F-Chart Software

EESy Solutions
Engineering Equation Solver Newsletter

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Welcome

This is the 26th issue of EESy Solutions, a newsletter that provides news, tips, and other updates to users of the Engineering Equation Solver software. This issue is dedicated to the use of EES to solve Heat Exchanger problems.

EES has been a commercial software for more than two decades. If you have missed any of the previous issues of EESy Solutions, they can be downloaded from www.fchart.com.
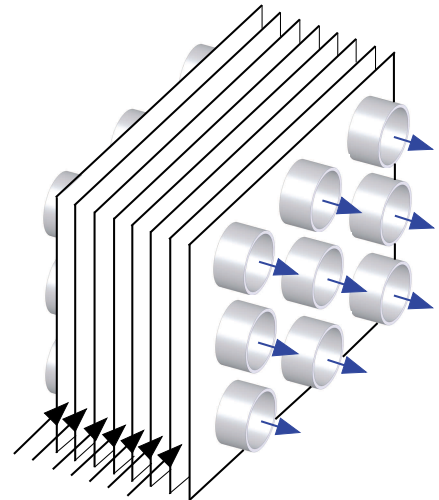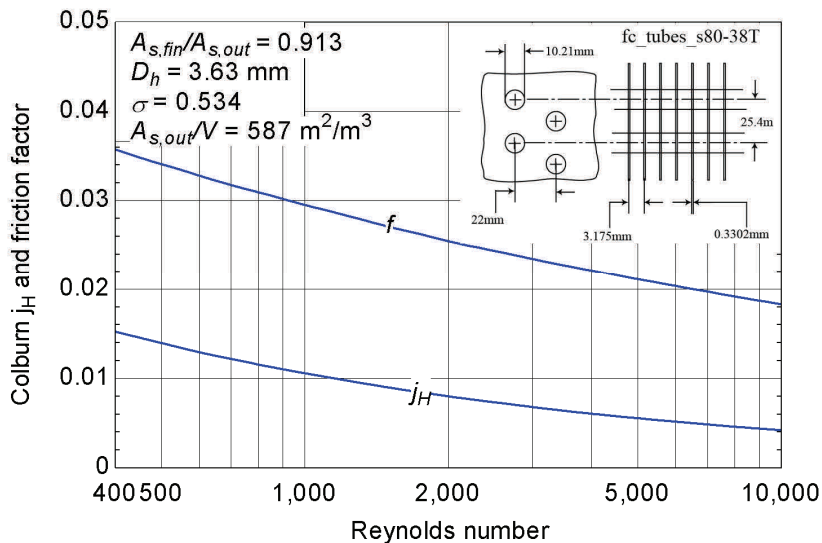
The Compact Heat Exchanger Library

Since it was first published in 1955, the book *Compact Heat Exchangers* by Kays and London has been considered the best reference for the performance of the surfaces used in compact heat exchangers. In most applications, the gas-side (typically air-side) heat transfer coefficient is quite small (usually one or more orders of magnitude less than a liquid-side heat transfer coefficient). Therefore it is almost always necessary to enhance the gas-side surface so that it has a high "area-density". This type of heat exchanger is referred to as a compact heat exchanger. Some examples include finned tubes and plate fin type heat exchangers.

The Compact Heat Exchanger Library in EES arranges the data presented in *Compact Heat Exchangers* in a functional form in order to facilitate simulating heat exchanger cores that have these common geometries.
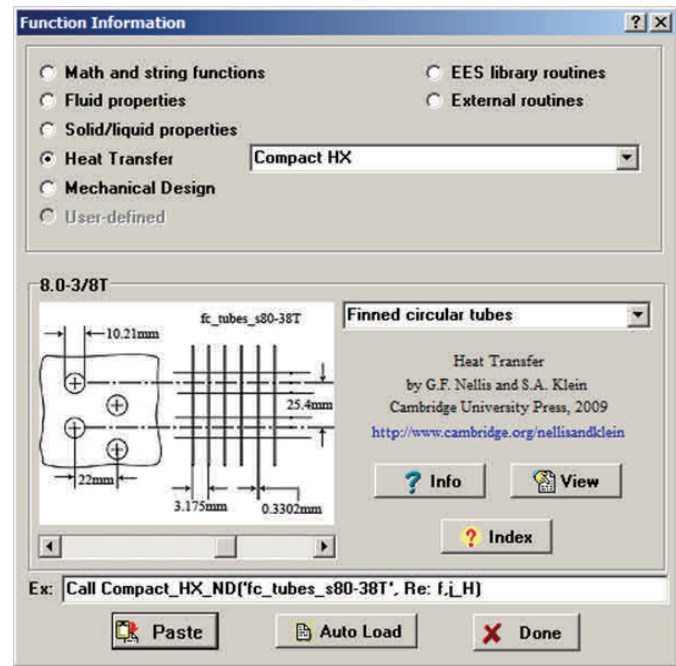
The Compact Heat Exchanger Library

Experimental data for a specific compact heat exchanger core are typically presented in terms of the dimensionless Colburn j_H factor and friction factor, f, as a function of the Reynolds number, Re. The Colburn j_H factor is related to the heat transfer coefficient and friction factor is related to the pressure drop. The plot below shows the relation for one type of heat exchanger.

