Flexibility Measures for HVAC Equipment in EnergyPlus

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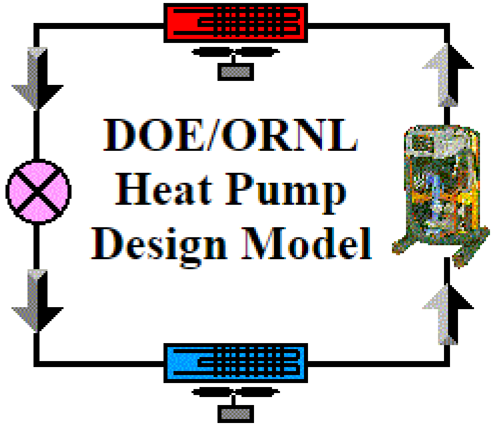
Goals

- Develop HVAC flexibility measures in EnergyPlus to assess impact of grid-responsive building equipment technologies and energy storage
- Open studio wrapping
- Open studio measures be applied to resStock and comStock for residential and commercial prototype buildings.

Resources

https://energyplus.net/

Building energy performance simulation engine



https://hpdmflex.ornl.gov/

Industry standard equipment design tool to provide preliminary configuration and off-design performance

https://www.openstudio.net/

Interface of EnergyPlus, bridge to ComStock and ResStock

ComStock https://www.nrel.gov/buildings/comstock.html

ResStock https://www.nrel.gov/buildings/resstock.html

Nationwide energy and technologies assessment tool

Customer Requests

1) Modulating Equipment

-lock high capacity, modify performance curves and control to allow improved part-load performance.

2) Separate Sensible and Latent Cooling

-Modify coil models using HPDM to modify latent and sensible loads. Employ controls for separate humidity and temperature set-points.

3) Dual Fuel Heating Systems

-Use gas to offset electricity during peak events

4) Thermal Energy Storage

-Ice, hot water, and PCM based storage for all residential and commercial buildings.

5) Liquid Desiccant Thermal Energy Storage

- Leverage existing models to develop desiccant storage for all residential and commercial buildings.

Problem Statement

- **Response to grid signals -** E+ control logics will allow individual coils responding to grid signals. e.g. electricity price, to switch energy sources, lock high capacity, shut off DX coils.
- **Multi-Mode:** Building equipment operate abnormally during peak hours, modulating coils with different performance curves, etc.—i.e. multiple modes (performance curves) by one unit.
- **Multi-source:** Integrated HVAC system including main cooling/heating coil and ice storage, liquid desiccant latent energy storage.

Development Roadmap

Introduce grid signals to HVAC control

Embed grid signal to variable-speed coils

Integrated heat pump (collection of coils) contains multi modes, energy storages, controls and sizing.

Size grid-responsive storages via main coil capacity

Develop new energy storage features, i.e. PCM, liquid desiccant, etc.

Solution I: Use schedule to represent grid signals

Example:

```
Schedule:Compact,
  GAS_EQUIP_SCH,            !- Name
  Fraction,                 !- Schedule Type Limits N
  Through: 12/31,           !- Field 1
  For: SummerDesignDay,     !- Field 2
  Until: 24:00,0.25,        !- Field 3
  For: WinterDesignDay,     !- Field 5
  Until: 24:00,0.0,         !- Field 6
  For: AllOtherDays,        !- Field 8
  Until: 05:00,0.02,        !- Field 9
  Until: 06:00,0.03,        !- Field 11
  Until: 07:00,0.09,        !- Field 13
  Until: 08:00,0.14,        !- Field 15
  Until: 10:00,0.10,        !- Field 17
  Until: 11:00,0.22,        !- Field 19
  Until: 12:00,0.27,        !- Field 21
  Until: 13:00,0.24,        !- Field 23
  Until: 14:00,0.21,        !- Field 25
  Until: 15:00,0.14,        !- Field 27
  Until:16:00,0.13,         !- Field 29
  Until:17:00,0.15,         !- Field 31
  Until: 20:00,0.17,        !- Field 33
  Until: 21:00,0.15,        !- Field 35
  Until: 22:00,0.14,        !- Field 37
  Until: 23:00,0.12,        !- Field 39
  Until: 24:00,0.02;        !- Field 41
```

- Modify equipment objects refer to a grid signal schedule (can be ON/OFF signal, or time)
- Add a set point to shut off or limit capacity of a cooling/heating coil when the grid signal falls within a range

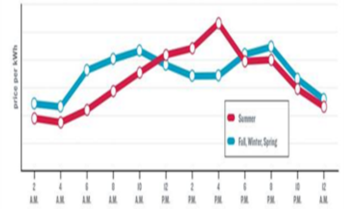
Solution II: Modify variable speed cooling and heating coils referring to grid schedules

- Coil:Cooling:DX:VariableSpeed (modified)
- Coil:Heating:DX:VariableSpeed (modified)
- Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed (modified)
- Coil:Chiller:AirSource:VariableSpeed (new) – same logic as other VS coils

→Extensive data holder to contain performance curves from 1 speed (single-speed) to 10 speeds (variable-speed)
→Add a grid signal schedule and control logic to these models

Embed grid signal to a VS coil

Grid signal schedule



Logic to shut off or limit capacity

COIL:HEATING :FUEL

Fan:OnOff

Coil:Cooling :DX:Variable Speed

AirLoopHVAC:UnitarySystem

ZoneControl:Thermostat

Control

Add Five Fields to Define Grid-Responsive Control

```
GRIDSUMMER,                              ! - grid signal schedule
10.0,                                ! - Low bound to apply grid responsive control
1000.0,                  ! - High bound to apply grid responsive control
5.0,                     ! - max speed when appy grid responsive control
Sensible,                                ! - load matched during grid responsive operation
```

- When the grid signal falls between the low and upper bounds, the grid-responsive control will turn on
- Input a top speed during the grid-response; if top speed is zero, the coil is off.
- The option of load to be matched will be feedbacked to the coil's parent (loop) object, to match the selected load in the loop object.

