Troubleshooting shell-and-tube heat exchangers

Use these techniques and guidelines to ensure more reliable heat transfer

D. Gulley, Gulley Computer Associates, Tulsa, Oklahoma

It is stressful when exchangers go online and don't perform as they should. But not all scary things go "bump in the night." Heat exchangers that go onstream and don't perform are also scary. This is especially true if there is a lack of thermal wells, pressure gages and flowmeters. In addition, you are told that many hundreds of thousands of dollars a day are being lost due to decreased production, so the problem has to be found immediately. In many cases, there has to be a shutdown.

Here is helpful information on finding a cure, including:

- What information to collect and what to look for
- The importance of calculated pressure drops and how they help analyze the problem
- Two-phase flow emphasizing low heat transfer due to stratified flow
- Actual case histories of design and fabrication errors to help with the diagnosis.

The concentration is on thermal problems; problems due to vibration and exchanger leaks are not discussed.

INFORMATION COLLECTION

Besides the obvious process information of flow, temperatures and pressure drops, you will probably need the manufacturer's heat exchanger drawings. Hopefully, you will not have to run heat exchanger tests. But if you do, there are procedures in the literature.[1,2]

Using the collected process information, make a full thermal design computer run. The printout will have much more information than a standard specification sheet. Check the printout with the following in mind:

1. Are there any error messages about the physical properties used?

2. Are there error messages for the input data?

3. Check the section that analyzes the design for comments. This is a section of the program that acts as expert system software.

4. Was the correct heat-transfer type specified on input?

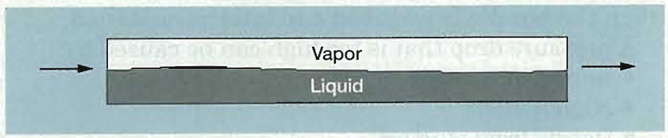

Fig. 1. Stratified flow pattern.

5. Have any warnings been ignored in the heat exchanger's design?

6. Was the advice on bundle-sealing devices followed?

7. If the problem is freezing or heat damage, could the temperatures in the clean condition be the problem?

In some cases, it is helpful to measure temperatures on the exchanger's exterior. This can identify unvented gas, stratified flow or fluid bypassing. If these temperatures are not too hot or cold, you can check the shell by feeling with your hands.

Pressure drops. These are a big help in analyzing performance problems. They also provide a rough check of flowrates. Single-phase streams should check reasonably close between calculated and measured pressure drops if there isn't a fouling problem. Two-phase pressure drops will be reasonably close if they are zoned and flow patterns are considered.

Measured pressure drops lower than calculated drops indicate fluid bypassing. A low pressure drop on the tubeside means that not all the flow is entering the tubes that should. There may be a problem where the channel pass plates or floating head pass plates meet the tubesheets. The bundle should be pulled and the pass plates and tubesheet gasket examined. It could be a corrosion problem, gasket problem or a manufacturing defect.

A shellside pressure drop lower than calculated indicates improper bundle sealing. Bundle bypass streams lower heat transfer. Any open areas above or below the bundle should have the crossflow component of flow blocked by seal strips. This is especially important for the laminar flow region. If the exchanger is a two shell-pass type, fluid is probably bypassing the long baffle if it is not welded in. Long baffles with leaf seals do not give a perfect seal. These thin strips of metal cannot take much punishment. Sometimes they are damaged in fabrication. Leaf seals can also be damaged at the plant

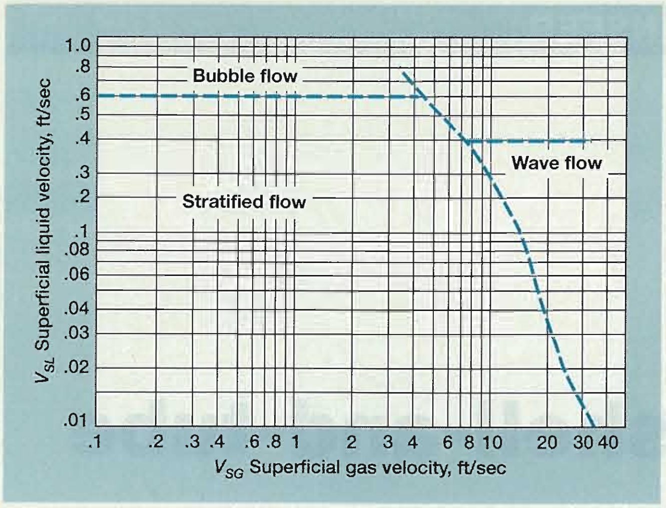

Fig. 2. Map of stratified flow showing limits.