$A_{s,fin}/A_{s,out} = 0.913$
$D_h = 3.63$ mm
$\sigma = 0.534$
$A_{s,out}/V = 587$ m^2/m^3

Colburn j_H and friction factor vs Reynolds number

There are a large number of core geometries discussed in the *Compact Heat Exchanger* book and these data are very useful because the air flow through the finned side of a compact heat exchanger is a complex combination of internal flow in passages and external flow over tubes and other obstructions. The internal and external flow heat transfer correlations that have been developed for simple geometries are not applicable for compact heat exchangers.

However, it is challenging to decipher the dimensionless data presented in the *Compact Heat Exchanger* book in order to provide useful engineering quantities like heat transfer coefficient and pressure drop. The Compact Heat Exchanger library in EES simplifies this process.

The Compact Heat Exchanger Library is accessed from the Function Information dialog by selecting the Heat Transfer radio button and then selecting Compact HX from the drop down menu.

Organization of the Compact Heat Exchanger Library

When the drop down menu associated with the Compact Heat Exchanger Library is selected, the user will see four categories of functions labeled Non-dimensional, Geometry, Coefficient of Heat Transfer, and Pressure Drop. Under each category there is a list of different types of cores. Selecting a certain type of core allows the user to scroll through the various specific geometries for which data are available.

Non-Dimensional Functions

Non-Dimensional functions provide the dimensionless parameters (j_H and f) as a function of Reynolds number; that is, they provide exactly the same information that could be obtained directly from the charts in the *Compact Heat Exchanger* book.

Geometry Functions

Geometry functions provide the core-level geometric details of the core. These geometric parameters are summarized below.

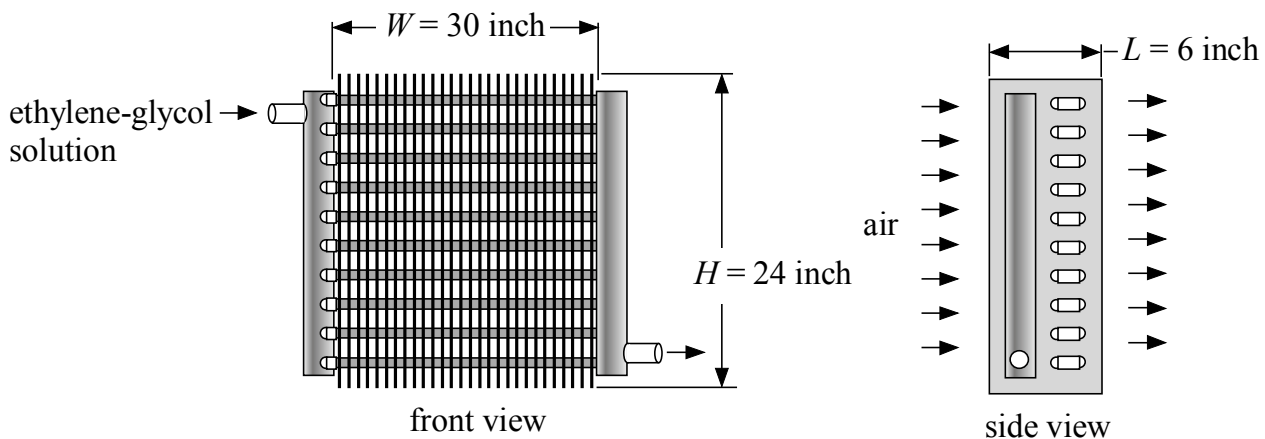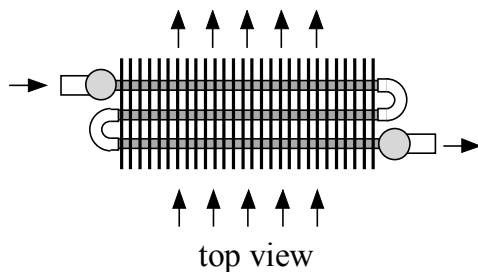| Parameter	SI Unit	English Unit	Description
D_o	m	ft	outer diameter of tube (only valid for circular tube and pin-fin plate-fin geometries)
fin_pitch	1/m	1/ft	number of fins per unit length
D_h	m	ft	hydraulic diameter of passages
fin_thk	m	ft	thickness of fins (valid for geometries other than pin-fin plate fin)
sigma	-	-	ratio of the minimum free flow area to the frontal area
alpha	m²/m³	ft²/ft³	ratio of the heat transfer surface area to the total volume
A_fin\A	-	-	ratio of the finned surface area to the total surface area
b_1	m	ft	thickness of passage through which fluid 1 flows

