Appendix 3A

Broad BCT16, 16 kW Steam-driven, Double-Effect, Water-LiBr Absorption Chiller Model

A mathematical model has been developed to calculate the performance of the Broad BCT16 absorption chiller. The chiller features include:

- water-LiBr sorbent solution at 55%
- steam heat input
- parallel solution flow
- series cooling-water flow (Absorber, LTRG)
- built-in water/air cooling tower

This model is a set of equations consisting of:

- mass balances
- energy balances
- phase equilibrium
- equations for the thermophysical properties of the working fluids
- heat and mass transfer correlations

Detailed heat transfer area calculations based on overall heat transfer coefficients for the following five heat exchangers:

- evaporator
- absorber
- condenser
- high-temperature regenerator (HTRG)
- low-temperature regenerator (LTRG)

Estimated UA values heat transfer model for:

- heat recovery heat exchanger (HRHX)
- by-pass heat exchanger (BPHX)

Estimated effectiveness values heat transfer model for:

- high temperature heat exchanger (HTHX)
- low temperature heat exchanger (LTHX)

Simultaneous heat and mass transfer model for:

- cooling tower
- absorber

Flow split ratio for dilute solution
Major progress:

- 09-21-05, absorber heat and mass transfer model added
- 09-26-05, evaporator heat transfer model added
- 09-27-05, condenser heat transfer model added
- 09-27-05, high temperature regenerator heat transfer model added
- 09-27-05, low temperature regenerator heat transfer model added
- 11-19-05, HTRG adjustment
- 11-30-05 Tuning up
- 12-31-05 Model assumption modifications
- 02-20-06 Cleanup and comments

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This section presents the annotated source code of the computational model. The modularized structure of the model is programmed on the basis of Figure 3A-1 below:
"Engineering Equation Solver, EES Performance Model of Steam-Driven Broad BCT 16 chiller"

{Global constants}

SI = 2
Cp = 4.2
P0 = 101.3
G = 9.80665
Pai = 3.14159265

Global units: meter, second, gram, °C

"Water, J/g-°C"

"Atmospheric pressure, kPa"

"Gravitational acceleration, m/s²"

"Radius"

{Assumptions}

"Water vapor quality assumptions, 1 refers to saturated vapor, 0 refers to saturated water. The quality of the refrigerant water leaving the various components of the chiller is an important factor in the performance of the chiller and of the model."

{Water refrigerant}

q[11] = 0
q[16] = 0
q[18] = 1
q[24] = -0.004zPhm + 0.4515

"Liquid water from condenser"

"Recirculation refrigerant"

"Water vapor from evaporator"

"Liquid water from LTRG, empirical equation proposed to minimize the differences in measurements and calculated state conditions."

{Steam and condensate}

q[51] = 1
q[53] = 0
q[54] = 0

"Steam vapor quality into HTRG"

"Condensate before steam trap"

"Condensate after steam trap"

{Measurements}

"When the model is exercised
• to evaluate the performance of specific chiller configuration
• to carry out a preliminary chiller design with UA
• to analyze a test data set

These assumed or measured quantities are supplied to the model."

{Major stream mass flow rate, kg/s}

m[31] = 0.55
m[41] = 1.55
m[51] = 0.00727

"Chilled water"

"Cooling water"

"Steam supply"

{Major stream inlet temperature, °C}

T[31] = 14
T[32] = 7
T[41] = 31
T[51] = 164

"Chilled-water return"

"Chilled-water supply"

"Cooling-water supply"

"Steam temperature at supply pressure of 6 bar"

{Heat transfer coefficient, UA, kW/C}

"BPHX and HRHX use estimated UA value in the simulation; HTHX and LTHX use estimated effectiveness value in the simulation. The available information on these exchangers is insufficient to calculate UA values. Other major heat transfer components use calculated heat transfer coefficients."

UABPHX = 0.0178*FOHTbphx

"UA value for BPHX"
UAHRHX = 0.03*FOHThrhx  
"UA value for HRHX"

Eff_LTHX = 0.756*FOHTlthx  
"Effectiveness value for LTHX"

Eff_HTHX = 0.885*FOHTthhx  
"Effectiveness value for HTHX"

{Tuning-up factors}

"Tuning-up factor is used to adjust the heat transfer coefficients for each heat transfer component within a limited degree to minimize the differences between the measurements and calculated state conditions."

FOHTlthx = 1.04
FOHTthhx = 1.04
FOHThrhx = 1
FOHTbphx = 1
FOHTthtrg = 1.06  
"HTRG tuning-up factor"
FOHTevp = 1.06
FOHTabs = 1.02
FOHTltrg = 1.04
FOHTcond = 1.05

{Pinch point temperature}

"Heat exchanger entrance/exit point temperature differences – The temperature differences between streams at each end of each heat exchanger are convenient parameters for the construction of T-Q diagram and Dühring plots. Those differences designate the pin for each exchanger are presumed pinch points, the minimum temperature difference between streams in the exchanger. For preliminary evaluation of chiller configuration, these pin values can be set to zero and all heat transfer equations turned off. For design calculations of UA values, pin values can be assigned and the heat transfer models turned off. If UA values are provided in the heat transfer models the entire pin and delta temperature differences are calculated."

PINENVP = T[32] - T[14]  
"Evaporator"
"By-pass heat exchanger"
PINABS = T[1] - T[41]  
"Absorber"
"LTHX"
"Heat recovery heat exchanger"
"LTRG"
"Low-temperature condenser"
PINHTRG = T[51] - T[21]  
"High-temperature regenerator"
PINHTHX = T[22] - T[19]  
"High-temperature heat exchanger"

{Phase equilibrium in cycle simulation}

"Each component of the steam-driven double-effect absorption chiller operates at one of 3 different pressures. These 3 pressures are the equilibrium vapor pressure of the refrigerant water at state points 24, 11, and 18."

