Electric Heaters: Fouling, Feeders, Vaporization, PSVs, and More

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Presenter: **Dennis O. Dever, Dever Technology, LLC**
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Abstract

Selected technical issues and numerical calculations associated with electric heaters are presented. Available electric heater technologies are listed. The advantages of electric heaters are described and the challenges regarding very high temperature electric heaters are summarized. The fundamental issues surrounding constant surface temperature turbulent heat transfer and constant flux turbulent heat transfer fluid will be explained with an eddy example.

Design calculations unique to electric heat applications will be presented:

- The results of a numerical study will be provided to demonstrate the problem of fouling with a radiation-based or impedance-based electric heater design.
- The results of a numerical heat transfer study for a common power feeder design will be provided.
- As an example of how direct electric heat differs from a steam heated exchanger, a comparison using vaporization will be given.
- The pressure relief calculation for a blocked pressure vessel with electric heat will be provided.

Important ohmic resistor materials will be listed with some characteristics important for their suitability in various applications. Changes and opportunities in the industry include improved radiant heat transfer software, new designs, new research, and new high temperature materials.

Introduction

There is a large increase in work and investigation into electric heaters throughout the world because of new renewable energy sources of electric power. Chemical Engineers are often not familiar with either the simple or sophisticated issues associated with electric heaters. This presentation will introduce engineers to some of these issues.

Lists and information are provided here for technologies, advantages, very high temperature challenges, resistors, radiant heater improvements, turbulent heat transfer, electric heater fouling, vaporization, and relief flow.

Electric Heater Technology List

1. Microwave. There are commercial microwave systems that heat fluids, chemicals, foods, sheet materials, and are used for drying. Systems are being promoted for the very high temperatures needed to dissociate methane.

2. Plasma. The biggest electric heater is an electric arc furnace (EAF) in Japan. In an EAF, current conducts through plasma from upper electrodes to a lower metal level. The power input is controlled, and heat radiates from the arc and ohmic heat is also generated in the metal. The electrodes attain temperatures as high as 3,000 °C (5,432 °F). Other plasma heaters ionize gas flowing past electrodes to discharge gas at higher temperatures.

3. Induction. Induction heaters create a magnetic field that generates eddy currents in a conductive material. If the process material is not conductive, a conductive material can be heated inside the equipment which will then heat the non-conductive process material by contact or radiation. This is a non-contact method used to melt metals, solder, heat silicon, and more. These can be used for very high power and temperature levels.

4. Electric Immersion Heaters. Electric immersion heaters are common electric heaters in refineries and chemical plants and are the least costly electric heaters. They resemble BEU steam heat exchangers but with sheathed U-tube elements. They heat air, water, heat transfer oil, hydrogen, and are used in reforming units.

5. Electric Radiant Heaters. Radiant heaters use high temperature resistors to radiate heat to a vessel, pipe coil, or tube coil. These are popular in high purity silicon production for the PV industry and high temperature hydrogen heaters. There are many types of radiant heaters.

6. Impedance. In impedance heaters, the live voltage in the heat source is in direct contact with the process. These work well for the very high pressures needed in supercritical water oxidizers and supercritical carbon dioxide processes. There are many types of impedance heaters.

7. Electric Conductive Fluid Heaters. In an electric conductive fluid heater, ohmic heat is generated directly in the fluid.

8. There are other technologies.

Advantages of Electric Heaters

1. High Temperatures. Electric heaters can provide very high temperatures. Whereas, even at 171.4 barg, saturated steam can only reach 353.4 C. Proven electric heater designs are available for heaters with a 3,000 °C process temperature.

2. Control. Electric heater power can be turned on and off every 0.01 second (half cycle) providing almost instantaneous power control and 0% to 100% turndown.

3. Stable Temperatures. Electric heaters do not have the fluctuating temperatures that flames have.

4. Negative Electricity Prices. There are some opportunities for very low energy prices at various locations and times because of renewable sources.

5. Regulatory Advantages. Electric heaters do not require the clean air permits that fired equipment require. Governments promote the use of electric heat to reduce carbon dioxide emissions.

Challenges with High Temperature Electric Heaters

1. Shutdowns. The electric heaters with the highest temperatures tend to use graphite electrodes or resistors and tend to be in the metals industry. In the metals industry, there are much more frequent shutdowns between runs than occur in refining or chemicals. Periodic replacement of graphite occurs, and this would be a major problem in a steady-state refining or chemical process.

2. Power Feeders. Penetrating a pressure boundary and insulation with conductors can be challenging. Electric current must conduct from the junction box where power is supplied at ambient temperatures to the interior of an electric heater, the interior of an electrically heated reactor, or the interior of other electrical equipment. Three issues must be addressed. The voltage must be isolated throughout the whole path. The ohmic heat generated in the conductor must be minimized and allowed to escape. The thermal expansion of the different materials must be managed.

