ME 502 Thermal Systems

Project #7 Thermal Management System for BESS

Ke Tang

Department of Mechanical Science and Engineering

University of Illinois at Urbana-Champaign

E-mail: ketang@illinois.edu

Outline

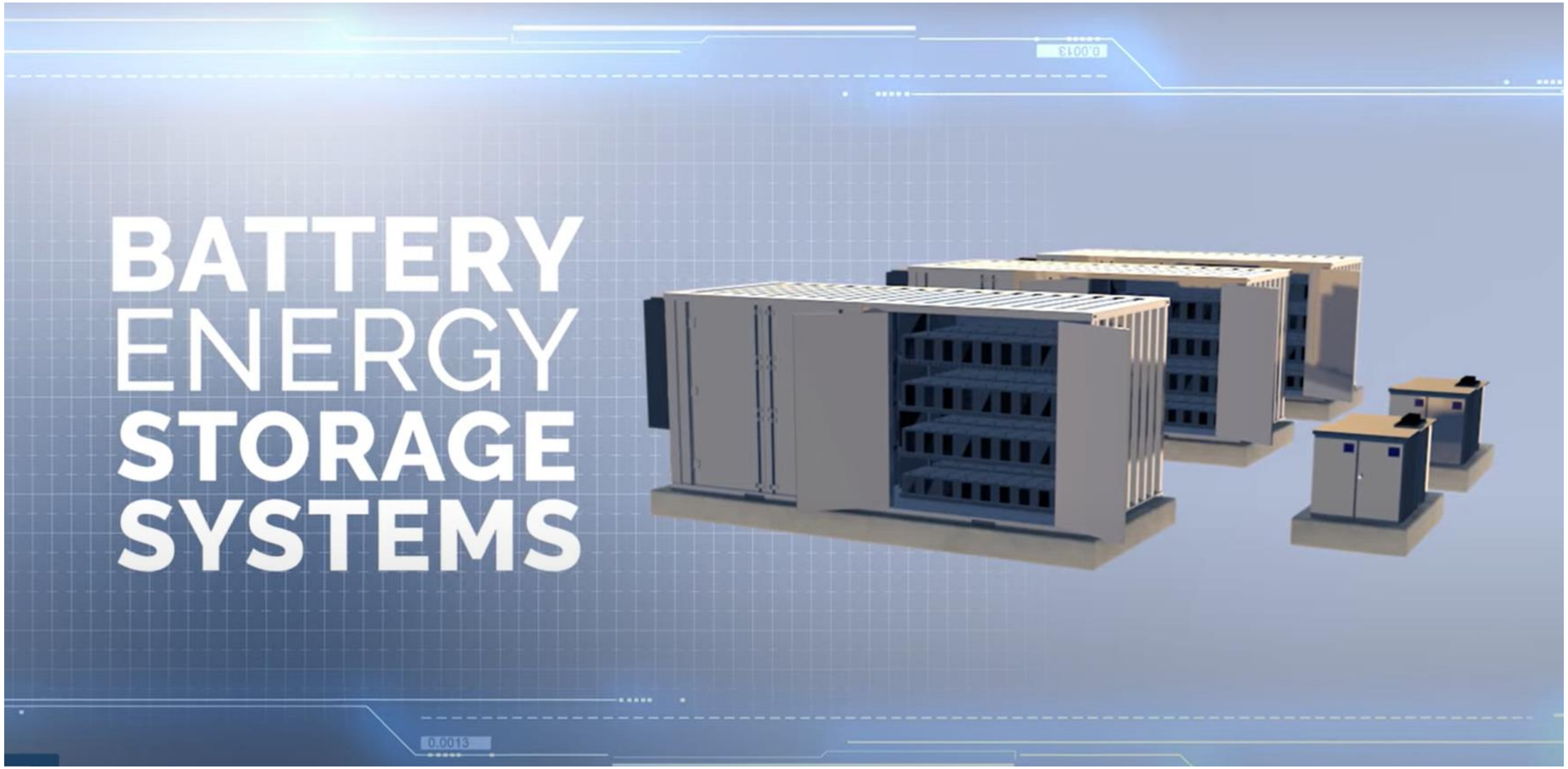
- **Battery Energy Storage System (BESS) and its Thermal Management**
- Project #7
- Simulation of Thermal Management System for BESS

Battery Energy Storage System (BESS)

- Renewable Energy is one of the solutions to the global problems of energy crisis and climate change.
- However, the generation of renewable energy, e.g., solar energy and wind energy, is inconsistent, and cannot match with users' demand well.
- Battery energy storage systems (BESS) are devices that enable energy from renewables, like solar and wind, to be stored and then released when customers need power.
- BESS will play an increasingly pivotal role between renewable energy supplies and responding to electricity demands.

Battery Energy Storage System (BESS)

- YouTube video: https://www.youtube.com/watch?v=jcZuG1mmty8&list=LL&index=1&t=21s



Thermal Management System for BESS

- However, the enclosures that contain battery energy storage systems are often located outdoors and exposed to extreme temperatures, severe weather, humidity, dirt, and dust.
- Like most heat-sensitive electrical equipment, operation within hot and cold temperatures can, over time, reduce power output and longevity of batteries. Even the batteries themselves generate heat during charging and discharging.
- Thus, active cooling and heating should be introduced to BESS enclosures to maintain ideal temperature and humidity ranges.

Outline

- Battery Energy Storage System (BESS) and its Thermal Management
- **Project #7**
- Simulation of Thermal Management System for BESS

Project #7

- Project #7 focuses on the transient simulation of a thermal management system for a battery energy storage system (BESS) to predict its dynamic thermal behavior.
- As shown in the figure, most components are sitting inside a container, except the condensing unit.

