

Shell and Tube Heat Exchanger Design Software for Educational Applications*

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A software for the thermal and hydraulic design of shell and tube heat exchangers with flow-induced vibration checks has been developed in a Windows-based Delphi programming environment. Its user-friendly input format and excellent colour graphics features make it an excellent tool for the teaching, learning and preliminary design of shell and tube heat exchangers. Design methodology is based on the open literature Delaware method while flow-induced vibration calculations adhere closely to the methodology prescribed by the latest TEMA standards for industry practice. It is hoped that the software will bridge the gap between the teaching of engineering fundamentals and the existing industry practice of shell and tube heat exchanger design.

INTRODUCTION

SHELL AND TUBE heat exchangers are commonly used as oil coolers, power condensers, preheaters and steam generators in both fossil fuel and nuclear-based energy production applications. They are also widely used in process applications and in the air conditioning and refrigeration industry. Although they are not specially compact, their robustness and shape make them well suited for high pressure operations. In view of the diverse engineering applications and basic configuration of shell and tube heat exchangers, the thermal analysis and design of such exchangers form an integral part of the undergraduate mechanical and chemical engineering curricula of most universities. Senior level or final year undergraduate courses often include an elective subject for thermal design of heat exchangers.

Reflecting the growing trend of using computers for design and teaching, recent heat transfer texts by Mills [1] and Incropera and DeWitt [2] incorporate computer software for the design and optimization of heat exchangers. These software are written to reinforce fundamental concepts and ideas and allow design calculations for generic configurations with no reference to design codes and standards used in the heat exchanger industry. For actual engineering applications, most shell and tube heat exchangers are designed using commercially available software such as those developed by co-operative research organizations such as Heat Transfer and Fluid Flow Service (HTFS)

and Heat Transfer Research Inc. (HTRI) and by computer service companies such as B-JAC International. These programs offer design and cost analysis for all primary heat exchanger types and incorporate multiple design codes and standards from the American Society of Mechanical Engineers (ASME), Tubular Exchangers Manufacturers Association (TEMA) and the International Standards Organisation (ISO). However, these programs are application oriented and contain company proprietary data with little pedagogical value to engineers with little or no knowledge of heat exchanger design and students in the mechanical and chemical engineering disciplines. This paper describes a user-friendly computer software developed for the thermal and hydraulic design of shell and tube heat exchangers based on the open literature Delaware method. The use of this software will bridge the gap between engineering practice and teaching of shell and tube heat exchanger design.

DESCRIPTION OF SOFTWARE

The shell and tube heat exchanger design software is developed for use in the teaching of thermal and hydraulic design of shell and tube heat exchangers usually at the senior undergraduate level of a mechanical or chemical engineering course. It may also be used for the preliminary design of shell and heat exchangers in actual industrial applications. Developed in Borland International's Delphi programming environment with advanced graphics features, the Microsoft Windows-based software can be implemented on an IBM or

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compatible personal computer with at least a 80386 microprocessor, 4MB of RAM and at least 5 MB of free hard disk space.

Components of the software

The software consists of four modules viz. Sizing, Rating, Vibration and Tutorial. The Sizing module allows the size of a shell and tube heat exchanger to be determined based on inputs of fluids temperatures, flowrates and pressure drop and dimensional constraints. The user can call out a graphics screen showing the different physical configurations of shell and tube heat exchangers based on the Standards of the Tubular Exchanger Manufacturers Association (TEMA) [3]. Thermo-physical properties of common fluids are included in the software and are automatically calculated based on input fluid temperatures. The existing database of fluid properties cater for water, air, Freon-12, ethylene glycol, glycerine and mercury. The module allows for user input of thermo-physical properties of fluids not found in the database. Figure 1 shows the user-friendly menu-driven input format which accepts either SI, Imperial or a combination of both units. The Imperial units option is built into the software in recognition of the fact that a large number of heat exchangers are designed, constructed and used in the United States. Design results can be presented in graphics showing a labelled and dimensioned heat exchanger. This feature enables the student or new engineer to quickly visualize the key constructional features of a shell and tube heat exchangers and its relative dimensions.