3. Pressure Vessel Code. The ASME pressure vessel code limits pressure boundaries to 980 °C (1,800 °F) maximum. Only three materials are allowed for a code material at this highest temperature, and it may be impossible to purchase two of those three in a quantity less than a mill run. The boundary consists of the metal resisting the pressure of the process. This typically includes a cylindrical shell, heads, nozzles, and flanges. A pressure vessel containing a process with a temperature greater than 980 °C must have internal insulation to protect the boundary. At the highest temperatures allowed by the vessel code, there are additional challenges such as a very low allowable stress.

4. Creep. Metal gradually changes dimension under stress at high temperatures. Therefore, the pressure vessel code limits the allowable life span of equipment at very high temperatures.

5. High Temperature Material. Several types of material tend to be required within an electric heater. Examples are structural supports, insulation, current conductors, or ohmic resistors. These materials must resist the chemical environment and maintain their functional use at elevated temperatures for a long duration. The properties tend to change at high temperatures.

6. Thermal Expansion. As temperature increases different materials grow at different rates. Stress occurs if materials are constrained.

Turbulent Flow in Electric Heaters

There is a fundamental difference between constant flux heat transfer and heat transfer with a constant surface temperature. Electric heat is often considered a constant flux application. However, electric heat differs from idealized constant flux and heating with condensing steam differs from constant surface temperature. This issue will be investigated using eddy estimates in a low velocity turbulent water flow example.

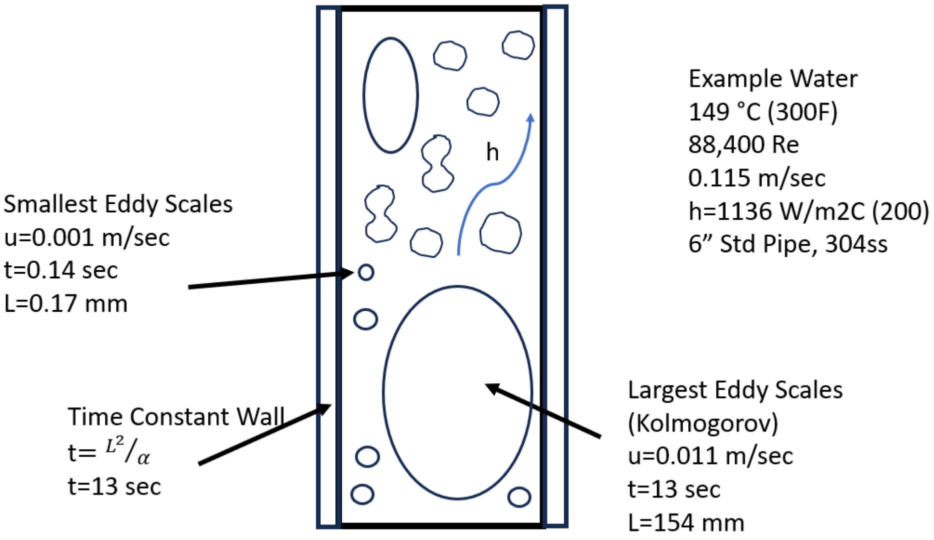

Figure 1 Eddy Size and Duration Example

In a turbulent fluid flow, there are volumes of fluid that are large enough to have enough momentum to break free of the laminar viscous forces holding them in place. These volumes are called eddies, and they are continually impinging on the wall. Local heat transfer is very high when these eddies crash into the wall. Heat transfer is low and laminar-like between eddies.

The largest and smallest eddy can be estimated using methods by the Russian mathematician Kolmogorov. This example is for water at 149 °C with an average velocity of 0.115 m/sec and Reynolds number of 88,400 in a 6-inch schedule 40 type 304 stainless steel pipe. In this low velocity example, the smallest eddy has an approximate lifespan of 0.14 seconds, and the largest lifespan is 13 seconds. This schedule 40 wall has a time constant of 13 seconds. Therefore, the thermal storage of the wall will dampen out the fluctuations of all the eddies except the largest. These three durations are order of magnitude estimates.

Because of this, the flux at the process surface of an electric heater will fluctuate somewhat because of the eddies impinging on the wall while the heat source is on the other side of the wall's thermal storage. The temperature at the process surface of a steam exchanger will fluctuate somewhat because of the eddies impinging on the wall while the condensing steam surface is on the other side of the wall. Although the idealized boundary conditions are not strictly accurate, this does not suggest that typical heat transfer correlations can be used for an electric heater. However, there are examples where the same heat transfer correlations can be used.

A typical liquid velocity in a process application will be about 0.6 m/sec to 3.6 m/sec. At these higher velocities, the largest eddies will still be about the size of the pipe inner diameter but there will be much smaller eddies. Therefore, the idealized cases are even less relevant at normal velocities.