Ph = pressure (Water, T= T[24], x=q[24])  
"High pressure"

Pm = pressure (Water, T = T[11], x=q[11])  
"Medium pressure"

Pl = pressure (Water, T = T[18], x=q[18])  
"Low pressure"

{Pressure differences}

zPHl = Ph-Pl  
"The pressure difference between HTRG and absorber"

zPm = Ph-Pm  
"The pressure difference between HTRG and LTRG"

zPnl = Pm-Pl  
"The pressure difference between LTRG and absorber"

{Pressure assignments for different state point}
P[10] = Pm
P[11] = Pm
P[17] = Pm
P[14] = Pl
P[16] = Pl
P[18] = Pl
P[21] = Ph
P[23] = Ph
P[24] = Ph
P[92] = P[91]

{Evaporator mass, energy balance, and heat transfer model}

{Properties}
T[18] = T[16]
T[16] = T[14]
h[16] = enthalpy(WATER, T=T[16], x=q[16])
h[18] = enthalpy(WATER, T=T[18], x=q[18])
q[14] = quality(WATER, h=h[14], T=T[14])

{Mass balance}
m[32] = m[31]
RSR = m[16]/m[14]
m[18] = (1-RSR)*m[14]

{Energy balance}
QEVP = m[31]* Cp* (T[31] - T[32])
QEVP = m[16]* h[16] + m[18]* h[18]- m[14]* h[14]

{Heat transfer model}
"EES recommends this form for the heat transfer model exponential calculations"
QEVP = UA*EVP*(TEVP)
AEVP = (T[31]-T[18]) / (T[32]-T[14])
AEVP = EXP((T[31]-T[18]) - (T[32]-T[14])) / TEVP

{Evaporator heat transfer model}
"The evaporator is composed of rough copper tubes, tube wall thickness is 0.95 mm, OD is 19 mm, ID is 17.1 mm, and evaporator tube bundle has 18 rows, and 2 columns, spiral upward. Chilled-water inlet is located at the bottom; the flow is split into 2 streams at the inlet and merged into one stream at top outlet water cell."

{Physical parameters}
"The heat transfer coefficient calculation is based on the equations for the water film on the vertical smooth copper tube surface."
Devpo=0.019[m]
Devpi=0.0171[m]
Pevp=Pai*Devpo
Devp1=0.216
Devp2=0.170
Nevp=18
Levp1=Pai*Devp1*Nevp
Levp2=Pai*Devp2*Nevp
Sevp=Pai*(Devpi^2)/4

\[\text{Heat transfer coefficient of evaporating liquid film on tube surface}\]

\{Properties\}
"Properties of saturated water table from thermodynamics textbook"

\[
\begin{align*}
\mu[14] &= 7E-17*\text{T}[14]^6-7E-14*\text{T}[14]^5+3E-11*\text{T}[14]^4-7E-09*\text{T}[14]^3+8E-07*\text{T}[14]^2-5E-05*\text{T}[14]+0.0018 \\
\text{"Viscosity"}
\end{align*}
\]

\[
\begin{align*}
\rho[14] &= 4E-13*\text{T}[14]^6-3E-10*\text{T}[14]^5+9E-08*\text{T}[14]^4-1E-06*\text{T}[14]^3 - 0.0043*\text{T}[14]^2 - 0.0289*\text{T}[14]+999.94 \\
\text{"Density"}
\end{align*}
\]

\[
\begin{align*}
\kappa[14] &= -2E-15*\text{T}[14]^6+8E-13*\text{T}[14]^5-1E-10*\text{T}[14]^4+2E-08*\text{T}[14]^3 - 1E-05*\text{T}[14]^2+0.0021*\text{T}[14]+0.5659 \\
\text{"Thermal conductivity"}
\end{align*}
\]

\[
\begin{align*}
\text{Pr}[14] &= 1E-12*\text{T}[14]^6-8E-09*\text{T}[14]^5+4E-07*\text{T}[14]^4 - 8E-05*\text{T}[14]^3+0.0078*\text{T}[14]^2 - 0.4335*\text{T}[14]+ 13.134 \\
\text{"Prandtl number"}
\end{align*}
\]

\[
\begin{align*}
\text{Re}[14] &= (4*(m[14]/2)/(1*Pevp))/\mu[14] \\
A[14] &= 0.0038*(\text{Re}[14]^{0.4}*(\text{Pr}[14]^{0.65})
\end{align*}
\]

\{Heat transfer coefficient of chilled water inside tube\}

\{Properties\}
"The chilled-water heat transfer properties are evaluated at the bulk temperature of chilled water, T30"

\[
\begin{align*}
\text{m}[30] &= m[31] \\
\mu[30] &= 7E-17*\text{T}[30]^6-7E-14*\text{T}[30]^5+3E-11*\text{T}[30]^4 - 7E-09*\text{T}[30]^3+8E-07*\text{T}[30]^2-5E-05*\text{T}[30]+0.0018 \\
\text{"Viscosity"}
\end{align*}
\]

\[
\begin{align*}
\rho[30] &= 4E-13*\text{T}[30]^6-3E-10*\text{T}[30]^5+9E-08*\text{T}[30]^4-1E-06*\text{T}[30]^3 - 0.0043*\text{T}[30]^2 - 0.0289*\text{T}[30]+999.94 \\
\text{"Density"}
\end{align*}
\]

\[
\begin{align*}
\text{"Thermal conductivity"}
\end{align*}
\]

\[
\begin{align*}
\text{Pr}[30] &= 1E-12*\text{T}[30]^6-8E-09*\text{T}[30]^5+4E-07*\text{T}[30]^4 - 8E-05*\text{T}[30]^3+0.0078*\text{T}[30]^2 - 0.4335*\text{T}[30]+ 13.134 \\
\text{"Prandtl number"}
\end{align*}
\]

\[
\begin{align*}
\text{vel}[30] &= \text{m}[30]/(\text{vel}[30]*2*\text{Sevp}) \\
A[30] &= (\text{Devpi}/\kappa[30])^\text{Hevpchw} \\
A[30] &= 0.023*(\text{Re}[30]^{0.8})*(\text{Pr}[30]^{0.3})
\end{align*}
\]

\{Overall heat transfer coefficient and total surface area\}

\[
U\text{evp}=1/((1/(\text{Hevpfilm}))+(1/\text{Hevpchw}))
\]
Aevp1=Pevp*Levp1 \quad \text{"The surface area of tube 1"}
Aevp2=Pevp*Levp2 \quad \text{"The surface area of tube 2"}
TSAevp=Aevp1+Aevp2
UAevp=Uevp*(TSAevp)/1000 \quad \text{"kW/\degree C"}

\{--------------------------------------------Evaporator Heat Transfer Model Finish--------------------------------------------\}

\{Refrigerant valve\}
\quad m[14] = m[13]
\quad h[14] = h[13]

