

2.3 Introduction to EES

Engineering Equation Solver (EES)

- EES solves non-linear sets of equations
 - » iterative solution technique starting from the Guess values
- Equations CAN (but shouldn't usually) be entered in any order
- EES will check that there are enough equations & unknowns
- There are sets of equations for which no solution exists
- Equations are entered in the Equations window
 - » EES is NOT case sensitive
 - » Variable names must start with a letter
 - » 1 equation per line
 - » typical rules (^, *, /, +, -)

Annotating EES Code

- Your equations can be annotated to make the problem more understandable
 - » use comments “”, or {}
 - » comments do not affect the solution

"EXAMPLE 3-2: Energy absorption in a lens"

k=1.5 [W/m-K] "conductivity"
L=1 [cm]*convert(cm,m) "lens thickness"
alpha=0.1 [1/mm]*convert(1/mm,1/m) "absorption coefficient"
q_flux=0.1 [W/cm^2]*convert(W/cm^2,W/m^2) "incident energy"
h=20 [W/m^2-K] "heat transfer coefficient"
T_a=20 [C] "ambient air temperature"

"Obtain constants of integration"

$T_a + q_flux / (k * alpha) - C_2 = -q_flux / h - k * C_1 / h$
 $-q_flux * exp(-alpha * L) / (k * alpha) + C_1 * L + C_2 - T_a = -q_flux * exp(-alpha * L) / h - k * C_1 / h$

"Maximize temperature"

x=x_cm*convert(cm,m)
 $T = -q_flux * exp(-alpha * x) / (k * alpha) + C_1 * x + C_2$

Using EES Effectively

- It is generally NOT a good idea to enter every equation in a problem and then try to solve it
 - » it is difficult to debug a large problem
 - » it is easy to make small mistakes (e.g., T1 is not T_1)
- Better approach – enter equations systematically and solve your problem often
 - » allows you to quickly isolate and fix problems
 - » reduces frustration

Using EES Effectively

"Heat Exchanger Geometry"

```
D_tube_out=0.0095
t_tube=0.0009
N_tube_row=10
N_tube_col=2
H=0.2
W=0.204
L=0.06
t_fin=0.00015
p_fin=0.0015
```

```
"tube outer diameter"
"tube thickness"
"number of tube rows"
"number of tube columns"
"height of core"
"width of core"
"length of core"
"thickness of fins"
"fin pitch - distance between adjacent fins"
```

"Operating Conditions"

```
T_f_in=converttemp(C,K,75)
T_a_in=converttemp(C,K,20)
P_f=1*convert(atm,Pa)
P_a=1*convert(atm,Pa)
Fluid$='Water'
Vdot_f_gpm=0.5
Vdot_f=Vdot_f_gpm*convert(gal/min,m^3/s)
```

```
"inlet temperature of fluid"
"inlet temperature of air"
"pressure of fluid"
"pressure of air"
"type of fluid"
"volumetric flow rate of fluid"
```

"Properties"

```
rho_f=density(Fluid$,T=T_f_in,P=P_f)
mu_f=viscosity(Fluid$,T=T_f_in,P=P_f)
k_f=conductivity(Fluid$,T=T_f_in,P=P_f)
Pr_f=Prandtl(Fluid$,T=T_f_in,P=P_f)
c_f=cP(Fluid$,T=T_f_in,P=P_f)
rho_a=density(Air,T=T_a_in,P=P_a)
mu_a=viscosity(Air,T=T_a_in)
k_a=conductivity(Air,T=T_a_in)
Pr_a=Prandtl(Air,T=T_a_in)
c_a=cP(Air,T=T_a_in)
```

```
"density of fluid"
"viscosity of fluid"
"conductivity of fluid"
"Prandtl number of fluid"
"specific heat capacity of fluid"
"density of air"
"viscosity of air"
"conductivity of air"
"Prandtl number of air"
"specific heat capacity of air"
```

"Air-Side Performance"

```
Vdot_a_cfm=60
Vdot_a=Vdot_a_cfm*convert(cfm,m^3/s)
mdot_a=Vdot_a*rho_a
Nf=W/p_fin
Ac_a=(H-N_tube_row*D_tube_out)*(W-Nf*t_fin)
per_a=Nf*2*(H-N_tube_row*D_tube_out)
dh_a=4*Ac_a/per_a
um_a=Vdot_a/Ac_a
Re_a=um_a*rho_a*dh_a/mu_a
f_a=96/Re_a
DP_a=f_a*(L/dh_a)*rho_a*um_a^2/2
DP_a_inH2O=DP_a*convert(Pa,inH2O)
DP_a_inH2O=0.3927-0.003437*Vdot_a_cfm2
```

```
"Guess for the air-side flow rate"
"Air side flow rate in SI units"
"Mass flow rate on air side"
"Number of fins on air side"
"Cross-sectional area available for air flow"
"Perimeter for flow"
"Hydraulic diameter of flow"
"Mean velocity of air"
"Reynolds number"
"Friction factor of flow"
"Pressure drop"
"Pressure drop in inch H2O"
"Fan curve"
```



equations are entered in order
- therefore, any bottom part of
code can be commented out
and the rest run

