Introduction to EES - 1

2.60/2.62/10.390 Fundamentals of Advanced Energy Conversion

Spring 2020

Omar Labban

Massachusetts Institute of Technology

Credits: Adapted from the presentations created by Xiaoyu Wu and Aniket Patankar for 2.60

Introduction to EES (Engineering Equation Solver)

EES is a computational platform and it can do the following:

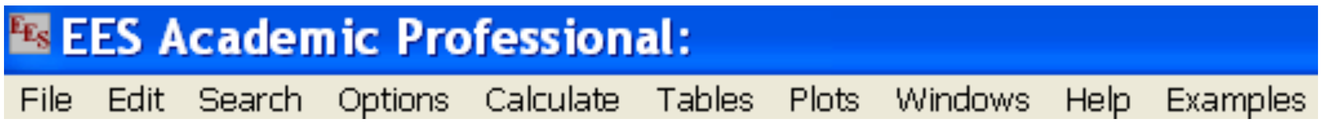
- Derive numerical solution of a set of *non-linear algebraic equations*
- Solve differential and integral equations
- Perform *parametric studies*, optimization, uncertainty analysis and linear/non-linear regression

Highlights

- *Thermo-physical* property and transport properties
- Equations and unknowns to be entered in *any order*

EES Commands

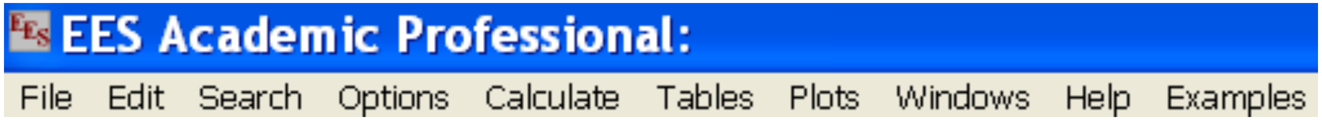
- 10 pull down menus in the ribbon



  - ***File***
  - ***Edit***
  - ***Search***: Find and replace
  - ***Options***: Information and preference
  - ***Calculate****: Solve, Check Units, etc.*

EES Commands (cont.)

- 10 pull down menus in the ribbon

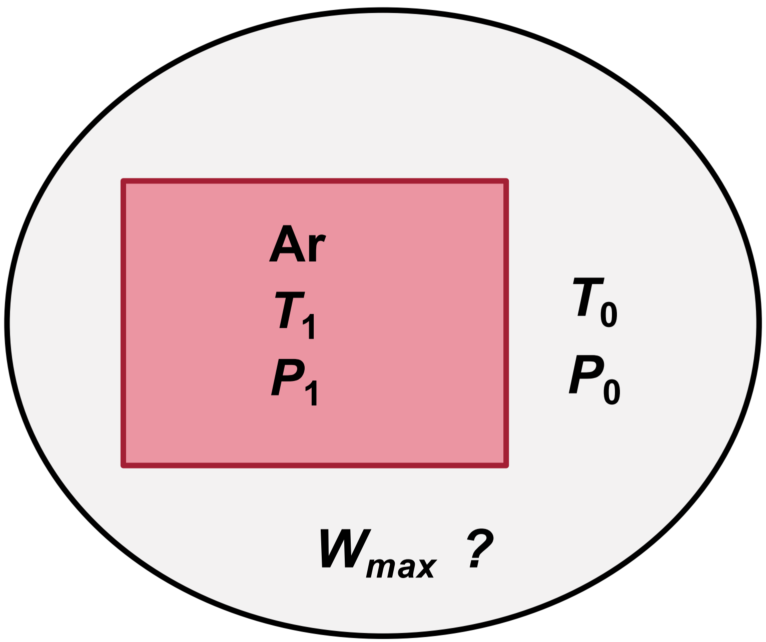


  - ***Tables***: Parametric studies
  - ***Plots***: Plot data in the Parametric studies
  - ***Windows***
  - ***Help***
  - ***Examples***: good to explore

You'll probably be using the toolbar more often!

Example 1: Maximum work

- A gas tank contains 1 kg Argon at T_1 = 500 K, P_1 = 1 bar.
- Environment T_0 = 300 K, P_0 = 1 bar
- **What is the maximum work of the gas tank?**

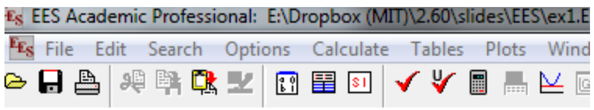


$$W_{\max} = (E_1 - T_0 S_1 + p_0 V_1) - (E_0 - T_0 S_0 + p_0 V_0)$$

(Refer slide 12 from lecture 2)

1. Enter known quantities

- Start EES and enter the following in the Equations *Window.*
- What are the knowns?



T_0
P_0
T_1
P_1
M
ρ
R
Cp
Cv

```
"knowns"
T_0 = 300 [K]
P_0 = 1*10^5 [Pa]
T_1 = 500 [K]
P_1 = 1*10^5 [Pa]
M = 1 [kg]
rho = 1.784 [kg/m^3]
R = 208 [J/kg-K]

C_p = 523 [J/kg-K]
C_v = 315 [J/kg-K]
```

- Comments must enclosed within **{ }** or **" "**

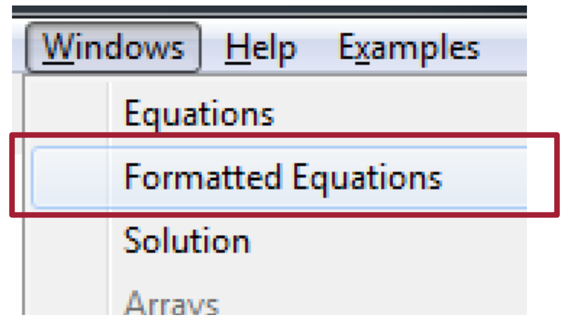
- Units ➔ in **[ ]**

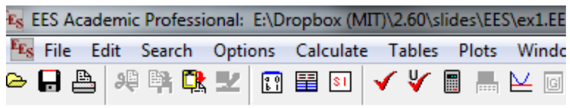
- Blank lines and spaces ➔ **ignored**

- Variable ***start with a letter***
- Upper and lower case ➔ ***NOT*** distinguished

2. Formatted Equations

- Equations in mathematical notation **(recommended Psets format)**
  - Select ***Formatted Equations*** in ***Windows*** menu.





knowns

T_0: Subscript

$T_0 = 300$ [K]

$P_0 = 1 \cdot 10^5$ [Pa]

$T_1 = 500$ [K]

$P_1 = 1 \cdot 10^5$ [Pa]

$M = 1$ [kg]

rho: Greek letter

$\rho = 1.784$ [kg/m^3]

$R = 208$ [J/kg-K]

$C_p = 523$ [J/kg-K]

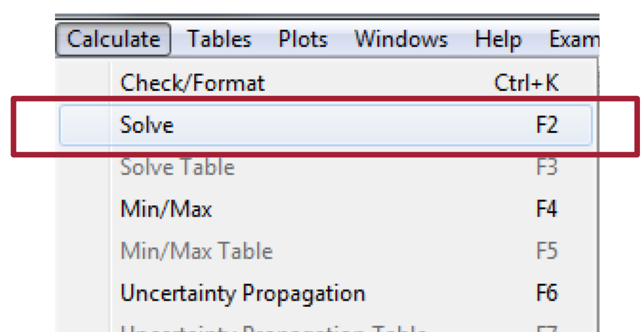
$C_v = 315$ [J/kg-K]

3. Enter equations

```
"Maximum Work"
W_max = (E_1 - T_0*S_1 + P_0 * V_1) - (E_0 - T_0*S_0 + P_0 * V_0)

E_1 = M*C_v*T_1
E_0 = M*C_v*T_0

V_1 = M*R*T_1/P_1
V_0 = M*R*T_0/P_0

S_1 = M * C_p * ln(T_1) - M * R * ln(P_1)
S_0 = M * C_p * ln(T_0) - M * R * ln(P_0)
```

- Variables are defined.

- To calculate
  - ***Solve*** in ***Calculate*** menu.



4. Check solutions

- Solutions

Main

Unit Settings: SI C kPa J mass deg

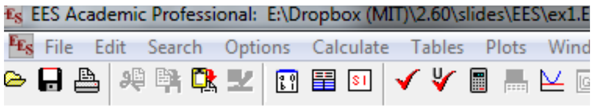
- Solution ➔

C_p = 523 [J/kg-K]	C_v = 315 [J/kg-K]	E_0 = 94500	E_1 = 157500
M = 1 [kg]	P_0 = 100000 [bar]	P_1 = 100000 [bar]	R = 208 [J/kg-K]
ρ = 1.784 [kg/m3]	S_0 = 588.4	S_1 = 855.6	T_0 = 300 [K]
T_1 = 500 [K]	V_0 = 0.624	V_1 = 1.04	W_{max} = 24451

- Unit ➔ 9 potential unit problems were detected. Check Units
- Time ➔ Calculation time = .0 sec.