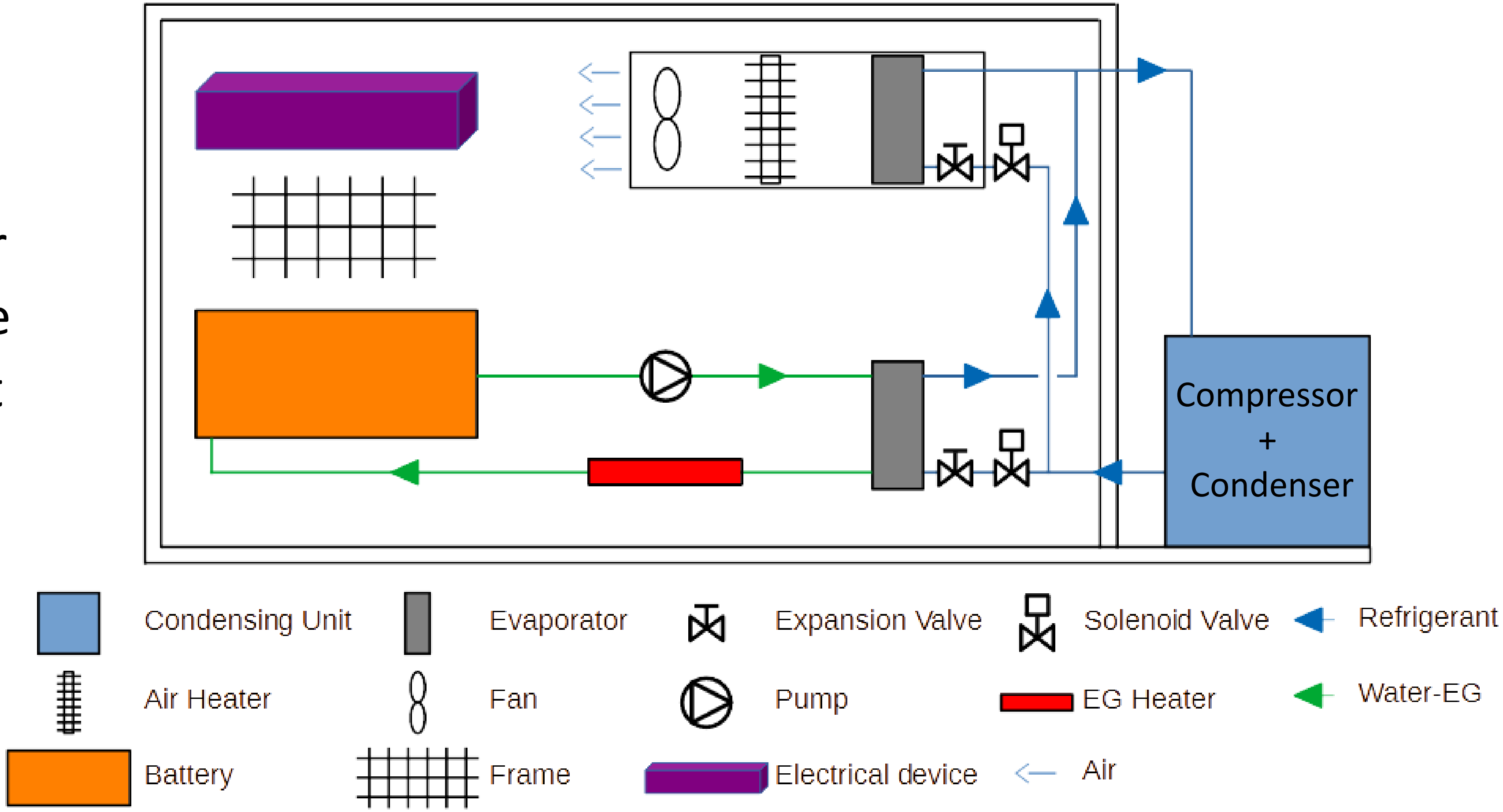


Figure 1 Schematic of thermal management system for BESS

Targets of Thermal Management System

- The thermal management system is used to condition the thermal status of the battery, and also the thermal and humid status of the air within the container.
- The details about the suggested range of operating parameters are listed in Table 1.

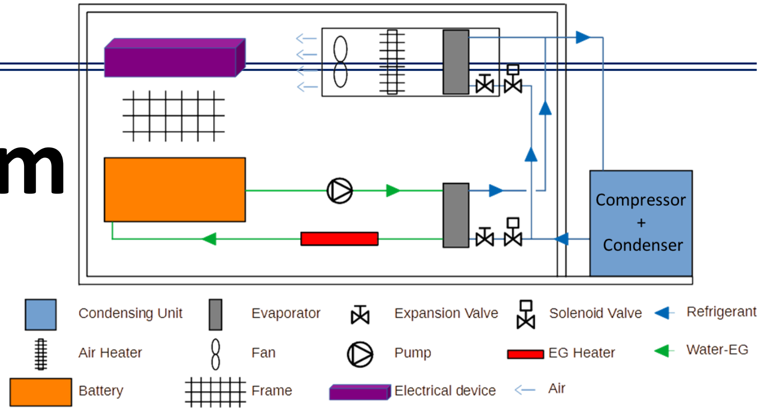
Table 1 Suggested ranges of operating parameters

Operating Parameters	Value
T_battery_max: the upper limit of batter temperature, [°C]	30
T_battery_min: the lower limit of batter temperature, [°C]	20
T_air_drybulb_max: the upper limit of air dry-bulb temperature, [°C]	30
T_air_drybulb_min: the lower limit of air dry-bulb temperature, [°C]	20
T_air_dewpoint_max: the upper limit of air dew point temperature, [°C]	16
T_air_dewpoint_min: the lower limit of air dew point temperature, [°C]	12

Additional Comments on Operating Parameter Range

- Although there is a lower temperature limit for battery, this limit is not hard. For the scenario that the air needs cooling to reach its lower limits of dry-bulb temperature or dew point temperature, the extra cooling of the condensing unit must be delivered to cool the battery and the temperature of battery is allowed to go below its lower limit. (There is a capacity mismatch between the condensing unit and the evaporator for the air loop, which is called the second evaporator working with the condensing unit.)
- Although there are the lower limits for both air dry-bulb temperature and dew point temperature, these two lower limits are not hard. For the scenario that the air needs cooling to reach either of these two, the other lower limit is allowed to be broken through.
- The dew point temperature of humid air in the container needs to be well controlled to be lower than its upper limit to avoid the risk of device damage due to water condensate.

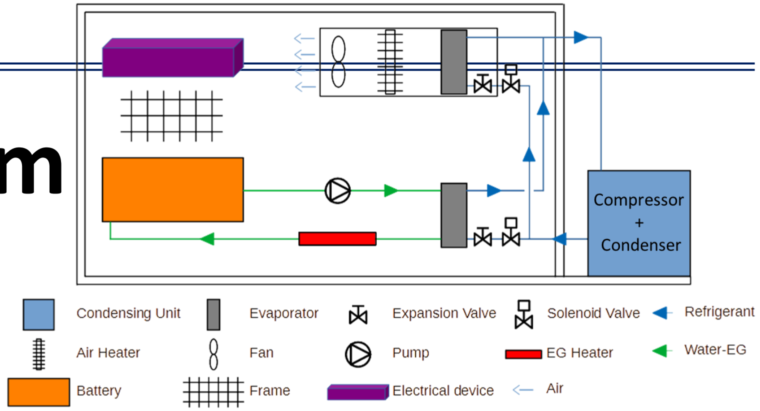
Operation of Thermal Management System



Water-EG loop

- The battery generates heat during charging and discharging. The coolant of water-EG mixture is circulated by a pump to cool the battery.
- The water-EG coolant gets cooling capacity through heat exchange with refrigerant in the first evaporator working with the condensing unit.
- The heater set on the coolant loop helps to consume the extra cooling capacity of the condensing unit. The heater employs an on-off control.
- The pump is always on to keep the circulation of the water-EG coolant.

