Chapter 7: Boiling and Condensation

Section 7.2: Pool Boiling

7.2-1 (7-1 in text) One method of removing water and other contamination from a gas is to pass it through a cooled tube so that contaminants with high freezing and liquefaction points (e.g., water) tend to be collected at the wall. A quick and easy liquid nitrogen trap for methane is constructed by placing a tube in a Styrofoam cooler that is filled with liquid nitrogen, as shown in Figure P7.2-1.

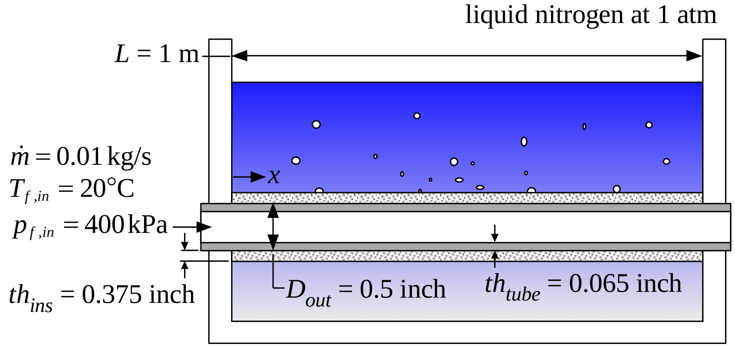


Figure P7.2-1: Liquid nitrogen trap.

The length of the tube is L = 1 m. The outer diameter of the tube is D_{out} = 0.5 inch and the tube thickness is th_{tube} = 0.065 inch. The tube conductivity is k_{tube} = 150 W/m-K. The tube is wrapped in insulation (to avoid liquefying the methane). The thickness of the insulation is th_{ins} = 0.375 inch and the insulation conductivity is k_{ins} = 1.5 W/m-K. Methane enters the tube at $\dot{m}$ = 0.01 kg/s with temperature $T_{f,in}$ = 20°C and pressure $p_{f,in}$ = 400 kPa. The liquid nitrogen that fills the container is at 1 atm and is undergoing nucleate boiling on the external surface of the insulation. You may neglect axial conduction through the tube.

a.) Set up an EES program that can evaluate the state equations for this problem. That is, given a value of position, x, methane temperature, T_f, and methane pressure, p_f, your program should be able to compute $\frac{dT_f}{dx}$ and $\frac{dp_f}{dx}$.

b.) Use the Integral command in EES to integrate the state equations from x = 0 to x = L. Plot the fluid temperature and pressure as a function of position.

c.) Plot the heat flux at the insulation surface and the critical heat flux as a function of position.

d.) Plot the temperature of the methane at the surface of the tube as a function of position.

e.) Plot the lowest temperature experienced by the methane in the trap as a function of the insulation thickness. If the methane temperature must be maintained at above its liquefaction point (131.4 K at 400 kPa) then what should the insulation thickness be?

7.2-2 (7-2 in text) An industrial boiler generates steam by heat exchanging combustion gases with saturated water at 125 kPa through mechanically polished AISI 302 stainless steel tubing having an inside diameter of 5.48 cm with a wall thickness of 2.7 mm and a total submerged length of 10 m. The combustion gases enter the tubing at 750°C with a mass flow rate of 0.0115 kg/s. The gases exhaust at ambient pressure. Assume that the combustion gases have the same thermodynamic properties as air.

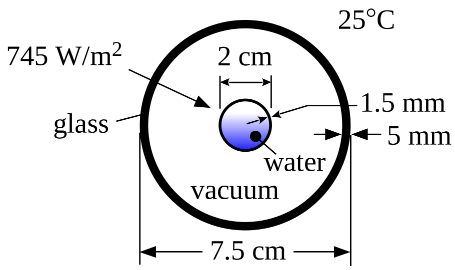
a) Identify the state equation for this problem; the differential equation that can be used to determine the rate of change of the temperature of the combustion gas with respect to position.
b) Integrate the state equations developed in part (a) in order to determine the outlet temperature of the combustion gases
c) Calculate the rate at which steam is generated in this boiler.

7.2-3 (7-3 in text) You are preparing a spaghetti dinner for guests when you realize that your heat transfer training can be used to answer some fundamental questions about the process. The pot you are using holds four liters of water. The atmospheric pressure is 101 kPa. When on its high setting, the electric stove heating unit consumes 1.8 kW of electrical power of which 20% is transferred to the surroundings, rather than to the water. The pot is made of 4 mm thick polished AISI 304 stainless steel and it has a diameter of 0.25 m. The burner diameter is also 0.25 m.

a) How much time is required to heat the water from 15°C to its boiling temperature?
b) What are the temperatures of the outside and inside surfaces of the bottom of pot while the water is boiling?
c) What would the burner electrical power requirement have to be to achieve the critical heat flux? Compare the actual heat flux during the boiling process to the critical heat flux.
d) How much water is vaporized during the 10 minutes required to cook the spaghetti?

