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Designing Pipe Insulation Systems

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Thermal insulation for piping systems has proven to be a simple and cost-effective means for reducing heat losses and gains in mechanical piping systems. Pipe insulation provides a barrier between the pipe and the environment and can provide many benefits. It is available in a variety of materials that achieve slightly different results depending on the critical properties desired for the given application. Improper insulation installations for HVAC piping can lead to excessive energy loss, safety hazards, condensation, corrosion and mold. It is beneficial for designers to understand the available material options and how to properly select and detail pipe insulation for various applications.

Insulation Failures

A piping insulation system design is only as good as its weakest link. A design for a refrigerant or chilled water system will almost always call out the areas to be insulated, type of insulation, and thickness of insulation, but if it does not address the wall and floor penetrations, longitudinal seams, butt joints, pipe supports, termination points, valves, and fittings, it is not addressing the most common areas of failure in an insulation system. For these systems, the designer should make sure that these areas meet the same requirements for thermal conductivity, water vapor transmission, etc. as the rest of the system. Otherwise, these areas become the weakest link and will be potential failure points in the system.

Photo 1 shows chilled water insulation penetrating a gypsum wall without carrying insulation through the penetration. The vapor barrier was not maintained and the fire caulk and gypsum wall show evidence of

condensation and water damage. *Photo 2* shows rust from condensation when an insulation insert was not used at supports. Note the open vapor barrier on both sides of the insulation with exposed mineral fiber leading to intrusion of moisture into the insulation. *Photo 3* shows condensation when a chilled water isolation valve was not properly insulated. *Photo 4* shows the impact of condensation when the chilled water piping to a fan coil unit located in a ceiling space was not fully insulated. The lack of insulation and vapor barriers on below ambient systems will eventually cause damage to the surrounding areas and lead to mold growth.

On cold operating systems, taped seams/joints and staples are seldom effective. Adhesive or glued seams are more secure and generally offer better water vapor permeability properties and better longevity. When insulation absorbs and retains water from condensation,

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its thermal conductivity increases, leading to greater surface condensation and potential corrosion under the insulation.

Understanding Insulation Physical Properties

Industry standards play an important role in specific methods of testing physical properties of insulation materials. These standards provide a means for achieving specific technical performance when installed in accordance with the standard guidelines. Insulation material comparison often involves contrasting the physical properties of available materials as represented on the manufacturer's data sheets. It is important that the physical properties being compared are tested to the same test method and procedure, and the values are expressed in the same units. If not, the comparison is not valid, resulting in an inaccurate analysis of materials. In order for piping insulation to be effective it needs to remain as close to its manufactured state as possible, meaning it should remain dry, uncompressed, and undamaged.

Service Temperature

Service temperature of the piping is often a primary consideration when selecting an insulation material. Insulation failure typically occurs when the insulation material is subjected to temperatures that exceed its maximum use temperature. Insulation material should be selected to not exceed the maximum temperature as determined by ASTM Standard C411. There is currently no industry-accepted test method for determining the minimum operating temperature of an insulation



PHOTO 1 Pipe penetration insulation failure.



PHOTO 2 Improper non-insulated CHW pipe support.



PHOTO 3 Improperly insulated CHW valve dripping.



PHOTO 4 Incomplete CHW insulation condensation.

material. Minimum temperatures are normally determined by evaluating the materials integrity and physical properties after exposure to low temperatures. The manufacturer's literature should be consulted on low temperature applications.

Thermal Conductivity

Thermal conductivity is the measure of how easily heat flows through a specific type of material, normalized for thickness. The lower the thermal conductivity of a material, the better the thermal performance. In the insulation industry, thermal conductivity is typically expressed as the symbol k , in units of $\text{Btu}\cdot\text{in}/(\text{h}\cdot\text{ft}^2\cdot^\circ\text{F})$ or λ , in units of $\text{W}/(\text{m}\cdot^\circ\text{C})$. Most insulation materials have k -values less than one. It is important to understand that thermal conductivity is a material property; meaning that actual heat transfer for the pipe will be a function of the

thermal resistance of the assembly, which is a function of the installation as described below.

Thermal conductivity changes depending on the mean temperature (the average of the temperatures on each side of the insulation). Many specifications call for insulation conductivity at a mean temperature of 75°F (24°C). Most manufacturers can provide the thermal conductivity over a range of operating temperatures. As the mean temperature goes up, so does the k -value. Therefore, a designer should evaluate the thermal conductivity closer to actual operating conditions to determine the actual thermal conductivity for a specific application. ASTM Standard C335 is used by manufacturers as a standard test method for determining steady-state heat transfer properties of pipe insulation for a material that can be placed around a test pipe.