The Rating module allows the user to calculate whether a selected exchanger can meet the required thermal and hydraulic duty. User inputs of geometrical dimensions of the heat exchanger to be rated is required.

Fluid flow, inter-related with heat exchanger geometry, can cause heat exchanger tubes to vibrate and cause possible damage to the exchanger. The Vibration module developed based on the methodology outlined in the 1988 edition of TEMA standards [4] allows the user to check the extent of flow-induced vibration after an exchanger is sized. To the best of the authors' knowledge, existing commercial flow-induced vibration software are offered separately from thermal and hydraulic design software. The integration of the Vibration module in this shell and heat exchanger design software allows the user to conveniently conduct flow induced vibration checks on his design.

The Tutorial module is a self-learning tool for the student and novice engineer. It introduces the basic construction of a shell and tube heat exchanger, exchanger selection and instructions on how to use the various software modules.

Two other features set this software apart from most software developed for educational applications. Firstly, calculated dimensions of the heat exchanger can be saved into a text file which can be conveniently incorporated into all commercially available word processing software. This feature is useful for the generation of design reports. Secondly, detailed calculation steps are also available to facilitate the understanding of concepts used in the design. This feature sets this software apart from most commercial packages which behave like 'black boxes' and have no pedagogical use.

Choice of programming environment and language

The use of conventional programming languages such as FORTRAN suffers from the disadvantage of poor graphical presentation. To develop a user-friendly software, the authors have decided to use

Performance		Unit	Shell Side	Tube Side
Fluid Allocation			Shell Side	Tube Side
Fluid Name			Air	Air
Total Fluid Flow Rate	kg/s		10	10
Density	kg/m ³		740	1.1614
Thermal conductivity	W/mK		0.105	26.3
Specific Heat	J/kg K		2407	1.007
Dynamic viscosity	Cp		0.45	184.6
Fouling Resistance			0	0
Temperatures	C		IN: 89.8, OUT: 147.3	IN: 178, OUT: 178

Buttons: OK, Cancel, Help

Fig. 1. Input format for sizing module.

Borland's latest programming environment, Delphi which is completely object-oriented. Delphi's programming language is Object Pascal and allows the software to be developed in a completely visual environment with the source code constantly being updated. The result is user-friendly input formats and excellent graphics which facilitates computer-aided learning.

Shell-side heat transfer

As most commercial programs are based on company-proprietary data, it is not possible to adapt these programs for engineering education. The authors have therefore chosen an open literature method called the Delaware Method first proposed by Bell in 1963 [4, 5]. The Delaware method is a rating method. Rating an exchanger means to evaluate the thermohydraulic performance of a fully specified exchanger. The result of a rating process is a judgement as to the ability of the unit to perform a desired duty and comply with other design conditions of operation such as good pressure drop utilization, cleaning, thermal expansion, safety, and tube vibration.

For a baffled shell-side flow, the analysis is so complex that it cannot be adequately expressed on a generalized basis by a simple approach such as the effectiveness-number of transfer units correlation. Only part of the fluid takes the desired path through the tube nest, whereas a potentially substantial portion flows through the 'leakage' area (baffle-to-shell and tube-to-baffle) and the 'bypass' area between tube bundle and the shell wall. However, these clearances are inherent to the manufacturing and assembly process of shell-and-tube exchangers, and the flow distribution within the exchanger must be taken into account. In the Delaware method, the fluid flow in the shell as illustrated in Fig. 2 is divided into a number of individual streams as follows:

1. Stream A is the leakage stream in the orifice formed by the clearance between the baffle tube hole and the tube wall.
2. Stream B is the main effective cross-flow

stream, which can be related to flow across ideal tube banks.

3. Stream C is the tube bundle bypass stream in the gap between the bundle and the shell wall.
4. Stream E is the leakage stream between the baffle edge and the shell wall.
5. Stream F is the bypass stream in flow channels due to omission of tubes in tube pass partitions.