What is the problem?

Undefined units in equation



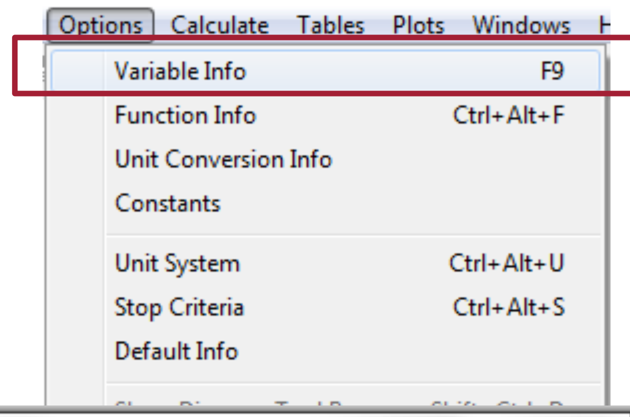

```
"knowns"
T_0 = 300 [K]
P_0 = 1*10^5 [Pa]
T_1 = 500 [K]
P_1 = 1*10^5 [Pa]
M = 1 [kg]


"Maximum Work"
W_max = (E_1 - T_0*S_1 + P_0 * V_1) - (E_0 - T_0*S_0 + P_0 * V_0)

E_1 = M*C_v*T_1
E_0 = M*C_v*T_0

V_1 = M*R*T_1/P_1
V_0 = M*R*T_0/P_0
```

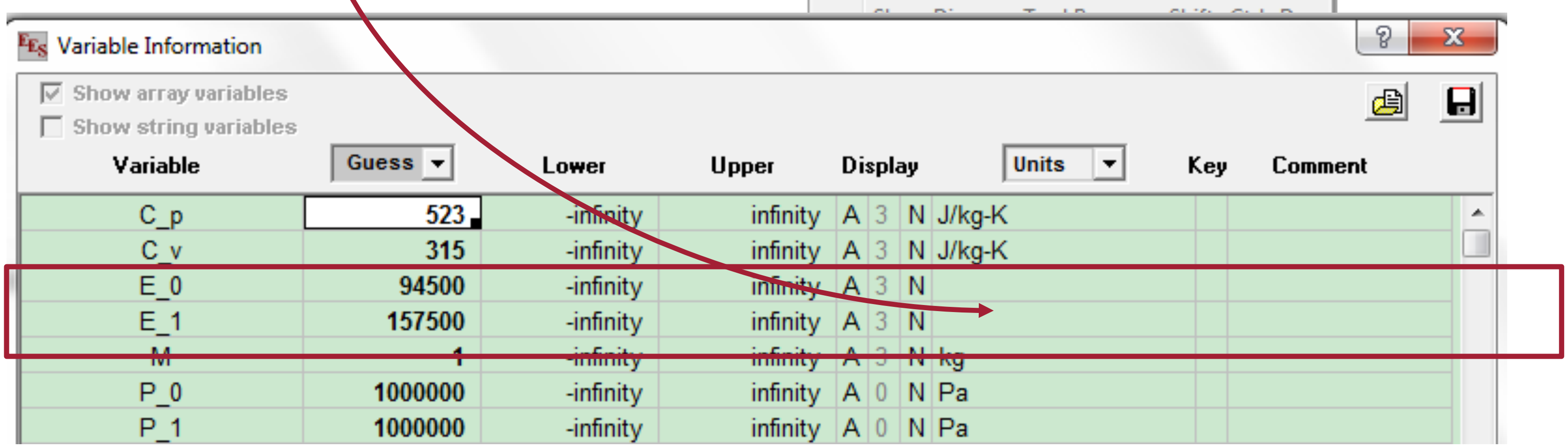
No unit [J] mentioned here.
Try out what happens if you do add it here?

5. Setting Units

- Options → Variable Information

Enter units here to ensure unit compatibility





No unit problems!

Main

Unit Settings: SI C kPa J mass deg

C_p = 523 [J/kg-K]
C_v = 315 [J/kg-K]
E_0 = 94500 [J]
E_1 = 157500 [J]
M = 1 [kg]
P_0 = 1000000 [Pa]
P_1 = 1000000 [Pa]
R = 208 [J/kg-K]
ρ = 1.784 [kg/m3]
S_0 = 0 [J/K]
S_1 = 267.2 [J/K]
T_0 = 300 [K]
T_1 = 500 [K]
V_0 = 0.0624 [m3]
V_1 = 0.104 [m3]
W_{max} = 24451 [J]

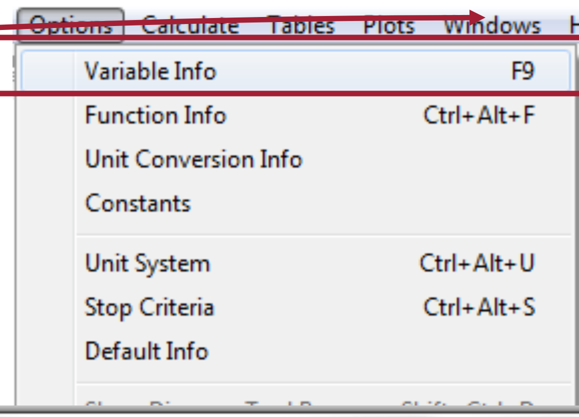
No unit problems were detected.

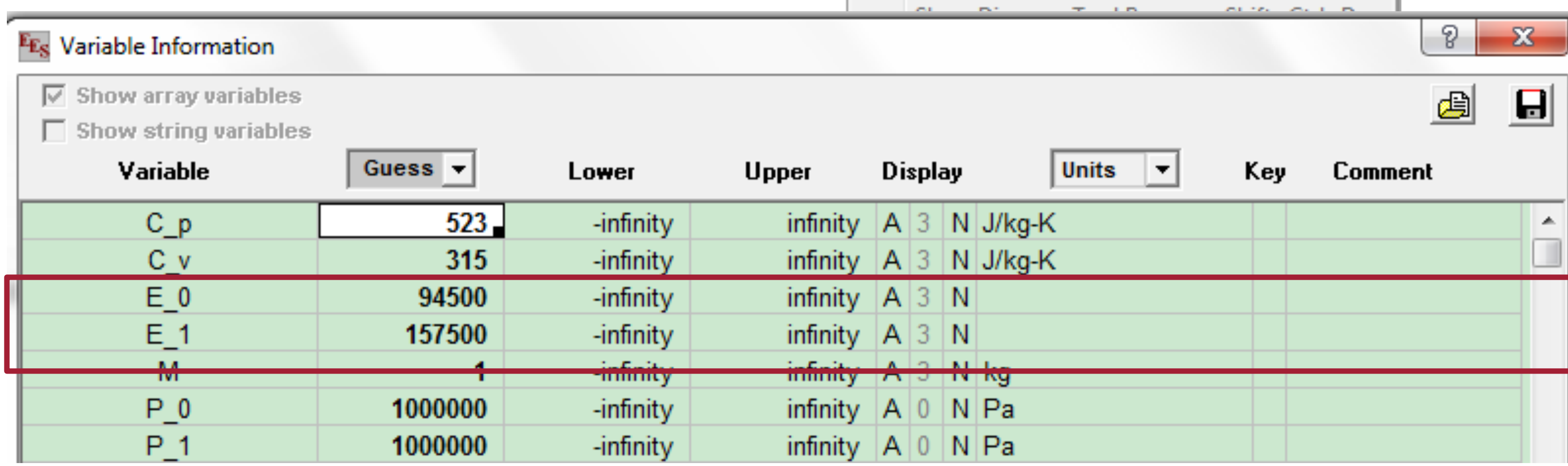
Calculation time = .0 sec.

6. Initial Guess, Lower and Upper bounds

- Options → Variable Information

Explore 'Computational Flow' and 'Residuals' titles in the windows menu to debug issues with solving systems of equations.