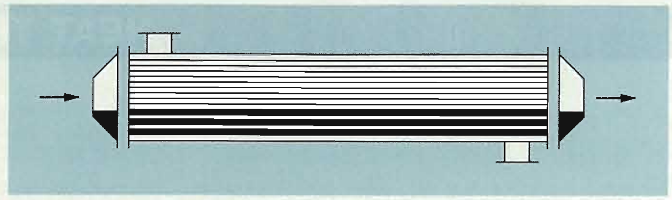

Fig. 3. Bad design that traps out condensate.

when the bundle is removed and later re-installed.

A pressure drop that is too high can be caused by:

- Improper venting
- High fouling
- Debris from startup
- Freezing of the process stream
- Slug flow for two-phase streams
- Fabrication problems.

Improper or no venting causes a high pressure drop. This should be one of the first items to check if there is a high pressure drop. This usually occurs in condensers and is discussed more fully in a later section.

Fouling. If there is a gradual decline in heat transfer, fouling may be the culprit. Heat exchanger software can give the available fouling as compared to design fouling. Sometimes fouling is so severe that tubes can be plugged inside or the shellside ligaments between the tubes can be filled. This is sometimes seen when bundles from a refinery are sent to be repaired. Actual fouling can be much higher than the TEMA (Tubular Exchanger Manufacturer's Association) specification.[3]

If you suspect that fouling is a problem, check the exchanger's operating history. Are there deviations from design conditions? Are there periods of operation where flows are lower than design? Heat exchangers will foul faster at low velocities. If water fouling is a problem, have the water flows been cut back in the winter?

If you determine that fouling is a problem, make a chemical analysis of the fouling material. Knudson[4] discusses different fouling control methods and types of cleaning. Online and offline mechanical cleaning plus chemical cleaning is discussed. If the fouling cannot be controlled, a tube electropolishing process can slow scale and other buildup. It eliminates small ridges and pits that contribute to fouling.

Debris. Check to see if there is a strainer in the piping ahead of the inlet nozzles. If there is no strainer, there may be debris in the exchanger. It is amazing what types of debris can be found in heat exchangers after startup—such things as rocks, trash, wrenches, gloves, weld rods, clothing, pencils, etc. Possibly during a work force shift change, the first shift left something that the second shift did not see before closing the piping.

Excess surface problems. In the design stage, the clean condition may not have been evaluated. Many exchangers are designed for fouled conditions only. Most of the time this is all that is necessary. However, in some situations the clean condition must be checked. More exchanger oversurface means more deviations from outlet design temperatures and a greater potential for problems.

For high-temperature applications, the outlet temperature of the heated stream must be checked. It will be higher than the process design temperature. If this temperature is higher than what was used to select the metallurgy, there may be a problem. Small[5] relates a case where the effect of oversurface and the clean condition was not checked. It resulted in ruptured tubing and the loss of tube fins. Another problem with higher-than-process-design outlet temperatures is that a liquid may degrade or lose its thermal stability. For cold applications, the outlet temperature of the stream to be cooled must be checked. It can cause stream freezing and tube plugging. It can also cause brittle tubing and tube failures.

Another case where excess surface can be a problem is in vaporizer design. If vaporizing is done too well, there will be surging of vapor leaving the exchanger. As a young engineer, I saw an ammonia vaporizer in a nitric acid plant creating surging vapor to the reactor. All the liquid would flash to vapor inside the kettle; liquid feed would then surge in and flash again. Our process group determined there was excess surface and plugged off some tubes. The kettle operation smoothed out and reactor efficiency improved.

Excess surface problems are cured by plugging tubes in the inlet channel. There are many different types of plugs, but metal plugs with a slight taper are most common. Unless the temperatures are high, wooden plugs can be used in a pinch.