Operation of Thermal Management System



Air loop

- An air handling unit (AHU), including a fan , an air heater, and the second evaporator working with the condensing unit, is used to circulate and condition the humid air in the container.
- The contributions to the thermal loads with respect to air are the heat transfer with the container wall and the components sitting inside the container, as well as the water vapor penetration into the container.
- The air heater employs an on-off control.
- The fan is always on to keep the circulation of air in the container.

Heat Capacities of Components

- The heat capacities of components are listed in Table 2.

Table 2 Heat capacities of components

Heat Capacity	Value
cp_battery: the specific heat of battery, [kJ/(kg-K)]	0.9
M_battery: the mass of battery, [kg]	15000
cp_device: the specific heat of devices, [kJ/(kg-K)]	0.5
M_device: the mass of devices, [kg]	200
cp_frame: the specific heat of frame, [kJ/(kg-K)]	0.5
M_frame: the mass of frame, [kg]	250
cp_wall: the specific heat of container wall, [kJ/(kg-K)]	0.5
M_wall: the mass of container wall, [kg]	1500
cp_eg: the specific heat of water-EG coolant, [kJ/(kg-K)]	3.3
M_eg: the mass of water-EG coolant, [kg]	300
cp_air: the specific heat of air in container, [kJ/(kg-K)]	CoolProp
V_air: the volume of air in container, [m^3]	20

Thermal Resistances

- The thermal resistances regarding the heat transfer between components and air or water-EG coolant are listed in Table 3.

Table 3 Thermal resistances between components and air or water-EG coolant

Thermal Resistance	Value
R_air_battery: the thermal resistance between air and battery, [K/kW]	5
R_eg_batttery: the thermal resistance between water-EG and battery, [K/kW]	0.5
R_air_device: the thermal resistance between air and devices, [K/kW]	10
R_air_frame: the thermal resistance between air and frame, [K/kW]	12
R_air_wall: the thermal resistance between air and container wall, [K/kW]	2

Operating Conditions

- Table 4 lists the operating conditions (i.e., boundary conditions) of interest.

Table 4 Operating conditions (i.e., boundary conditions)

Operating Conditions	Value
T_air_outdoor: the temperature of outdoor air, [°C]	27
Q_external: the external heat going to container walls , [kW]	2.5
Power_pump: the power input to pump, [kW]	1.5
Power_fan: the power input to fan, [kW]	0.75
Power_device: the power input to electrically-powered devices, [kW]	1.5
Q_batterygenerating: the heat generated by battery, [kW]	5
Q_eg_heater: the heating power of glycol heater, [kW]	5
Q_air_heater: the heating power of air heater, [kW]	3.5
m_dot_water_in*: the water vapor penetration, [g/s]	0.1

* m_dot_water_in: The water vapor penetrating into the container will increase the humidity of air inside of the container. The cooling is needed to dehumidify the humid air for the required working condition indicated by the dew point temperature.

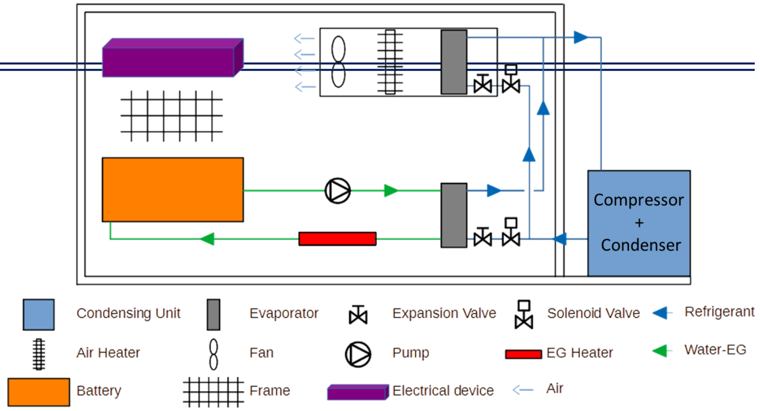
Initial Conditions

- Table 5 lists the initial conditions of interest.

Table 5 Initial conditions

Initial Conditions	Value
T_air_drybulb_0: the temperature of air in container, [°C]	32
T_air_dewpoint_0: the dewpoint temperature of air in container, [°C]	25
p_air_0: the pressure of air in container, [kPaA]	99.5
T_eg_0: the temperature of water-EG mixture, [°C]	25
T_battery_0: the temperature of battery, [°C]	25
T_device_0: the temperature of devices, [°C]	25
T_frame_0: the temperature of frame, [°C]	25
T_wall_0: the temperature of container wall, [°C]	25

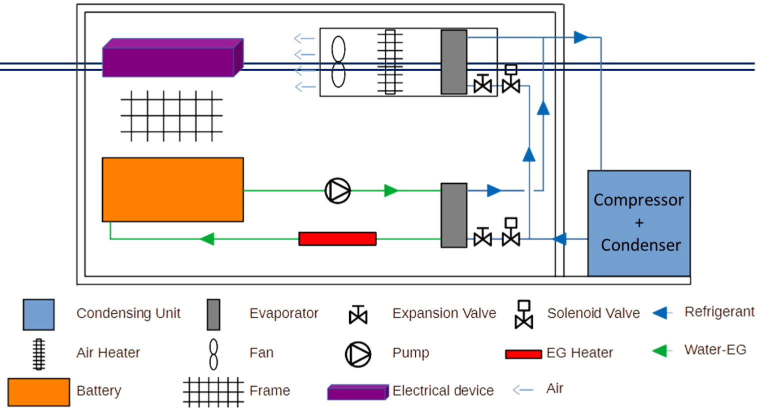
Condensing Unit and Two Evaporators



- The cooling capacity of the condensing unit $Q_{cooling}$ is a function of the outdoor air temperature $T_{air,outdoor}$. The following equation can be used to predict the cooling capacity of the condensing unit, where $T_{air,outdoor}$ is in °C and $Q_{cooling}$ in kW.

$$Q_{cooling} = -0.001T_{air,outdoor}^2 - 0.15T_{air,outdoor} + 20$$

- The size of the first evaporator to cool down water-EG coolant is sufficient to work alone with the condensing unit.
- The second evaporator to cool down air has a constant heat transfer capacity of 7 kW, which is generally smaller than the capacity of the condensing unit. Thus, the extra cooling capacity must be delivered to the water-EG coolant through the first evaporator to make the condensing unit work well.