7.2-4 (7-4 in text) A tungsten wire having a diameter of 1 mm and a length of 0.45 m is suspended in saturated carbon dioxide liquid maintained at 3.25 MPa. The fluid-surface coefficient needed in the nucleate boiling relation, C_{nb}, is estimated to be 0.01 and the emissivity of the tungsten wire is 0.4. Prepare a plot of the electrical power dissipated in the wire versus the excess temperature for power levels ranging from 10 W to the power corresponding to the critical heat flux for the nucleate boiling regime. What is your estimate of the excess temperature at the burnout point?

7.2-5 (7-5 in text) A cross-section of one type of evacuated solar collector is shown in Figure P7.2-5. The collector consists of a cylindrical glass tube with an outer diameter of 7.5 cm and wall thickness of 5 mm. In the center of the tube is a heat pipe, which is a copper tube with an outer diameter of 2 cm and wall thickness of 1.5 mm. The heat pipe contains a small amount of water at a pressure of 200 kPa that experiences nucleate boiling as solar radiation is absorbed on the outside surface of the copper tube at a rate of 745 W/m^2. You may assume that the glass is transparent to solar radiation and that the absorptivity of the copper tube with respect to solar radiation is 1.0. The surface of the copper tube has an emissivity of 0.13 with respect to its radiative interaction with the inner surface of the glass tube. The glass may be assumed to be opaque to thermal radiation from the copper tube with an emissivity of 1.0 on both its inner and outer surfaces. The outside surface of the glass interacts with the 25°C, 101.3 kPa surroundings through radiation and free convection.



P7.2-5: Cross-section of an evacuated tubular collector

a.) Calculate the net rate of energy transfer to the water per unit length.

b.) Calculate the efficiency of the solar collector, defined as the ratio of the rate of energy transfer to the water in the heat pipe to the incident solar radiation.

Section 7.3: Flow Boiling

7.3-1 (7-6 in text) When one fluid is changing phase in a heat exchanger, it is commonly assumed to be at a uniform temperature. However, there is a pressure drop in the evaporating fluid, which affects its saturation temperature. In a particular case, a 2 m long horizontal concentric tube heat exchanger made of copper is used to evaporate 0.028 kg/s of refrigerant R134a with an entering state of 300 kPa with a quality of 0.35. Heat transfer is provided by a flow of water that enters the heat exchanger at 12°C, 1.10 bar with a mass flow rate of 0.20 kg/s. The refrigerant passes through the central tube of the heat exchanger, which has an inner diameter of 1.25 cm and a wall thickness of 2 mm. The water flows through the annulus; the inner diameter of the outer tube is 2.5 cm.

a) Estimate the outlet temperature of the water and the outlet temperature and quality of the refrigerant.

7.3-2 (7-7 in text) A circular finned tube evaporator designed for cooling air is made from aluminum. The outer diameter of the tubes is 10.21 mm with a tube wall thickness of 1 mm. There evaporator is plumbed such that there are 12 parallel circuits of tubes with each circuit having a length of 0.6 m. Refrigerant R134a enters the evaporator at a mass flowrate of 0.15 kg/s. The refrigerant enters the throttle valve upstream of the evaporator as 35°C saturated liquid. The pressure in the evaporator is 240 kPa. The refrigerant exits as a saturated vapor.

a) What is the rate of heat transfer to the air for this evaporator.
b) Estimate of the average heat transfer coefficient between the R134a and the tube wall.
c) Estimate the pressure drop of the R134a as it pass through the evaporator. Does this pressure drop significantly affect the saturation temperature?

7.3-3 Problem 5.3-4 describes a solar electric generating system (SEGS) plant that uses solar collectors to heat oil. Use of the oil is problematic since a heat exchanger is required between the oil and the steam that is generated to operate the power cycle. In this problem we wish to investigate the option of boiling water directly within the tubes of the parabolic collectors. As in problem 5.3-4, we will analyze N = 50 tubes, each with an inner diameter of D_i = 0.066 m and a length of L = 750 m. The outer diameter of the tube is essentially equal to the inner diameter and the outer surface of these tubes is exposed to a uniform heat flux of q''_s = 15,000 W/m^2. In problem 5.3-4, each tube has oil (with specific heat of 2341 J/kg-K and a density of 825 kg/m^3) flowing through it with a volumetric flow rate (per tube) of $\dot{V}$ = 0.012 m^3/s. The oil enters the tube with a mean temperature of T_{in} = 500 K and exits at 600 K. The pump power for all 50 tubes with a pump having an efficiency of 0.5 is about 0.9 MW. Assume that, instead of the oil, saturated liquid water at 600 K enters the tubes and exits as saturated vapor.

a.) Compute the necessary mass flow rate of water so that the rate of energy transfer to the water is the same as that for the oil.
b.) Calculate the heat transfer coefficient on the inside surface of the tube when water is used as the heat transfer fluid and compare it to the heat transfer coefficient using oil.
c.) Determine the pressure drop across each of the 50 tubes
d.) Calculate the outlet temperature of the steam
e.) Estimate the minimum pump power required for all 50 tubes and compare the result with the minimum pump power needed for the oil. Note that the pump that provides the pressure operates with liquid water at 35°C.

