ELECTRIFYING THE FUTURE: PREDICTING THE LONGEVITY OF ELECTRIC RESISTIVE ELEMENTS

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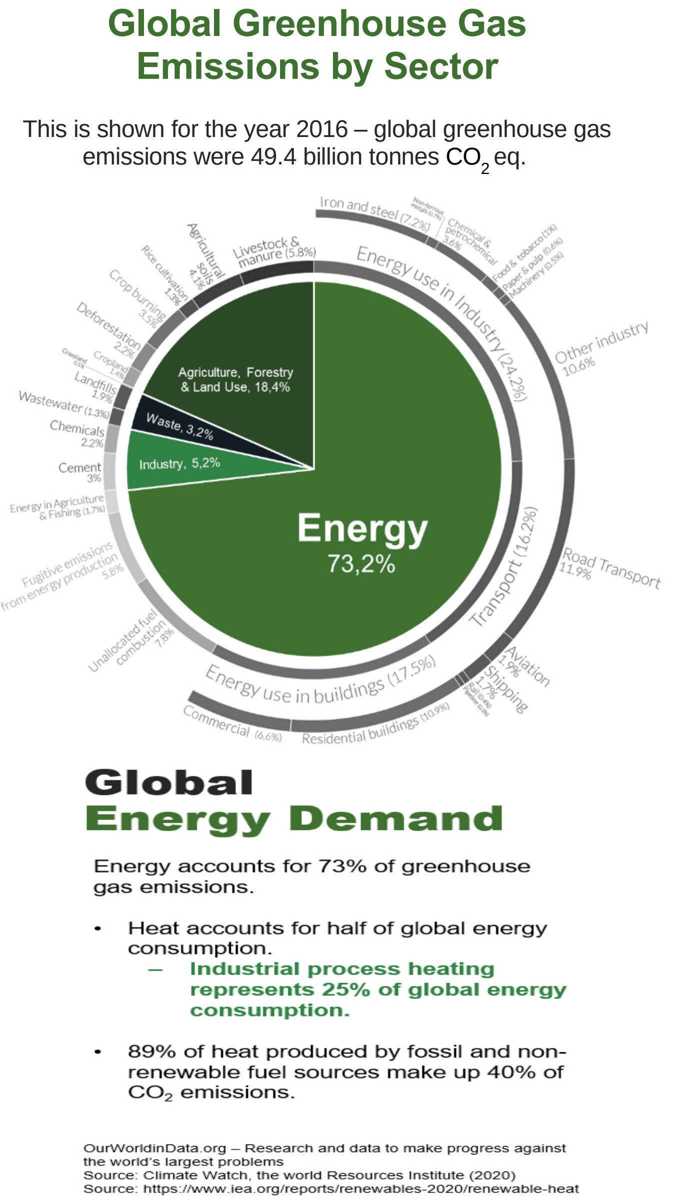
Abstract – Predicting the lifespan of electric resistive elements within conductive heating applications is crucial for operational efficiency and reduced downtime. In this paper, we present a comprehensive approach that emphasizes the accuracy of lifespan predictions through the utilization of predictive modeling, and advanced analysis techniques. We leverage cutting-edge third-party heat transfer software to design the heaters, focusing on the predictability of sheath temperatures and incorporating factors cyclic loading to enhance element longevity. Computational fluid dynamics (CFD) analysis and scientific validation by a test lab play key roles in validating the accuracy of our predictions. This multidimensional approach enables industries to improve maintenance planning, minimize unforeseen failures.

Index Terms –

I. INTRODUCTION

Electric resistive elements are fundamental components in conductive heating applications, playing a critical role in heating processes across various industries to electrify the future. The lifespan of these elements significantly impacts operational efficiency, downtime, and maintenance costs. Predicting the longevity of electric resistive elements with precision is essential for ensuring optimal performance and reliability. In this paper, we present a comprehensive approach to predicting the lifespan of electric resistive elements within conductive heating applications, emphasizing the importance of accurate lifespan predictions and highlighting the insights gained from predictive modeling, real-world operational data, and advanced analysis techniques.



