

## Use of Waste Heat from Electricity Generation

Electric power plants emit water streams containing significant amounts of low-temperature energy. For example, one power plant produces water at 29.5°C. One use for this energy is to provide heat for greenhouses, which are constructed near power plants just for this purpose.

A typical greenhouse has several heat exchangers that heat the circulating air using the warm-water stream. Together, all of these heat exchangers use 0.0018 m<sup>3</sup>/s of 29.5°C water to heat 3.3 m<sup>3</sup>/s of 10°C outdoor air at 74.7 Pa gauge to 20.3°C.

One of these heat exchangers has a crossflow configuration (one fluid mixed) and has a load of 17,584 W. Assume that the water-side heat transfer coefficient is 1000 W/m<sup>2</sup>°C, and that the air-side heat transfer coefficient, which has finned tubes, is 200 W/m<sup>2</sup>°C (per area of bare tube). The conduction resistance of the tube wall and the radius correction may be neglected.

Determine the area of this heat exchanger. If the tubes are 1 in OD and are 1 m long, how many tubes are needed for this heat exchanger?

Reference:

Boyd, L. L., R. V. Stansfield, G. C. Ashley, J. S. Hietala, and A. M. Flikke, "How Waste Heat from Electricity Generation Can Heat Greenhouses," *Agricultural Engineering*, **60** (1), 28-31 (1979).

## Recovery of Heat from Graywater

Graywater is the term used to describe wastewater generated at home from the sinks, showers, washing machines, dishwashers, etc. The graywater from showers contains heat that can be recovered. Graywater heat recovery systems have been designed and are available for home installation. (<http://oikos.com/gfx/>)

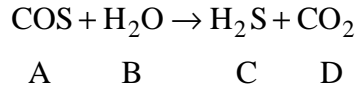
Consider one such device. It consists of a 3 in pipe wrapped with a coil of 0.5 in tubing, which replaces a section of the shower drain pipe. The shower drain water flows down the 3 in pipe, which triggers flow of incoming cold water through the coil. Assume the shower drain water flows at 2.1 gal/min at 95°F and is cooled to 61°F. The goal is to heat a portion of the incoming cold water from 41°F to 75°F. Some of this water goes to the hot water heater and the remainder is routed directly to the hot water tap in the shower. Determine the amount of cold water that can be heated with this system during a shower.

Determine the individual heat transfer coefficients in the drain pipe and in the coiled tube. The drain pipe is considered to be falling film flow, and negligible contact resistance may be assumed. You must determine if the flow in the coiled tube is laminar or turbulent. Then, estimate the overall heat transfer coefficient assuming the wall conduction resistance and the radius correction may be neglected.

What heat transfer area is required for this device? The manufacturer says that a typical device is 2-5 feet long. Is your heat transfer area within this specification?

## Reaction of Pollutant

Coal-fired power plants produce an acid gas waste stream containing hydrogen sulfide (H<sub>2</sub>S), steam, carbon dioxide (CO<sub>2</sub>), carbonyl sulfide (COS). Before the hydrogen sulfide and carbon dioxide are treated, it is possible to hydrolyze the carbonyl sulfide to produce additional hydrogen sulfide and carbon dioxide. The reaction is



and it is catalyzed by a titanium dioxide catalyst (CRS 31).

Consider the feed to a packed bed reactor containing the titanium dioxide catalyst. The reactor may be modeled as an isothermal PFR at 330°C and 2590 kPa. The feed contains 250 kmol/h each of components A-D. The bulk catalyst density is 950 kg/m<sup>3</sup>. The reaction kinetics are<sup>1</sup>

$$-r_A = \frac{k_1 k_2 P_A P_B}{1 + k_2 P_B} \quad \text{kmol}/(\text{kg catalyst h})$$

$$k_1 = 85.627 \exp(-5024/T) \quad \text{kmol}/(\text{kg catalyst h kPa})$$

$$k_2 = 2.066 \times 10^{-6} \exp(8101/T) \quad 1/\text{kPa}$$

where  $T$  is in Kelvin. Determine the reactor volume required to achieve 99.2% conversion of COS.

1. Tong, S., I. G. Dalla Lana, and K. T. Chuang, "Kinetic Modelling of the Hydrolysis of Carbonyl Sulfide by Either Titania or Alumina," *Canadian Journal of Chemical Engineering*, **71**, 392-400 (1993).