\{Recirculation Pump\}
\quad \{Mass balance\}
\quad m[17] = m[16]
\quad v[16] = \text{volume(WATER, } T=T[16], \ x=q[16])
\quad \{Pump work\}
\quad WRCP = m[16] \ast v[16] \ast (Pm-Pl)
\quad \{Energy balance\}
\quad h[17] = h[16] + WRCP/m[16]

\{Refrigerant combiner\}
\quad \{Mass balance\}
\quad m[13] = m[12] + m[17]
\quad T[13] = \text{TEMPERATURE(Water, } h=h[13], \ P=Pm)
\quad \{Energy balance\}

\{By-pass heat exchanger\}
\quad \{Mass balance\}
\quad m[12] = m[11]
\quad T[12] = \text{temperature(WATER, } h=h[12], \ P=Pm)
\quad h[11] = \text{enthalpy(WATER, } T=T[11], \ x=q[11])
\quad \{Energy balance\}
\quad QBPHX = m[11]*(h[11] - h[12])
\quad \{Heat transfer model\}
\quad QBPHX = UABPHX*TBPHX
\quad ABPHX = (T[12]-T[1])/(T[11]-T[1])
\quad ABPHX = EXP(((T[12]-T[1]) - (T[11]-T[1])) / TBPHX)

\{Absorber mass, energy balance, and heat transfer model\}
\quad \{Properties\}
\quad h[9] = H_LIBR(T[9], \ x[9], \ SI)
\quad h[1] = H_LIBR(T[1], \ x[1], \ SI)
\quad P[1] = P_LIBR(T[1], \ x[1], \ SI)
\quad \text{"At state point 1, the water vapor is in}
\quad \text{equilibrium with the water-LiBr sorbent solution"}
{Mass balance}
m[42] = m[41]
m[1]*x[1] = m[9]*x[9]
m[1]=m[9]+m[18]

{Energy balance}
QABS = m[41]* Cp* (T[42] - T[41])

{Heat transfer model}
QABS = UAABS*TABS
AABS = (T[91] - T[42])/(T[1] - T[41])
AABS = EXP(((T[91] - T[42]) - (T[1] - T[41]))/TABS)

{Absorber heat/mass transfer model}
"Absorber is composed of smooth copper tube, wall thickness is 0.7 mm, OD is 19 mm, ID is 17.4 mm. The absorber has 18 rows, and 2 columns, that spiral upward. The cooling water inlet is located at the bottom; the flow is split into 2 streams at the inlet and merged into one stream at top outlet water cell."

{Physical parameters, configuration see drawings}
Dabso=0.019[m]                "OD of absorber tube section"
Dabsi=0.0176[m]               "ID of absorber tube section"
Pabs=Pai*Dabso
Sabs=Pai*(Dabsi^2)/4
Nabs=2                       "Number of spiral tubes"
Mabs=18                      "Number of spiral tubes"
Dabs1=0.324 [m]
Dabs2=0.37 [m]
Labs1=Pai*Dabs1
Labs2=Pai*Dabs2
SAabs1=Pabs*Labs1*Mabs       "Surface area of tube 1"
SAabs2=Pabs*Labs2*Mabs       "Surface area of tube 2"
TSAabs=SAabs1+SAabs2         "Total surface area"

{Heat transfer coefficient of absorber liquid film outside tube}
{Properties of LiBr film}
"The properties of solution are evaluated at the temperature of state point 91 on the surface of tube"
mu[91]= VISC_LIBR(T[91], x[91], SI) "Viscosity"
vol[91]=V_LIBR(T[91], x[91],SI)/1000 "Specific volume, m^3/kg"
rou[91]=1/vol[91]                  "Density"
k[91]= COND_LIBR(T[91], X[91],SI) "Thermal conductivity"
Re[91]=(4*(m[91]-(Labs1+Labs2)))/mu[91] "Reynolds number"

{Thickness of LiBr film}
"The film heat transport mechanism is assumed to be molecular conduction through a laminar film of thickness defined by the Nusselt analysis for a vertical surface:

\[
\delta_{ji} = \left( \frac{1.5 \mu_{ji} \Gamma_{ji}}{\rho_{ji} g} \right)^{\frac{1}{3}}
\]

\[T_{\text{film}} = \left( 1.5 \mu_{[91]} (m_{[91]}/(2*(Labs1+Labs2)))/(g*(rou_{[91]}^2)) \right)^{(1/3)} \]

\[A_{[91]} = 0.3*Re_{[91]}^{0.46} \quad \text{"Nusselt number"} \]

\[A_{[91]} = (T_{\text{film}}/k_{[91]})*Habsfilm \quad \text{"Equation, see table 3-3"} \]

**Heat transfer coefficient of cooling water inside the tube**

"The virtual state point of 40 represents the average condition of cooling water in the tube; its temperature is equal to the average temperature between cooling water inlet and outlet"

**Properties of cooling water**

\[T_{[40]} = \left( T_{[41]} + T_{[42]} \right) / 2 \quad \text{"Average temperature of cooling water"} \]

\[m_{[40]} = m_{[41]} \]

"Property table from Heat Transfer Text Book"

\[\mu_{[40]} = 7E-17*T_{[40]}^6 - 6E-14*T_{[40]}^5 + 8E-11*T_{[40]}^4 - 7E-09*T_{[40]}^3 + 8E-07*T_{[40]}^2 - 5E-05*T_{[40]} + 0.0018 \]

\[\rho_{[40]} = 4E-13*T_{[40]}^6 - 3E-10*T_{[40]}^5 + 9E-08*T_{[40]}^4 - 1E-06*T_{[40]}^3 - 0.0043*T_{[40]}^2 - 0.0289*T_{[40]} + 999.94 \]

\[k_{[40]} = -2E-15*T_{[40]}^6 + 5E-13*T_{[40]}^5 - 1E-10*T_{[40]}^4 + 2E-08*T_{[40]}^3 - 1E-05*T_{[40]}^2 + 0.0021*T_{[40]} + 0.5659 \]

\[\Pr_{[40]} = 1E-12*T_{[40]}^6 - 5E-09*T_{[40]}^5 + 4E-07*T_{[40]}^4 - 8E-05*T_{[40]}^3 + 0.0078*T_{[40]}^2 - 0.437 * 5*T_{[40]} + 13.134 \]

\[v_{[40]} = \mu_{[40]} / \rho_{[40]} \]

\[\nu_{[40]} = m_{[40]} / (\rho_{[40]}*\text{Nabs}^*\text{Sabs}) \quad \text{"Velocity of cooling water"} \]

\[Re_{[40]} = (\rho_{[40]}*v_{[40]}*\text{Dabsi}) / \mu_{[40]} \]

\[A_{[40]} = 0.023*Re_{[40]}^{0.8} * Pr_{[40]}^{(0.4)} \quad \text{"Equation see Table 3-3"} \]

\[A_{[40]} = (\text{Dabsi}/K_{[40]}) * \text{Habscw} \quad \text{"Nusselt number"} \]

