ME 502 Thermal Systems

Project #5 Evaporator at Wet Condition

Ke Tang

Department of Mechanical Science and Engineering

University of Illinois at Urbana-Champaign

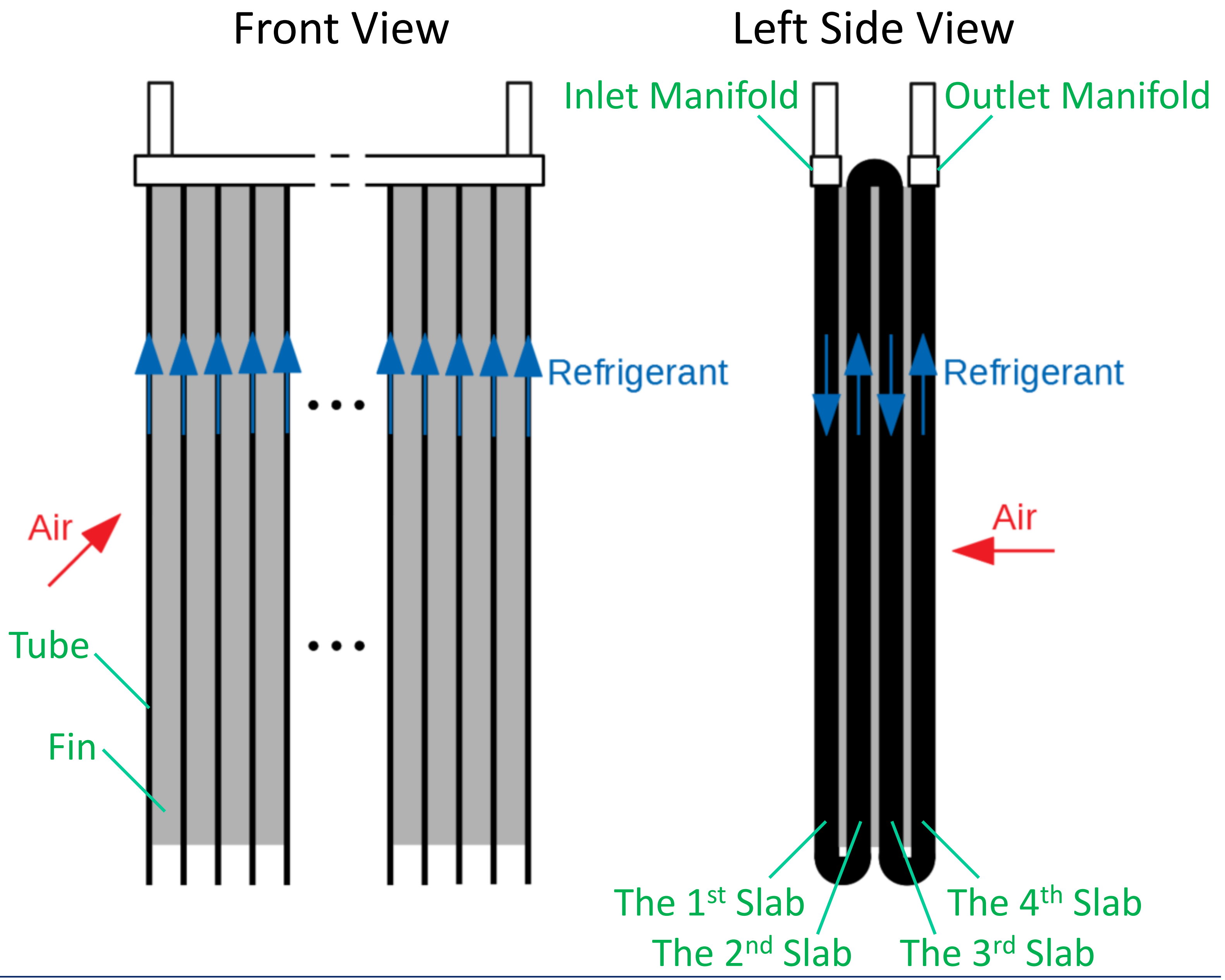
E-mail: ketang@illinois.edu

Outline

- **Project #5**
- Simulation of Evaporator at Wet Condition

Project #5

- Project #5 focuses on the simulation of a flat-tube-and-fin evaporator for an air conditioning unit at wet condition, i.e., the evaporator will cool and dehumidify the humid air.



