A Brief Whitepaper on Radiant Cooling

Any discussion of radiant cooling would be incomplete without first discussing the basics of radiant heating and how/why it works. Radiant heat is the same thing as infrared heat, it is a form of electromagnetic energy, and further, it is light (photons) at a wavelength that humans cannot see. Radiant heating offers a similar effect to the warmth felt on a cool day when the sun is shining on you. The expression, “it’s doesn’t really feel cold unless you are in the shade” really explains it well. Radiant heating warms people, and of course warms objects as well as walls, ceiling, floor, furniture etc., that are in the room. While radiant heating keeps people and animals comfortable, materials that are heated by a radiant heat system heat the room in a “ricochet” manner as materials absorb radiant heat then themselves re-radiate heat to other items/materials and pass heat along to the air via convection. As such, radiant heating does not directly warm the air, the air is warmed by convection from the radiant surface and from other surfaces that have received radiant heat and then release it. All objects and materials absorb radiant energy and this energy is then released via re-radiation (at a lower frequency), and by convection. Consequently, while “in-floor” radiant has historically been more prominent, radiant heat emitted from walls, or more particularly from the ceiling, will all have highly similar and improved performance on room temperature and human comfort.

When a person is in the path of radiant heat, comfort can be quite good even when the indoor air temperature is as much as 5-6 °F cooler than a traditional indoor heating indoor set-point. A side benefit of this is that when the indoor air is allowed to be cooler, there is less ΔT to the outdoor temperature, and therefore, you get a reduction in the heat loss of the building, further saving energy.

When designing a radiant heating system for use with a hydronic heat pump, care should be taken to design for the lowest possible operating temperature. Usually this means putting the PEX closer together, and limiting floor coverings such as thick carpet, etc. Radiant heating surfaces (eg. a floor) are generally targeted for around 86F surface temperature, depending on the R value of any materials separating the floor surface from the radiant, the fluid in the PEX tubes often is designed to be around 90-100 °F. A much warmer temp can be comfortably used in a ceiling or wall installation which allows for higher capacity per ft^2.

The other reason why a low temperature is best, and is considered a smarter design when performing radiant heating with a heat pump, is to minimize the Carnot lift. For example, on a 0°F Day when a heat pump lifts the water temperature at its outlet to, for example, 100 °F, the Carnot lift is 100 °F. If instead, the outlet needed to be at 120 °F, then the Carnot lift would be 20% higher. This will result is a lowering of capacity by around 20%, and, a reduction of efficiency. The reduction of efficiency may be as much as a 30% lower COP. More on this and how it applies to cooling shortly.

Just a quick aside to briefly touch on the physics of radiant heating (and cooling) – any and all objects or materials that are above 0 Kelvin (around -459 °F) emit radiant heat continuously. Likewise, all objects and materials continuously absorb radiant heat from all of the other objects and materials, including people. Any objects or materials that emit more radiant energy than they absorb are sources of heating. Any objects or materials that absorb more radiant heat than they emit are cooling sources. Objects that are the same temperature as the surrounding environment as said to be in radiant equilibrium, meaning that they are emitting and absorbing at the same rates. When radiant energy comes into contact with a person, or any thermally opaque object or material, it is either reflected (based on the reflectance value of that material) or absorbed (based on the absorbtivity value of the material).

Absorbtivity and emissivity are inverse to each other and are proportionally related. Absorbed energy is then emitted (re-radiated) based on the emissivity value of the materials surface. Material surfaces best for radiant transfer are the ones that have the higher values of absorptivity and emissivity. Therefore flat, non-reflective or painted surfaces of any color are generally very good with darker colors sometimes slightly better, reflective or shiny metallic objects have low absorbtivity and emissivity values and therefore should be avoided as a radiant emitter or panel surface.

So, to move on to our topic, Radiant cooling is somewhat of a misnomer since "cold" is not energy and cannot be radiated, however we will stick with that term since it is in common usage.

