Heat Transfer

Computational Laboratories

Heat Exchangers

(Laboratory IV)

Understanding the role of physical parameters and operating conditions on the thermal design and performance of heat exchangers

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Heat Exchangers (HXs) - Introduction

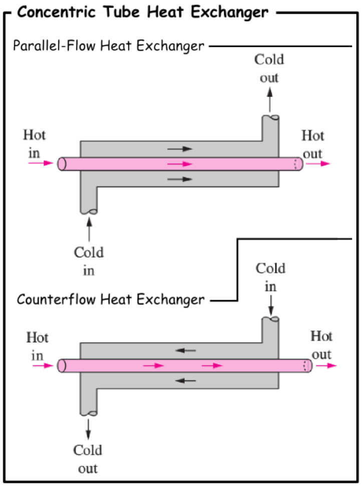
Heat Exchangers

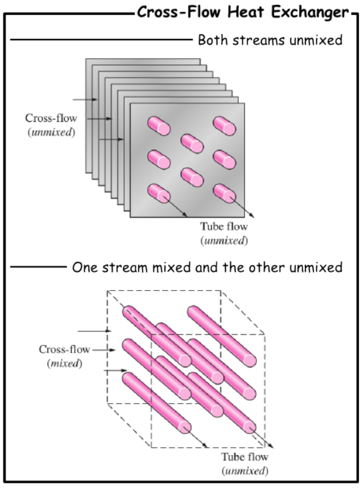
Heat exchangers are devices that promote heat exchange between two fluids that are at different temperatures, preventing at the same time their mixing.
The hot and cold fluid streams are separated by wall or are provided to the heat exchanger at different time instants (static-type regenerative).

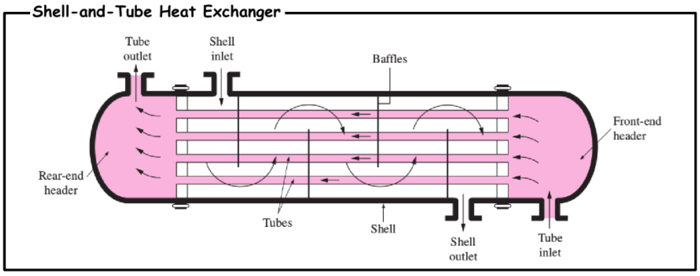
Applications

- Power production
- Air-conditioning
- Waste heat recovery
- Chemical process industry

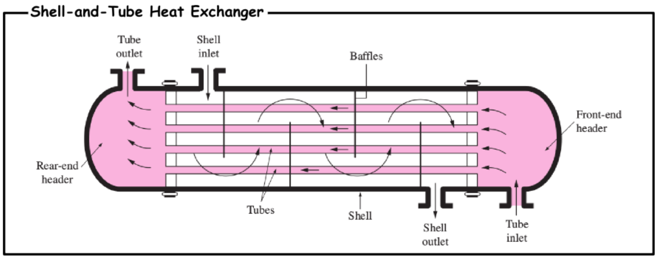
Types of Heat Exchangers (1/2)


Concentric Tube Heat Exchanger

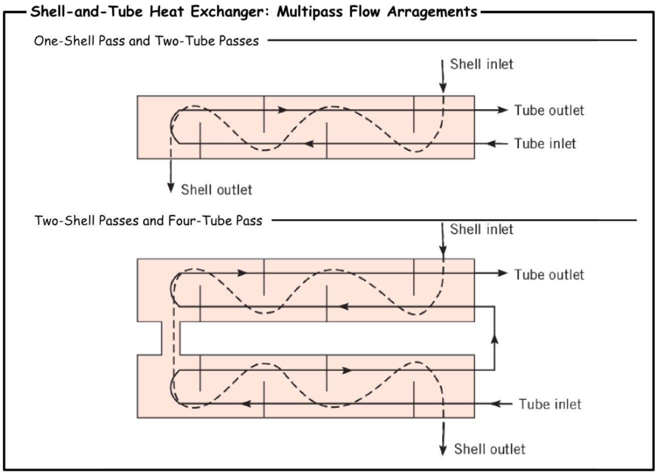

Cross-Flow Heat Exchanger

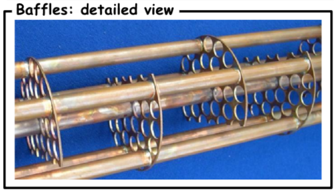

Shell-and-Tube Heat Exchanger

Types of Heat Exchangers (2/2): Shell-and-Tube HX


Shell-and-Tube Heat Exchanger

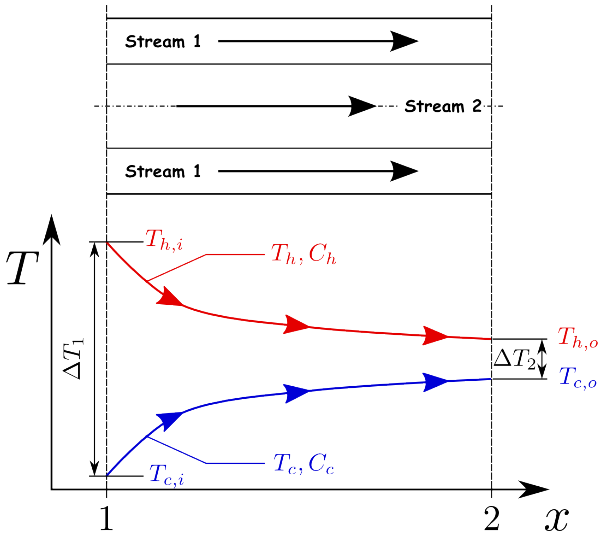

HX in Exhibition - South Tower (Atrium)


Shell-and-Tube Heat Exchanger: Multipass Flow Arragements

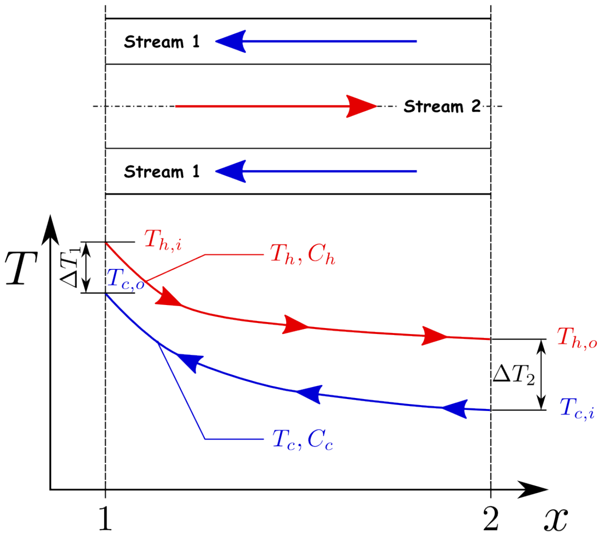

Baffles: detailed view

Temperature Distributions in Concentric Tube HXs

Parallel-Flow Heat Exchanger



Counterflow Heat Exchanger



T - Temperature; C - heat capacity rate ($= \dot{m} c_p$); h - hot fluid; c - cold fluid; i - inlet; o - outlet.