Dimensions of the Evaporator

- Tables 1 and 2 list the major dimensions of the evaporator. The tubes and fins are made from aluminum alloy whose thermal conductivity can be approximated as 155 W/(m-K).

Table 1 Dimensions of the tubes of the evaporator

Tube Geometry	Size
N_slab: number of slabs (rows), [-]	4
N_pass: number of passes in one slab, [-]	1
L_tube_pass: tube length in one pass, [mm]	300
N_tube_pass: number of tubes in one pass, [-]	25
t_wall*: wall thickness, [mm]	0.35
t_tube: tube thickness, tube minor, [mm]	1.7
D_tube: tube depth, tube major, [mm]	10
n_port: number of ports in one tube, [-]	7
Ra_tube: roughness of tube inner surface, [m]	10^{-6}

* t_wall: assume all the outer walls and inner walls have the same thickness.

Table 2 Dimensions of the fins of the evaporator

Fin Geometry	Size
theta_louver: louver angle, [deg]	15
P_louver: louver pitch, [mm]	1.3
L_louver: louver length, [mm]	7.2
N_louverbank: number of louver sets per fin [-]	2
h_fin: fin height, [mm]	8
t_fin: fin thickness, [mm]	0.1
P_fin: fin pitch, [mm]	1.8 (14 FPI*)
D_fin: fin depth, [mm]	10

* FPI: fin per inch.

Notes: The details about the definition of the geometric parameters can be found in the lecture notes for project #1.

Operating Conditions of the Evaporator

- The operating conditions of interest are listed in Table 3.
- The refrigerant is R1234yf.
- The humid air stream and the refrigerant stream are in a cross-flow arrangement.

Table 3 Operating Conditions

Parameter	Value
h_eri: refrigerant inlet vapor quality, [-]	$h_{eri} = h_{cro}$
m_dot_er: refrigerant mass flow rate, [g/s]	35
SH_ero: refrigerant superheat at the outlet, [°C]	8
T_eai: air inlet temperature, [°C]	35
p_eai: air inlet pressure, [kPaA]	99.5
phi_eai: air inlet relative humidity, [kPaA]	0.4 (i.e., 40%)
m_dot_eai: air inlet mass flow rate, [kg/min]	9

- The subcooled refrigerant R1234yf exits the condenser of the air-conditioning unit at the pressure of 1250 kPaA and the temperature of 40 °C.
- It is reasonable to assume $h_{eri} = h_{cro}$, i.e., the adiabatic throttling process via the expansion valve with negligible changes in the kinetic and gravitational potential energy with respect to the refrigerant.

Tasks of Project #5

- Develop the Python code to simulate the performance of the evaporator with the given geometry and operating conditions by using the finite volume concept and complete the project report.
- Both the thermal and hydraulic performance of the evaporator must be modeled in the simulation.
- Your report must show the schematic of the evaporator, as well as the evaporator geometries and operating conditions of interest.
- The ideas to model the evaporator (including assumptions) and the equations used in the simulation must be presented in the report.
- The simulation results must be completely and clearly presented in your report, including the overall performance, e.g., heat transfer rate, refrigerant-side pressure drop, and air-side pressure drop, and the profiles of the parameters of interest along the refrigerant circuit, e.g., T_er, T_eai, T_eao, T_dp_eao, p_er, x_er (vapor quality), HTC_er, and Q_seg (as well as Q_sen_seg (sensible) and Q_lat_seg (latent) from the viewpoint of airside).