7.3-4 (7-8 in text) Repeat EXAMPLE 7.3-1 using the Flow_Boiling_avg function rather than integrating to determine the average heat transfer coefficient. Compare the two methods of obtaining the average heat transfer coefficient.

7.3-5 (7-9 in text) A computer manufacturer is reviewing alternative ways to remove heat from electronic components. The electronic circuit board can be assumed to be a thin horizontal plate with a width of 8 cm and a length of 16 cm. Currently, air is blown over the top of the circuit board at a velocity of 10 m/s. Additional cooling could be obtained by a higher air velocity, but the increased noise associated with the larger fan required is judged to be unacceptable. Another alternative is to immerse the board in a fluid at atmospheric pressure that is undergoing nucleate boiling. The fluid R245fa has been chosen as a possibility. The surface tension of R245fa at atmospheric pressure is 0.0153 N/m. Other thermodynamic and transport properties are available from EES. Prepare a plot that shows the surface temperature of the plate as a function of the heat flux using air at 10 m/s and nucleate boiling at atmospheric pressure with R245fa for heat fluxes ranging from 100 to 10000 W/m^2.

7.3-6 The refrigerant R134a is evaporating as it flows through a pipe with inner diameter D = 0.5 inch. The mass flow rate is $\dot{m}$ = 40 lbm/min and the saturation temperature is T_{sat} = 54°F. The heat flux at the surface of the tube is $\dot{q}_s''$ = 5000 Btu/hr-ft^2.

a.) Plot the local heat transfer coefficient as a function of the quality of the R134a.

b.) Determine the average heat transfer coefficient in the pipe if the R134a enters the pipe as saturated liquid and leaves as saturated vapor. Use the function Flow_Boiling_avg.

Section 7.4: Film Condensation

7.4-1 (7-10 in text) Evacuated tubular solar collectors often employ a heat pipe to transfer collected solar energy for water heating. Heat transfer between the water that is being heated and the solar collector occurs at the condenser of the heat pipe, which is a thin-walled cylinder made of copper with a length of 6 cm and a diameter of 1 cm as shown in Figure P7.4-1. Water at 40°C and 1 atm flows past the condenser at a velocity that can be specified by the flow rate and duct diameter. The fluid inside the heat pipe is also water and it condenses at a pressure of 100 kPa. The heat transfer situation of the condensing water within the heat pipe is not known, but will here be assumed that is can be represented with the same relations as used for film condensation on the inside surface of a cylinder. This heat transfer coefficient for film condensation is provided by the Cond_Horizontal_Cylinder procedure when the mass flow rate is set to 0. Plot the rate of heat transfer from the solar collector to the water that is being heated as a function of the flow velocity of the water for velocities between 1 and 10 m/s.

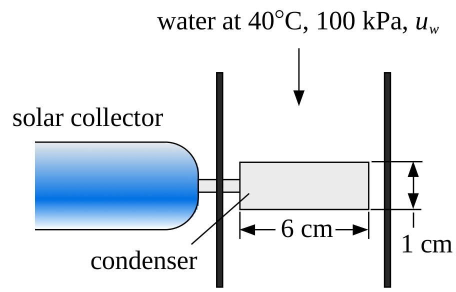


Figure P7.4-1: Condenser of evacuated solar collector.

7.4-2 (7-11 in text) The condenser in steam power cycle utilizes a shell and tube heat exchanger that consists of 1200 nominal 1.5 inch schedule 40 tubes made of brass. Each tube is 8 ft long internally smooth. Cooling water enters each of the tubes at 68°F and exits at 74°F. Saturated steam at 1 psia having a quality of 91% enters the condenser at a low velocity and is condensed on the tubes. Estimate the rate of condensate formation and the associated water flowrate at steady state conditions.

7.4-3 (7-12 in text) Problem 7.3-5 (7-9 in text) described an electronics cooling system that removes the heat dissipated in an electronic circuit board by submersing the board in R245fa. The circuit board is maintained at a relatively low and uniform temperature over a range of heat fluxes by boiling R245fa. However, a problem now arises in dealing with the vapor produced by the evaporation. One possibility is to condense the vapor on the bottom side of a vertical plate that is cooled by chilled water on its top side, as shown in Figure P7.4-3 in a sealed container. The top of the enclosure is made of metal and it can be considered to be isothermal. The chilled water is at 1 atm and has a free stream velocity of 10 m/s and a free stream temperature of 10°C. The circuit board is 8 cm wide and 16 cm long. The saturation pressure (and thus temperature) of the R245fa in the enclosure should vary with the heat flux.

