Franklin W. Olin College of Engineering
ENGR 3310: Transport Phenomena

Final Exam

Thursday, December 16 | Fall 2004
9:00 am – 12:00 pm

Instructions

The exam is in two parts, Part A and Part B. Part A consists of 10 questions with short answers requiring minimal calculations. There is a unique answer to each question and the answer you give is either correct or incorrect. Each correct answer is worth 2 points. Each incorrect answer worth 0 points. There is no partial credit!

You must write your answers on the attached answer sheet and hand that in with your solutions to Part B.

Part B consists of a single question with three sub-sections that involve the design of a Central Receiver Solar Power Plant. It is more complex physically than part A and requires more extensive calculations. Partial credit will be awarded only for work clearly presented. The solutions to each sub-section are independent of the other sub-sections.

The exam is worth 75 points.

The constants and conversions given below can be used for both Part A and Part B:
<u>Constants:</u>
$g = 9.81$ m/s^2
<u>Conversions:</u>
1 mile = 1609 m, 1 hr = 3600 s, 1 month = 30 days, 1 day = 24 hrs

Part A: (20 points)

For the purposes of the questions presented in this part only, you MUST use the following data:

<u>SAE 30</u> $\mu = 0.29$ kg/m-s, $k = 0.139$ W/m-K <u>Air</u> $\gamma = 1.4$, $R = 287$ J/kg-K <u>Water</u> $\rho = 1000$ kg/m^3 <u>Saturated water at 100 °C</u> $\rho_l = 960$ kg/m^3, $\rho_v = 0.6$ kg/m^3, $\sigma = .06$ N/m, $h_{fg} = 2300$ kJ/kg

1. A viscous fluid (SAE 30 Oil) is flowing between a fixed lower plate and an upper plate moving steadily at a velocity $V = 3$ m/s. The distance between the plates is 2 cm. What is the velocity at a distance 1 cm from the top plate? What is the shear stress, τ, in the oil (in Pa)?

2. A commercial airplane flies at 540 miles/hour at a standard altitude of 30,000 ft where the temperature is 230 K. What is the Mach number of the plane? The atmospheric (static) pressure at 30,000 ft is 30800 Pa. What is the stagnation pressure at the leading edge of the wing, in Pa?

3. Fill in the blank: For steady flow, pathlines, streamlines, and ____________ are identical.

4. Newfound Lake, a freshwater lake near Bristol, New Hampshire, has a maximum depth of 60 m, and the mean atmospheric pressure is 91 kPa. Estimate the absolute pressure in kPa at the maximum depth.

5. A horizontal steady jet of water hits a solid plate with a velocity of 5 m/s. The mass flow of the jet stream is 0.2 kg/s. What is the horizontal reaction force on the plate (in N) if the plate does not move?

6. The Stokes number, St, used in particle dynamics studies, is a dimensionless combination of five variables: acceleration of gravity g, viscosity μ, density ρ, particle velocity U, and particle diameter D. If St is proportional to μ and inversely proportional to g, find its form.

7. A hollow cylinder, of inner and outer diameters 3 and 5 cm, respectively, and length $L = 0.1$ m has an inner surface temperature of 400 K. The outer surface temperature is 326 K when exposed to fluid at 300 K with an outside heat transfer coefficient of 27 W/m^2 K. What is the thermal conductivity of the cylinder (in W/m-K)?

8. A thick stainless steel slab is heated by an electrical current causing internal heat generation in the slab. The slab is convectively cooled on both surfaces by an air stream at ambient temperature. Draw the temperature profile in the slab and on either side of the slab and indicate where the maximum temperature would occur.

9. SAE 30 Oil flows in a 1 cm diameter tube. The tube is heated electrically with a constant heat flux of 2400 W/m^2. The flow is laminar. At a point in the tube, the wall temperature is measured to be T_s = 370 K. What is the bulk oil temperature at this point (in K)?