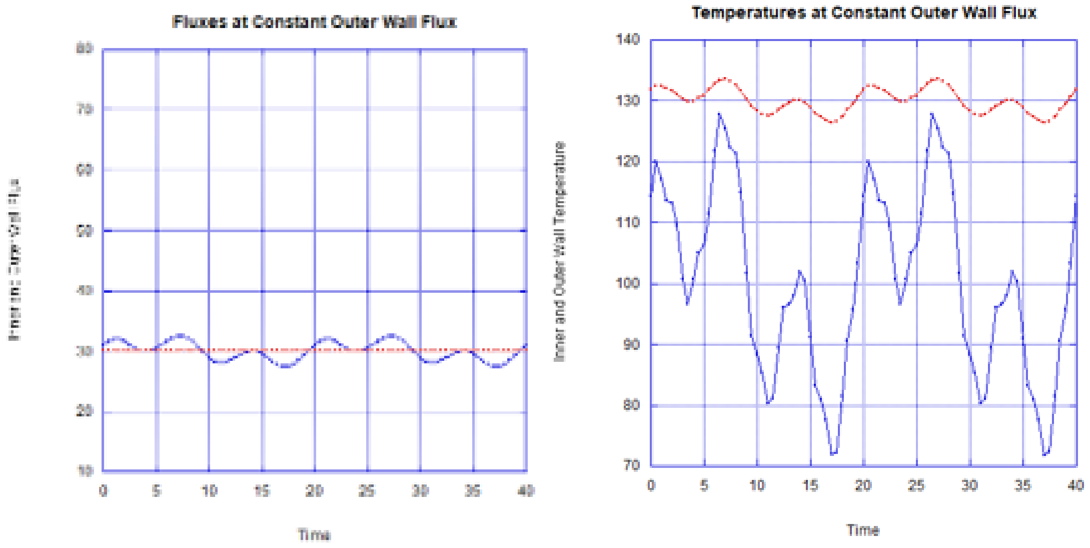

Figure 2 Flux and Temperature at Constant Flux

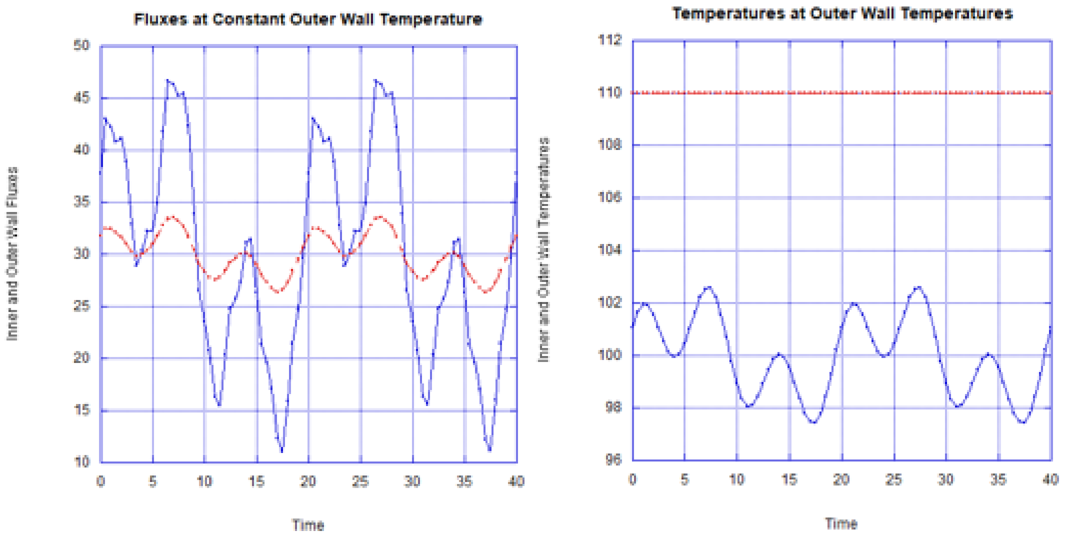

Figure 3 Flux and Temperature at Constant Temperature

Conceptual diagrams are displayed to illustrate this in Figures 2 and 3. These plots are neither data nor numerical calculations.

Numerical Study of Fouling in an Electric Heater

Fouling in a traditional heat exchanger will reduce the heat transfer flux at the location of the fouling. The total duty may be reduced so that the process requirements are threatened. In an electric heater, heat is generated in the ohmic resistors and the flux at the resistor is relatively constant. Therefore, if a thermal barrier like fouling occurs close to the electric heat source the temperature at that point will rise significantly. Therefore, fouling is a bigger problem in an electric heater and can destroy the equipment.

The effect of fouling will be investigated here using a numerical calculation and 2D geometry. One half of the 2D geometry is displayed with the other half above the horizontal line of symmetry across the top.

