industry: various
authors: scott boehmer & mike bange

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subject:

How Watt Density Specifications May Be Holding Back Optimal Electric Heat Exchanger Design

summary:

Typical customer specifications for a direct electric heat exchanger (DEHE) in forced convection gas applications aim for efficiency and safety given the technology principles that have been in place for the last two decades. For example, this has led to specifications calling for lower heat fluxes (watt densities) to maintain safe sheath temperatures reliably. More recently, newer technologies allow for higher watt densities while maintaining both safety and reliability. While the older specifications are conservative and safe, the design may be sub-optimal. Letting go of the assumption that watt density is roughly equivalent to a safe sheath temperature helps open up the possibilities of new design solutions, many of which can reduce overall footprint and make processes more efficient and less costly.

typical specifications for DEHEs:

Newer technologies incorporated into direct electric heat exchangers (DEHE) are allowing designs that take advantage of increased heat flux—i.e. watt density—for a given flowing gas composition and a set of application conditions. But DEHEs with higher watt densities tend to raise eyebrows due to the belief that this also coincides with higher sheath temperatures.

This is due, in part, to the industry adhering to specifications for DEHEs that were developed using outdated heater design principles and performance features. Thus, in an effort to “play it safe,” design engineers using these older specifications are ending up with sub-optimal designs, unable to take advantage of the full design space.

For example, below is a section from a typical-looking specification sheet detailing watt density for a DEHE used in the processing of hydrocarbon streams:

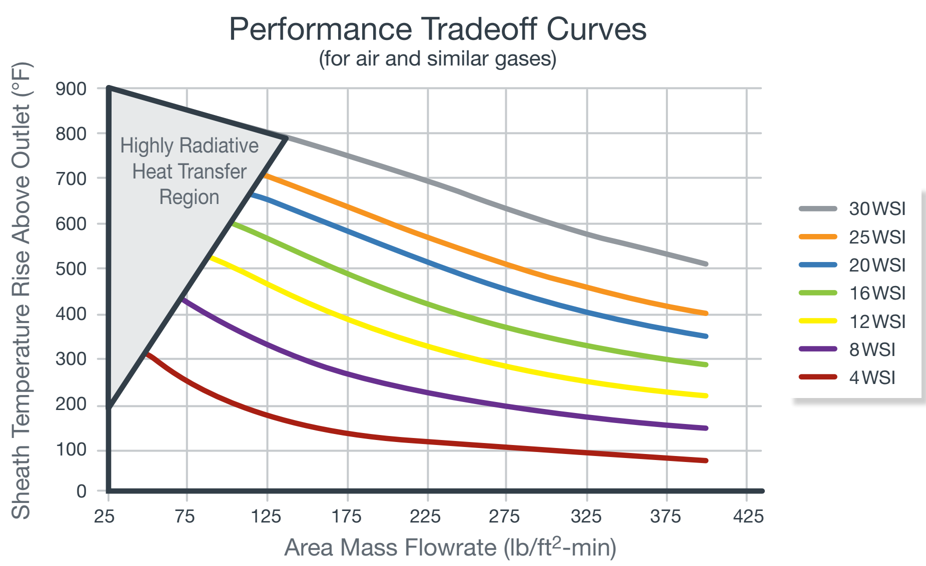
Element Design Conditions			
		Heater 1 (Outlet)	Heater 2 (Inlet)
Wattage	kW	83	168
Design Watt Density	W/in^2	7	12
Number of Elements		72	72

Or, the watt density specification may be in a section within a company's global standard:

5.1	Watt density of the heater is such that a heater life of 25 years is achieved. As a guideline, the maximum design watt densities for typical applications are:
a.	Water - 45 W/in^2 (7.0 W/cm^2)
b.	Gases and vapors - 20 W/in^2 (3.1 W/cm^2)
c.	Liquid hydrocarbons - depends on viscosity of the fluid. To be determined by the particular case and shall include the calculation for expected maximum sheath temperature at the designed watt density

