User-friendly simulator for an educational fin heat transfer module

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ABSTRACT. This work presents a user-friendly simulator of an educational module of heat transfer in fins, widely used in undergraduate courses. Simulator was developed in DELPHI, an object-oriented computer language. Data are entered through an interactive window and the results are presented as graphs. The simulator also includes an equation database to evaluate physical properties and thermal model parameters. Simulation results obtained by this simulator are similar to experimental measures.

Key words: fins, user-friendly interface, educational module, simulation.

RESUMO. Desenvolvimento de um simulador com interface amigável de um módulo didático de transferência de calor em aletas. Neste trabalho, foi implementado um simulador com interface amigável de um módulo didático clássico de transferência de calor em aletas, utilizado em várias instituições de ensino superior. O simulador foi desenvolvido em linguagem orientada a objetos DELPHI e apresenta um formulário de entrada de dados interativo em uma janela, enquanto o resultado da simulação é visualizado na forma gráfica. O simulador possui um banco de correlações de literatura para a estimação das propriedades físicas e dos parâmetros térmicos do modelo.

Palavras-chave: aletas, interface amigável, módulo educacional, simulação.

Fins are widely used in industry to increase thermal exchange between a solid surface and a surrounding fluid, that occurs simultaneously by conduction and convection. Due to their characteristics and easy construction, fins are also widely used in educational modules in undergraduate courses, as an aid to the comprehension of thermal phenomena. Crosby (1961) has published one of the earliest works describing such equipment. This module was composed of three metal rods (two made of stainless steel and one of aluminum), partially contained in thermally isolated chamber, with a steam inlet and a condensate outlet. As soon as the steam enters the chamber, heat is transferred to the inner part of the fin, while in the outer part, in direct contact with the external environment, heat propagation by conduction and thermal dissipation by natural convection occur (Figures 1 and 2).

A similar module is used in the Course Chemical Engineering Laboratory I at the Maringá State University. Experiments consist of supervision of the thermal behavior of the fin as from steam admission until the system reaches a steady state. After this, the students compare the obtained measurements with the estimations of some classical models of heat transfer in fins. As a matter of course, students just register the temperature evolution in fixed positions along the rod to verify the attainment of the steady state; it is only after a complete assay that the steady state data, i.e. the temperature profiles, are obtained and can be visualized. These limitations may be minimized by the use of computational user-friendly simulators to visualize instantly the influences of the rod dimension, used material, operational conditions etc., over thermal transients and achieved steady states. Consequently, planning the required experimental procedures is improved.

Such simulator was developed and implemented in Personal Computers using object-oriented DELPHI language. The simulator initially presents the user an interactive data entry form in a window; simulation results are graphically presented, including transients and steady state, in another window.

Comparison between this simulator outcome and sets of experimental data indicate that the developed simulator is capable of adequately representing the thermal behavior of the fin, not only in the steady state but also during transients.

Material and methods

The experimental module is similar to the one presented by Crosby (1961) and consists of three cylindrical horizontal rods with uniform transversal sections and a length of 103.7 cm. Two of them are made of stainless steel, while the third one is made of aluminum with diameters of 1.27 cm, 2.54 cm and 2.54 cm respectively (Figure 1). These rods are partially contained (13.5 cm) in a steam chamber with one of the ends thermally isolated. The steam chamber (Figure 2) is a thermally isolated steel box with internal dimensions 15.0 x 14.5 x 10.0 cm. Insulation is ensured by a 2.0 cm layer of mineral wool (K-Wool) enclosed in a 1.0 cm thick wooden box.

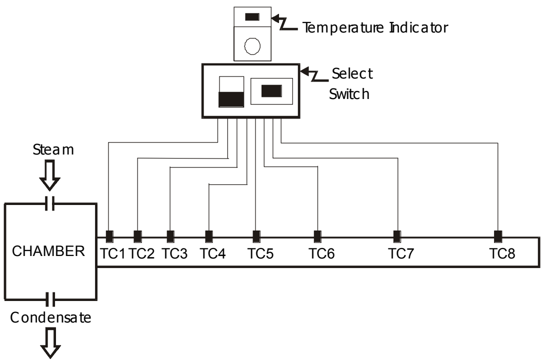

Figure 1. Educational module

Temperature monitoring is done by eight type J thermocouples distributed along the fins (TC1 through TC8), connected to a temperature indicator through a selecting switch. Table 1 shows the thermocouple allocation.