**Overall heat transfer coefficient**

\[U_{\text{abs}} = 1 / (1/H_{\text{film}} + 1/H_{\text{abs cw}}) \quad \text{"Unit is w/m}^2\text{-oC"} \]

\[U_{\text{Aabs}} = \text{FOHTabs} * (U_{\text{abs}} * T_{\text{SAbs}}) / 1000 \quad \text{"Unit is kW/oC"} \]

**Mass transfer rate for absorber liquid films outside the tube**

"In the absorber, the heat transfer limits the mass transfer. F. Cosenza et al relate the refrigerant vapor mass transfer rate of absorber with the heat transfer rate."

**Energy balance**

\[H_{\text{fgabs}} = -1E-05*T_{[40]}^3 + 0.0006*T_{[40]}^2 - 2.3706*T_{[40]} + 2501.4 \quad \text{"Condensate heat per unit mass"} \]

\[Q_{\text{sens}} = m_{[91]}* (h_{[91]} - h_{[1]}) \quad \text{"Approximate sensible heat"} \]

\[mvp = ((Q_{\text{abs}} - QBPHX - (Q_{\text{sens}})/H_{\text{fgabs}}) * A_{[91]} \quad \text{"Total mass transfer (absorption) rate"} \]

**Mass balance**

"Empirical mass transfer coefficient is made available from Y. Nagaoka and N. Nishiyama et al. studies, see Table 3-3, using this mass transfer coefficient, the pressure difference between the sorbent solution inlet and outlet can be calculated."

\[mvp = (m_{[18]} + m_{[92]}) \]

\[mvp = K_{\text{abs}} * T_{\text{SAbs}} * \Delta P_{\text{abs}} \]

\[D_{\text{abs}}_{[91]} = m_{[91]} / (2*(\text{Labs}1 + \text{Labs}2)) \quad \text{"The mass transfer rate per unit length"} \]

\[K_{\text{abs}} = 29.571 * D_{\text{abs}}_{[91]} + 0.405 \quad \text{"Empirical mass transfer coefficient"} \]

\[\Delta P_{\text{abs}} = P_{[1]} - P_{[91]} \quad \text{"Pressure difference between the entrance and exit of absorber and"} \]
{Solution Pump}

{Mass balance}
m[2] = m[1]
x[2] = x[1]

\(v[1] = V_{\text{LIBR}}(\text{SI}, T[1], x[1])/1000\)  "m^3/kg"

{Pump work}

\(W_{SP} = m[1] \times v[1] \times (P_{h} - P[1])\)  "Kw"

{Energy balance}

\(h[2] = h[1] + W_{SP}/m[1]\)
\(h[2] = H_{\text{LIBR}}(T[2], x[2], \text{SI})\)

{Solution valve}

{Mass balance}
m[8] = m[9]
x[8] = x[9]

{Energy balance}

\(h[8] = h[9]\)

{Virtual solution splitter before absorber}

{Mass balance}

\(m[9]=m[91]+m[92]\)
\(m[9] \times x[9]=m[91] \times x[91]\)
\(q[92]=1\)
\(T[91] = T_{\text{LIBR}}(P[91], x[91], \text{SI})\)
\(T[92]=T[91]\)

\(m[9] \times h[9]=m[91] \times h[91]+m[92] \times h[92]\)
\(h[91] = H_{\text{LIBR}}(T[91], x[91], \text{SI})\)
\(h[92] = \text{ENTHALPY(Steam, }T=T[92],P=P[91])\)

{Solution splitter}

{Properties}
\(T[19]=T[2]\)
\(h[19]=h[2]\)
\(x[19]=x[2]\)

\(h[3]=h[2]\)
\(x[3]=x[2]\)

{Mass balance}

\(R = m[19]/m[2]\)
\(m[3]=m[2] \times (1-R)\)

{Solution combiner}

{Properties}
\[ h[7] = H_{LIBR}(T[7], x[7], SI) \]
\[ T[8] = T_{LIBR}(Pm, x[8], SI) \]
\[ h[22] = H_{LIBR}(T[22], x[22], SI) \]

**{Mass balance}**
\[ m[8] = m[7] + m[22] \]
\[ m[8]*x[8] = m[7]*x[7] + m[22]*x[22] \]

**{Energy balance}**
\[ m[8]*h[8] = m[7]*h[7] + m[22]*h[22] \]

**{Low-temperature heat exchanger}**

**{Properties}**
\[ h[4] = H_{LIBR}(T[4], x[4], SI) \]
\[ T[6] = T_{LIBR}(Pm, x[6], SI) \]
\[ h[6] = H_{LIBR}(T[6], x[6], SI) \]

**{Mass balance}**

**{Energy balance}**
\[ Q_{LTHX} = m[3] \ast (h[4]-h[3]) \]
\[ Q_{LTHX} = m[6] \ast (h[6]-h[7]) \]

**{Heat exchanger effectiveness model}**
\[ \text{Eff}_{LTHX} = (T[6]-T[7]) / (T[6]-T[3]) \]

**{Heat exchanger log mean temperature difference model}**
\[ Q_{LTHX} = U_{LTHX} \ast T_{LTHX} \]
\[ U_{LTHX} = (T[6]-T[4])/(T[7]-T[3]) \]
\[ T_{LTHX} = \text{EXP}((T[6]-T[4])\ast(T[7]-T[3]))/T_{LTHX} \]

**{Heat recovery heat exchanger}**

**{Properties}**
\[ h[53] = \text{enthalpy}(\text{WATER, T}=T[53], x=q[53]) \]
\[ h[5] = H_{LIBR}(T[5], x[5], SI) \]

**{Mass balance}**
\[ m[52] = m[53] \]

**{Energy balance}**
\[ Q_{HRHX} = m[4] \ast (h[5]-h[4]) \]
\[ Q_{HRHX} = m[53] \ast C_p*(T[52]-T[53]) \]

**{Heat exchanger log mean temperature difference model}**
\[ Q_{HRHX} = U_{HRHX} \ast T_{HRHX} \]
AHRHX = ([T[52]-T[5]]/[T[53]-T[4]])
AHRHX= EXP(((T[52]-T[5]) - (T[53]-T[4]))/ THRHX )