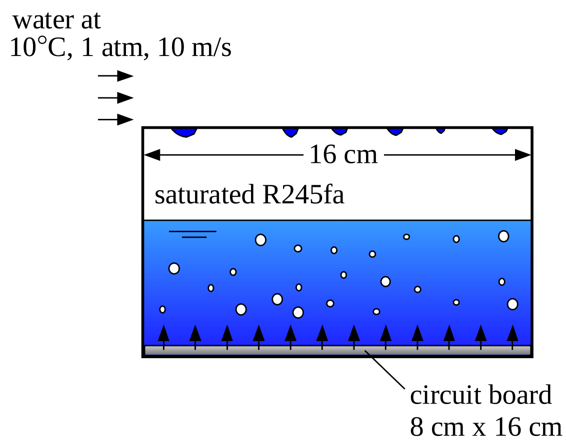


Figure P7.4-3: Sealed container full of evaporating and condensing R245fa.

a.) Prepare a plot of the saturation pressure and circuit board surface temperature as a function of the heat flux for heat fluxes ranging from 100 to 10000 W/m^2.
b.) How sensitive are the results to the velocity of the chilled water?

7.4-4 (7-13 in text) Recycled refrigerant R134a is purified in a simple distillation process in which a heater, submerged in the liquid refrigerant heats the liquid, which causes it to vaporize. The distillation unit is a container with a square base that is 25 cm on a side. Piping and a float valve (not shown) are provided to maintain a constant liquid level of refrigerant in the container as condensate is removed. The vapor condenses on the bottom side of a copper plate that is placed at the top of the device, as shown in Figure P7.4-4. Liquid water at 25°C with free stream velocity 3 m/s flows over the top of the copper plate. The plate is slightly inclined so that the condensed refrigerant travels to the left side of the bottom side of the plate and drips into a collection gutter.

a.) Calculate the saturation pressure and temperature of the refrigerant as a function of heater power for a range of heater powers from 100 W to 1000 W.

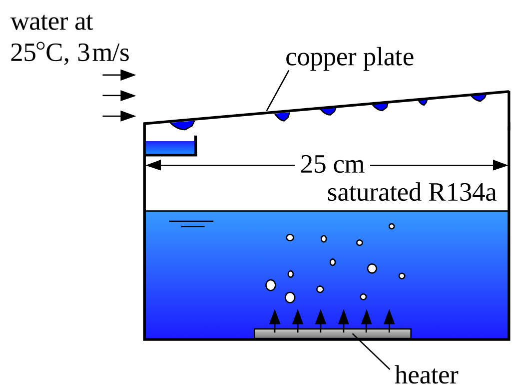


Figure P7.4-4: Refrigerant recycling apparatus

7.4-5 (7-14 in text) Calculate the heat flux for a square plate 1 m on each side condensing steam at 6 kPa. Consider three plate orientations: (1) horizontal facing downward; (2) horizontal facing upward; and (3) vertical (one-side only is active).

a.) Plot the heat flux for each orientation as a function of plate surface temperature.

b.) Which geometry provides the highest rate of condensation per unit surface area?

c.) How do the answers to (a) and (b) change if the plate dimensions are reduced to 0.5 m per side?

7.4-6 (7-15 in text) A heat pipe has been instrumented to test its ability to transfer thermal energy. The heat pipe consists of a sealed vertical thin-walled copper tube that is 1.5 m in length and 2.5 cm in diameter. The heat pipe contains liquid and vapor toluene. The bottom 5 cm of the tube are wrapped with heater tape that provides 100 W of heat input to the toluene. The toluene evaporates at the lower end of the tube and the vapor rises to the top where it is condensed by contact with the cold top surface of the tube. The top 6 cm of the heat pipe are maintained at 29°C by a flow of liquid water at 25°C and 1 atm. Toluene condensate flows back to the bottom of the tube; the flow is assisted by surface tension due to the presence of a wicking material on the inner surface of the copper tube. The heat pipe tube is well-insulated except for the bottom part that is in contact with the heater and the top part that is in contact with the water.

a.) Estimate the saturation temperature and pressure of the toluene in the heat pipe.

b) Estimate the surface temperature of the tube that is in contact with the heater.

c) Estimate the velocity of the cooling water provided at 25°C needed to maintain the top surface of the heat pipe at 29°C.

d) Compare the heat transfer rate provided by the heat pipe to the heat transfer rate that would occur if the tube were replaced with 2.5 cm diameter solid copper rod with the same temperatures imposed at the hot and cold ends.

e) What is the effective thermal conductivity of the heat pipe? What do you see as advantages of the heat pipe?

7.4-7 (7-16 in text) A vertical cylindrical container is made of aluminum having a wall thickness of 2.5 mm. The cylinder is 0.24 m in height and it has an outer diameter of 7.5 cm. Liquid water is placed in the cylinder and the bottom is heated, evaporating the liquid. The vapor that is produced escapes through a vent at the top of the cylinder. The flow of vapor drives out air that was originally in the cylinder. When all of the liquid has been boiled, the heating is stopped and the vent at the top of the cylinder is closed. The aluminum surfaces are nearly at a uniform temperature of 100°C. The cylinder is allowed to stand in a large room and it transfers energy by free convection to the 25°C air.

a.) Calculate and plot the pressure inside the cylinder as a function of time for a 5 minute period after the vent is closed. State and justify any assumptions that you employ. (Note that the heat transfer coefficient for film condensation on the inside surfaces of the cylinder can be estimated using the Cond_HorizontalTube procedure with a mass flow rate of zero.)

