Chapter 9: Mass Transfer

Section 9.1: Mass Transfer Concepts

9.1-1 (9-1 in text) A mixture is formed mixing M_m = 0.25 kg of methane (with molar mass MW_m = 16 kg/kgmol), M_e = 0.15 kg of ethane (MW_e = 30 kg/kgmol) and M_n = 0.1 kg of nitrogen (MW_n = 28 kg/kgmol). The mixture is placed in a container that is maintained at T = 25°C and p = 5 bar. At these conditions, the mixture behaves in accordance with the ideal gas law. Determine:

a.) the volume of the mixture
b.) the equivalent molecular weight of the mixture
c.) the density of the mixture on a mass basis
d.) the density of the mixture on a molar basis
e.) the mass fractions of each species
f.) the mole fractions of each species
g.) the mass concentration of each species
h.) the molar concentration of each species

9.1-2 (9-2 in text) The composition of mixtures of air and water vapor are often reported in terms of the humidity ratio. The humidity ratio, ω, is defined as the mass of water vapor per mass of dry air. The humidity ratio is related to, but not exactly the same as the the mass fraction. In a particular case, the humidity ratio is $\omega = 0.0078$ at temperature T = 30°C and pressure p = 101.3 kPa. Determine:

a.) the mass fraction of the water vapor
b.) the mole fraction of the water vapor
c.) the mass concentration of the water vapor
d.) the molar concentration of the water vapor
e.) the maximum possible value for the mole fraction of the water vapor at equilibrium.

Section 9.2: Mass Diffusion and Fick's Law

9.2-1 (9-3 in text) The air-conditioning load for a building can be broken into latent and sensible contributions. The latent represents the energy that must be expended to remove the water vapor from the building. Water vapor enters by infiltration as air from outdoors leaks inside and by diffusion through the walls and ceiling. The building in question is rectangular with outer dimensions of 40 ft by 60 ft with 8 ft ceilings. The infiltration rate is estimated at 0.65 air changes per hour. The diffusion coefficient for water through 3/8 inch gypsum board (without a vapor barrier) is approximately 4.5×10^{-5} ft^2/s at atmospheric pressure.

a.) Estimate and compare the rates of moisture transfer by infiltration and diffusion on a day in which the outdoor conditions are 95°F and 45% relative humidity and indoor conditions are 75°F, 40% relative humidity. Is the contribution by diffusion significant? If not, then why are people concerned with water vapor diffusion in a building?

9.2-2 (9-4 in text) Natural gas (methane) is transported at 25ºC and 100 bar over long distances through 1.2 m diameter pipelines at a velocity of 10 m/s. The pipeline is made of steel with a wall thickness of 2.0 cm. It has been suggested that hydrogen gas could be transported in these same pipelines. However, hydrogen is a small molecule that diffuses through most materials. The diffusion coefficient for hydrogen in steel is about $7.9\text{x}10^{-9}$ m^2/s at 25ºC.

a.) Calculate the power transported by methane (assuming it will be combusted) through the pipeline. The lower heating value of methane is $5.002\text{x}10^{7}$ J/kg.

b.) Estimate the velocity required to move the provide the same power if hydrogen rather than methane is transported through the pipeline at the same temperature and pressure. The lower heating value of hydrogen is $1.200\text{x}10^{8}$ J/kg.

c.) Compare the pumping power required to transport the natural gas and hydrogen a distance of 100 km.

d.) Estimate the rate of hydrogen loss from a 100 km pipeline. Do you believe this loss is significant?

9.2-3 (9-5 in text) A balloon made of a synthetic rubber is inflated with helium to a pressure of p_{ini} = 130 kPa at which point its diameter is D_{ini} = 0.12 m. The mass of the balloon material is M_{bal} = 0.53 g and its thickness is δ = 0.085 mm. The balloon is released in a room that is maintained at T = 25ºC filled with air (y_{N2} = 79% nitrogen and y_{O2} = 21% oxygen) at p_{atm} = 100 kPa. Over a period of time, helium diffuses out of the balloon and oxygen and nitrogen diffuse in. The pressure in the balloon above atmospheric pressure is linearly proportional to the balloon volume. The diffusion coefficients for helium, oxygen and nitrogen through this synthetic rubber are $D_{He,rubber}$ = $60\text{x}10^{-8}$, $D_{O2,rubber}$ = $16\text{x}10^{-8}$, and $D_{N2,rubber}$ = $15\text{x}10^{-8}$ cm^2/s, respectively.

a.) Prepare a numerical model of the balloon deflation process. Plot the volume and pressure within the balloon as a function of time. Plot the mole fraction of helium, oxygen, and nitrogen in the balloon as a function of time.

b.) At what time does the balloon lose its buoyancy?

