

AC 2003-366: TEST - THE EXPERT SYSTEM FOR THERMODYNAMICS

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TEST-The Expert System for Thermodynamics

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Abstract: Just as calculators revolutionized engineering problem solving, the day has come for web-delivered domain-specific software tools to bring about the next revolution in engineering education and practice. Students can not only solve a problem online, but conduct parametric studies, simulate engineering systems and gain an insight which is not possible in a traditional set up. Web delivery means the software is available anywhere, anytime from classroom to the dormitory without the hassles of installation, upgrades, or compatibility with operating systems.

Such a web-based tool, TEST, The Expert System for Thermodynamics, is being developed at San Diego State University for a comprehensive education of engineering thermodynamics. TEST is more than a thermodynamic calculator. It combines hundreds of HTML pages with the power of Java programming to offer a visual environment over the web to analyze thermodynamic problems, obtain paperless solution, plot thermodynamics graphs, generate solutions and reports, spreadsheet friendly thermodynamic tables, pursue what-if scenarios after a problem is solved, and produce TEST-Code which can be stored or emailed to regenerate a solution instantly. The topics covered include state evaluation, energy, entropy and exergy analysis, closed and open cycles, refrigeration, air-conditioning, combustion and gas dynamics.

Engineering systems are introduced through animations and classified according to how the governing equations simplify - open vs. closed systems, for instance. Once a system is classified, choosing an appropriate model for the working fluid - ideal gas, real gas, phase-change model, etc. - launches a Java Applet, called a daemon in TEST, which has the knowledge of the working fluid properties as well as the simplified form of the mass, energy, entropy, and exergy equations for the particular system. The expert system not only helps one solve a problem fast and accurately but also helps detect logical inconsistencies in the specifications of the input variables. If pressure and temperature are entered for an ideal gas, the daemon will prevent a user (with appropriate warning) from specifying the gas density. But the main advantage of the visual environment is the ease with which parametric studies can be performed. Because all the variables of a problem are visually exposed, any conceivable what-if scenario can be pursued with the click of a button without a single line of programming.

The usage of TEST is growing steadily. It has been installed in 175 different universities around the world and mirrored in nine different countries. More than 10,000 educators, professionals and students have registered although no registration or fee is necessary to use the site. TEST can be freely accessed from any of its mirror sites, which are linked from www.prenhall.com/thermo.

Introduction: In the last decade a number of software for thermodynamic analysis have been developed. The ASME provides a comprehensive database for thermodynamics analysis [1]. EES [2] is a comprehensive thermodynamic programming language that works under Windows environment. TPX [3] is an Excel plug-in where the core thermodynamic state can be evaluated

by entering two independent properties. Thermoptim [4] is a java-based software for analyzing thermodynamic cycles and can be run over the web. A graphical menu driven installable program is GasCAD [5]. The Qualitative Reasoning Group at Northwestern University has developed Windows installable CyclePad [6], which allows users to construct and analyze a wide variety of thermodynamic cycles. None of these packages, however, are designed to be integrated with thermodynamic textbooks

TEST is a web of carefully constructed HTML pages with schematics, equations, animations, thermodynamic explanations, and embedded Java Applets, called daemons, organized in a hierarchical tree structure. It is a general-purpose visual tool for solving thermodynamic problems and performing what-if scenarios online for students and professionals.

Overview: Briefly here is how TEST works. A problem solving session begins with the assumption of a most general system and the user is asked to modify the system according to the problem description by choosing a branch from a table of choices offered sequentially. As more specificity is added to a system (open vs. closed system for example), the changes in the system schematic and governing equations (mass, energy and entropy balance equations) are displayed. Finally the working fluid is chosen and a customized Java application, called a daemon, aware of material properties and governing equations for this particular problem is launched. (Takes about 10-60 seconds over the Internet and less than 2 seconds when locally installed).

Like Maxwell's demon, this custom calculator is a thermodynamic wizard that takes care of the menial task of a solution. The core of every daemon is its robust state calculator, which bundles an extended state (p , T , u , h , e , s etc.) into a single graphical interface called a State. A user enters any known state variables in any preferred units and calculates the state with the click of a Calculate button. The daemon checks for redundancy in inputs, determines phase composition, and plots simple thermodynamic diagrams (such as the T - s diagram, psychrometric plot etc.). Use of Excel type algebraic expressions makes it easy to construct related states (for instance, entropy for State-2, isentropic to State-1, can be entered as '=s1').

The calculated states are loaded onto the problem specific Analysis Panel as the inlet or exit (initial or final) states for a device (or a process). The panel displays the customized balance equations and a system schematic that dynamically adjusts to the choices made by the user. After the known device (or process) variables such as heat transfer or work transfer are entered, a click on Super-Calculate button solves the balance equations, transfers calculated state variables to the State Panel, recalculates the states based on the new information, and displays a detailed output in the I/O Panel. In the analysis of cycles, multiple devices (or processes) are loaded into the Cycle Panel where the cycle variables are automatically calculated after the completion of device (or process) calculations. These steps, almost identical to a manual solution procedure, may sound complicated, but are quite easy to follow in a visual environment.

The fun, however, begins after one finishes a detailed solution. Because all the variables are directly accessible, one can study any conceivable what-if scenario by simply changing one or more variables and updating all calculations by a single click (as in a spreadsheet). A simple problem of finding the mass of water vapor in a room can be converted to a humidifier design exercise by studying the water requirement to achieve a desired relative humidity. A study of

how condenser pressure affects the thermal efficiency of a Rankine cycle can be instantly turned around to see the effect of boiler pressure, or the turbine efficiency, or the maximum temperature - all without a single line of programming. This is especially useful for educators who want to back up theoretical conclusions with a quick in-your-face confirmation right in the classroom.