IDF - Coil:Cooling:DX:VariableSpeed

```
Coil:Cooling:DX:VariableSpeed,

    Heat Pump ACDXCoil 1,    !- Name
    DX Cooling Coil Air Inlet Node,  !- Indoor Air Inlet Node Name
    Heating Coil Air Inlet Node,  !- Indoor Air Outlet Node Name
    10.0,                    !- Number of Speeds {dimensionless}
    10.0,                    !- Nominal Speed Level {dimensionless}
    32000,                   !- Gross Rated Total Cooling Capacity At Selected N
    1.7,                     !- Rated Air Flow Rate At Selected Nominal Speed Le
    0.0,                     !- Nominal Time for Condensate to Begin Leaving the
    0.0,                     !- Initial Moisture Evaporation Rate Divided by Ste
    HPACCOOLPLFFPLR,         !- Energy Part Load Fraction Curve Name
    ,                        !- Condenser Air Inlet Node Name
    AirCooled,               !- Condenser Type
    ,                        !- Evaporative Condenser Pump Rated Power Consumpti
    200.0,                   !- Crankcase Heater Capacity {W}
    10.0,                    !- Maximum Outdoor Dry-Bulb Temperature for Crankca
    ,                        !- Minimum Outdoor Dry-Bulb Temperature for Compres
    ,                        !- Supply Water Storage Tank Name
    ,                        !- Condensate Collection Water Storage Tank Name
    ,                        !- Basin Heater Capacity {W/K}
    ,                        !- Basin Heater Setpoint Temperature {C}
    ,                        !- Basin Heater Operating Schedule Name
    GRIDSUMMER,              ! - grid signal schedule
    10.0,                    ! - Low bound to apply grid responsive control
    1000.0,                  ! - High bound to apply grid responsive control
    5.0,                     ! - max speed when appy grid responsive control
    Sensible,                ! - load matched during grid responsive operation
```

IDF - Coil:Heating:DX:VariableSpeed

```
Coil:Heating:DX:VariableSpeed,

    Sys 1 Heat Pump Heating Mode,                !- Name
    Sys 1 Heating Coil Air Inlet Node,                !- Air Inlet Node Name
    Sys 1 SuppHeating Coil Air Inlet Node,            !- Air Outlet Node Name
    10.0,                                    !- Number of Speeds
    10.0,                                    !- Nominal Speed Level
    Autosize,                                    !- Rated Heating Capacity {W}
    Autosize,                                        !- Rated Air Flow Rate {m3/s}
    VS Energy Part Load Fraction 1,                  !- Energy part load fraction curve
    VS Defrost Power Function 1,              !Defrost Energy Input Ratio Function of Temperature Curve Name
    0,                                        !Minimum Outdoor DB Temperature for Compressor Operation {C}
    47,                                       !Maximum Outdoor DB Temperature for Defrost Operation {C}
    200,                                      !Crankcase Heater Capacity {W}
    15,                                  !Maximum Outdoor DB Temperature for Crankcase Heater Operation {C}
    Reverse Cycle,                       !Defrost Strategy
    OnDemand,                            !Defrost Control
    0.0,                                 !Defrost Time Period Fraction
    0.0,                                 !Resistive Defrost Heater Capacity (W)
    GRIDWINTER,          ! - grid signal schedule
    10.0,                    ! - Low bound to apply grid responsive control
    1000.0,                  ! - High bound to apply grid responsive control
    5.0,                     ! - max speed when appy grid responsive control
```

IDF - Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed

```
Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed,

    HPWHVSCoil,                  !- Name
    1,                          !- Number of Speeds {dimensionless}
    1,                          !- Nominal Speed Level {dimensionless}
    4000.0,                      !- Rated Water Heating Capacity {W}
    29.44,                       !- Rated Evaporator Inlet Air Dry-Bulb Temperature {C}
    22.22,                       !- Rated Evaporator Inlet Air Wet-Bulb Temperature {C}
    55.72,                       !- Rated Condenser Inlet Water Temperature {C}
    autosize,                      !- Rated Evaporator Air Flow Rate {m3/s} 0.2685,
    autosize,                     !- Rated Condenser Water Flow Rate {m3/s} 0.00016,
    No,                          !- Evaporator Fan Power Included in Rated COP
    No,                          !- Condenser Pump Power Included in Rated COP
    No,                          !- Condenser Pump Heat Included in Rated Heating Capacity and Rated COP
    0.1,                         !- Fraction of Condenser Pump Heat to Water
    HPOutdoorAirInletNode,           !- Evaporator Air Inlet Node Name
    HPWHAirFanInletNode,           !- Evaporator Air Outlet Node Name
    HPWaterInletNode,            !- Condenser Water Inlet Node Name
    HPWaterOutletNode,           !- Condenser Water Outlet Node Name
    100.0,                       !- Crankcase Heater Capacity {W}
    5.0,                         !- Maximum Ambient Temperature for Crankcase Heater Operation {C}
    WetBulbTemperature,          !- Evaporator Air Temperature Type for Curve Objects
    HPWHPLFFPLR,                 !- Part Load Fraction Correlation Curve Name
    GRIDALL,                     ! - grid signal schedule
    10.0,                        ! - Low bound to apply grid responsive control
    1000.0,                      ! - High bound to apply grid responsive control
    5.0,                         ! - max speed when apply grid responsive control
```

