Web-Based Instructional Tools for Heat and Mass Transfer

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Abstract

This paper demonstrates four web-based instructional tools for heat and mass transfer based on JAVA applets. These tools are closely related to topics in two chemical engineering courses: transport phenomena and chemical reactor design. They simulate four classic problems which are one dimensional unsteady mass diffusion, one dimensional unsteady-state heat conduction in slabs, cylinders and spheres, Heisler charts for unsteady state heat transfer, and reaction and diffusion in porous catalytic substrates. They provide students with a dynamic observation of heat and mass transfer process unavailable in traditional textbooks. Educators and instructors can use these tools to enhance students understanding of the concepts of heat and mass transfer.

Introduction

As many efforts are being applied to the introduction of the World Wide Web (WWW) in the chemical engineering curriculum, WWW shows a growing significance in the engineering classroom, especially with the advent of web-based instructional tools. These web-based instructional tools are JAVA applet programs that are run by the JAVA Virtual Machine that is integrated in the web browser. However, web-based instructional tools for fundamental chemical engineering courses such as heat and mass transport are seldom found online.

Since the Java language and Virtual Machine have sufficient mathematical capability for mathematical simulations of mass and heat transfer, it is reasonable to develop web-based instructional tools to simulate classic problems from these fields. With the aid of these web-based instructional tools, students can capture the basic principles of these transport processes by observing dynamic phenomena that are often difficult to explain in textbooks. Observing these processes gives students valuable insight into heat and mass transfer concepts. Furthermore, the interactive nature of these web-based instructional tools may improve the motivation of students, which could be a significant factor in achieving student success.

This paper will describe four JAVA applets developed for simulation of basic heat and

mass transfer processes. These applets are a part of "Web Instructional Tools for Engineering," a one year project funded by the Michigan Space Grant Consortium. These four JAVA applets were to be developed with two goals in mind: to be visual enough to enable students to capture transport concepts, and to be interactive to keep the students' interest.

Description of JAVA applets

1. One dimensional unsteady mass diffusion

Introduction

Mass transfer is a crucial issue in the transport and unit operations course. Students are expected to learn the concept that mass transfer is due to a difference in concentration between two points. They also need to understand what a diffusion coefficient is and how it affects the process of mass diffusion.

In order to achieve these goals, a simple mass diffusion experiment, a solute diffusing through a stagnant fluid, is simulated in this applet. Diffusion of solutes in a stagnant fluid occurs in many industrial processes. One unique application of this mechanism is the manufacture of single crystal semiconductor materials with the design objective of optimizing the distribution of dopant molecules in a crystal. Often, fundamental experiments are performed in the microgravity environment of space [1]. Therefore, it is a very good example to demonstrate the mass diffusion concept.

Model description

As figure 1 shows, the concentration is initially zero at $x<L/2$, and is equal to C_0 at $x>=L/2$.
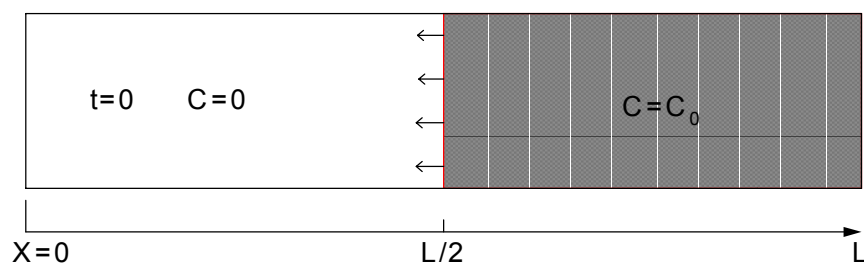
Figure 1.   Schematic of a microgravity semiconductor dopant diffusion experiment

With increasing time, the solute will diffuse from the right side to the left side of the tube. This unsteady mass diffusion process can be described by the following one dimensional mathematical model [1],

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

(1)

The initial and boundary conditions are

at $t = 0$, $x < L/2$, $C = 0$ (2)

at $t = 0$, $x >= L/2$, $C = C_0$ (3)

at $t = t$, $x = 0$ and $x = L$, $\frac{\partial C}{\partial x} = 0$ (4)

Graphical User Interface (GUI) of the applet

As mentioned above, a web-based instructional tool should keep the student's interest and allow for them to visualize the mass transfer process. To build an effective web-based instructional tool, the GUI of the applet must be designed to be user friendly.

As figure 2 shows, the GUI of the applet can be divided into three areas: display, parameter input, and control. The display area is the main area of the interface where the simulation of the mass diffusion process and the concentration profile are displayed. Therefore, this area occupies the most space.