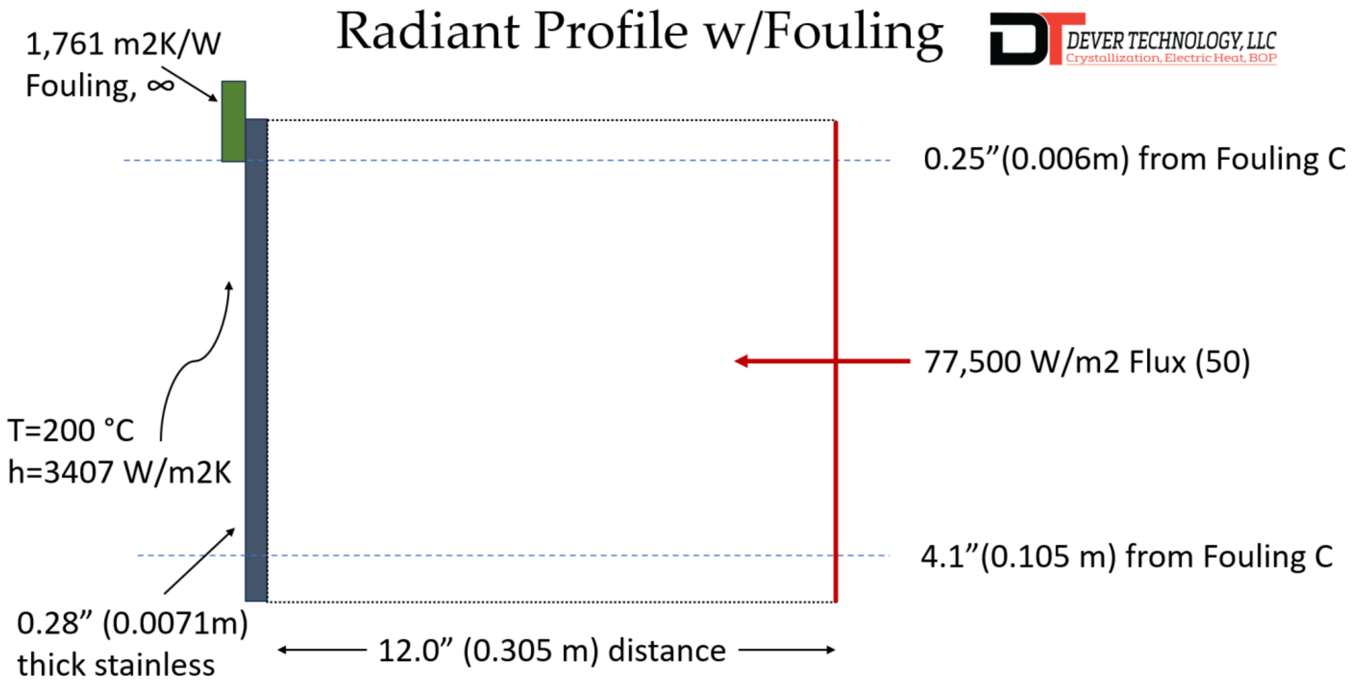

Figure 4 Inputs to the Radiant Heat Transfer Calculation with Fouling

The conditions and inputs for this numerical study of fouling with an electric heater are:

- A process fluid at 200 °C being heated by a vertical stainless-steel plate with a heat transfer film coefficient of 3,407 W/m^2K.
- The flat vertical stainless-steel plate has an emissivity of 0.60 and is 7.1 mm thick.
- A separation of 0.305 m between the hot side of the process plate and a radiant wall
- The radiant wall has an emissivity of 0.74 and an evenly distributed high flux of 77,500 W/m^2.
- At the line of symmetry, there is 12.7 mm of fouling blocking heat flux. Half of that height or 6.35 mm extends vertically into the visible symmetric plane.

This calculation is nonlinear. There is a domain with many surfaces exchanging heat by radiation and every radiant surface affects every other radiant surface. There is a separate domain internal to the process plate with many elements conducting heat, but only to the elements in direct contact. By guessing the temperatures along the line between the two domains, the two domains can be evaluated separately. Linear matrix math can calculate each domain separately and without iteration if the assumed temperatures are correct. A heat balance on the elements with assumed temperatures will indicate a net zero heat input rate if the temperature assumptions are correct. If more heat enters the elements by radiation, the assumed temperatures need to be increased for the next iteration. If more heat exits the elements by conduction, the assumed temperatures need to be reduced. The finite difference method was used for conduction and multi-surface gray body radiation was used for the surfaces with radiation.