IDF - Coil:Chiller:AirSource:VariableSpeed

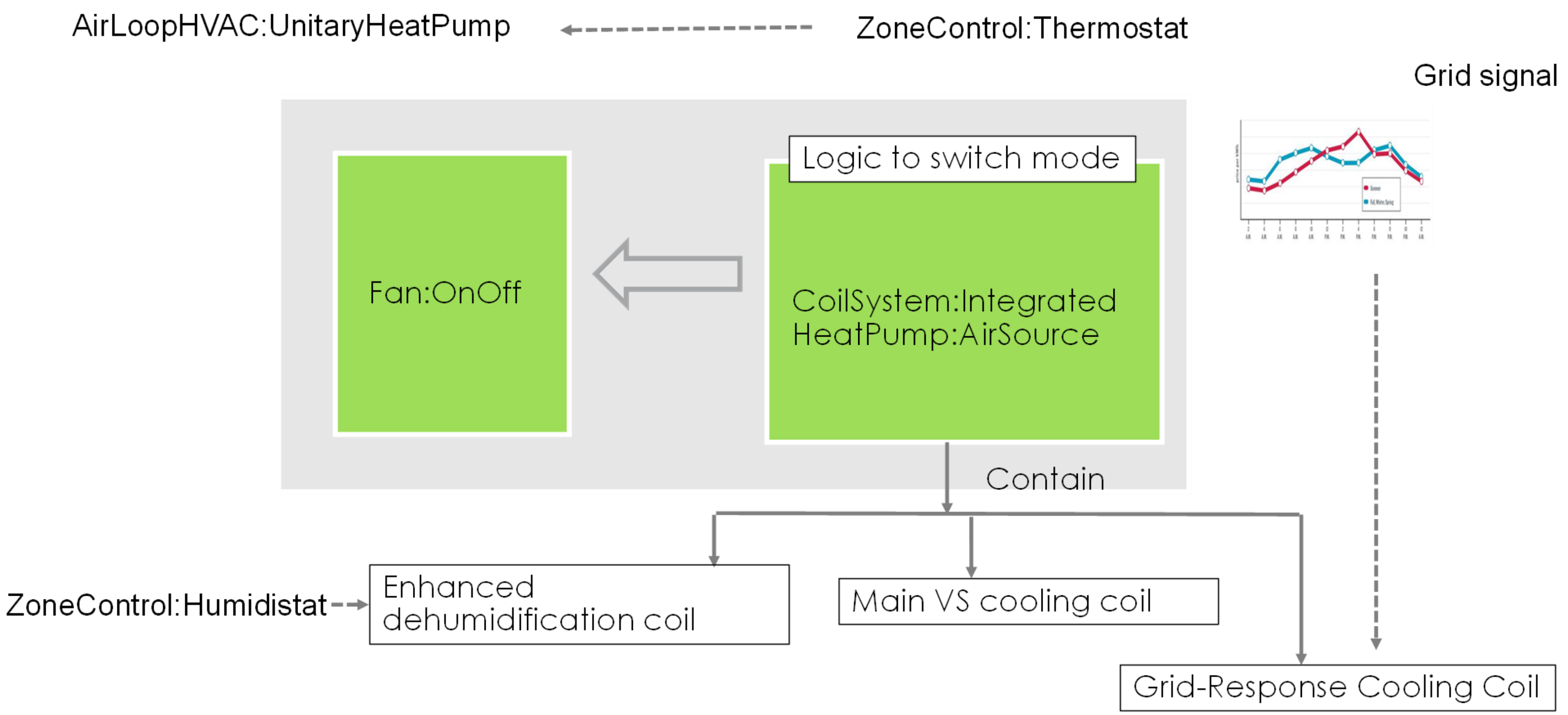
```
Coil:Chiller:AirSource:VariableSpeed,

  VSChillerCoil,                  !- Name
  1.0,                          !- Number of Speeds {dimensionless}
  1.0,                          !- Nominal Speed Level {dimensionless}
  autosize,                      !- Rated Cooling Capacity {W}
  -1.1,                       !- Rated Evaporator Inlet Water Temperature {C}
  35.0,                       !- Rated Condenser Inlet Air Temperature {C}
  0.00063,                        !- Rated Evaporator Water Flow Rate {m3/s}
  No,                          !- Evaporator Pump Power Included in Rated COP
  No,                          !- Evaporator Pump Heat Included in Rated Heating Capacity and Rated COP
  0.1,                         !- Fraction of Evaporator Pump Heat to Water
  ChillerInletNode,            !- Evaporator Water Inlet Node Name
  ChillerWaterOutletNode,      !- Evaporator Water Outlet Node Name
  100.0,                       !- Crankcase Heater Capacity {W}
  5.0,                         !- Maximum Ambient Temperature for Crankcase Heater Operation {C}
  HPWHPLFFPLR,                 !- Part Load Fraction Correlation Curve Name
  GRIDSUMMER,                  ! - grid signal schedule
  10.0,                        ! - Low bound to apply grid responsive control
  1000.0,                      ! - High boundar to apply grid responsive control
  0.0,                         ! - max speed when appy grid responsive control
```