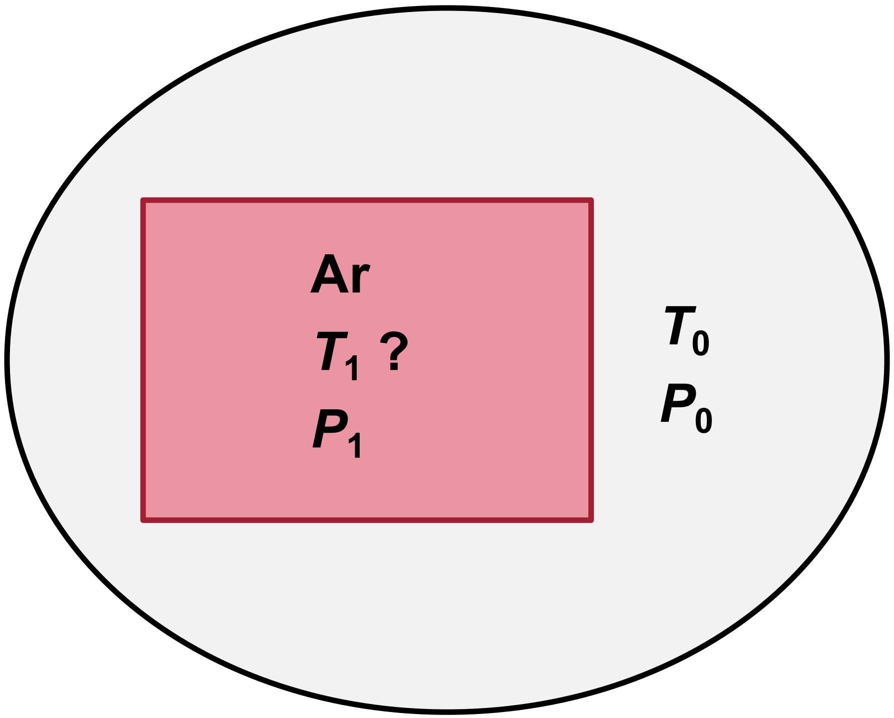




Variable	Guess	Lower	Upper	Display			Units	Key	Comment
C_p	523	-infinity	infinity	A	3	N	J/kg-K		
C_v	315	-infinity	infinity	A	3	N	J/kg-K		
E_0	94500	-infinity	infinity	A	3	N			
E_1	157500	-infinity	infinity	A	3	N			
M	1	-infinity	infinity	A	3	N	kg		
P_0	1000000	-infinity	infinity	A	0	N	Pa		
P_1	1000000	-infinity	infinity	A	0	N	Pa		

Example 2: Parametric Studies

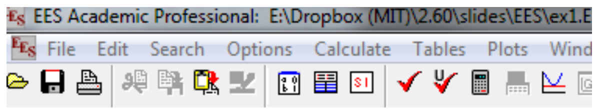
- A gas tank contains 1 kg Argon at T_1, P_1 = 1 bar.
- Environment T_0 = 300 K, P_0 = 1 bar
- **How does T_1 affect the maximum work (W_{max})?**



$W_{max}(T_1)$?

T1 is unknown

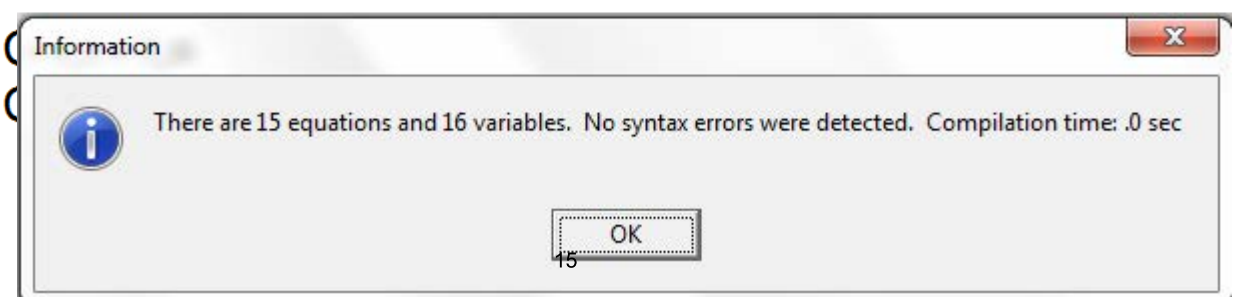
- Start EES and enter the following in the *Equations Window.*
- What are the knowns?



T_0
P_0
~~T_1~~
P_1
M
ρ
R
Cp
Cv

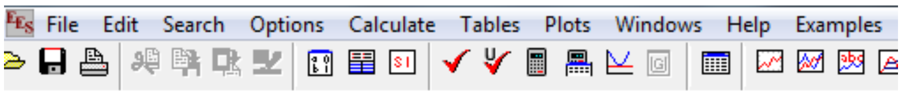
```
"knowns"
T_0 = 300 [K]
P_0 = 1*10^5 [Pa]
~~T_1 = 500 [K]~~
P_1 = 1*10^5 [Pa]
M = 1 [kg]
rho = 1.784 [kg/m^3]
R = 208 [J/kg-K]
```

Comment out the input parameter to be varied. Understandably, the system is no longer solvable.



Comments: { } or “ ”

- ***Equations***

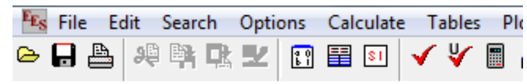


"knowns"
T_0 = 300 [K]
P_0 = 10e5 [Pa]
{T_1 = 500 [K]}
P_1 = 10e5 [Pa]
M = 1 [kg]
rho = 1.784 [kg/m^3]
R = 208 [J/kg-K]

C_p = 523 [J/kg-K]
C_v = 315 [J/kg-K]

- Comments

- ***Formatted Equations***



knowns

T_0 = 300 [K]

P_0 = 1000000 [Pa]

P_1 = 1000000 [Pa]

M = 1 [kg]

ρ = 1.784 [kg/m^3]

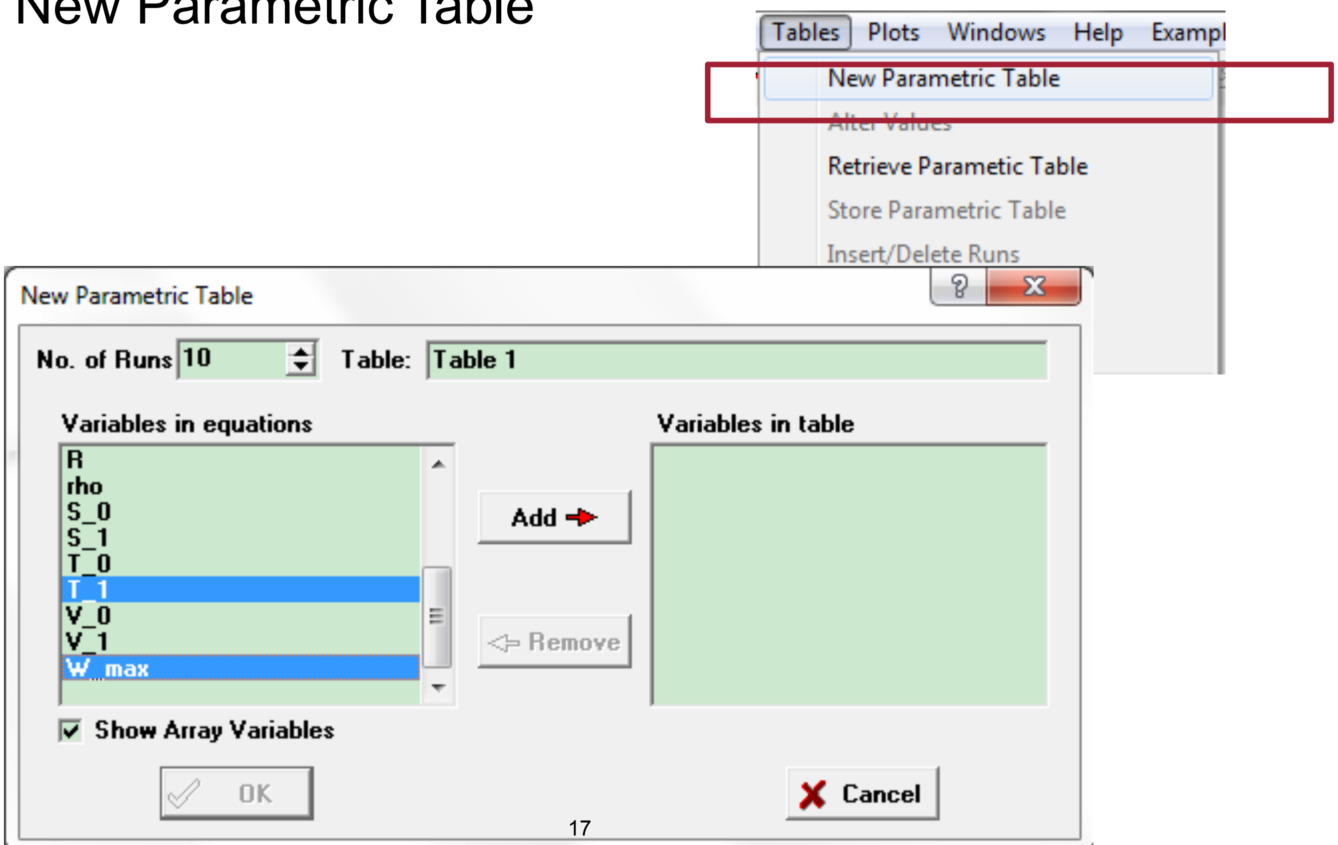
R = 208 [J/kg-K]