Tasks of Project #5

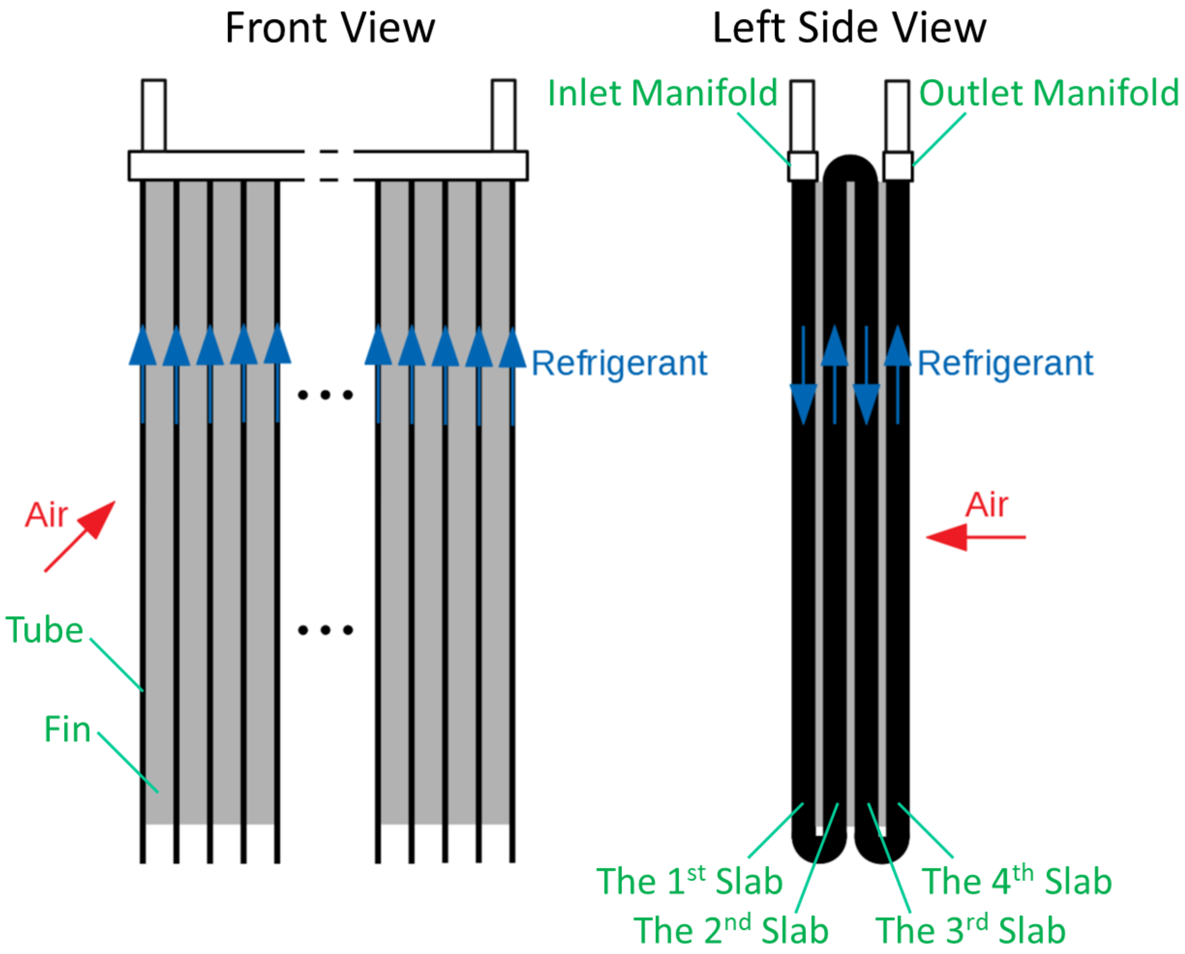
- Please also run the simulation with the developed code to investigate the effect of air inlet relative humidity in the range from 0.2 to 0.8. Please fix the other parameters as shown in Table 3, when investigating the effect of air inlet relative humidity. Please present the results and discussions in the report.