Venting. Proper venting is a startup necessity. Improper venting usually occurs on startup and is recognized by poor heat transfer and a high pressure drop. Exchangers operating under a vacuum can be more of a problem than those operating under pressure. The vacuum will suck air into the exchanger if it isn't perfectly sealed. Vents should be located at the exchanger's highest points. The shellside is especially vulnerable to pockets of air or noncondensables. Gas can get trapped at the bundle's top or by "ears" at the top of baffles. If a venting problem is suspected, talk to operations about their startup procedures. Fijas[6] recommends startup procedures. Yokell[7] has a more complete discussion of vents, especially vertical fixed tube sheet exchangers.

Two-phase heat transfer. Proper venting is especially important for two-phase streams. In addition to air that may be introduced during startup, noncondensable gases

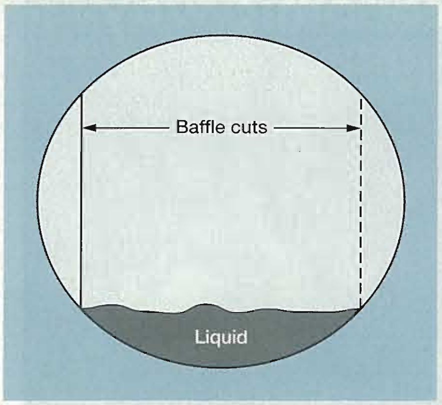

Fig. 4. Baffle cut that holds a condensate liquid level.

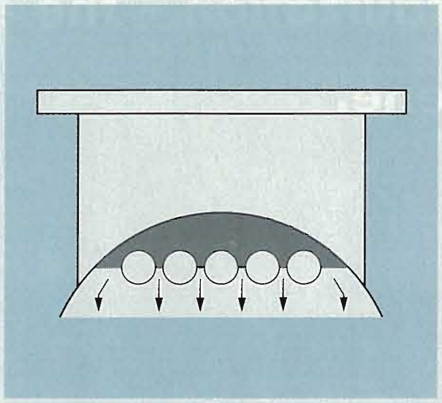

Fig. 5. A large nozzle/shell size ratio can restrict entrance or exit area.

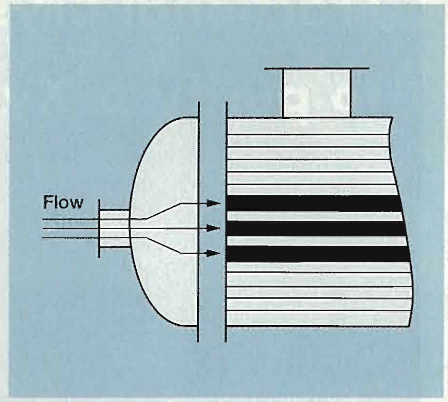

Fig. 6. Channel design that causes bad flow distribution.

can come from the process. These gases occur most often in condensers. Vents on horizontal condensers should be located at the opposite end from the inlet. This is such a problem on the condensing steam side of feed water heaters that they have startup and operating vents.

Common problems with two-phase streams are stratified flow and wave flow. The exception is pool boiling in a kettle. An illustration of stratified flow is in Fig. 1 where there is little mixing of the liquid and vapor. Vapor, with its lower thermal conductivity, blankets some of the exchanger surface and reduces its film coefficient. This type of flow can greatly lower the overall heat-transfer coefficient.

In one case, a manufacturer designed a cryogenic exchanger for an overall rate of approximately 35. The exchanger was not checked for stratified flow and the tubeside had a low velocity. When the overall rate was back-calculated from the operating temperatures, it was only 6.9. Apparently, most of the inside tube surface was in contact with gas only.

Fig. 2 can be used to check for stratified or wave flow.[8] Calculate the gas velocity and liquid velocity as if each is alone (superficial velocity). Stratified flow exists and there is a bad flow pattern for two-phase heat transfer if the liquid velocity is less than 0.5 ft/sec and the gas velocity is below the calculated value from:

$$Max\ V_{sg} = 3.5/(V_{sl})^{1/2}$$

The cure for stratified flow and slightly wavy flow is to keep dry gas away from the tubewall. If the stream inside the tubes has low fouling characteristics, twisted tape inserts can be used to swirl and mix the fluid. This insert type is available from some heat exchanger companies.

If the flow pattern is stratified flow or wave flow and it is boiling, the heat-transfer surface needs to be submerged so only liquid is in contact with the tubing. This is accomplished using a weir for kettle reboilers. In other exchanger types, this can be done using an external pipe loop or, if feasible, raising the exchanger to a vertical position. In this case, the lower thermal-conductivity vapor is in the form of bubbles and higher thermal-conductivity liquid coats the tube surface.