Heat Exchanger Analysis and Methods

Heat Exchanger Design (LMTD or ε-NTU methods)

Determination of the **heat exchanger type** and **size** (A - total heat transfer surface area) for prescribed:

- hot and cold mass flow rates ($\dot{m}_h$ and $\dot{m}_c$);
- inlet temperatures of the hot and cold fluid streams ($T_{h,i}$ and $T_{c,i}$);
- desired outlet temperature for the hot or cold fluid ($T_{h,o}$ or $T_{c,o}$).

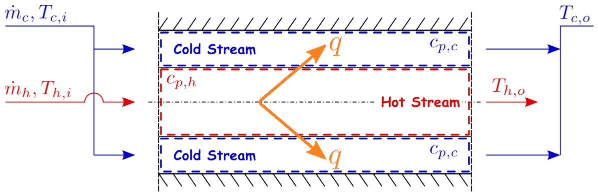
Heat Exchanger Performance (ε-NTU method)

Determination of the **rate of heat transfer** (q) and **fluid outlet temperatures** ($T_{c,o}$ and $T_{h,o}$) for prescribed:

- heat exchanger type;
- heat exchanger size (A);
- hot and cold mass flow rates ($\dot{m}_h$ and $\dot{m}_c$);
- inlet temperatures of the hot and cold fluid streams ($T_{h,i}$ and $T_{c,i}$).

Total Heat Transfer Rate

The **total heat transfer rate from the hot to the cold fluid stream** can be obtained by performing an overall energy balance for the hot or cold fluids.



- For the hot fluid stream:

$$q = \underbrace{\dot{m}_h c_{p,h}}_{C_h} (T_{h,i} - T_{h,o})$$

- For the cold fluid stream:

$$q = \underbrace{\dot{m}_c c_{p,c}}_{C_c} (T_{c,o} - T_{c,i})$$

The total heat transfer rate can also be obtained through a **modified form of the Newton's Law of cooling** as follows[†]:

$$q = UA\Delta T_{\mathrm{lm}}$$

where,
U - overall heat transfer coefficient;
A - total heat transfer surface area;
ΔT_{lm} - Log mean temperature difference (LMTD). Equivalent to a mean temperature difference between two fluids for the entire heat exchanger.

[†] This procedure to evaluate q corresponds to the LMTD Method.

Log Mean Temperature Difference: Single-Pass Heat Exchangers (Concentric Tube and Shell-and-Tube)

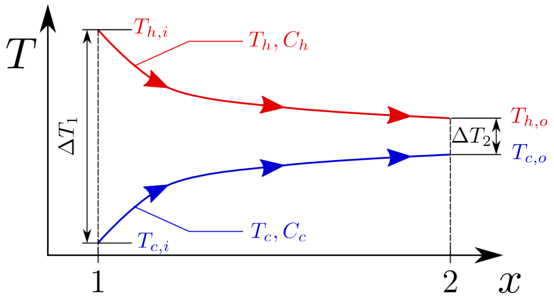
$$\Delta T_{\mathrm{lm}} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$$

$$\Delta T_1 = T_{h,1} - T_{c,1} = \begin{cases} T_{h,i} - T_{c,i} & \text{PF HX} \\ T_{h,i} - T_{c,o} & \text{CF HX} \end{cases}$$

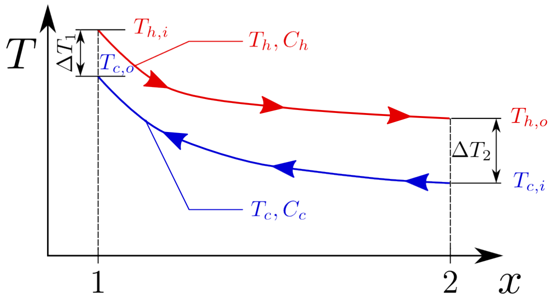
$$\Delta T_2 = T_{h,2} - T_{c,2} = \begin{cases} T_{h,o} - T_{c,o} & \text{PF HX} \\ T_{h,o} - T_{c,i} & \text{CF HX} \end{cases}$$

For specified inlet and outlet temperatures ($T_{h,i}$, $T_{c,i}$, $T_{h,o}$ and $T_{c,o}$) the log mean temperature difference for a counterflow heat exchanger is always greater than that for a parallel-flow heat exchanger, *i.e.*, $\Delta T_{\mathrm{lm,CF}} > \Delta T_{\mathrm{lm,PF}}$.

Parallel-Flow (PF) Heat Exchanger



Counterflow (CF) Heat Exchanger



Log Mean Temperature Difference: Multipass Shell-and-Tube and Cross-Flow Heat Exchangers (1/2)

- The LMTD as defined previously is limited to concentric tube HXs and single-pass shell-and-tube HXs.
- For multipass and cross-flow heat exchangers a mean temperature difference can also be defined as a function of the LMTD for a counterflow HX as follows:

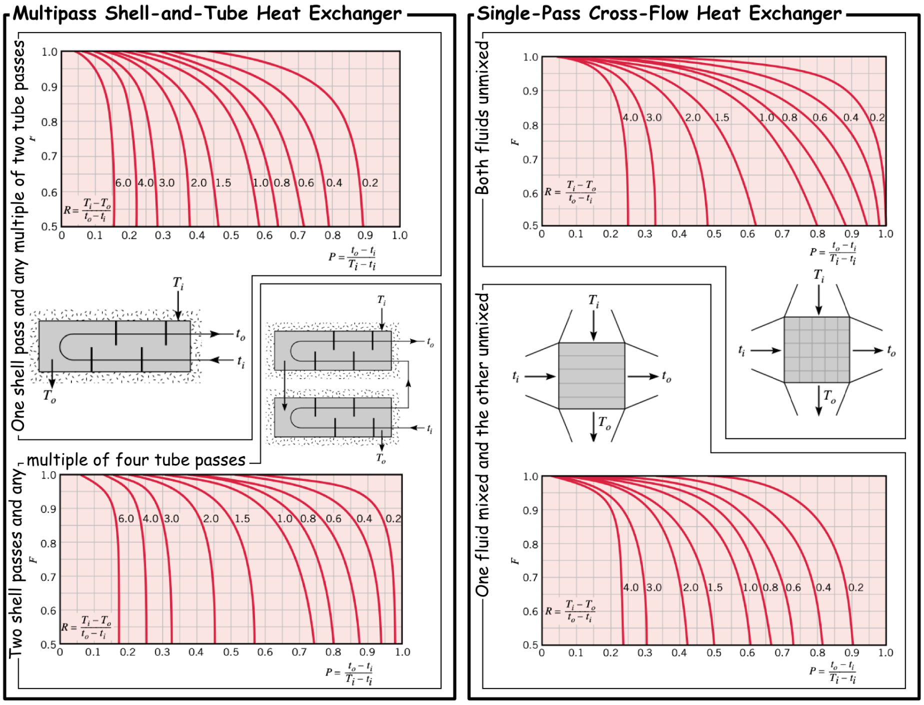
$$\Delta T_{\mathrm{lm,c}} = F \Delta T_{\mathrm{lm,CF}}$$

  where F is a **correction factor** that depends on the HX type and the inlet and outlet temperatures.
- $F = f\,(\text{HX geometry}, P, R)$ and is commonly given in charts. P and R are the following temperature ratios:

$$P = \frac{t_2 - t_1}{T_1 - t_1} \qquad R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{(\dot{m}C_p)_{\text{Tube side}}}{(\dot{m}C_p)_{\text{Shell side}}}$$