A cool surface actually acts as a "radiant heat sink" where it draws radiant heat away from the usual radiant emitters such as people, animals, and other objects and materials in the room, resulting in a remarkable cooling effect on people, animals, or objects. The heat is removed from the room. And as objects cool, they either emit less, or absorb more. Once a surface or object cools below the indoor ambient temperature, it too becomes a source of radiant cooling and in addition, provides convective cooling. A radiant cooling surface cools some by convection but mostly cools the air indirectly as it removes radiant heat from any objects or materials in the room, which altogether has a cooling effect on the air due to convection.

In addition, the cooling effect that proximity to a radiant cooling sink has on a person or animal, as heat is "sucked out" has to be felt to fully understand the advantage. This often means that even at 80 °F or higher indoor air temperature, and even with higher humidity, a person will be giving up net heat flowing away from the body to the radiant cool sink(s), and this transfer makes the body "feel" cool as the body can more easily emit its radiant energy. Many radiant cooling users will find that a normal indoor set point feels several degrees cooler than needed due to the nature of radiant cooling, and the thermostat can therefore be adjusted to a warmer temperature and still have the same level of comfort.

The above point is hard to describe without experiencing it. Here's an analogy – on a cool night, sitting several feet from a campfire (an emitter) makes you (the absorber) feel warm as your body absorbs radiant energy but the air between you and the fire is not heated. With radiant cooling, it Is reversed - you become the net emitter and the radiant cooling surface(s) becomes the net absorber. So even when the air between you and the absorber is quite warm, and even humid, you can feel the cooling effect since the absorber (cold sink) is "pulling" heat, causing net heat to be emitted from your body at a higher rate. As with radiant heating, when a person is in the path of radiant cooling sink, comfort can be quite good even when the indoor air temperature is as much as 5-6 °F warmer, even with high humidity, compared to a traditional indoor cooling set-point. A side benefit of this is that when the indoor air is not as cool, there is less ΔT to the outdoor temperature and therefore a reduction in the rate of heat gain of the building, which further saves cooling energy.

Another interesting effect of radiant cooling, is that unlike ductless or central forced air systems, it can be the basis for extremely high indoor air quality. For one thing, radiant cooling uses no forced air and has little or no air flow. And without forced air, the dust, mites, pollen, and other small particles that typically float on the indoor air get a chance to settle on the floor where they can be removed by normal floor cleaning, vacuum, etc.

Another indoor air quality advantage of radiant cooling or heating can be found in applications such as a very tight house with an outside air ventilator, or an ERV, as massive amounts of fresh air can be brought inside without causing an adverse effect on comfort, for reasons previously described.

At the application level, radiant heating or cooling works equally well from any direction, such as from a wall, ceiling, or floor. However, recall that radiant energy is photons, light that although it cannot be seen by the human eye due to the wavelength, is still light. With that in mind, would you light a room from the floor or from the ceiling? Note that considering the low transmittance of objects and materials in a room, radiant transfer is reflected or shaded in much the same way as visible light. When radiant is used from a floor, much of it can be blocked by a couch, chair, carpet, etc. And for example, when sitting on a couch, it is quite pleasant to receive the warm glow of ceiling radiant heating (or the body-skin cooling effects of radiant cooling) more directly, without being “shaded” by the couch.