Coefficient of Heat Transfer Functions

Coefficient of Heat Transfer functions require the operating conditions on the gas-side. These include the fluid name, mass flow rate, temperature and pressure, as well as the frontal area of the heat exchanger. These functions return the air-side heat transfer coefficient for the core of interest.

Pressure Drop Functions

Pressure Drop functions require the operating conditions including the fluid name, mass flow rate, inlet and exit temperatures, and pressure, as well as the frontal area and length of the heat exchanger. These functions return the air-side pressure drop for the core of interest.

Heat Exchanger Example

A finned tube cross-flow heat exchanger is used to transfer energy from a hot ethylene-glycol/water solution to a cold air flow.   The frontal area of the heat exchanger is W = 30 inch by H = 24 inch and the length of the heat exchanger is L = 6 inch. The liquid flows within the tubes while the air flows through across the tubes.

top view

front view

side view

The finned-tube geometry is consistent with compact heat exchanger core fc_tubes_sCF-775-58T.The ethylene-glycol solution has 1 20% concentration and enters at 80ºC with flow rate 25 gal/min. The liquid side is manifolded as shown. The air enters at 20ºC with flow rate 1920 ft^3/min. Both the air and the ethylene-glycol are near ambient pressure.

The unit system is specified using the $UnitSystem directive and the inputs are entered in EES. Notice that the inputs have been converted to base SI units.

```
$UnitSystem SI Mass J K Pa

T_H_in=ConvertTemp(C,K,80 [C])                "ethylene-glycol inlet temperature"
T_C_in=ConvertTemp(C,K,20 [C])                "air cold inlet temperature"
V_dot_H_gpm=25 [gal/min]                       "volumetric flow rate of ethylene-glycol, in gpm"
V_dot_H=V_dot_H_gpm*convert(gal/min,m^3/s)     "volumetric flow rate of ethylene-glycol"
V_dot_C=1920 [cfm]*convert(cfm,m^3/s)          "volumetric flow of air"
Conc_H=20 [%]                                  "concentration of ethylene-glycol"
W=30 [inch]*convert(inch,m)                    "width"
H=24 [inch]*convert(inch,m)                    "height"
L=6 [inch]*convert(inch,m)                     "length"
HX$='fc_tubes_sCF-775-58T'                     "core geometry"
```
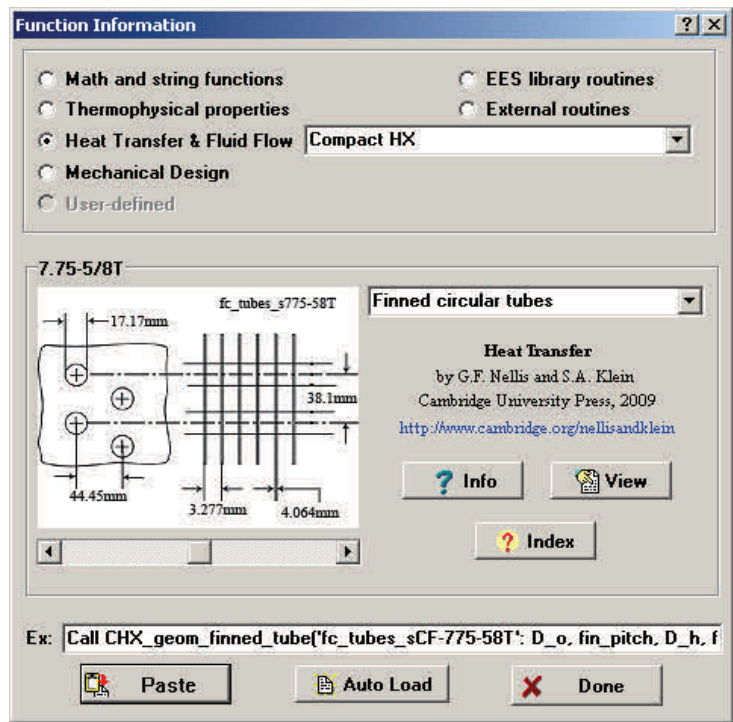
Heat Exchanger Example