- $F \leq 1$

Log Mean Temperature Difference: Multipass Shell-and-Tube and Cross-Flow Heat Exchangers (2/2)



- $P = \frac{t_2 - t_1}{T_1 - t_1}$
  - $0 \leq P \leq 1$
- $R = \frac{T_1 - T_2}{t_2 - t_1}$
  - $0 \leq R \leq \infty$
  - $R = 0$ - Phase change on the shell side
  - $R \to \infty$ - Phase change on the tube side
- $F = 1$ for a condenser or a boiler

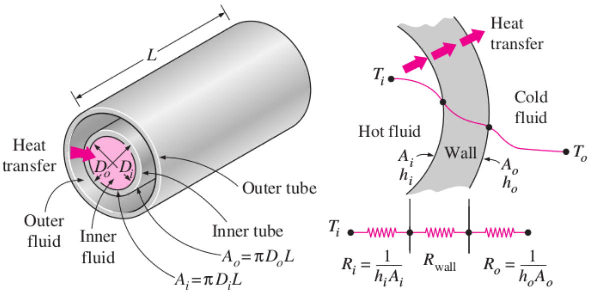
Overall Heat Transfer Coefficient

- For a finned surface with a layer of deposits that represents an additional heat transfer resistance (R''_f) the total heat transfer resistance is given by:

$$R_{t,total} = \frac{1}{UA} = \frac{1}{U_c A_c} = \frac{1}{U_h A_h} = \frac{1}{(\eta_0 hA)_c} + \frac{R''_{f,c}}{(\eta_0 A)_c} + R_w + \frac{R''_{f,h}}{(\eta_0 A)_h} + \frac{1}{(\eta_0 hA)_h}$$

- For an unfinned concentric tube HX without fouling (clean surfaces) the overall heat transfer coefficient can be obtained as follows

$$\frac{1}{UA} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = \frac{1}{(hA)_i} + \underbrace{\frac{\ln(D_o/D_i)}{2\pi kL}}_{R_w} + \frac{1}{(hA)_o}$$



Effectiveness-NTU Method (1/3)

1. The **heat transfer effectiveness** (ε) is defined as:

$$\varepsilon = \frac{q}{q_{max}}$$

where q is the **actual rate of heat transfer** and q_{max} is the **maximum possible heat transfer rate** give by:

$$q_{max} = C_{min}(T_{h,i} - T_{c,i})$$

C_{min} corresponds to the **minimum heat capacity rate** as follows:

$$C_{min} = Min(C_h, C_c)$$

2. For each exchanger the heat transfer effectiveness can be obtained through proper relations:

$$\varepsilon = f\left(NTU, \frac{C_{min}}{C_{max}}\right)$$

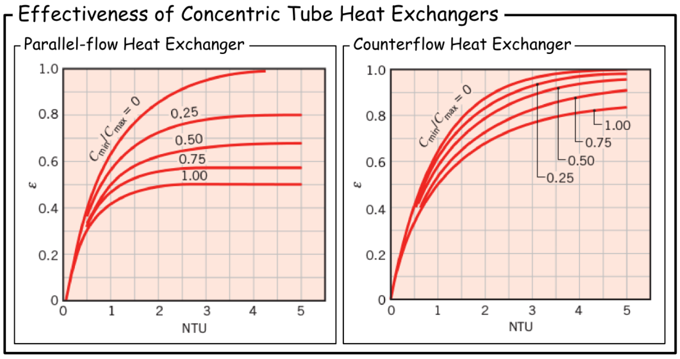
NTU corresponds to the **number of transfer units** and is given by:

$$NTU = \frac{UA}{C_{min}}$$

3. NTU can be obtained through relations of the form:

$$NTU = f\left(\varepsilon, \frac{C_{min}}{C_{max}}\right)$$

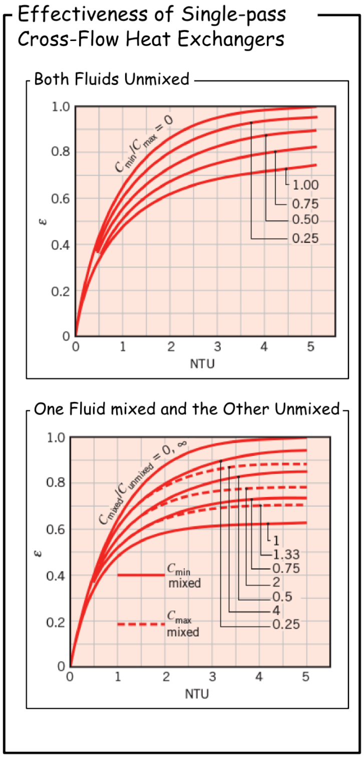
Effectiveness-NTU Method (2/3)



Effectiveness of Concentric Tube Heat Exchangers

Parallel-flow Heat Exchanger

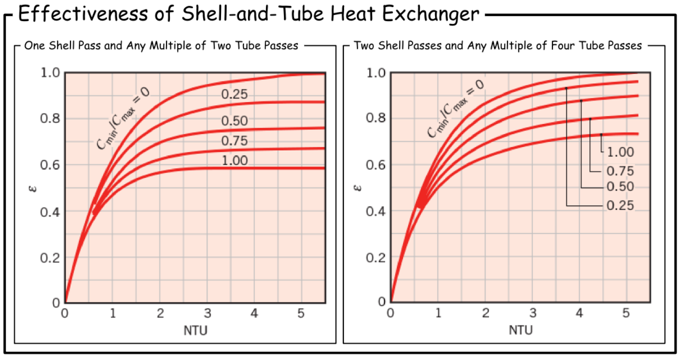
Counterflow Heat Exchanger



Effectiveness of Single-pass Cross-Flow Heat Exchangers

Both Fluids Unmixed

One Fluid mixed and the Other Unmixed



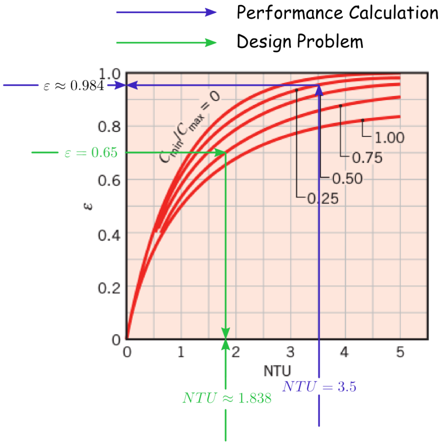
Effectiveness of Shell-and-Tube Heat Exchanger