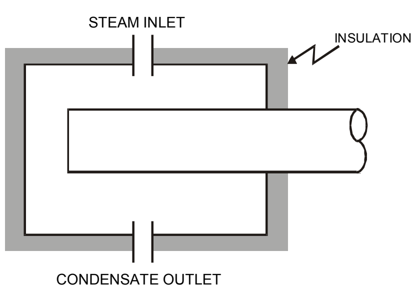

Figure 2. Steam chamber

Table 1. Thermocouple positions (measured from the steam chamber's outer wall).

Thermocouple	*X* (cm)
TC1	1.0
TC2	3.7
TC3	8.8
TC4	15.7
TC5	24.7
TC6	36.7
TC7	53.7
TC8	76.7

Mathematical modeling

A mathematical model was developed applying energy balance in volume elements of three distinct regions of the fin (domains), as may be seen on Figure 3. Domain I includes the part of the fin exposed to the saturated steam inside the chamber. Domain II refers to the insulated part of the fin, while Domain III encompasses the part exposed to the environment. These three domains were discretized in $N_I = 10$, $N_{II} = 5$ and $N_{III} = 12$ volume elements.

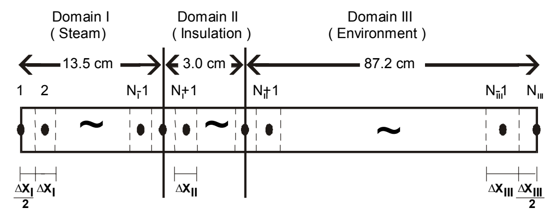

Figure 3. Fin discretization in finite volume elements

Although under different physical conditions, the resulting ordinary differential equations may be associated according to three groups:

End volume elements

$$\frac{dT}{dt} = \frac{\alpha}{\Delta X^2}\left[\begin{array}{l} 2\cdot\left(T_{i+C\cdot 1} - T_i\right) - \dfrac{4\cdot h_1\cdot \Delta X^2}{k\cdot D}\cdot\left(T_i - T_\infty\right) \\ -\dfrac{2\cdot h_2\cdot \Delta X}{k}\cdot\left(T_i - T_\infty\right)\end{array}\right] \quad (1)$$

Domain I $(i=1)$: $C=1$, $T_\infty = T_{vap}$, $h_1 = h_I^L$, $h_2 = h_I^P$, $\Delta X = \Delta X_I$

Domain III $(i = N_{III})$: $C = -1$, $T_\infty = T_{env}$, $h_1 = h_{III}^L$, $h_2 = h_{III}^P$, $\Delta X = \Delta X_{III}$

Central volume elements

$$\frac{dT}{dt} = \frac{\alpha}{\Delta X^2}\left[\begin{array}{l} T_{i-1} - 2\cdot T_i + T_{i+1} - \\ \dfrac{4\cdot h\cdot \Delta X^2}{k\cdot D}\cdot\left(T_\infty - T_i\right)\end{array}\right] \quad (2)$$

Domain I $(i \in \{2, N_I - 1\})$: $T_\infty = T_{vap}$, $h = h_I^L$, $\Delta X = \Delta X_I$

Domain II $(i \in \{N_I + 1, N_{II} - 1\})$: $h = 0$, $\Delta X = \Delta X_{II}$

Domain III $(i \in \{N_{II} + 1, N_{III} - 1\})$: $T_\infty = T_{env}$, $h = h_{III}^L$, $\Delta X = \Delta X_{III}$

Interface elements

$$\frac{dT}{dt}=\frac{a}{\Delta x_1^2}\cdot\left[\begin{array}{l}(T_{i-1}-T_i)+\dfrac{2\cdot h\cdot \Delta X_1^2}{k\cdot D}\cdot(T_\infty-T_i)\\ -\dfrac{2\cdot\Delta X_1}{(\Delta X_1+\Delta X_2)}\cdot(T_i-T_{i+1})\end{array}\right] \quad (3)$$

Domain I – Domain II $(i=N_I)$: $T_\infty=T_{vap}$, $h=h_I^L$, $\Delta X_1=\Delta X_I$, $\Delta X_2=\Delta X_{II}$

Domain II – Domain III $(i=N_{II})$: $T_\infty=T_{env}$, $h=h_{III}^L$, $\Delta X_1=\Delta X_{II}$, $\Delta X_2=\Delta X_{III}$

Model parameters

The model has four different parameters: two convective heat transfer coefficients in Domain I (h_I^L, h_I^P) and two in Domain III (h_{III}^L, h_{III}^P).