It has also been a long running practice in some market segments to use a simple trade-off chart for determining a temperature rise at a given mass flow rate and watt density level for air and similar gases. (Note: other standard charts are used for fluids and other liquids). While this is a step up from defaulting to a watt density value based on legacy standards, it still does not accurately take into account all the variables that influence sheath temperature in a DEHE. The data presented in these tradeoff curves would only be relevant to the particular heater design that was used during the testing.

figure 1: tradeoff curves



Using older existing specifications will produce a process that is safe and reliable for most applications, but it will not allow for any innovation. Nor will it allow for the most optimal designs.

So why have these specifications stayed around as long as they have? Answering that would involve mere speculation. Part of the story seems to be the assumption that watt density itself can be used as a proxy, roughly equivalent to safe sheath temperature. It is also possible that design specifications have simply been handed down through the years based on a company's legacy standards and methods, without considering improvements in heater technology. In these scenarios, having too high of watt density can raise reasonable concerns about safety and reliability.

On the other hand, letting go of these types of assumptions or others that are utilized in industry helps open up the design space, which can reduce overall footprint and make processes more efficient and less costly (while still providing a DEHE that meets all other critical temperature requirements and is reliable and safe for operation).

the classical approach to heat transfer:

The value of the heat transfer coefficient (h_c) has a significant effect on the value of thermal stress (i.e. temperature), which directly impacts safety and reliability. That said, improving the h_c would allow the watt density value to be increased while maintaining a given sheath temperature value.

Most specifications are based on the the classic approach to parallel flow heat transfer, which relies heavily on the A.P. Colburn approach for turbulent forced convection, which yields the equation:

Nusselt Number: $$Nu = 0.023Re^{0.8}Pr^{0.33}$$

Substituting and rearranging provides us the heat transfer coefficient expressed as:

Heat Transfer Coefficient: $$h_c = \frac{0.023G^{0.8}C_p^{0.33}}{D_e^{0.2}\mu^{0.47}}$$

Using $q = h_c \Delta T$, we get: **Watt Density:** $WSI = h_c(T_{sheath} - T_{outlet})$

Here we clearly see that increasing the value of h_c can allow for much higher values of watt density (WSI, or watts/inch^2) while maintaining a given sheath temperature value.

parameters that affect heat transfer and subsequent sheath temperatures:

Of course, the other factors embedded within the heat transfer coefficient formula, such as the thermophysical properties of the gas in question, will allow specifications to differ depending on the details of the application. Take a natural gas such as methane, for example. Methane's high specific heat and thermal conductivity values allow for a higher heat input for a given temperature rise.

It pays, then, to look beyond mere watt density and heat transfer to determine the optimal design for a DEHE. Parameters include:

- Bundle geometry (heating element diameter, quantity, pattern, spacing)
- Mass flow rate (per unit area)
- Flange size of the heater bundle (vessel pipe I.D.)
- Thermal properties of fluid being heated (air, hydrocarbon, etc.)

These considerations and others have led Watlow's research team to develop new heat transfer improvement technologies and a subsequent proprietary formula that better aligns with the true performance characteristics of a heater design. Though this equation is more complex, it is also more complete and accurate, allowing for better optimization across a wide range of applications.