Global Greenhouse Gas Emissions by Sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2 eq.

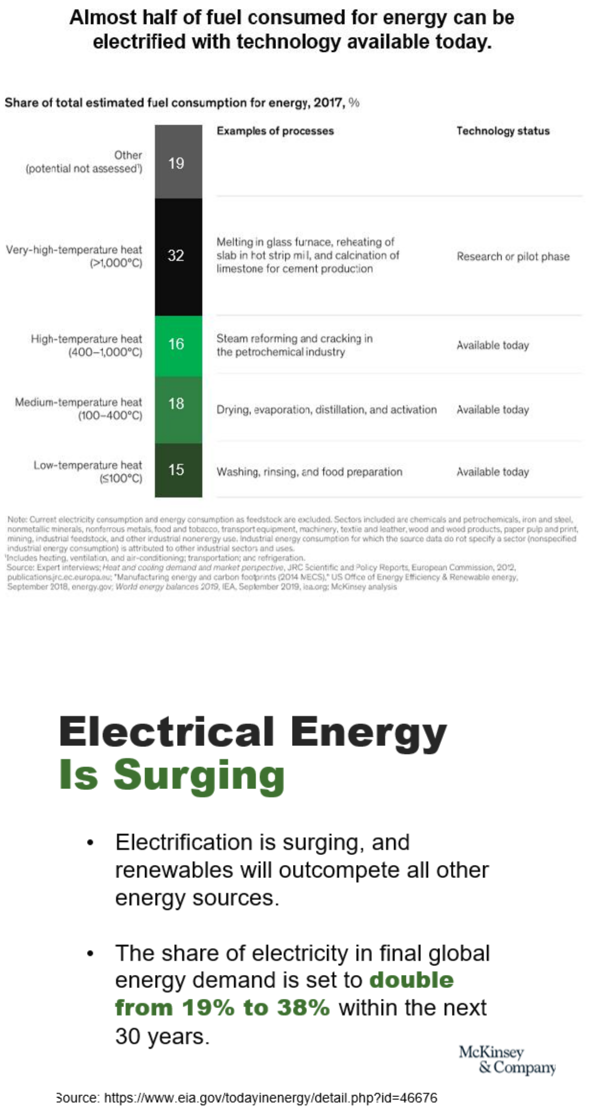
Global Energy Demand

Energy accounts for 73% of greenhouse gas emissions.

- Heat accounts for half of global energy consumption.
  – **Industrial process heating represents 25% of global energy consumption.**
- 89% of heat produced by fossil and non-renewable fuel sources make up 40% of CO_2 emissions.

OurWorldinData.org – Research and data to make progress against the world's largest problems
Source: Climate Watch, the world Resources Institute (2020)
Source: https://www.iea.org/reports/renewables-2020/renewable-heat

Fig. 1 Global Energy Demand Data



Almost half of fuel consumed for energy can be electrified with technology available today.

Share of total estimated fuel consumption for energy, 2017, %

		Examples of processes	Technology status
Other (potential not assessed¹)	19		
Very-high-temperature heat (>1,000°C)	32	Melting in glass furnace, reheating of slab in hot strip mill, and calcination of limestone for cement production	Research or pilot phase
High-temperature heat (400–1,000°C)	16	Steam reforming and cracking in the petrochemical industry	Available today
Medium-temperature heat (100–400°C)	18	Drying, evaporation, distillation, and activation	Available today
Low-temperature heat (≤100°C)	15	Washing, rinsing, and food preparation	Available today

Note: Current electricity consumption and energy consumption as feedstock are excluded. Sectors included are chemicals and petrochemicals, iron and steel, nonmetallic minerals, nonferrous metals, food and tobacco, transport equipment, machinery, textile and leather, wood and wood products, paper pulp and print, mining, industrial feedstock, and other industrial nonenergy use. Industrial energy consumption for which the source data do not specify a sector (nonspecified industrial energy consumption) is attributed to other industrial sectors and uses.

