The Impact of MathCad in an Energy Systems Design Course

B. K. Hodge, Robert P. Taylor
Mississippi State University

Abstract

Experiences using MathCad instead of a higher-level programming language in a required energy systems design course are related. MathCad was used for all computational requirements in the course; MathCad worksheets for a variety of energy systems design and analysis procedures were provided to the students. Students readily adapted to the change from programming languages to MathCad. Many MathCad solution approaches were found to differ significantly from conventional techniques and to be more congruent with problem formulations. The MathCad solution approach to the course resulted in more emphasis on engineering and less on programming and was judged a success.

Background

Since the 1950s, digital computers have become an increasingly important part of engineering education and the engineering workplace. Both engineering educators and engineering practitioners have struggled to evolve effective ways to fully utilize the increasing power and sophistication of computers in engineering analysis and design. For a number of years, engineers were heavily involved in developing applications-oriented programs via extensive coding; indeed, computer programming skills were viewed as a necessary adjunct to a contemporary engineering education. However, by the mid-1980s the ever-increasing availability, the user-friendliness, and the utility of engineering applications software portended a shift in the engineering workplace to less programming and more reliance on commercial software elements. In the 1990s that trend has continued, and, paraphrasing Baker (1) at the University of Tennessee, the days of amateur programming in the engineering workplace are over. Hodge and Taylor (2) identified the end of amateur programming as an important factor for change in mechanical engineering education.

Thus, coding and programming in the engineering workplace have diminished in importance in many engineering disciplines, including mechanical engineering. To be sure, in many research and development activities, programming skills by engineers continue and will continue to be mandatory, but such activity is far from amateur and is accomplished by engineering specialists with a high degree of expertise in the subject. The ability to use commercial software packages and systems in a variety of everyday activities is more important for most mechanical engineers than the ability to code and debug relatively short, specialized programs in a higher-level language. Mechanical engineering undergraduates need to develop skills in using commercial software packages and systems in a timely and correct fashion. Many mechanical engineering educators acknowledge this need and have endeavored to meet it by integrating existing software, either commercially available or locally written, into courses. This paper reports the results of one such endeavor in a required senior-level energy systems design course in the mechanical engineering curriculum at Mississippi State University.

Course Description And Evolution

ME 4333/6333 Energy Systems Design is a required senior-level design course in the mechanical engineering curriculum at Mississippi State University (MSU) and is also offered for beginning graduate credit. The course is design oriented and explores the following topics:

1. Piping Systems (series, parallel, and networks)

2. Heat Exchangers (ξ-NTU, finned surfaces, pressure drop, TEMA, cross-flow)

3. Pumps (selection, manufacturers' data, series/parallel, cavitation)

4. System Simulation (steady-state, systems of equations)

5. Uncertainty in Thermal Systems Design (piping networks, heat exchangers)

Typically, of the six homework assignments, two deal with piping systems, two with heat exchangers, one with pump selection validation, one with system simulation/uncertainty in thermal systems design. One of the piping systems and one of the heat exchanger assignments are individual assignments that deal with competencies in basic techniques in those subjects. The remaining four assignments are team (three students per team) design projects. All six assignments are computer based, are required to be prepared using word processing software, and are graded on technical content (75 percent) as well as composition (25 percent). The workload is considered heavy, but the students rate the course high because of its applied nature and perceived utility.

Energy Systems Design (ESD) has been a required course in the MSU mechanical engineering curriculum for more than fifteen (15) years and has been in virtually a continuous state of evolution because of the ever-increasing hardware capabilities and the ever-increasing software utility. Hodge and Taylor (3) detail the evolution of the course from its inception in 1981 until 1993. In its original offering, ESD was based on the use of hand-held calculators, but it quickly changed, and in the early years the course was programming intensive. In the middle years of ESD, as locally-developed software with some generality was made available, the course gravitated from programming intensive to applications intensive. This era of ESD was characterized by modifications to existing software, so some programming skills were required. However, the level of programming skills required was significantly less than in the earlier years of the course. As the mode of computations was changing so was the level of assignments. The availability of generalized software that required only modifications permitted the assigned design projects to be more meaningful and more involved. The evolution of the course meant that the student experience moved increasingly from programming tasks to energy systems design tasks, in fact making the course more effective in design experiences. However, the rapidity of changes in computer hardware and software has continued, and the course has undergone significant modification since 1993.