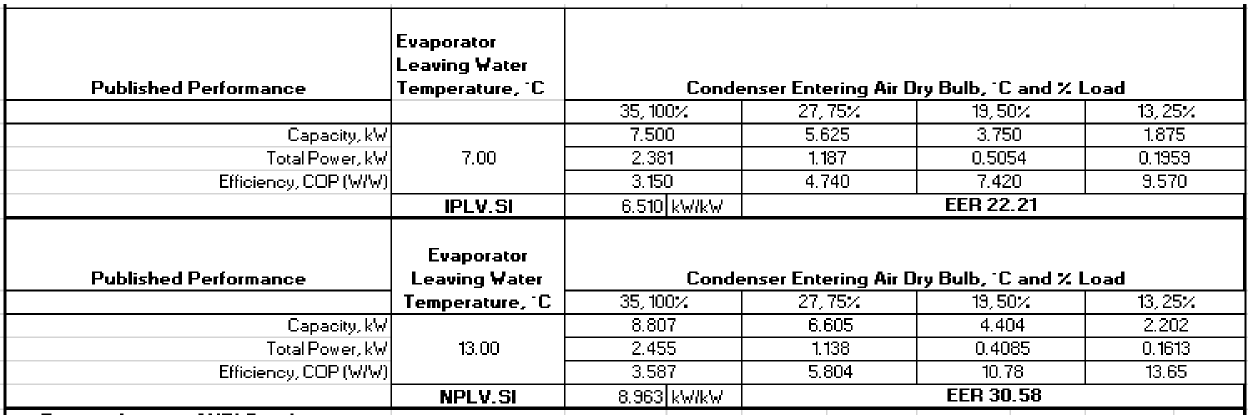
An important design criterion with radiant cooling is that radiant cooling must be configured such that the cooling surface temperature never drops below the dew point. If the radiant cooling surface were allowed to be cooler than the dew point, condensation will form on the cooling surface. To prevent the unwanted accumulation of condensate water on the radiant surface, the water in the radiant cooling system must not be too cold, i.e., it must be such that the radiant surface is kept above the dew point. For this reason, the water temperature setting should be such that the radiant surface will be at or above the dew point, therefore in most cases the actual water temperature can be adjusted based on the R-value of the material that separates the radiant cooling source (Eg. PEX tubing) from the actual radiant surface (floor or ceiling material etc.)

Additionally, a radiant cooling controller should be used to make sure that while the cooling surface remains above the dew point, it is still as cold as possible. For example, the Chiltrix CXRC1 radiant cooling controller uses multiple indoor dew point sensors located in the area of the cooling surface, a water temperature sensor measuring the water fed from the chilled water source to the radiant supply manifolds, and a mixing valve that can recycle from 0% up to 100% of the return water back into the supply. The system is configured to dynamically adjust the temperature of the water that flows to the radiant cooling manifolds, keeping the radiant surface close to but above the dew point. The Chiltrix radiant calculators can make it easy to understand the relationship between water temperature and the radiant surface temperature.

Other radiant cooling controllers exist which offer various methods of radiant cooling control. With the Chiltrix CXRC1, the main design differences being firstly, simplicity, and secondly, the CXRC1 controller is an “add-on” that works with and can be added to any radiant heating controller. That means allowing the user or the installing contractor to select and use any existing or commonly available radiant heating controller and easily enable such controller for cooling by adding a CXRC1.

Radiant cooling is known to work well in dry and moderate climates although a strong case can often be made for radiant cooling to augment a traditional cooling system even in a humid climate. For example, a room with a lot of south facing glass may be absorbing and re-emitting the solar generated radiant heat from the floor. A radiant cooling system in the floor, kept just warmer than the dew point, can mitigate or eliminate the radiant heating effect of the solar heated floor. In other seasonally humid climates, there may be a large part of the year that radiant cooling by itself can be used. And in any climate, at any time, radiant cooling can provide a much higher level of efficiency by doing a portion of the total cooling.

Radiant cooling efficiency is of course much higher than forced air cooling, generally experiencing up to 40% or more increase in seasonal average EER. That's because of the Carnot implications of operating a heat pump - the cooling efficiency of a heat pump increases when the ΔT between the outdoor air temperature and the leaving water temperature (this ΔT is called "Carnot Lift" that was mentioned previously) of the heat pump is reduced. For example, an advanced hydronic heat pump may have the following performance characteristics:



Published Performance	Evaporator Leaving Water Temperature, °C	Condenser Entering Air Dry Bulb, °C and % Load			
		35, 100%	27, 75%	19, 50%	13, 25%
Capacity, kW	7.00	7.500	5.625	3.750	1.875
Total Power, kW		2.381	1.187	0.5054	0.1959
Efficiency, COP (W/W)		3.150	4.740	7.420	9.570
	IPLV.SI	6.510 kW/kW	EER 22.21		

Published Performance	Evaporator Leaving Water Temperature, °C	Condenser Entering Air Dry Bulb, °C and % Load			
		35, 100%	27, 75%	19, 50%	13, 25%
Capacity, kW	13.00	8.807	6.605	4.404	2.202
Total Power, kW		2.455	1.138	0.4085	0.1613
Efficiency, COP (W/W)		3.587	5.804	10.78	13.65
	NPLV.SI	8.963 kW/kW	EER 30.58		

Above from official AHRI Certification test data of the Chiltrix CX34.