C_p = 523 [J/kg-K]

C_v = 315 [J/kg-K]

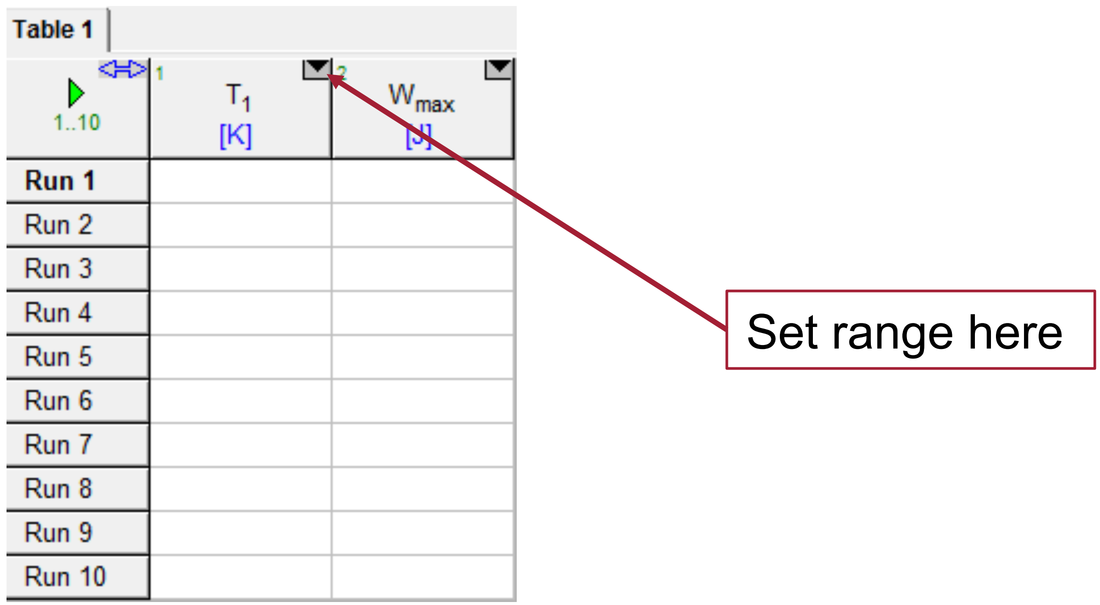
Parametric Table for T_1 and W_{max}

- Study the relationship between unknowns.
- Tables ➔ New Parametric Table



Define the range of study

- After chosen the two variables T_1 and W_{max}



- The range of T_1
  - 300 – 1000 K

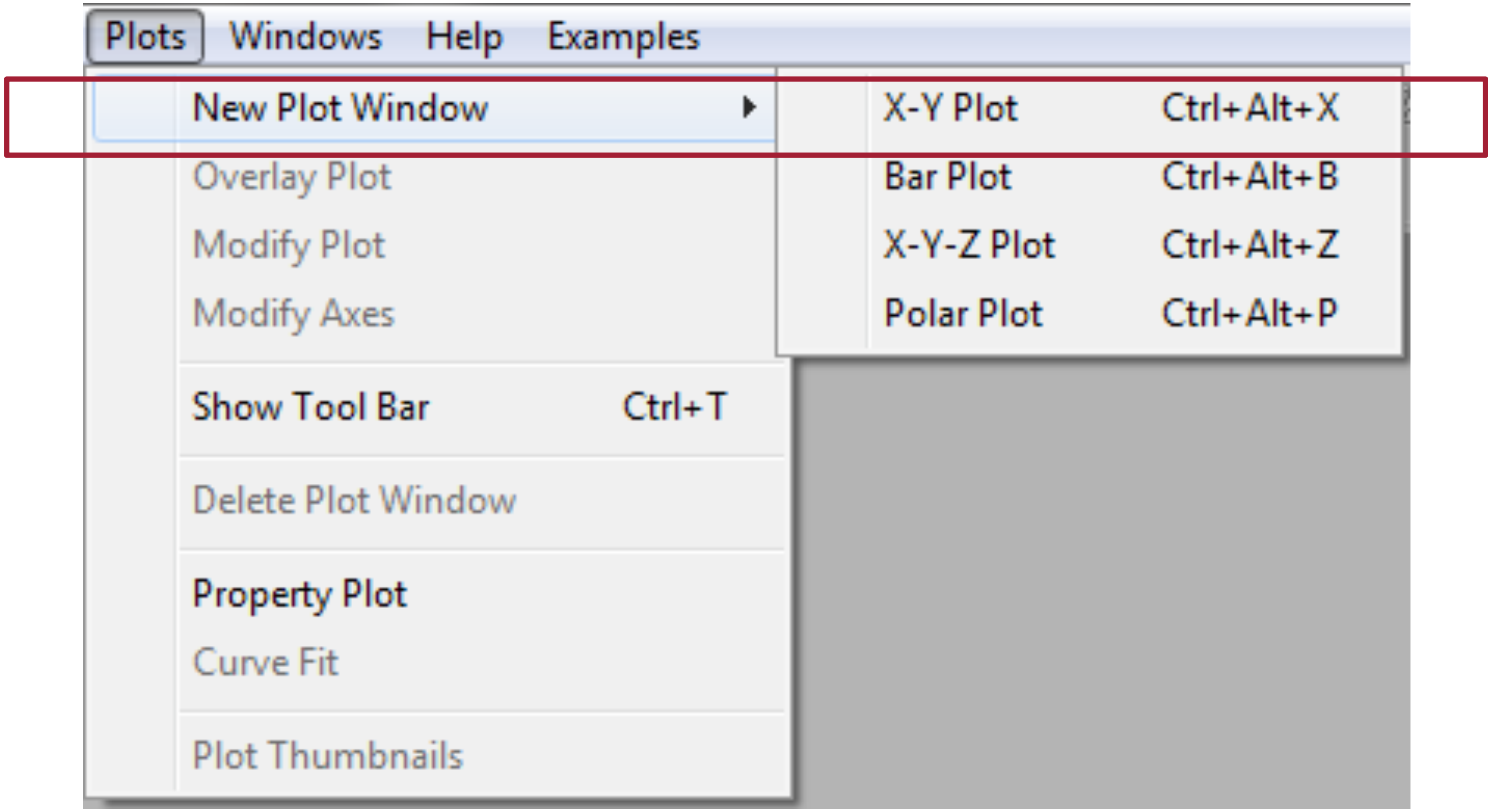
Run

- Click the green button on the left

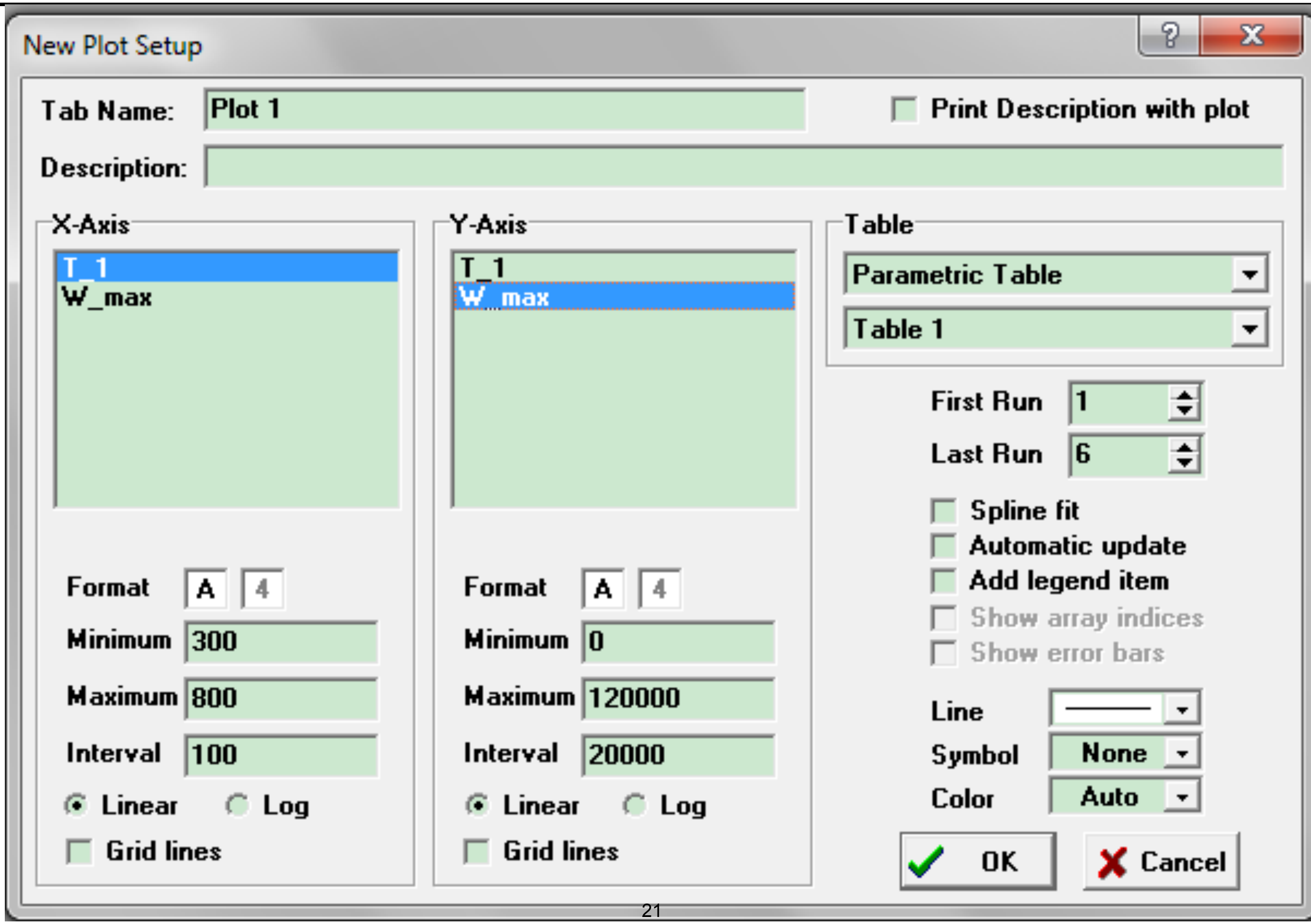
Table 1

1..6	T_1 [K]	W_{max} [J]
Run 1	300	0
Run 2	400	7163
Run 3	500	24451
Run 4	600	48145
Run 5	700	76259
Run 6	800	107608

Plot the results

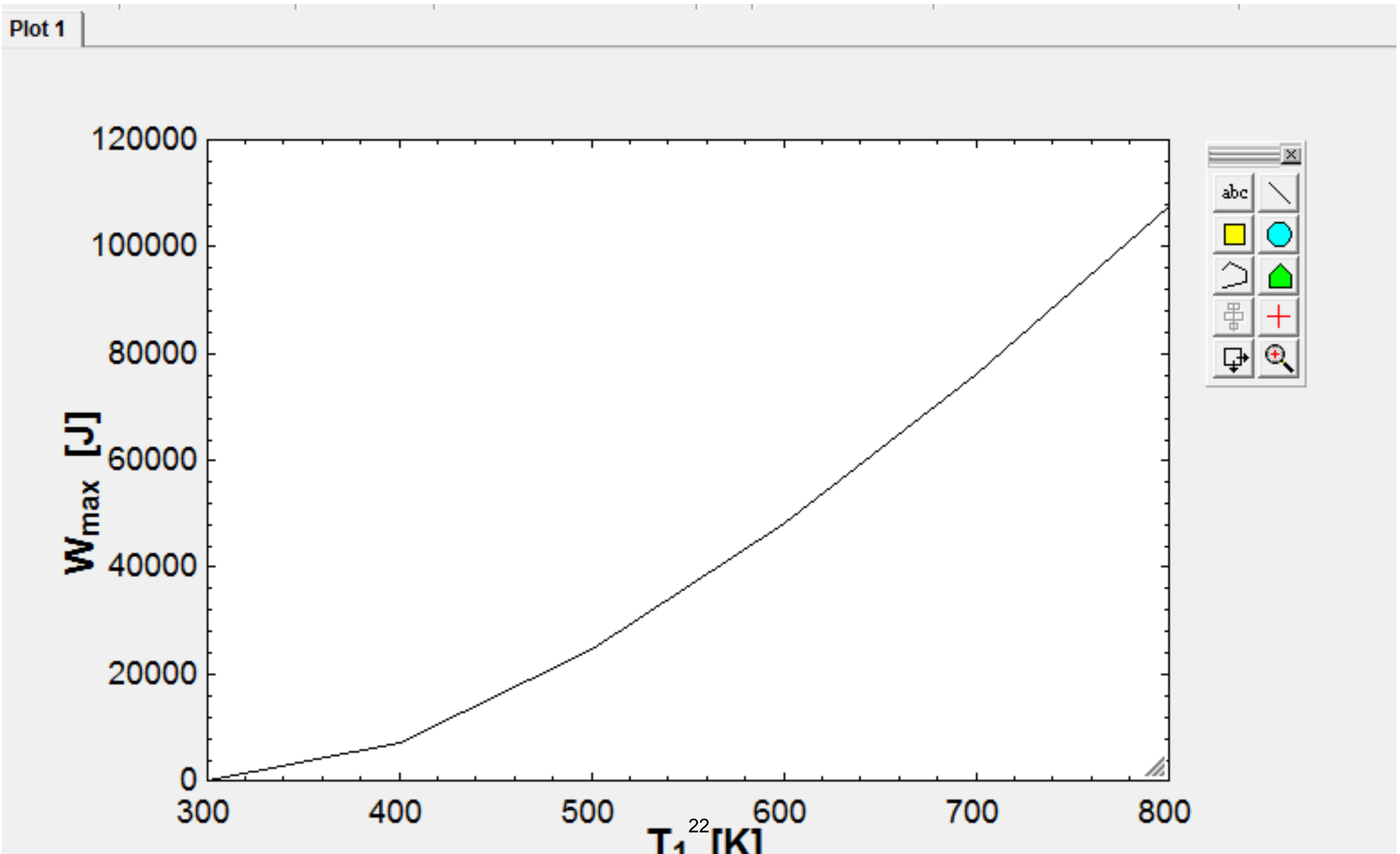


Choose X and Y axes



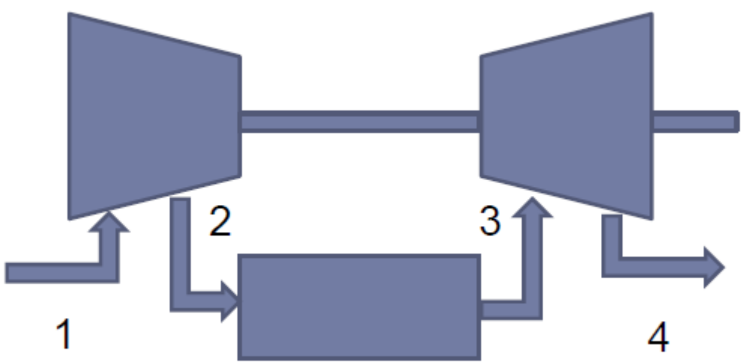
View and Edit the Graph

- Change the plot axes/labels by double clicking on them.



Example 3: Problem

- An open Brayton-cycle engine operates with a compressor-pressure ratio of 4.5 and inlet temperature of 20^{o}C, and a turbine-inlet temperature of 900^{o}C.
- The engine drives an electric generator that produces 25 MWe with a generator efficiency of 90%.