Solution III: Extend Integrated Heat Pump Model (IHP)-to present multiple operation modes in one unit

Contains multiple space cooling, heating and water heating modes; already connected to air loop and water loop; implement control logics and energy balance between modes

---Multi-Mode Grid-Responsive Integrated Heat Pump



IDF – Multi-Mode Grid Responsive IHP

```
CoilSystem:IntegratedHeatPump:AirSource,

   PACU_VAV_bot_CoolC DXCoil,                   !- Name
   ,!- Supply Hot Water Flow Sensor Node Name
   Heat Pump ACDXCoil 1,    !- Space Cooling Coil  Name
   Heat Pump DX Heating Coil 1,  !- Space Heating Coil Name
   ,     !- Dedicated Water Heating Coil Name
   ,               !- SCWH Coil Name
   ,          !- SCDWH Cooling Coil Name
   ,            !- SCDWH Water Heating Coil Name
   ,          !- SHDWH Heating Coil Name
   ,            !- SHDWH Water Heating Coil Name
   ,                         ! - Enhanced dehumidification coil name
   GridCoolingCoil,                         ! - Grid Response Cooling coil name
   ,                         ! - Grid Response Heating coil name
   23.0,                    !- Indoor Temperature Limit for SCWH Mode {C}
   28.0,                    !- Ambient Temperature Limit for SCWH Mode {C}
   20.0,                    !- Indoor Temperature above Which WH has Higher Priority {C}
   16.0,                    !- Ambient Temperature above Which WH has Higher Priority {C}
   0,                       !- Flag to Indicate Load Control in SCWH Mode {dimensionless}
   1,                       !- Minimum Speed Level for SCWH Mode {dimensionless}
   3.0,                     !- Maximum Water Flow Volume before Switching from SCDWH to SCWH Mode {m3}
   1,                       !- Minimum Speed Level for SCDWH Mode {dimensionless}
   600,                     !- Maximum Running Time before Allowing Electric Resistance Heat Use during SHD
   1,                       !- Minimum Speed Level for SHDWH Mode {dimensionless}
   1.0,                     ! - sizing ratio of space heating coil to space cooling coil
   1.0,                     !- sizing ratio of dedicated water heating capacity to space cooling coil
   1.0,                     !- sizing ratio of combined space cooling and water heating with full condensin
   1.0,                     !- sizing ratio of combined space cooling and water heating with desuperheating
   0.15,                    !- sizing ratio of combined space cooling and water heating with desuperheating
   1.0,                     !- sizing ratio of combined space heating and water heating with desuperheating
   0.15,                    !- sizing ratio of combined space heating and water heating with desuperheating
   1.0,                     ! - sizing ratio of enhanced dehumidification coil to space cooling coil
   1.0,                     ! - sizing ratio of grid response cooling coil to space cooling coil
   1.0,                     ! - sizing ratio of grid response heating coil to space cooling coil
```

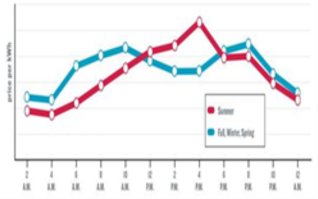
Ice storge integrated heat pump

AirLoopHVAC:UnitaryHeatPump ← - - - - - - - - - - ZoneControl:Thermostat

Fan:OnOff

Logic to switch mode

CoilSystem:Integrated HeatPump:AirSource



Grid signal

Contain

- Curve of Chiller water temperature versus ice fraction
- Ice-making chiller
- Chilled water coil
- Ice/PCM storage tank
- Main VS cooling coil

Plant loop (delivery side)