TEST produces a complete solution rather than a narrow answer. For instance, in a problem to determine the nozzle exit velocity, the exit area is also calculated providing a more comprehensive insight. With the click of a button the visual solution generates detailed printer-friendly output and spreadsheet-friendly property table. Because Java applets are vaporware, there is no built-in mechanism to regenerate a solution. TEST offers its unique TEST-Code, that is automatically generated with every visual solution. The TEST-Code can be simply copied and pasted on any local word-processor. At a later session, the code, pasted back on the daemon's I/O panel, instantly regenerates the visual solution.

Navigation: TEST can be launched (Fig. 1) by clicking the *index.html* file in a locally installed copy or pointing a browser to <http://www.thermofluids.net>.

At the bottom of the display window (see Fig. 1), a ribbon of links or the Task Bar permanently connects the user with all the major components of TEST. Except for the Tutorial and the Problems, which appear on floating windows, all other components are displayed right above the Task Bar. For instance, Fig. 2 shows the Home>Daemons>Systems page, which appears when the Daemons link on the Task Bar is clicked followed by the Systems link.

There are several features in Fig. 2 that are common to all TEST pages. The header consists of a title for the page followed by a unique hierarchical address of the page (Home>Daemons>Systems in Fig. 2). The icons that link the current page to its ancestor pages are designed to remind the user the series of assumptions that lead to the current page. They also provide direct links to all the nodes that precede the current page.

The TEST-Map (Fig. 3) presents the organizational chart of various modules and allows an experienced user to directly navigate to a desired node bypassing the page-by-page alternative offered by the simplification tables that appear directly below the page header.

Simplification Pages: Most TEST pages offer a simplification table (see Fig. 2) that can be used for further simplification of the governing equations leading ultimately to an appropriate daemon. The table, displayed right under the page header, provides guidelines for choosing an appropriate path. A system animation and the governing balance equations that fit the description of the system at hand are also displayed on the same page. A single frame of the animation and the customized equations for an open system undergoing a process is shown in Fig. 4. The animation and the equation set adjust to the assumptions made as the user continues simplification. Systems are organized in two stems – generic systems, which handle most problems typically encountered in the first half of thermodynamic textbooks, and specific systems, which are application specific and are generally found in the second half of the texts. Both generic and specific systems are classified according to the charts shown in Fig. 3. Each branch in this chart represents a large class of problems. For instance, a steam turbine would fall

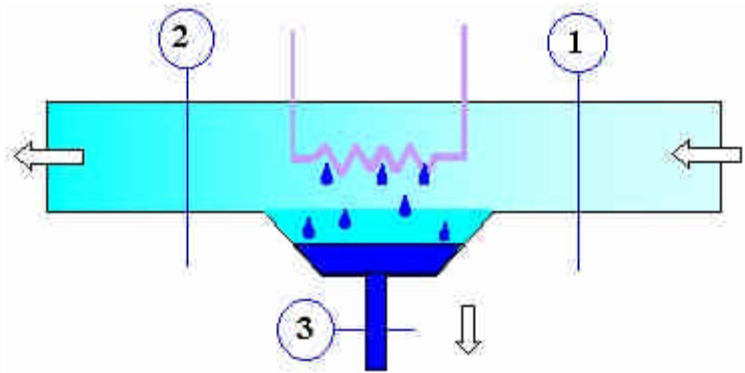
under the generic, open, steady branch while the analysis of an internal combustion cycle should be carried out under the specific, closed, process branch.

Material Models: After appropriate assumptions are made to simplify a system, the last step in launching a daemon is the selection of a material model for the working fluid. For evaluation of a state, Fig. 6 displays the available material models. In addition to the phase-change (PC), solid/liquid (SL), perfect gas (PG), ideal gas (IG) and real gas (RG) models, TEST also offers various mixture models.

Hands on Tutorial: A look at the TEST-Map (Fig. 3) reveals the depth and the richness of the TEST-tree encompassing almost all aspects of undergraduate engineering thermodynamics. The tutorial section presents some of the capabilities of TEST in solving problems from almost any chapter in a thermodynamics textbook. Here we give just one example of using TEST for problem solving and parametric studies for a fairly complex problem.

EXAMPLE Moist air 40°C and 90% R.H. enters a dehumidifier at the rate of 300 m³/min with a velocity of 10 m/s. The condensate and the saturated air exit at 10°C through separate exits. The pressure remains constant at 100 kPa.

Determine (a) the mass flow rate of dry air, (b) the exit velocity (assume the exit area to be the same as the inlet area) (c) the water removal rate, and (d) the required refrigeration capacity, in tons. (e) **What-If Scenario:** How would the answer in part c change if the pressure were 1000 kPa?



SOLUTION:

A. Choose the appropriate daemon.

Classify the system as Open>Steady> Specific> HVAC and navigate to the corresponding page on the primary window using page-by-page navigation or the TEST-Map. There are one inlet and two exits for the open system. Let us use State-1 for the i1-State, State-2 for the e1-State, and State-3 for the e2-State as shown in the problem schematic.

B. Evaluate states as best as possible. Choose State-1, enter T1=40 deg-C, RH1=90%, Voldot1=300 m3/min, Vel1=10m/s. The default pressure is 100 kPa. Calculate. The mass flow rate of dry air is calculated as: mdot1=311 kg/min (see Fig. 7).

