heat transfer tubes in the bundle. They should go through codes and standards, e.g. TEMA, API, ASME, among others, as a preview of their engineering practice. For example, the number o tubes that can be practically put inside a shell of certain internal diameter, with defined tube pitch, was standardized by TEMA and is available in most text books.

One of the most important design decisions the student should learn how to make is the allocation of the fluid in the heat exchanger. At this time, the engineer has to specify which fluid goes through the shell or tube bundle side. Usually, the recommended allocation is the one that evens the pressure drop as most as possible on both sides. However, when corrosion effects are critical issue, they are to be taken into account also with the proper priority.

Generally, aside the pressure drop issue, the fluid allocation may have a direct impact on the exchanger heat transfer area, which relates proportionally to the equipment cost. This is especially true if there is a controlling fluid involved. Since the heat transfer coefficient of the controlling fluid is going to dictate the overall coefficient, the allocation favoring a greater heat transfer coefficient for this fluid corresponds most probably to a more efficient design.

With *DHXA* software, fluid allocation analysis is simple and fast, thus the assigned exercises encourage the students to think critically about which fluid allocation gives a better design. They may effortlessly experiment with different design options and evaluate the impact of their decisions on key equipment characteristics like heat transfer coefficients, heat transfer area, or effective fouling coefficient.

The operation module screen is presented in Fig. 3. In this module, the student has to deal with both input and output data regarding the actual operation of the equipment. For example, the flow rates and entrance temperatures for the cold and hot fluids should be assigned. As in a real process situation, when an exchanger goes online, the process engineer does not know for sure what output temperatures it will perform, he/she just take a seat and observes. This is essentially what the students are supposed to do in this module, i.e., they discover the outcome of their design decisions.

Several thermal variables are available for monitoring the ongoing simulation. While the exchanger transient differential equations are solved, the software allows direct monitoring of the exit temperature of both fluids and their temperature range between inlet and outlet nozzles. Additionally, the current heat load can be seen in “real-time”. These are