Since 1993 the Energy Systems Design (ESD) course has evolved so that no structured programming in languages such as FORTRAN or PASCAL is used. This is perhaps the most significant change in the life of the course, but it mimics the changes taking place in the engineering workplace.

Starting with arithmetic systems such as TK Solver about a decade ago, the number of similar offerings have increased dramatically . Moreover, each new release of these arithmetic systems has resulted in enhancements to existing capabilities and additions of other useful capabilities. One has only to examine the evolution of MathCad to see this startling progress. Indeed, one view is that the current systems, such as MathCad, that combine significant arithmetical capabilities with acceptable graphics and word processing functions are in reality just the first useful systems for general engineering computing and reporting and that later releases of the current systems as well as new systems will only make them more useful—and necessary. MathCad combines in one software package not only significant arithmetical, plotting, and word processing capabilities but also beneficial capabilities for matrix manipulation, symbolic algebra and calculus, differential equation solution, curve fitting, and units tracking. The full impact of these systems on the engineering workplace has yet to be felt, but engineering educators must investigate the possibilities and acclimate students to this new non-programming mode of operation.

The use of MathCad has fundamentally altered the manner in which many engineering calculations can be accomplished. A significant number of the various procedures that are developed in engineering textbooks are numerical approaches formulated to solve non-linear systems of equations. Since MathCad can solve directly many of the non-linear algebraic systems of equations of engineering importance, the engineer no longer need be concerned with solution algorithm details, but can concentrate on problem formulation. Consider the impact of MathCad in the Energy Systems Design course.

MathCad Implementation In ESD

Starting the Fall Semester of 1994, an early release of MathCad was accepted, but not required, as suitable for use in the Energy Systems Design course. MathCad at that time was relatively new and was not used in any mechanical engineering course at MSU. Neither MSU nor the ME department offered any formal instruction in MathCad. None-the-less, student acceptance was immediate. The general rapidity with which MathCad displaced higher-level programming languages in ESD was astonishing—about as rapidly as hand-held calculators displaced the slide rule in the early 1970s! By the end of the Fall 1994 Semester **all** students in ESD were using MathCad when appropriate; the students having learned it on their own. The Spring and Fall 1996 Semeters continued in the same vein with MathCad usage when appropriate, but with some generalized software still being used. However, starting with the Spring 1997 Semester, all computations were ported to MathCad and all work submitted in MathCad. MathCad procedures were discussed in class, copies of MathCad worksheets were handed out, and students were permitted to use the worksheets as the starting points for homework assignments. MathCad procedures and worksheets for the following topics were developed for ESD:

1. Series piping systems

2. Parallel piping systems

3. Piping network (Hardy-Cross method with minor losses and devices)

    a. Hazen-William major losses

    b. Friction factor major losses

4. Finned-wall heat transfer performance analysis

5. Shell-and-tube heat exchanger analysis

6. Shell-and-tube heat exchanger design (rating, tube-side pressure drop)

7. Finned-tube heat exchanger analysis

8. Finned-tube heat exchanger design (rating, both pressure drops)

9. Series and parallel pump operation

10. Pump-system operating point

11. Steady-state system simulation (non-linear systems of equations)

12. Method of characteristics water hammer

Length constraints preclude discussion for each of the MathCad procedures listed in the preceding paragraph. However, many of the procedures utilize the same MathCad capabilities so that a reasonable sample can be examined.

Series Piping Systems

Consider, as in Figure 1, a series piping system with pipes of different diameters, a variety of major and minor losses, and a pump with an increase in head of W_s. Assuming that the flow is from a to b, the energy equation becomes

$$W_S \frac{g_c}{g} = \frac{P_b - P_a}{\gamma} + z_b - z_a + \sum_{i=1}^{J} \frac{8}{\pi^2} \frac{Q^2}{gD_i^4}\left[f_i \frac{L_i}{D_i} + C_i f_{T_i} + K_i \right] \quad (1)$$