If there is condensing, no bubbling action thins the liquid film. The liquid film needs to be thin for good heat transfer. One cure for tubeside condensing is to use inserts that give the fluid a higher velocity and a swirling action to thin the liquid film. Another solution is to raise the exchanger to a vertical position and condense downward.

Another possible problem with condensing is holding up condensate flow. This thickens the liquid film so that part of the heat exchanger surface acts as a liquid cooler with lower heat transfer. A steam trap is an example of a device that keeps condensate moving. It does not allow condensate to build up a thick film. Fig. 3 shows an example of bad tubeside nozzle location for a condensing stream. Tubeside condensate can build up in the heat exchanger's lower part. The outlet channel acts as a dam or weir to the condensate.

Another case of condensate flow hold-up and low heat transfer is when there is one horizontal tube pass and the operating pressure is only slightly above atmospheric. There is not enough driving force to keep the condensate flowing well. This condenser type should be sloped enough so the liquid condensate flows freely out of the tubes. A sulfur condenser is an extreme example. The operating pressure is low, it has one tube pass and the viscous sulfur does not flow freely.

Shellside baffles can also act as dams. Horizontal-cut baffles should not be used in most condensing streams. Vertical-cut baffles can be used, but make sure that small baffle cuts do not flood too much of the bundle. Fig. 4 shows how small baffle cuts can create a liquid level. The worst case is when the condenser has a low operating pressure and the condensate has a natural hydraulic level lower than what the baffle cut submerges.

Just because superheated steam is the heating medium does not mean hotter steam is better. A high amount of superheat is not much of a problem at high operating pressures. However, at low operating pressures the mass velocity will be low and the gas heat transfer in the desuperheat zone will be low. So, more superheat causes a bigger problem. More of the exchanger surface will be in contact with dry steam with its low heat transfer.

Film boiling can be a problem if the hot fluid temperature is much higher than the boiling stream temperature. The bubbling action can be so violent that only vapor contacts the exchanger tubing. In this case, the critical heat flux is exceeded. For hydrocarbons that are steam-heated, maximum temperature drop across the boiling film is approximately 80°F to 100°F. This corresponds to a mean temperature difference of approximately 150°F. This is cured by reducing the steam pressure.

Poor thermosyphon performance can be caused by an incorrectly set tower liquid level. There needs to be

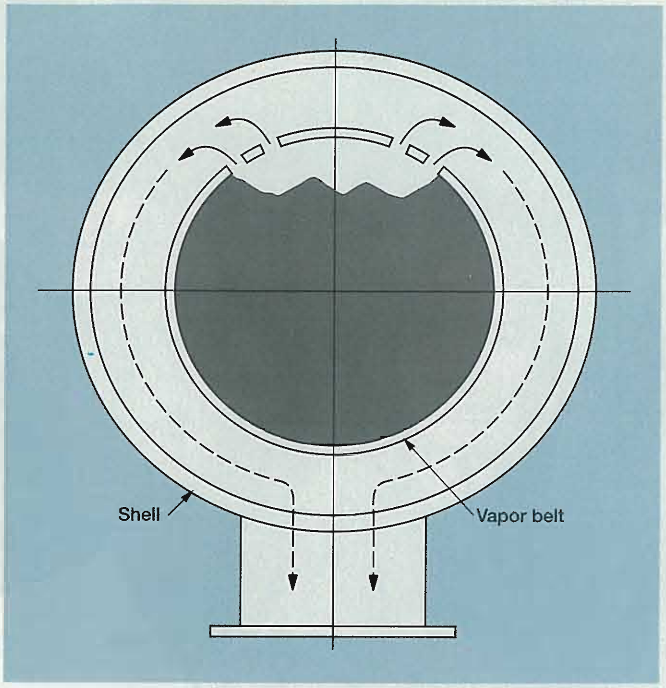

Fig. 7. Improper placement of outlet vapor belt slots in a condenser.