Outline

- Project #5
- **Simulation of Evaporator at Wet Condition**

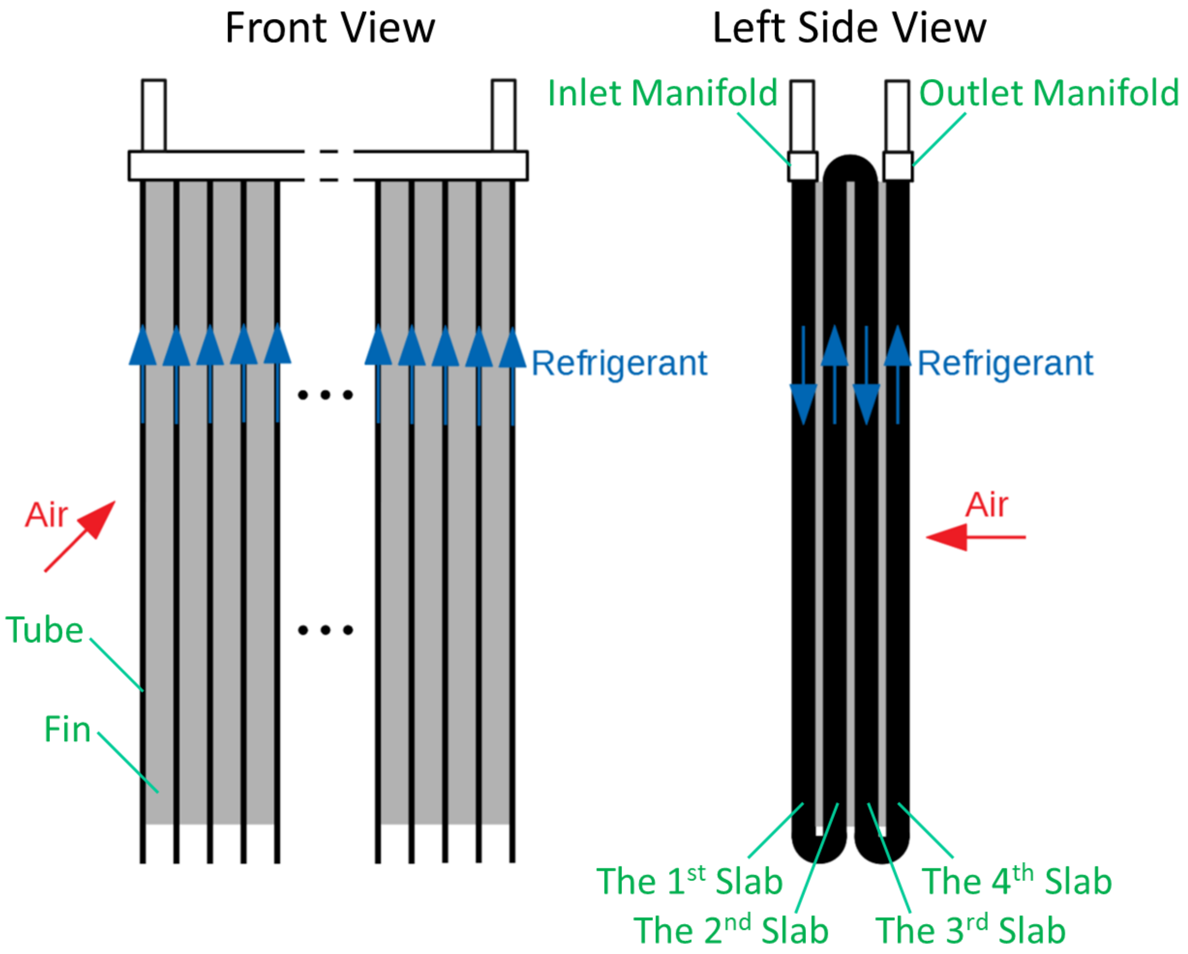
Overview of the Evaporator

- Fluids: refrigerant R1234yf and humid air
- State of fluids: single-phase + two-phase (evaporation) fluid to single-phase fluid
- Configuration:
  - Vertical flat tubes + corrugated louver fins
  - Four slabs and one pass