Note the top section, the seasonal average EER (similar to SEER, called IPLV) is 22.21 when leaving water temp is at 7 °C (44 °F). In the second section, the seasonal average EER (called NPLV) is 30.58 when leaving water temperature is 13 °C (55F). The outdoor conditions are the same for both tests. Note that when the heat pump leaving water temperature is higher by 6 °C (11 °F) the efficiency rating (EER) is 39% higher. And the warmer temperatures used in a radiant cooling system are such that the system will nearly always operate at or above EER 30.58, and can at times be > EER 35 which would be a 59% increase above what is already a world's record efficiency rating.

One issue and potential downside of radiant cooling that must be addressed is humidity. Due to the nature of radiant cooling, humidity up to as high as 75% or more can still be quite comfortable for humans or animals, however for most building types there are other reasons to keep humidity under control, for example to protect against corrosion, mold risk, and EMC (equilibrium moisture content). For this reason, regardless of human comfort, ASHRAE suggests to keep relative humidity at or below 60% RH.

Recall that in order to use radiant cooling, dehumidification will have been deliberately "turned off" by the radiant cooling controller, keeping the radiant surface above the dew point in order to prevent unwanted condensation. Therefore, in a more humid climate, indoor ambient humidity may be such that a dehumidifier can be needed at times. Note that in a fairly tight home, once indoor humidity has been lowered by a dehumidifier, it does not need to run continuously unless there is a persistent source of indoor humidity. Humidity cannot pass easily through a vapor barrier such as an exterior wall, and humidity does not happen on its own, it requires some type of a "humidity event". Once indoor humidity has been controlled by a dehumidifier, the humidifier will stop. When the next humidity event occurs, such as a door opening that allows ingress of humid air, or some other humidity event is in process such as taking a hot shower, the dehumidifier will start again for a short time, until the indoor humidity target is again satisfied.

Therefore, the energy needed to operate a dehumidifier over the course of the day may be very small and once all of the doors have been closed for the evening, only minor dehumidification may be needed to account for respiration and perspiration of occupants. Therefore, controlling indoor humidity with a dehumidifier when needed may be simpler and more cost-effective than one would think. “Whole house” dehumidifiers with some ducting are available, but such type may not be necessary for users in a dry or moderate climate, who can solve a humidity problem with a non-ducted centrally located dehumidifier. That’s because humidity in the home tends to seek equilibrium on its own, via diffusion, and generally will levelize naturally across the entire indoor area, absent a persistent source of humidity such as a leaky pipe.

The remainder of this paper is a shallow dive into the physics of radiant cooling (and heating) and we will try to make this as simple as possible.

First, about emissivity. When radiation (photons) strikes a thermally opaque material, only 3 things can happen – energy is absorbed, and then emitted, or it is reflected. In the case of a translucent material, some energy is transmitted all the way through the material. A blackbody is a theoretical material that absorbs and emits perfectly with no reflection and no transmittance. A blackbody is a perfect absorber-emitter, where both the absorbtivity and the emissivity value is 1 on a scale of 0-1. In real life, no black body exists although certain materials come very close. Here are the emissivity values of certain common materials found in a typical room served by a radiant heating or cooling application:

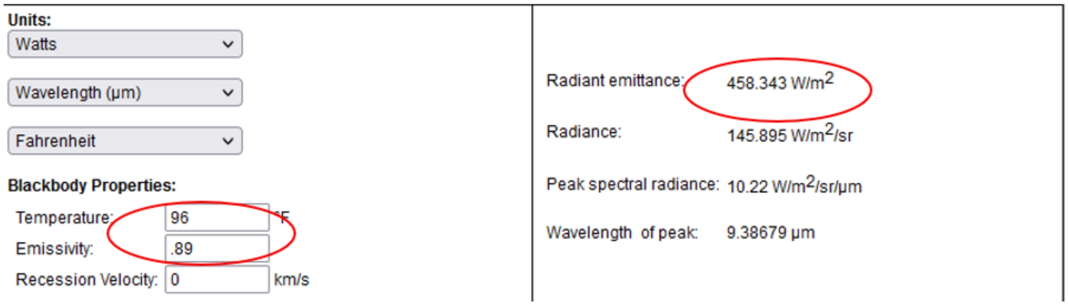
Wood, Oak ~.88 to ~.93	Granite ~ .96	Cotton cloth, ~.77	Concrete, ~.85	Drywall, ~.89
Oil based paints, ~.92 to ~.96	Plaster, ~.98	Marble, ~.95	Plastics, ~.90 to ~.97	Glass, ~.92 to~.92