¹Includes heating, ventilation, and air-conditioning; transportation; and refrigeration.

Source: Expert interviews; *Heat and cooling demand and market perspective*, JRC Scientific and Policy Reports, European Commission, 2012, publications.jrc.ec.europa.eu; "Manufacturing energy and carbon footprints (2014 MECS)," US Office of Energy Efficiency & Renewable energy, September 2018, energy.gov; *World energy balances 2019*, IEA, September 2019, iea.org; McKinsey analysis

Electrical Energy
Is Surging

- Electrification is surging, and renewables will outcompete all other energy sources.
- The share of electricity in final global energy demand is set to **double from 19% to 38%** within the next 30 years.

McKinsey & Company

Source: https://www.eia.gov/todayinenergy/detail.php?id=46676

Fig. 2 Fuel Consumption Data

II. ELECTRIFYING THE FUTURE

Electrification can be a key strategy [1] [2] for eliminating or reducing emission of harmful gases, but it can also improve overall efficiency. Electrifying process heating is highly efficient because it generates heat directly, requiring less equipment, fewer processes and the temperatures can be precisely controlled, which reduces heat waste. These methods are also suitable for a wide range of heating applications, such as heating metal surfaces, ambient air, water or viscous liquids. For companies that rely on process heating systems, making the switch from natural gas-fired heaters to electric heaters holds many advantages. Modern electric heating systems can be used to provide clean, reliable, safely controlled heating for industrial processes.

III. CHALLENGES IN ELECTRICAL RESISTANCE HEATING

The history of electric process heating traces back to the late 1800's, when electric resistance heating emerged as a promising alternative to conventional heating methods. Since then, electric heaters have undergone significant advancements, evolving into specialized equipment for industrial applications. With the advent of modern engineering design tools and simulation software, engineers are now able to create more accurate, efficient, and customized designs for electric process heaters.

In the past, engineers relied heavily on rule-of-thumb heating element watt density selection guidelines developed throughout the years for various fluids and gases. However, these methods lacked precision and often resulted in suboptimal designs. Legacy design rules were based on approximations and simplified assumptions, failing to account for crucial factors like fluid flow patterns and thermal behavior. This led to over-engineered or underperforming designs that limited optimization possibilities.

In stark contrast, modern engineering design tools such as Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), and third-party process heating design simulation software has revolutionized the field. These advanced tools employ sophisticated numerical algorithms to simulate and analyze complex physical phenomena, enabling engineers to model fluid flow, structural design, and heat transfer with unparalleled accuracy and detail.

By leveraging these tools, engineers can optimize electric process heater designs for maximum efficiency and improved performance. Parameters such as mass flow rate, specific heat capacity, thermal properties of the fluid, power requirements, and physical design constraints can be precisely modeled and analyzed. This comprehensive approach captures the intricacies of heat transfer phenomena, leading to designs that are smaller and tailored to specific requirements.

Electric process heaters are designed solely for the purpose of generating heat, using an electric heating element. Electric heaters do not involve the transfer of heat between fluids but rather the direct conversion of electrical energy into heat energy. While the operating temperature of the heat exchanger tubes are limited by the temperature of the heat transfer fluid, the operating temperature of electric heating element tubes depends on the heat flux of the heating element and how effective the heat transfer between the heating element and process fluid. Advancements in electric heater design have highlighted the need for more modern designs, including directional flow baffles.

There are however several challenges that need to be addressed when using electrical resistance heaters, particularly those with constant heat flux elements. One of the main challenges in electrical resistance heating applications is the limitation that certain process fluids have. Excessive temperatures can lead to coke formation, chemical disintegration, and negative yield performance.