{Steam trap}

{Mass balance}
m[54] = m[53]

{Energy balance}
h[54] = h[53]
T[54] = temperature(WATER, h=h[54], P=P0)

{Low-temperature regenerator mass, energy balance, and heat transfer model}

{Properties}
h[10] = ENTHALPY(Steam, T=T[10] ,P=Pm)

{Mass balance}

{Energy balance}

{Heat transfer log mean temperature difference model}
QLTRG = UALTRG*TLTRG
ALTRG = (T[24]-T[6])/(T[24]-T[5])
ALTRG = EXP(((T[24]-T[6]) - (T[24]-T[5]))/TLTRG)

Low temperature regenerator heat transfer model

"LTRG is composed of 14 rows of horizontal tubes. The tube surface is rough, and the wall thickness is 0.8 mm, OD is 19 mm, and ID is 17.4 mm."

{Physical parameters}
Dltrgo=0.019[m]                "OD of LTRG tube section"
Dltrgi=0.0174[m]               "ID of LTRG tube section"
Pltrg=Pai*Dltrgi
Sltrg=Pai*(Dltrgi^2)/4
Nltrg=14                      "Number of tubes"
Dltrg1=0.303                  "Diameter of tube spiral"
Ll.trg1=Pai*Dltrg1

{Heat transfer coefficient for nucleate boiling outside tube}

{Properties}
DeltaT=T[24]-T[6]
Hltrgnucleate[6]=(1042*DeltaT^(1/3))*(Pm/P0)^0.4      "Equation see Table 3-3"

{Heat transfer coefficient of condensing film inside tube}

{Properties}
"Properties of saturated water table"
\[ \mu_{24} = 7 \times 10^{-17} T_{24}^6 - 7 \times 10^{-14} T_{24}^5 + 3 \times 10^{-11} T_{24}^4 + 8 \times 10^{-07} T_{24}^3 - 5 \times 10^{-05} T_{24}^2 - 0.0018 \]

\[ \tau_{24} = 4 \times 10^{-13} T_{24}^6 - 3 \times 10^{-10} T_{24}^5 + 9 \times 10^{-08} T_{24}^4 - 1 \times 10^{-06} T_{24}^3 - 0.0043 T_{24}^2 - 0.0289 T_{24} + 999.94 \]

\[ k_{24} = -2 \times 10^{-15} T_{24}^6 + 8 \times 10^{-13} T_{24}^5 - 1 \times 10^{-10} T_{24}^4 + 2 \times 10^{-08} T_{24}^3 - 1 \times 10^{-05} T_{24}^2 + 0.0021 T_{24} + 0.5659 \]

\[ \Pr_{24} = 1 \times 10^{-12} T_{24}^6 - 1 \times 10^{-09} T_{24}^5 + 4 \times 10^{-07} T_{24}^4 - 8 \times 10^{-05} T_{24}^3 + 0.0078 T_{24}^2 - 0.4335 T_{24} + 13.134 \]

\[ v_{24} = \frac{\mu_{24}}{\tau_{24}} \]

\[ M_{ltrg} = \left( \frac{m_{24}}{L_{ltrg1} \left( N_{ltrg} \right)^{2/3}} \right) \]

\[ A_{24} = 1.51 \left( \frac{4 \cdot M_{ltrg} / \mu_{24}}{\left(1/3 \right)} \right)^{-1/3} \]

\[ A_{24} = H_{ltrgfilm24} \left( \frac{(v_{24}^2 / (k_{24}^3 g))^{1/3}}{(1/3)} \right) \]

\{'Overall heat transfer coefficient'}

\[ U_{ltrg} = 1 / \left( 1 / (H_{ltrg nucleate6}) + 1 / (H_{ltrg film24}) \right) \]

\[ T_{SA ltrg} = P_{ltrg} * L_{ltrg1} * N_{ltrg} \]

\[ U_{Altg} = F_O H_{Altg} * U_{ltrg} * T_{SA ltrg} / 1000 \]

\{---Low Temperature Regenerator Heat Transfer Model Finish---\}

\{High-temperature condenser\}

\{'Properties'}

\[ h_{24} = \text{enthalpy}(\text{WATER}, T=T_{24}, x=q_{24}) \]

\{'Mass balance'}

\[ m_{24} = m_{23} \]

\{'Energy balance'}

\[ Q_{LTCD} = m_{23} * h_{23} - m_{24} * h_{24} \]

\[ Q_{HTCD} = Q_{LTCD} \]

\{'Refrigerant expansion valve 2'}

\{'Properties'}

\[ h_{25} = h_{24} \]

\[ T_{25} = \text{temperature}(\text{WATER}, h=h_{25}, P=P_m) \]

\[ q_{25} = \text{quality}(\text{WATER}, h=h_{25}, P=P_m) \]

\{'Mass balance'}

\[ m_{25} = m_{24} \]

\{'Condenser mass, energy balance, and heat transfer model'}

\{'Mass balance'}

\[ m_{11} = m_{25} + m_{10} \]

\[ m_{43} = m_{42} \]

\{'Energy balance'}

\[ Q_{LTCD} = m_{43} * C_p * (T_{43} - T_{42}) \]

\[ Q_{LTCD} = m_{25} * h_{25} + m_{10} * h_{10} - m_{11} * h_{11} \]

\{'Heat transfer model'}

\[ Q_{LTCD} = U_{ALTCD} * T_{LTCD} \]

\[ ALTCD = (T_{11} - T_{43}) / (T_{11} - T_{42}) \]

\[ ALTCD = \text{EXP} \left( (T_{11} - T_{43}) - (T_{11} - T_{42}) / T_{LTCD} \right) \]

\{---Condenser Heat Transfer Model Start---\}
Condenser heat transfer model

"Smooth copper tube, wall thickness 0.95 mm, OD 19 mm, ID 17.1 mm, tube arrangement 3 rows, 2 columns, spiral upward, chilled-water inlet at the bottom, the flow is split into 3 streams at the inlet and merged into one stream at top outlet water cell."