Section 9.3: Transient Diffusion through a Stationary Medium

9.3-1 (9-6 in text) A janitor is about to clean a large window at one end of a corridor with an ammonia-water solution. The corridor is 2.5 m high, 2 m wide and 3 m in length. The conditions in the corridor are 25C, 101 kPa. The concentration of the ammonia that evaporates from the window is estimated to be 100 ppm. Many humans can detect ammonia by smell at levels of 1 ppm. Estimate the time required for a person standing at the other end of the corridor to detect the ammonia after the janitor starts to wash the window.

Section 9.4: Mass Convection

9.4-1 A cylindrical tank having an internal diameter of D_t = 0.42 m and an internal height of H_t = 1.4 m was originally used to store hot water, but is no longer used. A custodian cut the two pipes that were used to charge and discharge the tank leaving L = 0.12 m of pipe sticking up from the top of the tank. The internal diameter of the pipes is D_p = 2.2 cm. The water remaining in the tank is at room temperature, T = 25°C. The building in which the tank is located is at atmospheric pressure and it is maintained at an average relative humidity of 40%.

a.) What is the rate of moisture transport to the building?

b.) How much time is required for the level in the tank to drop by 1.0 m?

9-4-2 (9-7 in text) In order to detect chemical threats that are being smuggled into the country within a shipping container, the government is working on a system that samples the air inside the container on the dock as it is being unloaded. The chance of detecting the chemical threat is strongly dependent upon its concentration distribution at the time that the container is sampled. Therefore, you have been asked to prepare a simple model of the migration of the threat species from its release point within a passage formed by the space between two adjacent boxes. The problem is not a simple diffusion problem because the threat chemical is adsorbed onto the walls of the passage. The situation is simplified as 1-D diffusion through a duct. One end of the duct is exposed to a constant concentration of the threat chemical that is equal to its saturation concentration, c_{sat} = 0.026 kg/m^3. The duct is filled with clean air and the walls of the duct are clean (i.e., at time t = 0 there is no threat chemicals either in the air in the duct or on the walls of the duct). The hydraulic diameter of the duct is D_h = 10 cm. The length of the duct is infinite. The diffusion coefficient for the threat chemical in air is D = 2.2x10^{-5} m^2/s. The mass of threat chemical per unit area adsorbed on the wall of the container (M''_w) is related to the concentration of the chemical in the air (c) according to:

$$\frac{M''_w}{M''_{w,m}} = \frac{A\dfrac{c}{c_{sat}}}{\left(1-\dfrac{c}{c_{sat}}\right)\left[1+\left(A-1\right)\dfrac{c}{c_{sat}}\right]}$$

where $M''_{w,m}$ = 4x10^{-4} kg/m^2 is the mass per unit area associated with a single monolayer and A = 20 is a dimensionless constant. The total time available for diffusion between loading the container and unloading is $t_{transit}$ = 14 days. Because the length of the duct is so much larger than the hydraulic diameter of the duct, it is reasonable to assume that the concentration distribution is 1-D. Further, because the concentration of the threat chemical is so small, it is reasonable to neglect any bulk velocity induced by the diffusion process; that is, only mass transfer by diffusion is considered.

a.) Prepare a 1-D transient model of the diffusion process using the `ode45` solver in MATLAB.

b.) Plot the concentration distribution within the passage at various times.

c.) Plot the concentration distribution within the passage at $t = t_{transit}$ and overlay on this plot the zero-adsorption solution to show how adsorption has retarded the migration of the threat chemicals within the container.

