Taking a Look Under the 
Radiant Hood

How to calculate floor temperatures as well as tubing materials and spacing

BY KOLYN MARSHALL
When I was 16, I bought my first car. It was a red ‘78 Ford Pinto Rally Sport with “racing wheels” and a manual four speed. Don’t laugh; it was a great car. Anyhow, back in the day, you could actually work on things yourself. Things like distributors, carburetors, and good ol’ spark plugs. Even though it was a good little car, it still needed some occasional TLC. Oh, it was a different time, one of excitement and creativity. *Knight Rider* was a TV hit, and *Star Wars* was the hottest thing around.

A friend’s dad taught me how to work on my car. Oil change, new filters and sparkplug wires. I was amazed to learn what all the parts were, how they functioned and why — then watch to see how much better that old four-cylinder ran afterwards — lessons I later took with me into my engineering career. What was true for a ‘78 Ford Pinto remains true today for radiant systems.

**Performance versus expectation**

One of the biggest hurdles we have in the radiant industry is overcoming perceptions. Good design starts with understanding what our customers want and what the system needs. For most, perception is 9/10 reality. A classic example of this is a homeowner named Bob — a radiant heat newbie for all intents and purposes. He had in his mind what he thought a radiant system should be: hot floors.

A wood-frame flooring system and a distribution manifold. The installer can “walk” the tubing into the flooring system, pushing the tube into the grooves with his feet.
When I arrived at his residence with the installer, Tony, Bob was not a happy camper. He complained that his radiant system wasn’t working. It was February and the outside temp was -10°F. Inside, it was well above 72°F. Tony had a digital infrared thermometer, so we took lots of floor surface readings. Most were 85°F or higher because, of course, that’s what homeowners do when they don’t think a system’s working; they crank up the temperature.

Bob’s complaint really wasn’t about system performance or whether he was comfortable. Incredibly, Bob’s complaint was that he couldn’t hear the system run. For Bob’s entire life, he’d lived in homes with forced air heating. He was accustomed to hearing the furnace kick on and then the blower, tangible signs things were right in the heating universe. Well, radiant is different, isn’t it? Bob’s new system had no noise, no blowers or swirling hot air. Nothing but warmth and silence. He needed, simply, to understand.

When we talk about automotive performance systems, we generally hear people talk about limits. How quickly cars brake, how fast they get from zero to 60, how much gross weight it can haul. These are the extremes, the one-offs and oddities. Radiant heat, a performance system, is no different. For most of us in the radiant industry, we talk about floor temps of 80°F or 85°F, the maximum comfortable temperature our bodies can be in contact with a heated surface. This is a system limit, the maximum one could expect. That doesn’t mean that’s where a given radiant floor will operate, especially when a system is using outdoor reset, or boiler modulation. Most radiant floor systems will actually operate in the mid-70°F range to achieve optimal comfort, which is often a lot lower than most folks might expect. That’s a good thing, that is, if our customers understood what it means.

Heat load versus floor temp
As with most things, automobiles are made for specific purposes. Sedans are ideal for routine use or executive commutes; mini vans, for soccer weekends; 4x4s are built to conquer rugged terrain. Vehicle performance is tied to design.

The same is true for a radiant system’s floor temperature. The heat load of the space directly impacts what the required floor temperature needs to be. Of course, the envelope’s R-value and floor covering help to determine what the radiant tube temperature needs to be. Before any radiant design can begin, we need to know what the heat load is. A radiant heat loss generally results in a lower load than a conventional forced air system. There are a few factors that drive this.

- Radiant systems are generally designed with a lower indoor air temperature as a target. While most forced air systems use 72°F as a target temperature, radiant generally uses 68°F (approximately 10%-15% boost in efficiencies alone).
- The physical dynamic of the space is different. Forced air keeps most of its energy at the ceiling; radiant energy is concentrated at the floor.
- Hydronic systems hold heat better than air (an insulator), a mere 2,000-3,000 times more efficient.
- In many cases, hydronic boilers can be more fuel-efficient than a forced air furnace.

Most radiant floor systems will actually operate in the mid-70°F range to achieve optimal comfort, which is often a lot lower than most folks might expect.
• Radiant systems tend to have a lower infiltration rate than forced air, resulting in less wasted heat.
• Finally, radiant systems have little to no air movement, which reduces convective heat loss from our bodies.