Choose State-2. Enter p2 as '=p1', RH2=100%, and T2=10 deg-C and A2 as '=A1'. Make Vel2 an unknown. Calculate (see Fig. 8). The state is partially calculated at this point.

Choose State-3. Choose Condensed Water as the working fluid. Enter p3 as '=p1' and T3 as '=T2'. Calculate (see Fig. 9).

C. Solve balance equations. Go to the Analysis panel and load State-1 as the i1-State, State-2 as the e1-State and State-2 as the e1-State. Enter the known device variable Wdot_O (=0 kW).

Calculate and Super-Calculate. Go to the States panel to find the answer: $\dot{m}_3=11.44$ kg/min. All the other answers are displayed on the images (Fig. 7-9)

D. Change parameter and Super-Calculate. For the parametric study, simply change p_1 to the new value (1000 kPa). A Calculate and a Super-Calculate produce: $\dot{m}_3=11.31$ kg/min.

TEST Features: Unlike other visual applications, TEST reinforces a student's understanding of thermodynamics by sticking to the traditional approach of thermodynamic problem solving – simplify the system, choose a material model, evaluate the relevant states, customize the balance equations, solve the balance equations, iterate between state evaluations and the solution of the balance equations to produce the desired solution. There are many features of TEST that are quite useful in learning thermodynamics. Some of those are listed below.

- To evaluate a thermodynamic state, elect a material model (Fig. 5), choose the working fluid, enter the known variables on a simple form and click the Calculate button. The state (defined as an extended set of variables related to the local thermodynamic equilibrium) is partially or completely evaluated depending on the amount of information supplied.
- The solution procedure for finding a state remains identical no matter how complex is the material model, keeping the learning curve to a minimum. For phase-change fluids, the phase composition is part of the solution. For ideal gases, there is no need to calculate the intermediate reduced variables. For complicated materials such as moist air, real gases, or a gas mixture, new state variables are added, but the look and feel or the evaluation method do not change. For gas mixtures, of course, the composition must be supplied.
- Although a student may be interested in a single property, the daemon displays the entire state giving a complete picture. A curious student may easily find out, for instance, how changing the temperature would affect the entropy of the state.
- A good amount of details have gone into the construction of the state panel (See Figs. 6 and 7). Variables are color-coded, blue for thermodynamic properties, red for material properties, green for extrinsic properties and black for system variables. Moving the pointer over any variable displays its definition and the current value on the message panel. Different background colors are used to display the calculation status of each variable, green for the user input, cyan for the calculated values and gray for the deduction from the balance equations.
- If the inputs to a state are inconsistent (for instance a student try to enter values for two dependent variables, say, density and specific volume), the daemon warns the user and does not allow the solution to proceed.
- Variables can be entered in any units (English, SI or mixed) at any order, and the solution can be converted to any desired set of units at any time with a single click. Mixed units are also allowed.
- In calculating a related state, algebraic equations can be used (see Fig. 6), making parametric studies feasible. The format used is that of Microsoft Excell, which many students are already familiar with.

- Thermodynamic plots, such as the p-V, T-s, h-s diagrams etc., can be instantly plotted to discern accuracy of the evaluated states (see Fig. 11). The data used in the plot can be displayed in a spread sheet format for further processing.
- Exergy - both stored and flow exergy-are calculated as part of the state properties if the designated dead state (State-0) is evaluated first.
- The system daemons build upon the state daemons. Mass, energy, entropy and exergy balance equations can be solved for closed processes or steady devices. The cycle daemons build upon the system daemons in a similar manner. The particular form of the balance equation used by a daemon is displayed right inside the equation panel of the applet (see Fig. 9).
- The system schematic that is displayed inside the Analysis Panel is dynamic in that, when states are loaded as inlet, exit, begin or finish states, the diagram is automatically updated to reflect the choices made.
- Once a solution is obtained, Super-Calculate produces a detailed output and a few lines of codes called the TEST-Code describing the solution algorithm. The TEST-Code can be saved and used to regenerate the visual solution instantly at a later time. A visual solution can be emailed through TEST-Codes, making group effort to solve a problem over the net possible.
- The I/O Panel of all TEST daemons can be used as a scientific calculator. The syntax used is that of Microsoft Excel. The calculator also recognizes any computed state variables. For example, $'=\text{Sin}(30)*p1*(v2/v1)^{1.4}'$ is a valid expression if $p1$, $v2$ and $v1$ are known..
- The detailed output produced by a solution on the I/O window can be copied to other applications for saving or printing. Part of the output is a spreadsheet friendly table that can be copied to any spreadsheet software.
- After a problem is solved, a parametric study is a simple matter of changing a variable and clicking the Super-Calculate button. Because all the variables of the problem are visually exposed every possible combination of variables can be altered or played with for a user to pursue what-if scenarios. This feature can be valuable, particularly in the second course in thermodynamics with its emphasis on engineering design.
- Super-Calculate also produces what is called the TEST-Code (see Fig. 10). The code can be copied to any word processor and saved for later use. To regenerate the solution instantly, copy the code back on this panel, use the Load button and then the Super-Calculate button.
- Written in Java and HTML, TEST is a complete web ware. It is not necessary to install TEST, all that is required is a modern web browser. This feature makes it particularly easy to upgrade TEST to the latest version.