Additionally, pressure vessel temperatures can also pose a challenge in electrical resistance heating applications. The heat generated by the resistance elements can cause an increase in pressure vessel temperatures, which can lead to issues such as thermal expansion, material degradation, and radiation heat loss. Proper thermal calculations and heat shields must be implemented to control the temperature of the pressure vessel and prevent any potential damage.

Fig. 3 Effect of Fluid Overtemperature

Fig. 4 Effects of Overpressure of Vessel

Lastly, but very important, is the challenge in electrical resistance heating applications for the life expectancy of the resistance elements. Constant heat flux elements can degrade over time due to factors such as thermal stress, oxidation, and mechanical wear, but mainly because the sheath temperature, and thus the wire temperature is higher than anticipated.

Fig. 5 Failed Electric Heating Elements

IV. DESIGNING ELECTRICAL RESISTANCE HEATERS

Using state of the art and accurate thermal design tools for electrical resistance heaters is crucial to ensure the sheath temperatures are controlled and predictable. Engineers must follow a comprehensive design approach to achieve this, which includes the following key steps:

First the design process uses an industry-recognized third-party sizing tool which provides reliable heat transfer and pressure drop predictions. This software provides critical design data for predicting the thermal design parameters.

Next, the flow rate must be used to determine the flow conditions based on the heater design, the fluid being heated and the temperatures that will be used during the heating process. This will often involve the use of directional flow baffles to provide an optimized solution.

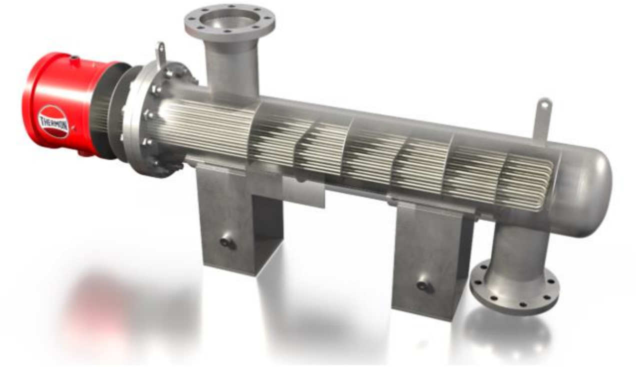
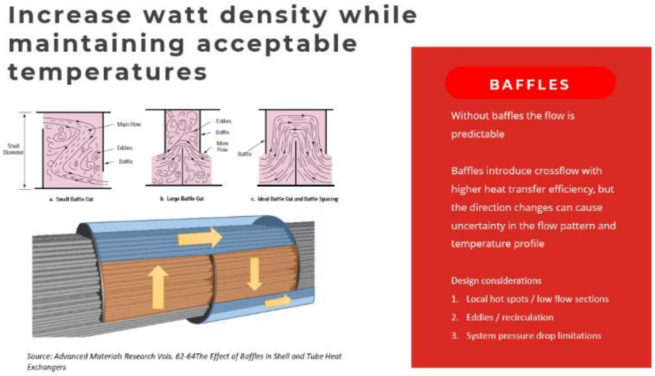


Fig. 6 Electric Heater with Flow Baffles

Directional flow baffles have long been utilized in heat exchanger designs to enhance heat transfer efficiency. Heat exchangers are devices used for transferring heat between two fluids, with the goal of heating the process fluid, or cooling. Directional flow baffles are strategically engineered structures placed within heaters to control fluid flow patterns.



Increase watt density while maintaining acceptable temperatures

Source: Advanced Materials Research Vols. 62-64The Effect of Baffles in Shell and Tube Heat Exchangers

BAFFLES

Without baffles the flow is predictable

Baffles introduce crossflow with higher heat transfer efficiency, but the direction changes can cause uncertainty in the flow pattern and temperature profile

Design considerations

1. Local hot spots / low flow sections
2. Eddies / recirculation
3. System pressure drop limitations

Fig. 7 Directional Flow Baffle Diagram

The advantages of directional flow baffles in industrial electric process heating equipment are critical for design optimization. Firstly, they enhance heat transfer by creating controlled turbulence and efficient fluid mixing, reducing the boundary layer thickness, and if done correctly could prevent stagnant zones. This leads to higher overall heat transfer coefficients, enhanced heat transfer rates, and more compact heater designs, or lower temperatures.