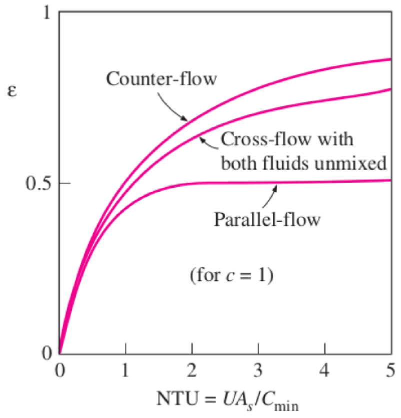
One Shell Pass and Any Multiple of Two Tube Passes

Two Shell Passes and Any Multiple of Four Tube Passes

Effectiveness-NTU Method (3/3)

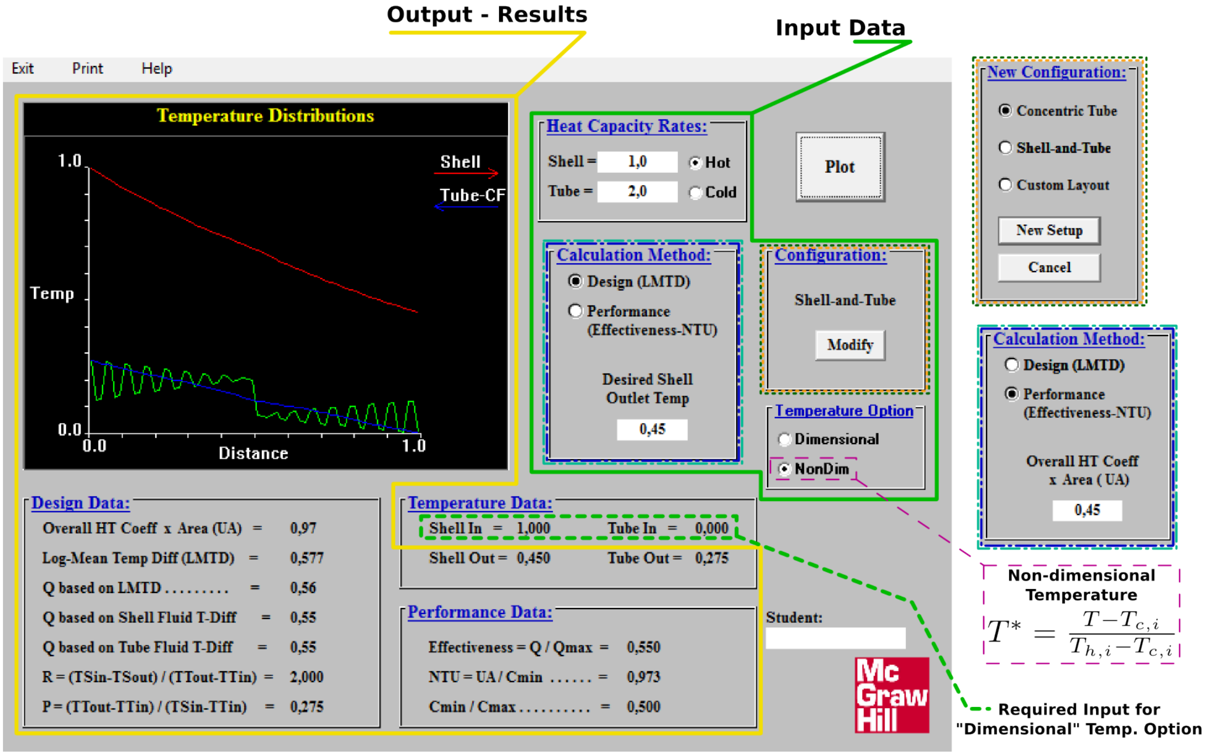
- For performance calculations, effectiveness relations ($\varepsilon = f\,(NTU, C_r)$) are employed whereas for design purposes, NTU relations ($NTU = f\,(\varepsilon, C_r)$) are considered.
- For a boiler or condenser ($C_r (= \frac{C_{min}}{C_{max}}) = 0$) ε is independent of the heat exchanger type and flow arrangement, *i.e.*, all heat exchangers have the same effectiveness value.





- For $C_r > 0$ and $NTU \gtrsim 0.25$ the counterflow heat exchanger is the most effective.
- For any HX $C_r = 0$ and $C_r = 1$ corresponds to the maximum and minimum effectiveness values.

Exploring the Software - The Interface (1/2)



Output - Results

Input Data

Heat Capacity Rates:
Shell = 1,0 ● Hot
Tube = 2,0 ○ Cold

Calculation Method:
● Design (LMTD)
○ Performance (Effectiveness-NTU)
Desired Shell Outlet Temp 0,45

Configuration:
Shell-and-Tube
Modify

Temperature Option
○ Dimensional
● NonDim

Design Data:
Overall HT Coeff x Area (UA) = 0,97
Log-Mean Temp Diff (LMTD) = 0,577
Q based on LMTD .... = 0,56
Q based on Shell Fluid T-Diff = 0,55
Q based on Tube Fluid T-Diff = 0,55
R = (TSin-TSout) / (TTout-TTin) = 2,000
P = (TTout-TTin) / (TSin-TTin) = 0,275

Temperature Data:
Shell In = 1,000 Tube In = 0,000
Shell Out = 0,450 Tube Out = 0,275

Performance Data:
Effectiveness = Q / Qmax = 0,550
NTU = UA / Cmin ...... = 0,973
Cmin / Cmax .... = 0,500

Student:

New Configuration:
● Concentric Tube
○ Shell-and-Tube
○ Custom Layout
New Setup
Cancel