Parameter input is at the right side of the display area. Several key parameters for mass diffusion such as diffusion coefficient and tube length are listed here. The control area is at the bottom of the interface which is separated from the other two areas by a yellow bar. In order to keep the control unit as simple as possible, there are only three buttons in the control area: start, stop, and pause/resume. These three sections are organized in such a way as a game-like environment. With such a design, students can easily run the applet, even without reading instructions.

Functions and features of the applet

This applet leads the student through the exploration of short-time, unbounded diffusion and long-time diffusive processes with a no-flux condition. The student inputs a set of parameters and presses the "Start" button. The button activates a graphic simulation of mass diffusion in the tube. The clock at the top of the display area displays the simulated time elapsed. Under the clock, a contour plot and graph of the concentration profile are shown.

This dynamic animation illustrates the nature of the mass diffusion process in the tube. Watching this animation is just like watching a real mass diffusion experiment. This can greatly aid student understanding of the basic principles of mass diffusion.
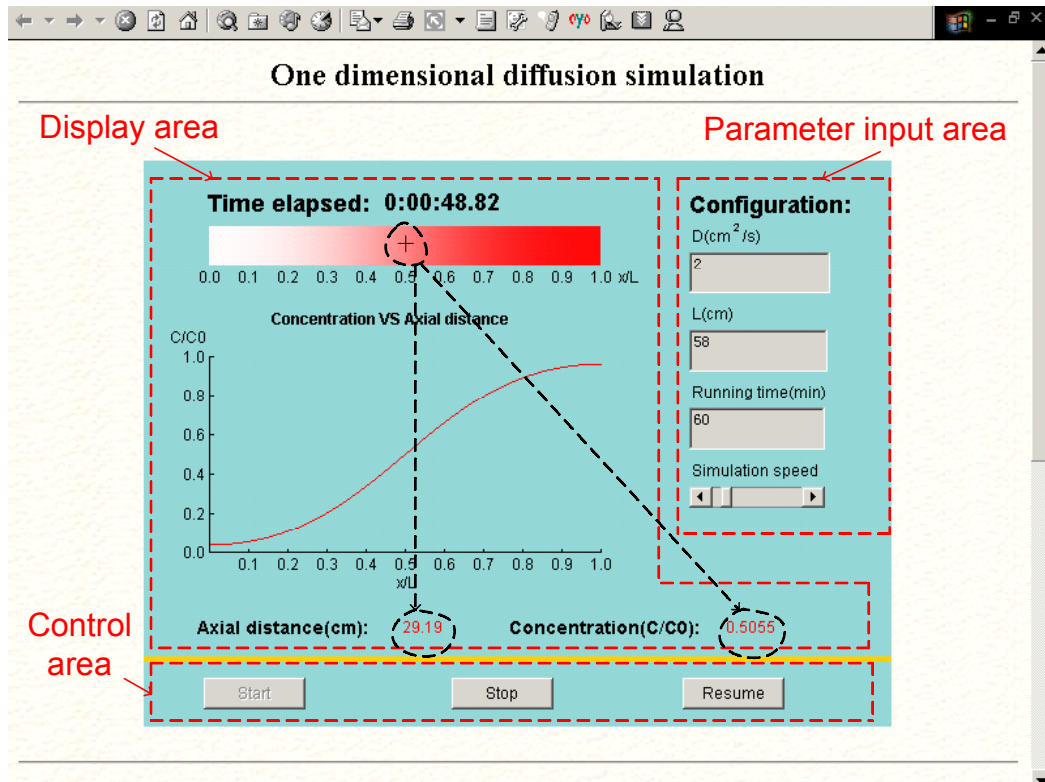
Figure 2. Screenshot of the JAVA applet for one dimensional mass diffusion

To visualize the mass diffusion process, the color in the tube represents the concentration of solute at that position. In the JAVA language, a specific color can be expressed by three integer values for red, green and blue (R, G, B) which range between 0 and 255. In this applet, red (R=255, G=0, B=0) represents the initial concentration C_0, and white (R=255, G=255, B=255) represents zero. The color for any concentration C between C_0 and 0 is calculated by the following equations.

$$R = 255 \quad \text{and} \quad G = B = 255\left(1 - \frac{C}{C_o}\right) \tag{5}$$

One key feature is that this applet allows the student to specify the diffusion coefficient and the tube length. This interactive feature not only keeps the student's interest when he/she is running this applet, but also allows the student to find out how these parameters affect the mass diffusion process.

Another useful feature is that this applet allows the mass diffusion process to pause at any time. As figure 2 shows, the student can obtain the x and concentration values of every position in the tube simply by moving the cursor in the color bar during the pause status.