- Find the thermal efficiency, the specific work, and the air-mass-flow rate, if the compressor and turbine efficiencies are 80 percent.



Example 3: Equations

Assume air as ideal gas with constant C_p

$C_p = 1.005$

$k = 1.40$

$$\frac{T_{2s}}{T_1} = r_c^{\frac{k-1}{k}}$$

$$\frac{T_{2s} - T_1}{T_2 - T_1} = \eta_c$$

$$w_c = C_p \;\; T_2 - T_1$$

Compressor

$$q_{in} = C_p \;\; T_3 - T_2$$

$$\frac{T_{4s}}{T_3} = 1/r_t^{\frac{k-1}{k}}$$

$$\frac{T_4 - T_3}{T_{4s} - T_3} = \eta_t$$

$$w_t = C_p \;\; T_3 - T_4$$

Turbine

$$\eta_{th} = \frac{w_t - w_c}{q_{in}}$$

$$\dot{W} = \dot{W}_{gen} / \eta_{gen}$$

$$\dot{m} = \dot{W} / \;\; w_t - w_c$$

"Assume air as ideal gas with constant Cp"
Cp = 1.005 [kJ/kg.K]
K = 1.40

$T_{2s}/T_1 = r_{p-c}$^(k-1)/k
$T_2 = T_1 + 1/\eta_c(T_{2s}-T_1)$
$W_c = Cp(T_2-T_1)$

$Q_{in} = Cp(T_3-T_2)$

$T_{4s}/T_3 = 1/r_{p-t}$^(k-1)/k
$T_4 = T_3 - \eta_t(T_3-T_{4s})$
$W_t = Cp(T_3-T_4)$

$\eta_{th} = (W_t-W_c)/Q_{in}$

W_dot = W_dot_gen/ η_g
m_dot = W_dot/(W_t-W_c)