It is supposed that inside the steam chamber (Domain I) heat transfer occurs by film condensation on the fin surface. Accordingly, the lateral and end heat transfer coefficients h_I^L e h_I^P were estimated using condensation correlations for horizontal cylinders and vertical plates, presented by Incropera and Dewitt (1992), as shown in Eq. 4.

$$h=C\cdot\left[\frac{g\cdot\rho_l(\rho_l-\rho_v)\cdot k_l^3\cdot h'_{fg}}{\mu_l\cdot(T_{VAP}-T_S)\cdot D}\right]^{\frac{1}{4}} \quad (4)$$

where

$$C=\begin{cases}0.943-(\text{vertical plate})\\ 0.729-(\text{horizontal cylinder})\end{cases}$$

$$h'_{fg}=h_{fg}\cdot(1+0.68\cdot Ja)$$

In the external part of the fin (Domain III), heat transfer to the environment occurs by natural convection. The lateral thermal parameter (h_{III}^L) was established using the correlation for horizontal cylinders presented by Eq. 5 of Churchill and Chu (1975), while the end heat transfer coefficient (h_{III}^P) was obtained from the correlation for vertical plates presented by Eq. 6 of Holman (1983).

$$\overline{Nu}^{1/2}=0.60+0.387\cdot\left(Gr\cdot \mathrm{Pr}\cdot C^{-1}\right)^{\frac{1}{6}} \quad (5)$$

where

$$C=\left[1+\left(\frac{0.559}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right]^{\frac{16}{9}}$$

$$\overline{Nu}=0.508\cdot \mathrm{Pr}^{\frac{1}{2}}\cdot(0.952+\mathrm{Pr})^{\frac{-1}{4}}\cdot Gr^{\frac{1}{4}} \quad (6)$$

The physical properties of air and steam needed to obtain these coefficients were taken from correlations of the Literature (Reid *et al*., 1966; Holman, 1983; Perry, 1984).

Results and discussion

The mathematical model is composed by Eqs. 1-6, resulting in a system of 27 ordinary differential equations, numerically integrated, using the Runge-Kutta-Gill algorithm. Additionally the heat transfer coefficients are calculated accordingly to finite volume element temperature at all given times. Temperature values at previously selected positions on the rod are estimated by Lagrangean interpolation.

Briefly after the simulator start up, the user is led to a sequence of seven different screens. The first five are for data entry and the last two present simulation results in graphical form, as shown below.

Presentation

The presentation screen shows the version, operational environment and authors' credits. The user may also specify the desired unit system (International or English System), as in Figure 4.

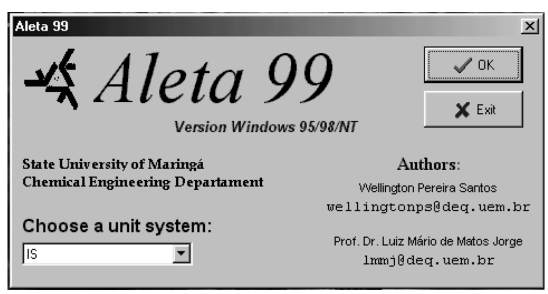

Figure 4. Presentation screen

Main form

It includes specifications of the physical characteristics of the fin, the rod lengths exposed to steam, insulated and in contact with the environment, the material selection (data for copper, aluminum and stainless steel are already stored in the simulator database) and operational temperatures of the module, as shown in Figure 5.

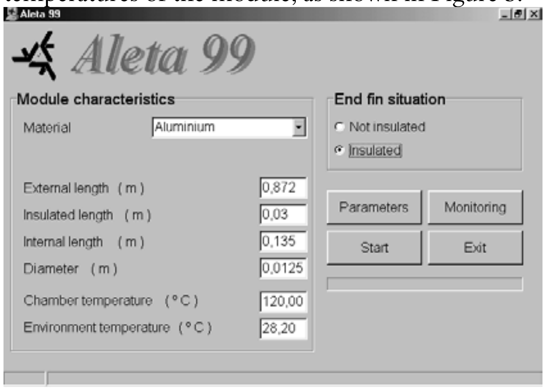

Figure 5. Main form

Blanks are also available for the configuration of simulation parameters and temperature monitoring. Interfaces for these configurations are presented on Figures 6 and 7.