Physical parameters

\[
\begin{align*}
D_{condo} &= 0.019 \text{[m]} & \text{"OD condenser tube section"} \\
D_{condi} &= 0.0171 \text{[m]} & \text{"ID condenser tube section"} \\
P_{cond} &= \pi D_{condo} \\
S_{cond} &= \pi \left( \frac{D_{condi}^2}{4} \right) \\
N_{cond} &= 3 & \text{"Number of tubes"} \\
M_{cond} &= 2 & \text{"Number of tubes"} \\
D_{cond1} &= 0.303 \text{[m]} & \text{"Diameter of tube spiral"} \\
D_{cond2} &= 0.259 \text{[m]} & \text{"Diameter of tube spiral"} \\
D_{cond3} &= 0.215 \text{[m]} & \text{"Diameter of tube spiral"} \\
L_{cond2} &= \pi D_{cond2} \\
A_{cond2} &= \pi D_{cond2} L_{cond2} \\
T_{SA_{cond}} &= N_{cond} A_{cond2} \\
P_{cond} &= \pi D_{condo} \\
S_{cond} &= \pi \left( \frac{D_{condi}^2}{4} \right) \\
N_{cond} &= 3 \\
M_{cond} &= 2 \\
D_{cond1} &= 0.303 \text{[m]} \\
D_{cond2} &= 0.259 \text{[m]} \\
D_{cond3} &= 0.215 \text{[m]} \\
L_{cond2} &= \pi D_{cond2} \\
A_{cond2} &= \pi D_{cond2} L_{cond2} \\
T_{SA_{cond}} &= N_{cond} A_{cond2} \\
\end{align*}
\]

Heat transfer coefficient of condensing liquid films outside tube

Properties

"Properties of saturated water table"

\[
\begin{align*}
\mu_{11} &= 7E-17 \cdot {T_{[11]}^6} + 7E-14 \cdot {T_{[11]}^5} + 3E-11 \cdot {T_{[11]}^4} - 7E-09 \cdot {T_{[11]}^3} + 8E-07 \cdot {T_{[11]}^2} + 5E-05 \cdot {T_{[11]}} + 0.0018 \\
\rho_{11} &= 4E-13 \cdot {T_{[11]}^6} - 3E-10 \cdot {T_{[11]}^5} + 9E-08 \cdot {T_{[11]}^4} - 1E-06 \cdot {T_{[11]}^3} + 0.0043 \cdot {T_{[11]}} - 2E-09 \cdot {T_{[11]}} - 0.0289 \cdot {T_{[11]}} + 999.94 \\
k_{11} &= 2E-15 \cdot {T_{[11]}^6} + 8E-13 \cdot {T_{[11]}^5} - 1E-10 \cdot {T_{[11]}^4} + 2E-08 \cdot {T_{[11]}^3} - 1E-05 \cdot {T_{[11]}} + 0.0021 \cdot {T_{[11]}} + 5.659 \\
Pr_{11} &= 1E-12 \cdot {T_{[11]}^6} - 1E-09 \cdot {T_{[11]}^5} + 9E-07 \cdot {T_{[11]}^4} - 8E-05 \cdot {T_{[11]}} + 0.0078 \cdot {T_{[11]}} - 2E-03 \cdot {T_{[11]}} + 13.14 \\
v_{11} &= \mu_{11} / \rho_{11} \\
A_{11} &= \left( \frac{4 \cdot ((m_{[10]} + (m_{[25]} * q_{[25]})) / 3) / ( P_{cond} * (M_{cond})) / \mu_{[11]}) }{(-1/3)} \right) \quad "Equation, see Table 3-3" \\
A_{11} &= H_{condfilm_{[11]}} \left( \frac{\left( v_{[11]} / 2 \left( k_{[11]} / 3 \cdot g \right) \right) }{1/3} \right) \\
\end{align*}
\]

Heat transfer coefficient of chilled water inside tube

Properties

"Average temperature of cooling-water inlet and outlet"

\[
\begin{align*}
T_{[49]} &= \left( T_{[42]} + T_{[43]} \right) / 2 \\
m_{[49]} &= m_{[41]} \\
\mu_{[49]} &= 7E-17 \cdot {T_{[49]}^6} - 7E-14 \cdot {T_{[49]}^5} + 3E-11 \cdot {T_{[49]}^4} - 7E-09 \cdot {T_{[49]}^3} + 8E-07 \cdot {T_{[49]}^2} + 5E-05 \cdot {T_{[49]}} + 0.0018 \\
\rho_{[49]} &= 4E-13 \cdot {T_{[49]}^6} - 3E-10 \cdot {T_{[49]}^5} + 9E-08 \cdot {T_{[49]}^4} - 1E-06 \cdot {T_{[49]}^3} + 0.0043 \cdot {T_{[49]}} - 2E-09 \cdot {T_{[49]}} - 0.0289 \cdot {T_{[49]}} + 999.94 \\
k_{[49]} &= 2E-15 \cdot {T_{[49]}^6} + 8E-13 \cdot {T_{[49]}^5} - 1E-10 \cdot {T_{[49]}^4} + 2E-08 \cdot {T_{[49]}^3} - 1E-05 \cdot {T_{[49]}} + 0.0021 \cdot {T_{[49]}} + 5.659 \\
Pr_{[49]} &= 1E-12 \cdot {T_{[49]}^6} - 1E-09 \cdot {T_{[49]}^5} + 9E-07 \cdot {T_{[49]}^4} - 8E-05 \cdot {T_{[49]}} + 0.0078 \cdot {T_{[49]}} - 2E-03 \cdot {T_{[49]}} + 13.14 \\
v_{[49]} &= \mu_{[49]} / \rho_{[49]} \\
vel_{[49]} &= m_{[49]} / (\rho_{[49]} * N_{cond} * S_{cond}) \\
Re_{[49]} &= (\rho_{[49]} * vel_{[49]} * D_{condi}) / \mu_{[49]} \\
A_{[49]} &= (D_{condi} / K_{[49]}) * H_{condcw_{[49]}} \quad "Equation, see Table 3-3" \\
A_{[49]} &= 0.023 \cdot (Re_{[49]} / 0.8) \cdot (Pr_{[49]} / 0.3) \\
\end{align*}
\]
{Overall heat transfer coefficient}

\[
U_{cond} = \frac{1}{(1/H_{condfilm}[11])+(1/H_{condcw}[49])}
\]

\[
U_{Altcd} = FOHTcond*U_{cond}*TS\text{A}_{cond}/1000
\]