Another welcome feature is that this applet allows the student to adjust the speed of

simulation. This can significantly reduce the time for completing simulations in such instances as the student wants to run a long time simulation to estimate the time to reach steady-state or run a simulation in which the solute diffuses in a fluid with a very small diffusion coefficient.

2. One dimensional unsteady-state heat conduction in slabs, cylinders and spheres

Introduction
Heat conduction is another key concept in transport phenomena because of the larger number of heating and cooling problems occurring in industrial processes. Unsteady state heat conduction in various geometries is the classic example for demonstration of the heat conduction concept. However, students must refer to cumbersome charts to estimate local temperatures without visualizing the process. The second JAVA applet will dynamically simulate the heat conduction in slabs, cylinders and spheres,

Model description for unsteady-state conduction in a large flat plate [2]

As figure 3 shows, unsteady state heat conduction occurs in a large flat plate of thickness 2L in the x direction and having infinite dimensions in the y and z direction. The plate with original uniform temperature T_0 is exposed to an environment at temperature T_1 at time t=0. Heat conduction occurs only in the x direction.
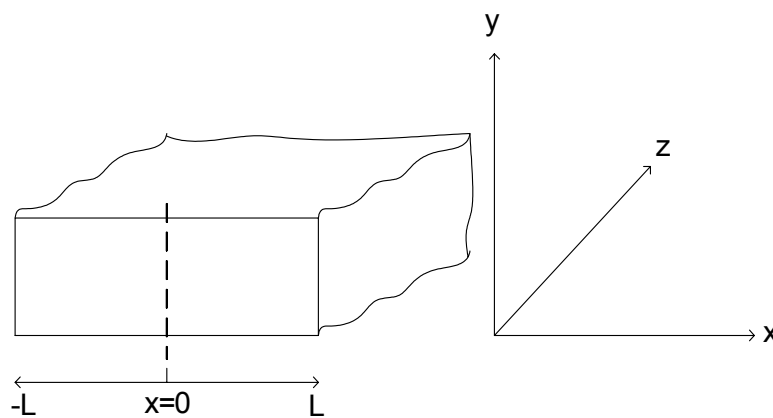
Figure 3. Schematic of unsteady-state conduction in a large flat plate

The mathematical model to describe this heat conduction problem is

$$\rho C_P \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$
(6)

with boundary and initial conditions that:

$$\text{at} \quad t = 0, \qquad T = T_0$$
(7)

$$\text{at} \quad x = 0, \qquad \frac{\partial T}{\partial x} = 0 \qquad\qquad (8)$$

$$\text{at} \quad x = \pm L, \qquad h(T - T_1) = -k \frac{\partial T}{\partial x} \qquad\qquad (9)$$

Similar models are developed for a long cylinder and for a sphere [2].