Each of the above streams introduces a correction factor to the heat transfer correlation for ideal cross-flow across a bank of tubes. The basic equation for calculating the effective average shell-side heat transfer coefficient h is given as:

$$h = h_{ideal} J_c J_l J_b J_s J_r \quad (1)$$

where h_{ideal} = heat transfer coefficient for pure cross-flow in an ideal tube bank,

J_c = correction factor for baffle cut and spacing,

J_l = correction factor for baffle leakage effects,

J_b = correction factor for bundle bypass flow (C and F streams),

J_s = correction factor for variable baffle spacing in the inlet and outlet sections, and

J_r = correction factor for adverse temperature gradient build-up.

The combined effect of all of these correction factors for a well-designed shell-and-tube heat exchanger is typically of the order of 0.6; that is, the effective mean shell-side heat transfer coefficient for the exchanger is 60% of that calculated if the entire flow took place across an ideal tube bank corresponding in geometry to one cross-flow section. It is interesting to observe that this value has long been used as a rule of thumb.

Shell-side pressure drop

Shell-side pressure drop is built up in the Delaware method by summing the pressure drops

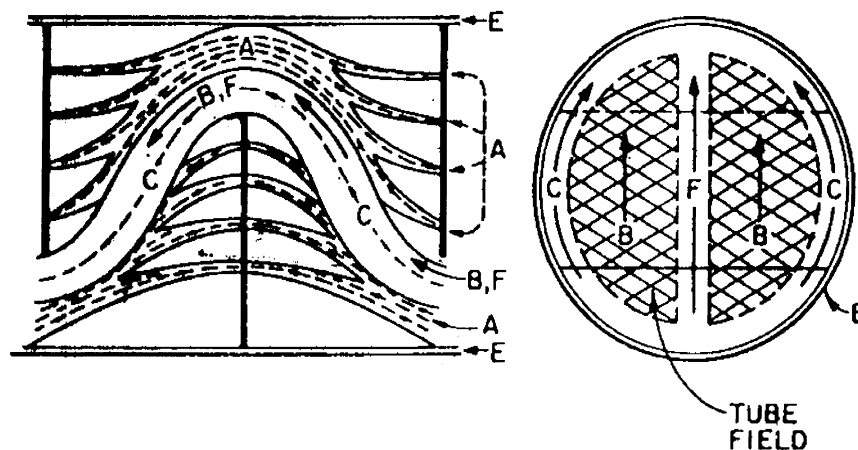


Fig. 2. Shell-side flow streams.

Table 1. Design information

Description	Quantity
Flow rate for shell-side fluid	1.689 kg/s
Flow rate for tube-side fluid	10 kg/s
Fouling factor in shell	0.0001
Fouling factor in tubes	0.000175
Temperature in (shell-side fluid)	100°C
Temperature out (shell-side fluid)	40°C
Temperature in (tube-side fluid)	30°C
Temperature out (tube-side fluid)	36.1°C
Maximum allowable shell diameter	1000 mm
Maximum allowable shell-side pressure drop	4.8 kPa
TEMA configuration	AET

for the inlet and exit sections. The total pressure drop over the exchanger is given by:

$$\Delta p_{tot} = \Delta p_c + \Delta p_w + \Delta p_e \quad (2)$$

where Δp_c = pressure drop in the interior cross-flow sections from baffle tip to baffle tip,

Δp_w = pressure drop in the window sections, and

Δp_e = pressure drop in the entrance and exit sections.

This does not include the pressure drop in the nozzles, which is usually included in the specification. Each of the above pressure drop terms has correction factors analogous to those for heat transfer. A detailed description is given in Ref. [4].

The total shell-side pressure drop of a typical shell and tube exchanger is of the order of 20% to 30% of the pressure drop that would be calculated for flow through the corresponding heat exchanger without baffle leakage and without tube bundle bypass effects.

Flow-induced vibration

Fluid flow, interrelated with heat exchanger geometry, can cause heat exchanger tubes to

vibrate. This phenomenon is highly complex and the present state-of-the-art is such that the solution to this problem is difficult to define. Hence, after an exchanger is designed, it is necessary to check for any flow-induced vibration which may cause damage to the exchanger. The methodology adopted in the Vibration module of this software follows closely the prescribed formulae in the 1988 edition of the TEMA standards [3] for calculating the natural frequency of a tube, critical flow velocity for a tube span, acoustic frequency, vortex shedding frequency and turbulent buffeting frequency. The calculations for this module are performed in Imperial units and the results converted to SI units.