Formatted Equations

- The formatted equations window provides the equations in a more readable format
 - » greek variable names become greek symbols
 - » {} comments do not appear in formatted equations
 - » "" comments do appear in formatted equations
 - » _ gives subscript, _dot gives a dot, others

The image shows two windows from a software application. The left window, titled "Equations Window", contains the following text:

```
X^2+Y^3=77
sqrt(X/(Y^2+1))=alpha
alpha=1.23456
DELTAT=25
m_dot=X+Y
V_1=alpha^2

$TabStops 1.25 in
```

The right window, titled "Formatted Equations", shows the rendered output of these equations:

$$X^2 + Y^3 = 77$$

This is a comment

$$\sqrt{\frac{X}{Y^2 + 1}} = \alpha$$

$\alpha = 1.23456$ Greek names appear in symbol font

$\Delta T = 25$ Use upper case letters for upper case symbol

$$\dot{m} = X + Y$$

$V_1 = \alpha^2$ note that underscores signify subscripts

Parametric Tables

- Parametric tables allow you to run EES multiple times
 - » enables parametric studies
 - » each row in the table corresponds to solving the equations
 - » variables that are set in the table are pasted into the Equations window
 - » the results of the calculation are stored in the other columns
 - » be careful not to over-constrain your problem

The image shows two windows from the EES software. The 'New Parametric Table' dialog box is in the foreground, showing 'No. of Runs' set to 10 and 'Table' named 'Table 2'. Under 'Variables in equations', variables x, y, and z are listed. An 'Add' button is visible. The 'Table 2' window in the background shows a table with columns for variables x, y, and z, and rows for 'Run 1', 'Run 2', and 'Run 3'. The table contains numerical values for each variable in each run.

	1	2	3
	x	y	z
1..10			
Run 1	0	0.2805	1
Run 2	11.11	-40.83	1.272
Run 3	22.22	-81.66	2.544

Plotting

- Data in any table can be plotted (parametric, lookup, array, or integration)
 - » Select New Plot Window from Plots menu


The screenshot shows the 'New Plot Setup' dialog box with the following fields and options:

- Tab Name:** Plot 1
- Description:** (empty)
- Print Description with plot:**
- X-Axis:** List containing x, y, z. Variable 'x' is selected.
- Y-Axis:** List containing x, y, z. Variable 'z' is selected.
- Table:** Parametric Table (selected), Table 1
- First Run:** 1
- Last Run:** 10
- Format:** A 0 (for X-axis), A 4 (for Y-axis)
- Minimum:** 0.0 (for X-axis), There are no d (for Y-axis)
- Maximum:** 100.0 (for X-axis), (empty for Y-axis)
- Interval:** 20.0 (for X-axis), (empty for Y-axis)
- Line Style:** Linear, Log
- Grid lines:**
- Options:** Spline fit, Automatic update, Add legend item, Show array indices, Show error bars
- Line:** (empty)
- Symbol:** None
- Color:** (black)
- Buttons:** OK, Cancel

Annotations:

- (1) select source of data: points to the 'Table' dropdown menu.
- (2) select independent variable: points to the 'X-Axis' list.
- (3) select dependent variable(s): points to the 'Y-Axis' list.
- (4) formatting can be done later: points to the 'Format' and 'Interval' fields.

Plot Formatting

- Plot axes, legends, etc. can be created
- Grid lines
- Data symbols
- Splines
- Adding text or images 
- Adding arrows
- Moving plots

Curve Fitting

- Any data that is plotted can be curve fit
- You can use standard curve fits or build a custom functional form