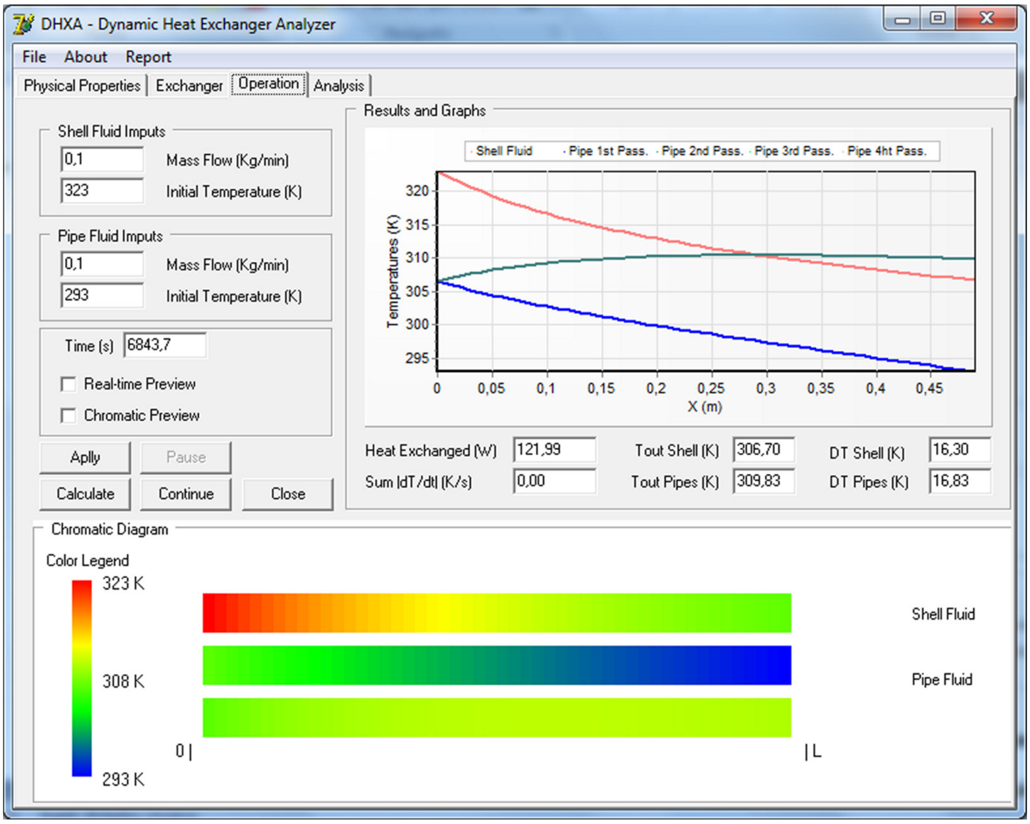

Fig. 3 – Operational module of the heat exchanger simulator.

important information, because they empower the students to make decisions during the equipment startup time, what mimics a real-life process situation that may require critical and quick decisions, such as opening or closing valves in order to adjust flow rates, shutdown the exchanger to do ventilation or other corrective procedures.

Most heat exchanger design software (commercial or academic) focuses on providing the final results, which, when dealing with heat exchanger, usually means to calculate the required area and consequent pressure drop. Differently, *DHXA* was designed to take a heat exchanger configuration and its operating conditions as input and evaluate its behavior along the service time. When solving a problem with the software, the student is going to find the final steady-state temperature conditions for the equipment; however also it is possible to access all the intermediary local temperature profiles developed inside the heat exchanger.

The ability to know the internal temperature profile over time is critical for the students' absorption of an important concept regarding a heat exchanger operation: steady output variables (i.e. temperatures) do not assure the equipment reached steady-state as a whole. Usually, in the industry, the process engineer assesses the exchanger closeness to steady-state by measuring some output process variable, such as a fluid temperature.

Since solely the variation of output fluid temperatures in time does hold as a fully reliable criterion, it is necessary to devise a more general measure that indicates when the exchanger reaches their steady operating conditions and the simulation can be stopped. While there are many possible ways to define a stop condition, the *DHXA* software presents continually the summation of the absolute values of the time derivative of temperature at every point the differential equation is being solved. Additionally, this module also interfaces current values in each time-step for the exit temperatures and temperature ranges of both fluids. With this global and local exit temperature information in their hands, students are pointed to analyze critically the concept of transient and steady-state operation in the specific context of a heat exchanger.

In synthesis, this exercise module encourages the students to take advantage of the full access allowed to several intermediate variables values, such as heat transfer coefficients on both sides, global heat transfer coefficients at any position and on both terminals, and internal temperature profiles, varying both in position and time. If the student knows what happens with such important values (e.g., a heat transfer coefficient) after changing an input parameter, they acquire insight about the design method and the equipment operation, which are invaluable knowledge resources at field practice. This is expected to enhance their ability of mentally predict cause–effect relations regarding the heat exchanger operation.

4. Transient analysis module

The transient analysis module is presented in the screen of Fig. 4. At this module, the students have access to how the heat exchanger system responds dynamically throughout the time of operation. The equipment dynamics during startup may be observed from the initial condition until the steady-state is reached or the student is instructed to create hypothetical process perturbations, such as variations on the inlet flow rates and temperatures.

The exercises in this module are designed to explore the output data available through several charts. Furthermore