SHR of the Second Evaporator

- When an evaporator cools humid air, part of the water vapor in humid air may be condensed to liquid water.
- Thus, the total heat transfer capacity includes the sensible heat part which reduces the dry-bulb temperature of air and the latent heat part which corresponds to the water vapor condensation.
- Sensible Heat Ratio (SHR) is the ratio of the sensible heat transfer capacity to the total heat transfer capacity of the heat exchanger. Assume that the SHR of the second evaporator under the conditions involved in this project can be estimated by the following equation, where $T_{air,dewpoint}$ is in °C .

$SHR = -0.019T_{air,dewpoint} + 1.12$ for $0 < SHR < 1$.

If the predicted $SHR \geq 1$, let $SHR = 1$.

If the predicted $SHR \leq 0$, let $SHR = 0$.

Tasks of Project #7

- Develop the Python code to simulate the dynamic behavior of the thermal manage system for BESS with the given heat capacities and thermal resistances under the operating conditions of interest and complete the project report.
- The transient simulation focuses on the thermal behavior, i.e., the variation in the temperatures of the components with time.
- Your report must show the schematic of the thermal manage system, as well as the given heat capacities, thermal resistances, and operating conditions of interest.
- The ideas to model the thermal manage system (including the assumptions and programming flowchart) and the equations used in the simulation must be presented in the report.

Tasks of Project #7

- The simulation results must be completely and clearly presented in your report, including:
  - the temperature variation with time regarding air, water-EG mixture, battery, devices, frame, and container wall, as well as the dewpoint temperature to show the dynamic behavior of humidity of air in the container (All the temperature curves can be grouped in one figure.)
  - the variation in the heat transfer rates between air and each components as well as between water-EG coolant and battery (All the heat transfer rate curves can be grouped in one figure.)
  - the net heat transfer rate into air, water-EG coolant, and each component whose heat capacity is given, to change their states (All the net heat transfer rate curves can be grouped in one figure.)
- Please run your code for the dynamic behavior of 20 hours. The results in the report should show the variation with time for 20 hours, as well as the details for the 1st hour in separate figures. (The separated figures for the 1st hour should be presented to show the details during the 1st hour.)
- Please compare the dynamic behaviors in the 1st and the 20th hour and discuss the reasons for the difference.

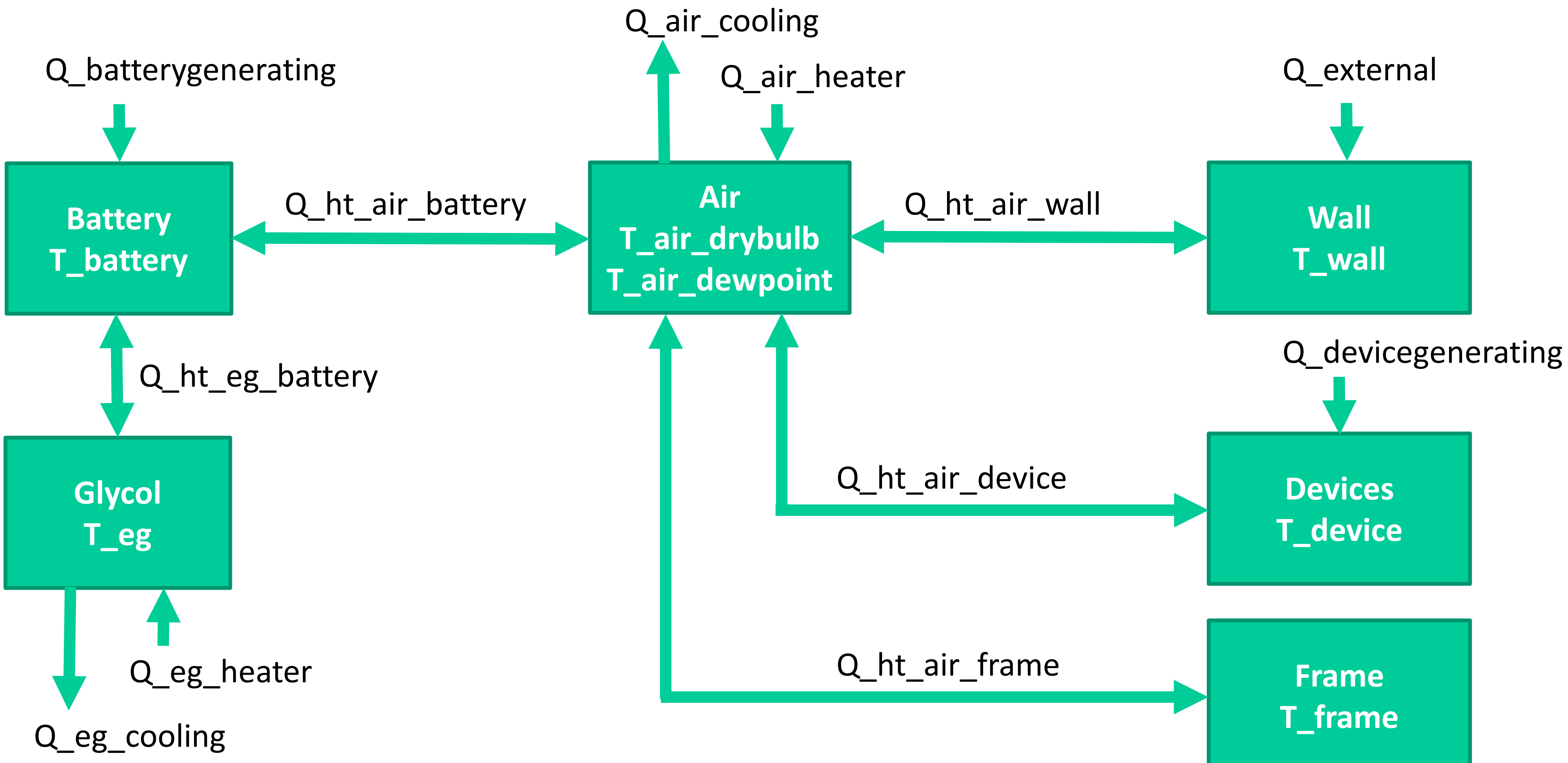
Tasks of Project #7

- Please run the simulation for the following two cases (i.e. Case 2 and Case 3) and compare the results with the above baseline condition (i.e. Case 1):
  - Case 2: Q_external = 4 kW to mimic a hot weather
  - Case 3: Q_batterygenerating = 9 kW to mimic an extreme operating conditions