This calculation confirms that a high source temperature is required to generate a high heat flux. The radiant surface here is about 1,100 °C. Because of the fouling, the process temperature here is 48.4 °C hotter at the fouling centerline. The fouling does not have much effect farther than 30 mm from the centerline of the fouling. The driving force for radiation is the difference between the fourth power of the absolute temperatures. At these temperatures, the fourth power of the source temperature is about 48 times greater than the fourth power of the target temperature (1104.8 °C versus 250.8 °C is 3.61×10^{12} K^4 versus 7.54×10^{10} K^4). A change in the target surface temperature has little effect. A 19% increase in the absolute target temperature would change the relative driving force from (48-1) to (48-2). These results may motivate consideration in other electric heater designs.

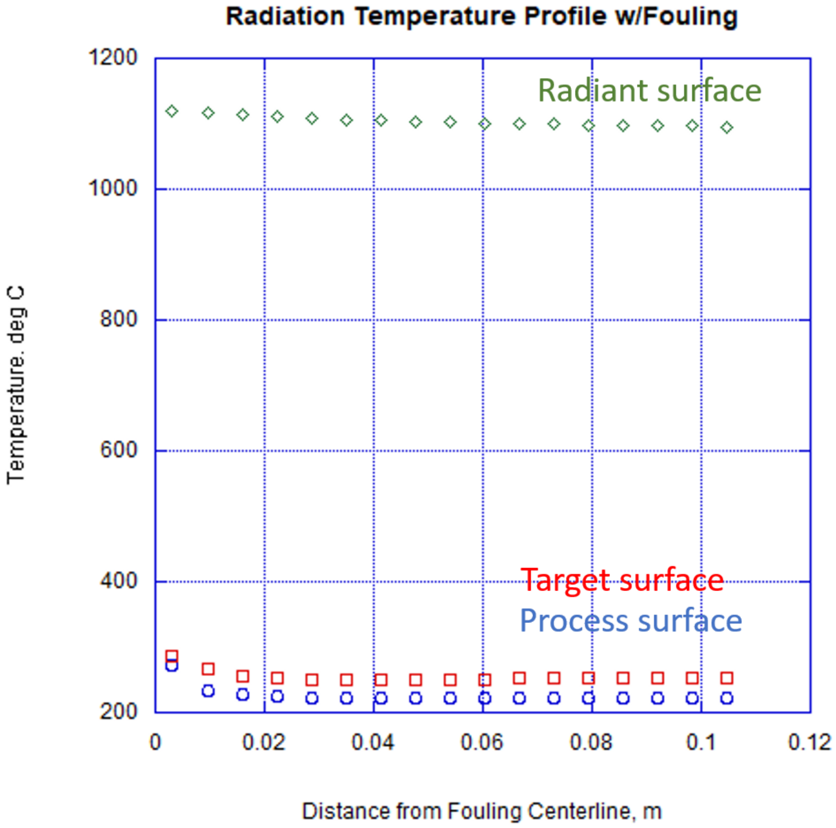

Figure 5 Temperatures with Radiation and Fouling

The same calculation was also executed without radiation as in an impedance heater. The full 77,500 w/m^2 flux was imposed directly on the hot face of the 7.1 mm process plate. In this case, the heat conduction cannot penetrate the semi-infinite fouling and can only bypass it by conduction. Again, over 30 mm from the centerline of the fouling, the fouling does not have an effect. The process temperature here is 53.3 °C hotter at the fouling centerline. This is 10% worse than the radiation case. Conduction is very effective in by-passing the fouling because the wall is thick at 7.1 mm. The hope was that radiation would bypass the fouling because of the temperature rise, but little of this happened because of the 48 to 1 driving force ratio.