Graphical User Interface (GUI) of the applet

As figure 4 shows, this applet has a similar GUI design as the mass transfer applet. Everything is put onto one screen to make this applet as easy as possible to understand and run. Although this applet simulates heat conduction in three geometries, the same GUI is used for three geometries except some changes of the labels.
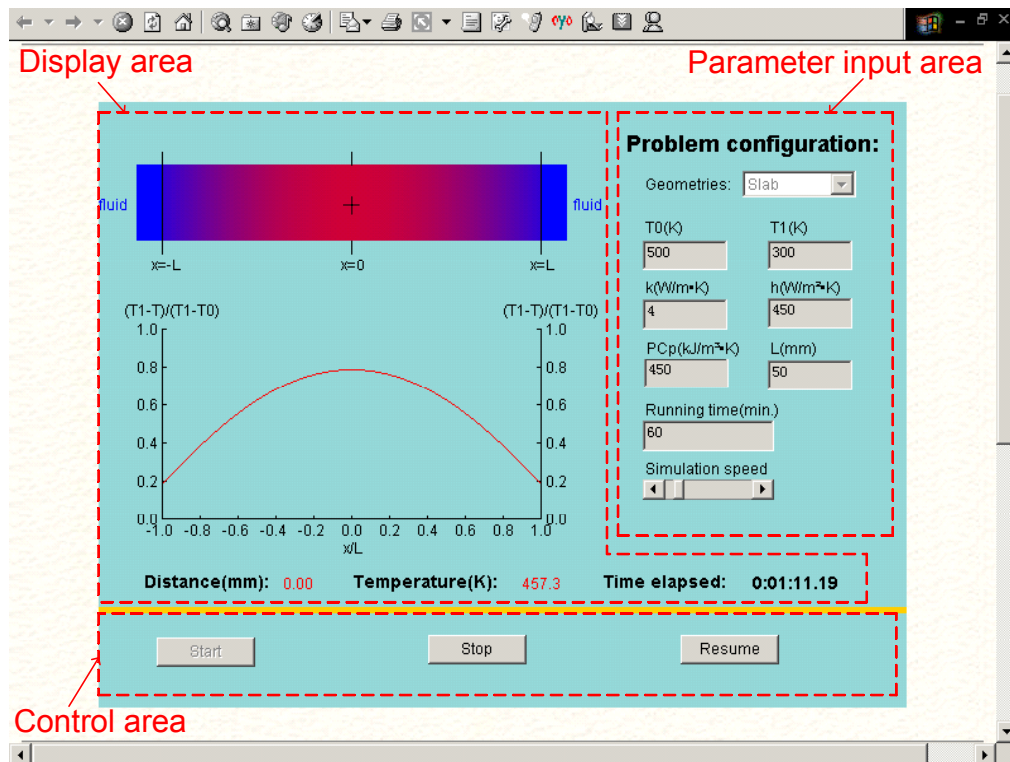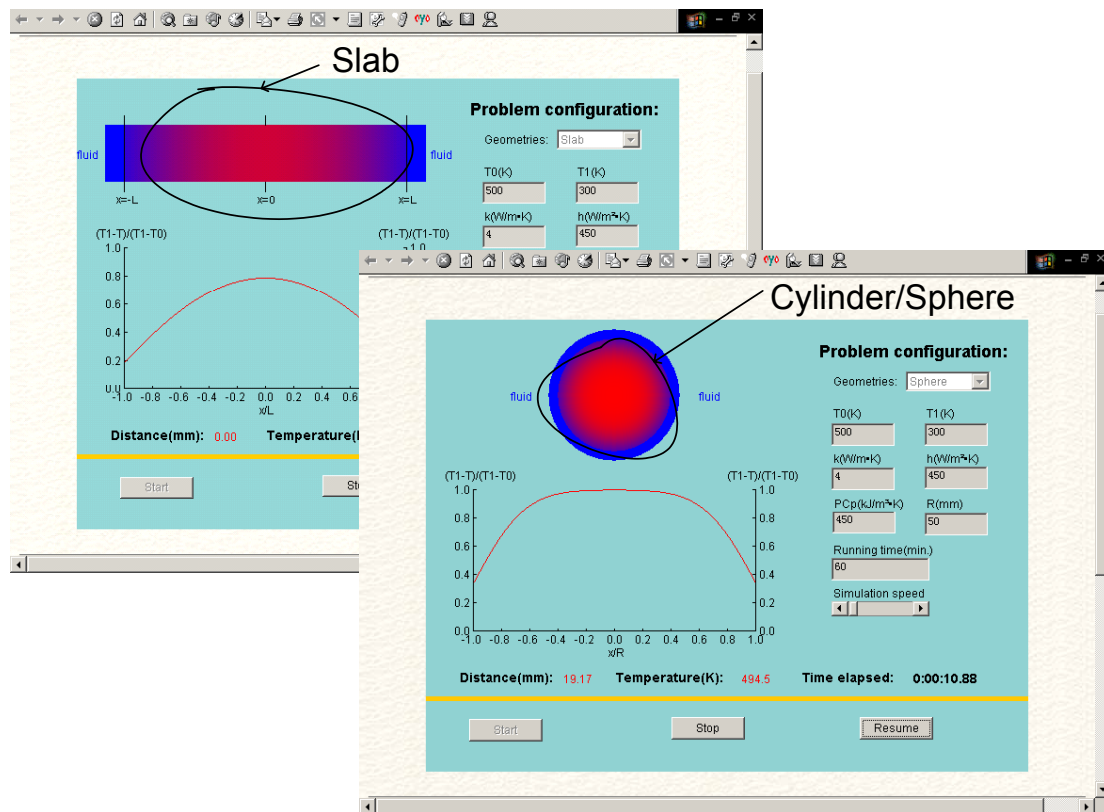

Figure 4. Screenshot of the heat conduction JAVA applet

Functions and features of the applet

This applet is a collection of three similar heat conduction models: heat conduction in slabs, cylinders, and spheres. The simulations for these models together help students grasp the principles of heat conduction.

The student first chooses the geometry where heat conduction occurs. The geometry

is set as a slab by default. As figure 5 shows, a colored bar represents the cross section of slab, and a colored circle represents the cross section of a cylinder or a sphere. The student enters a set of initial conditions and parameters and presses the "Start" button to initiate the simulation. Later, the student can press the "Pause" button to pause the simulation or the "Stop" button to stop the simulation.