Outline

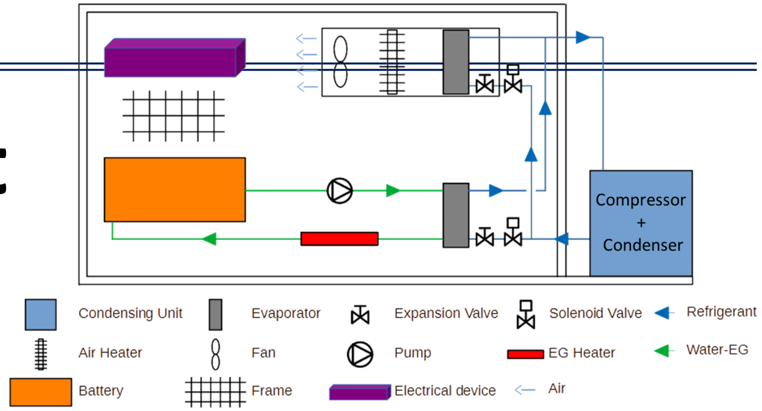
- Battery Energy Storage System (BESS) and its Thermal Management
- Project #7
- **Simulation of Thermal Management System for BESS**
  - **Thermal Model Concept**
  - Transient Thermal Analysis of Component
  - System-Level Transient Simulation

Thermal Model Concept



Outline

- Battery Energy Storage System (BESS) and its Thermal Management
- Project #7
- **Simulation of Thermal Management System for BESS**
  - Thermal Model Concept
  - **Transient Thermal Analysis of Component**
  - System-Level Transient Simulation



Transient Thermal Analysis of Component

Key assumption:

- Lumped capacitance method is used for the transient conduction analysis of all the components with nonzero thermal capacitance.

Notes:

- Academically, the criterion for the application of lumped capacitance method is Bi<1 (Biot number $Bi = HTC \cdot L/k$).
- For the scenario with Bi>1, there will be nonuniform spatial distribution of temperature varying with time within the component. You can refer to the course ME 412 Numerical Thermo-Fluid Mechs for more details of the numerical simulation.
- For a system-level transient thermal analysis, the lumped capacitance method is usually applied to simplify the simulation and can reasonably predict the system's dynamic behavior.

Transient Thermal Analysis of Component

In-Class Discussion (4 Students in a Group)

Topics:

- What is the key assumption of lumped capacitance method for transient conduction analysis?
- How to run transient thermal analysis of a component by the lumped capacitance method?

Sample of peer evaluation sheet:

Name________________ Date______________

Topic____

Name of group members	Rating (number 0 – 3)
________________________	___________________
________________________	___________________
________________________	___________________
________________________	___________________

Rubric:

3 **Excellent** Actively involved in the discussion, and clearly present his or her ideas

2 **Satisfactory** Listened to other members, and participated in the discussion occasionally

1 **Ordinary** Listened to other members, but didn’t present his or her ideas

0 **Absence**

Transient Thermal Analysis of Component

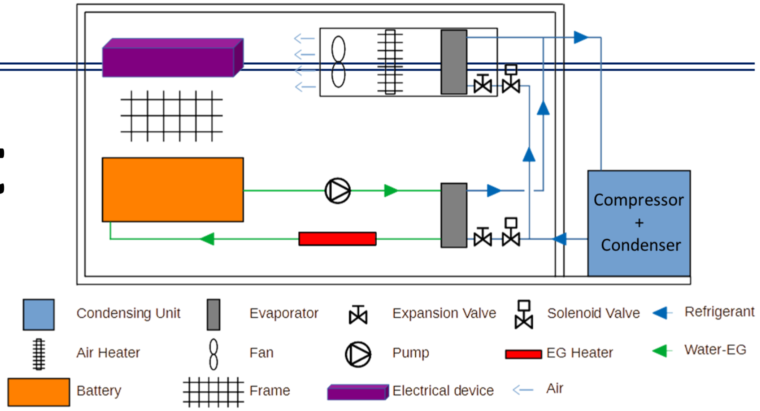
In-Class Discussion (4 Students in a Group)

Topics:

- What is the key assumption of lumped capacitance method for transient conduction analysis?
- How to run transient thermal analysis of a component by the lumped capacitance method?

- **Key assumption:**
  Compared to the thermal resistance on the surface, the internal conduction thermal resistance is small enough to make the assumption of uniform temperature distribution within the component acceptable.
  $$Bi = \frac{HTC \cdot L}{k} = \frac{L/K}{1/HTC} = \frac{R_{internal,cond}}{R_{extermal,conv}} < 1$$
- **Application of lumped capacitance method:**
  I would like to show an example.

Transient Thermal Analysis of Component



Example:

The battery is taken as an example to show the development of the equation for transient thermal analysis regarding a time interval (or time step) of DTime.

Energy conservation equation for transient process: $\dot{E}_{in} - \dot{E}_{out} = \dot{E}_{st}$

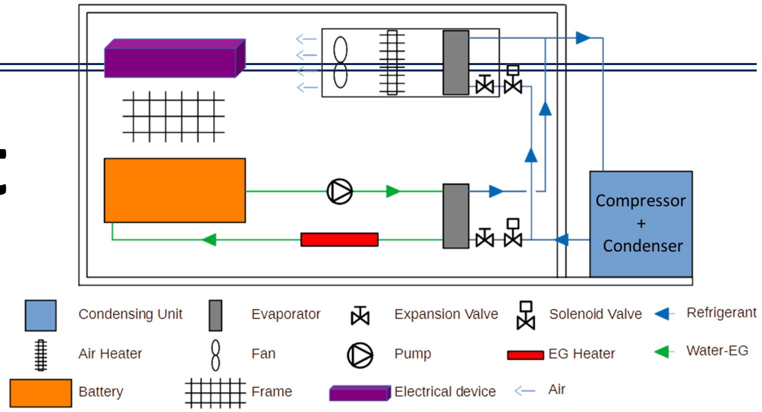
Apply the lumped capacitance method for transient conduction: $\dot{E}_{st} = \rho V c \dfrac{dT}{dt}$

Apply the above equation to the battery numerically:

Q_battery = Q_batterygenerating + Q_ht_gly_battery + Q_ht_air_battery

T_battery_2 = T_battery_1 + Q_battery*DTime/cpM_battery

Transient Thermal Analysis of Component



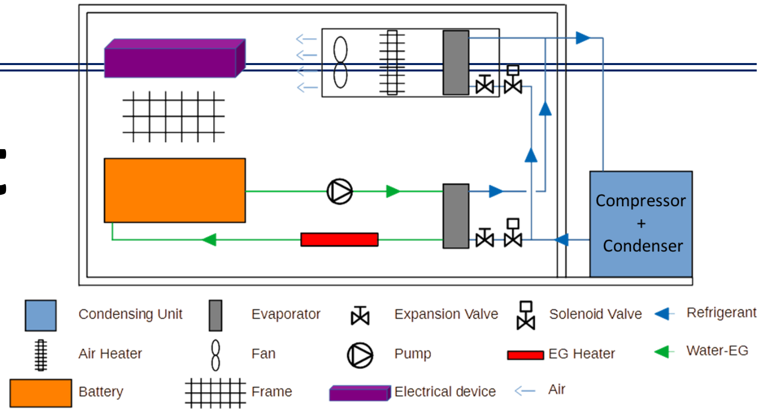
Example: (battery)

Q_battery = Q_batterygenerating + Q_ht_gly_battery + Q_ht_air_battery

T_battery_2 = T_battery_1 + Q_battery*DTime/cpM_battery

Q_battery: the net (or total) rate of heat going into battery to change its temperature
Q_batterygenerating: the rate of heat generated by battery
Q_ht_gly_battery: the rate of heat transfer from water-EG to battery
Q_ht_air_battery: the rate of heat transfer from air to battery
T_battery_1: the temperature of battery at the beginning of the time interval DTime
T_battery_2: the temperature of battery at the end of the time interval DTime
DTime: the time interval (or time step) for transient analysis
cpM_battery: the heat capacity of battery

Transient Thermal Analysis of Component



Example: (battery)

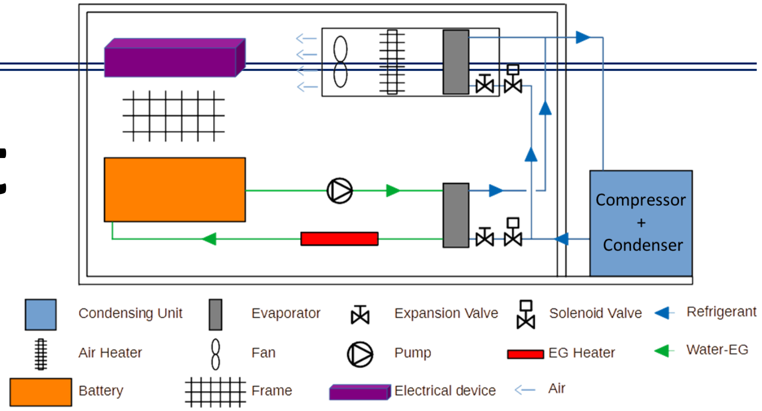
Q_ht_gly_battery: the rate of heat transfer from water-EG to battery
Q_ht_air_battery: the rate of heat transfer from air to battery

Q_ht_gly_battery = (T_gly_1 - T_battery_1)/R_gly_battery

Q_ht_air_battery = (T_air_drybulb_1 - T_battery_1)/R_air_battery

T_gly_1: the temperature of water-EG coolant at the beginning of the time interval DTime
T_battery_1: the temperature of battery at the beginning of the time interval DTime
R_gly_battery: the thermal resistance of heat transfer between water-EG and battery
T_air_drybulb_1: the temperature of air at the beginning of the time interval DTime
R_air_battery: the thermal resistance of heat transfer between air and battery

Transient Thermal Analysis of Component

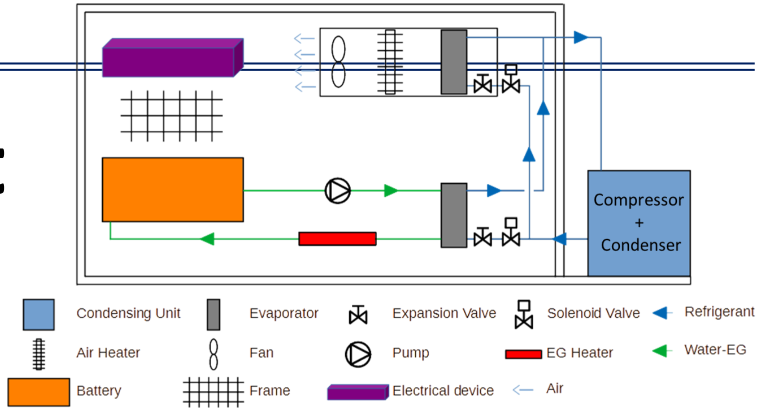


- Similar transient thermal analysis can be applied to air, water-EG coolant, container wall, frame structure, and electrically-powered device.
- Assume that the heat capacities of the pump, fan, two evaporators, two electrical heaters, valves, and pipes are negligible.
- The humid air also involves the variation in humidity with time. The mass of water condensate for the time interval DTime can be calculated by

M_watercondensate = Q_air_cooling*(1-SHR)/ h_lv_water * DTime

Q_air_cooling*(1-SHR): the cooling capacity used to condense water vapor
h_fg_water: latent heat of liquid-vapor phase change of water at T_air_dewpoint

Transient Thermal Analysis of Component



- The efficiency of the pump is not given. We can assume a pump efficiency of 0.8. For a pump with an efficiency of 0.8, we can assume that 80% of the power input to the pump will finally become the thermal load with respect to the water-EG coolant, and 20% of the power input to the pump will become the thermal load with respect to air.
- All the power input to fan will contribute to the thermal load with respect to air.
- There is no any power input to the frame structure. For a steady-state analysis, the frame structure must have the same temperature as its surrounding air without heat transfer between them. However, for a transient behavior analysis, the temperature of the frame structure is generally not same as its surrounding air at any moment, and there will be heat transfer between them, which will affect the thermal load of air.