7.4-8 In the condenser in a lithium bromide-water absorption refrigeration system, water vapor at 16 kPa is condensed on the outside surface of horizontal tubes, thereby transferring energy to liquid water flowing inside of the tubes at atmospheric pressure. The tubes are made of copper with an inner diameter of 2.5 cm and a wall thickness of 3 mm. The tubes are arranged in banks with N tubes, stacked vertically, in each bank. The N tubes are plumbed in parallel, with water at 30°C and a total mass flow rate of 4 kg/s split between the tubes. The cooling water exits at a mean temperature of 41.4°C.

a) Determine the rate of heat transfer resulting from this condensation process.
b) Estimate the flow rate of condensate.
c) Calculate and plot the total length of all tubes required for the condensation process as a function of the number of vertical tubes plumbed in parallel for N = 2 to 12. Also, calculate and plot the pressure drop for the cooling water in the tube bank as a function of N.

Section 7.5: Flow Condensation

7.5-1 (7-17 in text) You have fabricated an inexpensive condenser for your air conditioner by running the refrigerant through a plastic tube that you have submerged in a lake. The outer diameter of the tube is D_o = 7.0 mm and the inner diameter is D_i = 5.0 mm. The tube conductivity is k_{tube} = 1.4 W/m-K. The refrigerant is R134a and enters the tube with quality x = 0.97, temperature T_{sat} = 35°C and mass flow rate $\dot{m}_r$ = 0.01 kg/s. The water in the lake has temperature T_∞ = 10°C.

a.) Determine the heat transfer rate per unit length from the refrigerant to the lake at the tube inlet.

b.) If the length of the tube is L = 6 m, then what is the quality of the refrigerant leaving the tube? Plot the quality and refrigerant heat transfer coefficient as a function of position s in the tube.

7.5-2 (7-18 in text) Condensation and boiling are analogous processes in that both a involve phase change. Heat exchangers that provide condensation and boiling are often designed in a similar manner. In a particular case, a phase change of R134a takes place within horizontal tubes having an inner diameter of 1 cm. The mass velocity is 300 kg/s-m^2.

a.) Prepare a plot of the heat transfer coefficient for condensation and boiling as a function of quality at a saturation temperature of 10°C for heat fluxes of 5,000 and 10,000 W/m^2.

b.) Plot the excess temperature for condensation and boiling as a function of quality.

c.) What conclusion can you draw from the results?

7.5-3 (7-19 in text) Absorption refrigeration cycles are often used to operate small refrigerators in hotel rooms because they do not require compressors or fans and thus operate quietly. In a particular case, an absorption refrigeration system uses an ammonia-water mixture. The ammonia is separated from the water and passes through a condenser where it is isobarically changed from saturated vapor at 76°C to subcooled liquid at 40°C. The condenser consists of a single unfinned thin-walled copper tube with a 1 cm inner diameter. The thermal energy released from the ammonia in this process is transferred to the 25°C room air by free convection. The subcooled ammonia is throttled to a saturation temperature of -5° and evaporated to saturated vapor to produce a refrigeration capacity of 110 W.

a) Determine the mass flow rate of ammonia through the evaporator and condenser.

b) Estimate the length of piping required to condense the ammonia from saturated vapor to saturated liquid at 76°C.

c) Estimate the additional length of piping required to subcool the ammonia to 40°C.

Chapter 7: Boiling and Condensation

Section 7.2: Pool Boiling

7.2-1 (7-1 in text) One method of removing water and other contamination from a gas is to pass it through a cooled tube so that contaminants with high freezing and liquefaction points (e.g., water) tend to be collected at the wall. A quick and easy liquid nitrogen trap for methane is constructed by placing a tube in a Styrofoam cooler that is filled with liquid nitrogen, as shown in Figure P7.2-1.

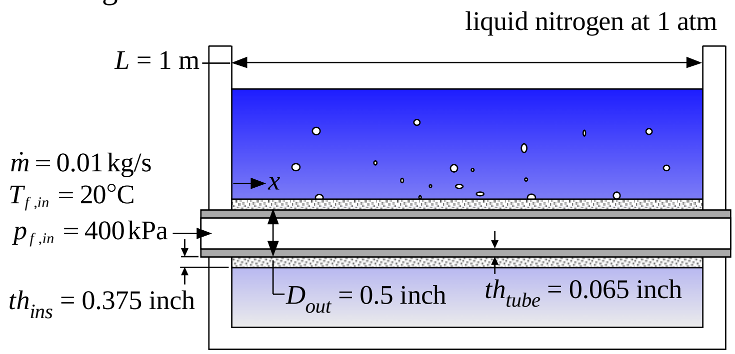


Figure P7.2-1: Liquid nitrogen trap.