Air-Side Calculations

The geometric details are obtained from the appropriate geometry procedure in the Compact Heat Exchanger Library. The procedure CHX_geom_finned_tube returns the geometric details associated with the specific compact heat exchanger core that is being simulated. These parameters include the outer diameter of the tube (D_o), the fin pitch (fin_pitch), the hydraulic diameter on the air-side (D_h), the fin thickness (fin_thk), the ratio of free flow to frontal flow area (sigma), the specific surface area (alpha, the surface area on the air side per volume of heat exchanger core), and the ratio of the fin surface area to total surface area (A_fin\A).

The most important of these parameters is the specific surface area. In this example we will assume that the fin efficiency is 100%. The parameter A_fin\A and fin_thk coupled with information about the fin material would allow us to compute a fin efficiency for a more detailed analysis, but is is normally greater than 90%.

In most compact heat exchangers, the gas-side (typically air-side) resistance dominates and therefore it is often sufficient to compute the heat transfer coefficient on the gas-side for the simulation. In this analysis we will determine the resistance on both the air-side and fluid-side and also estimate the resistance associated with fouling on the liquid side.

```
Call CHX_geom_finned_tube(HX$: D_o, fin_pitch, D_h, fin_thk, sigma, alpha, A_fin\A)
                                                     "geometry parameters"
```

The air properties should be calculated at the average temperature of the air (i.e., the average of the air inlet and air exit temperatures). Because the air exit temperature is an output of the calculation, it is necessary to assume a reasonable value. One way to do this is to enter a temporary equation that sets the variable to a guess value (as shown in the highlighted EES code below) and proceed with the calculations. Eventually, the guessed value will be removed and replaced with the actual calculated value.

```
"Air-side calculations"
T_C_out=T_H_in                          "initial guess for T_C_in"
T_C_bar=(T_C_in+T_C_out)/2              "average temperature on air-side"
```

Heat Exchanger Example

The appropriate heat transfer coefficient procedure is selected from the Compact Heat Exchanger Library. The function CHX_h_finned_tube requires the heat exchanger core geometry, the mass flow rate, the frontal area, the fluid, the temperature at which to compute properties, and the pressure. The function returns the heat transfer coefficient on the air-side (h_C)

```
A_fr=W*H                                    "frontal area"
rho_C=Density(Air,T=T_C_in,P=Po#)           "density of air"
m_dot_C=V_dot_C*rho_C                        "mass flow rate of air"
Call CHX_h_finned_tube(HX$, m_dot_C, A_fr, 'Air',T_C_bar,Po#:h_C)
                                            "heat transfer coefficient on air-side"
```

In order to compute the thermal resistance on the air-side it is necessary to determine the total air-side heat transfer area. This is the product of the total heat exchanger volume and the specific surface area.

```
Vol=W*H*L                                   "total heat exchanger volume"
A_C=Vol*alpha                               "total air-side surface area"
R_C=1/(h_C*A_C)                             "air-side resistance"
```

The pressure drop on the air-side is obtained using the appropriate pressure drop procedure in the Compact Heat Exchanger Library. The CHX_DELTAp_finned_tube procedure requires the core geometry, mass flow rate, frontal area, length in the flow direction, fluid, and inlet and outlet temperatures.
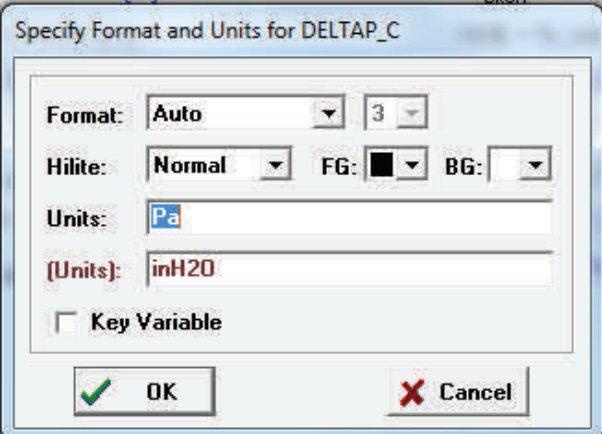
```
Call CHX_DELTAp_finned_tube(HX$, m_dot_C, A_fr,L, 'Air', T_C_in, T_C_out, Po#: DELTAP_C)
                                            "pressure drop on air-side"
```

Note that the entrance and exit effects are included in the pressure drop returned by the procedure (DELTAP_C). Solve and select the variable DELTAP_C in the Solutions Window. Specify inH2O in the alternate units box in order to display the value of the pressure drop in both primary (Pa) and alternate (inH2O) units as shown.