Outline

- Battery Energy Storage System (BESS) and its Thermal Management
- Project #7
- **Simulation of Thermal Management System for BESS**
  - Thermal Model Concept
  - Transient Thermal Analysis of Component
  - **System-Level Transient Simulation**

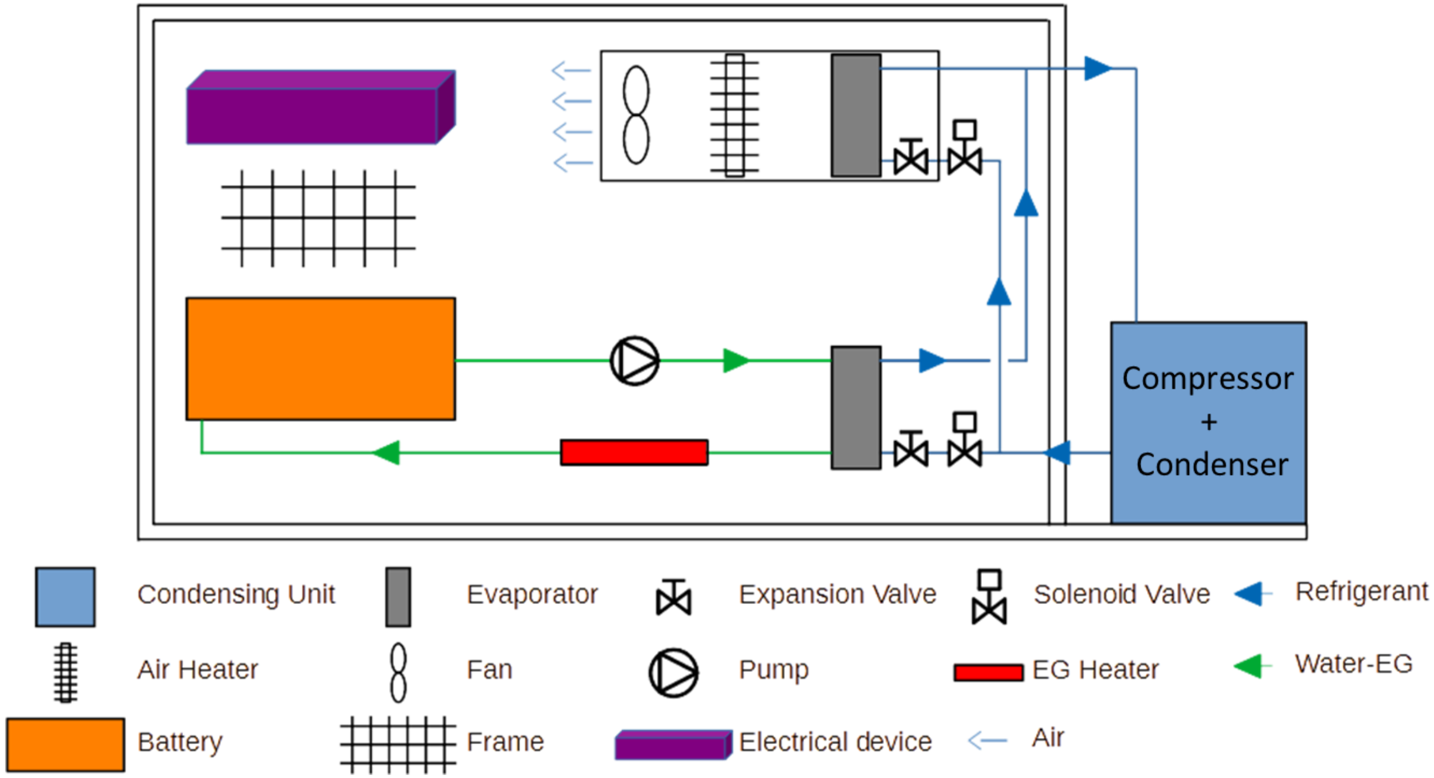
System-Level Transient Simulation

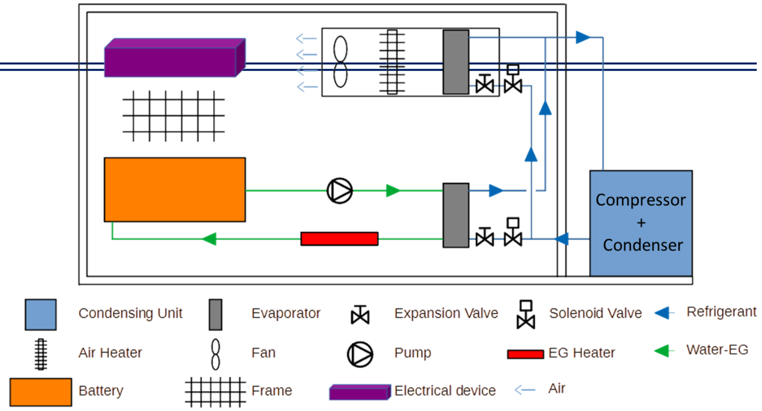
Similar to the modeling of steady-state thermal system we have discussed in Project # 6, figuring out the control logic to make the system functional is the key to build a system-level transient simulation.

In-Class Discussion (4 Students in a Group)

Topics:

- The control logic of the thermal management system for BESS in Project #7.

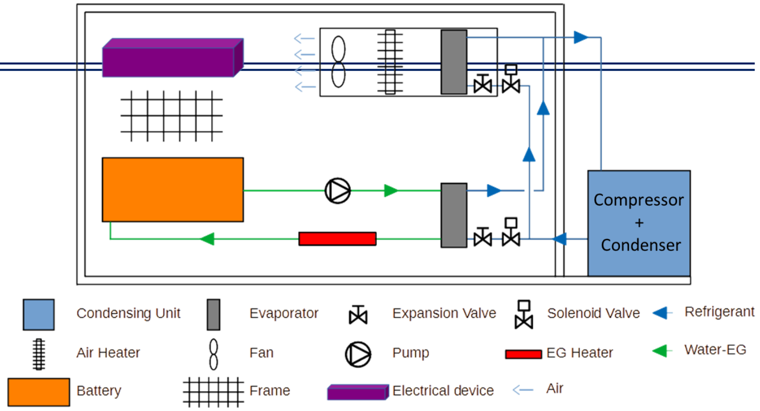




Control Logic of Thermal Management System

- When the temperature of battery reaches its upper limit, the first evaporator will start to work until the battery temperature reaches 0.5 °C lower than its upper limit.
- When either air dry-bulb temperature or dew point temperature reaches its upper limit, the second evaporator will start to work until both reach their lower limits.
- Constraints:
  - The condensing unit can work with the first evaporator only or with both evaporators.
  - The second evaporator has a constant capacity of 7 kW when it works and cannot match the cooling capacity of the condensing unit. The extra cooling capacity is delivered to the first evaporator to cool the battery.