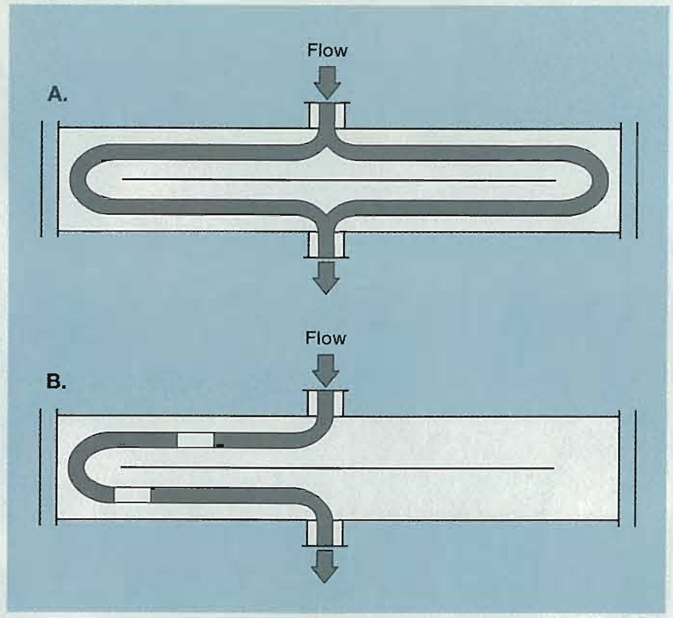

Fig. 8. A) Normal split flow pattern; B) One end closed of long baffle by mistake.

enough head to overcome the hydraulic resistance in the reboiler circuit. Too high a tower liquid level raises the liquid level on the exchanger's boiling side. This creates a zone of poor heat transfer where there is no boiling. Love[9] discusses where to set the tower liquid level.

It is possible for a vertical thermosyphon to have a mist flow pattern. This is created when the percent vaporization is high and there is a high circulation rate. There is no longer a liquid film on the tubes and liquid is entrained in the vapor. Mist flow gives a reduced type of heat transfer. This is one reason a butterfly value is usually put in the liquid feed line to the reboiler. Then the feed rate can be controlled.

Design and fabrication errors. Not removing enough tubes under the shell nozzles can cause pressure drop and vibration problems. Refer to Fig. 5 where the lowest edge of the nozzle is below the top tube row. The entering shell fluid cannot disburse in all directions. It can only go parallel to the tubes and down between the tubes. The opposite is true at the exit. Tubes too close to the nozzles will cause a high pressure drop and possibly bundle vibration.

This problem is normally found when older exchangers are used in a new service. The problem can occur if nozzles are enlarged to handle more flow for the new service, but the bundle layout is not changed. One cure for exchangers with high bundle entrance/exit pressure drops is to add another nozzle so two parallel streams enter or leave the exchanger. This cure is also good if there is a vibration problem in the bundle end zones.

Nozzles larger than 4 in. should have the shell entrance and exit area checked. The worst case is fixed-tubesheet or U-tube exchangers with only a small clearance between the bundle and shell inside diameter (ID). In these types of exchangers where the nozzles are greater than approximately ¼ of the shell ID, the velocity will be more than four times the nozzle velocity.

Inlet channels that have a high pressure drop can cause bad tubeside flow distribution. A small nozzle combined with a shallow channel, as in Fig. 6, causes the flow to jet into a small group of tubes. The large group of remaining tubes do not get their share of the flow. Mueller[10] shows how to estimate the fraction of the tube flow that is affected by the axial nozzle. From this information, the surface calculation can be done with two zones to evaluate exchanger performance. To improve the performance of a channel nozzle jet problem, a baffle can be installed halfway between the nozzle opening and tube sheet.

Bad shellside flow distribution is cured by sealing off bypass areas. A typical example is a U-tube exchanger with two tube passes and baffles with a vertical cut. It has a gap across the center created by the smallest U-bends. If the tube's outside diameter (OD) is ¾ in., the gap is usually 1½ in. This is usually not blocked off as well as it should be. Yokell[7] discusses bad shellside and tubeside flow distribution in more detail.

Improper slot placement in a distributor belt can cause low condenser performance. **Example:** A partial condenser was fabricated with slots in the exit belts in the upper part of the shell (Fig. 7). This is fine for vaporization, but not for a condenser. In this condenser, the liquid level is near the shell's top due to a dam effect. The liquid level is higher than normal unless there is a high operating pressure. Thus, the submerged surface acts as a liquid cooler, which has a much lower film coefficient than a condenser.