Conclusions: TEST is freely accessible to anyone online from www.thermofluids.net. Even registration is optional; nevertheless, more than 10,000 students, educators and professionals have registered. Educators are sent free CD's for installation of TEST in their PC's. Many universities have created mirror site for TEST for faster access. Precisely how many people are using TEST is difficult to know. But the access statistics from one of the SDSU server is summarized in Fig. 12. A visual manual for TEST has been recently published [7] by Prentice Hall. Some of the daemons have been reviewed and included in various public domain educational web sites such as the MERLOT project [8]. Judging from the comments received

from educators, it is fair to say that TEST has the potential to become a very useful tool for thermodynamics education. Work is currently underway to develop a chemical equilibrium module.

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- [8] The MERLOT project <http://www.merlot.org>

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Address <http://www.thermofluids.net/>



The Expert System for Thermodynamics[®]

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www.thermofluids.net

WEB EDITION

On Line

Your Email:

*

Student
 Educator
 Professional
 Others

Registered-
 Students = 6758
 Educators = 1579
 Professionals = 2640

"Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you any more."

- Arnold Sommerfield

Welcome to TEST, a visual environment to solve problems, pursue what-if scenarios, perform numerical experiments, and have fun learning thermodynamics! Take a [Feature Tour](#) (5 min) or, better, browse a few slides from the [Slide Show](#) (20 min) and put TEST to use without a learning curve.

Begin a systematic problem solving session in the world of [Daemons](#) - smart thermodynamic calculators customized for specific classes of problems. If you are an advanced user, navigate the [Map](#) to launch a daemon directly. The [Tutorial](#) provides hands-on instructions to complement the [Slide Show](#). The [Problems](#) contains 15 chapters of solved examples and TEST-Codes - solution macros that can be loaded to instantly recreate the visual solutions ready for parametric studies.

If speed is a problem, [mirror](#) TEST free or acquire a TEST-CD . Serious users should consider acquiring TEST-Pro, the professional version of TEST.

MIRROR

Visual Solution For The What-If People

AUTHOR

Home

Daemons

Map

SlideShow

Tutorial

Problems

Comments


TEST-CD

Help

6.9

Fig. 1 Image of the TEST Home Page (www.thermofluids.net), the starting point of all TEST solutions. The buttons on the Task Bar at the bottom provide access to different modules.

System Daemons: Closed or Open
[HOME](#) [Daemons](#) [Systems](#)

test 

Classify the system you are analyzing and select a branch.



Closed System Daemons		<p>If there is no mass transfer across the boundary, the system is <i>closed</i>. Problems involving a closed system - a block of solid, steam in a closed container, a gas trapped in a piston-cylinder device, a heat engine, or a refrigerator may involve a transfer of heat and work, but no mass, between the system and its surroundings.</p> <p>You inspect only the boundary of the control volume to detect the presence or absence of mass transfer. There may be mass flow among different components of a refrigerator, but this internal mass transfer in no way affects the conclusion that the refrigerator, in its entirety, is a closed system with only heat and work transfer with the surroundings.</p>
Open System Daemons		<p>A system with mass transfer, in addition to possible work and heat transfers, across its boundary is an <i>open</i> system. Pumps, compressors, diffusers, turbines, pipes, and nozzles are examples of open systems.</p>

Fig. 2 : Each TEST page, like this Daemon Page, has a similar layout.