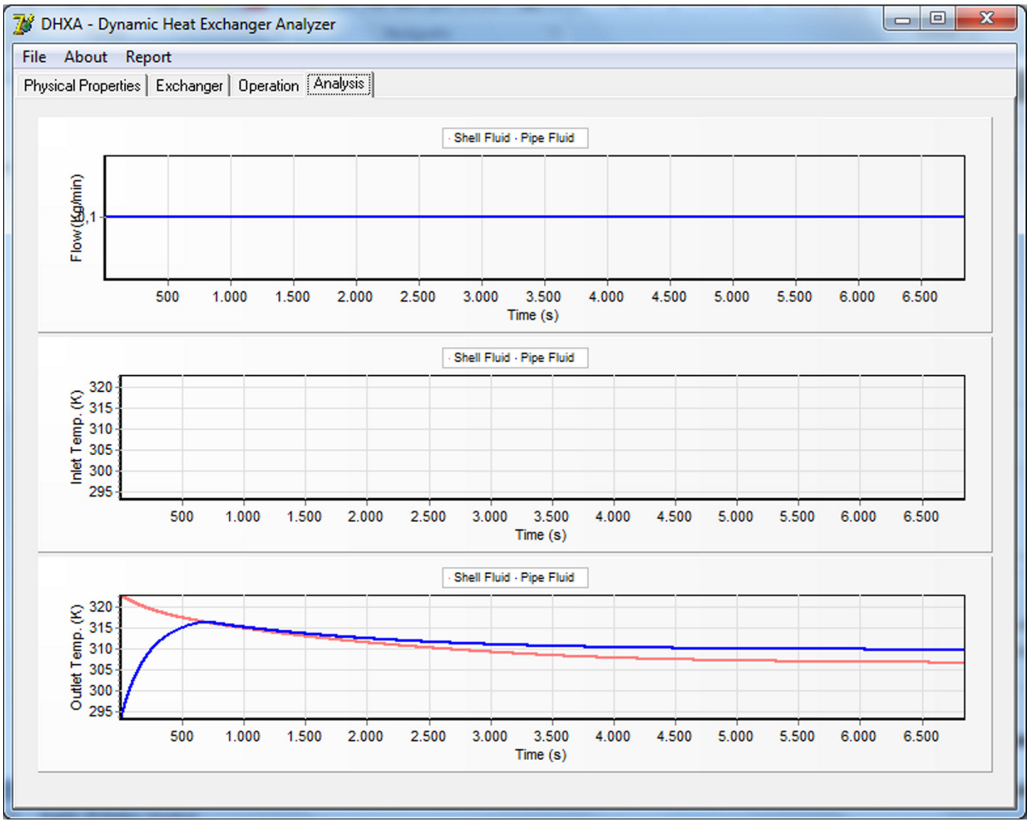

Fig. 4 – Time transient analysis module of the simulator.

a selection of input variables, such as inlet flow rates and temperatures for both fluid streams, is presented with the purpose to facilitate the operation analysis and promote the students' engineering insight. Showing input and output variables aligned second by second, the students are able to compare directly the equipments' response to changes made in the process variables affecting the exchanger performance, for example, by modifying the input temperature for, say, the hot fluid, they can observe how long it takes for the cold fluid to sense this input perturbation. Important concepts like "response time" or "time lag" are explored with these software features, which would be hard to convey by using conventional educational tools and methods (Lachi et al., 1997; Huang et al., 2007; Guellal and Abdesselam, 2009).

Another type of exercises using the functionality herein the transient analyses module aims the compensation of a temperature change in a process stream by modifying a service stream property. In a typical case-study, the students are asked to consider a process situation where a product of a crude oil distillation column is cooled using regular cooling water before being pumped to the storage park. Assume the exchanger is initially running in steady-state and suddenly the crude cut increases its temperature by, say, 10 °C in a step change. Since the maximum storage temperature limit still holds, playing the process engineer, the student has the job of deciding what process property of the cooling water should be modified to offset the perturbation from the distillation column. The most plausible options are the flow rate and inlet temperature of the cooling water, however running a number of trials conditions for the cooling water stream, the students may find that the flow rate or temperature adjustment provides a more immediate correction. Such "change-response" sensibility analysis of the heat exchanger might turn to be the preparation basis for designing a controller strategy, subject matter regularly dealt with in subsequent courses of a chemical engineering undergraduate program.

Most of the exercises that can be formulated and that would use the software are open-ended. There is not a single possible answer, however there are wrong answers for the exercises. Usually a final objective should be reached. How the student will meet this objective is up to the student, since there are many options in the software that can be changed for the student to choose. The professor must point out which kind of possibilities exists and how these possibilities will influence the process, but it should be left for the student to decide which solution they will want to implement. The student will learn more trying several options to solve the problem using the software as a learning tool and learning with his/her successes and errors.