Figure 5. Screenshot of the heat conduction JAVA applet

The different colors represent different temperatures. T_0 and T_1 are respectively the initial solid temperature and the fluid temperature. To keep consistency, red always represents the higher temperature between T_0 and T_1, and blue (R=0, G=0, B=255) always represents the lower temperature. Therefore, there are two instances for the color representing any temperature T between T_0 and T_1.

$$\text{if } T_0 > T_1, \quad R = 255 \times \frac{T_1 - T}{T_1 - T_0}, \quad G = 0 \text{ and } B = 255 \times (1 - \frac{T_1 - T}{T_1 - T_0}) \qquad (10)$$

$$\text{if } T_0 < T_1, \quad R = 255 \times (1 - \frac{T_1 - T}{T_1 - T_0}), \quad G = 0 \text{ and } B = 255 \times \frac{T_1 - T}{T_1 - T_0} \qquad (11)$$

In addition to visualizing the heat conduction process using color, a temperature profile is shown simultaneously during the simulation to strengthen the visual effect of the simulation of the heat conduction process.

The input parameter interface allows the student to input different heat transfer coefficients, thermal conductivities and heat capacities. The student can learn how these parameters affect the heat conduction through the comparison of the different simulation results. For example, the student can verify when internal resistance is negligible (Bi=hL/k < 0.1) with this applet.

Another feature mentioned in the previous applet is that this applet also allows the student to suspend the simulation and move the cursor in the color bar or circle to find out the temperature at any position in the solid at the elapsed time.

3. Heisler charts for unsteady state heat transfer [2]

Introduction

Analytical solutions are available for the above three heat conduction models. Therefore a chart for determining the temperatures at any position in the solid and at any time can be constructed for a convenient reference to practical applications. Although such charts can be found in textbooks, an online implementation is easier to use due to the unprecedented popularity of WWW and the power of JAVA to determine the exact coordinates on the graph. This applet implements the charts for slabs, cylinders, and spheres.

Graphical User Interface (GUI) of the applet

As figure 6 shows, the GUI of this applet is a TV-like design with a big screen at the left side and a small control panel at the right side. The screen occupies almost 70% of the interface area. On the control panel, there is a list of geometry choices, which the student can use to choose the channel he/she wants to look: slab, cylinder, or sphere. There are also such control buttons on the control panel. Two are for adjustment of the key parameters m (a ratio of conduction to convection) and n (a dimensionless distance). The other four buttons adjust the position of graph.