Example 3: Equations

Equations Window

```
C_p = 1005 [J/kg-K]
k = 1.40
eta_c = 0.80
eta_t = 0.80
r_p_c = 4.5
r_p_t = 4.5
eta_e = 0.90
T_min = 293 [K]
T_max = 1173 [K]
W_dot_e = 25000000 [W]
W_dot_m = W_dot_e/eta_e

"Simple Brayton Cycle"
"compressor"
T1 = T_min
Ts2 = T1 * (r_p_c)^((k-1)/k)
T2 = T1 + (1/eta_c)*(Ts2 - T1)
w_c = C_p * (T2 - T1)
"turbine"
T3 = T_max
Ts4 = T3 * (1/r_p_t)^((k-1)/k)
T4 = T3 -  eta_t * (T3 - Ts4)
w_t = C_p * (T3 - T4)
w_net = w_t - w_c
q_in = C_p * (T3 - T2)
eta_th = w_net/q_in
m_dot = W_dot_m/w_net
```

"Assume air as ideal gas with constant Cp"

Cp = 1.005 [kJ/kg.K]

K = 1.40

$T_{2s}/T_1 = r_{p-c}$^(k-1)/k

$T_2 = T_1 + 1/\eta_c(T_{2s}-T_1)$

$W_c = Cp(T_2-T_1)$

$Q_{in} = Cp(T_3-T_2)$

$T_{4s}/T_3 = 1/r_{p-t}$^(k-1)/k

$T_4 = T_3 - \eta_t(T_3-T_{4s})$

$W_t = Cp(T_3-T_4)$

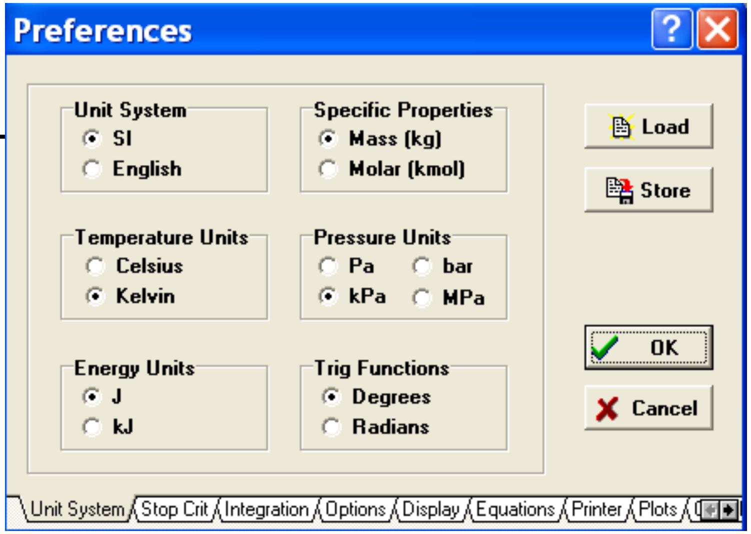
$\eta_{th} = (W_t-W_c)/Q_{in}$

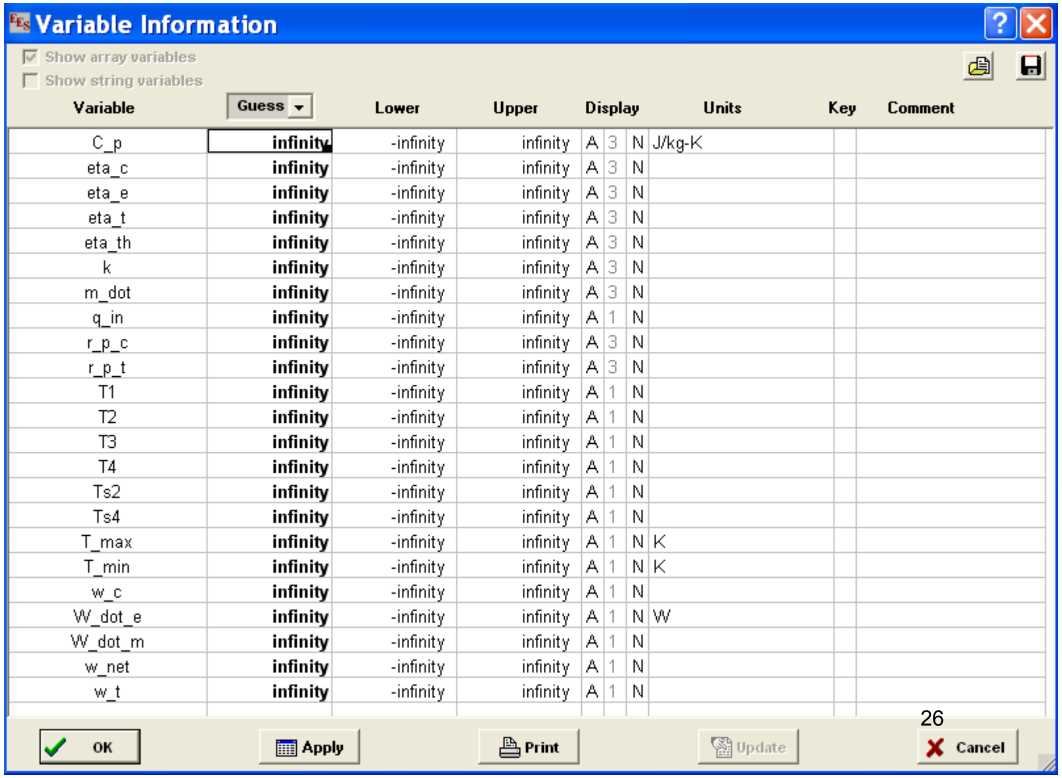
W_dot = W_dot_gen/ η_g

m_dot = W_dot/(W_t-W_c)

Example 3: Units

- Options → Variable Information

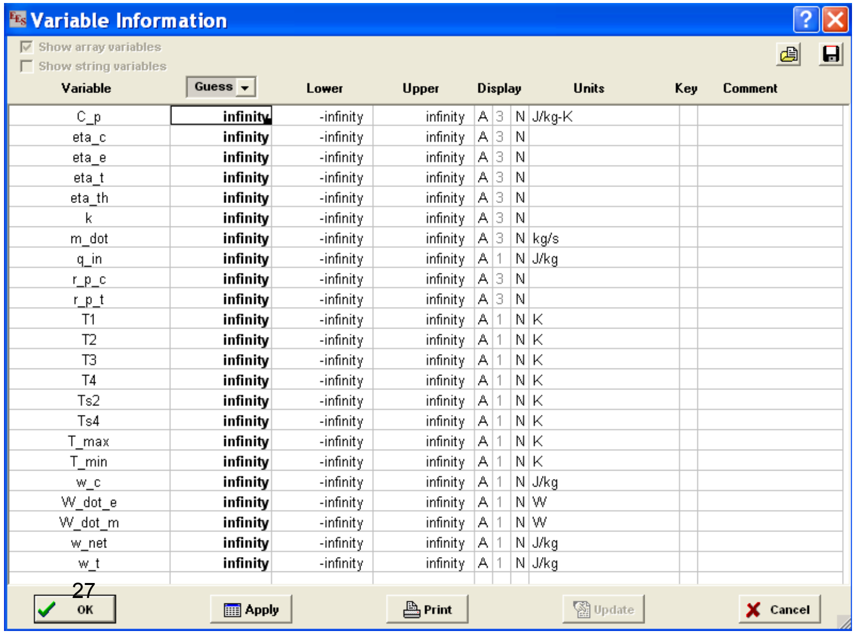




Variable	Guess	Lower	Upper	Display	Units	Key	Comment
C_p	infinity	-infinity	infinity	A 3 N	J/kg-K		
eta_c	infinity	-infinity	infinity	A 3 N			
eta_e	infinity	-infinity	infinity	A 3 N			
eta_t	infinity	-infinity	infinity	A 3 N			
eta_th	infinity	-infinity	infinity	A 3 N			
k	infinity	-infinity	infinity	A 3 N			
m_dot	infinity	-infinity	infinity	A 3 N			
q_in	infinity	-infinity	infinity	A 1 N			
r_p_c	infinity	-infinity	infinity	A 3 N			
r_p_t	infinity	-infinity	infinity	A 3 N			
T1	infinity	-infinity	infinity	A 1 N			
T2	infinity	-infinity	infinity	A 1 N			
T3	infinity	-infinity	infinity	A 1 N			
T4	infinity	-infinity	infinity	A 1 N			
Ts2	infinity	-infinity	infinity	A 1 N			
Ts4	infinity	-infinity	infinity	A 1 N			
T_max	infinity	-infinity	infinity	A 1 N	K		
T_min	infinity	-infinity	infinity	A 1 N	K		
w_c	infinity	-infinity	infinity	A 1 N			
W_dot_e	infinity	-infinity	infinity	A 1 N	W		
W_dot_m	infinity	-infinity	infinity	A 1 N			
w_net	infinity	-infinity	infinity	A 1 N			
w_t	infinity	-infinity	infinity	A 1 N			

Example 3: Initial Guess

- It is usually a good idea to set the guess values and (possibly) the lower and upper bounds for the variables before attempting to solve the equations.
- The Variable Information dialog contains a line for each variable appearing in the Equations window. By default, each variable is given a guess value of 1.0 with lower and upper bounds of negative and positive infinity before solving.