The length of the tube is L = 1 m. The outer diameter of the tube is D_{out} = 0.5 inch and the tube thickness is th_{tube} = 0.065 inch. The tube conductivity is k_{tube} = 150 W/m-K. The tube is wrapped in insulation (to avoid liquefying the methane). The thickness of the insulation is th_{ins} = 0.375 inch and the insulation conductivity is k_{ins} = 1.5 W/m-K. Methane enters the tube at $\dot{m}$ = 0.01 kg/s with temperature $T_{f,in}$ = 20°C and pressure $p_{f,in}$ = 400 kPa. The liquid nitrogen that fills the container is at 1 atm and is undergoing nucleate boiling on the external surface of the insulation. You may neglect axial conduction through the tube.

a.) Set up an EES program that can evaluate the state equations for this problem. That is, given a value of position, x, methane temperature, T_f, and methane pressure, p_f, your program should be able to compute $\frac{dT_f}{dx}$ and $\frac{dp_f}{dx}$.

b.) Use the Integral command in EES to integrate the state equations from x = 0 to x = L. Plot the fluid temperature and pressure as a function of position.

c.) Plot the heat flux at the insulation surface and the critical heat flux as a function of position.

d.) Plot the temperature of the methane at the surface of the tube as a function of position.

e.) Plot the lowest temperature experienced by the methane in the trap as a function of the insulation thickness. If the methane temperature must be maintained at above its liquefaction point (131.4 K at 400 kPa) then what should the insulation thickness be?

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a) Identify the state equation for this problem; the differential equation that can be used to determine the rate of change of the temperature of the combustion gas with respect to position.
b) Integrate the state equations developed in part (a) in order to determine the outlet temperature of the combustion gases
c) Calculate the rate at which steam is generated in this boiler.

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b) What are the temperatures of the outside and inside surfaces of the bottom of pot while the water is boiling?
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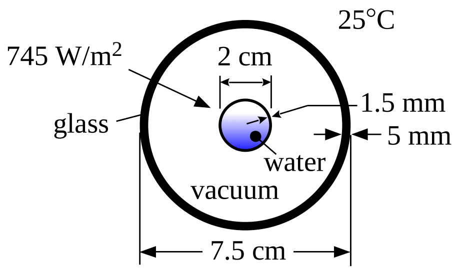

P7.2-5: Cross-section of an evacuated tubular collector

a.) Calculate the net rate of energy transfer to the water per unit length.

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Section 7.3: Flow Boiling

7.3-1 (7-6 in text) When one fluid is changing phase in a heat exchanger, it is commonly assumed to be at a uniform temperature. However, there is a pressure drop in the evaporating fluid, which affects its saturation temperature. In a particular case, a 2 m long horizontal concentric tube heat exchanger made of copper is used to evaporate 0.028 kg/s of refrigerant R134a with an entering state of 300 kPa with a quality of 0.35. Heat transfer is provided by a flow of water that enters the heat exchanger at 12°C, 1.10 bar with a mass flow rate of 0.20 kg/s. The refrigerant passes through the central tube of the heat exchanger, which has an inner diameter of 1.25 cm and a wall thickness of 2 mm. The water flows through the annulus; the inner diameter of the outer tube is 2.5 cm.

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7.3-5 (7-9 in text) A computer manufacturer is reviewing alternative ways to remove heat from electronic components. The electronic circuit board can be assumed to be a thin horizontal plate with a width of 8 cm and a length of 16 cm. Currently, air is blown over the top of the circuit board at a velocity of 10 m/s. Additional cooling could be obtained by a higher air velocity, but the increased noise associated with the larger fan required is judged to be unacceptable. Another alternative is to immerse the board in a fluid at atmospheric pressure that is undergoing nucleate boiling. The fluid R245fa has been chosen as a possibility. The surface tension of R245fa at atmospheric pressure is 0.0153 N/m. Other thermodynamic and transport properties are available from EES. Prepare a plot that shows the surface temperature of the plate as a function of the heat flux using air at 10 m/s and nucleate boiling at atmospheric pressure with R245fa for heat fluxes ranging from 100 to 10000 W/m^2.

Section 7.4: Film Condensation

7.4-1 (7-10 in text) Evacuated tubular solar collectors often employ a heat pipe to transfer collected solar energy for water heating. Heat transfer between the water that is being heated and the solar collector occurs at the condenser of the heat pipe, which is a thin-walled cylinder made of copper with a length of 6 cm and a diameter of 1 cm as shown in Figure P7.4-1. Water at 40°C and 1 atm flows past the condenser at a velocity that can be specified by the flow rate and duct diameter. The fluid inside the heat pipe is also water and it condenses at a pressure of 100 kPa. The heat transfer situation of the condensing water within the heat pipe is not known, but will here be assumed that is can be represented with the same relations as used for film condensation on the inside surface of a cylinder. This heat transfer coefficient for film condensation is provided by the Cond_Horizontal_Cylinder procedure when the mass flow rate is set to 0. Plot the rate of heat transfer from the solar collector to the water that is being heated as a function of the flow velocity of the water for velocities between 1 and 10 m/s.