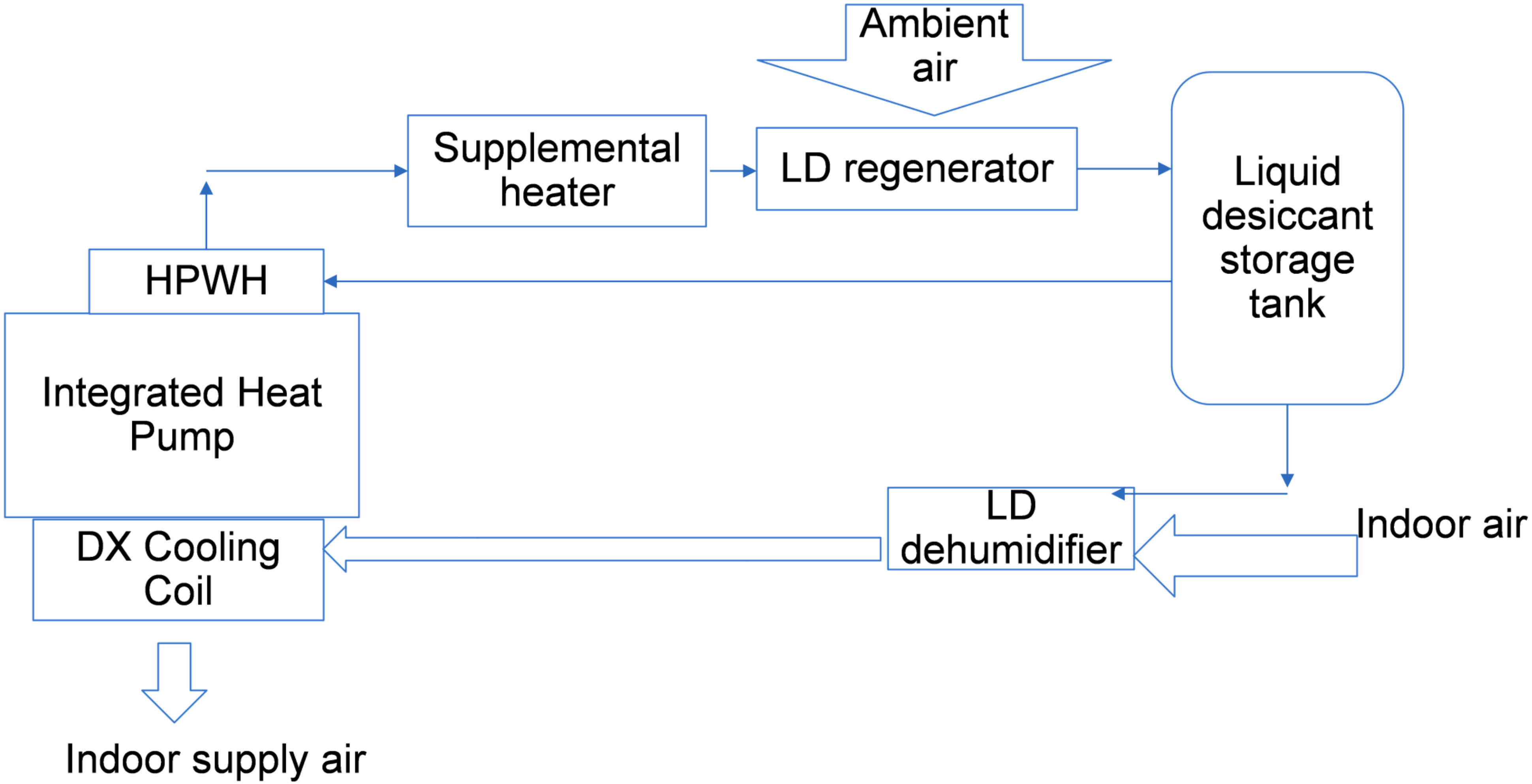
IDF – Ice Storage Integrated Heat Pump

```
CoilSystem:IntegratedHeatPump:AirSource,

  PACU_VAV_bot_CoolC DXCoil,                    !- Name
  ,!- Supply Hot Water Flow Sensor Node Name
  Heat Pump ACDXCoil 1,     !- Space Cooling Coil  Name
  Heat Pump DX Heating Coil 1,   !- Space Heating Coil Name
  ,      !- Dedicated Water Heating Coil Name
  ,                !- SCWH Coil Name
  ,           !- SCDWH Cooling Coil Name
  ,             !- SCDWH Water Heating Coil Name
  ,           !- SHDWH Heating Coil Name
  ,             !- SHDWH Water Heating Coil Name
  ,                         ! - Enhanced dehumidification coil name
  ,                         ! - Grid Response Cooling coil name
  ,                         ! - Grid Response Heating coil name
  23.0,                     !- Indoor Temperature Limit for SCWH Mode {C}
  28.0,                     !- Ambient Temperature Limit for SCWH Mode {C}
  20.0,                     !- Indoor Temperature above Which WH has Higher Priority {C}
  16.0,                     !- Ambient Temperature above Which WH has Higher Priority {C}
  0,                        !- Flag to Indicate Load Control in SCWH Mode {dimensionless}
  1,                        !- Minimum Speed Level for SCWH Mode {dimensionless}
  3.0,                      !- Maximum Water Flow Volume before Switching from SCDWH to SCWH Mode {m3}
  1,                        !- Minimum Speed Level for SCDWH Mode {dimensionless}
  600,                      !- Maximum Running Time before Allowing Electric Resistance Heat Use during SHDWH Mode {s}
  1,                        !- Minimum Speed Level for SHDWH Mode {dimensionless}
  1.0,                      ! - sizing ratio of space heating coil to space cooling coil
  1.0,                      !- sizing ratio of dedicated water heating capacity to space cooling coil
  1.0,                      !- sizing ratio of combined space cooling and water heating with full condensing - water heating ca
  1.0,                      !- sizing ratio of combined space cooling and water heating with desuperheating - space cooling cap
  0.15,                     !- sizing ratio of combined space cooling and water heating with desuperheating - water heating cap
  1.0,                      !- sizing ratio of combined space heating and water heating with desuperheating - space heating cap
  0.15,                     !- sizing ratio of combined space heating and water heating with desuperheating - water heating cap
  1.0,                      ! - sizing ratio of enhanced dehumidification coil to space cooling coil
  1.0,                      ! - sizing ratio of grid response cooling coil to space cooling coil
  1.0,                      ! - sizing ratio of grid response heating coil to space cooling coil
  VSChillerCoil,            ! - chilled water coil
  SEPARATE,                     ! - chiller is from a single unit or not
  1,                       ! - chiller operating speed
  1.0,                      ! - chiller sizing ratio to the main cooling coil
  Coil:Cooling:Water,       ! - supplemental cooling coil type
  Main Cooling Coil 1,         !- supplemental cooling coil name
  1.0,                         !-chilled water coil air flow ratio to the main cooling coil, i.e. space cooling mode
  1.0,                         !-chilled water coil water flow ratio to the chiller water coil
  ThermalStorage:Ice:Detailed,   ! - ice storage tank type
  Ice Tank,                 !- Ice storage tank Name
  0.9,                      ! - ice fraction below which starts charging
  0.0,                    !-entering coolant temperature to chiller at 0 tank fraction [C]
  TempVsFraction;         !- offset temperature deviation to the starting temperature [K] as a function of the tank fraction
```