10. What is the maximum heat flux (in W/m^2) for which stable boiling is possible for boiling of water on a large, flat heater at a saturation temperature of 100 °C?

PART A ANSWER SHEET

NAME____

1. u = ____________________ m/s

   τ = ____________________ Pa

2. M = ___________________

   P = ____________________ Pa

3. Fill in the blank ___________________________________

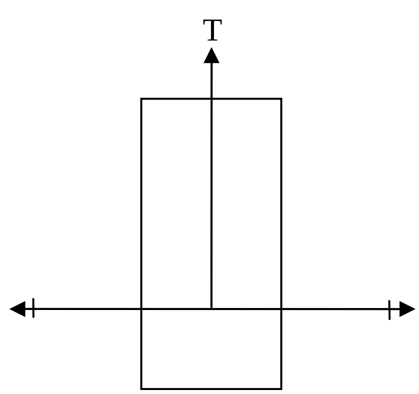
4. P = ____________________ kPa

5. F = ____________________ N

6. St = ____________________

7. k = _____________________ W/m-K

8. Draw temperature profile on figure.



9. T_b = ____________________ K

10. $\dot{Q}_{max}$ ____________________ W

Part B: Solar Two: A Central Receiver Solar Power Plant

Solar Two is a central-receiver power plant capable of producing 10-MW located outside of Barstow, California. Solar Two was built in 1996 and was used to demonstrate the viability of molten salt as the heat transfer fluid for a solar power plant. In the Solar Two molten salt central-receiver plant, a field of sun-tracking mirrors called heliostats reflect the sun's energy onto a cylindrical receiver that is mounted on a tower in the center of the field (see photo above). Molten salt runs through pipes in the cylindrical receiver and is heated. From the receiver, the hot salt goes to a hot thermal storage tank. The molten salt is pumped from the hot tanks to a steam generation system to produce steam (using two heat exchangers and a boiler). The steam is used to power a turbine to produce electricity. The cooled salt is then pumped to the cold thermal storage tank and is returned to the receiver tower, completing the cycle. Figure 1 shows a diagram of a molten salt central-receiver plant.

A report was produced on the performance of the Solar Two Power Plant which describes many of the key features and performance characteristics of the molten-salt cycle. However, some parameters are not given, and these are usually the ones we would like to know! To do this, we must work backward with what is given. Each part of this problem will use information from the report to work out a parameter we would like to know.

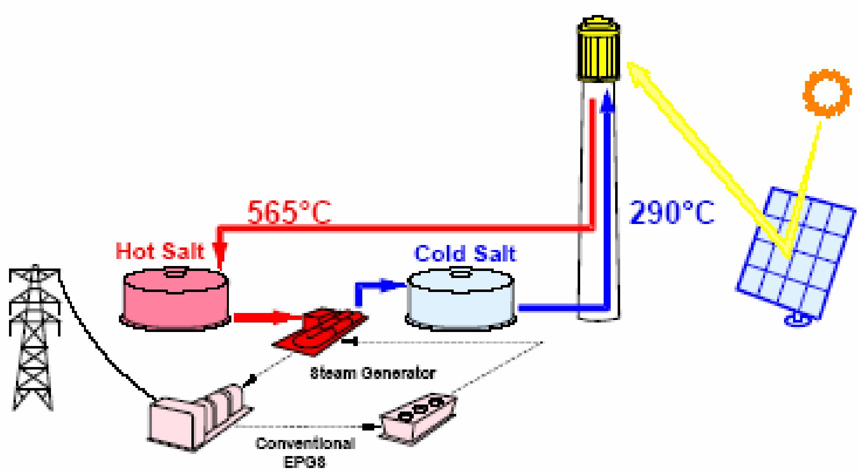


Figure 1: Schematic of Central Receiver Solar Plant

Properties:

The **molten salt** heat transfer fluid is a mixture of sodium nitrate and potassium nitrate and has a density of ρ = 1900 kg/m^3, a viscosity of $\mu = 7.73\times10^{-4}$ kg/ m-s, and a specific heat of c_p = 2930 J/kg K.