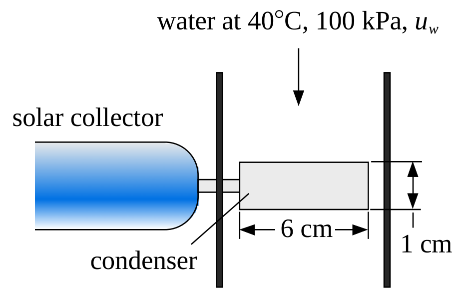

Figure P7.4-1: Condenser of evacuated solar collector.

7.4-2 (7-11 in text) The condenser in steam power cycle utilizes a shell and tube heat exchanger that consists of 1200 nominal 1.5 inch schedule 40 tubes made of brass. Each tube is 8 ft long internally smooth. Cooling water enters each of the tubes at 68°F and exits at 74°F. Saturated steam at 1 psia having a quality of 91% enters the condenser at a low velocity and is condensed on the tubes. Estimate the rate of condensate formation and the associated water flowrate at steady state conditions.

7.4-3 (7-12 in text) Problem 7.3-5 (7-9 in text) described an electronics cooling system that removes the heat dissipated in an electronic circuit board by submersing the board in R245fa. The circuit board is maintained at a relatively low and uniform temperature over a range of heat fluxes by boiling R245fa. However, a problem now arises in dealing with the vapor produced by the evaporation. One possibility is to condense the vapor on the bottom side of a vertical plate that is cooled by chilled water on its top side, as shown in Figure P7.4-3 in a sealed container. The top of the enclosure is made of metal and it can be considered to be isothermal. The chilled water is at 1 atm and has a free stream velocity of 10 m/s and a free stream temperature of 10°C. The circuit board is 8 cm wide and 16 cm long. The saturation pressure (and thus temperature) of the R245fa in the enclosure should vary with the heat flux.

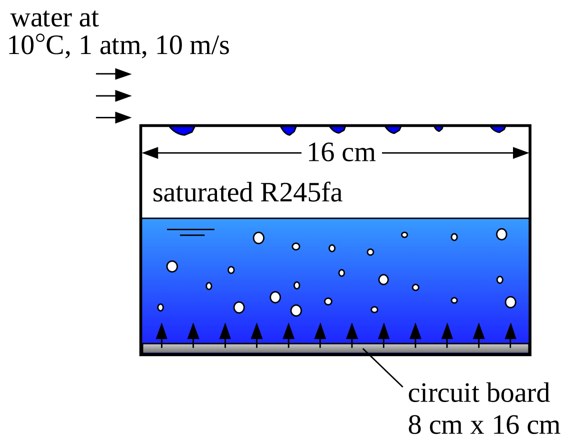

Figure P7.4-3: Sealed container full of evaporating and condensing R245fa.

a.) Prepare a plot of the saturation pressure and circuit board surface temperature as a function of the heat flux for heat fluxes ranging from 100 to 10000 W/m^2.
b.) How sensitive are the results to the velocity of the chilled water?

7.4-4 (7-13 in text) Recycled refrigerant R134a is purified in a simple distillation process in which a heater, submerged in the liquid refrigerant heats the liquid, which causes it to vaporize. The distillation unit is a container with a square base that is 25 cm on a side. Piping and a float valve (not shown) are provided to maintain a constant liquid level of refrigerant in the container as condensate is removed. The vapor condenses on the bottom side of a copper plate that is placed at the top of the device, as shown in Figure P7.4-4. Liquid water at 25°C with free stream velocity 3 m/s flows over the top of the copper plate. The plate is slightly inclined so that the condensed refrigerant travels to the left side of the bottom side of the plate and drips into a collection gutter.

a.) Calculate the saturation pressure and temperature of the refrigerant as a function of heater power for a range of heater powers from 100 W to 1000 W.

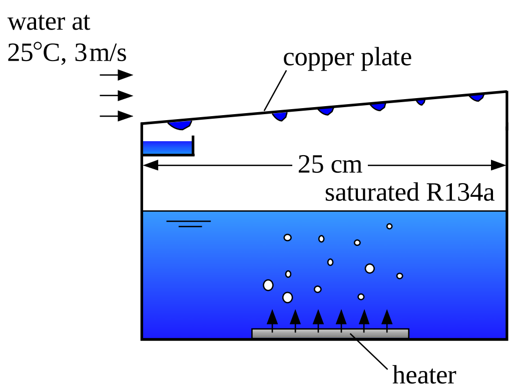

Figure P7.4-4: Refrigerant recycling apparatus

7.4-5 (7-14 in text) Calculate the heat flux for a square plate 1 m on each side condensing steam at 6 kPa. Consider three plate orientations: (1) horizontal facing downward; (2) horizontal facing upward; and (3) vertical (one-side only is active).

a.) Plot the heat flux for each orientation as a function of plate surface temperature.

b.) Which geometry provides the highest rate of condensation per unit surface area?

c.) How do the answers to (a) and (b) change if the plate dimensions are reduced to 0.5 m per side?