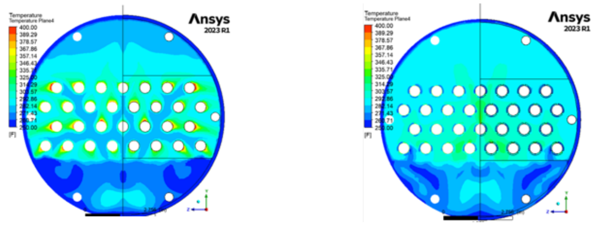
Furthermore, directional flow baffles improve flow distribution by guiding the flow uniformly across the heat transfer surfaces. This optimized flow distribution minimizes thermal gradients over the element bundle, ensures efficient heat transfer throughout the heater, and eliminates hotspots.

Dead zones and fouling present a risk, which can hinder heat transfer efficiency, leading to local low heat transfer coefficient, but can be effectively mitigated by correctly designed directional flow baffles. These baffles disrupt the formation of stagnant regions by inducing fluid motion and turbulence, preventing the accumulation of deposits and fouling. This, in turn, reduces cleaning and maintenance cycles, leading to improved heater performance and reduced downtime.

One notable advantage of directional flow baffles is their ability to increase element surface watt density without raising the element surface temperatures, as the heat transfer coefficient has been significantly increased. This increased element surface watt density facilitates the design of smaller, more cost-effective heaters, offering benefits in terms of equipment size, installation space, and overall system costs.

In contrast, incorrectly designed flow baffles could lead to hot spots and dead zones thereby reducing heater performance and heater life. For this reason, modern design tools are critical to ensure safe and reliable heater operation.

Once the design and performance data has been analyses, the next step is CFD analysis of local hot spots: We perform computational fluid dynamics (CFD) analysis to identify and address any potential hot spots in the system. By simulating the flow and heat transfer processes, we can optimize the design to ensure uniform heating along the length of the heater.



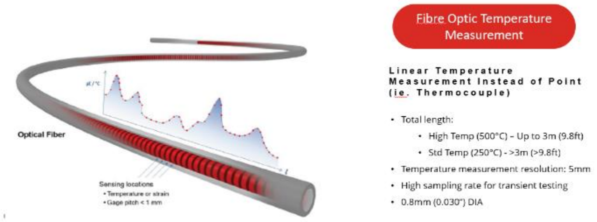
Standard Opening

Modified Opening with Flow-Through Design

Fig. 8 CFD Flow Analysis

V. VALIDATION OF DESIGN SIMULATIONS

Once the design parameter computer-aided simulations have been completed, it is most crucial to perform a validation test to verify the results of the design software and CFD analysis to ensure correct assumptions. The validation test lab should use high accuracy thermocouples or fiber optic sensors to measure the local temperatures along the length of the heating elements. This experimental data provides valuable insights into the actual thermal performance of the system, allowing validation and to refine the design calculations.

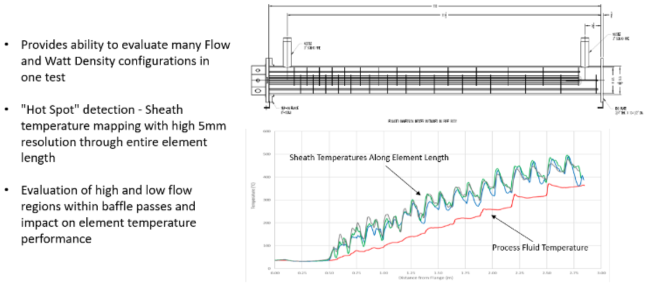


Fibre Optic Temperature Measurement

Linear Temperature Measurement Instead of Point (ie. Thermocouple)