Three different categories of problems are associated with series piping systems: (1) Category I in which the required increase in head, W_s, of the pump is the unknown, (2) Category II in which the flow rate Q is the desired results, and (3) Category III in which the pipe diameter is to be obtained. Category I problems are direct, but Categories II and III are iterative. The usual treatment in fluid mechanics textbooks, Munson et al. (4) for example, is centered about solving Eq. (1) for the three problem categories. However, the SOLVE block structure of MathCad permits all three category solutions to be obtained by simply indicating the required variable (unknown) in a FIND statement. Figure 2 presents a segment of a MathCad worksheet illustrating the SOLVE block/FIND statement sequence for a Category II problem. For a Category I or Category III problem only the required solution variable (and an initial guess) must be changed. A detail that should be mentioned is that Category I problems can be computed directly without the SOLVE block, but simplicity suggests that adopting the same solution process for all category problems is appropriate. As with any well-posed problem, all other terms in the equation must be defined. The student needs only to apply and reduce the energy equation, define the variables in Eq. (1), and specify the unknown in order to obtain a solution to the problem. The explicit formulas for the friction factors are presented and are used as an alternative to the Moody diagram. Thus, in the MathCad approach, the solution algorithm is of little concern and the problem formulation and interpretation of the results are the center of activities.

Parallel Piping Systems

No better example exists for the effects of MathCad on solution techniques than that for parallel piping systems. Such systems, as illustrated in Fig. 3, have long been solved in iterative fashion by enforcing equality of change in head across each pipe and conservation of mass at the two nodes. The usual, pre-MathCad procedure was to assume a flow rate in one pipe, compute the change in head in that pipe, compute the flow rate in the remaining pipes by requiring their changes in head to be equal to that of the first pipe, and iterating until convergence. In MathCad, the procedure is more straightforward and closer to the formulation of the problem. Figure 4 presents a portion of the MathCad worksheets illustrating the SOLVE block arrangement required to find the flow rates in and pump increase in head required for a system consisting of two parallel pipes. The formulation of the problem requires one equation summing the flow rates and one energy equation for each parallel piping segment. The MathCad SOLVE block/FIND statement then solves the non-linear system for the individual flow rates and the required increase in head of the pump (to make the pressures at a and b equal). The solution algorithm is completely transparent to the user. Students find this approach to parallel problems appealing since getting an answer is not overwhelmed by the arithmetic and because the formulation process leads directly to the MathCad input required for the solution.

Finned-Wall Performance Program

This is a very simple procedure, but awareness is necessary if students are to understand how and when fins are appropriate for heat transfer rate enhancement. The MathCad worksheet for finned-wall analysis is straightforward, but the capability to easily do parametric studies makes the procedure very useful. Figure 5, a portion of the finned-wall performance worksheet, illustrates the use of the MathCad RANGE variable to compute and present information. In this worksheet segment, fin length and thickness are varied in such a manner as to keep the fin volume constant. The percentage enhancement in UA is then plotted as a function of fin length to determine the fin geometry that maximizes UA. In a very few lines of MathCad, considerable insight into the performance of finned walls can be obtained.

Shell-and-Tube Heat Exchanger Design Program

This is called a program even though it is written in MathCad. Units are carried throughout the computation sequence. The problem statement is to determine the dimensions of a shell-and-tube heat exchanger subject to a rating and tube-side pressure-drop constraint. The procedure of Shah [see Hodge (5)] is used. The MathCad worksheet required for this design problem is presented in Figure 6. The program returns only the information in the last array or variable listed, in this instance an array containing a summary of heat exchanger parameters at convergence. Once the mass velocity is known, all remaining parameters can be computed. In reality this example is not much different from using a programming language, but it is more intuitive and illustrates that MathCad procedures can be adapted from conventional programming.

Pump-System Operating Point

Determining the operating point (flow rate, increase in head) of a particular pump in a particular system is a common requirement for many situations. Most fluid mechanics textbooks present a graphical approach in which the pump characteristics (H vs Q) curve and the system characteristics curve are plotted on the same graph. The intersection of the two curves defines the operating point of the piping system. Most commercial piping system programs possess options that numerically determine the system operating point. The determination of the systems operating point in MathCad uses the series piping procedure, discussed previously in this section, together with a curve fit of the pump characteristics to determine the operating point. Figure 7 illustrates a portion of the worksheet. The SOLVE block contains two equation: the energy equation and the pump characteristics curve fit. The unknowns are the flow rate and the pump increase in head. Again the problem formulation is congruent with the MathCad input, and the operating point information is returned in the FIND statement.