SOFTWARE UTILIZATION IN DESIGN EDUCATION

The software is suitable for teaching thermal and hydraulic design of shell and tube heat exchangers to senior undergraduate students in mechanical and chemical engineering and also to train new graduate engineers in thermal design. Students may be asked to use the software to undertake a few mini projects in shell and tube heat exchanger design. The following example illustrates how the software can be used in such a manner.

Example

Use the computer program to design a shell and tube heat exchanger based on the information given in Table 1. Perform a flow-induced vibration check on the designed exchanger. Take the shell-side fluid to be air and the tube-side fluid to be water.

Depending on the limitations imposed on the shell size, there can be numerous design solutions. For the sake of brevity, only four solutions are

Table 2. Some design solutions

Solution	1	2	3	4
Shell internal diameter (mm)	838	889	889	940
Layout pitch (mm)	31.75	31.75	39.69	36.69
Tube length (mm)	2095	1955.8	2578.1	2397
Baffle spacing (mm)	335.2	311.150	355.6	329
Tube outer diameter (mm)	25.4	25.4	31.75	31.75
Tube layout angle (degrees)	90	90	90	90
Number of tubes	439	497	316	355
Number of sealing strips (pair)	1	1	1	1
Baffle cut (%)	24.5	23.375	24.5	23.375
Number of baffles	3	3	4	4
Actual heat duty (kW)	260 305.8	258 447.9	278 526.5	275 955.1
Required heat duty (kW)	257 403.6	257 403.6	257 403.6	257 403.6
Pressure drop shell side (kPa)	4.43724	4.61526	4.10141	4.24115
Number of tube passes	2	2	2	2
Critical velocity (m/s)	98.88	87.22	147.18	184.86
Cross-flow velocity (m/s)	32.53	29.61	29.74	31.71
Vortex shedding frequency (Hz)	538.05	489.70	393.47	419.50
Natural frequency (Hz)	145.48	130.13	163.14	199.78
Turbulent buffeting frequency (Hz)	329.52	299.90	241.03	257.00
Acoustic frequency (Hz)	117.63	111.25	111.25	105.53

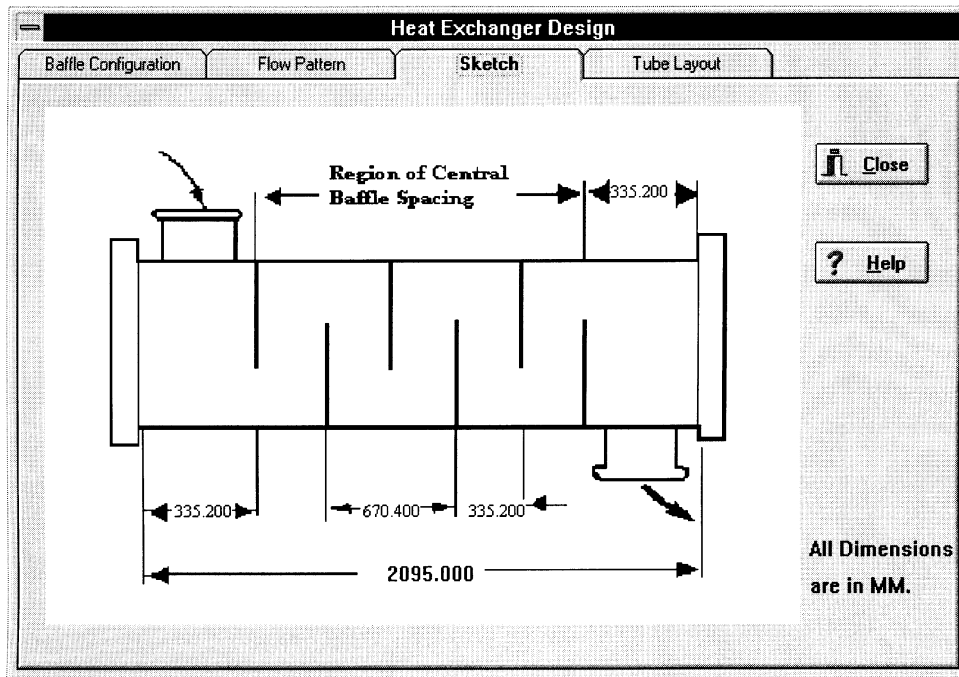


Fig. 3. Sketch of heat exchanger corresponding to solution 1.

shown in Table 2. All solutions are based on single segmental baffle design.