The assessment of the students work is not an easy task when an open-ended problem is given. Of course the professor can give grades based simply on if the objective of the problem has been met, or the professor can give grades based on how the student has met the objective that was proposed. A suggestion is to divide the class in groups and make a competition of which group can come up with the best plan to solve the objective, considering the time that takes to reach the goal (faster or slower pathway towards the objective) and safety concerns that should be taken.

5. Student feedback

The software was used with 8th semester chemical engineering students during two semesters (in 2012 and 2013) on a "Modeling and Simulation" course at Universidade Federal do Ceará (Fortaleza – Brazil). All students had previous knowledge on heat exchangers, but not on the transient behavior of heat exchangers. The pedagogical effectiveness of the

Table 1 – Survey results for assessing the pedagogical methodology and use of the software.

	Questions	Negative	Neutral	Positive
1	I acquired significant new knowledge from the extra activities developed in the course.	4%	12%	84%
2	The practical activity has increased my interest in the disciplines involved.	6%	16%	78%
3	I could use my previous knowledge acquired in undergraduate studies.	3%	7%	90%
4	I believe that this activity fits into the scope of the professional profile of a chemical engineer.	1%	6%	93%
5	The activity was more interesting and motivating than the usual assessment methods (exams) used in the course.	3%	15%	82%
6	I consider very interesting the use of active learning problems in the course.	1%	9%	90%
7	Group work influenced the development of the activities.	6%	25%	69%
8	The activity allowed the discovery of tools (software, content, etc.) that would not be done by other means.	10%	19%	70%

methodology and the software was evaluated by means of a feedback survey. The survey involved a group of 67 students that have used the software in class, being 55% male and 45% female.

Privacy is a common student's concern when responding to surveys regarding pedagogical methods, because they usually assume that their answers may affect negatively their grades. So, to promote the engagement of the students, no identification data was requested from the respondents and appropriate care was taken during the questionnaire application.

The survey was implemented using an inquiry form with questions regarding the student own perspective about the software. Each response was quantified by a psychometric Likert scale containing five levels, ranging from "strongly disagree" to "strongly agree". They were asked to indicate their degree of accordance with a proposed statement. With the aim of evaluating the crude impression of the students about the methodology, the responses were processed into three levels, namely "Positive", "Neutral" and "Negative".

The results have indicated an overall satisfaction in regard to the didactical approach. Table 1 presents the survey marks. The feedback of the students was highly positive for the majority of the questions. A fraction of 84% of the students considered that the methodology promoted knowledge acquisition that could not be attained with customary instructive methods. The alignment of the activities with the content of the other disciplines may be inferred by question 3 (Table 1), where 90% reported positively that previous knowledge was an important factor for their performance. The personal motivation perceived by the students was verified with question 5, where 82% of the students answered affirmatively to the use of this "learn through doing" approach in classes.

6. Conclusions

In this article, we have presented an educational software developed to teach dynamic design and rating of shell-and-tube heat exchangers. The software provides an attractive way to introduce chemical engineering students to the analysis of thermal processes and its simulation; and is designed with a user-friendly Windows interface. The software can be used as a didactical tool in complement to theoretical classes or alone as a self study tool. The use of this kind of software can improve technical knowledge and develops a critical analysis in the students. Not only, but it makes the learning activity and classes more exciting and productive once the students get in touch with close to real engineering activity.

References

Ali Kara, Y., Güraras, Ö., 2004. A computer program for designing of shell-and-tube heat exchangers. Appl. Therm. Eng. 24, 1797–1805.

Beier, R.A., 2014. Transient heat transfer in a U-tube borehole heat exchanger. Appl. Therm. Eng. 62, 256–266.

Butterworth, D., 1987. Changes in heat exchangers for process applications: incentives and barriers. Heat Transfer Eng. 8, 19–22.