Liquid Desiccant Storage Integrated Heat Pump

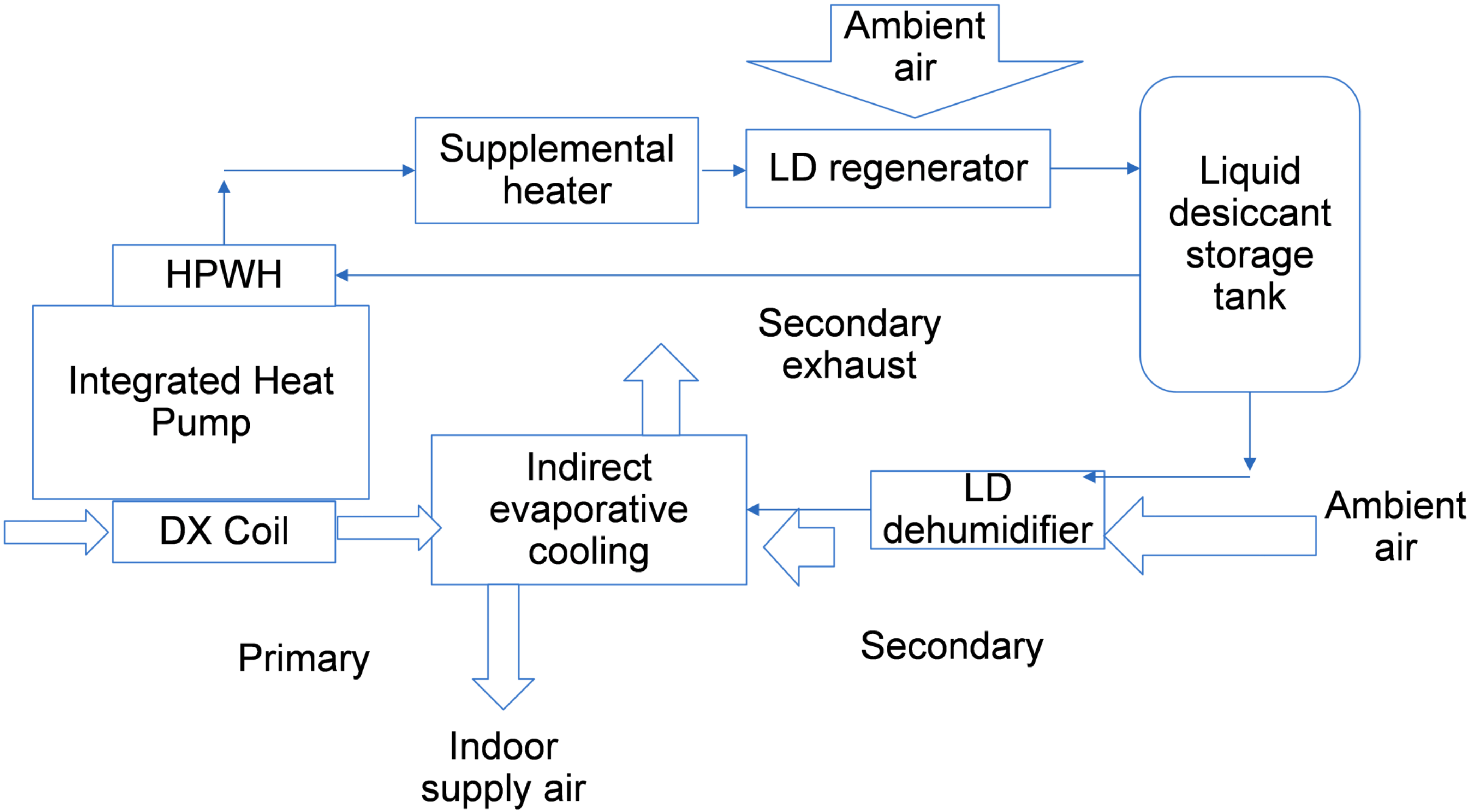
Scenario I- indoor liquid desiccant coil upstream of a DX cooling coil



IDF – liquid desiccant storage upstream of indoor DX coil

```
CoilSystem:DesiccantStorageHeatPump:AirSource,
  ASIHP1,                          !- Name
  DX Cooling Coil_unit1,            !- Space Cooling Coil  Name
  Main DX Heating Coil_unit1,   !- Space Heating Coil Name
  HPWHOutdoorDXCoilVS,          !- Dedicated Water Heating Coil Name
  SINGLE,                          ! --DWH mode belongs to a single unit or a separate unit
  SCWHCoil1,                       !- SCWH Coil Name
  SCDWHCoolCoil1,                  !- SCDWH Cooling Coil Name
  SCDWHWHCoil1,                    !- SCDWH Water Heating Coil Name
  ,                                ! - Enhanced dehumidification coil name
  ,                                ! - Grid Response Cooling coil name
  Coil:LiquidDesiccant:Simple, ! -- dehumidification coil type
  DehumLDCoil,                     !--dehumidification coil name
  UPSTREAM,                        ! - dehumidification coil placement: OUTDOOR; UPSTREAM; DOWNSTREAM
  Coil:LiquidDesiccant:Simple, ! -- regeneration coil type
  RegenLDCoil,                     !--Regeneration coil name
  ,  !- First Evaporative Cooler Object Type
  ,  !- First Evaporative Cooler Object Name
  ,                                ! - Grid Response Heating coil name
  GAS,                             ! - supplemental liquid desiccant heater type
  WaterHeater:HeatPump:PumpedCondenser,  ! - heat pump type
  OutdoorHeatPumpWaterHeater,  !- heat pump Name
  1.0,                              !- Minimum Speed Level for SCWH Mode {dimensionless}
  1.0,                              !- Minimum Speed Level for SCDWH Mode {dimensionless}
  60.0,                            ! - entering water temperature limit to apply SCWH mode
```