Functions and features of the applet

This online chart is very easy to use. Unlike the charts in the textbook that show many lines simultaneously, this chart shows only one line at one time. This gives the student a clear look and allows the student to determine the value quickly.
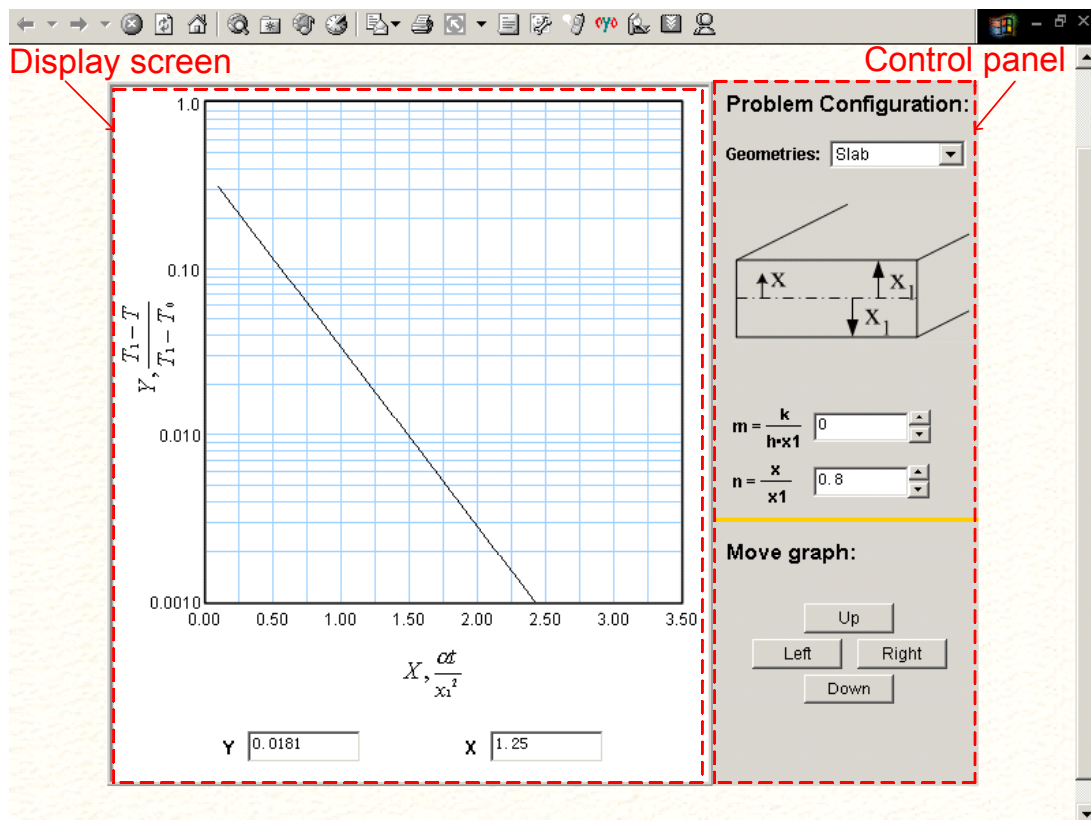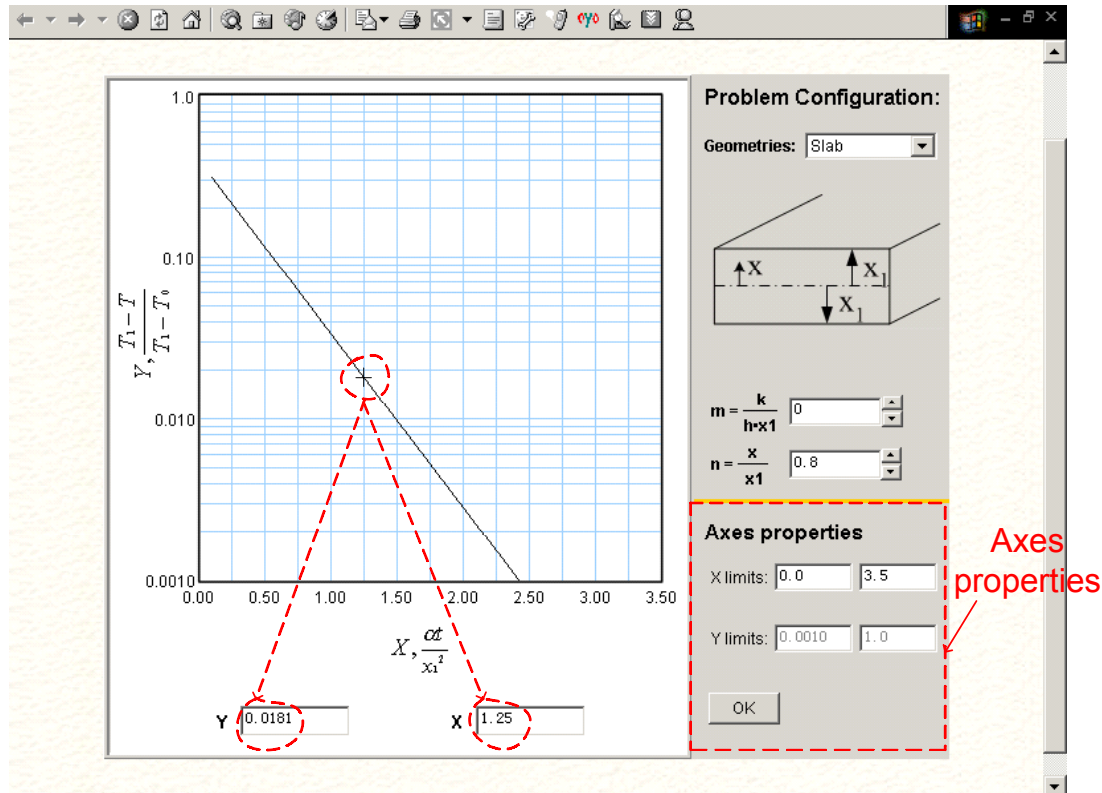
Figure 6. Screenshot of JAVA applet for the Heisler charts

Originally, the geometry is set as a slab by default. The parameters m and n are set as 0.0 and 0.8, respectively. The student can use the control panel to make his/her own choice. For the parameters m and n, the student can input directly the desired value in the text field or increase/decrease the value by pressing the buttons.

This applet allows the student to move the graph by press the "Up", "Down", "Left", and "Right" buttons. As figure 7 shows, double clicking the chart calls an axes properties dialog box. This allows the student to zoom in and out the graph.

One nice feature is that the student can obtain the values of the dimensionless time, X and the dimensionless time, Y from the "X" and "Y" text field simply by moving the cursor to the desired position on the line (shown in figure 7). This applet also can be used as a calculator. A relative value of X can be obtained by input of a value in the "Y" text field and pressing "Enter" and vice versa. This gives the student a quicker and more precise way to determine the dimensionless temperature or concentration than by using the charts in the textbook.