{---------------------------------------------Condenser Heat Transfer Model Finish-------------------------------------------------}

{High-temperature regenerator mass, energy balance, and heat transfer model}

{Properties}

\[
h[51] = \text{Enthalpy(STEAM, T=T[51], x=q[51])}
\]

\[
h[52] = \text{Enthalpy(WATER, T=T[52], x=q[52])}
\]

\[
P[51] = \text{P\_SAT(Steam, T=T[51])}
\]

\[
T[23] = T[21]
\]

\[
h[20] = H_{\text{LIBR}}(T[20], x[20], \text{SI})
\]

\[
h[21] = H_{\text{LIBR}}(T[21], x[21], \text{SI})
\]

\[
x[21] = \text{X\_LIBR}(T[21], Ph, \text{SI})
\]  

"Phase equilibrium"

\[
h[23] = \text{ENTHALPY(Steam, T=T[23], P=Ph)}
\]

{Mass balance}

\[
m[21] = m[20] - m[23]
\]

\[
m[52] = m[51]
\]

\[
m[21]*x[21] = m[20]*x[20]
\]

{Energy balance}

\[
Q_{HTRG} = m[51]*(h[51] - h[52])
\]

\[
Q_{HTRG} = m[21]*h[21] + m[23]*h[23] - m[20]*h[20]
\]

{Heat transfer model}

\[
Q_{HTRG} = U_{A\text{HTRG}}*T_{HTRG}
\]

\[
A_{HTRG} = (T[51]-T[21])/(T[52] - T[20])
\]

\[
A_{HTRG} = \text{EXP(((T[51]-T[21])-(T[52]-T[20]))/T_{HTRG})}
\]

{--------------------------High-Temperature Regenerator Heat Transfer Model Start-----------------------------------}

{High-temperature regenerator heat transfer model}

"HTRG is composed of rough copper tube. The wall thickness is 1 mm, the OD is 16mm, and the ID is 14 mm. HTRG has 11 rows and 3 columns staggered horizontal tubes" 

{Physical parameters}

\[
D_{htrgo}=0.016[m]
\]  

"OD of HTRG tube section"

\[
D_{htrgi}=0.014[m]
\]  

"ID of HTRG tube section"

\[
Ph_{trg}=3.14159265*D_{htrgi}
\]

\[
Sh_{trg}=3.14159265*(D_{htrgi}^2)/4
\]

\[
N_{htrg}=11
\]

\[
M_{htrg}=3
\]

\[
D_{htrgl}=0.206
\]

\[
L_{htrgl}=\text{Pai}*D_{htrgl}
\]

\[
L_{htrg2}=\text{Pai}*D_{htrg1}*N_{htrg}
\]

{Heat transfer coefficient for nucleate boiling outside tube}
DeltaTh_{reg} = T_{51} - T_{21}

H_{htrg nucleate} = 1042 \cdot \Delta T_{reg}^{(1/3)} \cdot (\frac{P}{P_0})^{0.4} \hspace{1cm} \text{"Equation, see table 3-3"}

\text{Heat transfer coefficient of condensing film inside tube}

\{Properties\}

\\mu_{51} = \text{VISCOSITY (Water, } T = T_{51}, P = P_{51})

\\rho_{51} = 4E-13 \cdot T_{51}^6 - 3E-10 \cdot T_{51}^5 + 9E-08 \cdot T_{51}^4 - 1E-06 \cdot T_{51}^3 - 999.94 \cdot T_{51}^2 - 0.0289 \cdot T_{51} + 0.0043 \cdot T_{51}^2 - 0.0289 \cdot T_{51} + 999.94

k_{51} = -2E-15 \cdot T_{51}^6 + 8E-13 \cdot T_{51}^5 - 1E-10 \cdot T_{51}^4 + 2E-08 \cdot T_{51}^3 - 1E-05 \cdot T_{51}^2 + 0.0021 \cdot T_{51} + 0.5659

Pr_{51} = \text{PRANDTL (Water, } T = T_{51}, P = P_{51})

v_{51} = \frac{\mu_{51}}{\rho_{51}}

ML_{htrg} = \frac{((m_{51}))}{(0.5 \cdot L_{htrg} \cdot M_{htrg})} \hspace{1cm} \text{"Horizontal tube assumption"}

A_{51} = 1.51 \cdot ((4 \cdot ML_{htrg} / \mu_{51}))^{(1/3)} \hspace{1cm} \text{"Condensing number"}

A_{51} = H_{htrg film} \cdot ((v_{51})^2 / it{2 / (k_{51} \cdot 3 \cdot it{g}))}^{(1/3)} \hspace{1cm} \text{"Equation, see table 3-3"}

U_{htrg} = \frac{1}{((1/(H_{htrg nucleate}) + (1/H_{htrg film})))} \hspace{1cm} \text{"Overall heat transfer coefficient"}

TSA_{htrg} = P_{htrg} \cdot L_{htrg} \cdot M_{htrg}

UA_{htrg} = FOH_{Thtrg} \cdot U_{htrg} \cdot TSA_{htrg} / 1000

\text{------------------------------High-Temperature Regenerator Heat Transfer Model Finish------------------------------}

\{High-temperature heat exchanger, HTHX\}

\{Mass balance\}

m_{22} = m_{21}

m_{20} = m_{19}

x_{22} = x_{21}

x_{20} = x_{19}

\{Energy balance\}

Q_{HTHX} = m_{19} \cdot (h_{20} - h_{19})

Q_{HTHX} = m_{21} \cdot (h_{21} - h_{22})

\{Heat exchanger effectiveness model\}

Eff_{HTHX} = \frac{(T_{21} - T_{22})}{(T_{21} - T_{19})}

\{Heat exchanger log mean temperature difference model\}

A_{HTHX} = (T_{21} - T_{20}) / (T_{22} - T_{19})

T_{HTHX} = \frac{((T_{21} - T_{20}) - (T_{22} - T_{19}))}{\ln(A_{HTHX})}

Q_{HTHX} = U_{A_{HTHX}} \cdot T_{HTHX}
The chiller has a built-in cooling tower attached with the machine. The cooling tower maintains the cooling water inlet temperature relative constant by controlling a four-speed cooling-tower fan. In the chiller, the cooling-tower cools the water by simultaneous heat and mass transfer.