Watt Density:

$$WSI = C1kA\frac{dT}{dZ} + C2h_c(T_s - T_{gas,\,local}) + \ldots$$

Conduction + Convection +

$$C3f_1\sigma\varepsilon_1 V(T_s^4 - T^4{}_{shell}) + C4f_2\sigma\varepsilon_2 V(T_s^4 - T^4{}_{env,\,local})$$

Radiation to shell + Radiation to Elements Supports

Note: C1-C4 are Watlow proprietary

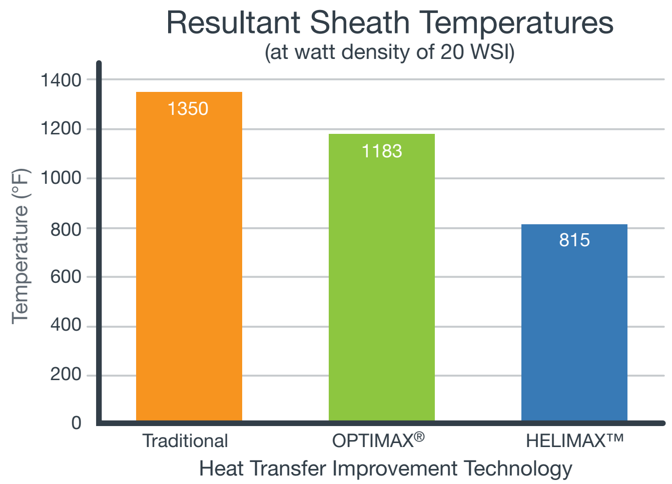
testing and case studies:

Watlow has done extensive testing over the last three years on both traditional heater designs and on designs with enhanced heat transfer performance features (many of which have been incorporated into our OPTIMAX® and soon to be released HELIMAX™ designs). Our goal is to prove, through both sound engineering principles and extensive test data, that smaller heater package designs using higher watt densities will always meet all critical specifications for sheath temperature, shell temperature and other customer constraints.

Using the formulas developed from our test data, we can evaluate cases that show the impact of improved heat transfer on heater size and sheath temperatures.

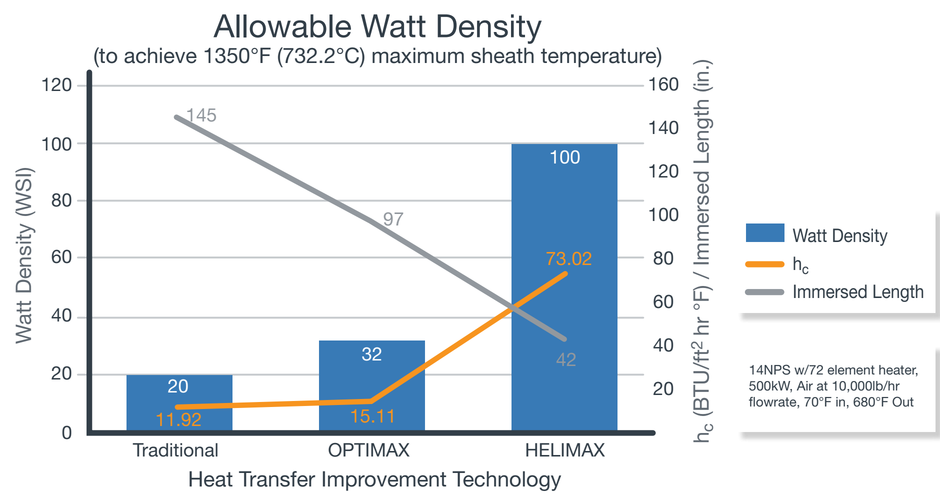
impact of heat transfer technologies:

First we consider air heated at a 10,000 lb/hr flow rate through three heaters with different heat transfer configurations: a traditional DEHE, our OPTIMAX DEHE and our HELIMAX DEHE. The air was heated from 70°F to 680°F, with a constant watt density of 20 WSI. We found that the resultant sheath temperature could be significantly reduced, solely due to the fluid dynamics and mixing technology involved.