$= 39.22 \, [m^2]$

$nc_H = 20 \, [\%]$

$= 0.01717 \, [m]$

$A_{fin\backslash A} = 0.95 \, [-]$

$\Delta P_C = 42.81 \, [Pa] \, \{0.1718 \, [inH2O]\}$

$fin_{pitch} = 305 \, [1/m]$

es_sCF-775-58T'

Specify Format and Units for DELTAP_C

Format: Auto ▼ 3 ▼

Hilite: Normal ▼ FG: ■ ▼ BG: ▼

Units: Pa

(Units): inH2O

☐ Key Variable

✓ OK   ✗ Cancel

Heat Exchanger Example

Tube-Side Calculations

The ethylene-glycol solution properties should be calculated at the average temperature of the liquid. The liquid exit temperature is an output of the calculation and therefore it is again necessary to assume a reasonable value (highlighted in the EES code below) to proceed with the calculations.
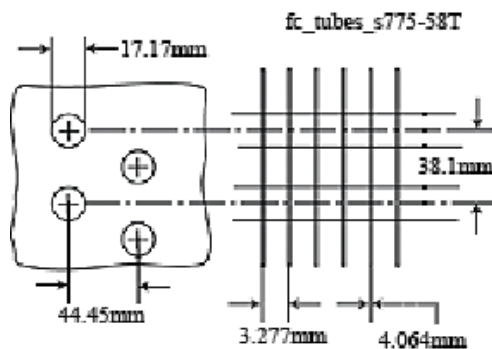
```
"Tube-side calculations"
T_H_out=T_C_in                              "initial guess for T_H_out"
T_H_bar=(T_H_in+T_H_out)/2                  "average temperature on liquid-side"
```

The tube-side geometry (i.e., the horizontal and vertical distance between tubes and the tube wall thickness) is entered based on the dimensions of the compact heat exchanger core. The number of tubes in the vertical and horizontal directions are computed and used to compute the total length of a single pass. The internal flow convection library is used to determine the heat transfer coefficient on the tube-side and the frictional pressure drop on the tube side. Note that the pressure input corresponds to concentration when the specified fluid is a brine.

```
W_tube=0.0445 [m]                           "horizontal distance between tubes"
H_tube=0.0381 [m]                           "vertical distance between tubes"
th_tube=0.065 [inch]*convert(inch,m)        "tube wall thickness"
N_tube_h=floor(L/W_tube)                    "number of tubes horizontally"
N_tube_v=floor(H/H_tube)                    "number of tubes vertically"
L_tube=W*N_tube_h                           "length of one tube"
D_i=D_o-2*th_tube                           "inner tube diameter"
rho_H=Density(EG,T=T_H_bar,C=Conc_H)        "density of ethylene-glycol"
m_dot_H=V_dot_H*rho_H                       "mass flow rate of ethylene-glycol"
call PipeFlow('EG',T_H_bar,Conc_H,m_dot_H/N_tube_v,D_i,L_tube,0[-]:h_H_T, h_H_H ,&
     DELTAP_H_tube, Nusselt_H_T, f_H, Re_H)  "correlations for internal flow in a circular tube"
```

Heat Exchanger Example

In addition to the frictional loss in the tubes there are minor losses associated with each 180º tube bend in the pass as well as the tube inlet and outlet. The Minor Losses library is used to determine the loss coefficient associated with these flow obstructions. The total pressure drop and tube-side thermal resistance is determined.

```
u_H=V_dot_H/(N_tube_v*pi*D_i^2/4)                    "velocity of ethylene-glycol"
K_total=K_Sharp_Edged_Pipe_Exit('turbulent')+K_Sharp_Edged_Pipe_Inlet(D_i)&
    +(N_tube_h-1)*K_ReturnBend(0 [-])                "total minor loss coefficient"
DELTAP_H=DELTAP_H_tube+K_total*rho_H*u_H^2/2   "total liquid-side pressure loss"
A_H=N_tube_v*pi*D_i*L_tube                        "total liquid-side surface area"
R_H=1/(h_H_T*A_H)                                      "liquid-side resistance"
```