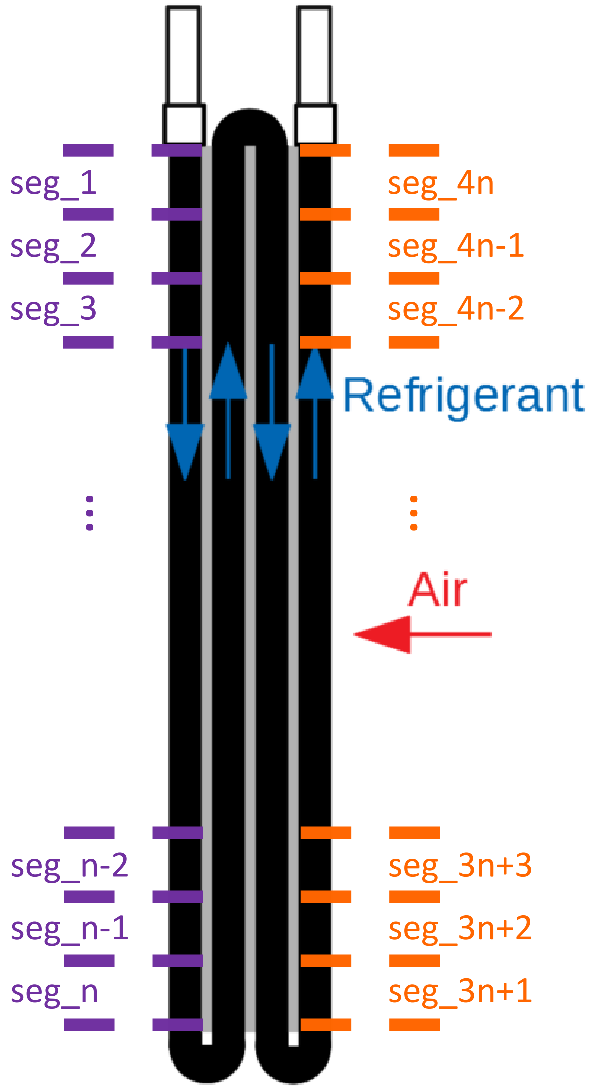
Overview of the Evaporator

- Flow arrangement: cross flow
- Focus the simulation of the core of the HX with the assumptions:
  - The refrigerant R1234yf flows through all the parallel tubes (including all the tube ports) evenly (i.e., uniform refrigerant flow distribution).
  - The air flows through the HX evenly (i.e., uniform air flow distribution).



Finite Volume Method for Heat Exchanger Simulation

- The evaporator in Project #5 has the same configuration and geometry as the evaporator in Project #3.
- The evaporator in Project #5 can be divided into segments and also be simulated in the similar way as we did in Project #3.
  - The heat exchanger can be divided into segments as shown in the figure. That is, there are n segments for each slab and all of them are in series.
  - For each segment, the model is still 1-D.



Thermal and Hydraulic Analyses on the Segment with Length dx

The thermal and hydraulic analyses on the segment of the evaporator in Project #5 are quite similar to those for the cooling coil working with humid air in Project #4. The difference is

- The evaporator involves the flow evaporation (boiling) of the refrigerant and the related correlations for heat transfer and pressure drop can be found in literatures, e.g.,
  - Sung-Min Kim, Issam Mudawar, Review of databases and predictive methods for heat transfer in condensing and boiling mini/micro-channel flows, International Journal of Heat and Mass Transfer, Volume 77, 2014, Pages 627-652.
  - Sung-Min Kim, Issam Mudawar, Review of databases and predictive methods for pressure drop in adiabatic, condensing and boiling mini/micro-channel flows, International Journal of Heat and Mass Transfer, Volume 77, 2014, Pages 74-97.

A Simplified Model for Heat and Mass Transfer of Humid Air Involving Dehumidification

In-Class Discussion (4 Students in a Group)

Topics:

- The summary of the equations for the heat transfer analysis of the cooling coil in Project #4 is presented here. Which equations need to be modified for the segment involving flow boiling refrigerant in the simulation of the evaporator? And How?

Summary of the equations:

Q_a:

$Q_{a,sen}$:

$$T_{a,o} = T_{s,a} + (T_{a,i} - T_{s,a})exp\left(-\frac{HTC_a A_{s,a}}{\dot{m}_a c_{p,a}}\right)$$

$$Q_{a,sen} = \dot{m}_a c_{p,a}(T_{a,i} - T_{a,o})$$

$Q_{a,lat}$:

$$\rho_{A,o} = \rho_{A,s} + (\rho_{A,i} - \rho_{A,s})exp\left(-\frac{MTC_a A_{s,a}}{\dot{V}_a}\right)$$

$$MTC_a = \frac{HTC_a}{\rho_a c_{p,a} Le_a^{1-n}}$$

$$\omega_{a,o} = \frac{\rho_{A,o}}{\rho_{da,o}} = \frac{\rho_{A,o}}{\rho_{da,i}} = \rho_{A,o} v_{da,i}$$