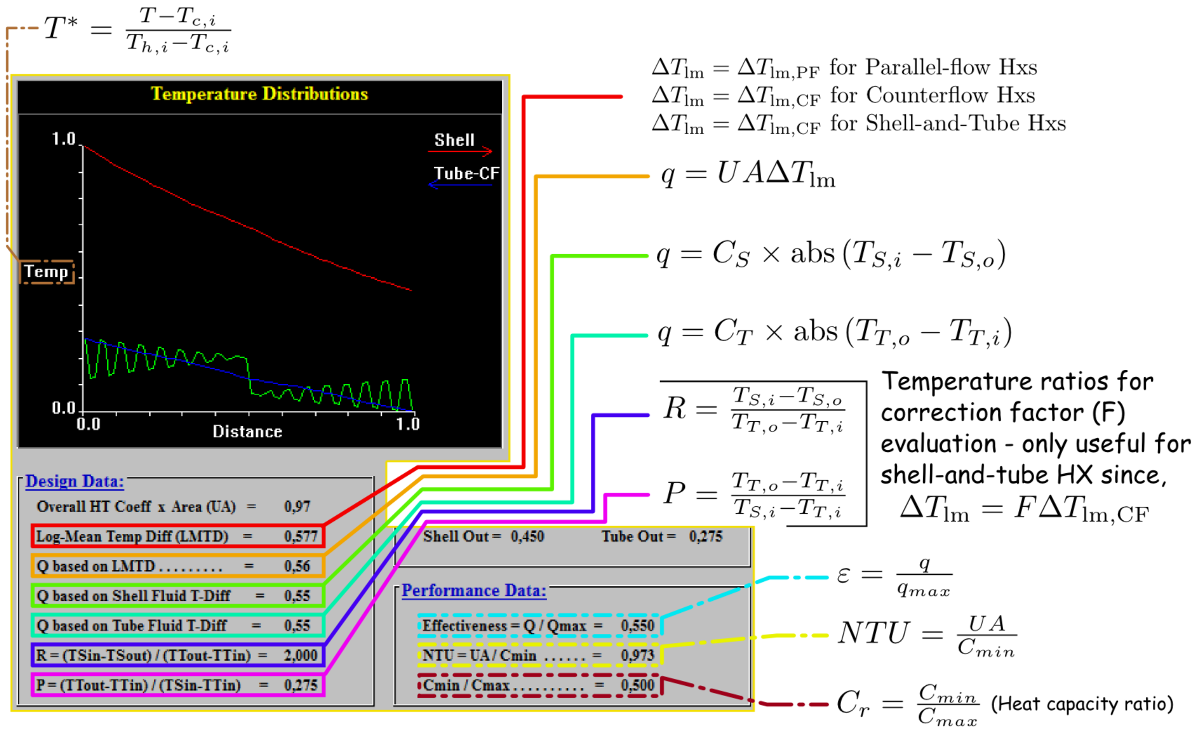
Calculation Method:
○ Design (LMTD)
● Performance (Effectiveness-NTU)
Overall HT Coeff x Area (UA) 0,45

Non-dimensional Temperature

$$T^* = \frac{T - T_{c,i}}{T_{h,i} - T_{c,i}}$$

Required Input for "Dimensional" Temp. Option

Exploring the Software - The Interface (2/2)



$$T^* = \frac{T - T_{c,i}}{T_{h,i} - T_{c,i}}$$

Design Data:
Overall HT Coeff x Area (UA) = 0,97
Log-Mean Temp Diff (LMTD) = 0,577
Q based on LMTD .... = 0,56
Q based on Shell Fluid T-Diff = 0,55
Q based on Tube Fluid T-Diff = 0,55
R = (TSin-TSout) / (TTout-TTin) = 2,000
P = (TTout-TTin) / (TSin-TTin) = 0,275

Shell Out = 0,450 Tube Out = 0,275

Performance Data:
Effectiveness = Q / Qmax = 0,550
NTU = UA / Cmin ...... = 0,973
Cmin / Cmax .... = 0,500

$\Delta T_{\mathrm{lm}} = \Delta T_{\mathrm{lm,PF}}$ for Parallel-flow Hxs
$\Delta T_{\mathrm{lm}} = \Delta T_{\mathrm{lm,CF}}$ for Counterflow Hxs
$\Delta T_{\mathrm{lm}} = \Delta T_{\mathrm{lm,CF}}$ for Shell-and-Tube Hxs

$$q = UA\Delta T_{\mathrm{lm}}$$

$$q = C_S \times \mathrm{abs}\left(T_{S,i} - T_{S,o}\right)$$

$$q = C_T \times \mathrm{abs}\left(T_{T,o} - T_{T,i}\right)$$

$$R = \frac{T_{S,i} - T_{S,o}}{T_{T,o} - T_{T,i}}$$

$$P = \frac{T_{T,o} - T_{T,i}}{T_{S,i} - T_{T,i}}$$

Temperature ratios for correction factor (F) evaluation - only useful for shell-and-tube HX since, $\Delta T_{\mathrm{lm}} = F\Delta T_{\mathrm{lm,CF}}$

$$\varepsilon = \frac{q}{q_{max}}$$

$$NTU = \frac{UA}{C_{min}}$$

$$C_r = \frac{C_{min}}{C_{max}}$$ (Heat capacity ratio)

Exploring the Software - **Design Problem** (1/4)

A heat exchanger is to be designed to cool ethyl alcohol solution from 75 °C ($T_{h,i}$) to 45 °C ($T_{h,o}$) with cooling water entering the tube side at 15 °C ($T_{c,i}$). The heat capacity rates ($C = \dot{m}.c_p$) for the hot fluid and cold fluid are $30\,\mathrm{kW.K^{-1}}$ and $40\,\mathrm{kW.K^{-1}}$, respectively. Consider that the overall heat transfer coefficient (U) based on the outer tube surface is equal to $500\,\mathrm{W.m^{-2}.{}^{\circ}C^{-1}}$.

Determine the total heat transfer surface area required for each HX type:

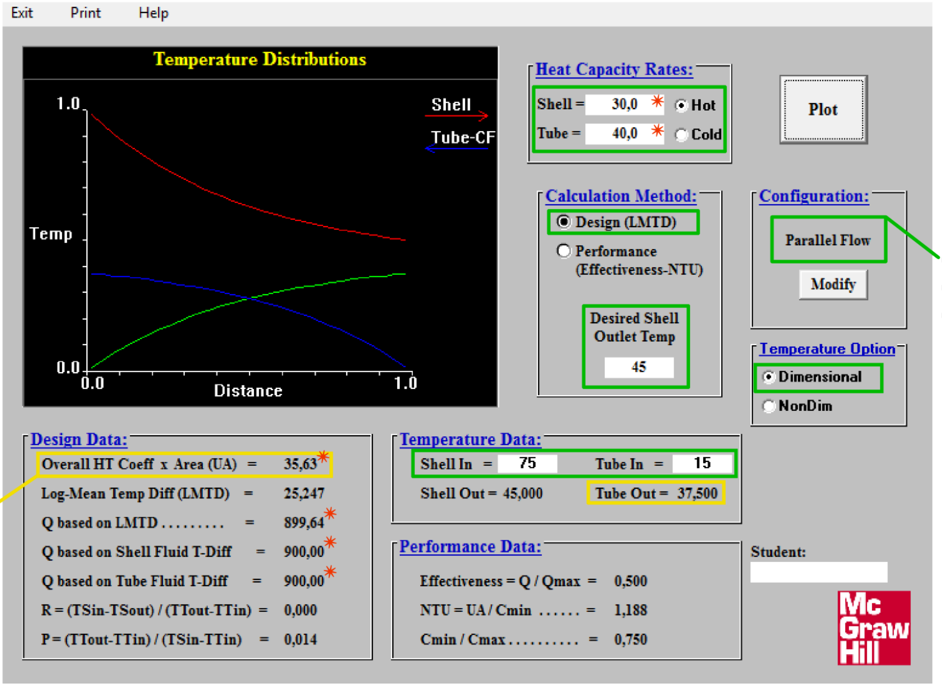
(a) Parallel-flow heat exchanger;

(b) Counterflow heat exchanger;

(c) shell-and-tube heat exchanger with three shell passes and six tube passes.