Cartaxo, S.J.M., Fernandes, F.A.N., 2009. Educational software for heat exchanger equipment. Comput. Appl. Eng. Educ. 18, 193–199.

Castier, M., Amer, M.M., 2011. XSEOS: an evolving tool for teaching chemical engineering thermodynamics. Educ. Chem. Eng. 6, e62–e70.

Dı′az, G., Sen, M., Yang, K., McClain, R.L., 2001. Dynamic prediction and control of heat exchangers using artificial neural networks. Int. J. Heat Mass Transfer 44, 1671–1679.

Diaz-Mendez, S.E., Patiño-Carachure, C., Herrera-Castillo, J.A., 2014. Reducing the energy consumption of an earth-air heat exchanger with a PID control system. Energy Convers. Manage. 77, 1–6.

Fernandes, F.A.N., Cartaxo, S.J.M., 2010. An object-oriented graphics interface simulator for analysis of Fischer-Tropsch synthesis. Chem. Prod. Process Model. 5 (1.).

Fernandes, F.A.N., Rodrigues, S., 2004. Educational software for gas–solid and liquid–solid separation equipment. Comput. Appl. Eng. Educ. 11, 226–232.

Fu, J., Xu, Q., 2013. Simultaneous study on energy consumption and emission generation for an ethylene plant under different start-up strategies. Comput. Chem. Eng. 56, 68–79.

Guellal, M., Abdesselam, H., 2009. Empirical correlation for the time lag of double pipe heat exchanger operating with variable flow rates. Energy Convers. Manage. 50, 970–976.

Henini, G., Souahi, F., Laidani, Y., 2013. Development of a simulation model for controlling and improving the productivity of batch reactors. Pol. J. Chem. Technol. 15, 78–87.

Huang, C.-J., Chu, S.-S., Guan, C.-T., 2007. Implementation and performance evaluation of parameter improvement mechanisms for intelligent e-learning systems. Comput. Educ. 49, 597–614.

Ibrahim, O., Fardoun, F., Younes, R., Louahlia-Gualous, H., 2014. Air source heat pump water heater: dynamic modeling, optimal energy management and mini-tubes condensers. Energy 64, 1102–1116.

Lachi, M., El Wakil, N., Padet, J., 1997. The time constant of double pipe and one pass shell-and-tube heat exchangers in the case of varying fluid flow rates. Int. J. Heat Mass Transfer 40, 2067–2079.

Lona, L.M.F., Fernandes, F.A.N., Roque, M.C., Rodrigues, S., 2000. Computers & chemical engineering developing an educational software for heat exchangers and heat exchanger networks projects. Comput. Chem. Eng. 24, 1247–1251.

Kern, D.Q., 2001. Process Heat Transfer. McGraw-Hill, New York.

Kirk, R.E., Othmer, D.F., Kroschwitz, J.I., Howe-Grant, M., 1992. Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, New York.
Martín, A., Mato, F.A., 2008. Hint: an educational software for heat exchanger network design with the pinch method. Educ. Chem. Eng. 3, e6–e14.
Rhinehart, R.R., 1991. Improve the quality of chemical engineering education. Chem. Eng. Prog. 87, 67–70.
Selbaş, R., Kızılkan, Ö., Reppich, M., 2006. A new design approach for shell-and-tube heat exchangers using genetic algorithms from economic point of view. Chem. Eng. Process. Process Intens. 45, 268–275.
Shen, L., Chen, H., Xiao, F., Yang, Y., Wang, S., 2014. The step-change cooling performance of miniature thermoelectric module for pulse laser. Energy Convers. Manage. 80, 39–45.
Shreve, R.N., Austin, G.T., 1984. Shreve's Chemical Process Industries. McGraw Hill Professional, New York.
Yan, S., Wang, P., Wan, J., Fang, H., Luo, R., Zhao, F., 2014. Control strategy research and controllers design of the China lead alloy cooled reactor. Prog. Nucl. Energy 71, 258–268.