7.4-6 (7-15 in text) A heat pipe has been instrumented to test its ability to transfer thermal energy. The heat pipe consists of a sealed vertical thin-walled copper tube that is 1.5 m in length and 2.5 cm in diameter. The heat pipe contains liquid and vapor toluene. The bottom 5 cm of the tube are wrapped with heater tape that provides 100 W of heat input to the toluene. The toluene evaporates at the lower end of the tube and the vapor rises to the top where it is condensed by contact with the cold top surface of the tube. The top 6 cm of the heat pipe are maintained at 29°C by a flow of liquid water at 25°C and 1 atm. Toluene condensate flows back to the bottom of the tube; the flow is assisted by surface tension due to the presence of a wicking material on the inner surface of the copper tube. The heat pipe tube is well-insulated except for the bottom part that is in contact with the heater and the top part that is in contact with the water.

a.) Estimate the saturation temperature and pressure of the toluene in the heat pipe.

b) Estimate the surface temperature of the tube that is in contact with the heater.

c) Estimate the velocity of the cooling water provided at 25°C needed to maintain the top surface of the heat pipe at 29°C.

d) Compare the heat transfer rate provided by the heat pipe to the heat transfer rate that would occur if the tube were replaced with 2.5 cm diameter solid copper rod with the same temperatures imposed at the hot and cold ends.

e) What is the effective thermal conductivity of the heat pipe? What do you see as advantages of the heat pipe?

7.4-7 (7-16 in text) A vertical cylindrical container is made of aluminum having a wall thickness of 2.5 mm. The cylinder is 0.24 m in height and it has an outer diameter of 7.5 cm. Liquid water is placed in the cylinder and the bottom is heated, evaporating the liquid. The vapor that is produced escapes through a vent at the top of the cylinder. The flow of vapor drives out air that was originally in the cylinder. When all of the liquid has been boiled, the heating is stopped and the vent at the top of the cylinder is closed. The aluminum surfaces are nearly at a uniform temperature of 100°C. The cylinder is allowed to stand in a large room and it transfers energy by free convection to the 25°C air.

a.) Calculate and plot the pressure inside the cylinder as a function of time for a 5 minute period after the vent is closed. State and justify any assumptions that you employ. (Note that the heat transfer coefficient for film condensation on the inside surfaces of the cylinder can be estimated using the Cond_HorizontalTube procedure with a mass flow rate of zero.)

Section 7.5: Flow Condensation

7.5-1 (7-17 in text) You have fabricated an inexpensive condenser for your air conditioner by running the refrigerant through a plastic tube that you have submerged in a lake. The outer diameter of the tube is D_o = 7.0 mm and the inner diameter is D_i = 5.0 mm. The tube conductivity is k_{tube} = 1.4 W/m-K. The refrigerant is R134a and enters the tube with quality x = 0.97, temperature T_{sat} = 35°C and mass flow rate $\dot{m}_r$ = 0.01 kg/s. The water in the lake has temperature T_∞ = 10°C.

a.) Determine the heat transfer rate per unit length from the refrigerant to the lake at the tube inlet.

b.) If the length of the tube is L = 6 m, then what is the quality of the refrigerant leaving the tube? Plot the quality and refrigerant heat transfer coefficient as a function of position s in the tube.

7.5-2 (7-18 in text) Condensation and boiling are analogous processes in that both a involve phase change. Heat exchangers that provide condensation and boiling are often designed in a similar manner. In a particular case, a phase change of R134a takes place within horizontal tubes having an inner diameter of 1 cm. The mass velocity is 300 kg/s-m^2.

a.) Prepare a plot of the heat transfer coefficient for condensation and boiling as a function of quality at a saturation temperature of 10°C for heat fluxes of 5,000 and 10,000 W/m^2.

b.) Plot the excess temperature for condensation and boiling as a function of quality.

c.) What conclusion can you draw from the results?

7.5-3 (7-19 in text) Absorption refrigeration cycles are often used to operate small refrigerators in hotel rooms because they do not require compressors or fans and thus operate quietly. In a particular case, an absorption refrigeration system uses an ammonia-water mixture. The ammonia is separated from the water and passes through a condenser where it is isobarically changed from saturated vapor at 76°C to subcooled liquid at 40°C. The condenser consists of a single unfinned thin-walled copper tube with a 1 cm inner diameter. The thermal energy released from the ammonia in this process is transferred to the 25°C room air by free convection. The subcooled ammonia is throttled to a saturation temperature of -5° and evaporated to saturated vapor to produce a refrigeration capacity of 110 W.

a) Determine the mass flow rate of ammonia through the evaporator and condenser.

b) Estimate the length of piping required to condense the ammonia from saturated vapor to saturated liquid at 76°C.

c) Estimate the additional length of piping required to subcool the ammonia to 40°C.