System Simulation

In the Energy Systems Design course, only steady-state simulation problems are considered. The primary system simulation technique presented in the ESD course is based on describing an energy system with a set (system) of algebraic equations. Because the system of equations is generally nonlinear, the usual approach is to use a multi-variable Newton-Raphson method. Again the SOLVE block/FIND statement in MathCad is invoked to solve the system. MathCad's FIND routines are quite robust, and MathCad is capable of solving nonlinear systems of equations that would be difficult to solve using a conventional Newton-Raphson approach. As an example of a systems simulation using MathCad consider the fluid transfer system shown in Figure 8. The system consists of a pipe with major and minor losses, two pumps in parallel, and two reservoirs separated by an elevation of 300 feet. Figure 9 presents the MathCad worksheet illustrating the system simulation formulation required to find the operating point of the arrangement. Four equations are involved: one conservation of mass statement, one energy equation for the piping system, and the two characteristic equations for the two pumps. Initial guesses must be provided for the four unknowns, and, as usual in a SOLVE block, all of the remaining parameters must be defined.

The preceding descriptions of the MathCad procedures are typical of those used in the ESD course. MathCad possesses many other capabilities, but they are not exercised in the ESD course. As is evident, the SOLVE block/FIND statement is the basis of many of the MathCad procedures examined in this paper. Other problems would require other MathCad capabilities. However, in the ESD course, MathCad has altered the manner in which problems are solved; it has resulted in more effort being devoted to problem formulation and results interpretation.

Assessment

Since no formal evaluation instruments were devised and validated, the following assessment comments are anecdotal in nature. The rapidity with which students embrace MathCad over options of programming languages in the ESD course indicate general student recognition of the utility of arithmetic/graphics/word processing systems such as MathCad. Results of student surveys during both the Spring and Fall 1997 Semesters corroborated that students find the sequence of class presentation of worksheets and then application in homework to meaningful problems a useful approach. Porting all the computational procedures to MathCad permitted some increase in the complexity and realism of homework assignments. Use of MathCad also meant that competency problems (individual assignments on piping systems and heat exchangers) in homework assignments could require more involved parametric studies with more general inferences available to the students.

Some negatives were also observed. Perhaps the major one is that the word processing capabilities in MathCad can degrade problem explanation and discussion as students tend to focus on the arithmetic aspects and to string computations over several pages with little text (narrative) clarification. The argument can be made that the use of systems such as MathCad neglects the numerical analysis details and that, as a result, the students tend to be working with black boxes. To the authors this does not appear to happen or to be a problem. Most of the applications software used in the engineering workplace could also be faulted with the same argument. Students have sufficient background to understand the general approach of what is occurring in the MathCad procedures; in many instances the students develop a better understanding and appreciation of the engineering aspects of the problems.

Conclusions

MathCad has had an enormous impact on the Energy Systems Design course. In the nearly twenty-year history of the course, the use of MathCad is clearly the most significant evolutionary step. MathCad has moved the course closer to the engineering workplace and has resulted in increased emphasis on the engineering aspects, rather than numerical analysis or programming aspects, of the course. Plans are to continue in the path of general arithmetic systems with the awareness that new releases and new systems could require another evolutionary change in the Energy Systems Design course.

References

1. Baker, A. J., Pionke, C. D., Taylor, M. J., and Luttrell, B., "FEM Brought to the Academic Engineering Desktop, " Proceedings of the 1996 ASEE Southeastern Section Meeting, Gatlinburg, TN, April 1996.

2. Hodge, B. K., and Taylor, R. P., "Factors for Change in Mechanical Engineering Education," Proceedings of the 1997 ASEE Annual Meeting, Milwaukee, WI, June 1997.

3. Hodge, B. K., and Taylor, R. P., "Integrating Computers and Software into Two Thermal Sciences Courses," Proceedings of the International Conference on Simulation in Engineering Education (ICSEE '95), pp. 195-199, Los Vegas, NV, Jan. 1995.

4. Munson, B. R., Young, D. F., and Okiishi, T. H. *Fundamentals of Fluid Mechanics*. 2nd ed. New York: Wiley, 1994.

5. Hodge, B. K. *Analysis and Design of Energy Systems*. 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 1990.

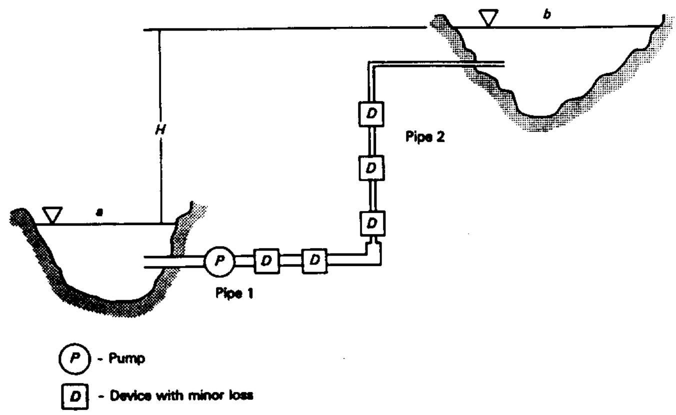

Figure 1. Series Piping System Schematic

Input the initial flow rate guess in cms:

$Q := 1 \cdot \frac{m^3}{sec}$ **Initial guess on flow rate.**

Increase in head of the pump:

$W_s := 5000 \cdot newton \cdot \frac{m}{kg}$

Define the functions for Reynolds number, fully-rough friction factor, and friction factor:

$Re(q,d) := \frac{4 \cdot q}{\pi \cdot d \cdot \nu}$ $\quad f_T(d,\varepsilon) := \frac{0.3086}{\log\left[\left(\frac{\varepsilon}{3.7 \cdot d}\right)^{1.11}\right]^2}$

$$f(q,d,\varepsilon) := \begin{cases} \frac{0.3086}{\log\left[\frac{6.9}{Re(q,d)} + \left(\frac{\varepsilon}{3.7 \cdot d}\right)^{1.11}\right]^2} & \text{if } Re(q,d)>2300 \\ \frac{64}{Re(q,d)} & \text{otherwise} \end{cases}$$

The generalized energy equation is:

Given

$$W_s \cdot \frac{g_c}{g} = \frac{P_b - P_a}{\rho \cdot g} \cdot g_c + Z_b - Z_a + \sum_{i=1}^{N} \frac{8}{\pi^2} \cdot \frac{Q^2}{(D_i)^4 \cdot g} \cdot \left(f(Q,D_i,\varepsilon_i) \cdot \frac{L_i}{D_i} + K_i + C_i \cdot f_T(D_i,\varepsilon_i)\right)$$

$q := Find(Q)$

$q = 2.445 \cdot m^3 \cdot sec^{-1}$ $\quad q = 1.467 \cdot 10^5 \cdot \frac{liter}{min}$

Pump power (input to fluid): $Power := q \cdot \rho \cdot W_s$

$Power = 1.222 \cdot 10^4 \cdot kW$

Additional output of useful quantities:

$i := 1 .. N$ $\quad V(q,D) := \frac{4 \cdot q}{\pi \cdot D^2}$

D_i	$V(q,D_i)$	$Re(q,D_i)$	$f(q,D_i,\varepsilon_i)$	$f_T(D_i,\varepsilon_i)$
$0.3 \cdot m$	$34.584 \cdot m \cdot sec^{-1}$	$9.101 \cdot 10^6$	0.013	0.013
$0.3 \cdot m$	$34.584 \cdot m \cdot sec^{-1}$	$9.101 \cdot 10^6$	0.013	0.013

Figure 2. Series Piping Worksheet Segment

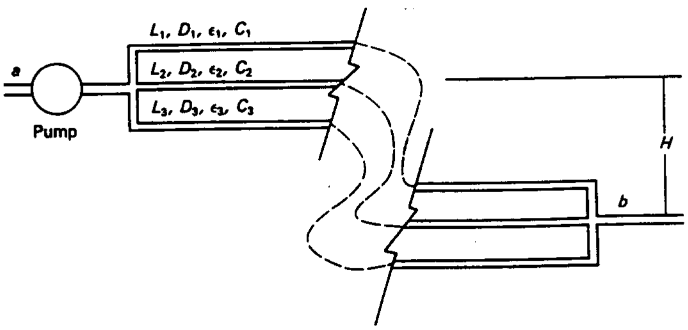

Figure 3. Parallel Piping System Schematic

Setup Solve Block by defining specified inputs and guessed values:

$$Q_T := 5.3\cdot\frac{ft^3}{sec} \qquad Q1 := \frac{Q_T}{N} \qquad Q2 := \frac{Q_T}{N} \qquad W_s := 1\cdot ft\cdot\frac{lbf}{lb}$$