## Absorption of Pollutant

When coal is burned to form synthesis gas (syngas), which contains mostly CO, H<sub>2</sub>, H<sub>2</sub>S, and CO<sub>2</sub>, the H<sub>2</sub>S must be removed. The gas is called syngas because H<sub>2</sub> and CO are the building blocks for synthesis of hydrocarbons. One method for removal of H<sub>2</sub>S is the Selexol solvent, in which the H<sub>2</sub>S is highly soluble. The Selexol solvent is the dimethyl ether of polyethylene glycol and may be assumed to have a molecular weight of 300 kg/kmol,  $\rho = 900 \text{ kg/m}^3$ , and  $\mu = 2.5 \times 10^{-3} \text{ kg/m s}$ .

Consider the removal of H<sub>2</sub>S only from an otherwise inert mixture of gases, i.e., none of the other gases are soluble in the Selexol solvent. The partition coefficient for H<sub>2</sub>S between gas and solvent is given by the relationship

$$\frac{y}{x} = m = 3.6 \times 10^{-4} \left[ \frac{460 + T(^{\circ}\text{F})}{P(\text{atm})} \right]$$

The problem at hand is the removal of H<sub>2</sub>S from a gas stream with the properties of air, initially containing 2% H<sub>2</sub>S, so that the exit gas only contains 0.05% H<sub>2</sub>S. The H<sub>2</sub>S rich Selexol solvent is regenerated in a stripper using air. The absorber operates at 100 psig (6.8 atm gauge) and 70°F. The stripper operates at 1 atm absolute and 200°F. The stripper reduces the H<sub>2</sub>S content of the Selexol solvent to 0.5%, which is the feed concentration to the absorber. The gas to be treated is at 1000 kmol/h, and it may be assumed that the Selexol solvent circulates at 50,000 kg/h. In the packed bed absorber, it is known that  $H_{oG} = 3.5 \text{ m}$ . In the packed bed stripper, it is known that  $H_{oL} = 0.25 \text{ m}$ . It is proposed to use an existing stripper which is packed with a 5 m high section of 1.5 in ceramic Raschig Rings and has a diameter of 1.8 m.

- Determine the required absorber height.
- Determine the exit H<sub>2</sub>S mole fraction in the Selexol solvent.
- For the stripper, determine the amount of air needed.
- At what percent of flooding is the stripper operating? Do you recommend operating under these conditions?
- Determine the pressure drop across the stripper, in kPa.
- A new catalyst may require that the H<sub>2</sub>S concentration leaving the absorber be reduced to 0.025%. Therefore, it is necessary to determine if the designs in Parts a and c are flexible enough to accommodate this proposed change. Examine the possibility of increasing the Selexol circulation rate. What do you conclude? Suggest alternatives.

## Design of H<sub>2</sub>S Absorber

When coal is burned, the sulfur in the coal forms hydrogen sulfide (H<sub>2</sub>S). This effluent H<sub>2</sub>S must be removed. This can be accomplished by absorption of the H<sub>2</sub>S into the Selexol solvent, a polyether.

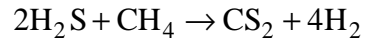
Consider a gas stream with a flow of 1241.8 kmol/h containing 36.78 mole % H<sub>2</sub>S with the remainder of the gas assumed to have the properties of CO<sub>2</sub>. The effluent mole fraction of H<sub>2</sub>S must be 0.001. The Selexol solvent is assumed to enter as a pure component. The equilibrium relationship between H<sub>2</sub>S in the gas phase and the Selexol solvent is  $y = 1.86x$ . The molecular weight of the Selexol solvent may be assumed to be 300 kg/kmol.

It is necessary to redesign the absorber in a process for which the flow of Selexol solvent is 1890 kmol/h. Determine the number of theoretical stages required for this separation.

Design the tray tower required for this separation. The average tray efficiency must be determined, which allows calculation of the actual number of trays. If the weir height is 3 in, determine the column pressure drop, assuming that the total head on the tray is equal to the weir height. Assume a 24 in tray spacing and an active area of 75% of the total column area.

### **Stoichiometry on H<sub>2</sub>S Reaction**

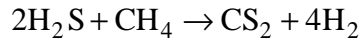
Coal-fired power plants produce an acid gas waste stream containing hydrogen sulfide (H<sub>2</sub>S). One way to treat the H<sub>2</sub>S pollutant is to react it to form carbon disulfide (CS<sub>2</sub>), which can be sold as a product. The reaction is



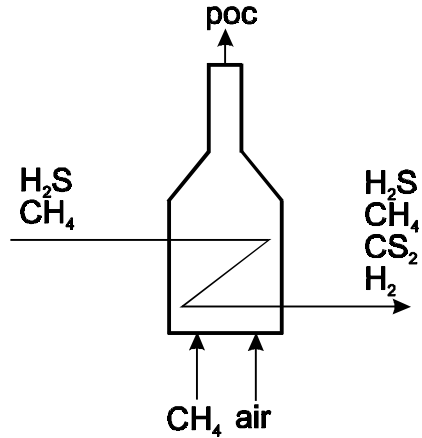
The feed to this reactor is 4392.8 kg/h H<sub>2</sub>S and 516.8 kg/h CH<sub>4</sub>. Conversion of the limiting reactant is 100%. Determine the mass flowrate of each component in the outlet stream to this reactor.