- Total length:
    - High Temp (500°C) – Up to 3m (9.8ft)
    - Std Temp (250°C) - >3m (>9.8ft)
- Temperature measurement resolution: 5mm
- High sampling rate for transient testing
- 0.8mm (0.030") DIA

Fig. 9 Fiber-Optic Sensors



- Provides ability to evaluate many Flow and Watt Density configurations in one test
- "Hot Spot" detection - Sheath temperature mapping with high 5mm resolution through entire element length
- Evaluation of high and low flow regions within baffle passes and impact on element temperature performance

Fig. 10 Example of Validation Test Results

Through a combination of CFD analysis and validation test data, a heater manufacturer can develop a proprietary tool that enhances the thermal predictability of the sheath temperatures. This tool incorporates the insights gained from simulations and experiments to further improve the accuracy of the thermal design calculations.

By following this design approach, engineers can ensure that our electrical resistance heaters maintain controlled and predictable sheath temperatures, leading to more and reliable heating processes. This unique methodology combines advanced simulation techniques with practical testing methods to deliver high-performance thermal solutions to users of electric process heating equipment.

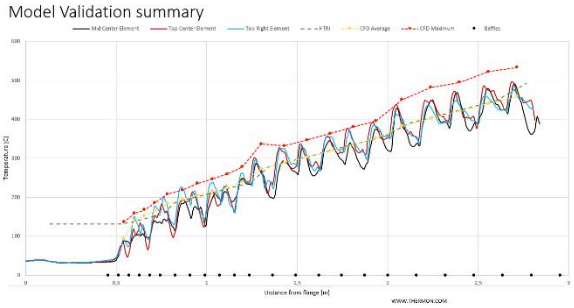


Fig. 11 Heater Validation Test Results

VI. ABOUT HEATING ELEMENT OPERATIONAL LIFE

There are many factors which affect the operational life of a heating element. Some of these factors can be controlled by proper design, manufacturing, testing and inspection controls. There are other factors which can not be controlled by standard manufacturing, testing and inspection processes, and which are affected by operational and environmental conditions. To provide a better understanding of these factors, they are categorized into three groups as shown below.

1) Design Related
   a) Selection of correct sheath material for the fluid or gas being heated
   b) Selection of the heat flux or watt density based on the fluid or gas, and based on flow conditions and operating temperature
   c) Selection of the element diameter based on the rated voltage
   d) Selection of the resistance wire coil material and cold pin material
   e) Spacing of the resistance coil diameter and coil pitch
   f) Selection of the amount and type of dielectric material between live parts and grounded element sheath
   g) Design of the electrical connections between resistance wire coil and cold pin
2) Manufacturing Related
   a) Compaction density of the dielectric material
   b) Impurities in dielectric material
   c) Amount of dielectric material between the element sheath and resistance wire coil
   d) Off-centering of resistance coil
   e) Resistance coil spacing creating localized hot-spot
   f) Damaged resistance coil
   g) Electrical connection between resistance coil and cold pin
   h) Manufacturing defect
   i) Repressing of hairpin bends
   j) Cold end junction located inside of bend area
3) Operational or Environmental Related
   a) Manufacturing defect
   b) Repressing of hairpin bends
   c) Cold end junction located inside of bend area
   d) Operational and Environmental Related
   e) Overtemperature operation
   f) Coking or scaling
   g) Overvoltage
   h) Incorrect flow or loss of flow
   i) Contamination of dielectric material
   j) Degradation of resistance coil
   k) Mechanical damage
   l) Voltage spikes
   m) Sheath corrosion
   n) Overheating of electrical connections

It is important to note that the factors listed in Group 1 – Design Related, and Group 2 – Manufacturing Related can be controlled by proper design, manufacturing, testing and inspection controls. These controls include manufacturers' internal standards, in-house inspections and third-party certification and testing standards. The Group 3 – Operational and Environmental Related factors can be unpredictable, and although they may cause a heater failure are not able to be identified during normal manufacturing and inspection testing. Heating equipment for use in process heating applications can be used under very adverse conditions and sometimes little or no maintenance is performed on the heating equipment. This can often lead to heater failure prior to the predicted theoretical heating element life.