(1) select data to be curve fit

(2) select standard equations

(4) fits coefficients (a_0 , etc.) to data

(3) form of equation is shown

Curve Fit Plotted Data

Plot

1. z vs x
2. y [Y2] vs x

Equation form

Polynomial order 1
 Exponential
 Power
 Logarithmic
 Enter/edit equation

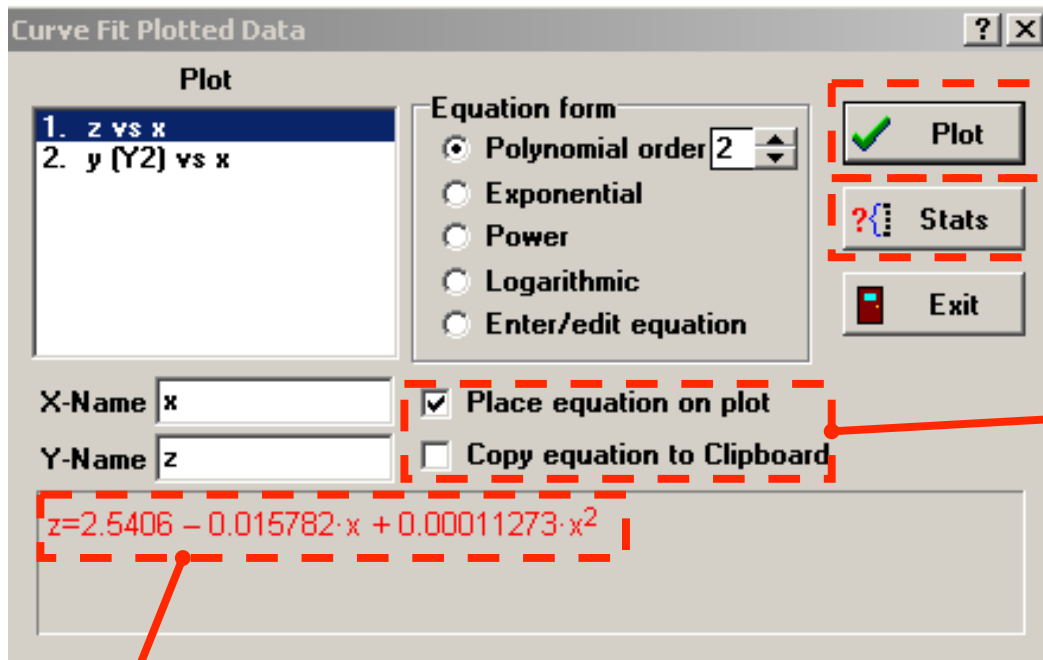
Fit
Stats
Exit

X-Name x
Y-Name z

Place equation on plot
 Copy equation to Clipboard

$z = a_0 + a_1 \cdot x$

Curve Fitting (continued)



best fit equation
can be plotted

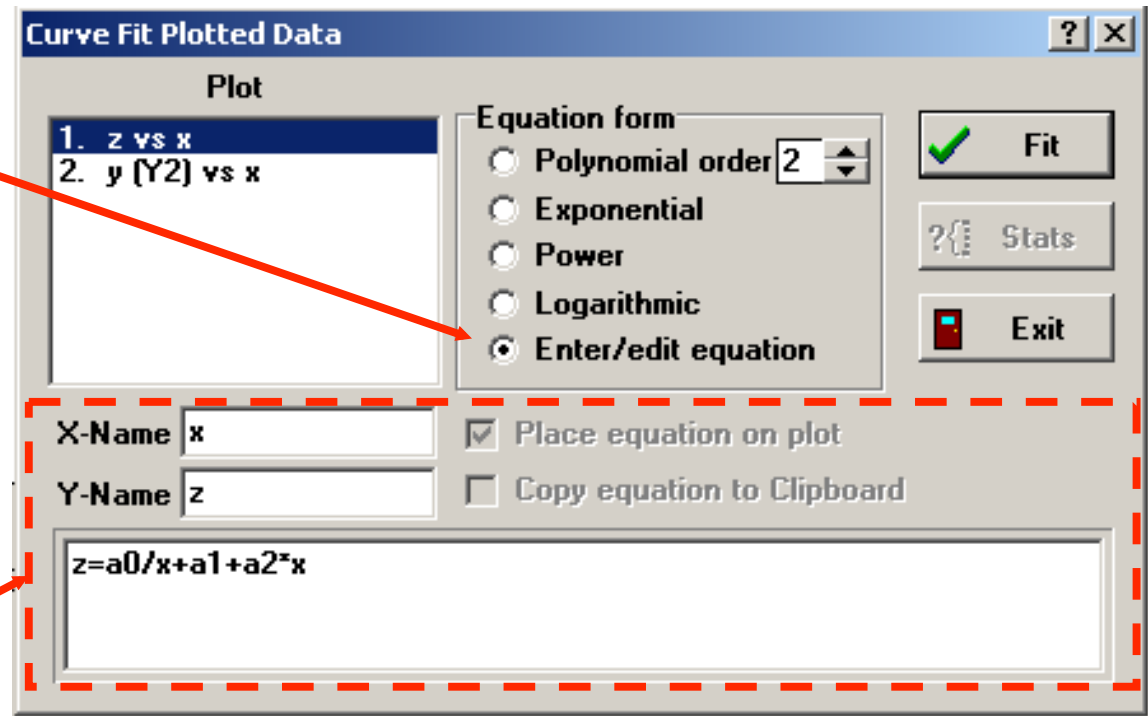
details about fit
can be examined

best-fit equation
can be exported to
plot or clipboard

best-fit
coefficients
are shown

Non-Standard Curve Fitting

(1) select Enter/edit equation



(2) make up your own equation type:
 $z = \text{some function of } x$ where a_0 , a_1 ,
etc are coefficients to be adjusted

Problem #1

(try on your own)

Problem 1

Solve the equation: $a/x + b + cx^2 = 1$

for $a = 1$, $b = 2$, and $c = 0.5$.