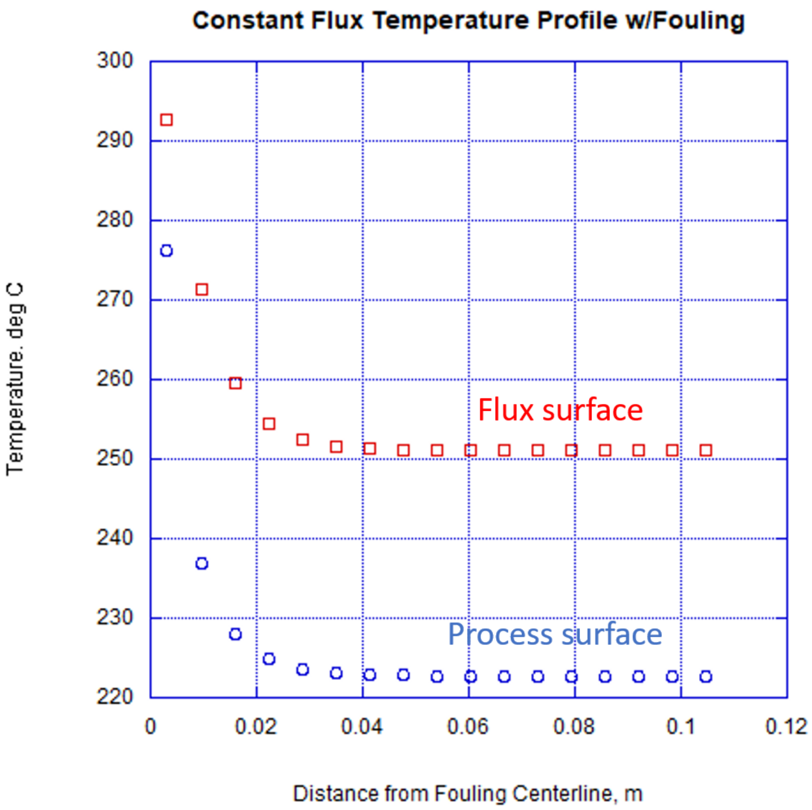

Figure 6 Temperatures with Direct Heat Flux and Fouling

Electric Heater Power Feeder and Cold Pin

The inner temperature profile for a power feed conductor (cold pin) was estimated by numerical calculation. The cold pin is the conductor transmitting current from the junction box into the interior of an electric immersion heater where the hot length starts. The agencies approving electric heaters for installation in hazardous areas require this calculation and others. The safety concern relates to high surface temperatures igniting division 2 or zone 2 hazardous atmospheres. The conduction of current through the cold pin generates heat which must be conducted through packed magnesium oxide and an outer metallic sheath and then must be transmitted by convection to the surrounding air or gas. The thermal conductivity of solid crystal Magnesium Oxide is relatively high. Loose powder has a low effective thermal conductivity. In the past, the thermal conductivity of packed and compressed Magnesium Oxide was published by major manufacturers. There is also a thermal gap resistance because the different materials expand.

This calculation demonstrated that the heat transfer that cools the sheathed element in the cold region is dominated by external free convection. The temperature across the radius of an element is approximately constant. This type of power feed can be used in other designs.

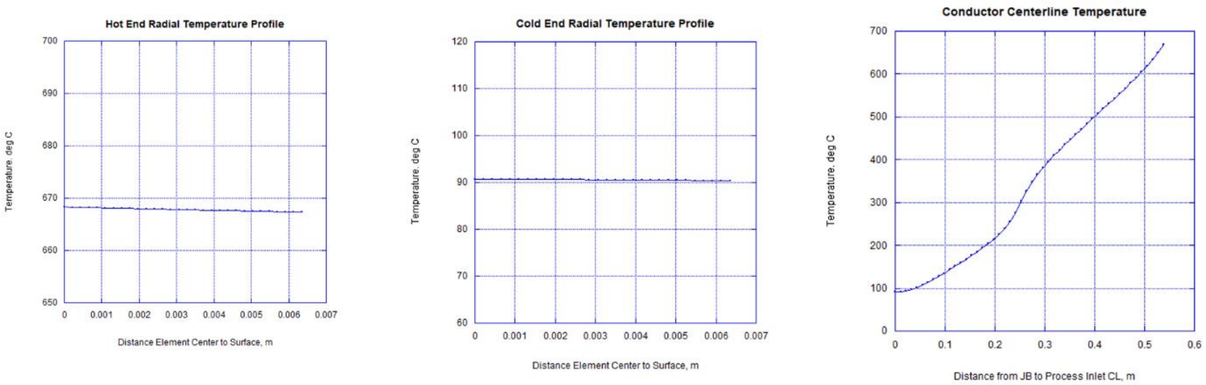

Figure 7 Temperature Profile at Cold and Hot Ends and Along Conductor

Comparison of a Steam Heated Vaporizer versus an Electrically Heated Vaporizer

The difference between process electric heaters and common heat exchangers is illustrated well by comparing vaporizers. The boiling curve for water is shaped similarly for mixtures and other liquids although the temperatures and heat fluxes are different. The x-axis is the temperature difference between the hot surface and the bulk fluid. The y-axis is the heat flux or rate. At lower temperatures, as the hot surface increases in temperature the heat flux increases greatly until the critical heat flux is achieved. For pure water, this occurs when the surface is about 30 °C hotter than the boiling fluid. At higher surface temperatures, a gas film forms at the surface and the heat transfer rate is reduced.

To design a vaporizer with steam or a constant surface temperature, conceptually draw a vertical line on the boiling curve, predict the heat flux, and select a surface and geometry that will supply the duty you need. The primary focus is to supply enough heat. These vaporizers operate in the downslope region. Notice that higher temperatures tend to reduce capacity which has resulted in many bad initial control loops.

To design a vaporizer with electric heat, conceptually draw a horizontal line and select a geometry that will not overheat the process or hardware at any point. The focus with electric heat is to avoid overheating. These vaporizers cannot operate in the downslope region. If the design ever allows the flux to exceed the maximum, the heater will be destroyed. Above the critical heat flux, the heat cannot all be removed, and it will accumulate and overheat before it can reach the radiant region.