Of course, there are health benefits, too. Forced air systems dry the air, which causes people and furniture to lose moisture. Additionally, forced air systems move air, resulting in airborne dust and allergens. When designing radiant systems, we tend to refer to floor temperatures as averages. Saying a system needs a 75°F floor doesn’t mean it will be 75°F degrees everywhere equally. Directly over the tubing it may be 77°F, while the space between may be 73°F.

To calculate the necessary floor temperature requires just a bit of math. To start, let’s assume the target air temperature is 68°F and the calculated heat load is 20 Btu/sq.ft. We will need two equations to determine the average floor temperature.

\[
q = (t_{\text{surface}} - t_{\text{air}})(A)(h_r + h_c)
\]

\[
h_r = se(T^2_{\text{surface}} - T^2_{\text{air}})(T^2_{\text{surface}} - T^2_{\text{air}})
\]

- \( q \) = heat intensity (20 BTU/sf)
- \( A \) = heated area (1 sf)
- \( h_r \) = coefficient of convective heat transfer for air (2.1)
- \( h_c \) = coefficient of radiant heat transfer for air
- \( h_{air} \) = design air temperature (68°F)
- \( h_{surface} \) = average surface temperature of the floor (F)
- \( T \) = design air temperature in Kelvin
- \( s \) = 1.712 E-09 (a constant)
- \( e \) = emissivity of the floor covering (0.91)

Right away we have a problem we need to overcome. The two equations require the same two unknowns \( h_r \) and \( t_{\text{surface}} \). To remedy this, we take an intermediate step by using

\[
t_{\text{surface}} = (q/U) + t_{\text{air}} = q/(A*h_{air}) + t_{\text{air}}
\]

This will establish a base line for the average floor temperature, which is calculated to be 77°F. Using this value in the other two equations yields an average floor temperature of 74°F. With a computer program, we can run this iteration over and over until the two values equal. For the sake of ballpark physics and Excel-friendly math, I’m going to average the two and use a target average floor temperature of 76°F.

System performance

So, we’ve decided we want a 4x4 truck with enough bed space for the camping gear and maybe a few weekend necessities. Need to pull that deer from the woods somehow, right? But, do we go for the diesel, gas, or maybe one of the new electric varieties? Which one is better for my expectations? Which one outperforms the others?

Like with our truck, a radiant system has a wide range of options when considering what goes in the floor. There’s PEX, PERT, EPDM, and even copper. Which one we should consider may be influenced by factors such as application type, installation method, and available fluid temperatures.
Regardless of these options, a few things remain constant, such as the average floor temperature calculated earlier and the required skin temperature of the pipe necessary to reach the floor temperature through the flooring material.

\[
\text{tpipe} = t_{\text{air}} + \left( (t_{\text{surface}} - t_{\text{air}}) \frac{M}{(2Wh + D_{\text{pipe}})} \right) + q(r_{\text{panel}})
\]

- \( t_{\text{pipe}} \) = skin temperature of the pipe (F)
- \( M \) = tube spacing (ft)
- \( W \) = factor of tube spacing relative to tube outside diameter
- \( h \) = fin efficiency
- \( D_{\text{pipe}} \) = pipe (tubing) outside diameter (ft)
- \( r_{\text{panel}} \) = total insulation (r) value for the panel

\[
W = \frac{(M - D_{\text{pipe}})}{2}
\]

\[
h = \frac{(\tanh fW)}{fW}
\]

\[
f = \frac{q}{(m(t_{\text{surface}} - t_{\text{air}}) \sum kx)}
\]

\[
m = 2 + \frac{r_{\text{covering}}}{(2r_{\text{panel}})}
\]

\[
k = \text{conductivity (BTU/hr*ft*°F)}
\]

\[
x = \text{thickness (ft)}
\]

\[
r_{\text{pipe}} = \ln(D_{o}/D_{i})/(2*\pi*k_{\text{pipe}})
\]

\[
r_{\text{panel}} = \ln(r_{o}/r_{i})/(2*\pi*k_{\text{panel}}L)
\]

- \( L \) = pipe length over given area (ft)
- \( D_{o} \) = outside pipe diameter (ft)
- \( D_{i} \) = inside pipe diameter (ft)
- \( r_{o} \) = outside pipe radius (ft)
- \( r_{i} \) = inside pipe radius (ft)

Once a skin temperature is determined, the operating fluid temperature can be found. In order to properly assess the fluid temperature, the back loss from the floor is needed. We’ve already determined the load to the space to be 20 Btu/sq.ft. Back and edge loss is easily calculated using standard heat loss conventions. In most applications this equates to about 10% - 15% of the overall load.

\[
t_{\text{water}} = (q + q_b)Mr_{\text{pipe}}
\]

This is where we begin to see design variances based on some of our system options, mainly pipe choice. PEX and PERT have relatively thin walls and slightly higher material conductivity than an equivalent EPDM product. The result is a slightly lower fluid temperature for PEX and PERT compared to its EPDM counterpart. Likewise, copper will have a lower fluid temperature than PEX.