Given

$$Q_T = Q1 + Q2$$

$$W_s\cdot\frac{g_c}{g} = Z_b - Z_a + \frac{8}{\pi^2}\cdot\frac{(Q1)^2}{g\cdot(D_1)^4}\cdot\left(f(Q1, D_1, \varepsilon_1)\cdot\frac{L_1}{D_1} + K_1 + C_1\cdot f_T(D_1, \varepsilon_1)\right)$$

$$W_s\cdot\frac{g_c}{g} = Z_b - Z_a + \frac{8}{\pi^2}\cdot\frac{(Q2)^2}{g\cdot(D_2)^4}\cdot\left(f(Q2, D_2, \varepsilon_2)\cdot\frac{L_2}{D_2} + K_2 + C_2\cdot f_T(D_2, \varepsilon_2)\right)$$

$$\begin{pmatrix} W_s \\ Q1 \\ Q2 \end{pmatrix} := Find(W_s, Q1, Q2)$$

$$W_s = 3.393\cdot\frac{ft\cdot lbf}{lb} \qquad Q1 = 3.824\cdot ft^3\cdot sec^{-1} \qquad Q2 = 1.476\cdot ft^3\cdot sec^{-1}$$

Additional output of useful quantities:

$$i := 1..N \qquad V(q, D) := \frac{4\cdot q}{\pi\cdot(D)^2} \qquad Q_1 := Q1 \qquad Q_2 := Q2$$

D_i	$V(Q_i, D_i)$	$Re(Q_i, D_i)$	$f(Q_i, D_i, \varepsilon_i)$	$f_T(D_i, \varepsilon_i)$
$1\cdot ft$	$4.869\cdot ft\cdot sec^{-1}$	$1.623\cdot 10^5$	0.021	0.02
$0.667\cdot ft$	$4.229\cdot ft\cdot sec^{-1}$	$9.4\cdot 10^4$	0.019	0.013

Figure 4. Parallel Piping System Worksheet Segment.

$$Vol_{fin} := L_{fin}\cdot t_{fin} \qquad Vol_{fin} = 6.9444\cdot 10^{-4}\cdot ft^2 \qquad i := 0..17$$

$$t_{fin_i} := (0.2 - 0.01\cdot i)\cdot in \qquad L_{fin_i} := \frac{Vol_{fin}}{t_{fin_i}}$$

$$Pitch := 0.3\cdot in \qquad W_i := Pitch - t_{fin_i} \qquad L_{c_i} := L_{fin_i} + \frac{t_{fin_i}}{2}$$

$$A_{fin_i} := L_{fin_i}\cdot 1\cdot ft\cdot 2 + t_{fin_i}\cdot 1\cdot ft \qquad A_i := A_{fin_i} + W_i\cdot 1\cdot ft$$

Convective coefficients and thermal conductivity:

$$h_h := 10\cdot\frac{BTU}{hr\cdot ft^2\cdot R} \qquad h_c := 500\cdot\frac{BTU}{hr\cdot ft^2\cdot R} \qquad k := 26\cdot\frac{BTU}{ft\cdot hr\cdot R}$$

$$R_{cond} := \frac{t_{wall}}{k_w\cdot A_{wall}} \qquad Rc_{no} := \frac{1}{h_c\cdot A_{wall}}$$

Fin computations:

$$m_i := \left(\frac{h_h\cdot 2}{k\cdot t_{fin_i}}\right)^{0.5} \qquad \eta_{fh_i} := \frac{\tanh(m_i\cdot L_{c_i})}{m_i\cdot L_{c_i}}$$

$$\eta_{th_i} := 1 - \frac{A_{fin_i}}{A_i}\cdot\left(1 - \eta_{fh_i}\right) \qquad Rh_{f_i} := \frac{1}{\eta_{th_i}\cdot A_i\cdot h_h}$$

$$UA_{ho_i} := \frac{1}{Rc_{no} + R_{cond} + Rh_{f_i}} \qquad PC_{h_i} := \frac{UA_{ho_i} - UA_{no}}{UA_{no}}\cdot 100$$