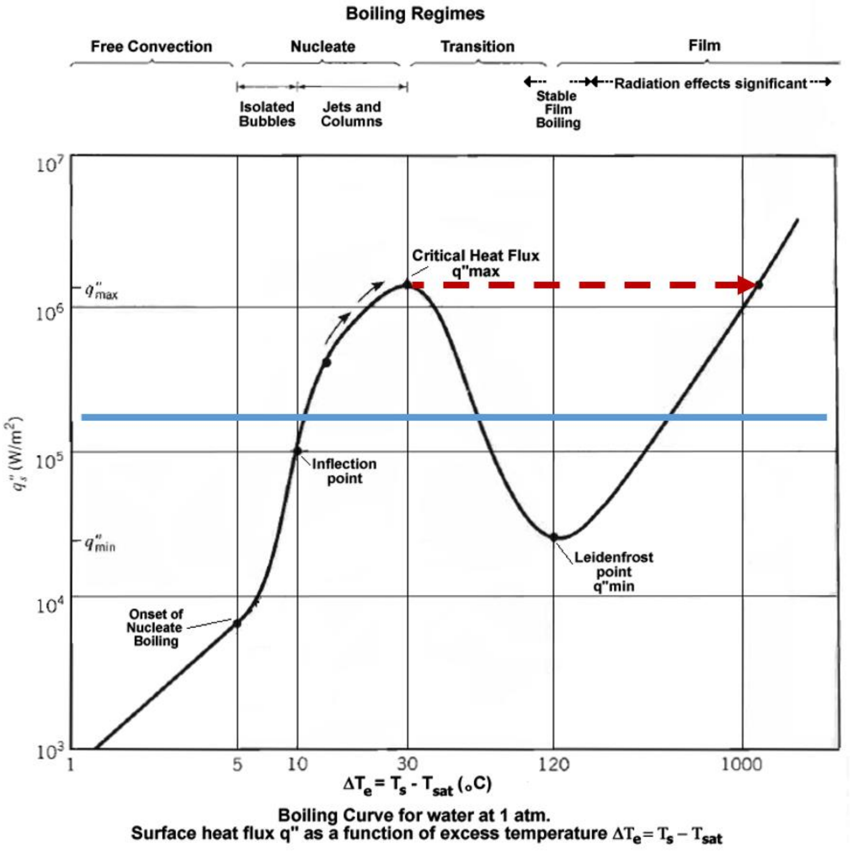

Figure 8 Constant Flux/Electric Vaporizer Example (Wikipedia – Venny85)

Electric Heater Pressure Relief with Thermal Expansion

A Mollier diagram for water is used to illustrate single-phase blocked fluid electric heater pressure relief. This concept applies to a liquid, a gas, a supercritical fluid, or a two-phase fluid that is slowly heated into the supercritical region. The X-axis is enthalpy, and the Y-axis is pressure. Along the liquid region on the left are constant density lines where a very small heat input quickly raises the pressure.