Fouling

Fouling may be important in any heat exchanger. There is a library of empirical fouling factors built into the Heat Transfer library in EES that are useful for estimating the impact of fouling. Select Fouling Factors from the drop-down menu and then scroll down to the fluid of interest (Ethylene glycol solution). The resulting fouling factor is used to estimate the fouling resistance on the tube-side. Air-side fouling is neglected in this analysis.
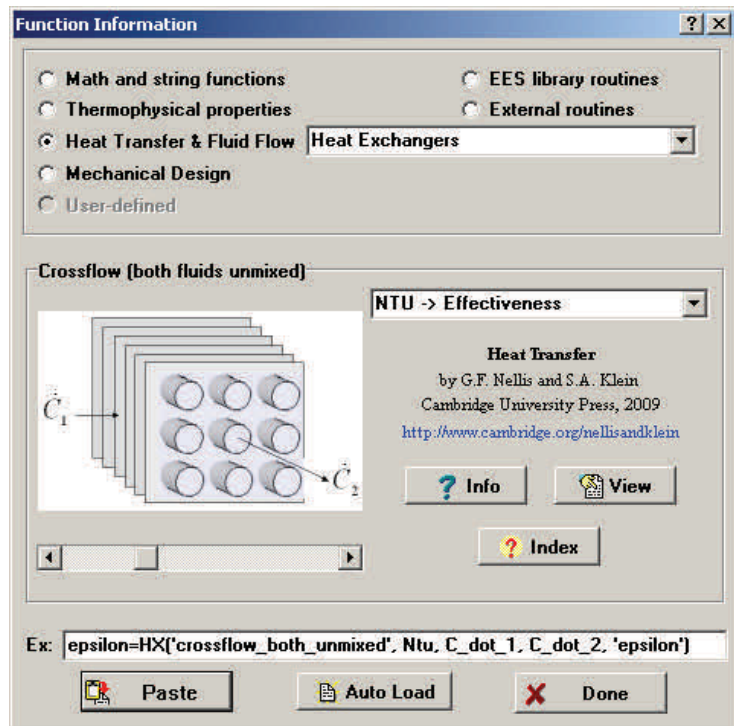
```
"Fouling"
FF_H=FoulingFactor('Ethylene glycol solution')       "liquid-side fouling factor"
R_foul=FF_H/A_H                                        "fouling resistance"
```

Heat Exchanger Example

Heat Exchanger Calculations

The total thermal resistance is computed and used to determine the conductance of the heat exchanger. The capacitance rates of the two fluids are obtained and used to determine the number of transfer units associated with the device. The heat exchanger is modeled as a cross-flow heat exchanger in which both fluids are unmixed. The effectiveness is obtained using the effectiveness-NTU function in the Heat Transfer library. The maximum possible and actual rates of heat transfer are computed using the effectiveness.

```
"Heat Exchanger Calculation"
R_total=R_C+R_foul+R_H                          "total resistance"
UA=1/R_total                                     "conductance"
c_C=cP(Air,T=T_C_bar)                           "specific heat capacity of air"
C_dot_C=c_C*m_dot_C                             "capacitance rate of air"
c_H=cP(EG,T=T_H_bar,C=Conc_H)                   "specific heat capacity of ethylene-glycol"
C_dot_H=c_H*m_dot_H                             "capacitance rate of ethylene-glycol"
C_dot_min=MIN(C_dot_C,C_dot_H)                  "minimum capacitance rate"
NTU=UA/C_dot_min                                "number of transfer units"
eff=HX('crossflow_both_unmixed', NTU, C_dot_C, C_dot_H, 'epsilon')
                                                "effectiveness"
Q_dot_max=C_dot_min*(T_H_in-T_C_in)             "maximum possible rate of heat transfer"
Q_dot=Q_dot_max*eff                             "actual rate of heat transfer"
```

At this point the solution is complete. However, it is based on assumed values of the outlet temperatures. Update the guess values used by EES so that the most recent solution is used as the starting point for the iteration. Comment out the assumed values of outlet temperature.

```
{T_C_out=T_H_in}                                "initial guess for T_C_in"
{T_H_out=T_C_in}                                "initial guess for T_H_out"
```