14NPS w/72 element heater, 500kW, Air at 10,000lb/hr flowrate, 70°F in, 680°F Out, 145" immersed length

Assuming that one would want to maintain a constant sheath temperature, different technologies would allow for different watt densities. Here are the same three fluid (gas) mixing technologies and their allowable watt densities for maintaining a 1350°F maximum sheath temperature:



14NPS w/72 element heater, 500kW, Air at 10,000lb/hr flowrate, 70°F in, 680°F Out

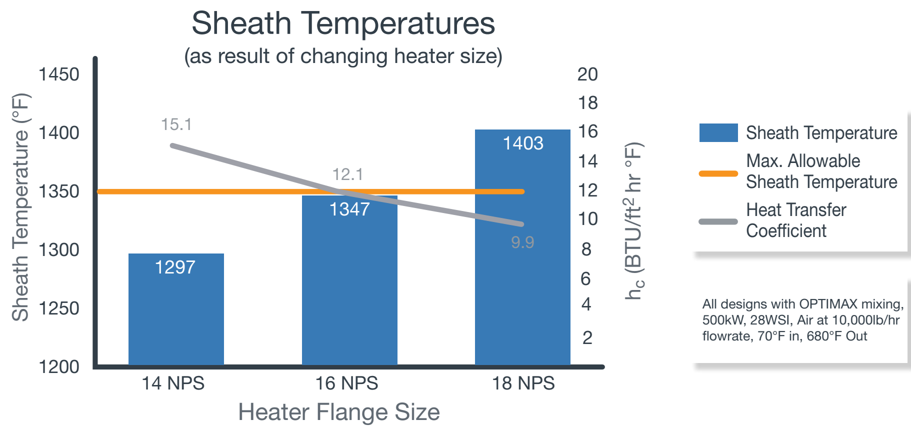
Again, a higher value of h_c means that a higher watt density is allowable. This is obvious with the OPTIMAX and much more pronounced in the HELIMAX. Increasing the watt density allows for optimizing the heater size without exceeding any key specification parameters like maximum sheath temperature. The increase in allowable watt density also results in much shorter allowable immersion lengths, which opens up new possibilities for more efficient heater and process design.

impact of heater size:

As the heater flange size/vessel is changed, the effective net free area for the fluid flow will change correspondingly. If the heater flange size is reduced from a 16 NPS to a 14 NPS as shown in graph below, the net free area will be reduced, causing an increase in fluid velocity and therefore the heat transfer coefficient.

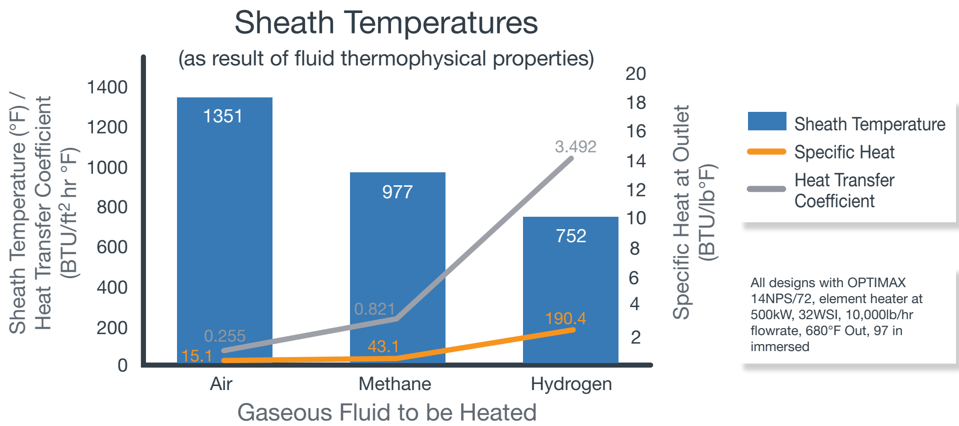
If watt density is held constant and nothing else is changed for the process conditions and the heater design, the sheath temperature will now be 50 degrees cooler, which would allow the watt density to be further increased while staying below the 1350°F maximum allowable sheath temperature.