Figure 7. Screenshot of the JAVA applet for Heisler charts

4. Reaction and diffusion in porous catalytic substrates [3]

Introduction

Reaction and diffusion in porous catalytic substrates are demonstrated in transport and reactor design courses. Although analytical solution for catalysts with simple geometries such as slabs, cylinders and spheres are shown in textbooks, a graphical solution is more suitable to illustrate the reaction and the diffusion in catalysts. This is achieved by this JAVA applet.

*Graphical User Interface (GUI) of the applet*

As figure 8 shows, this applet has the same TV-like GUI as the previous applet. The difference is that there are buttons to choose the concentration profile within the catalyst pellet or the effectiveness factor plot as a function of the Thiele modulus.

Functions and features of the applet

This applet can show the concentration profile and the effectiveness factor plot. The student chooses the geometry and enters the values of the following parameters: the diffusion coefficient D, the first order reaction rate constant k and the characteristic length R of the catalyst pellet. Pressing the "Concentration profile" button illustrates

the concentration profile in the catalyst pellet.

On the concentration profile screen, the student can obtain the concentration at every position in the catalyst pellet by moving the cursor on the concentration profile (shown in figure 8). The student also can directly get the concentration value simply by input of the position value in the "r" text field and pressing "Enter" and vice versa.
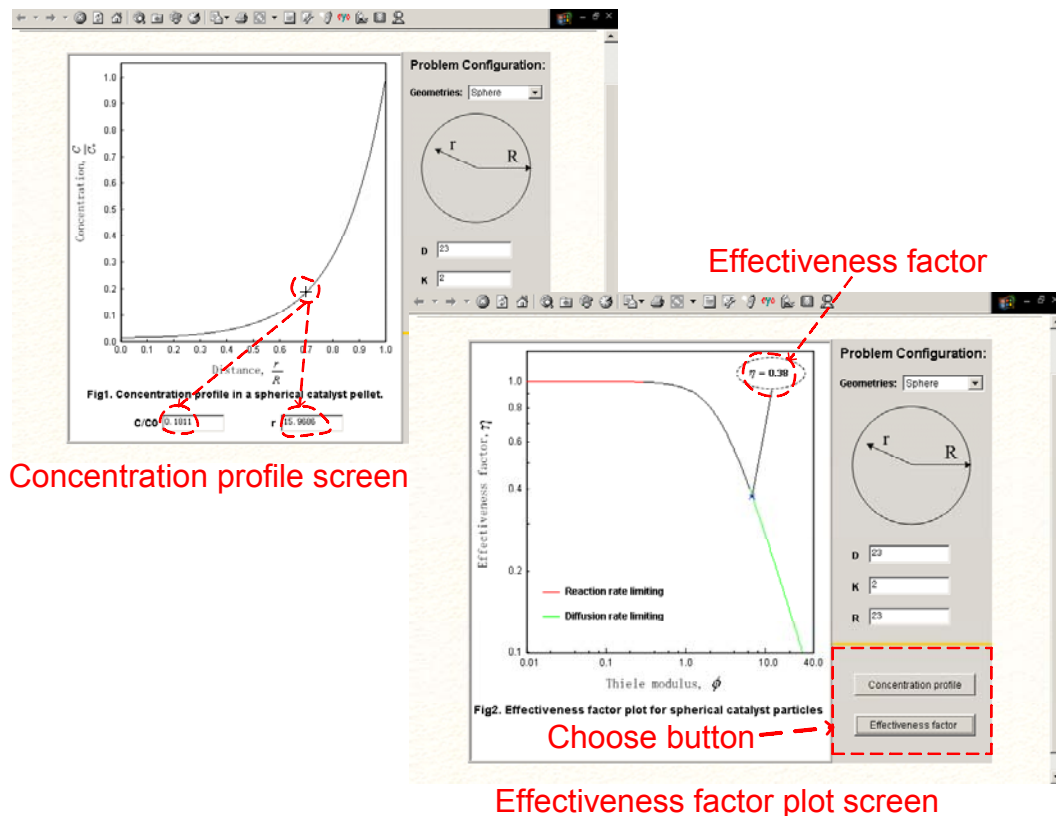
Figure 8. Screenshot of the JAVA applet for diffusion and reaction in porous catalysts

When the student presses the "Effectiveness factor" button, the screen changes to the effectiveness factor plot. On this screen, the applet shows the effectiveness factor plot and points out the value of the effectiveness factor for this specific instance (shown in figure 8). The effectiveness factor plot uses a red color to indicate the reaction rate limiting area and a green color to indicate the diffusion rate limiting area. Therefore, the student can learn to which limiting area this instance belongs, and understand how diffusion and reaction rate affect the reaction within porous catalysts.