Compute the outlet temperatures using energy balances.
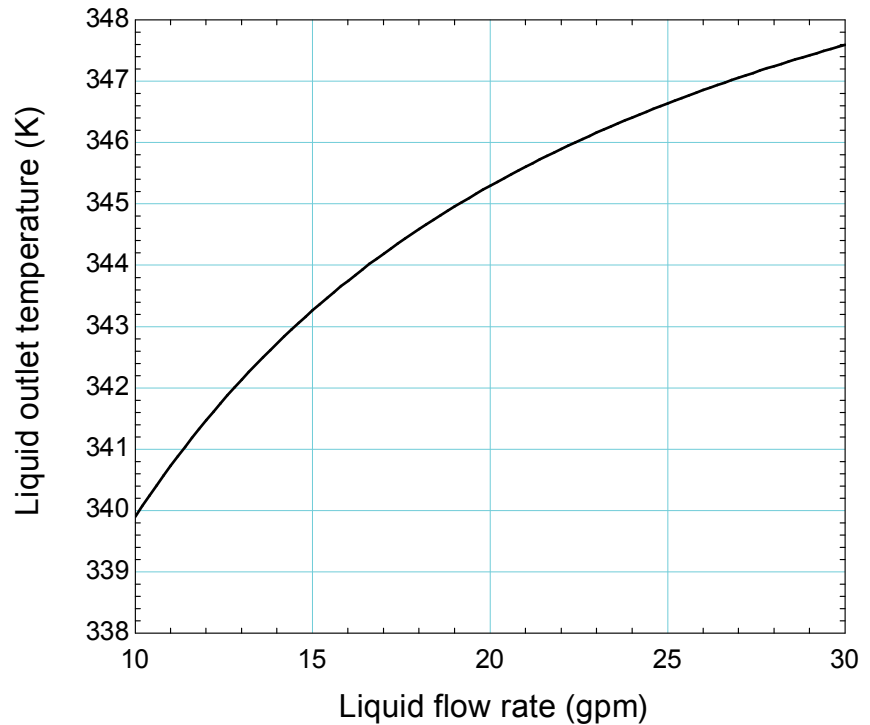
```
T_C_out=T_C_in+Q_dot/C_dot_C                    "energy balance on air"
T_H_out=T_H_in-Q_dot/C_dot_H                    "energy balance on ethylene-glycol"
```

Heat Exchanger Example

Plotting in Dual Units

The simulation can be used to predict the performance of the heat exchanger over a range of conditions. For example, comment out the flow rate of the ethylene glycol and create a Parametric Table that includes the liquid flow rate and liquid outlet temperature. Vary the flow rate from 10 gpm to 30 gpm and run the table.

Parametric Table

Table 2

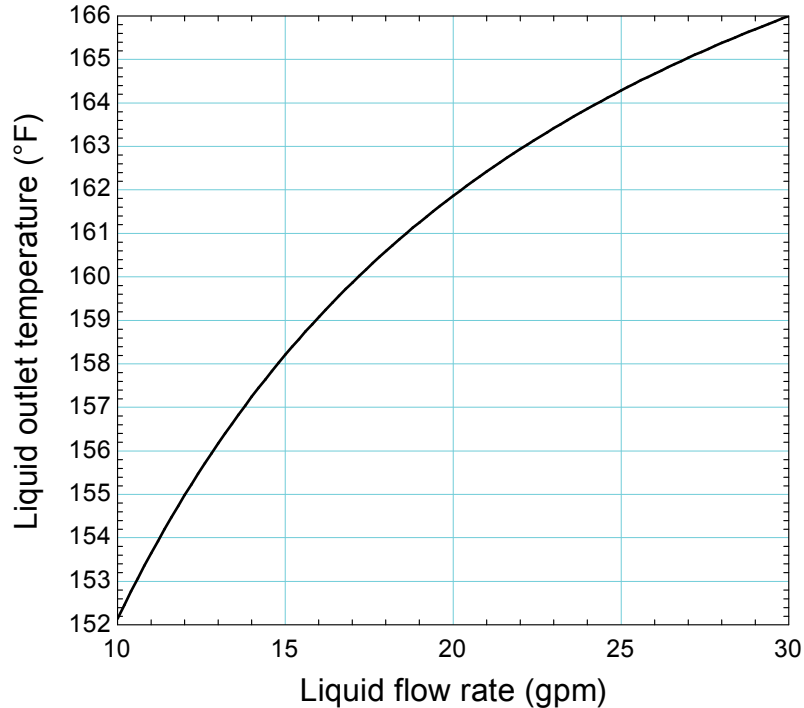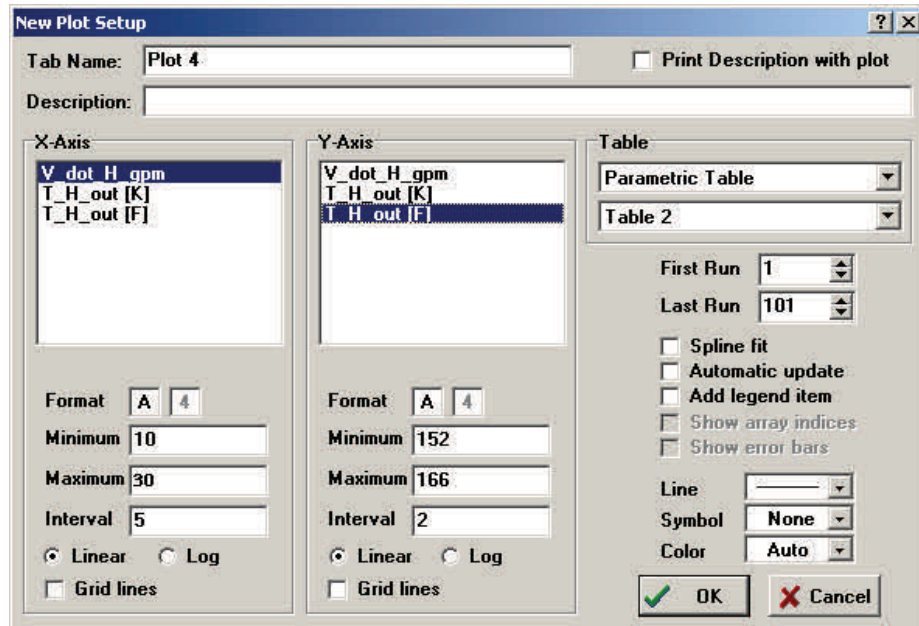| 1..101	$\dot{V}_{H,gpm}$ [gal/min]	$T_{H,out}$ [K]
Run 1	10	339.9
Run 2	10.2	340.1
Run 3	10.4	340.2
Run 4	10.6	340.4
Run 5	10.8	340.6
Run 6	11	340.7
Run 7	11.2	340.9
Run 8	11.4	341
Run 9	11.6	341.2
Run 10	11.8	341.3
Run 11	12	341.5
Run 12	12.2	341.6