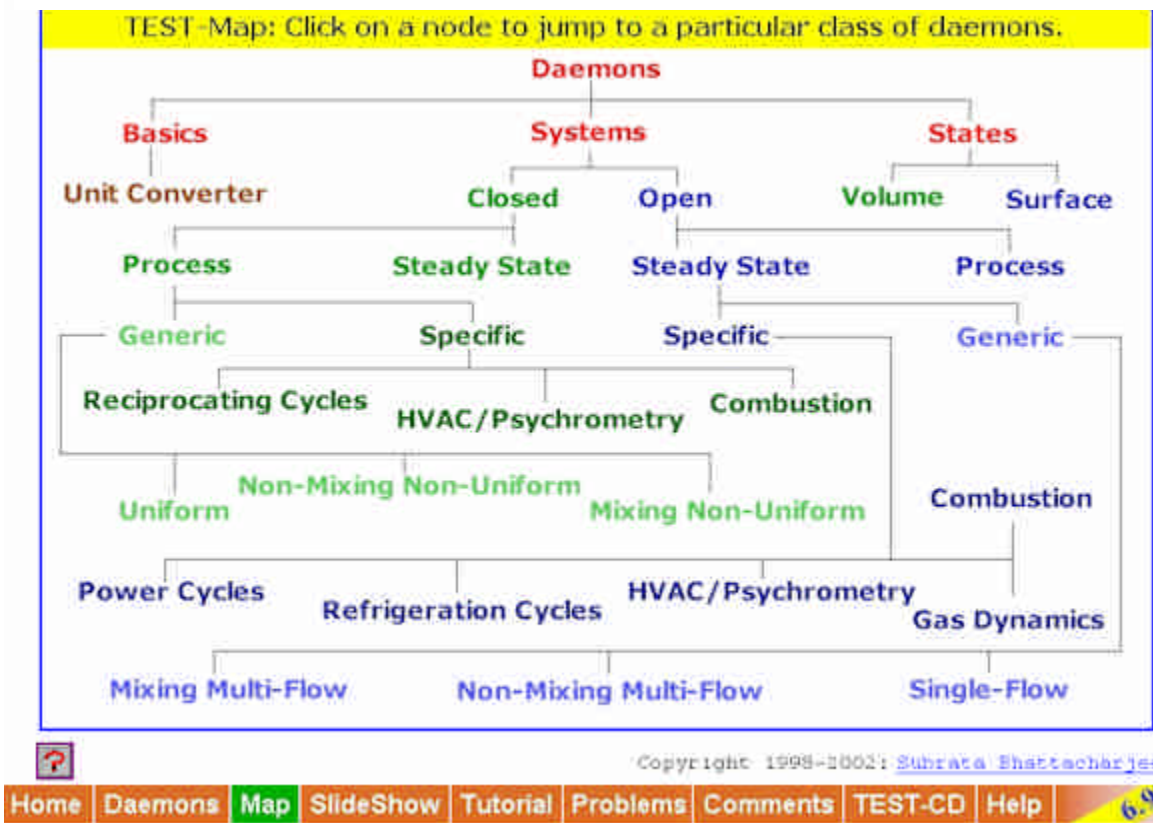


Fig. 3 Image of the TEST Map displaying the tree-structure of TEST. Experienced users can jump to a page using this map bypassing the step-by-step navigation..

<p>System</p>	
<p>Balance Equations</p>	<p>Mass: $\Delta m = m_f - m_b = \sum_i m_i - \sum_e m_e \quad [\text{kg}]$</p> <p>Energy: $\Delta E = E_f - E_b = \sum_i m_i j_i - \sum_e m_e j_e + Q - W_{\text{ext}} \quad [\text{kJ}]$</p> <p>Entropy: $\Delta S = S_f - S_b = \sum_i m_i s_i - \sum_e m_e s_e + \frac{Q}{T_B} + S_{\text{gen}} \quad \left[\frac{\text{kJ}}{\text{K}} \right]$</p> <p>Exergy: $\Delta \Phi = \Phi_f - \Phi_b = \sum_i m_i \psi_i - \sum_e m_e \psi_e + \sum_k Q_k \left(1 - \frac{T_0}{T_k} \right) - I \quad [\text{kJ}]$</p>
<p>Copyright 1998-2002: Subrata Bhattacharjee</p>	
<p>Home Daemons Map SlideShow Tutorial Problems Comments TEST-CD Help 6.9</p>	

Fig. 4 Partial image of the Open Process page. The system animation and the governing balance equations for this particular class of problems appear under the simplification table (not shown).

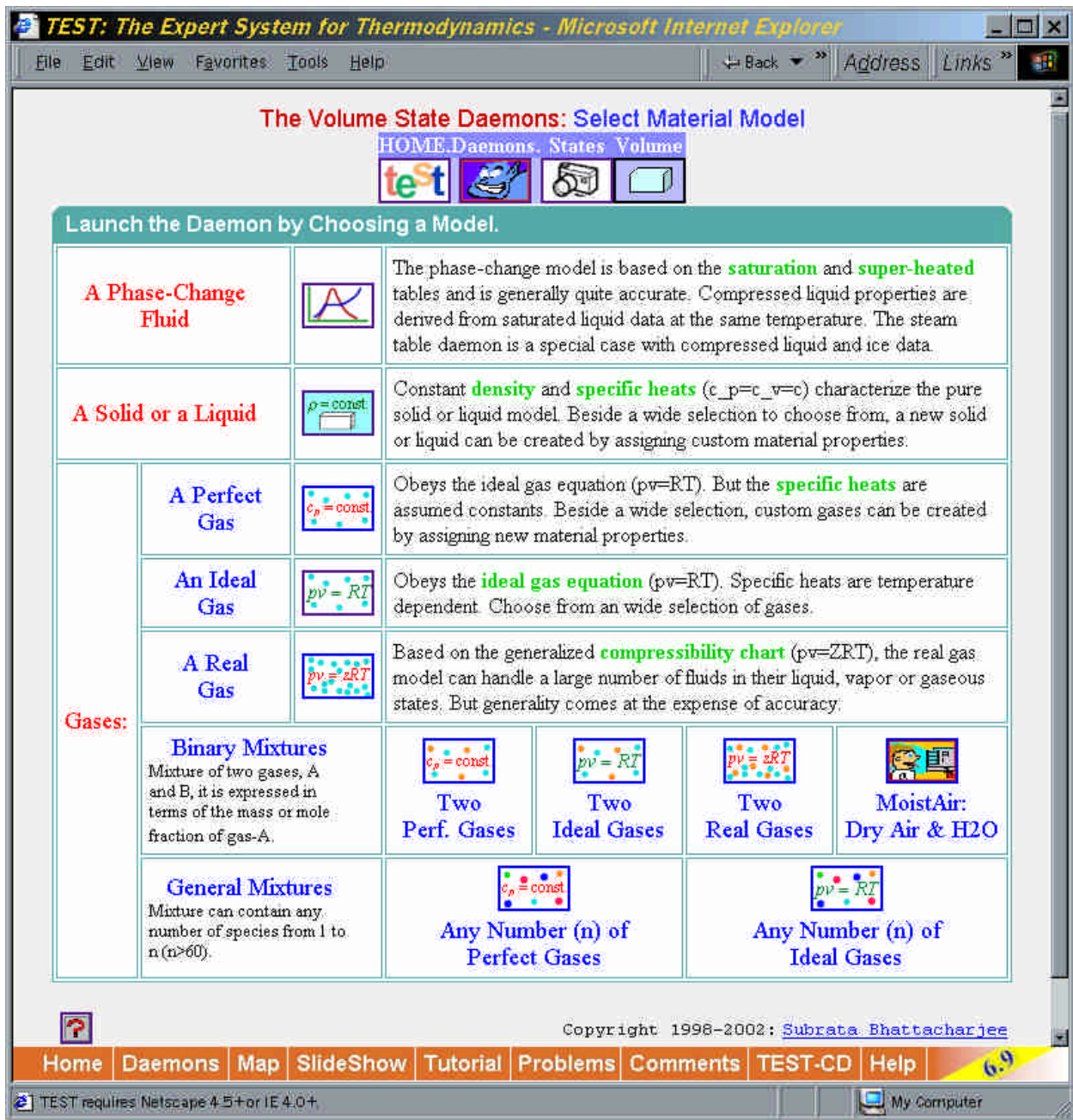


Fig. 5 Many different models are offered by TEST to model the working fluid. Selecting a working fluid model is the last step to launch a daemon.