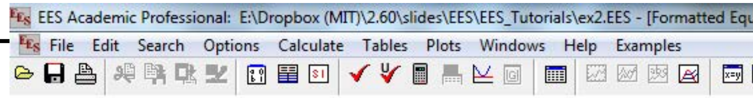
Variable Information

Show array variables
Show string variables

Variable	Guess	Lower	Upper	Display			Units	Key	Comment
C_p	infinity	-infinity	infinity	A	3	N	J/kg-K		
eta_c	infinity	-infinity	infinity	A	3	N			
eta_e	infinity	-infinity	infinity	A	3	N			
eta_t	infinity	-infinity	infinity	A	3	N			
eta_th	infinity	-infinity	infinity	A	3	N			
k	infinity	-infinity	infinity	A	3	N			
m_dot	infinity	-infinity	infinity	A	3	N	kg/s		
q_in	infinity	-infinity	infinity	A	1	N	J/kg		
r_p_c	infinity	-infinity	infinity	A	3	N			
r_p_t	infinity	-infinity	infinity	A	3	N			
T1	infinity	-infinity	infinity	A	1	N	K		
T2	infinity	-infinity	infinity	A	1	N	K		
T3	infinity	-infinity	infinity	A	1	N	K		
T4	infinity	-infinity	infinity	A	1	N	K		
Ts2	infinity	-infinity	infinity	A	1	N	K		
Ts4	infinity	-infinity	infinity	A	1	N	K		
T_max	infinity	-infinity	infinity	A	1	N	K		
T_min	infinity	-infinity	infinity	A	1	N	K		
w_c	infinity	-infinity	infinity	A	1	N	J/kg		
W_dot_e	infinity	-infinity	infinity	A	1	N	W		
W_dot_m	infinity	-infinity	infinity	A	1	N	W		
w_net	infinity	-infinity	infinity	A	1	N	J/kg		
w_t	infinity	-infinity	infinity	A	1	N	J/kg		

OK Apply Print Update Cancel

Example 3: Mathematical Notation



$C_p = 1005$ [J/kg-K]

$k = 1.4$

$\eta_c = 0.8$

$\eta_t = 0.8$

$r_{p,c} = 4.5$

$r_{p,t} = 4.5$

$T_{min} = 293$ [K]

$T_{max} = 1173$ [K]

Simple Brayton Cycle

compressor

$T1 = T_{min}$

$$Ts2 = T1 \cdot r_{p,c}^{\left[\frac{k-1}{k}\right]}$$

$$T2 = T1 + \frac{1}{\eta_c} \cdot (Ts2 - T1)$$

$w_c = C_p \cdot (T2 - T1)$

Example 3: Solution

- The display and other defaults can easily be changed with the Default information command in the Options menu.

Main

Unit Settings: SI K Pa J mass deg

C_p = 1005 [J/kg-K]	η_c = 0.8	η_e = 0.9	η_t = 0.8	η_{th} = 0.192
k = 1.4	$\dot{m}$ = 210.7 [kg/s]	q_{in} = 686795 [J/kg]	$r_{p,c}$ = 4.5	$r_{p,t}$ = 4.5
T1 = 293 [K]	T2 = 489.6 [K]	T3 = 1173 [K]	T4 = 845.2 [K]	Ts2 = 450.3 [K]
Ts4 = 763.2 [K]	T_{max} = 1173 [K]	T_{min} = 293 [K]	w_c = 197605 [J/kg]	$\dot{W}_e$ = 2.500E+07 [
$\dot{W}_m$ = 2.778E+07 [W]	w_{net} = 131835 [J/kg]	w_t = 329440 [J/kg]		

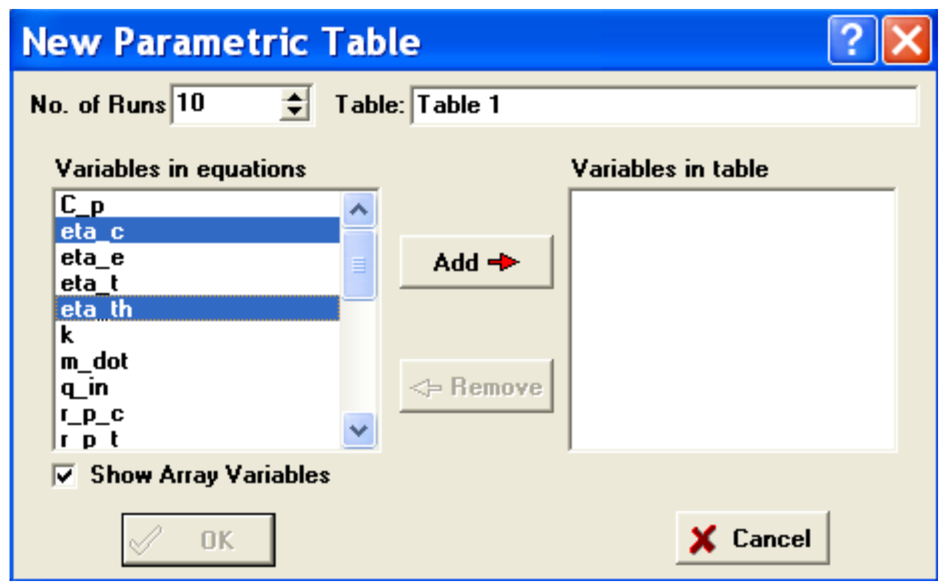
No unit problems were detected.

Calculation time = .0 sec.

Example 3: Parametric Studies

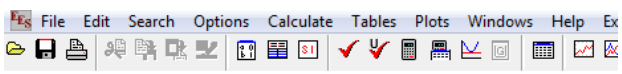
- Tables → New Parametric Table
- A dialog will be displayed listing the variables appearing in the Equations window.
- In this case, we will construct a table containing the variables eta_c and eta_th.
- Click on eta_cfrom the variable list on the left. This will cause it to be highlighted and the Add button will become active. Repeat for eta_th, using the scroll bar to bring the variable into view if necessary.

- As a short cut, you can double-click on the variable name in the list on the left to move it to the list on the right. You can also select multiple variables at one time.
- Click the Add button to move the selected variables into the list on the right and then click the OK button to create the table.



Example 3: Equations

- Parametric Table works much like a spreadsheet. You can type numbers directly into the cells. Numbers that you enter are shown in black and produce the same effect as if you set the variable to that value with an equation in the Equations window.
- Delete the eta_c= 0.8 equation currently in the Equations window or enclose it in comment brackets { }. This equation will not be needed because the value of eta_c will be set in the table.




```
C_p = 1005 [J/kg-K]
k = 1.40
{eta_c = 0.80}
eta_t = 0.80
r_p_c = 4.5
r_p_t = 4.5
eta_e = 0.90
T_min = 293 [K]
T_max = 1173 [K]
W_dot_e = 25000000 [W]
W_dot_m = W_dot_e/eta_e
```

Example 3: Parametric Table

- Now enter values of eta_c in the table for which eta_th is to be determined. Values of eta_c between 0.5 to 0.95 have been chosen for this example.
- (The values could also be automatically entered using Alter Values in the Tables menu or by using the Alter Values control at the upper right of each table column header.)