Scenario I- outdoor liquid desiccant cycle to drive an indirect evaporative-cooler



IDF – liquid desiccant cycle to drive an indirect evaporative cooler

```
CoilSystem:DesiccantStorageHeatPump:AirSource,
  ASIHP1,                       !- Name
  DX Cooling Coil_unit1,         !- Space Cooling Coil  Name
  Main DX Heating Coil_unit1,   !- Space Heating Coil Name
  HPWHOutdoorDXCoilVS,          !- Dedicated Water Heating Coil Name
  SINGLE,                       ! --DWH mode belongs to a single unit or a separate unit
  SCWHCoil1,                    !- SCWH Coil Name
  SCDWHCoolCoil1,               !- SCDWH Cooling Coil Name
  SCDWHWHCoil1,                 !- SCDWH Water Heating Coil Name
  ,                             ! - Enhanced dehumidification coil name
  ,                             ! - Grid Response Cooling coil name
  Coil:LiquidDesiccant:Simple, ! -- dehumidification coil type
  DehumLDCoil,                  !--dehumidification coil name
  OUTDOOR,                      ! - dehumidification coil placement: OUTDOOR; UPSTREAM; DOWNSTREAM
  Coil:LiquidDesiccant:Simple, ! -- regeneration coil type
  RegenLDCoil,                  !--Regeneration coil name
  EvaporativeCooler:Indirect:CelDekPad,  !- First Evaporative Cooler Object Type
  Indirect Evaporative Cooler 1,  !- First Evaporative Cooler Object Name
  ,                             ! - Grid Response Heating coil name
  GAS,                          ! - supplemental liquid desiccant heater type
  WaterHeater:HeatPump:PumpedCondenser,  ! - heat pump type
  OutdoorHeatPumpWaterHeater,   !- heat pump Name
```

Solution IV: Size energy storage objects according to the main cooling/heating coil for intended operation hours

- ThermalStorage:Cooling:Pair (new)
- ThermalStorage:Heating:Pair (new)

IDF - ThermalStorage:Cooling:Pair

```
ThermalStorage:Cooling:Pair,

  CoolingStorePair,       !- Name
  Coil:Cooling:DX:VariableSpeed, !- Cooling Coil Object Type
  DX Cooling Coil 1,      !- Cooling Coil Name
  ThermalStorage:Ice:Detailed,  !- Tank Object Type
  Ice Tank,                  !- Tank Name
  4.0,                       !-Maximum Peak Operation Hours
  0.0,                       !-temperature change
  TOTAL,                     ! - load met type
  Chiller:Electric,          ! - recovery unit type
  Central Chiller,           ! - recovery unit name
  0.5;                       ! - recovery unit ratio to the main cooling coil
```

If choose to use the energy storage to meet the **total capacity** for a given period,
→The storage device's capacity = Main coil's Rated Total Cooling Capacity * Operation Hours
If choose to use the energy storage to meet the **sensible capacity** for a given period,
→The storage device's capacity = Main coil's Rated Total Cooling Capacity * Main coil's Rated Sensible Heat Ratio * Operation Hours
If choose to use the energy storage to meet the **latent capacity** for a given period,
→The storage device's capacity = Main coil's Rated Total Cooling Capacity *(1.0 - Main coil's Rated Sensible Heat Ratio) * Operation Hours

The rated capacity of the recovery unit = Main coil's Rated Total Cooling Capacity * recovery unit ratio to the main cooling coil

IDF - ThermalStorage:Heating:Pair

```
ThermalStorage:Heating:Pair,

  HeatingStorePair,      !- Name
  Coil:Heating:DX:VariableSpeed, !- Heating Coil Object Type
  Heat Pump DX Heating Coil 1,     !- Heating Coil Name
  WaterHeater:Mixed,  !- Tank Object Type
  HPWHZoneTank,                 !- Tank Name
  4.0,                        !-Maximum Peak Operation Hours
  15.0,                        !-temperature change
 Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed,        ! - recovery unit type
 HPWHVSCoil,          ! - recovery unit name
 1.0;                        ! - recovery unit ratio to the main heating coil
```

The storage device's capacity [kg] = Main coil's Rated Total Heating Capacity * Operation Hours/(Cpwater * temperature rise)

The rated capacity of the recovery unit = Main coil's Rated Total Heating Capacity * recovery unit ratio to the main heating coil