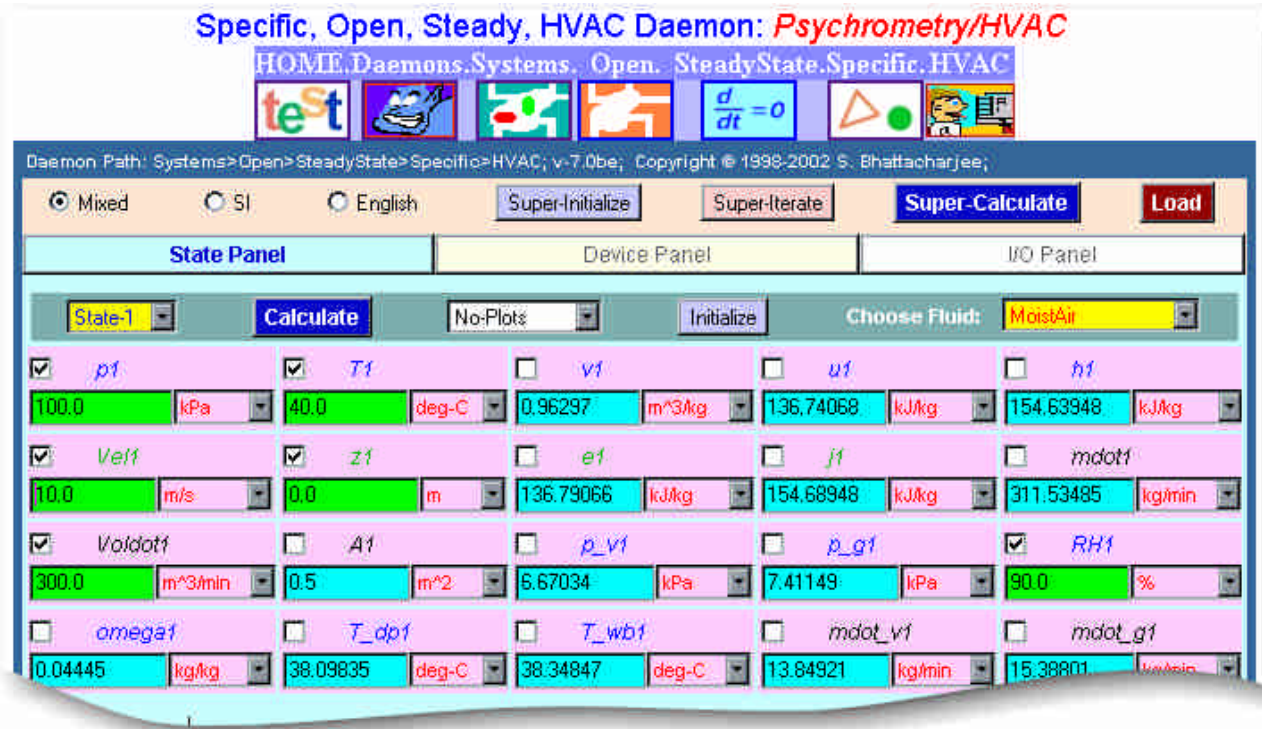


Fig 6 The HVAC daemon has three tabbed panels, States, Device-Analysis and I/O. State-1 is shown after the calculations are completed.