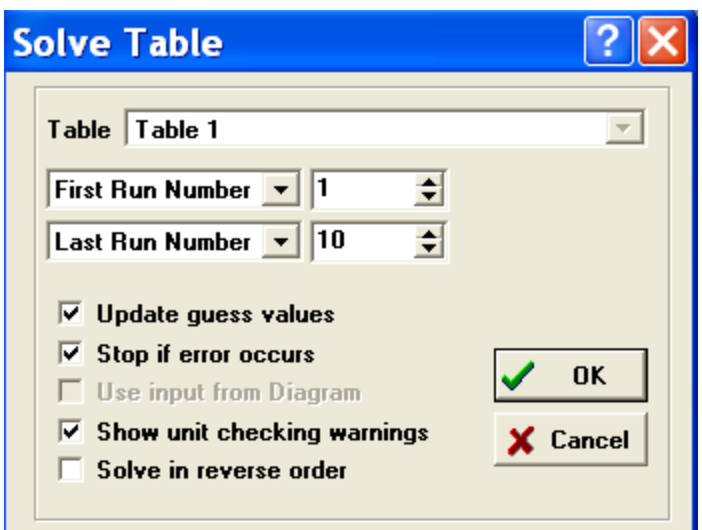
Parametric Table

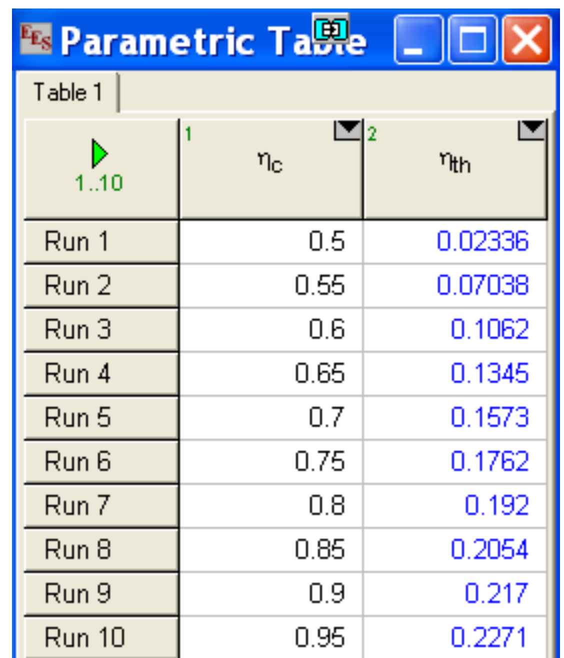
Table 1

9..9	1 η_c	2 η_{th}
Run 1	0.5	
Run 2	0.55	
Run 3	0.6	
Run 4	0.65	
Run 5	0.7	
Run 6	0.75	
Run 7	0.8	
Run 8	0.85	
Run 9	0.9	
Run 10	0.95	

Example 3: Solution

- Calculate → Solve Table
  - The Solve Table dialog window will appear, allowing you to choose the runs for which calculations will be done.
  - When the Update Guess Values control is selected, the solution for the last run will provide guess values for the current run. Click the OK button.
  - When the calculations are completed, the calculated values of eta_th will be entered into the table.





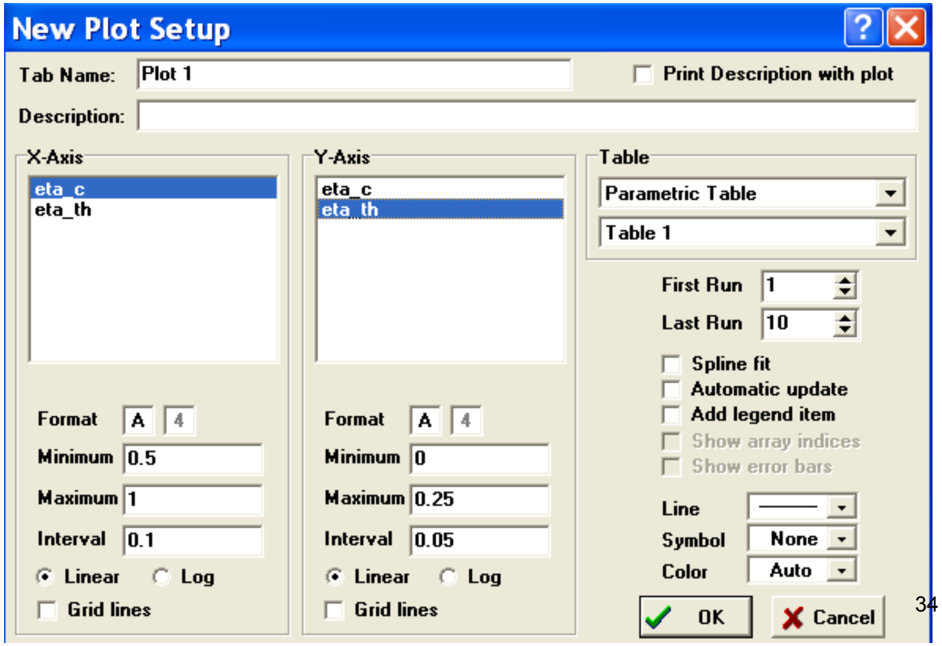
Parametric Table

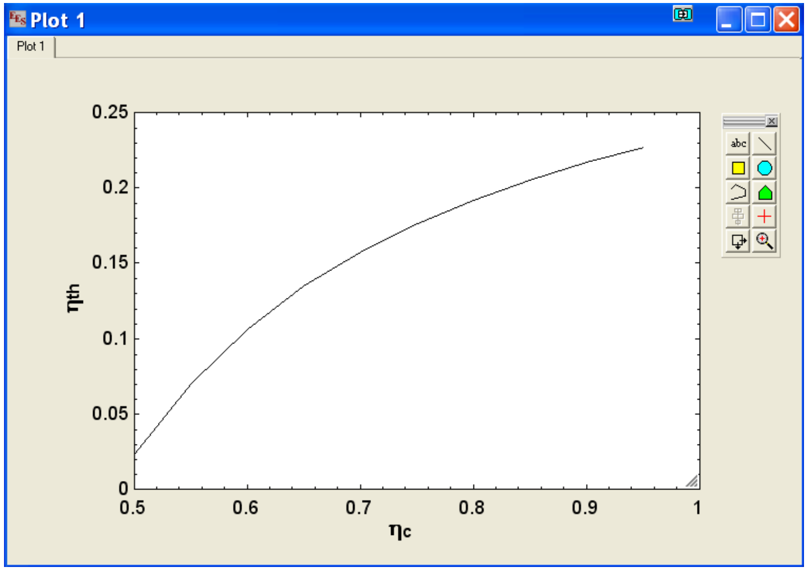
Table 1

1..10	η_c	η_{th}
Run 1	0.5	0.02336
Run 2	0.55	0.07038
Run 3	0.6	0.1062
Run 4	0.65	0.1345
Run 5	0.7	0.1573
Run 6	0.75	0.1762
Run 7	0.8	0.192
Run 8	0.85	0.2054
Run 9	0.9	0.217
Run 10	0.95	0.2271

Example 3: Plots

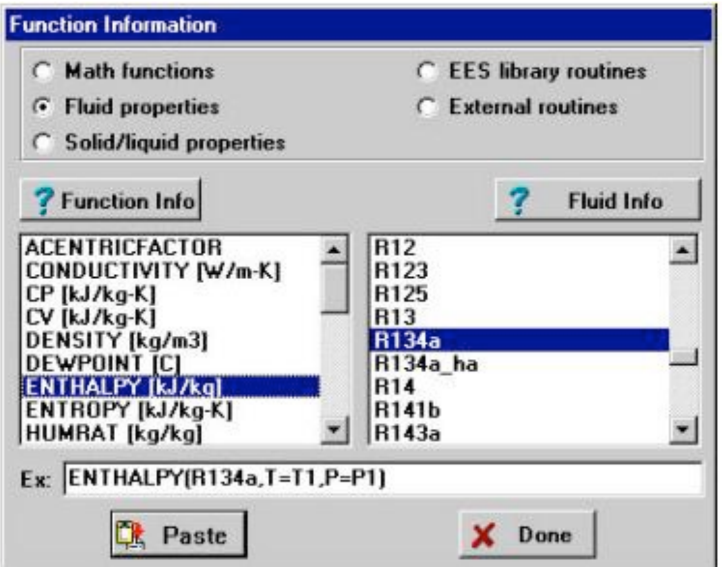
- Plot → New Plot Window
  - The New Plot Setup dialog window will appear.
  - Choose eta_c to be the X-axis by clicking on eta_c in the X-axis list. Click on eta_th in the Y-axis list. You may wish to adjust the scale limits or add grid lines. When you click OK, the plot will be constructed and the plot window will appear.





Thermophysical Functions

- EES has built-in property data for many engineering fluids. They are accessed as functions taking temperature, pressure etc. as arguments.
- These functions may be accessed from the Function Information Window:



Thermophysical Functions – Example 1

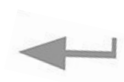
V_1 = M*R*T_1/P_1
V_0 = M*R*T_0/P_0

V_1 = M***volume**(***Argon***,***T***=T_1,***P***=P_1)
V_0 = M***volume**(***Argon***,***T***=T_0,***P***=P_0)

The two ways of calculating volume are not entirely equivalent: the first set uses the ideal gas assumption.

EES gets its thermophysical properties from a variety of sources.
See the entire catalog of thermophysical functions/properties at:
http://fchart.com/ees/eeshelp/fluid_property_information.htm

Recap: Formatting rules

- Upper and lower case ➔ ***NOT*** distinguished.
- Blank lines and spaces ➔ ***ignored***
- Comments must enclosed within ***{ }*** or ***" "***
  - In effect for lines
  - ***""*** comments showed in Formatted Equations **(recommended Psets format)**
- Variable ***start with a letter***
- Array variables ➔ **ArrayName[Index]**
- Equations separated by newline  or **;**
- Units ➔ in **[ ]**

Happy EES’ing !