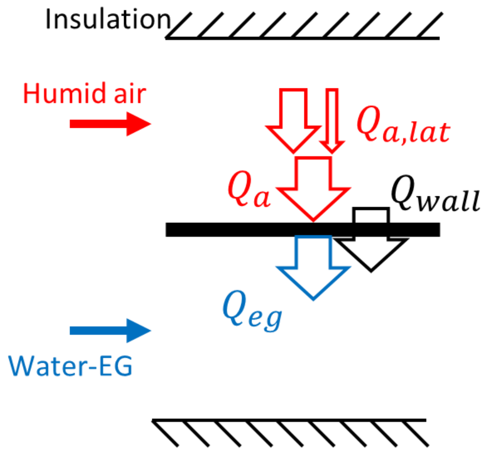
$$\dot{m}_{condensate} = \dot{m}_{da}(\omega_{a,i} - \omega_{a,o})$$

$$Q_{a,lat} = \dot{m}_{condensate} h_{fg}$$

Q_{eg}:

$$T_{eg,o} = T_{s,a} - (T_{s,a} - T_{eg,i})exp\left\{-\frac{1}{\dot{m}_{eg} c_{p,eg}[R_{wall} + 1/(HTC_{eg} A_{s,eg})]}\right\}$$

$$Q_{eg} = \dot{m}_{eg} c_{p,eg}(T_{eg,o} - T_{eg,i})$$



For a finned air-side surface, an overall surface efficiency $\eta_{o,m}$ for mass transfer can be applied to the surface area $A_{s,a}$, like the heat transfer on the finned surface.

A Simplified Model for Heat and Mass Transfer of Humid Air Involving Dehumidification

In-Class Discussion (4 Students in a Group)

Topics:

- The summary of the equations for the heat transfer analysis of the cooling coil in Project #4 is presented here. Which equations need to be modified for the segment involving flow boiling refrigerant in the simulation of the evaporator? And How?

The thermal equations for the single-phase water-EG coolant, as shown below, need to be modified, since the c_p becomes infinite for the liquid-vapor two-phase fluid:

Q_{eg}

$$\boxed{T_{eg,o} = T_{s,a} - \left(T_{s,a} - T_{eg,i}\right) exp\left\{-\frac{1}{\dot{m}_{eg} c_{p,eg}\left[R_{wall} + 1/\left(HTC_{eg} A_{s,eg}\right)\right]}\right\}}$$

$$\boxed{Q_{eg} = \dot{m}_{eg} c_{p,eg}\left(T_{eg,o} - T_{eg,i}\right)}$$

For the two-phase flow boiling refrigerant, the thermal equations can be:

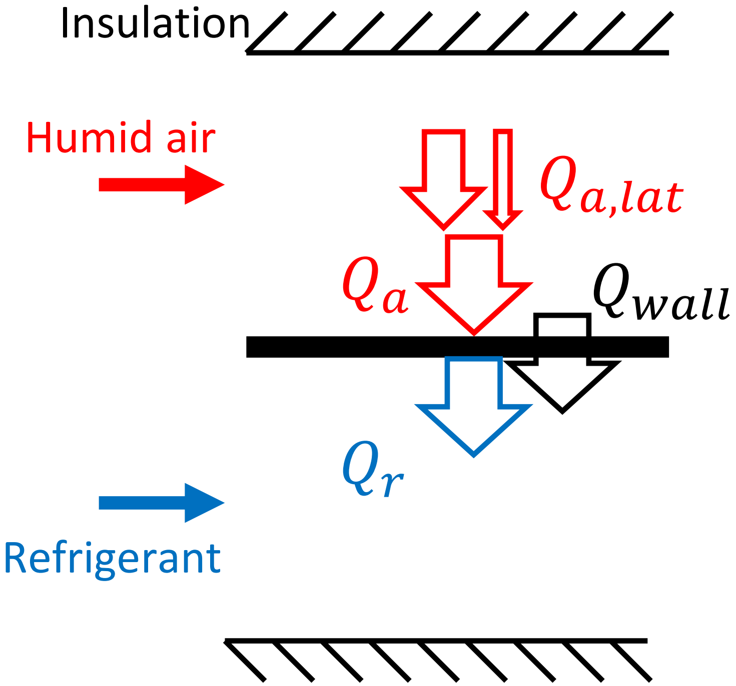
Q_{er}

$$\boxed{Q_{er} = \frac{T_{s,a} - T_{eri}}{R_{wall} + 1/\left(HTC_r A_{s,r}\right)}} \quad \text{or} \quad \boxed{Q_{er} = \frac{T_{s,a} - T_{ero}}{R_{wall} + 1/\left(HTC_r A_{s,r}\right)}}$$

$$\boxed{h_{ero} = h_{eri} + \frac{Q_{er}}{\dot{m}_{er}}} \qquad \boxed{h_{eri} = h_{ero} - \frac{Q_{er}}{\dot{m}_{er}}}$$

Application of the Simplified Model for Heat and Mass Transfer of Humid Air Involving Dehumidification

Schematic:



In-Class Discussion (4 Students in a Group)

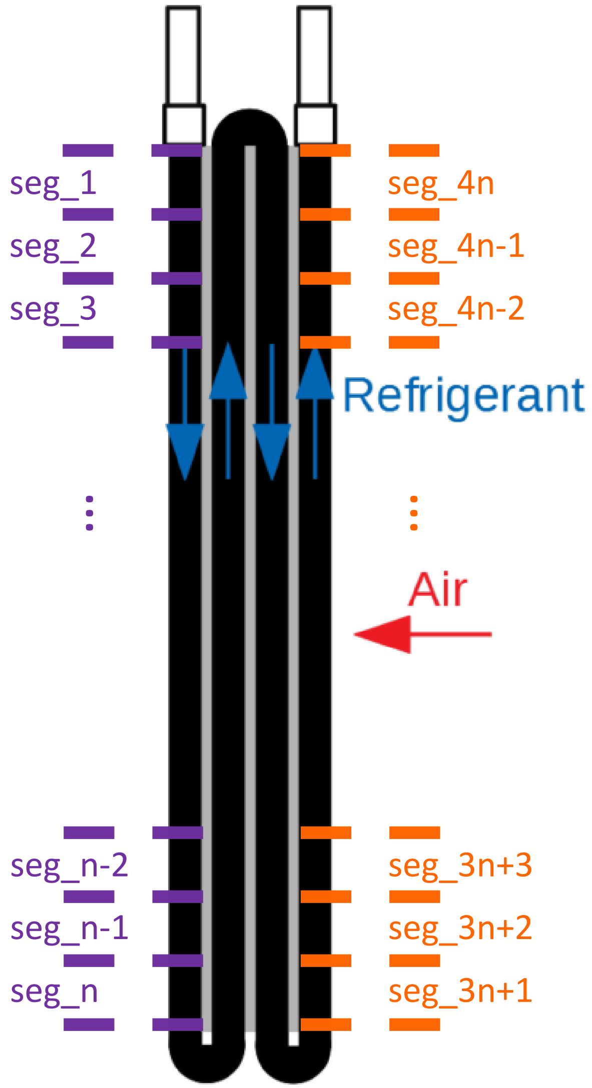
Topics:

- Please construct the programming flowchart for the application of the simplified model to an evaporator segment. (The refrigerant can be single-phase or two-phase state.)

The air-side surface temperatures $T_{s,a}$ ($\rho_{A,s}$ is also determined by $T_{s,a}$) is the key parameters to match the energy transfer rates, i.e., the energy balance: $Q_a = Q_{wall} = Q_r$.

Finite Volume Method for Heat Exchanger Simulation

- Grouping the analysis outputs of all the segments gives the overall performance, e.g., Q_e, Δp_{er}, Δp_{ea}, and the profiles of the parameters, e.g., T_{er}, p_{er}, x_{er}, T_{eai}, T_{eao}, etc., are also available.



Summary

- Project #5
- Simulation of Evaporator at Wet Condition