**Floor profiles**

There are a lot of things to consider when selecting that next auto, from size and shape to fuel economy. Likewise for a radiant system from its heat source to tubing in the floor. Our slab-on-grade profile example is comprised of a standard 4-in. slab with 2-in. of covering and a ¾-in. hardwood floor. When designing a radiant system, a few key factors become important: application, the type of tubing selected, and heat source.

The easiest to evaluate is the application. Is the project using a standard slab-on-grade application or will it be one of a few varieties of frame floor? Knowing the application sets a few other parameters automatically, such as the allowable tube spacing and how the tubing interacts with the floor. Most frame floor applications will limit the tube spacing to 4- or 8-in. on-center, depending on the joist spacing. By contrast, slabs will generally allow for any tube spacing with 6-, 9-, 12-, and 18-in. on-center being the most common.

Even though either application type can use all available tubing options on the market today, there are some variables that may...
impact the overall design. PEX and PERT tubing — with thinner walls and higher conductivity — allow them to provide the same outer skin temperature with lower fluid temperatures. This may be an important consideration when selecting a modulating-condensing boiler or other low-temperature heat source. Flexible EPDM tubing allows for faster and easier installations in tight or hard to access areas. It also provides extended UV resistance or additional durability for harsh job-site conditions.

Tube type isn’t the only thing that impacts fluid temperature. Spacing is also a factor. The farther apart the tubing, the warmer the fluids need to be to keep the average the same. Conversely, the closer the tubing is, the lower the tube temperature needs to be. With this we also see a corresponding change in the peak and valley temperatures.

Response times
The last thing I look for in choosing a car is responsiveness. Although it’s not the most critical feature, it can be important. I’ve never liked pressing on an accelerator to have the dang thing ignore me. That can be a major hazard when speed is needed.

Luckily, radiant systems rarely fall into the category of life-or-death, but they do suffer from response issues rather frequently. The greater a system’s physical mass, the slower it’ll respond. Think of a concrete slab as a fully loaded 18-wheeler and a frame floor as a sleek European roadster. The roadster accelerates fast, powers through curves and breaks on a dime. The loaded semi? Well, that’s a different story. It’s just impossible to get roadster performance out of a big ol’ beast with 18 wheels. The same holds true for a radiant system.

Although the heat load is the same in our frame floor and the slab, response times are different. Assuming the outside temperature is a moderate 50°F, the frame floor might come up to temperature within an hour or two, but the slab may take half a day to get there. And, just like the loaded semi, once all that thermal mass is up to temperature, it’s going to take a while for it to cool. Climates where large temperature swings are present in the fall and spring from one day to the next will experience comfort issues with this “Mack Truck Syndrome.” However, in the middle of winter when the power goes out, your customers will be thankful for a system with a bit of staying power!

To avoid overheating or sluggish response, a smart controller is recommended. These controls, generally in the form of an injection control, regulates the slab temperature by monitoring not only the slab temperature and room temperatures but how rapidly they change. By evaluating these factors, the control can anticipate the time needed to cool down or warm up. Think of it like cruise control for your coupe.

Back in the garage
Although things are different today than when I was a kid, my car still needs an occasional oil change. I may not be able to do the work like I once did, I still like to stand back to appreciate what’s under the hood. Even though there are more cables and CPU boxes, the basics are still the same.

The same is true for radiant systems. Boilers may be more efficient, and smarter. Thermostats may be able to play music and give you a weather forecast, but their key responsibility remains true. There’s tubing in the floor and warm water moving through them, and the physics of conduction haven’t changed. No matter how fancy the home gets, the radiant floor will always be a classic.

Kolyn Marshall has been with Watts and active in the hydronic radiant market since 1995. During his tenure with Watts, he has held various roles, beginning his career in outside sales and migrating to various leadership roles within technical support, strategic marketing, and product management. He authored the technical manual, “Understanding Radiant Systems,” for RSES. Kolyn holds a Bachelor’s Degree in Mechanical Engineering from the University of Missouri at Columbia. He can be reached at kolyn.marshall@wattswater.com, or 417/447-8050.