Liquid Desiccant Coil

The heat transfer in air side:

$$m_a dh_a = h_c A_v dV(T_s - T_a) + h_{v,Ts} m_a dW_a$$

The mass transfer in air side:

$$m_a dW_a = h_D A_v dV(W_{Ts,sat} - W_a)$$

The Lewis number and NTU are given as,

$$Le = \frac{h_c}{h_D C_{p,m}}$$

$$NTU = \frac{h_D A_V V_T}{m_a}$$

The saturation specific heat is defined as the derivative of the saturated air enthalpy with respect to temperature,

$$C_{sat} = \frac{dh_{Ts,sat}}{dT_s}$$

The capacitance ratio is defined as,

$$m* = \frac{m_a C_{sat}}{m_s C_{ps}}$$

With assumption of C_{sat} being constant, a heat exchanger counterflow effectiveness relationship is used,

$$\varepsilon = \frac{1-e^{-NTU(1-m*)}}{1-m*\,e^{-NTU(1-m*)}}$$

Then, the air outlet enthalpy can be solved as,

$$h_{a,o} = h_{a,i} + \varepsilon(h_{Ts,sat,i} - h_{a,i})$$

Also, the air outlet humidity ratio is given by,

$$W_{a,o} = W_{Ts,sat,eff} + (W_{a,i} - W_{Ts,sat,eff})e^{-NTU}$$

Where the effective state is solved by the below equation,

$$h_{Ts,sat,eff} = h_{a,i} + \frac{h_{a,o} - h_{a,i}}{1-e^{-NTU}}$$

Reference:

- Dawne Stevens, 1988, Analysis of liquid-desiccant systems and component modeling, Master of Science, University of Wisconsin – Madison
- Zhiyao Yang, Ming Qu, 2015, Sorption simulation software v1.0 user' guide and reference, ORNL Report, US DOE

Connected and used in the same way as chilled water coil

IDF - Coil:LiquidDesiccant:Simple – for both dehumidifier and regenerator

```
Coil:LiquidDesiccant:Simple,
  RegenLDCoil,     !- Name
  PlantHPWHSch,   !- Availability Schedule Name
  autosize,                !- Design Water Flow Rate {m3/s}
  autosize,                !- Design Air Flow Rate {m3/s}
  autosize,                !- Design Inlet Water Temperature {C}
  autosize,                !- Design Inlet Air Temperature {C}
  autosize,                !- Design Outlet Air Temperature {C}
  autosize,                !- Design Inlet Air Humidity Ratio {kgWater/kgDryAir}
  autosize,                !- Design Outlet Air Humidity Ratio {kgWater/kgDryAir}
  autosize,                !- Design Inlet Solution Concentration
        55.0,                    !- Design fan power per unit mass flow rate
        autosize,                !- Outdoor Air Flow Rates {m3/s}
        75.0,                    !- Design pump power
        0.9,                    !- Design peffectiveness
  HPOutdoorWaterOutletNode,  !- Water Inlet Node Name
  Regen Out,              !- Water Outlet Node Name
  Regen OA In,                     !- Air Inlet Node Name
  Regen OA Out,                     !- Air Outlet Node Name
  RegenerationMode,        !- Type of Operation Mode: 1- RegenerationMode, 2-DehumidificationMode
  OutdoorAirSource,        !- air source: 1-OutdoorAirSource 2-ZoneAirSource (default)
        LiCl;                   !-  material
```

PCM Thermal Energy Storage

Charge

Energy balance equations at current state of charge (fraction) x_t

$$uQ_{norm}/_{\Delta t} = \varepsilon Q_{max} = m_w C_{pw}(T_{w,out} - T_{w,in})$$

$$\varepsilon = 1 - exp(-NTU) = 1 - exp\left(-{}^{UA_x}/_{m_w C_{pw}}\right)$$

$$Q_{max} = m_w C_{pw}(T_x - T_{w,in})$$

$$UA_x = (1 - x)UA_l + xUA_s$$

$$T_x = (1 - x)T_l + xT_s$$

The next time step state of charge (fraction) $x_{t+\Delta t}$

$$x_{t+\Delta t} = u\Delta t + x_t$$

Discharge

Energy balance equations at current state of discharge (fraction) x_t

$$-uQ_{norm}/_{\Delta t} = \varepsilon Q_{max} = m_w C_{pw}(T_{w,in} - T_{w,out})$$

$$\varepsilon = 1 - exp(-NTU) = 1 - exp\left(-{}^{UA_x}/_{m_w C_{pw}}\right)$$

$$Q_{max} = m_w C_{pw}(T_x - T_{w,out})$$

$$UA_x = (1 - x)UA_l + xUA_s$$

$$T_x = (1 - x)T_l + xT_s$$

The next time step state of discharge (fraction) $x_{t+\Delta t}$

$$x_{t+\Delta t} = u\Delta t + x_t$$

Similar to simple ice storage model
Input separate UAs and phase change temperature at 0 and 1.0 solid fraction
Interpolate UA and phase change temperature as a linear function of the solid fraction

IDF - ThermalStorage:Pcm:Simple

```
ThermalStorage:Pcm:Simple,
    Ice Tank,                    !- Name
    IceOnCoilInternal,           !- Ice Storage Type
    0.5,                         !- Capacity {GJ}
    Ice Tank Inlet Node,         !- Inlet Node Name
    Ice Tank Outlet Node,        !- Outlet Node Name
    5.5,                         !- Onset temperature of phase change
    7.0,                         !- Finish temperature of phase change
    20000,                       !- Onset UA of phase change material
    20000;                       !- Finish UA of phase change material
```

THANK YOU