Impact on learning

The web based tools create possibilities for students to learn effectively. Felder [4] gives a good review of four learning style models (Myers-Briggs Type Indicator, Kolb's Learning Style Model, Hermann Brain Dominance Instrument, and the Felder-Silverman Learning Style Model). Kolb's Learning Style Model says that

learning includes four processes, which are: concrete experience, reflective observation, abstract conceptualization, and active experimentation [5]. The ideal teaching would include all the four processes. For example, to illustrate the concept of heat conduction, the instructor begins with a heat conduction experiment. Next, the instructor reflects on this experiment, explaining the meaning, and then applies the meaning into abstract mathematical equations. Finally, the instructor gives students homework with similar problems. Additional information about the Kolb model is available in the literature [6-8].

Unfortunately, the instructor usually cannot perform suitable heat conduction experiments in the classroom. Showing data may be useful but not as effective as a computer-based applet that the students can relate to. The web based tools developed here permit the instructor to show real heat transfer processes in the classroom. This will greatly enhance two of Kolb's learning processes: concrete experience and reflective observation. Furthermore, students can explore more problems through the simulation of the web based tools after class. This allows students to explore the concept of heat conduction through active experimentation. Therefore, the web based tools improve learning by provide the possibility for students to make use of all the four learning processes.

The web-based tools are being used by J. Keith as auxiliary teaching tools in CM3120: Transport / Unit Operations 2, during the Spring 2003 semester at Michigan Technological University. This course focuses on the fundamentals of heat and mass transfer. Several demonstrations and homework assignments, using these web-based tools, will be applied during the course. To illustrate the potential use of these tools, an example that has been already used will now be described.

Example Problem: Cooking a Slab of Meat

In this exercise, students were asked to solve the following problem "cooking a slab of meat" using the Heisler charts in the textbook, the web-based java applet "One dimensional unsteady-state heat conduction in slabs, cylinders and spheres", and the web-based java applet "Heisler charts for unsteady state heat transfer". The problem is modified from number 5.3-5 from the 3rd Edition of Geankoplis' textbook [2].

> A slab of meat 25.4 mm thick originally at a uniform temperature of 10 ^{o}C is to be cooked from both sides until the center reaches 121 ^{o}C in an oven at 177 ^{o}C. The convection coefficient can be assumed constant at 25.6 W/m^{2}K. Neglect any latent heat changes. The thermal conductivity is 0.69 W/mK and the thermal diffusivity is 5.85 x 10^{-4} m^2/h.
> a) Calculate the time t_{cook} required to reach 121 ^{o}C
> b) Calculate the surface temperature of the meat at time t_{cook}

The results obtained from the two web-based java applets are very close to the results

obtained from the charts in the textbook. Both java applets provide the student with a quicker and easier way to solve the problem than using the charts in the textbook. The java applet "One dimensional unsteady-state heat conduction in slabs, cylinders and spheres" also offers the visualization of the heat conduction in meat. This characteristic allows the student to understand the diffusive motion of the heat in the media. Both the java applets allow the student to change the convection coefficient, thermal conductivities and heat capacities, and quickly see what effect these changes have on the system. The student benefits from this characteristic to quickly explore the relationships between these parameters and the heat conduction process without having to do lengthy calculations. Therefore, the two java applets enhance the student understanding the concept of the heat conduction.

To measure the effectiveness of using the java applets, students are also required on their homework to write a statement about the utility of the java applets. The students seemed to genuinely enjoy using the java applets. When using the java applets, students felt more motivated to simulate some different problems by changing the parameters. Student also found the java applets to be very useful in understanding the concept of the heat conduction. Shown below are quotes from the students:

- "The conduction web tool is neat to watch. You can actually see how different convection coefficients, thermal conductivities, and thermal diffusivities affect the temperature at the different points in your object. It is easier to learn these things by visualizing the effects and not just starting at the equations. They are excellent teaching aids".

- "The animation gives the user a good idea of how the heat conduction takes place, changing from blue to red as the object heats up. These tools are very easy to use and provide the added element of visualization. You can't get that in a book."

- "If this were my applet that I designed I would get it patented immediately for it is useful. Hopefully it will remain on the web while I am at my co-op so I can demonstrate it's simplicity and accuracy with minimal time."

Conclusions

This paper demonstrates four web-based instructional tools for heat and mass transfer that are based on JAVA applets. These web-based instructional tools closely relate to instruction topics in transport phenomena and reactor design courses. They can be accessed for free at the web address: http://www.chem.mtu.edu/~jmkeith/webtools. Educators and instructors can use these web-based tools in the classroom to instruct students and enhance their understanding. They were first used in the spring semester of 2003 at Michigan Technological University, and student feedback has been extremely positive.

Acknowledgements

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