The program gives a choice of various graphics depicting the baffle configuration, flow pattern, sketch of heat exchanger and tube layout of each chosen solution. Figure 3 shows a sketch of the dimensioned exchanger corresponding to solution 1 while Fig. 4 shows its shell-side fluid flow pattern. Consider the case in which the tube length and baffle spacing are changed to 20950 mm and 3352 mm, respectively. The program can then be used to

quickly re-evaluate the solution and the corresponding sketch and shell-side fluid flow pattern are shown in Figs 5 and 6, respectively. From Fig. 6, it can be seen that the shell-side flow pattern is not ideal and solution can then be rejected.

Tutorial

The tutorial module in the software supplements classroom teaching of the basics of a shell and tube heat exchanger. It allows the student and the new engineer to review some of the concepts and

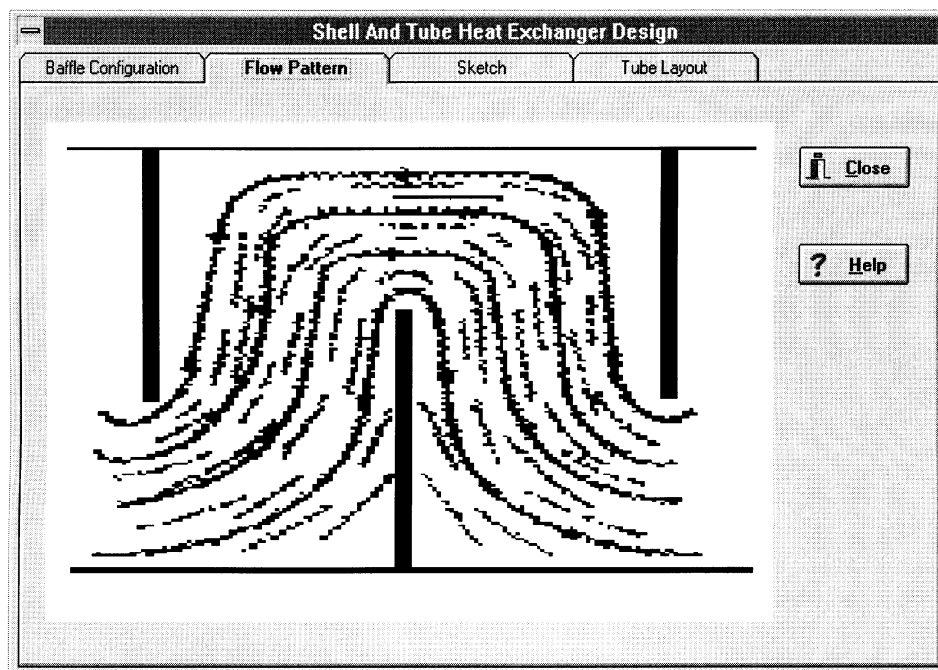


Fig. 4. Shell-side flow pattern for solution 1.