9.4-3 (9-8 in text) Naphthalene is an aromatic hydrocarbon with a molecular weight of MW = 128.2 kg/kgmol that sublimes at a reasonable rate a room temperature. Naphthalene was commonly used for moth balls, but is now considered to be a carcinogen. At T = 25°C, solid naphthalene has a density of ρ = 1.16 g/cm^3 and a vapor pressure of p_v = 0.082 mm Hg. An engineer has recognized that heat and mass transfer are analogous processes and he plans to estimate the heat transfer coefficient for an unusual geometry by measuring how much mass of napthalene is sublimed. A review of the literature indicates that the Schmidt number for naphthalene is Sc = 2.5. To test accuracy of the heat /mass transfer analogy, the engineer first measures the mass of naphthalene that sublimes from a sphere of D = 2.5 cm diameter when exposed to a stream of pure air at temperature T = 25°C, pressure p = 101.3 kPa, and velocity u_∞ = 10 m/s. The test is run for t_{test} = 2 hr and during this time the mass of the naphthalene sphere is reduced by Δm = 250 mg.

a.) Determine the error relative to accepted correlations for this geometry.

9.4-4 (9-9 in text) Data for naphthalene at 25C are provided in problem 9.4-3. Determine the time required for 90% of the mass in a 1.0 cm sphere of naphthalene to sublime into an air stream at 25ºC and 100 kPa that is flowing at 5 m/s.

9.4-5 A square slab of dry ice (solid carbon dioxide) that is th = 1 inch thick and W = 9 inches on each side is place on an insulated surface in a large room filled with air at T_∞ = 75ºF and p = 1 atm. Dry ice has a density of ρ_s = 93.6 $\text{lb}_\text{m}/\text{ft}^3$ and it sublimes with a vapor pressure of p_v = 1 atm. During this phase change, the dry ice remains at T_s = -109.4ºF. Estimate the time required for the dry ice to disappear.

Section 9.5: Simultaneous Heat and Mass Transfer

9.5-1 A spherical raindrop is falling through air at T_∞ = 20°C, atmospheric pressure, and a relative humidity of RH = 0.5. The diameter of the sphere is D_{ini} = 1 mm. You may assume that the sphere is always at its terminal velocity (i.e., the velocity at which the drag and gravitational forces are balanced) and at the temperature where evaporation and convection are balanced. Assume that the droplet remains spherical.

a.) Plot the diameter of the droplet as a function of time.

9.5-2 (9-10 in text) You have asked to join the team of engineers responsible for the design of an air-washer. Your part of this project is to prepare an analysis that will determine the diameter, velocity, and temperature of droplets as they fall in an upward flowing air stream. You are considering a single water droplet with an initial diameter of 1.5 mm and initial temperature of 45°C that is released into a 25°C, 35% relative humidity, 100 kPa air stream that is flowing upward at 30 m/s.

a.) Plot the diameter, velocity and temperature of the droplet as a function of time. Assume that the droplet remains spherical and that it can be considered to have a uniform temperature at any time.

9.5-3 (9-11 in text) One type of household humidifier operates by expelling water droplets into the air. The droplets have an average diameter of 10 μm. After leaving the dehumidifier, the droplets "float" around the room and evaporate. In a particular case, the room is maintained at 25°C, 100 kPa and 25% relative humidity. You may assume that the droplet is at the temperature where evaporation and convection are balanced.

a.) Plot the mass of the droplet as a function of time and determine the time required for the droplets to completely evaporate.

b.) The humidifier requires a work input to form the droplets. The work input is related to the change in area of the water as it is transformed from one large "drop" to many smaller droplets. Calculate the energy required to distribute 1 kg of droplets with this vaporizer and compare it to the energy needed to vaporize one kg of water at 25°C. Comment on whether you believe that this humidifier saves energy compared to traditional vaporization process based on boiling water.

Section 9.6: Cooling Coil Analysis

9.6-1 Determine the performance of the cooling coil described in EXAMPLE 9.6-1 if R134a, rather than chilled water is used as the coolant. The R134a enters at $T_{r,in}$ = 5°C with a quality of $x_{r,in}$ = 0.35 at a flow rate of $\dot{m}_r$ = 0.02 kg/s. Also, determine the outlet quality of the R134a.