As you can see, the emissivity of most materials found in a home is around .9 or above, on average. Approximate emissivity values for almost any material can be found with an online search. If precision is needed, the emissivity of any material can be measured with an accurate thermometer to measure a surface temperature, and then, measured with a laser thermometer that has adjustable emissivity. You may then dial in the emissivity until the temperatures match, and you will know the emissivity value of the materials surface.

Once the emissivity values of the materials are known, the total emissions of a material can be calculated using two back-to-back Stefan-Boltzmann calculations. Without going into any mind-numbing math, just use an online calculator such as this one https://www.spectralcalc.com/blackbody_calculator/blackbody.php

Below, we assume PEX tubing in a wall or ceiling, covered by and in thermal contact with aluminum heat transfer plates which are in thermal contact with the drywall. We assume the drywall emissivity is .89, and we assume a 95 °F surface temperature. Below based on 1m^2 radiant aperture (1m^2 surface area).

BELOW, SHOWN AS A HEATING APPLICATION:

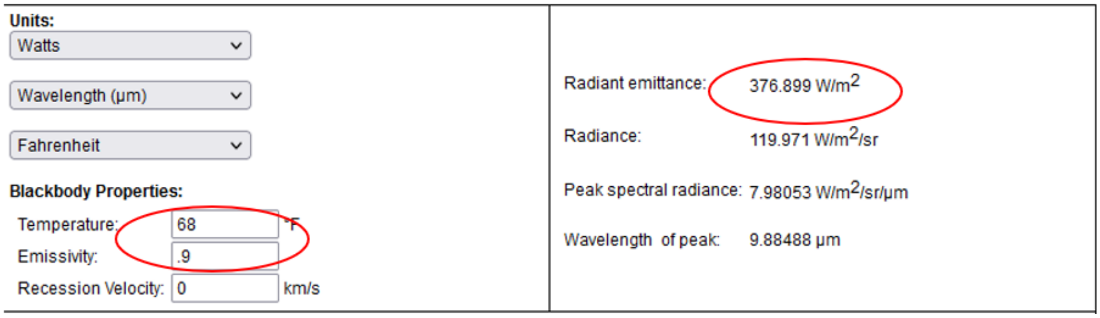


Units:
Watts
Wavelength (µm)
Fahrenheit

Blackbody Properties:
Temperature: 96 °F
Emissivity: .89
Recession Velocity: 0 km/s

Radiant emittance: 458.343 W/m^2
Radiance: 145.895 $W/m^2/sr$
Peak spectral radiance: 10.22 $W/m^2/sr/\mu m$
Wavelength of peak: 9.38679 µm

Above, with a radiant surface temperature of 95 °F, we see that the total emittance is 458w. But that doesn't tell the whole story. As mentioned earlier, all objects both absorb and emit. So, let's assume the average emissivity of the objects in the heated area is .9. and are at a temperature of 68 °F, as follows:



Units:
Watts
Wavelength (µm)
Fahrenheit

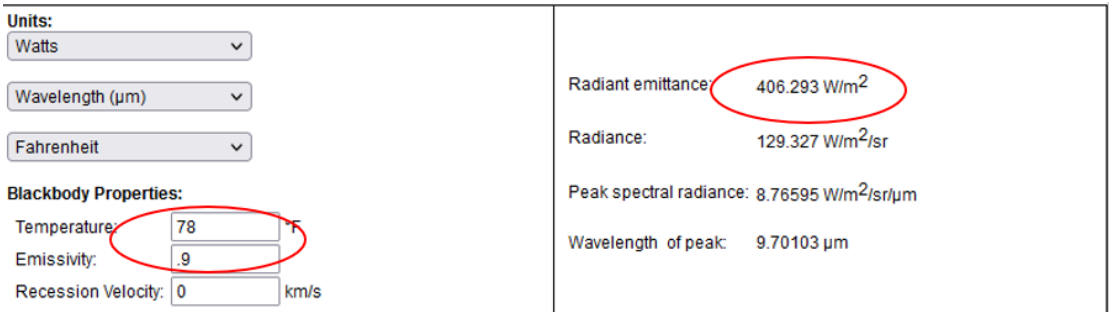
Blackbody Properties:
Temperature: 68 °F
Emissivity: .9
Recession Velocity: 0 km/s

Radiant emittance: 376.899 W/m^2
Radiance: 119.971 $W/m^2/sr$
Peak spectral radiance: 7.98053 $W/m^2/sr/\mu m$
Wavelength of peak: 9.88488 µm

To know the NET emittance, we take the amount of energy emitted by the drywall, 458w, and subtract the energy it is receiving from the nearby objects in the heated area, 376w, and we get a NET emittance of 82w, multiplied by 3.412 to get BTUs. That comes out to 279 BTU per m2, or 26 BTU/ft.^2.

BELOW, SHOWN AS A COOLING APPLICATION:

To calculate radiant cooling, we do the same calculation. Let's assume the drywall surface is 62 °F and the objects in the room are at average 78 °F.

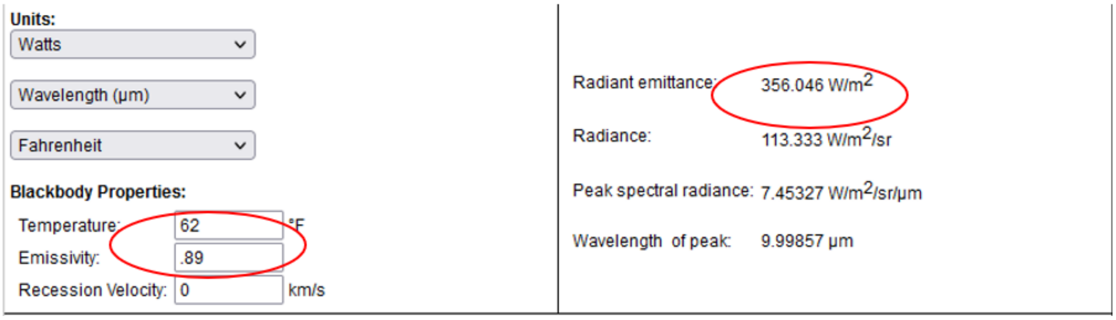


Units:
Watts
Wavelength (µm)
Fahrenheit

Blackbody Properties:
Temperature: 78 °F
Emissivity: .9
Recession Velocity: 0 km/s

Radiant emittance: 406.293 W/m^2
Radiance: 129.327 $W/m^2/sr$
Peak spectral radiance: 8.76595 $W/m^2/sr/\mu m$
Wavelength of peak: 9.70103 µm

Above, emitted by nearby room objects. Below, absorbed by drywall. NET cooling 50w=171BTU=15.85 BTU/ft.2.



Units:
Watts
Wavelength (µm)
Fahrenheit

Blackbody Properties:
Temperature: 62 °F
Emissivity: .89
Recession Velocity: 0 km/s

Radiant emittance: 356.046 W/m^2
Radiance: 113.333 W/m^2/sr
Peak spectral radiance: 7.45327 W/m^2/sr/µm
Wavelength of peak: 9.99857 µm

As stated before, all of the objects and materials are always emitting and absorbing radiation energy. When the radiant surface is cooler, it is a net absorber and absorbs energy to cool the objects (and indirectly, the air) of the surrounding area, removing heat from the room. When the radiant surface is warmer, it is a net emitter and emits energy to heat the objects (and indirectly, the air) of the surrounding area adding heat to the room.

Logical Topology of CXRC1 radiant Cooling Controller Installation