Exploring the Software - **Design Problem** (2/4)

(a) Parallel-flow HX



Heat Capacity Rates:
Shell = 30,0 * ● Hot
Tube = 40,0 * ○ Cold

Calculation Method:
● Design (LMTD)
○ Performance (Effectiveness-NTU)
Desired Shell Outlet Temp 45

Configuration: Parallel Flow

Temperature Option:
● Dimensional
○ NonDim

Design Data:
Overall HT Coeff x Area (UA) = 35,63*
Log-Mean Temp Diff (LMTD) = 25,247
Q based on LMTD .... = 899,64*
Q based on Shell Fluid T-Diff = 900,00*
Q based on Tube Fluid T-Diff = 900,00*
R = (TSin-TSout) / (TTout-TTin) = 0,000
P = (TTout-TTin) / (TSin-TTin) = 0,014

Temperature Data:
Shell In = 75 Tube In = 15
Shell Out = 45,000 Tube Out = 37,500

Performance Data:
Effectiveness = Q / Qmax = 0,500
NTU = UA / Cmin ...... = 1,188
Cmin / Cmax .... = 0,750

Student:

🟩 Input Data

🟨 Relevant Output Data

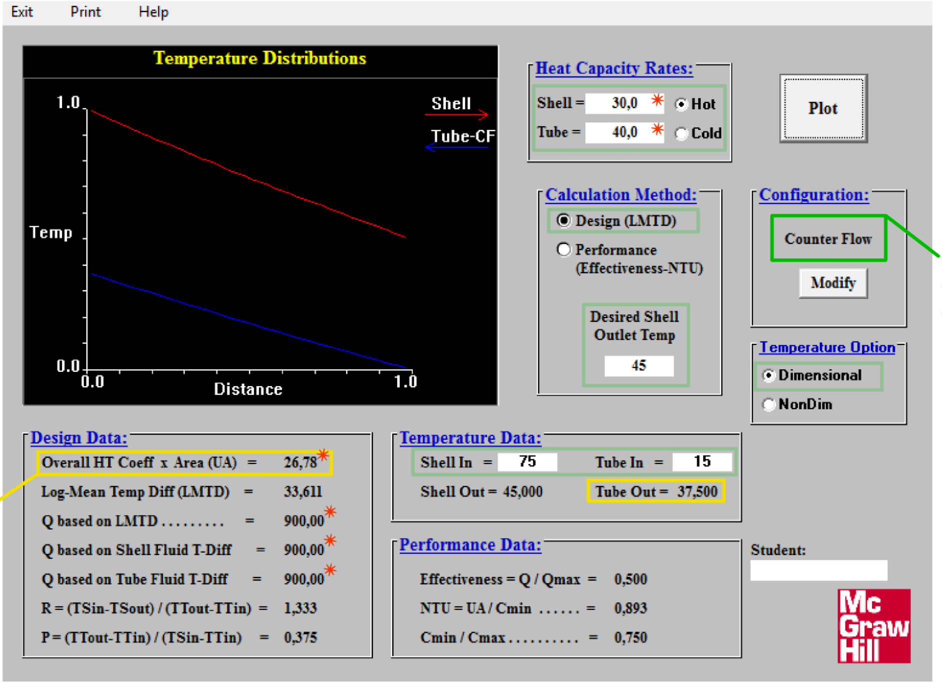
"Modify">>"Concentric Tube">>
"New Setup">>"Parallel Flow">>
"Nodes=30">>"**Update**">>"Return"

$UA = 35.63\,\mathrm{kW.K^{-1}} \Rightarrow$
$\Rightarrow A = 71.26\mathrm{m}^2$

* When the heat capacity rates are specified in $\mathrm{kW.K^{-1}}$ UA is given in $\mathrm{kW.K^{-1}}$ and the rates of heat transfer in kW.

Exploring the Software - **Design Problem** (3/4)

(b) Counterflow HX



Heat Capacity Rates:
Shell = 30,0 * ● Hot
Tube = 40,0 * ○ Cold

Calculation Method:
● Design (LMTD)
○ Performance (Effectiveness-NTU)
Desired Shell Outlet Temp 45

Configuration:
Counter Flow
Modify

Temperature Option
● Dimensional
○ NonDim

Design Data:
Overall HT Coeff x Area (UA) = 26,78*
Log-Mean Temp Diff (LMTD) = 33,611
Q based on LMTD .... = 900,00*
Q based on Shell Fluid T-Diff = 900,00*
Q based on Tube Fluid T-Diff = 900,00*
R = (TSin-TSout) / (TTout-TTin) = 1,333
P = (TTout-TTin) / (TSin-TTin) = 0,375

Temperature Data:
Shell In = 75
Tube In = 15
Shell Out = 45,000
Tube Out = 37,500

Performance Data:
Effectiveness = Q / Qmax = 0,500
NTU = UA / Cmin ...... = 0,893
Cmin / Cmax .... = 0,750

Student:

🟩 Input Data

🟨 Relevant Output Data

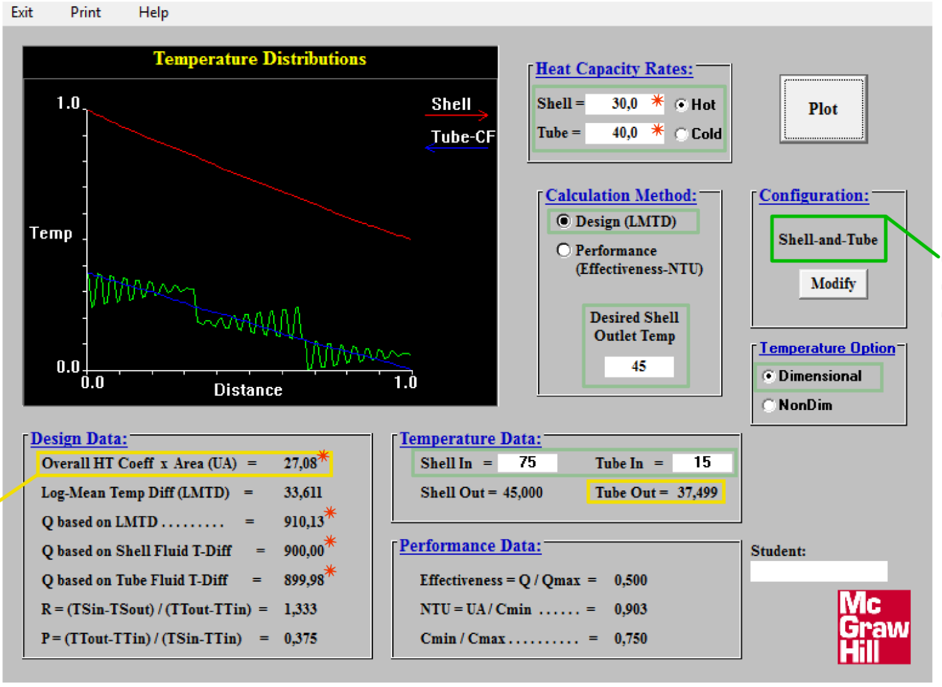
"Modify">>"Concentric Tube">>
"New Setup">>"Counter Flow">>
"Nodes=30">>"**Update**">>"Return"

$UA = 26.78\,\mathrm{kW.K^{-1}} \Rightarrow$
$\Rightarrow A = 53.56\,\mathrm{m^2}$

* When the heat capacity rates are specified in kW.K^{-1} UA is given in kW.K^{-1} and the rates of heat transfer in kW.