Make a plot showing how the solution, x , varies as a function of c for values of c ranging from 0.1 to 10. Label your axes. Overlay on your plot the solution if $a=2$ and $a=3$ and use a legend to differentiate the curves.

Units

- Most engineering problems involve variables that correspond to physical quantities with units
 - EES can:
 - » help you convert between units
 - » allows you to assign a unit to each variable
 - » checks to see if the units assigned to the variables are consistent with the set of equations that you are using
 - EES will **NOT** adjust your units so that they are consistent
- :

The Convert & Converttemp Functions

The function **Convert('unit1','unit2')** returns the conversion factor to go from 'unit1' to 'unit2'

$$L = 10 \cdot \text{convert}(\text{ft}, \text{inch})$$

returns the factor 12 inch/ft

$$L = 10 \cdot \left| 12 \cdot \frac{\text{inch}}{\text{ft}} \right|$$

The function **Converttemp('unit1','unit2',temperature)** returns the temperature converted from 'unit1' to 'unit2'

$$T = \text{converttemp}(\text{C}, \text{K}, 10)$$

returns the 283 K (which is 10°C)

Units and Engineering Problems

(1) Problem statement
(mixed units)

What is the gravitational force exerted on a 2 lbm object placed on the surface of Mercury (where gravity is $=3 \text{ m/s}^2$)?

(2) **Convert** all variables to SI units as they are entered:
N, kg, K, m, s, Pa, etc.

and (2) is converted to kg using the **convert** function

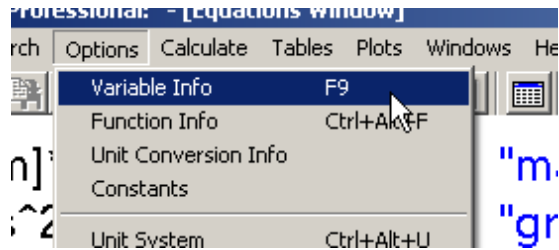
(1) the constant 2 has units [lbm]

`M=2 [lbm]*convert(lbm,kg)`
`g=3 [m/s^2]`

"mass of object"
"gravity"

Units and Engineering Problems

(3) **Set** the units of every variable as it is entered



Variable Information

Show array variables
 Show string variables

Variable	Guess	Lower	Upper	Display	Units
g	3	-infinity	infinity	A 3	m/s^2
M	-9999	-infinity	infinity	A 3	kg

Units and Engineering Problems

(4) **Solve** the problem in SI units & set the units of each variable in the problem

$$F=M*g$$

"force on object"

Variable Information

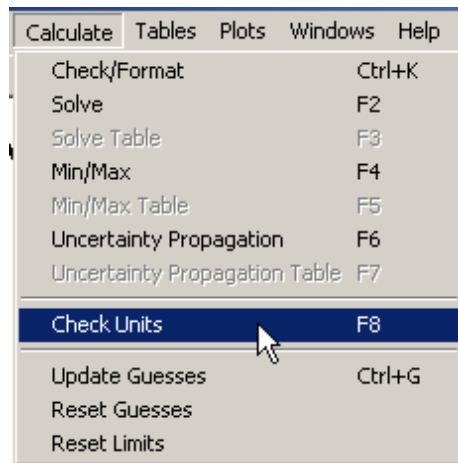
Show array variables
 Show string variables

Variable	Guess	Lower	Upper	Display	Units
F	2.722	-infinity	infinity	A 3 N	N
g	3	-infinity	infinity	A 3 N	m/s^2
M	0.9072	-infinity	infinity	A 3 N	kg

the SI unit of force is N

Units and Engineering Problems

(5) **Check** your equations for dimensional consistency



→ No unit problems were detected.

(6) **Convert** your solution to whatever units you want

$$F_lbf = F * \text{convert}(N, lbf)$$

"force in lbf"

You will never make a unit error and you have ensured that your equations are dimensionally consistent

Problem #2

(try on your own)

Problem 2

A concrete wall is 8 ft high and 10 ft long with a 10 inch thickness. The concrete wall has thermal conductivity 0.7 W/m-K. The wall separates conditioned room air from ambient air. The temperature of the inner surface of the wall is maintained at 25°C.