VII. ABOUT HEATING ELEMENT THEORETICAL LIFE

Tubular metal sheath heating elements have been around for over 100 years and for the most part the basic design and construction has remained the same. The main components being a metal tube commonly known as the element sheath, a dielectric refractory material such as magnesium oxide, a center coil of resistance wire used to produce the heat, and low resistance metal connection rods extending out both ends known as cold pins. During manufacturing, the element sheath is compacted typically by roll-reduction or swaging methods, to ensure that the dielectric strength and heat transfer capabilities between the resistance coil and element sheath are maximized. Figure 11 below shows a pictorial view of a typical heating element.

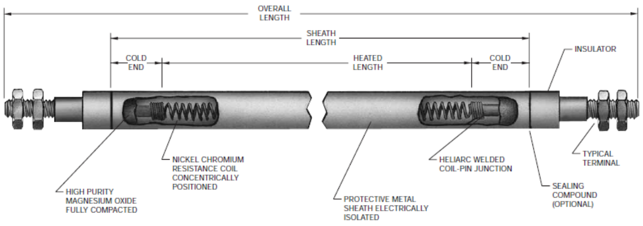
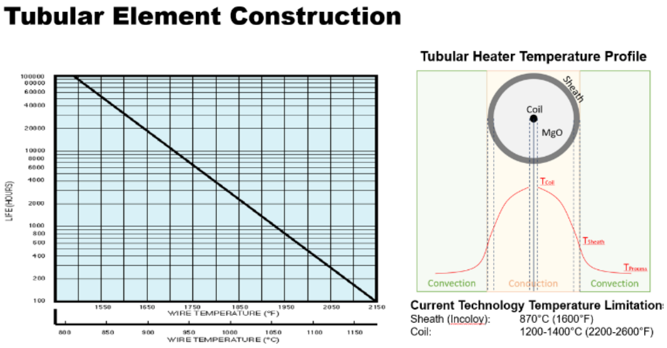


Fig. 11 Heating Element Construction

What has changed is the materials of construction used to make the heating element. Advancements in sheath tube materials, refractory insulation materials and the resistance wire materials have provided for heating elements to be used in specialized applications where corrosion protection and high temperature service is required. Currently many different sheath materials are available including high and low nickel content alloys, stainless steel, titanium and other materials. Insulating materials can contain magnesium oxide, aluminum oxide, and other additives such as aluminum nitrate, boron nitrate and other materials to either increase dielectric strength and/or allow for increased element operating temperatures and provide extended element life. Resistance wires have also been developed for high temperature operation with increased resistance to oxidation.

When designing a heating element to provide maximum effective life, it is important to consider how heating elements work, and the factors affecting element life. Heating elements require that all heat produced internally by the element resistance wire coils is transferred by conduction through the refractory material to the element sheath until a balance is maintained. It is critical that the refractory insulating material is compacted well to ensure that the heat transfer rate allows for the heat to be conducted to the sheath, otherwise the internal resistance wire can overheat. The main factors affecting element life expectancy are: 1) the heating element internal resistance wire operating temperature, which is a function of the element sheath operating temperature, 2) the cycling frequency, and 3) the continuous hours of operational use.