Thermal resistance (R-value) is the insulation's resistance to heat flow. Thermal resistance for flat surfaces is dependent on the k-value and thickness of the insulation and for flat insulation, like duct liner, the R-value is simply the thickness divided by the k-value. Thermal resistance of insulation for pipe is dependent on the k-value, thickness of the insulation and the inner diameter of the insulation with smaller pipe diameters having higher R-values for a given insulation thickness.

Energy standards and codes typically specify the minimum pipe insulation thickness requirements based on the fluid temperature range with assumed thermal conductivity ranges. The equivalent minimum insulation thickness can be calculated for other conductivity values using the following formula:

$$T = PR \left(1 + \frac{t}{PR} \right)^{\frac{K}{k}} - 1 \quad (1)$$

where

T = minimum insulation thickness for material with conductivity K , inches

PR = pipe actual outside radius, inches

t = minimum insulation thickness in standard

K = conductivity of alternate material at mean rating temperature in standard for applicable fluid range, in Btu·in/(h·ft²·°F)

k = The lower value of the conductivity range listed in the standard for the applicable fluid temperature range, in Btu·in/(h·ft²·°F)

The above formula allows the designer to consider alternate insulation material where the thermal conductivity is not within the range in the standard specified thicknesses. This can be helpful when evaluating options for higher compressive resistance or reducing insulation thickness with higher performance insulation.

Compressive Resistance

Compressive resistance is defined as the compressive load per unit of area at a specified deformation. Compressive strength is defined as the compressive load at which the specified deformation is the start of complete failure. Compressive strength is important where the insulation material must support a load without crushing. Compressive resistance should be evaluated for insulation inserts in pipe supports or where the pipe insulation could be subjected to mechanical damage. Piping insulation installed outdoors is generally subject

to more mechanical damage than insulation installed indoors in inaccessible spaces. ASTM Standard C165 is used to measure the compressive resistance of fibrous and cellular materials.

Water Vapor Permeability

Permeability is primarily an issue with insulation on low-temperature piping where ambient humidity is high over long periods of time. Water vapor permeability is defined as the time rate of water vapor transmission through unit area of flat material of unit thickness induced by unit vapor-pressure difference between two specific surfaces, under specified temperature and humidity conditions. For insulating materials, water vapor permeability is commonly expressed in units of perm·in (ng/Pa·s·m).

For cellular insulation, closed cell insulation has a structure that includes millions of unconnected microscopic and intact bubbles, which effectively contain the blowing agent over a long period of time. Consequently, the thermal performance of a closed cell insulation can be maintained since moisture will not penetrate the material. In contrast, open cell insulation has a structure that allows moisture and vapor to permeate through it.

If the insulation material is vapor permeable, as indicated by a high permeability value, moisture can move through the insulation to reach areas where the temperature is low enough to form condensation. These conditions require vapor retarders to provide a continuous vapor barrier. An insulation material with low permeability would prevent this situation from occurring if all the seams are sealed. Over time, with highly permeable materials, air with moisture will come in contact with the cold pipe and form condensation between the pipe and the insulation. The condensed moisture creates wet insulation, which increases the chances for pipe corrosion, mold growth, and degradation of the insulation's thermal conductivity, resulting in insulation and system failure. This situation is severe and would warrant removal and replacement of the insulation. However, this is generally a long, slow process taking years to develop.

In contrast, if there is evidence of moisture between the insulation and the pipe in a short period of time, the cause is almost always poor installation with open vapor barriers where moisture-laden air can travel unabated to the cold pipe and form condensation. These situations also occur when metal pipe supports and clamps

TABLE 1 Common pipe insulation material properties.^a

	MINERAL FIBER PIPE	CALCIUM SILICATE PIPE	PHENOLIC PIPE	CELLULAR GLASS PIPE	POLYISOCYANURATE PIPE	ELASTOMERIC TUBE
ASTM STANDARD	C534 Grade III	C533 Type I	C1126 Type III	C552 Grade 6, Type II	C591	C534 Type I, Grade I
TEMPERATURE RANGE, °F	0 to +1000	Ambient to +1200	-290 to +250	-450 to +900	-297 to +300	-297 to +220
THERMAL K, BTU-IN/H·FT ² ·F	0.23 at 75°F	0.34 at 100°F	0.18 at 75°F	0.29 at 75°F	0.19 at 75°F	0.25 at 75°F
DENSITY, LBS/FT ³	3 to 6	14	2.5	7	2	3 to 6
COMPRESSIVE RESISTANCE, PSI AT 10%	Low ^b	>100	18	90	30	Low ^b
WATER VAPOR PERMEABILITY, PERM-IN	75	32	0.9	0.005	4	0.05
ASTM E84 FLAME/SMOKE RATING	0/0	25/50	25/50	25/50	25/450	25/50

^a The values listed in this table are from manufacturer data for general comparison of properties. Actual manufacturer insulation properties should be reviewed when selecting pipe insulation.