Fabrication errors can cause high pressure drops. There was an exchanger that did not have the long baffle slotted on one end (Fig. 8). The shell flow pattern was split flow (TEMA type G). The flow should split and form two parallel streams (Fig. 8A). With access to only one long baffle opening, the flow did not split and a much higher pressure drop and poor heat transfer resulted (Fig. 8B).

In one case, the inlet channel gasket was installed backwards. It was a U-tube with 4 tube passes. In Fig. 9B, the dashed line shows where the gasket rib on the right side should have been on the left, as in Fig. 9A. In this case, there was not a seal between the first and fourth passes, result-

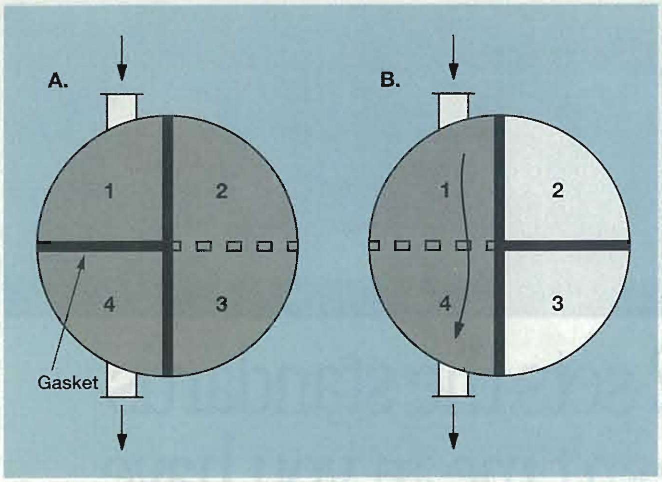

Fig. 9. A) Proper gasket location; B) Gasket reversed by mistake.

ing in flow bypassing the tubes. The second and third passes were starved for flow. This situation can occur when gaskets and gasket grooves have a nonsymmetrical pattern.

Field mistakes. In one instance, a heat exchanger was piped up backwards. The fluid that should have been on the shellside was piped to the channel side and vice versa. When both streams are in turbulent flow, this switch may go unnoticed. In this case, fluid that should have been in the shell was semiviscous. On the shellside, the fluid would have been turbulent and given better heat transfer. When on the tubeside, the fluid flowed in the transition region between turbulent and viscous. This gave a noticeably lower heat transfer, although better heat transfer than calculated.

LITERATURE CITED

1 Gilmour, C. H., "Troubleshooting heat exchanger design," *Chemical Engineering,* June 19, 1967, pp. 221–228.
2 American Institute of Chemical Engineers, New York, New York.
3 TEMA, 7th edition, 1988.
4 Hewitt, G. F., "Hemisphere handbook of heat exchanger design," Hemisphere Publishing Corp., 1990, pp. 3.17.4-1 to 3.17.5-3.
5 Small, W. M., "Not enough fouling? You're fooling!" *Chemical Engineering Progress,* March 1968, pp. 82–84.
6 Fijas, P. F., "Getting top performance from heat exchangers," *Chemical Engineering,* December 1989, pp. 141–145.
7 Yokell, S., "A working guide to shell and tube heat exchangers," McGraw-Hill, 1990, pp. 314–315 and 543–546.
8 Manohane, J. M., G. A. Gregory and K. Aziz, "A flow pattern map for gas-liquid flow in horizontal pipes," *Int. J. Multiphase Flow,* Vol. 1, 1974, pp. 537–553.
9 Love, D. L., "No hassle reboiler selection," *Hydrocarbon Processing,* October 1992, pp. 41–47.
10 Mueller, A. C., "Effects of maldistribution on the performance of heat exchangers," Thermal/Mechanical Heat Exchanger Design—Karl Gardner Memorial Session, winter meeting ASME, December 1986, pp. 1–11.

The author

Dale Gulley *is president of Gulley Computer Associates, a corporation he founded in 1966 that specializes in heat exchanger design and consulting. They provide software for heat exchanger design and process calculations. Mr. Gulley has heat exchanger and software development experience that spans 40 years and has previously published articles in* Hydrocarbon Processing. *He is a chemical engineering graduate from Oklahoma State University. Mr. Gulley is a director of the Tulsa Science Foundation and a member of AIChE and ASME. He is a registered professional engineer in Oklahoma.*