## Stoichiometry and Energy Balance on H<sub>2</sub>S Reaction

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The feed to this reactor is 4392.8 kg/h H<sub>2</sub>S and 516.8 kg/h CH<sub>4</sub> at 1060°C. The reactor outlet is at 1100°C. Determine the mass flowrate of each component in the outlet stream to this reactor. How much heat is required for this reaction? If the required heat is to be supplied by burning natural gas, assumed to be pure methane, in 100% excess air, determine the required amounts of natural gas and air. Assume the LHV of methane in determining the required amount of natural gas. Since the products of combustion will be above 25°C, additional methane will actually be required.



## Emergency Dumping from Fuel Storage Tank

Many chemical plants store fuel oil in a “tank farm” on the outskirts of the plant. In order to prevent an environmental disaster, there are specific rules regarding the design of such facilities. One such rule is that there be an emergency dump tank with the capacity of the largest storage tank. Should there be a leak or structural problem with a tank, the fuel oil can be pumped into the emergency dump tank.

Consider the design of the pumping system from an 80,000 gal tank storing #6 fuel oil into an 80,000 gal dump tank. The viscosity of #6 fuel oil is 0.5376 lb/ft sec, and its density is 62.4 lb/ft<sup>3</sup>. The piping system consists of 188 ft of commercial steel pipe, 4 90° flanged regular elbows, a sharp entrance, an exit, and a pump. The oil must be pumped to an elevation 15 ft above the average liquid level in the source tank.

Do a steady state analysis for all of the following problems.

### Problem 1

If 24 in schedule 40 pipe is used, and if it is necessary to accomplish the transfer within 60 minutes, determine the horsepower rating required of the pump. Assume the pump is 75% efficient.

### Problem 2

If the pump to be used has 10 hp at 75% efficiency, and the pipe is 24 in schedule 40, determine how long the transfer will take.

### Problem 3

If the pump to be used has 20 hp at 75% efficiency, and the transfer is to be accomplished in 60 minutes, determine the required pipe size.

### Problem 4

What combination of pump horsepower and pipe size (schedule 40 only) gives the minimum capital cost for the pump and piping system? Assume the transfer of 80,000 gal must occur in 60 minutes or less. The cost equations are:

$$\begin{aligned} \$\text{pump} &= 560(\text{power, hp})^{0.4} \\ \$\text{pipe} &= 5D(\text{in})L(\text{ft}) \end{aligned}$$

An interesting extension for these problems would be to do the unsteady-state analyses. A simpler variation would be to determine, semi-quantitatively, whether the steady state analysis is an upper or lower bound on the rigorous, unsteady-state analysis.

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Consider the design of the pumping system from an 303 m<sup>3</sup> tank storing #6 fuel oil into an 303 m<sup>3</sup> dump tank. The viscosity of #6 fuel oil is 0.8 kg/m s, and its density is 999.5 kg/m<sup>3</sup>. The piping system consists of 57 m of commercial steel pipe, 4 90° flanged regular elbows, a sharp entrance, an exit, and a pump. The oil must be pumped to an elevation 15 ft above the average liquid level in the source tank.

Do a steady state analysis for all of the following problems.

### Problem 1

If 24 in schedule 40 pipe is used, and if it is necessary to accomplish the transfer within 60 minutes, determine the power rating required of the pump. Assume the pump is 75% efficient.

### Problem 2

If the pump to be used has 15 kW at 75% efficiency, and the pipe is 24 in schedule 40, determine how long the transfer will take.

### Problem 3

If the pump to be used has 30 kW at 75% efficiency, and the transfer is to be accomplished in 60 minutes, determine the required pipe size.

### Problem 4

What combination of pump power and pipe size (schedule 40 only) gives the minimum capital cost for the pump and piping system? Assume the transfer of 303 m<sup>3</sup> must occur in 60 minutes or less. The cost equations are:

$$\begin{aligned} \$_{\text{pump}} &= 630(\text{power, kW})^{0.4} \\ \$_{\text{pipe}} &= 646D(\text{m})L(\text{m}) \end{aligned}$$

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