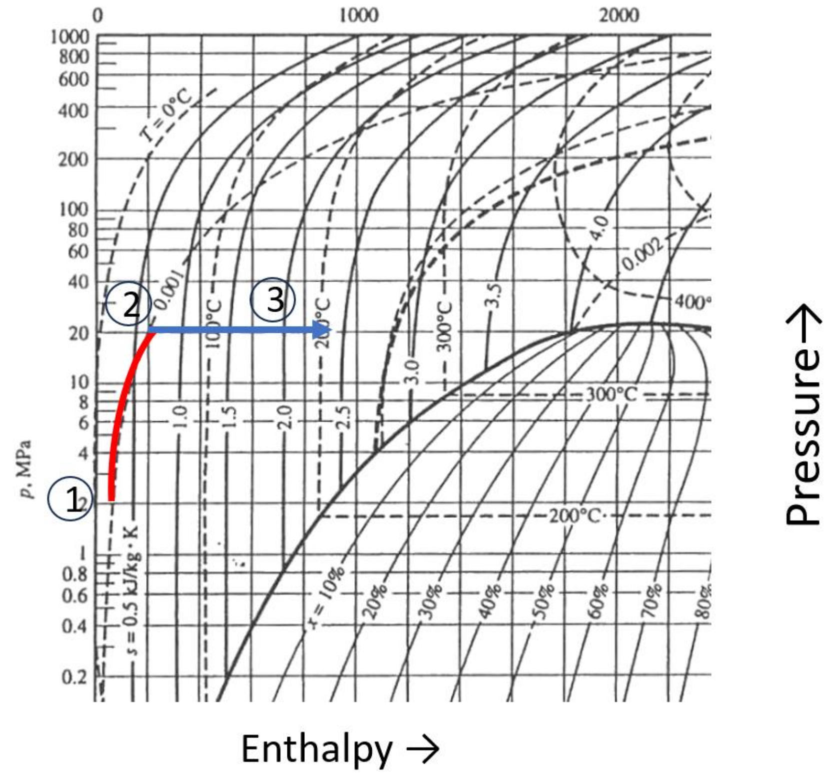

Figure 9 Blocked Volume Electric Heater Relief

If a fluid is trapped in a fixed volume electric heater, then the fluid density equals the trapped mass divided by the vessel volume. If the distortion of the vessel is negligible, the relief scenario involves movement from point 1 to point 2 along the constant density line. It is conservative to neglect the distortion of the vessel but alternately the volume distortion can be estimated. Point 1 is the normal operating point. Point 2 is at the safety valve pressure set point where the valve opens. The heat addition or power from point 1 to point 3 is based on a simple ohmic calculation. For a steam heated exchanger, the heating from point 1 to 3 would be an irregular free convection and dynamic heat transfer mechanism with a changing driving force. In this case, relief flow equals the heat input rate times the ratio of the incremental mass change per incremental heat addition. Vessel volume is not required in the final solution. A constant pressure after the PSV opens is used here. A dynamic flow calculation could be considered to estimate the slope from point 2 to 3. Generally, a Mollier diagram is not available for a process mixture so property correlations can be used to create a 3-point or 5-point Mollier diagram near points 1, 2, and 3. In this equation, $\dot{m}$ equals mass flow (kg/hr), Q equals heat input (kJ/hr), β equals thermal expansivity (1/C), and C_p equals heat capacity (kJ/kgC).

$$\dot{m} = \frac{Q\beta}{C_p}$$

This method provides a flow value. The sizing and selection of the safety valve is separate. Consider the following,

- Single phase thermal expansion has been traditionally handled without calculations by choosing the smallest safety valve (PSV) with a Code Stamp. Trapped electric heat is like thermal expansion but with greater heat input. This method is an improvement.
- Large safety factors are used to convert yield and tensile stresses into allowable stresses.
- Vessel internal pressure is allowed to drift upwards by 10% of the set point during relief flow.
- Metal allowable stresses are effectively larger in a highly dynamic scenario.
- Extreme slopes could be applied to the line from 2 to 3 to investigate sensitivity.

Electric Heater Resistor List

Nickel Chromium alloys are very common resistors for electric heaters. The 70/30 alloy is suitable for higher temperatures than the 80/20 alloy but it should not be used in Magnesium Oxide. The resistance change with temperature is very low for the Nickel Chromium alloys which is a significant benefit.

The maximum temperature allowed on a pressure vessel material is 980 °C which is available with Alloy 800H. Two other code materials are allowed at 980 °C but commercial availability for them is very challenging. There are serious challenges such as creep and very low allowable stress at temperatures near 980 °C for all code materials. This issue is important for type 1 impedance heaters because the pressure boundary heats the fluid.

Tungsten and APM are suitable at higher temperatures, but tungsten quickly oxidizes in air. Tungsten has a 550% change in resistance with temperature which requires special power controls.

Silicon Carbide and Molybdenum Disilicide may be used at very high temperatures, but the resistivity curves require extra cost and effort. Some chemical environments are restricted.

Designs at process temperatures of 2,000 °C to 3,000 °C tend to be in the metals industry and use graphite. The graphite is used for electrodes, resistors, and insulation. The graphite is frequently replaced which is unacceptable in industries with long periods between shutdowns.

Electric Radiant Heater Improvements

A helical pipe or tube coil heated by hot ohmic resistors near the wall has been a common radiant design for several decades. There are four big improvements versus the old designs.

- The helical geometry with outer elements will result in hot spots at high heat fluxes. At high temperatures or high fluxes, there are better geometries.
- Improvements in ohmic resistor materials
- Excellent radiation and view factor software
- Good research and correlations for helical flow pressure drop and heat transfer

Published view factors are not available for the most common commercial geometries like helices or radial patterns of cylinders in an outer cylindrical shell. In one case, the element-to-element view factor for a helix design was 0.22 whereas a manual estimate was 0.05. A high view factor from radiant elements to themselves is undesirable.

Flux based design methods by experienced engineers are good for estimates, preliminary proposals, and initial iterations. However, avoid flux-based designs for high temperatures.

Conclusions

At typical process temperatures an electric radiant heater will probably not greatly improve the peak temperatures that can occur with localized fouling in a more direct electric heater design. At very high target surface temperatures, radiation may provide benefits. The extent to which wall conduction can allow heat to bypass fouling was demonstrated with one example.

A numerical calculation indicated that external free convection dominates the cooling needed in the power feeder to an immersion heater. The need to design and control an electrically heated vaporizer below the critical heat flux was described. A safety valve sizing method was provided for an electric heater with a blocked fluid. Four improvements in modern radiant heaters versus legacy designs were listed.

Dennis O. Dever, PE, PhD

ddever@devertechnology.com

www.devertechnology.com