9.6-2 (9-12 in text) Air enters a cooling coil with volumetric flow rate 20,000 cfm, temperature 90°F and 50% relative humidity and is cooled and dehumidified by heat exchange with chilled water that enters the cooling coil with a mass flow rate of 80,000 lbm/hr and a temperature of 45°F. The total thermal resistance on the water-side of the heat exchanger is $4.44\text{x}10^{-6}$ hr-°F/Btu. The air-side is finned and the total thermal resistance on the air side, including the effect of the fins, ranges from $1.0\text{x}10^{-5}$ hr-°F/Btu when the coil is completely dry to $3.33\text{x}10^{-6}$ hr-°F/Btu when the coil is completely wet. The coil is large and employs many rows of tubes so that a counterflow heat transfer analysis is appropriate. Use the Dry Coil/Wet Coil analysis that is described in Section 9.6.2.

a.) Estimate the fraction of the coil that is wetted.
b.) Determine the heat transfer rate between the chilled water and the air.
c.) Determine the outlet air temperature.
d.) Determine the rate of condensate.
e.) Determine the outlet temperature of the water.

9.6-3 (9-13 in text) Repeat Problem 9.6-2 using the enthalpy-effectiveness method described in Section 9.6.3.

9.6-4 (9-14 in text) Cooling towers are direct-contact heat and mass exchangers. The performance of a cooling tower can be analyzed using the enthalpy-based effectiveness method described in Section 9.6.3. In this case, the maximum rate of heat transfer between the air and water is based on the difference between the enthalpy of the inlet air and the enthalpy of saturated air exiting at the inlet water temperature. The saturation specific heat should be evaluated using the enthalpies of saturated air at the water inlet and air inlet temperatures, respectively. A steady flow of water enters an induced draft cooling tower with a mass flow rate of 15 kg/s and a temperature of 35°C. The fans provide 4.72 m^3/s of ambient air at a dry-bulb temperature of 23°C and a relative humidity of 50%. Makeup water is supplied at 25°C. Use the enthalpy-based effectiveness technique to analyze this cooling tower.

a.) Prepare a plot of the outlet water temperature and the rate of water loss as a function of the number of transfer units associated with the cooling tower for *NTU* values between 0.5 and 5.

b.) Plot the range and approach as a function of *NTU*. The range is the difference between the inlet and outlet water temperatures. The approach is the difference between the outlet water temperature and the wet bulb temperature.

c.) Compare the rate of heat transfer associated with the cooling tower to the heat transfer rate that would be achieved by an air-cooled dry heat exchanger with the same air flow rate and *NTU*.

9.6-5 A cooling coil with a cross-flow geometry is used to dehumidify a stream of air. The flow rate of air is $\dot{V}_a$ = 750 ft^3/min and the air enters at $T_{a,in}$ = 75°F and relative humidity $RH_{a,in}$ = 0.75. Chilled water passes through the cooling coil with flow rate $\dot{V}_w$ = 5.1 gal/min and temperature $T_{w,in}$ = 45°F. The conductance of the coil under dry conditions is UA_{dry} = 700 Btu/hr-R.

a.) Determine the outlet temperature of the air and the mass flow rate of condensate.

b.) Plot the air outlet temperature and the mass flow rate of condensate as a function of the dry-coil conductance of the coil.

Chapter 9: Mass Transfer

Section 9.1: Mass Transfer Concepts

9.1-1 (9-1 in text) A mixture is formed mixing M_m = 0.25 kg of methane (with molar mass MW_m = 16 kg/kgmol), M_e = 0.15 kg of ethane (MW_e = 30 kg/kgmol) and M_n = 0.1 kg of nitrogen (MW_n = 28 kg/kgmol). The mixture is placed in a container that is maintained at T = 25°C and p = 5 bar. At these conditions, the mixture behaves in accordance with the ideal gas law. Determine:

a.) the volume of the mixture
b.) the equivalent molecular weight of the mixture
c.) the density of the mixture on a mass basis
d.) the density of the mixture on a molar basis
e.) the mass fractions of each species
f.) the mole fractions of each species
g.) the mass concentration of each species
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9.1-2 (9-2 in text) The composition of mixtures of air and water vapor are often reported in terms of the humidity ratio. The humidity ratio, ω, is defined as the mass of water vapor per mass of dry air. The humidity ratio is related to, but not exactly the same as the the mass fraction. In a particular case, the humidity ratio is $\omega = 0.0078$ at temperature T = 30°C and pressure p = 101.3 kPa. Determine:

a.) the mass fraction of the water vapor
b.) the mole fraction of the water vapor
c.) the mass concentration of the water vapor
d.) the molar concentration of the water vapor
e.) the maximum possible value for the mole fraction of the water vapor at equilibrium.

