ENGINEERING WHITE PAPER

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January 6, 2021

Heat Transfer

Before we can advocate for our customers on HVAC equipment & system design, we must know the basics of Mechanical Engineering. Key to the understanding of this discipline is Thermodynamics & Heat Transfer. This EWP is dedicated to Heat Transfer.

Modes of Heat Transfer

All modes of heat transfer move energy from hotter areas to colder areas. Heat transfer is driven by a temperature difference, much as a pressure difference drives fluid movement or a voltage difference drives electric current. To move heat the opposite direction, from a cold area to a hot one, outside energy must be used in a device such as a compressor. The three forms of heat transfer are conduction, convection and radiation.

Conduction

Conduction is heat transfer within a solid, or between two surfaces in contact with each other. In conduction, molecular forces transfer energy between neighboring atoms and molecules. The molecular structure of a material determines how well it conducts or insulates heat. This property is described by the thermal conductivity of a material, measured in BTU / ft^2°F.

Thermal conductivity describes heat transfer within a material, such as fiberglass or stainless steel. However, it is more common that we want to calculate heat transfer through an object, such as a batt of fiberglass insulation or a 0.4mm stainless steel plate. R-values and U-values describe heat transfer through objects, with higher R-values describing better insulation and higher U-values describing better conductors of heat. The U-value is the inverse of the R-value, $U=1/R$. Given a surface area A through which heat is conducted, heat transfer can be calculated as:

Q(BTUH) = A (sq ft) × ΔT (°F) × U (BTUH / sq ft °F)

Q(BTUH) = A (sq ft) × ΔT (°F) / R (sq ft °F / BTUH)

When heat goes through multiple layers, such as insulation and sheeting on a roof, the R-values add.

$R_{total} = R1 + R2 + \ldots$

Resistance to heat transfer also happens where two surfaces touch. There are two sources of this resistance, contact resistance and fouling. Contact resistance comes from microscopic gaps between two solids. Rough surfaces will have high contact resistance, while surfaces that are bonded by welding or brazing have very low contact resistance. Fouling comes from dirt, oil, or debris on the heat exchanger surface. Fouling is described by a fouling factor, which is the R-value added from fouling.

Where there are multiple paths that heat can follow, we must calculate the heat transfer (BTUH) from each path, then add them together. The least insulated path will transfer the most heat. Thermal bridging occurs when most of a surface is well insulated, but a thermally conductive 'bridge' allows heat transfer. A thermal bridge can leak a large amount of heat even when the rest of the surface is well insulated.

Convection

Convection is heat transfer within a fluid (a liquid or gas) due to movement in the fluid. Convection can be divided into forced convection where a fan or pump moves the fluid, and natural convection where the fluid moves due to its density changing with temperature.

In forced convection, a hot surface heats the fluid. The hot fluid is moved by a pump or fan to a cold surface. The fluid then heats the cold surface, cooling off. Heat transfer happens at both surfaces through conduction, but the movement of the heat through the fluid is convection. One example of forced convection is an electric wall heater. A fan moves air over a hot electric coil and into a room, where the air heats surfaces and occupants.

In natural convection, the density difference between the hot and cold fluid causes movement. A hot fluid is less dense than a cold fluid, so the hot fluid rises while the cold fluid sinks. The rate of movement is determined by the density difference and how high the column of hot fluid is. A tall column of hot air can produce rapid movement, called the "chimney effect".

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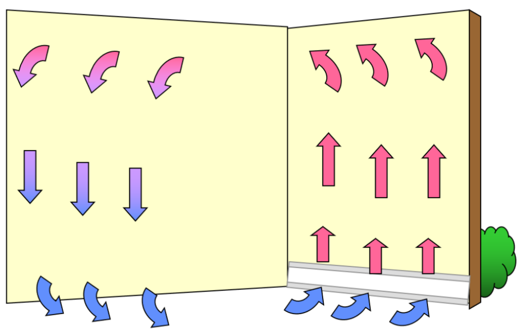
One example of natural convection is a finned-tube radiator. A hot water coil creates a column of hot air inside the unit cabinet. The hot air rises, heating the room and forcing cold air into the unit. Air in the room slowly sinks and is pulled toward the unit intake near the floor.



Natural convection in a room with a finned-tube radiator

Radiation

Radiation is heat transferred through light. Most heat transfer occurs through infrared light, which is not visible.

Every surface emits light based on its temperature and color. Hotter surfaces emit more light and higher frequency light. As a surface gets very hot it starts to emit visible light as well as infrared light, glowing 'red hot'. Dark objects emit and absorb more light, while light colored or reflective objects emit and absorb less.

Radiation is different from conduction or convection because the heat goes directly from one surface to another instead of passing through the air between them. This can be used to our advantage to heat people and objects directly without using energy to heat the air.

There are two main disadvantages of radiant heat. The first is that it only heats objects in line-of-sight from the radiator. This can create cold shadows under tables or behind furniture or equipment. It can also be uncomfortable for people to have one side of their body heated and the other side away from the radiator cold. Radiators also require either very hot and/or large surfaces. Hot radiator surfaces can be a fire or burn hazard.

An indoor hydronic radiator

An outdoor radiator (also called an infrared heater)

While all surfaces emit radiation, in total, heat always moves from hot surfaces to cold surfaces. Unlike conduction and convection, the rate of heat transfer depends not only on the temperature difference, but also the temperature of the radiator. Heat transfer from a 180°F surface to an 80°F surface is faster than heat transfer from a 140°F surface to a 40°F surface.

The rate of heat transfer by emitted radiation is determined by the *Stefan-Boltzmann* law of radiation:

$$\frac{Q}{t} = \sigma e A T^4$$

Where *Q*=5.67 x 10^{-8} J/s*m^2*K^4 is the constant, A is surface area of the object, and T is its absolute temperature in Kelvin. The symbol e stands for the emissivity of the object which is a measure of how well it radiates. Emissivity (*e*) values range from 0 to 1. A perfect radiator has an e value of 1 while a perfect reflector has an e value of 0. Our skin has an *e* value of 0.97.

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The radiation rate is directly proportional to the fourth power of the absolute temperature—a remarkably strong temperature dependence. Furthermore, the radiated heat is proportional to the surface area of the object. Think about the sun on a winter's day—you feel warm until you step behind a tree and you are cold.

Heat Exchangers

To move heat from one fluid (gas or liquid) to another without mixing them, we use a heat exchanger. All heat exchangers have flow passages for the two fluids and a solid barrier separating them. The barrier must be thermally conductive to allow heat to move between the two fluids. Heat exchangers are a very important component of hvac equipment, and the topic of heat exchangers will be thoroughly discussed in Engineer White Paper 18.b.

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