**Figure 3A-1: Cooling-tower configuration and flow diagram**

In the chiller, cooling-tower model is programmed on the basis of the flow diagram in Figure 3A-4, where cooling water sprays from the top of the cooling-tower at state point 43. The water is cooled and collected in the water tank at the bottom of the cooling tower. The air is blow from the bottom at state point 45 to the top of the cooling tower at state point 46. This process is modeled by the F-LMED method; where F is a correction factor for log means enthalpy difference (LMED).

**Cooling tower physical parameters**

- \( x = 0.6 \text{ [m]} \)
- \( y = 0.6 \text{ [m]} \)
- \( z = 0.725 \text{ [m]} \) "Height of the fill"

**Cooling tower operating conditions**

- \( Af = xy \) "Cross section area of the fill"
- \( Rct = \frac{m[43]}{m[45]} \) "Air/water ratio"
- \( HTU = 2 \) "Height of heat transfer unit"

**Test conditions**

- \( T[45] = 28.8 \) "Ambient dry bulb temperature"
- \( rh[45] = 0.409 \) "Ambient relative humidity"
- \( T[47] = 20 \) "City-water temperature"
- \( rhs[44] = 1 \) "Saturated relative humidity"
- \( rhs[43] = 1 \) "Saturated relative humidity"
- \( rhwav = 1 \) "Saturated relative humidity"
\{Property\}

\[
\text{h}[45] = \text{Enthalpy}(\text{AIRH}_2\text{O}, P=P_0, T=\text{T}[45], r=\text{rh}[45])
\]

\[
\text{hs}[44] = \text{Enthalpy}(\text{AIRH}_2\text{O}, P=P_0, T=\text{T}[44], r=\text{rh}[44])
\]

\[
\text{hs}[43] = \text{Enthalpy}(\text{AIRH}_2\text{O}, P=P_0, T=\text{T}[43], r=\text{rh}[43])
\]

\[
\text{Twb}[45] = \text{Wetbulb}(\text{AIRH}_2\text{O}, T=\text{T}[45], P=P_0, R=\text{rh}[45])
\]

\[
\text{Twav} = (\text{T}[44]+\text{T}[43])/2
\]

\[
\text{hwav} = \text{enthalpy}(\text{AIRH}_2\text{O}, P=P_0, T=\text{Twav}, r=\text{rh}[45])
\]

\[
\text{dct} = (\text{hs}[44]+\text{hs}[43]-2*\text{hwav})/4
\]

\[
\text{h}[41] = \text{Enthalpy}(\text{Water}, T=\text{T}[41], P=P_0)
\]

\[
\text{h}[43] = \text{Enthalpy}(\text{Water}, T=\text{T}[43], P=P_0)
\]

\[
\text{h}[44] = \text{Enthalpy}(\text{Water}, T=\text{T}[44], P=P_0)
\]

\{Mass balance\}

\[
\text{m}[43] = \text{m}[44]+\text{m}[47]
\]

\[
\text{m}[45]+\text{m}[47] = \text{m}[46]
\]

\{Energy balance\}

\[
\text{Qct1} = \text{m}[43] \times (\text{h}[43]-\text{h}[44])
\]

\[
\text{Qct1} = \text{m}[45] \times (\text{h}[46]-\text{h}[45])
\]

\{LMED\}

"Log mean enthalpy difference (LMED) method is used for cooling-tower model"

\[
\text{DeltahCT1} = \text{hs}[44]-\text{h}[45]
\]

\[
\text{DeltahCT2} = \text{hs}[43]-\text{h}[46]
\]

\[
\text{Arg} = (\text{DeltahCT2}-\text{dct})/(\text{DeltahCT1}-\text{dct})
\]

\[
\text{Arg} = \exp((\text{DeltahCT2}-\text{DeltahCT1})/\Delta \text{CThm})
\]

\[
\text{NTU} = (\text{h}[46]-\text{h}[45])/\Delta \text{CThm}
\]

\[
\text{HTU} = \text{m}[45]/\text{Kma} \cdot \text{Af}
\]

\[
\text{z} = \text{NTU} \cdot \text{HTU}
\]

\{City water\}

\[
\text{m}[47] = \text{Kma} \cdot \text{Ap} \cdot \text{z}
\]

\[
\text{h}[47] = \text{Enthalpy}(\text{Water}, T=\text{T}[47], P=P_0)
\]

\[
\text{m}[41] \times \text{h}[41] = \text{m}[47] \times \text{h}[47] + \text{m}[44] \times \text{h}[44]
\]

\{Coefficient of performance\}

"The coefficient of performance and cooling capacity of the chiller operating with given test condition can be determined from model calculations and/or from test measurements"

\[
\text{COP} = \text{QEVP}/\text{QHTRG}
\]

\{Test COP and cooling capacity from measured data\}

"Test COP and cooling capacity are calculated on the basis of the data directly measured from building control system. In the control system, the COP and chiller capacity are calculated for monitoring."

\[
\text{COPexp} = \text{Qcooling}/\text{Qheating}
\]

\[
\text{Qheating} = \text{m}[51] \times (\text{h}[51e]-\text{h}[54e])
\]

"Experiment COP"

"Experiment Heat input"
\[ Q_{\text{cooling}} = m_{31e}(h_{31e} - h_{32e}) \]  
"Experiment cooling capacity"

**{Steam and Condensate}**

\[ h_{51e} = \text{Enthalpy}(\text{STEAM}, \ T = T_{51e}, \ x = q_{51e}) \]
\[ T_{51e} = T_{[51]} \]
\[ q_{51e} = 1 \]  
"Condensate vapor quality"

\[ h_{54e} = \text{Enthalpy}(\text{Water}, \ T = T_{54e}, \ P = P_0) \]
\[ T_{54e} = 99.42 \]  
"Measured condensate temperature"

**{Chilled water}**

\[ m_{31e} = m_{[31]} \]
\[ h_{31e} = \text{Enthalpy}(\text{Water}, \ T = T_{31e}, \ P = P_0) \]
\[ h_{32e} = \text{Enthalpy}(\text{Water}, \ T = T_{32e}, \ P = P_0) \]
\[ T_{31e} = T_{[31]} \]
\[ T_{32e} = T_{[32]} \]

"The thermophysical properties used in this model come from the textbook. [18, 19] "