Determine the heat flow through the wall (\dot{q}) for an outer surface temperature of -5°C. The equation for this calculation is:

$$\dot{q} = k A \frac{(T_{in} - T_{out})}{t}$$

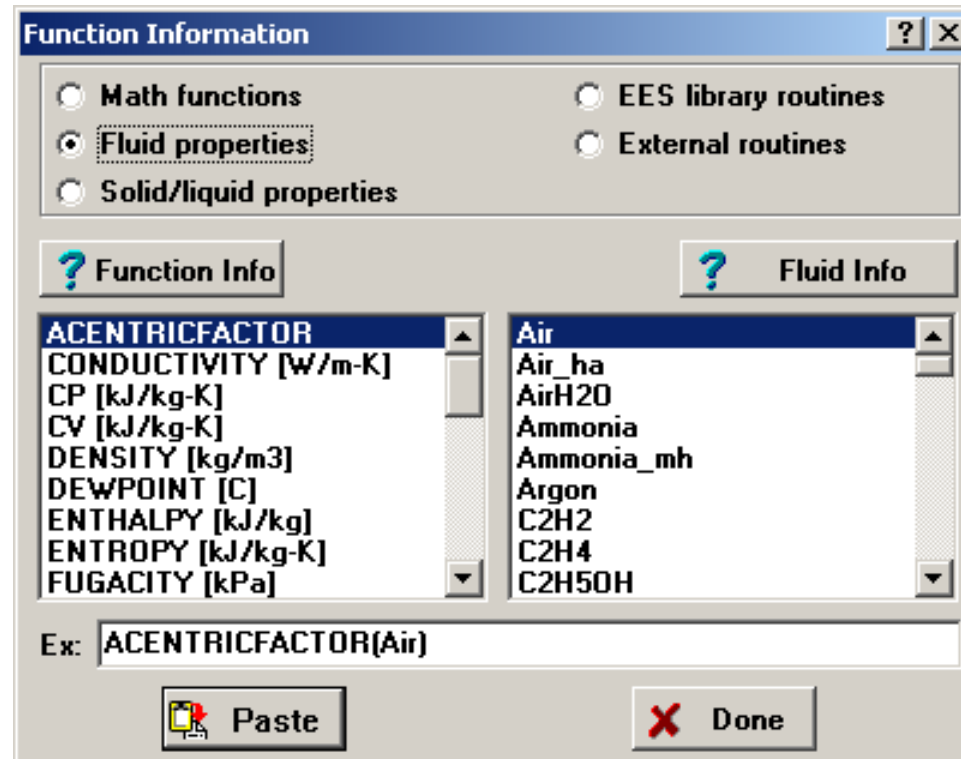
where k is the thermal conductivity, A is the area of the wall, t is its thickness, and T_{in} and T_{out} are its inner and outer temperatures.

Make sure you check your units.

Make a plot that shows the heat flow through the wall as a function of wall thickness.