Conversely, increasing the heater flange size to a 18 NPS will slow down the flow velocity, lowering the heat transfer coefficient and resulting in higher sheath temperatures that in this case exceed the maximum allowable.



impact of fluid thermophysical properties:

Finally, the thermophysical properties of a gaseous fluid, in particular its specific heat capacity, also can have a significant impact on the heat transfer coefficient and resulting sheath temperature. Hydrogen, for example, has a much higher specific heat than air, and so heat transfer is higher. At a constant watt density (in this example, 32 WSI) hydrogen gives a much lower sheath temperature than air.



What these cases show is that sheath temperature is not solely determined by watt density. The heat transfer fluid mixing technology involved, the flange size and the thermophysical properties of the fluid all contribute significantly. It is thus possible to have much higher watt densities and still remain within key specifications for reliability and safety, like sheath temperature.

Furthermore, these cases show that newer technologies really do open up the design space, allowing for more efficient heating processes that take up a smaller overall footprint.

a note on the importance of heater technology validation:

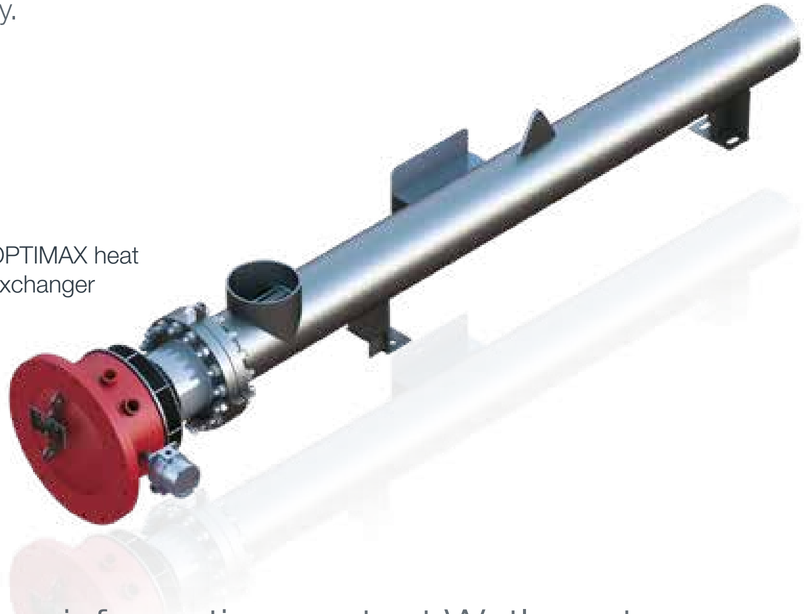
Just because a DEHE can use a higher watt density does not mean that it should. Nor does it mean that watt density is never a consideration when shopping for the most reliable designs.

What it does mean is that claims of higher watt densities need to be supported both by the mathematics involved and by extensive test data. When the principles are sound and careful attention is paid to parameters of the application, it opens up a wider design space wherein a more optimal design can be found. This burden of proof lies largely on the heater supplier, however, which is why the engineers at Watlow have worked so hard to validate the data on designs like our OPTIMAX and forthcoming HELIMAX.

The recommendation is not to change the current customer specifications/standards but to engage with your heater supplier to discuss newer heat transfer improvement technologies relative to higher watt densities. Let them prove that they have done the appropriate engineering and validation work to be qualified to provide optimized heater designs.

takeaway:

By relying too much on watt density as a proxy for safe sheath temperature, many engineers are specifying sub-optimal designs. How watt density impacts sheath temperature is relative to how good the heat transfer is within the design. Through both sound engineering principles and careful testing, we have proven that it is possible to have DEHEs that take advantage of higher watt densities while still meeting critical specifications for sheath temperature and shell temperature, as well as maintaining safe and reliable operations. When sending out such specifications for bids, we recommend considering such designs, even if the given watt densities seem out of specification. Even better, ask your vendor to compare a more traditional design to a more modern design with higher watt density.



OPTIMAX heat exchanger

For more information contact Watlow at www.watlow.com