The **ambient air** at 27 °C has a density of ρ = 1.16 kg/m^3, a viscosity of $\mu = 1.85\times10^{-5}$ kg/ m-s, a thermal conductivity k = 0.026 W/m-K, Pr = 0.707, thermal diffusivity $\alpha = 2.25\times10^{-5}$ m^2/s, and a specific heat of c_p = 1007 J/kg-K.

1. Central Receiver Heat Transfer (20 points)

The central receiver is a cylinder (D = 5.1 m, H = 6.2 m) on top of the tower. The mirrors are angled to reflect all incoming sunlight onto this cylinder which results in a evenly distributed heat flux over the entire surface of the cylinder of 430 kW/m^2. A number of small tubes carrying the molten salt run lengthwise along the inner surface of the cylinder. The incident heat flux is used to heat the molten salt in the pipes.

Close-up of Central Receiver

(a) The thermal efficiency of the central receiver, η_t, is defined as

$$\eta_t = \frac{\text{Heat flux absorbed by molten salt}}{\text{Heat flux incident on receiver}}.$$

If the thermal efficiency is 0.88, what is the amount of heat flux lost through other modes of heat transfer?

(b) One of the ways that heat can be lost is through convective losses on the outside of the cylinder, particularly on a windy day. Assuming a constant wind of 20 km/hr blowing across the central receiver on a T_∞ = 27 °C day, what is the heat flux lost to external convection? The surface temperature of the central receiver cylinder can be estimated to be 565 °C.

(c) An energy balance of the heat fluxes we now know (heat flux incident on the receiver, heat flux to heat the molten salt, and heat flux lost to external convection) will show that we have not accounted for all the losses. What is the unaccounted for heat loss, in kW/m^2? Describe in one sentence where you think the remaining heat flux is going.

2. Molten Salt Thermal Storage (15 points)
Molten salt is stored in the hot tank until ready for use in the steam generation plant. The hot tank contains several immersed heaters to keep the molten salt hot enough for use in the steam generator. Heat is lost through the sides and the top of the tank due to natural convection, and through the bottom of the tank due to conduction to the ground. The tank is cylindrical with a diameter of 11.6 m and a height of 8.4 m.

(d) Write down the energy balance showing the various contributions to the change in internal energy (or temperature) of the tank. You can refer to these contributions as a heat transfer rate $\dot{Q}$ with an appropriate descriptive subscript.

(e) A test was done to see how quickly the tank would cool if power was lost and the heaters were not activated. With the immersed heaters turned off, it was found that the temperature of the tank decreased by 75 °C in one month. (Hint: use this to approximate *dT/dt*.) If the external heat transfer coefficient due to natural convection is 2.6 W/m^2-K, and the outside surface temperature of the tank is 100 °C, determine how much heat is lost to the ground. The average ambient temperature during the experiment was 27 °C.

3. Steam Generation Heat Exchangers (20 points)
Hot molten salt is pumped from the hot tank to the steam generation plant where it is used to convert water to steam for use in a steam turbine electrical generation plant. This is done in stages. The first stage is called a feedwater heater, where the molten salt is used to heat the liquid water just to the saturation point. We will be examining only this part of the steam generation process. The feedwater heater is actually a shell and tube heat exchanger with one shell and two tube passes.

The water enters the heat exchanger (on the tube side) at $T_{c,i}$ = 260 °C and exits at the same pressure as a saturated liquid at 307 °C. The molten salt exits the heat exchanger at $T_{h,o}$ = 290 °C. The heat capacity rate of the molten salt, C_h, is 2.4×10^5 W/K and the heat capacity rate of the water, C_c, is 4.8×10^5 W/K. The overall heat transfer coefficient for the heat exchanger is U = 1940 W/m^2-K.

(f) What is the required heat transfer area, A, in m^2?