Section 9.2: Mass Diffusion and Fick's Law

9.2-1 (9-3 in text) The air-conditioning load for a building can be broken into latent and sensible contributions. The latent represents the energy that must be expended to remove the water vapor from the building. Water vapor enters by infiltration as air from outdoors leaks inside and by diffusion through the walls and ceiling. The building in question is rectangular with outer dimensions of 40 ft by 60 ft with 8 ft ceilings. The infiltration rate is estimated at 0.65 air changes per hour. The diffusion coefficient for water through 3/8 inch gypsum board (without a vapor barrier) is approximately $4.5\text{x}10^{-5}$ ft^2/s at atmospheric pressure.

a.) Estimate and compare the rates of moisture transfer by infiltration and diffusion on a day in which the outdoor conditions are 95°F and 45% relative humidity and indoor conditions are 75°F, 40% relative humidity. Is the contribution by diffusion significant? If not, then why are people concerned with water vapor diffusion in a building?

9.2-2 (9-4 in text) Natural gas (methane) is transported at 25ºC and 100 bar over long distances through 1.2 m diameter pipelines at a velocity of 10 m/s. The pipeline is made of steel with a wall thickness of 2.0 cm. It has been suggested that hydrogen gas could be transported in these same pipelines. However, hydrogen is a small molecule that diffuses through most materials. The diffusion coefficient for hydrogen in steel is about 7.9×10^{-9} m^2/s at 25ºC.

a.) Calculate the power transported by methane (assuming it will be combusted) through the pipeline. The lower heating value of methane is 5.002×10^7 J/kg.

b.) Estimate the velocity required to move the provide the same power if hydrogen rather than methane is transported through the pipeline at the same temperature and pressure. The lower heating value of hydrogen is 1.200×10^8 J/kg.

c.) Compare the pumping power required to transport the natural gas and hydrogen a distance of 100 km.

d.) Estimate the rate of hydrogen loss from a 100 km pipeline. Do you believe this loss is significant?

9.2-3 (9-5 in text) A balloon made of a synthetic rubber is inflated with helium to a pressure of p_{ini} = 130 kPa at which point its diameter is D_{ini} = 0.12 m. The mass of the balloon material is M_{bal} = 0.53 g and its thickness is δ = 0.085 mm. The balloon is released in a room that is maintained at T = 25ºC filled with air (y_{N2} = 79% nitrogen and y_{O2} = 21% oxygen) at p_{atm} = 100 kPa. Over a period of time, helium diffuses out of the balloon and oxygen and nitrogen diffuse in. The pressure in the balloon above atmospheric pressure is linearly proportional to the balloon volume. The diffusion coefficients for helium, oxygen and nitrogen through this synthetic rubber are $D_{He,rubber}$ = 60x10^{-8}, $D_{O2,rubber}$ = 16x10^{-8}, and $D_{N2,rubber}$ = 15x10^{-8} cm^2/s, respectively.

a.) Prepare a numerical model of the balloon deflation process. Plot the volume and pressure within the balloon as a function of time. Plot the mole fraction of helium, oxygen, and nitrogen in the balloon as a function of time.

b.) At what time does the balloon lose its buoyancy?

Section 9.3: Transient Diffusion through a Stationary Medium

9.3-1 (9-6 in text) A janitor is about to clean a large window at one end of a corridor with an ammonia-water solution. The corridor is 2.5 m high, 2 m wide and 3 m in length. The conditions in the corridor are 25C, 101 kPa. The concentration of the ammonia that evaporates from the window is estimated to be 100 ppm. Many humans can detect ammonia by smell at levels of 1 ppm. Estimate the time required for a person standing at the other end of the corridor to detect the ammonia after the janitor starts to wash the window.