Exploring the Software - **Design Problem** (4/4)

(c) Shell-and-tube HX with 3 shell passes and 6 tube passes



Heat Capacity Rates:
Shell = 30,0 * ● Hot
Tube = 40,0 * ○ Cold

Calculation Method:
● Design (LMTD)
○ Performance (Effectiveness-NTU)
Desired Shell Outlet Temp 45

Configuration:
Shell-and-Tube
Modify

Temperature Option
● Dimensional
○ NonDim

Design Data:
Overall HT Coeff x Area (UA) = 27,08*
Log-Mean Temp Diff (LMTD) = 33,611
Q based on LMTD .... = 910,13*
Q based on Shell Fluid T-Diff = 900,00*
Q based on Tube Fluid T-Diff = 899,98*
R = (TSin-TSout) / (TTout-TTin) = 1,333
P = (TTout-TTin) / (TSin-TTin) = 0,375

Temperature Data:
Shell In = 75
Tube In = 15
Shell Out = 45,000
Tube Out = 37,499

Performance Data:
Effectiveness = Q / Qmax = 0,500
NTU = UA / Cmin ...... = 0,903
Cmin / Cmax .... = 0,750

Student:

🟩 Input Data

🟨 Relevant Output Data

"Modify">>"Shell-and-Tube">>
"New Steup">>"Shell Passes=3">>
"Baffles=16">>"**Update**">>"Return"

$UA = 27.08\,\mathrm{kW.K^{-1}} \Rightarrow$
$\Rightarrow A = 54.16\,\mathrm{m^2}$

* When the heat capacity rates are specified in kW.K^{-1} UA is given in kW.K^{-1} and the rates of heat transfer in kW.

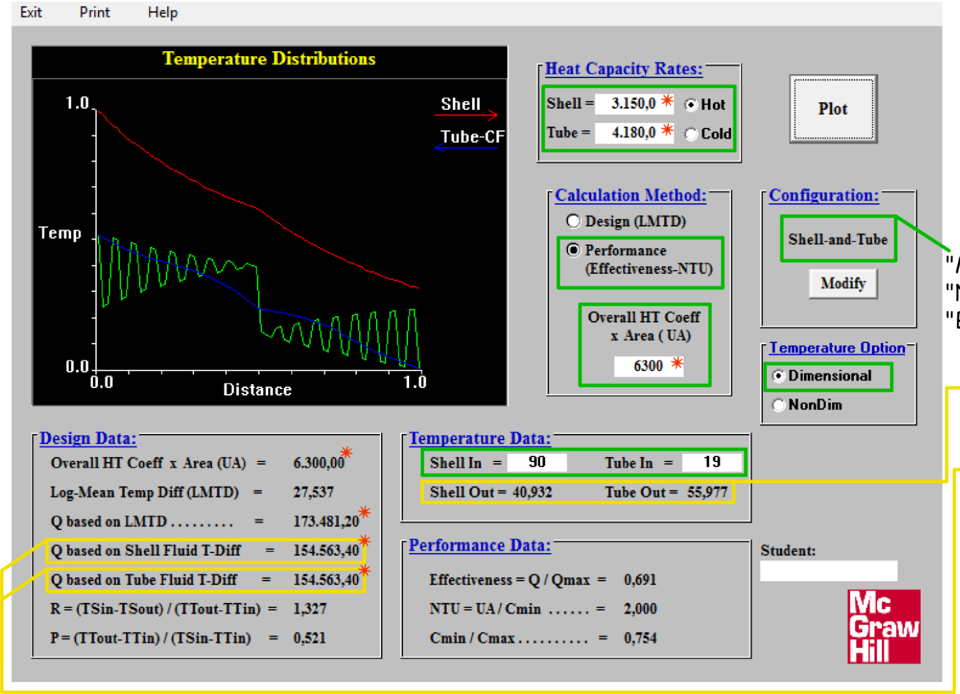
Exploring the Software - **Performance Calculation** (1/4)

A shell-and-tube HX with **two shell passes and four tube passes** is cooling $1.5\,\mathrm{kg.s^{-1}}$ of oil initially at $90\,^{\circ}\mathrm{C}$ with water entering at $19\,^{\circ}\mathrm{C}$ with a mass flow rate of $1.0\,\mathrm{kg.s^{-1}}$. Consider $UA = 6300\,\mathrm{W.K^{-1}}$, $c_{p,h} = 2100\,\mathrm{J.Kg^{-1}.K^{-1}}$ and $c_{p,c} = 4180\,\mathrm{J.Kg^{-1}.K^{-1}}$. Determine the heat transfer rate and the outlet oil and water temperatures.
The heat capacity rates of the hot and cold fluid streams, C_h and C_c, respectively are:

$$C_h = \dot{m}_h c_{p,h} = 1.5 \times 2100 = 3150\,\mathrm{W.K^{-1}}$$

$$C_c = \dot{m}_c c_{p,c} = 1.0 \times 4180 = 4180\,\mathrm{W.K^{-1}}$$

Exploring the Software - **Performance Calculation** (2/4)



Heat Capacity Rates:
Shell = 3.150,0 * ● Hot
Tube = 4.180,0 * ○ Cold

Calculation Method:
○ Design (LMTD)
● Performance (Effectiveness-NTU)

Overall HT Coeff x Area (UA) 6300 *

Configuration: Shell-and-Tube

Temperature Option
● Dimensional
○ NonDim

Design Data:
Overall HT Coeff x Area (UA) = 6.300,00 *
Log-Mean Temp Diff (LMTD) = 27,537
Q based on LMTD . . . . = 173.481,20 *
Q based on Shell Fluid T-Diff = 154.563,40 *
Q based on Tube Fluid T-Diff = 154.563,40 *
R = (TSin-TSout) / (TTout-TTin) = 1,327
P = (TTout-TTin) / (TSin-TTin) = 0,521

Temperature Data:
Shell In = 90 Tube In = 19
Shell Out = 40,932 Tube Out = 55,977

Performance Data:
Effectiveness = Q / Qmax = 0,691
NTU = UA / Cmin . . . . . . = 2,000
Cmin / Cmax . . . . = 0,754

Student:

🟩 Input Data

🟨 Relevant Output Data

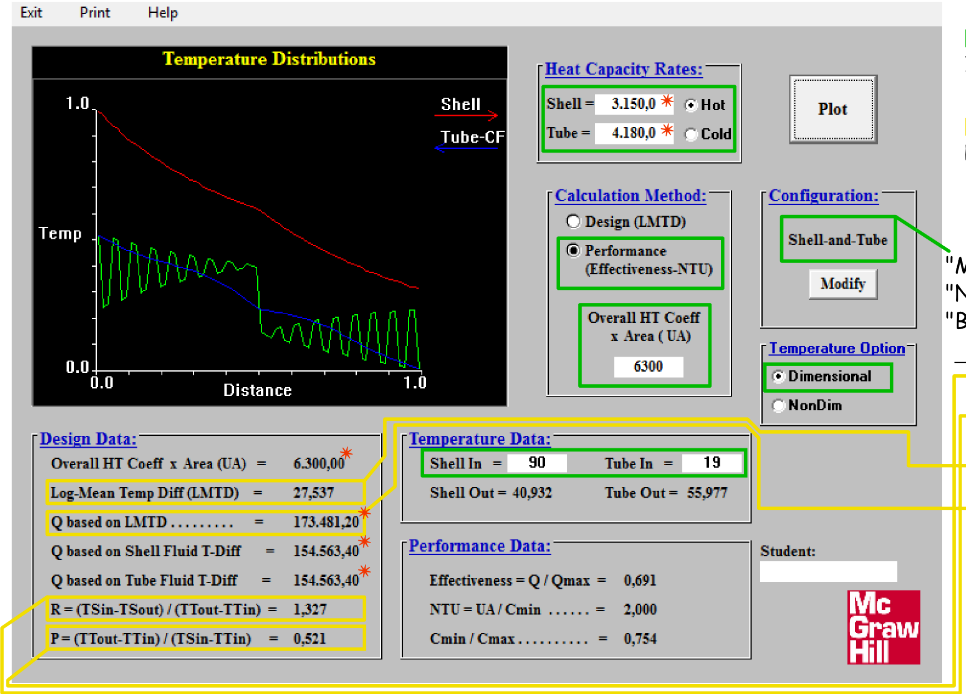
"Modify">>"Shell-and-Tube">>
"New Setup">>"Shell Passes=2">>
"Baffles=16">>"**Update**">>"Return"

$T_{oil,out} = 40.932°\mathrm{C}$
$T_{water,out} = 55.977°\mathrm{C}$

$q \approx 154.6\mathrm{kW}$

* When the heat capacity rates are specified in $\mathrm{W.K^{-1}}$ UA needs to be specified also in $\mathrm{W.K^{-1}}$ and the rates of heat transfer are given in W.

Exploring the Software - **Performance Calculation** (3/4)



Heat Capacity Rates:
Shell = 3.150,0 * ● Hot
Tube = 4.180,0 * ○ Cold

Calculation Method:
○ Design (LMTD)
● Performance (Effectiveness-NTU)

Overall HT Coeff x Area (UA) 6300

Configuration:
Shell-and-Tube

Temperature Option
● Dimensional
○ NonDim

Design Data:
Overall HT Coeff x Area (UA) = 6.300,00 *
Log-Mean Temp Diff (LMTD) = 27,537
Q based on LMTD .... = 173.481,20 *
Q based on Shell Fluid T-Diff = 154.563,40 *
Q based on Tube Fluid T-Diff = 154.563,40 *
R = (TSin-TSout) / (TTout-TTin) = 1,327
P = (TTout-TTin) / (TSin-TTin) = 0,521

Temperature Data:
Shell In = 90 Tube In = 19
Shell Out = 40,932 Tube Out = 55,977

Performance Data:
Effectiveness = Q / Qmax = 0,691
NTU = UA / Cmin ...... = 2,000
Cmin / Cmax .... = 0,754

Student:

🟩 Input Data

🟨 Relevant Output Data

"Modify">>"Shell-and-Tube">>
"New Setup">>"Shell Passes=2">>
"Baffles=16">>"**Update**">>"Return"

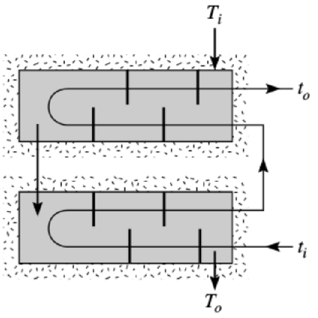
$$\boxed{\begin{aligned} R &= 1.327 \\ P &= 0.521 \end{aligned}} \quad F = 0.89048$$

$$\Delta T_{\mathrm{lm,c}} = F \Delta T_{\mathrm{lm,CF}} = 24.52\,°\mathrm{C}$$

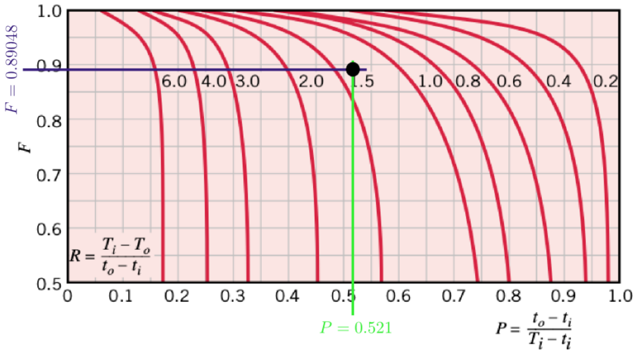
$$q_{\mathrm{lm,c}} = UA\Delta T_{\mathrm{lm,c}} = \\ = F q_{\mathrm{lm}} \approx 154.5\,\mathrm{kW}$$

* When the heat capacity rates are specified in W.K^{-1} UA needs to be specified also in W.K^{-1} and the rates of heat transfer are given in W.

Exploring the Software - **Performance Calculation** (4/4)



$$\boxed{\begin{aligned} R &= 1.327 \\ P &= 0.521 \end{aligned}} \Rightarrow \quad F = 0.89048$$



Useful Relations

1. **Overall Energy Balance:**
   - Hot Fluid
     $q = C_h\left(T_{h,i} - T_{h,o}\right)$
   - Cold Fluid
     $q = C_c\left(T_{c,o} - T_{c,i}\right)$
2. **Log Mean Temperature Difference (LMTD) Method:**
   - $q = UA\Delta T_{\mathrm{lm}}$
   - For Multipass and cross-flow HXs

$$\Delta T_{\mathrm{lm,c}} = F\Delta T_{\mathrm{lm,CF}}$$
$$\Rightarrow F = \frac{q}{q_{\mathrm{lm}}}$$

3. **Effectiveness-NTU Method:**

$$\varepsilon = \frac{q}{q_{\mathrm{max}}}$$

$$q_{\mathrm{max}} = C_{\mathrm{min}}\left(T_{h,i} - T_{c,i}\right)$$

$$C_{\mathrm{min}} = \mathrm{Min}\left(C_c, C_h\right)$$

$$NTU = \frac{UA}{C_{\mathrm{min}}}$$

$$\varepsilon = f(NTU, C_r)$$

$$NTU = f(\varepsilon, C_r)$$

   - $C_r = C_{\mathrm{min}}/C_{\mathrm{max}}$ - Heat capacity ratio
   - $C = \dot{m}.c_p$ - Heat capacity rate