To change the units used to create the plot, simply right-click on the T_H_out column and specify the alternate unit F. Click the box labeled Show values in alternate units.

Format Parametric Table Column 2

Column Header
Title: T_H_out
Units: K
(Units): F
☑ Show values in alternate units

Format: 339.9
Style: Auto   Digits: 1
Background color: White
Column width: 91 pixels

Position
Move to column number: 2

Statistics
Sum:	34825
Average:	344.8
Std. Dev:	2.161
Minimum:	339.9
Maximum:	347.6

✓ OK   Delete   ✗ Cancel

Parametric Table

Table 2

1..101	$\dot{V}_{H,gpm}$ [gal/min]	$T_{H,out}$ [K] {[F]}
Run 1	10	339.9 {152.1}
Run 2	10.2	340.1 {152.5}
Run 3	10.4	340.2 {152.8}
Run 4	10.6	340.4 {153.1}
Run 5	10.8	340.6 {153.4}
Run 6	11	340.7 {153.6}
Run 7	11.2	340.9 {153.9}
Run 8	11.4	341 {154.2}
Run 9	11.6	341.2 {154.5}
Run 10	11.8	341.3 {154.7}
Run 11	12	341.5 {155}
Run 12	12.2	341.6 {155.2}

Heat Exchanger Example

Select New Plot Window and X-Y Plot from the Plots menu and notice that you can now select T_H_out in either the primary (K) or alternate (F) units as the data to be plotted.

This example is included as one of the example EES programs accessible from the Examples menu within EES (starting with version 9.652).

F-Chart Software

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http://fchart.com

- Thermodynamic property data are available for the fluids SES36, R236ea, n-Undecane, and cyclopentane

- Both the text color and background color of radio button groups and check boxes can be programmatically changed in the Diagram Window

- Alternate units can now be used in tables and also to create plots

- Tables can be saved in a Excel (.xls) file format

- Side-by-side bar plots can be created

- Text and graphics items in the Plot and Diagram Windows can be moved using the arrow keys

- Deuterium properties are computed using the correlation developed by Richardson et al. (2014)

- External functions and procedures can return warning messages that are displayed in the Warning Window

- The Beep # command can be used in internal functions and procedures to create an audible sound

- The Residuals and Computational Flow Windows display the total accumulated computational time required to solve each equation

- The partial derivatives and fractional uncertainties used to compute uncertainties can be accessed with the Uncert.ParDif and Uncert.Percent functions

- Unit checking has been enabled for external functions and procedures.

Instant Update Service

EES uses a different model for updating than most other programs. Each time that there is a change in the EES program, either to correct a problem or to add a new feature, the version number is incremented by 0.001 and the latest version of EES is placed on our website. Although the program has become very robust and stable, there have been many new versions of EES released since the last EESy Solutions was distributed.

Any user who has a current subscription to our Instant Update Service can download the latest version. All new licenses of EES are provided with one year of Instant Update Service. The fee to continue Instant Update Service after the first year is 20% of the current cost of the program per year. Contact F-Chart Software if you wish to re-subscribe to the Instant Update Service