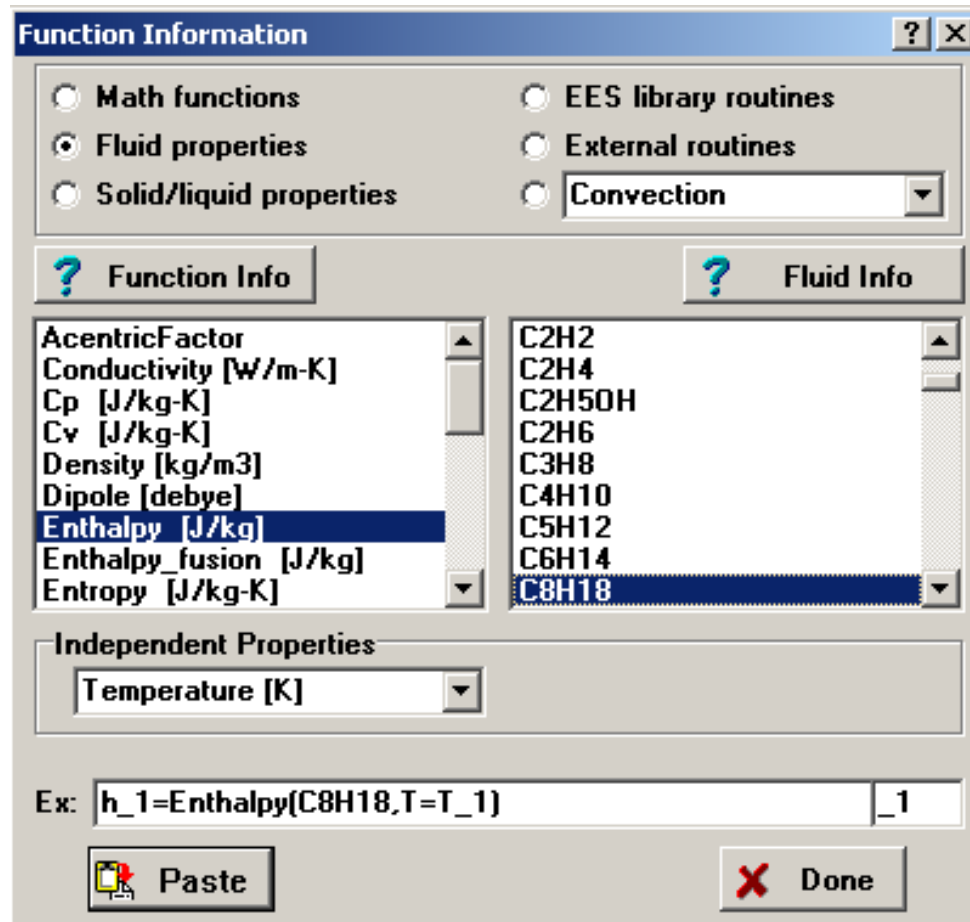
Built-in Functions

- EES provides many built-in functions
- Use the Function Information command (Options menu) to review
- Click the Function Info button for specific help



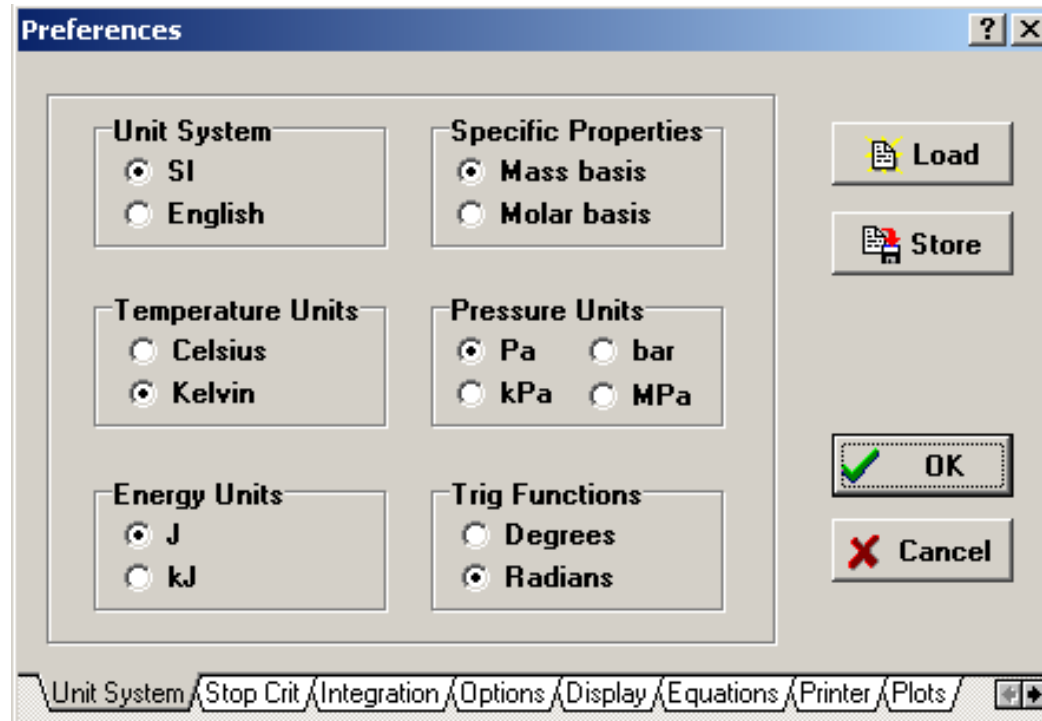
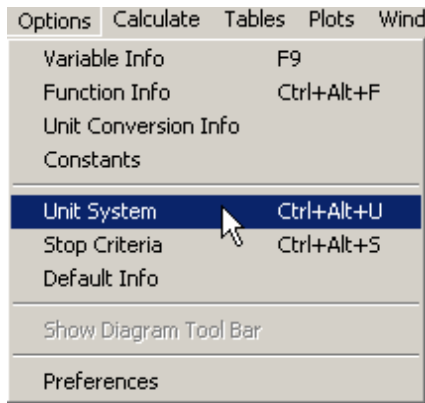
Property Functions