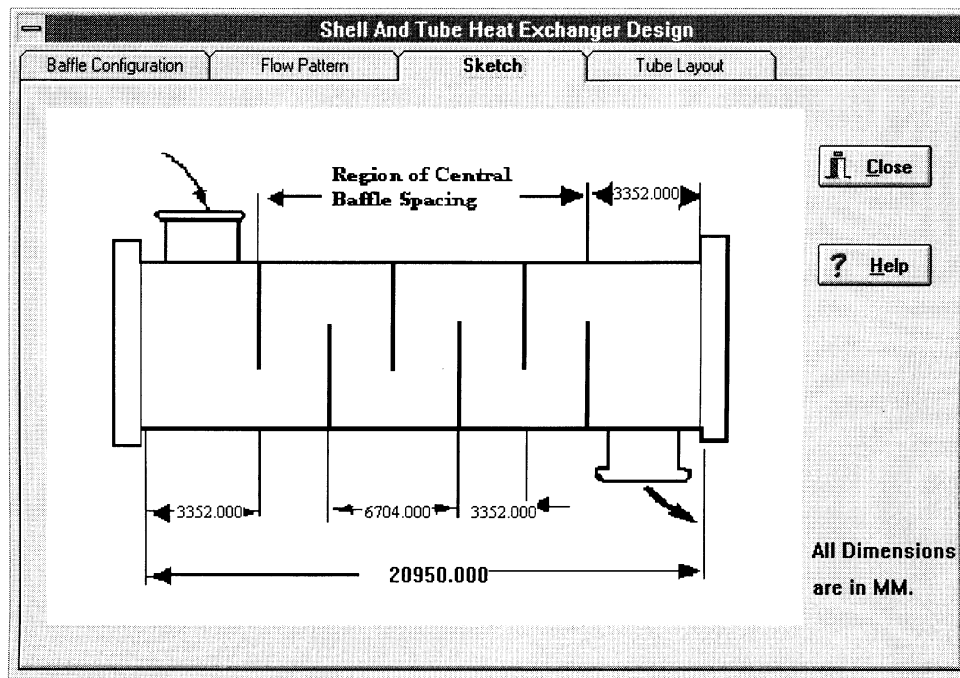


Fig. 5. Sketch of heat exchanger of increased dimensions.

practical aspects of heat exchangers at his own pace. At present, three topics are incorporated into this module:

- Introduction to heat exchangers.
- Selection of exchangers.
- How to use the programs in the sizing, rating and vibration modules.

A sample screen extracted from the topic,

'Introduction to Heat Exchangers' is shown in Fig. 7. More self-learning topics may be programmed into the tutorial module as and when the need arises.

Naturally, the ultimate design of the exchanger depends very much on the user's experience in the field of heat exchanger design. However, this program can serve as a general guide to the field of designing shell and tube heat exchangers.

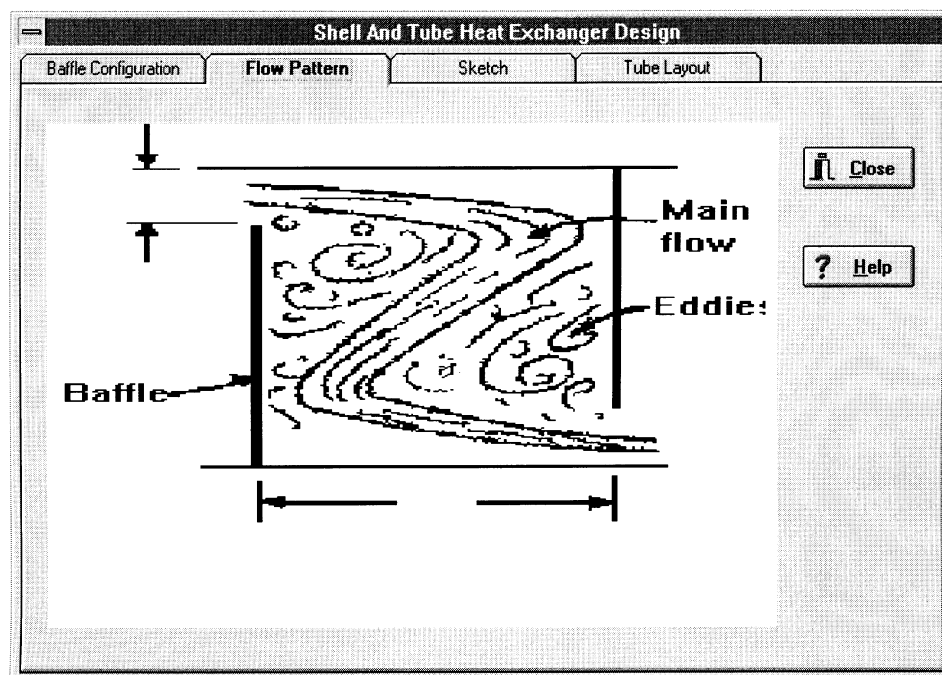


Fig. 6. Undesirable shell-side flow pattern.