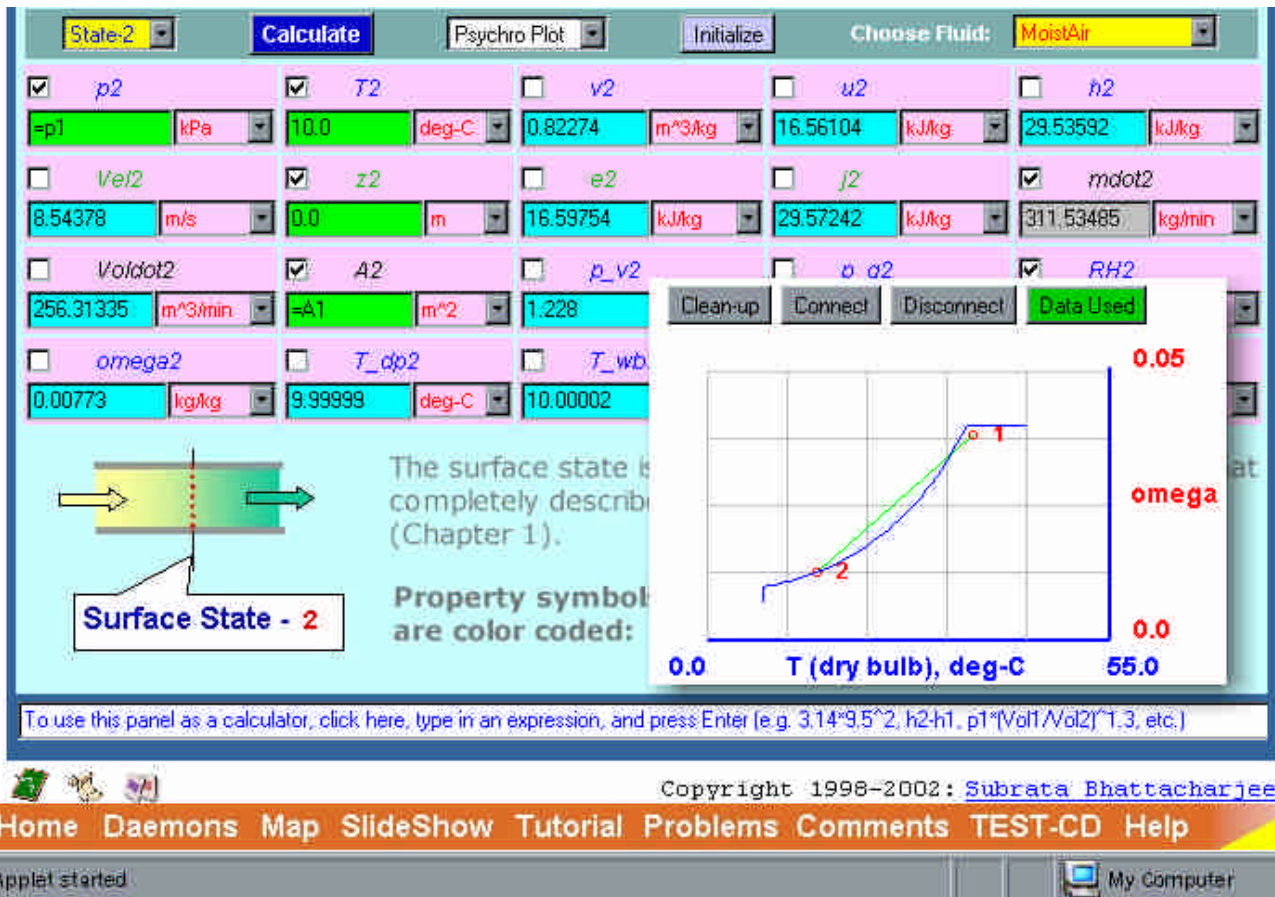


Fig 7 Image of State-2 after Super-Calculate. Superposed is a plot generated by the Psychrometric Plot option. *Proceedings of the 2003 American Society for Engineering Education Annual Conference & Exposition Copyright 2003, American Society for Engineering Education*

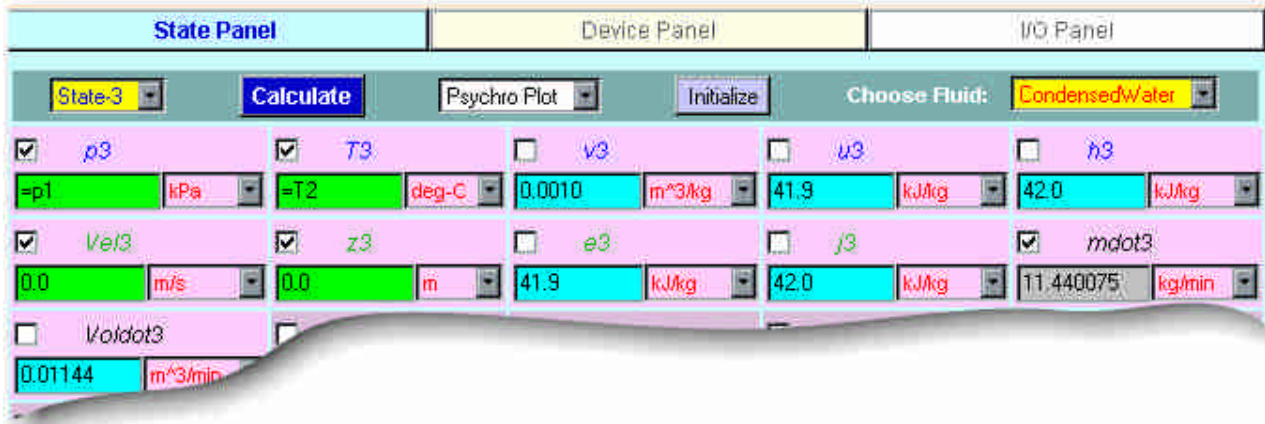


Fig 8 Image of State-3. $mdot3$, calculated on the Device Panel is posted here as indicated by its gray background.

Open Steady Device - A

Mass: $\dot{m}_{i1} + \dot{m}_{i2} = \dot{m}_{e1} + \dot{m}_{e2}$

$\dot{m}_{H_2O,i1} + \dot{m}_{H_2O,i2} = \dot{m}_{H_2O,e1} + \dot{m}_{H_2O,e2}$

Energy:

$$0 = \underbrace{(\dot{m}_{i1} J_{i1} + \dot{m}_{i2} J_{i2})}_{\dot{J}_{in}} - (\dot{m}_{e1} J_{e1} + \dot{m}_{e2} J_{e2}) + \dot{Q} - \dot{W}_{ext}$$

Note: By using appropriate combinations, this versatile device can be used for simple heating, cooling, humidification, or dehumidification.

The schematic diagram shows a steam injection cooling coil. Steam is injected at port $i2$. Cooling water enters at port $i1$ and exits at port $e1$. Condensate exits at port $e2$. The heat transfer rate is \dot{Q} and the external work rate is \dot{W}_{ext} .