^b Value typically not specified by manufacturer.

come in contact with the cold piping making it difficult to thermally insulate and achieve a proper vapor barrier. ASTM Standard E96 is used to measure the water vapor transmission properties of insulation materials.

Material Options

Many different piping insulation material types are available with a wide range of cooling and heating applications. Some material types are better suited for one purpose over another depending on what is most important in the application. Closed-cell and compressive resistance could be the deciding factor for pipe insulation in manholes where maintenance personnel may need to climb over piping and mechanical damage is the primary concern. Common standard pipe insulation materials include mineral or glass wool, calcium silicate, phenolic, closed-cell cellular glass, and closed-cell elastomeric.

Table 1 compares material properties of some common pipe insulation materials to guide selection for a specific application. With so many versatile materials available, designers have various options for each application and may use several different types of materials on a specific project. Designers are encouraged to compare the properties when evaluating other alternate materials.

Achieving Optimal Performance

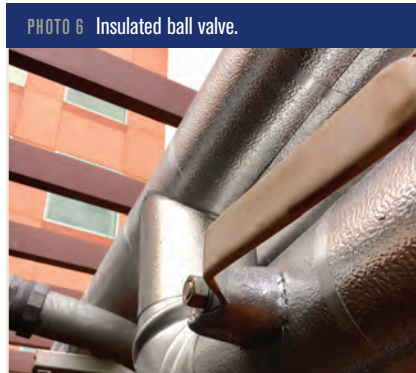
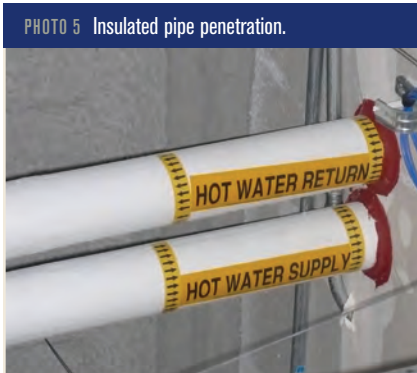
Using materials and practices that minimize the risk of the insulation becoming wet will assist in maintaining the performance of the system. The ASHRAE Handbook provides good guidance when designing piping insulation systems. NAIMA provides good details for piping insulation and jacketing systems on chilled water systems. Insulation with high vapor permeability should

have a vapor barrier that is continuous. For example, if the end of mineral fiber insulation is left exposed, it allows the insulation to absorb moisture and reduces the thermal performance. Weather barrier mastics and coatings can be used to help retard the flow of vapor through an insulation system.

Steam and high-temperature hot water systems operate at elevated temperatures so insulation is needed not just for thermal efficiency but to eliminate the risk of burns. Over time, thermal insulation on pipe components can be damaged or removed from components such as gate valves, steam traps, and wye strainers due to component maintenance or repair. These components are usually never reinsulated. Removable thermal insulation jackets can be very useful in both dry or wet applications. The jacket is manufactured to insulate pipe components like valves and steam traps that eventually need to be accessed by operating personnel.

It is generally best to avoid mineral fiber insulation when piping systems will be operating with service temperatures below the ambient air if there is any chance of the vapor barrier getting punctured. Once the jacket is punctured, the vapor barrier is broken and the insulation eventually gets wet and degrades. For instance, mineral fiber insulation for chilled water piping outdoors in a humid climate is not the best choice because the vapor barrier will almost surely be damaged at some point in the life of the system. If mineral fiber insulation is used on below ambient services, vapor dams or seals should be used per NAIMA recommendations to limit the extent of insulation damage if the jacket is punctured.

Closed cell elastomeric, cellular glass and phenolic are generally better alternatives to consider for below



ambient services. Closed cell insulation material also performs better on below grade services since there is a high probability of water exposure to the insulation.

Insulation jacketing provide an additional layer of protection from moisture, physical, and mechanical damage. Metal and PVC jacketing provide protection from minor physical and mechanical damage and should be considered when insulating exposed piping that is accessible to personnel. Metal jackets also provide additional weather protection. Bituminous type membrane jacketing can provide an external vapor seal for cellular glass insulation.

Generally, insulation should be continuous through wall/floor penetrations as shown in *Photo 5* to minimize heat loss and avoid the flow of vapor and condensation. Bruno and Stahl provide guidance for firestopping insulated pipe penetrations for various insulation materials. Valve handle stem extensions on below ambient systems allow the insulator to insulate around the valve as shown in *Photo 6* to maintain a vapor barrier and wrap insulating tape on the stem extension to prevent condensation. Insulation should also be continuous through supports by using insulation inserts as shown in *Photo 7*.

Conclusions

One standard piping insulation specification will not fit every application. Designers need to have information on the local environmental conditions and application requirements for various areas of a project to properly design high-performing pipe insulation systems. All aspects of the systems are important. Attention to detail, following best practices, and industry-standard installation techniques can help designers and contractors achieve long term performance with piping insulation system design.

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