- EES provides thermodynamic and transport properties for many fluids



Property Functions

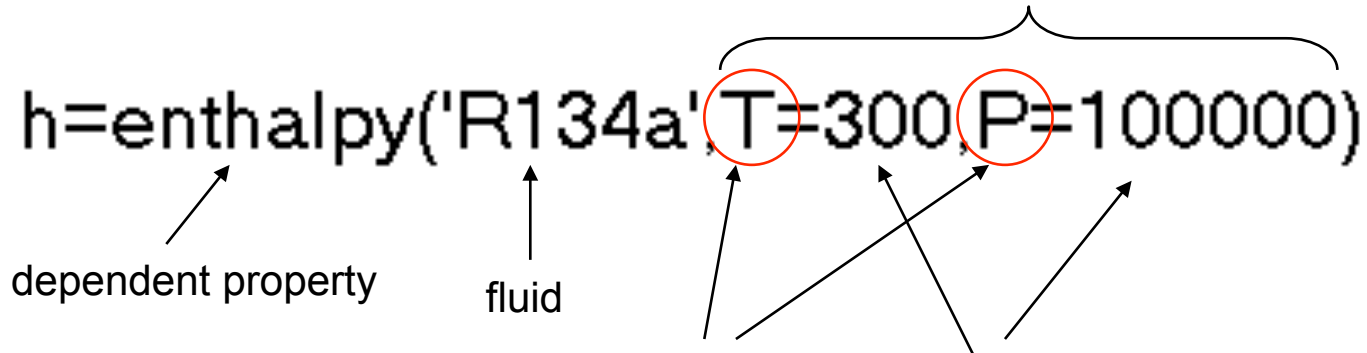
- In order to use these functions, you **MUST** set the unit system (Pa, N, K, J, etc.)
 - » indicates the units of the independent properties provided to the functions and
 - » the units of the dependent properties returned from the function



Property Functions

- The property functions are very flexible

Specify any set of 2 independent properties



independent properties are temperature & pressure

& their values are 300 **K** and 100000 **Pa**

- » the values could be variables
- » other independent properties are also possible

`h=enthalpy('R134a', T=300, s=1)`

enthalpy at T=300 K and s=1 J/kg-K

Property Functions

- ACENTRICFACTOR
- CV and CP
- CONDUCTIVITY
- DENSITY
- DEWPOINT
- ENTHALPY
- ENTROPY
- FUGACITY
- HUMRAT
- INTENERGY
- MOLARMASS
- PRESSURE
- P_CRIT
- PRANDTL
- QUALITY
- RELHUM
- SPECHEAT
- SOUNDSPEED
- SURFACETENSION
- TEMPERATURE
- T_CRIT
- T_TRIPLE
- VISCOSITY
- WETBULB
- VOLUME
- VOLEXPCOE
- V_CRIT
- B= wet-bulb temperature
- D=dew-point temperature
- H=specific enthalpy
- P=pressure
- R=relative humidity
- S=specific entropy
- T=temperature
- U=specific internal energy
- V=specific volume (=1/density)
- W=humidity ratio
- X=quality

Problem #3

(try on your own)

Problem 3

Determine the density of carbon dioxide (in kg/m^3) at a temperature of 500 R and a pressure of 600 bar.

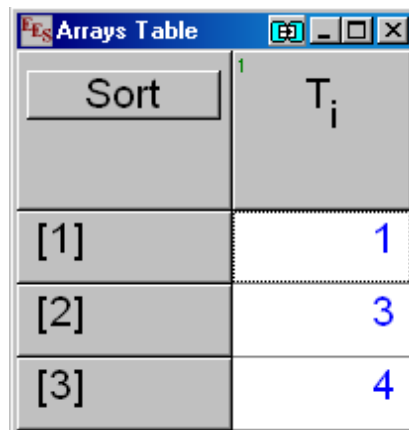
Plot the temperature (in K) of deuterium as a function of pressure from 100 kPa to 10,000 kPa at constant specific volume = $0.1 \text{ m}^3/\text{kg}$.

Arrays

- An array is a variable with multiple elements (a vector rather than a scalar)
- You access the elements with brackets []

```
T[1]=1  
T[2]=3  
T[3]=4
```