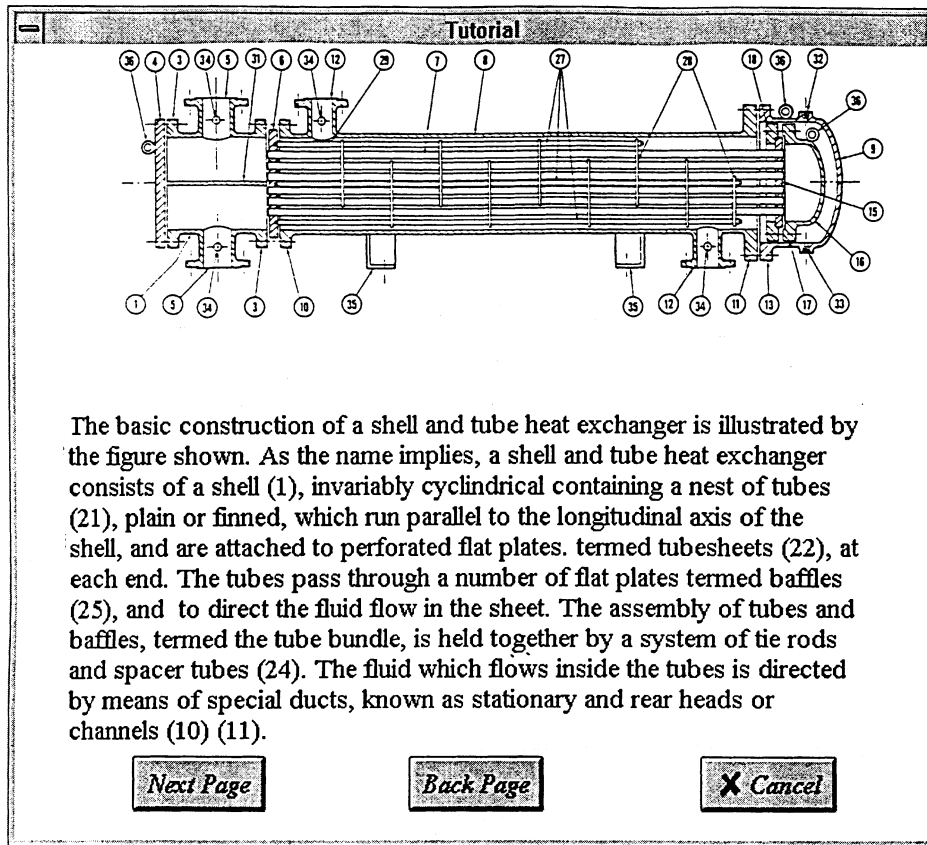


Fig. 7. Sample tutorial session.

LIMITATIONS OF THE SOFTWARE

Since the software is developed in the university with limited manpower and financial resources, it will not have the aesthetic appearance and database of commercially developed ones. At present, thermophysical properties of six fluids are stored in the database. It is a simple though tedious task of incorporating more fluid data into the software. This limitation does not hinder the use of the software and in fact allows the student the opportunity to search for thermophysical data of fluids encountered in engineering applications.

Being a Windows-based software, it requires more random access memory (RAM) on the PC than most software written for the DOS environment. This problem becomes more acute when more windows are opened in the course of using different modules of the software. As the software is divided into many individual units, the problem can be circumvented by closing unwanted windows and thus freeing up the memory. With the proliferation of 486 and Pentium-based PCs with at least 8 MB of RAM and the obsolescence of 286 and

386 based PCs, there should be no problem implementing the software for educational applications.

CONCLUDING REMARKS

A software has been developed for the thermal and hydraulic design of shell and tube heat exchangers based on the Delaware method. Flow-induced vibration calculations based on the latest TEMA publication [3] have also been incorporated. Its interactive graphics feature allows the selection of exchanger configurations and change of design conditions to be performed with ease. Students can use its Tutorial Module to learn the basics of shell and tube heat exchangers at their own pace. As with the case of all software, it is always in a constant state of development. The addition of a mechanical design, optimization and costing modules are some of the enhancements that will be undertaken in the not too distant future. It is hoped that the software will bridge the gap between the teaching of fundamentals and industry practice of shell and tube heat exchanger design.

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