9-4-2 (9-7 in text) In order to detect chemical threats that are being smuggled into the country within a shipping container, the government is working on a system that samples the air inside the container on the dock as it is being unloaded. The chance of detecting the chemical threat is strongly dependent upon its concentration distribution at the time that the container is sampled. Therefore, you have been asked to prepare a simple model of the migration of the threat species from its release point within a passage formed by the space between two adjacent boxes. The problem is not a simple diffusion problem because the threat chemical is adsorbed onto the walls of the passage. The situation is simplified as 1-D diffusion through a duct. One end of the duct is exposed to a constant concentration of the threat chemical that is equal to its saturation concentration, c_{sat} = 0.026 kg/m^3. The duct is filled with clean air and the walls of the duct are clean (i.e., at time t = 0 there is no threat chemicals either in the air in the duct or on the walls of the duct). The hydraulic diameter of the duct is D_h = 10 cm. The length of the duct is infinite. The diffusion coefficient for the threat chemical in air is D = 2.2x10^{-5} m^2/s. The mass of threat chemical per unit area adsorbed on the wall of the container (M''_w) is related to the concentration of the chemical in the air (c) according to:

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where $M''_{w,m}$ = 4x10^{-4} kg/m^2 is the mass per unit area associated with a single monolayer and A = 20 is a dimensionless constant. The total time available for diffusion between loading the container and unloading is $t_{transit}$ = 14 days. Because the length of the duct is so much larger than the hydraulic diameter of the duct, it is reasonable to assume that the concentration distribution is 1-D. Further, because the concentration of the threat chemical is so small, it is reasonable to neglect any bulk velocity induced by the diffusion process; that is, only mass transfer by diffusion is considered.

a.) Prepare a 1-D transient model of the diffusion process using the `ode45` solver in MATLAB.

b.) Plot the concentration distribution within the passage at various times.

c.) Plot the concentration distribution within the passage at $t = t_{transit}$ and overlay on this plot the zero-adsorption solution to show how adsorption has retarded the migration of the threat chemicals within the container.

9.4-3 (9-8 in text) Naphthalene is an aromatic hydrocarbon with a molecular weight of MW = 128.2 kg/kgmol that sublimes at a reasonable rate a room temperature. Naphthalene was commonly used for moth balls, but is now considered to be a carcinogen. At T = 25°C, solid naphthalene has a density of ρ = 1.16 g/cm^3 and a vapor pressure of p_v = 0.082 mm Hg. An engineer has recognized that heat and mass transfer are analogous processes and he plans to estimate the heat transfer coefficient for an unusual geometry by measuring how much mass of napthalene is sublimed. A review of the literature indicates that the Schmidt number for naphthalene is Sc = 2.5. To test accuracy of the heat /mass transfer analogy, the engineer first measures the mass of naphthalene that sublimes from a sphere of D = 2.5 cm diameter when exposed to a stream of pure air at temperature T = 25°C, pressure p = 101.3 kPa, and velocity u_∞ = 10 m/s. The test is run for t_{test} = 2 hr and during this time the mass of the naphthalene sphere is reduced by Δm = 250 mg.

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a.) Plot the mass of the droplet as a function of time and determine the time required for the droplets to completely evaporate.

b.) The humidifier requires a work input to form the droplets. The work input is related to the change in area of the water as it is transformed from one large "drop" to many smaller droplets. Calculate the energy required to distribute 1 kg of droplets with this vaporizer and compare it to the energy needed to vaporize one kg of water at 25°C. Comment on whether you believe that this humidifier saves energy compared to traditional vaporization process based on boiling water.

9.6-2 (9-12 in text) Air enters a cooling coil with volumetric flow rate 20,000 cfm, temperature 90°F and 50% relative humidity and is cooled and dehumidified by heat exchange with chilled water that enters the cooling coil with a mass flow rate of 80,000 lbm/hr and a temperature of 45°F. The total thermal resistance on the water-side of the heat exchanger is $4.44\text{x}10^{-6}$ hr-°F/Btu. The air-side is finned and the total thermal resistance on the air side, including the effect of the fins, ranges from $1.0\text{x}10^{-5}$ hr-°F/Btu when the coil is completely dry to $3.33\text{x}10^{-6}$ hr-°F/Btu when the coil is completely wet. The coil is large and employs many rows of tubes so that a counterflow heat transfer analysis is appropriate. Use the Dry Coil/Wet Coil analysis that is described in Section 9.6.2.

a.) Estimate the fraction of the coil that is wetted.

b.) Determine the heat transfer rate between the chilled water and the air.

c.) Determine the outlet air temperature.

d.) Determine the rate of condensate.

e.) Determine the outlet temperature of the water.

9.6-3 (9-13 in text) Repeat Problem 9.6-2 using the enthalpy-effectiveness method described in Section 9.6.3.