Control Logic of Thermal Management System



- Although there is a lower temperature limit for battery, this limit is not hard. For the scenario that the air needs cooling to reach its lower limits of dry-bulb temperature and dew point temperature, the extra cooling of the condensing unit must be delivered to cool the battery and the temperature of battery is allowed to go below its lower limit.
- Although there are lower limits for both air dry-bulb temperature and dew point temperature, these two lower limits are not hard. For the scenario that the air needs cooling to reach either of these two, the other lower limit is allowed to be broken through.

Operating Modes

In-Class Discussion (4 Students in a Group)

Topics:

- How many operating modes will be involved in the thermal management system for BESS? What are these operating modes?

Sample of peer evaluation sheet:

Name________________ Date______________

Topic____

Name of group members	Rating (number 0 – 3)
________________________	___________________
________________________	___________________
________________________	___________________
________________________	___________________

Rubric:

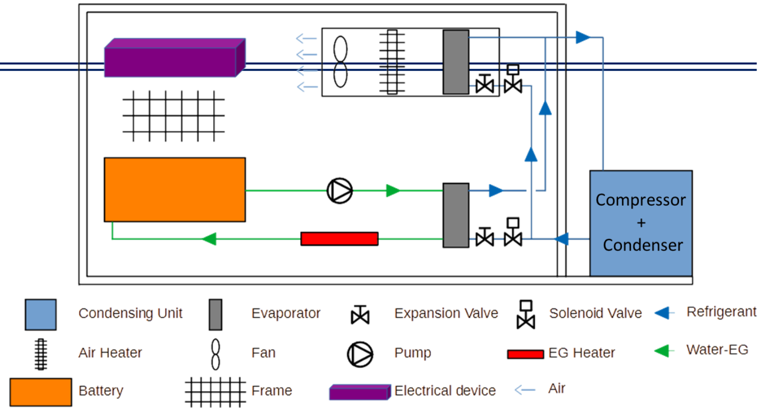
3 **Excellent** Actively involved in the discussion, and clearly present his or her ideas

2 **Satisfactory** Listened to other members, and participated in the discussion occasionally

1 **Ordinary** Listened to other members, but didn't present his or her ideas

0 **Absence**

Operating Modes



- **Mode 1:** No cooling is needed. (Condensing unit is off.)

- **Mode 2:** Only the battery needs cooling. (Condensing unit is on, and all the cooling is delivered to the battery via glycol.)

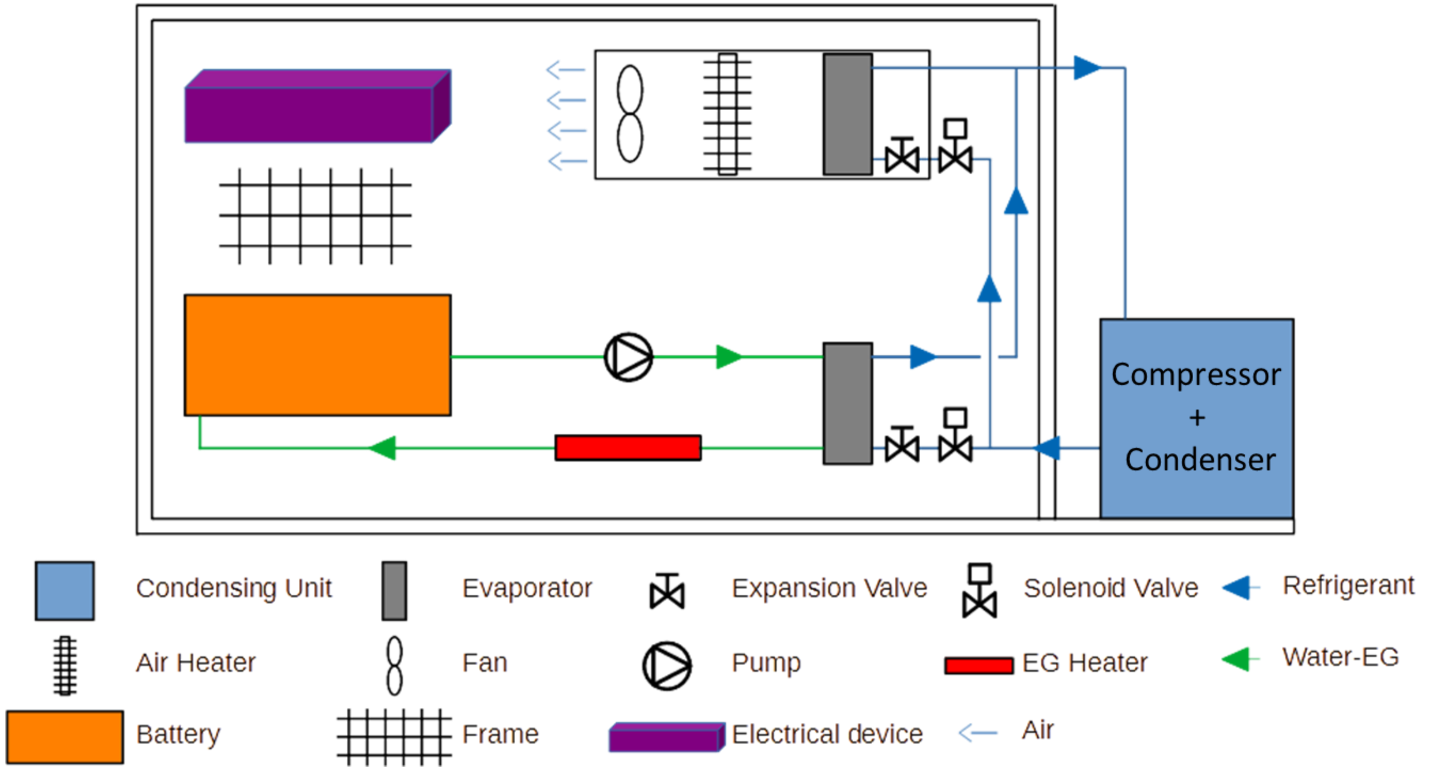
- **Mode 3:** Air needs cooling to either reduce T_air_drybulb or decrease T_air_dewpoint or both, and extra cooling is delivered to the battery. (Condensing unit is on. Heater in glycol loop will be turned on to slow down the temperature decrease when the battery temperature reaches it lower limit.)

Programming Flowchart

In-Class Discussion (4 Students in a Group)

Topics:

- Please construct the programming flowchart for the transient simulation of the thermal management system for BESS.



Summary

- Battery Energy Storage System (BESS) and its Thermal Management
- Project #7
- Simulation of Thermal Management System for BESS
  - Thermal Model Concept
  - Transient Thermal Analysis of Component
  - System-Level Transient Simulation