Thermal and operational parameters

Thermal parameters may be given explicitly by the user or obtained from Literature correlations (Figure 6).

Monitoring configuration

The user is asked to choose the positions and times in which s/he desires to present the simulation results. Software has a current limit of 10 points for each graphic.

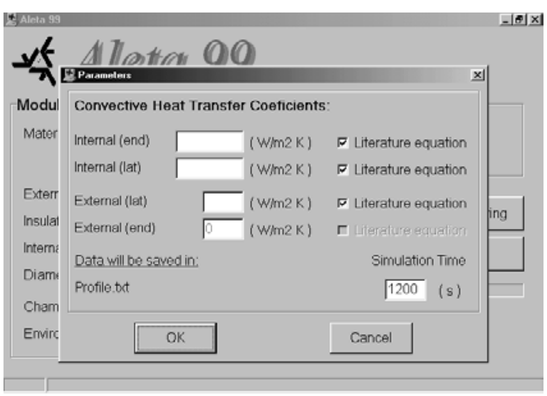

Figure 6. Thermal and operational parameter configuration

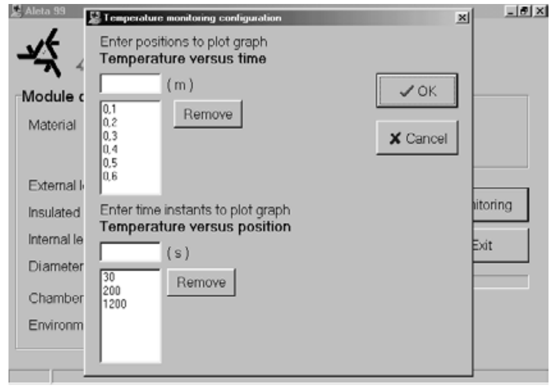

Figure 7. Temperature monitoring configuration

Temperature evolution monitoring

When simulation is finished, a new window is shown with temperature evolution at the positions chosen earlier (see Figure 8). These curves are also stored in a disk file in ASCII format for posterior analysis. Three pushbuttons are available in this window: one to close it and return to the main form, another to show a new window with the temperature profile along the rod, and a third to present the used thermal parameters.

Temperature profile monitoring

Derived from the previous one, this window shows a graph with the history of temperature variation along the rod for the positions chosen on the window of Figure 7 (Figure 9). Window has also zooming resources, with the use of the mouse.

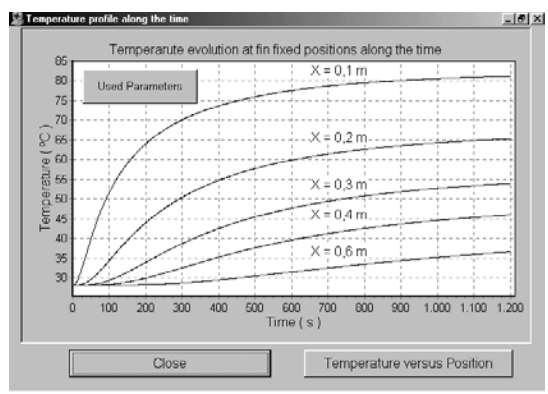

Figure 8. Temperature evolution at fixed positions

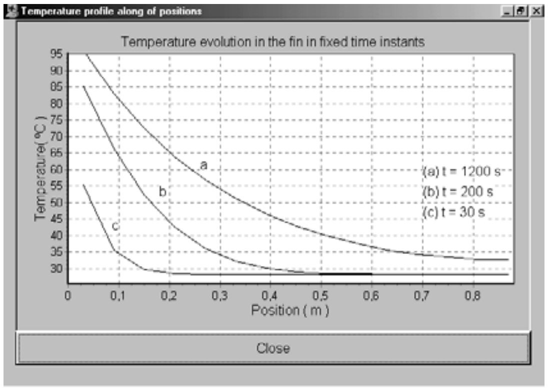

Figure 9. Temperature profile at chosen times

Result analysis

Simulation results presented in Figures 8 and 9 are for an horizontal aluminum fin with a uniform circular transversal section (specifications are those of Figures 5, 6 and 7; notice that literature correlations were used for all thermal parameters). It was also supposed that the fin had an insulated end.