Fig 9 The Device Panel displays the balance equations that are solved. If a state variable is evaluated, it is automatically posted back onto the state panel. The device diagram is dynamically updated as the inlet and exit ports are labeled.


```

Mixed SI English Super-Initialize Super-Iterate Super-Calculate Load
State Panel Device Panel I/O Panel
#####
#
#-----Start of TEST-Codes-----
States
{
State-1: MoistAir;
Given: { p1= 100.0 kPa; T1= 40.0 deg-C; Vel1= 10.0 m/s; z1= 0.0 m; Volldot1= 300.0 m^3/min; RH1= 90.0 %;

State-2: MoistAir;
Given: ( p2= "p1" kPa; T2= 10.0 deg-C; z2= 0.0 m; A2= "A1" m^2; RH2= 100.0 %; )

State-3: CondensedWater;
Given: { p3= "p1" kPa; T3= "T2" deg-C; Vel3= 0.0 m/s; z3= 0.0 m; }
}

Analysis
{
Device-A: i-State = State-1; e-State = State-2, State-3; CoolingTower: false;
Given: { Wdot_ext= 0.0 kW; }
}
#-----End of TEST-Codes-----

```

Fig. 10. TEST-Code created by Super-Calculate which can be used to reproduce the visual solution.

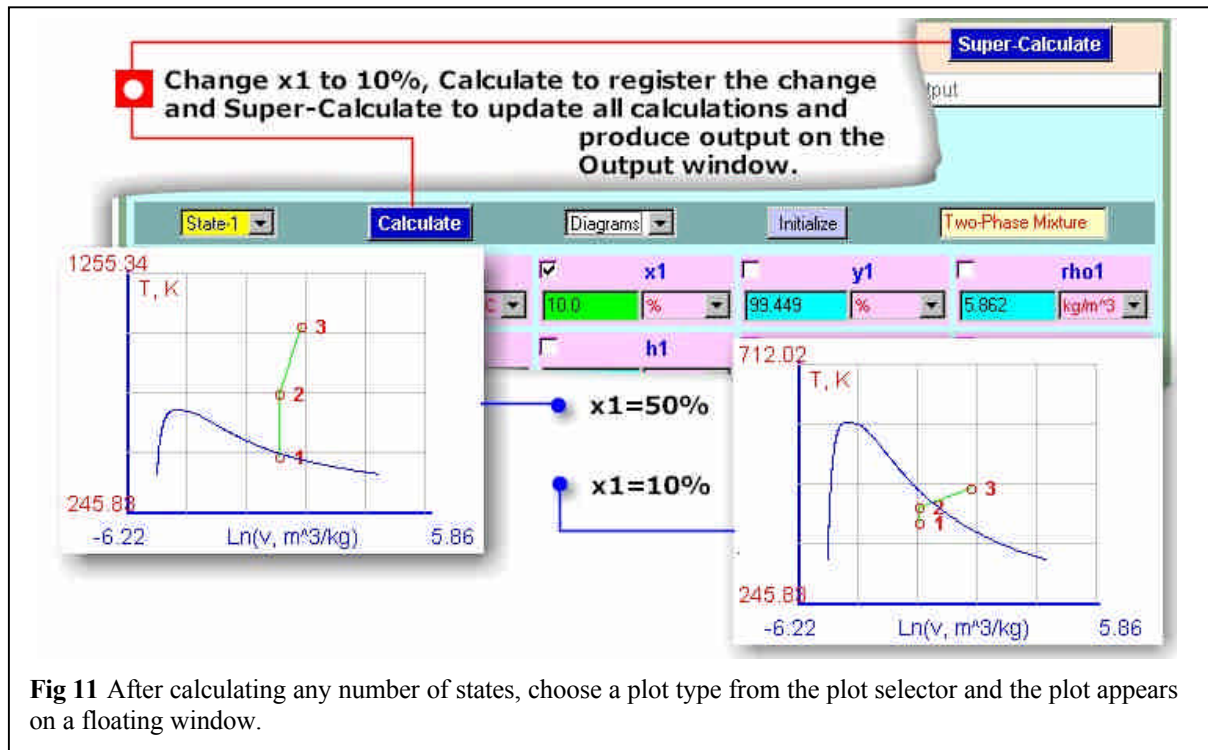


Fig 11 After calculating any number of states, choose a plot type from the plot selector and the plot appears on a floating window.

General Summary

Program started at Thu, Dec 05 2002 00:00.

Analyzed requests from Fri, Feb 19 1999 16:01 to Thu, Dec 05 2002 01:01 (1384.4 days).

(Go To: [Top](#): General Summary: [Monthly Report](#): [Daily Report](#): [Domain Report](#): [Host Report](#): [Status Code Report](#): [Request Report](#): [Failure Report](#))

(Figures in parentheses refer to the last 7 days).

Successful requests: 5,641,138 (71,121)

Average successful requests per day: 4,074 (10,160)

Successful requests for pages: 1,187,994 (12,103)

Average successful requests for pages per day: 858 (1,728)

Failed requests: 224,835 (1,062)

Redirected requests: 18,366 (58)

Distinct files requested: 13,950 (3,362)

Distinct hosts served: 107,821 (2,173)

Corrupt logfile lines: 44

Unwanted logfile entries: 2,114,349

Data transferred: 48,861 Mbytes (839,963 kbytes)

Average data transferred per day: 36,142 kbytes (119,994 kbytes)

Fig 12 Access statistics for the server <http://eng.sdsu.edu/testcenter>.