- Arrays are viewed in the Arrays window

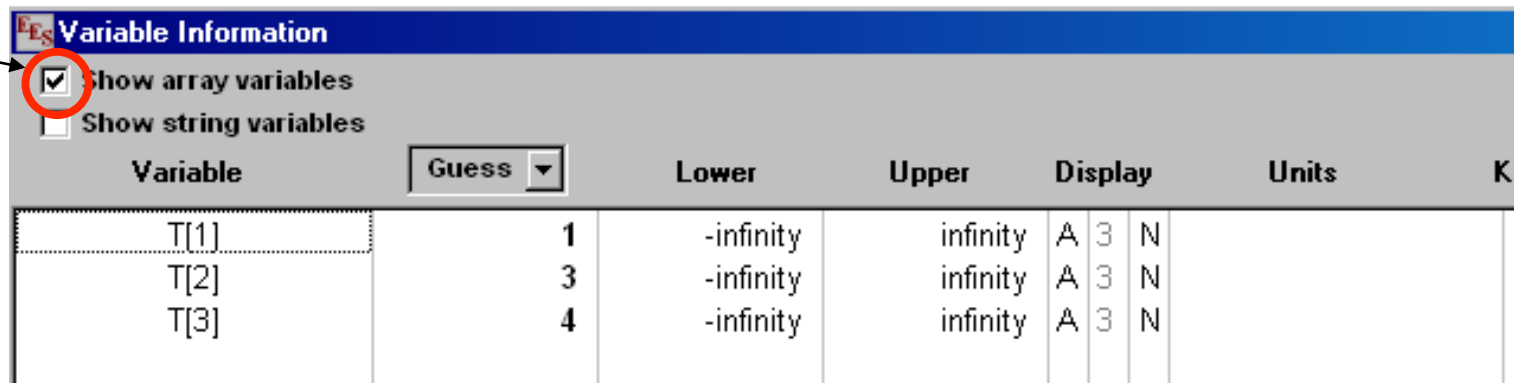


Sort	T _i
[1]	1
[2]	3
[3]	4

Arrays

- Units can be set for arrays all at once

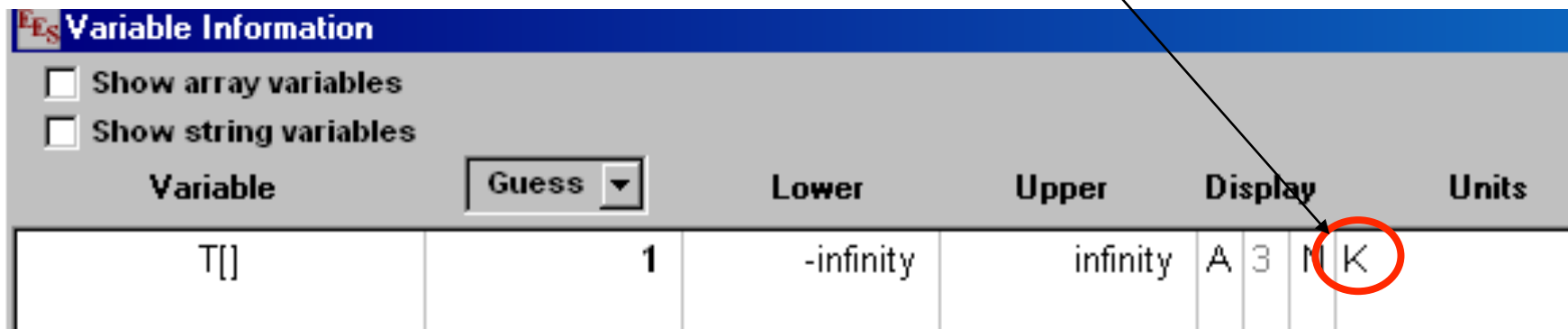
de-select to collapse array



The screenshot shows the 'Variable Information' dialog box in EES. The 'Show array variables' checkbox is checked and circled in red. An arrow points from the text 'de-select to collapse array' to this checkbox. Below the checkboxes is a table with columns: Variable, Guess, Lower, Upper, Display, Units, and K. The table lists three array elements: T[1], T[2], and T[3].

Variable	Guess	Lower	Upper	Display	Units	K
T[1]	1	-infinity	infinity	A 3 N		
T[2]	3	-infinity	infinity	A 3 N		
T[3]	4	-infinity	infinity	A 3 N		

and set all units for T[] at once



The screenshot shows the 'Variable Information' dialog box in EES. The 'Show array variables' checkbox is unchecked. The 'Units' column for the variable T[] is circled in red. An arrow points from the text 'and set all units for T[] at once' to this circled 'K'. The table below shows the variable T[] with its units set to 'K'.

Variable	Guess	Lower	Upper	Display	Units	K
T[]	1	-infinity	infinity	A 3 N	K	

Duplicate Loops

- Duplicate loops carry out a command a certain number of times
- Each time the loop iterates the index increases

index begin value end value

```
duplicate i=1,10  
  T[i]=200  
end
```

commands placed between duplicate and end are repeated for each value of i

- Be careful!
- ```
duplicate i=1,10
 a=10
 T[i]=200
end
```

| Sort | T <sub>i</sub><br>[K] |
|------|-----------------------|
| [1]  | 200                   |
| [2]  | 200                   |
| [3]  | 200                   |
| [4]  | 200                   |
| [5]  | 200                   |
| [6]  | 200                   |
| [7]  | 200                   |
| [8]  | 200                   |
| [9]  | 200                   |
| [10] | 200                   |