In order to quantify the simulator performance, simulation results were compared to the corresponding experimental curves obtained by Konish *et al* (1997). As may be seen on Figure 10, simulator is capable of satisfactorily describing the experimental behavior. The mean differences between the measured temperatures and the simulator outcome were 7.77°C.

Note that simulation results were obtained with the use of literature correlations. A better approximation could be obtained with a proper adjustment.

In view of the obtained results and the graphical resources, the didactic value of this simulator becomes evident. It allows the user to visually explore the different influential characteristics of the problem, such as the rod dimensions, construction material, steam chamber temperature etc. over the thermal behavior of the system, shown in graphical plots.

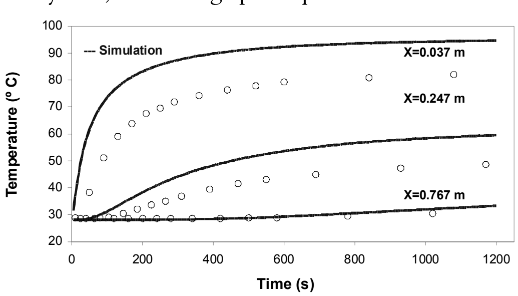

Figure 10. Comparison between experimental results and the simulator outcome

The mathematical model developed using the energy balance technique in finite volume elements represents satisfactorily the thermal behavior of the experimental module.

The simulator is able to produce an adequate representation of the experimental temperature curves using thermal parameters taken from the literature.

The simulator is a very interesting educational tool. It is easy to use, flexible, presents customizable monitoring configurations and may present the simulation results in a number of ways.

Nomenclature

α - thermal diffusivity $(k/\rho Cp)$ (L^2/t);
β - compressibility coefficient $(1/t)$;
C - non dimensional coefficient;
Cp - thermal capacity at constant pressure (L^2/t^2);
D - diameter (L);
Δ - increment;
g - gravity acceleration (L/t^2);
Gr - Grashof number $(g\beta(T_S - T_\infty)X^3/\nu^2)$
h - convective heat transfer coefficient (Mt/T), enthalpy (L^2/t^2);
Ja - Jacob number $(Cp_l(T_{VAP} - T_S)/h_{fg})$;
k - thermal conductivity (ML/T^3t);
μ - dynamic viscosity (M/Lt);
N - number of finite volume elements;
Nu - Nusselt number (hD/k);
ν - kinematic viscosity (L^2/T);
Pr - Prandtl number $(Cp\mu/k)$;
ρ - density (M/L^3);
T - temperature (T);
t - time (t);
X - linear dimension; characteristic dimension (L)

Subscripts

I,II,III - Domain I, II or III, respectively;
∞ - related to bulk fluid conditions;
l - lateral, liquid;
p - end;
env - external environment;
VAP - steam;

v - steam;
s - surface;
fg - difference betwen liquid and gas properties;

References

CHURCHILL, S. W.; CHU, H. S. S. Correlating equations for laminar and turbulent free convection from a horizontal cylinder. *Int. J. Heat Mass Transfer*, Kidlington, v. 18, p. 1049, 1975.

CROSBY, E. J. *Experiments in transport phenomena*, New York: John Wiley & Sons, Inc., 1961.

HOLMAN, J. P. *Heat transfer.* 5. ed. New York: McGraw-Hill International Book, 1983.

INCROPERA, F. P.; DEWITT, D. P. *Fundamentos de transferência de calor e massa*, 3. ed. Rio de Janeiro: Editora Guanabara Koogan S. A., 1992.

KONISH, C. Y. *et al. Modelagem e simulação da dinâmica da trnasformação de vapor do reator de gás natural.* Maringá: Universidade Estadual de Maringá, Maringá, 1996. (Relatório final do projeto de Iniciação Científica-CNPq)

PERRY, R. H. *Perry's Chemical Engineer's handbook.* 6. ed. New York: McGraw-Hill Book Company, 1984.

REID *et al. The properties of gases and liquids.* 2. ed. New York: McGraw-Hill Book Company, 1966.

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