The design considerations that an engineer uses to select the heating element for use in a particular heating application depends on the fluid or gas being heating, the flow rate, the operating temperature, and the watt density on the outer surface of the element sheath. The sheath watt density is defined as the watts per unit of surface area of the heated section of the heating element. The selection of the watt density to be used for a particular application is the most important parameter affecting heating element life. Since the watt density determines the temperature gradient between the element sheath and the resistance coil, it is essentially the element sheath watt density and the selection and design of the resistance coil that determines the heating element life. Other factors that can affect the element life include the sheath material and possible corrosion by the fluid being heated, and the manufacturing methods including the sheath compaction method and effectiveness. The graph below in Figure 12 shows the theoretical life expectancy of a tubular heating element.


Tubular Element Construction

Current Technology Temperature Limitation
Sheath (Incoloy): 870°C (1600°F)
Coil: 1200-1400°C (2200-2600°F)

Fig. 12 Heater Element Life Prediction

VIII. CONCLUSION

This paper discusses the significance of electric resistive elements in conductive heating applications for the electrification demand and the importance of predicting their lifespan accurately. The transition to electrification in heating processes can lead to, reduced emissions, and improved control over temperature, making it an attractive option for various industries. Modern engineering design tools and simulation software have revolutionized the design of electric heaters, allowing engineers to create more precise and efficient designs.

One of the challenges in electrical resistance heating applications is the limitation that certain process fluids impose, such as material degradation, coking, fouling, and unintended phase change due to excessive temperatures. Pressure vessel temperatures can also pose challenges, leading to issues like thermal expansion, material degradation, and radiation heat loss. The lifespan of electric resistive elements is another important aspect, as they can degrade over time due to factors like thermal stress, oxidation, and mechanical wear. Proper design, manufacturing, and testing controls are essential to maximize the lifespan of these elements.

The paper presents a comprehensive approach to designing large-scale electrical resistance heaters, focusing on controlling and predicting sheath temperatures. Key steps include using a sizing tool for initial thermal design parameters, optimizing flow with directional flow baffles, and conducting computational fluid dynamics (CFD) analysis to identify and address potential hot spots. Empirical test data is used to validate and refine design calculations, leading to the development of a proprietary tool for enhancing thermal predictability.

The factors affecting the life of a heating element are categorized into design-related, manufacturing-related, and operational and environmental-related factors. Factors such as the selection of materials, spacing of resistance coils, and proper dielectric insulation play a crucial role in extending the lifespan of heating elements. It is essential to control these factors through proper design, manufacturing, testing, and inspection processes.

The theoretical life expectancy of tubular metal sheath heating elements is analyzed, considering factors like operating temperature, cycling frequency, and continuous hours of use. The selection of watt density plays a significant role in determining the heating element's life, along with factors like sheath material, manufacturing methods, and resistance coil design. Advances in sheath tube materials, insulation materials, and resistance wire materials have enabled the use of heating elements in specialized applications requiring corrosion protection and high-temperature service.

In conclusion, this paper emphasizes the importance of accurately predicting the lifespan of electric resistive elements in conductive heating applications. By employing modern engineering design tools, simulation software, and comprehensive design approaches, engineers can optimize the performance and efficiency of electric heaters while ensuring controlled and predictable sheath temperatures. Proper design, manufacturing, testing, and inspection controls are essential to maximize the lifespan of heating elements and ensure reliable operation in various industrial applications.

X. REFERENCES

[1] OurWorldinData.org – Research and data to make progress against the world's largest problems
Source: Climate Watch, the world Resources Institute (2020)Source: https://www.iea.org/reports/renewables-2020/renewable-heat

[2] McKinseyCompany: https://www.eia.gov/todayinenergy/detail.php?id=46676

VII. VITAE

Paul Moors is a technical business development manager at Thermon, specializing in process heating products for the EMEA market. With over a decade of experience in the process industry, he has expertise in designing and selling various heat transfer equipment such as shell & tube heat exchanger heaters, air cooled systems, industrial heat pumps, and now focuses on electrical heat exchangers at Thermon. His background in mechanical engineering has equipped him with knowledge as a thermal and heat transfer engineering, with a particular focus on electrification and decarbonization efforts.
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