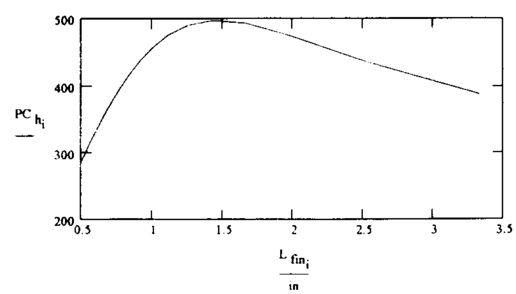

Figure 5. Fin-Walled Performance Worksheet

$$
\text{ShahST}(G) :=
\begin{array}{|l}
tol \leftarrow 1\cdot\frac{lbf}{ft^2} \\
PressD \leftarrow 100\cdot\frac{lbf}{ft^2} \\
\text{while } PressD > tol \\
\quad
\begin{array}{|l}
Re \leftarrow G\cdot\frac{ID}{\mu} \\
Nu \leftarrow 0.023\cdot Re^{.8}\cdot Pr^{0.333} \\
Nu \leftarrow Nu\cdot\left(\frac{\mu_w}{\mu}\right)^{-0.11} \\
J \leftarrow \frac{Nu}{Re\cdot Pr^{0.333}} \\
f \leftarrow f_F(Re, ID, E) \\
f \leftarrow f\cdot\left(\frac{\mu_w}{\mu}\right)^{0.25} \\
h_i \leftarrow Nu\cdot\frac{k}{ID} \\
R1 \leftarrow \frac{1}{h_i} \\
R2 \leftarrow 0.5\cdot\frac{ID}{k_w}\cdot\ln\left(\frac{OD}{ID}\right) \\
R3 \leftarrow \frac{ID}{OD\cdot h_o} \\
U_i \leftarrow \frac{1}{R1 + R2 + R3} \\
A_i \leftarrow NTU\cdot\frac{C_{min}}{U_i} \\
Jf \leftarrow \frac{J}{f} \\
W \leftarrow Q\cdot denin \\
A_o \leftarrow \frac{W}{G} \\
N \leftarrow \frac{A_o\cdot 4}{\pi\cdot ID\cdot ID}
\end{array}
\end{array}
$$

(1)

(1)

$$
\begin{array}{|l}
\quad
\begin{array}{|l}
L \leftarrow ID\cdot\frac{A_i}{4\cdot A_o} \\
T1 \leftarrow K_c + 1 - \sigma^2 \\
T2 \leftarrow 2\cdot(dratio - 1) \\
T3 \leftarrow \frac{f\cdot A_i\cdot denin}{denout\cdot A_o} \\
T4 \leftarrow \left(1 - \sigma^2 - K_e\right)\cdot dratio \\
\Delta P_a \leftarrow G\cdot G\cdot\frac{T1 + T2 + T3 - T4}{2\cdot denin} \\
G \leftarrow \left(\frac{2\cdot\Delta P_r\cdot denin}{T1 + T2 + T3 - T4}\right)^{0.5} \\
PressD \leftarrow \left|\Delta P_r - \Delta P_a\right|
\end{array} \\
OT_0 \leftarrow N \\
OT_1 \leftarrow L \\
OT_2 \leftarrow G \\
OT_3 \leftarrow \Delta P_a\cdot\frac{ft^2}{lbf} \\
OT_4 \leftarrow f \\
OT_5 \leftarrow Jf \\
OT_6 \leftarrow h_i\cdot hr\cdot ft^2\cdot\frac{R}{BTU} \\
OT
\end{array}
$$

$ans := \text{ShahST}(G)$

ans =	
79.782	Number of tubes
25.51	Tube length, ft
$1.21\cdot10^3$	G, lb/ft² s
$2.304\cdot10^3$	Pressure drop, lbf/ft²
$5.007\cdot10^{-3}$	friction factor, f
0.445	J/f
$2.826\cdot10^3$	h_i, BTU/ft² hr F

Figure 6. MathCad Computer Program ShahST.mcd for Shell-and-tube heat Exchanger Design

$W_s := 100\cdot ft\cdot\frac{lbf}{lb}$ **(Initial guess of pump increase in head.)**

$Q := 50\cdot\frac{gal}{min}$ **(Initial guess of flow rate.)**

Given

$$W_s = vp_4\cdot ft\cdot\frac{lbf}{lb} + vp_5\cdot\frac{ft\cdot lbf\cdot min}{lb\cdot gal}\cdot Q + vp_6\cdot\frac{ft\cdot lbf\cdot min^2}{lb\cdot gal^2}\cdot Q^2 + vp_7\cdot\frac{ft\cdot lbf\cdot min^3}{lb\cdot gal^3}\cdot Q^3$$

$$W_s\cdot\frac{g_c}{g} = \frac{P_b - P_a}{\rho\cdot g}\cdot g_c + Z_b - Z_a + \frac{8}{\pi^2}\cdot\frac{Q^2}{g\cdot(D)^4}\cdot\left(f(Q,D,\varepsilon)\cdot\frac{L}{D} + K + C\cdot f_T(D,\varepsilon)\right)$$

$\begin{pmatrix} W_s \\ Q \end{pmatrix} := \text{Find}(W_s, Q)$ $\quad W_s = 394.576\cdot ft\cdot\frac{lbf}{lb}$ $\quad Q = 100.327\cdot\frac{gal}{min}$

Pump power (input to fluid): $Power := Q\cdot\rho\cdot W_s$

$Power = 9.991\cdot hp$

Additional output of useful quantities:

$V(q,d) := \frac{4\cdot q}{\pi\cdot(d)^2}$ $\quad V(Q,D) = 4.554\cdot ft\cdot sec^{-1}$ $\quad Re(Q,D) = 1.078\cdot10^5$

$D = 0.25\cdot ft$ $\quad f(Q,D,\varepsilon) = 0.02$ $\quad f_T(D,\varepsilon) = 0.017$

Figure 7. Pump System Operating Point Worksheet Segment.

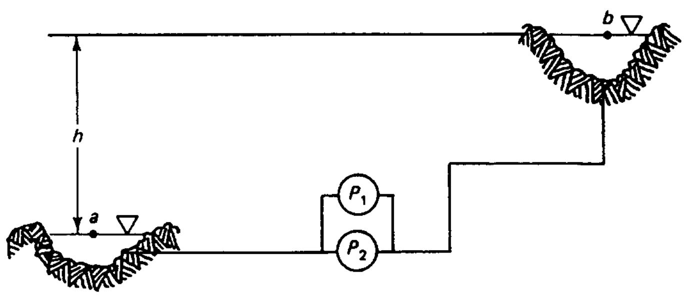

Figure 8. Parallel Pump System Schematic

$\Delta H := 575$ --Initial guess of head change

$Q_T := 4.0$ --Initial guess for total flow rate

$Q_1 := 2$ --Initial guess for flow rate for pump 1

$Q_2 := 2$ --Initial guess for flow rate of pump 2

Specify the system of equations inside a ***Given*** command.

Given

$Q_T = Q_1 + Q_2$	Conservation of mass
$\Delta H = 18.72\cdot Q_T^2 + 300$	Energy equation
$\Delta H = 740. + 40.579\cdot Q_1 - 39.21\cdot Q_1^2$	Pump 1 characteristics
$\Delta H = 740. + 40.579\cdot Q_2 - 39.21\cdot Q_2^2$	Pump 2 characteristics

Use the ***Find*** command to obtain the solution.

$ans := \text{Find}(\Delta H, Q_T, Q_1, Q_2)$

ans =	
646.035	ΔH, ft-lfb/lbm
4.299	Q_T, gpm
2.15	Q_1, gpm
2.15	Q_2, gpm

Figure 9. Parallel Pump System Operating Point Worksheet

B. K. HODGE

Dr. Hodge received his aerospace engineering BS and MS degrees from Mississippi State University (MSU) and his mechanical engineering MS and PhD from the University of Alabama. He has worked for Thiokol Corporation and Sverdrup (AEDC). Currently he is a Giles Distinguished Professor, a Hearin-Hess Professor of Engineering, and Professor of Mechanical Engineering at MSU where he teaches graduate and undergraduate courses in the thermal sciences and conducts related research. In 1993 he was named as one of four Master Teachers at MSU. Since joining the faculty Dr. Hodge has developed six new courses and written two textbooks. He serves as the undergraduate coordinator for the mechanical engineering program at MSU.

R. P. TAYLOR

Dr. Taylor received the BS and PhD in mechanical engineering from Mississippi State University and the MS in mechanical engineering from Purdue University. From 1975-1978, he worked for Texaco Inc. in Houston, Texas, as a mechanical engineer. Currently he is a Herrin-Hess Professor of Engineering and Professor of Mechanical Engineering. Dr. Taylor teaches courses in the thermal sciences and experimental procedures and conducts research in heat transfer, fluid mechanics, and uncertainty analysis. He directs the nationally-recognized surface roughness boundary-layer program at MSU and has made substantial contributions in the use of uncertainty analysis in experimentation and thermal systems design.