TECHNICAL FEATURE

Pipe Insulation 101: Fundamentals & Basics

BY DARRELL PEIL, ASSOCIATE MEMBER ASHRAE

Pipe insulation has been essential for mechanical systems for decades, improving energy efficiency, safety and system performance. Without it, energy consumption is 85% to 90% higher,* condensation and microbial growth become rampant, hot systems present hazards and water systems freeze routinely. Despite being a simple, cost-effective solution, pipe insulation is often overlooked until problems arise. As many new professionals enter the field, understanding its uses and impact is crucial.

What is Pipe Insulation?

Pipe insulation provides thermal and acoustic control, without requiring the addition of any energizing force or routine maintenance, and offers a short-term payback with long-term performance and savings. Recommendations and information surrounding the use of pipe insulation are detailed in the *2025 ASHRAE Handbook—Fundamentals*, Chapter 23, Insulation for Mechanical Systems. This chapter is maintained by ASHRAE Technical Committee 1.8, Mechanical Systems Insulation.

Pipe insulation, a thermal and acoustical energy transfer control medium, is formed into a tubular shape to fit the outside diameter of the pipe. Commonly, the pipes or tubes are made of steel, copper, aluminum, stainless steel, polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), cross linked polyethylene (PEX) and polypropylene random copolymer (PPR). Pipe insulation is produced in sizes to fit the outside diameters of most types, including those sized in Imperial or U.S. Customary units (inches) or

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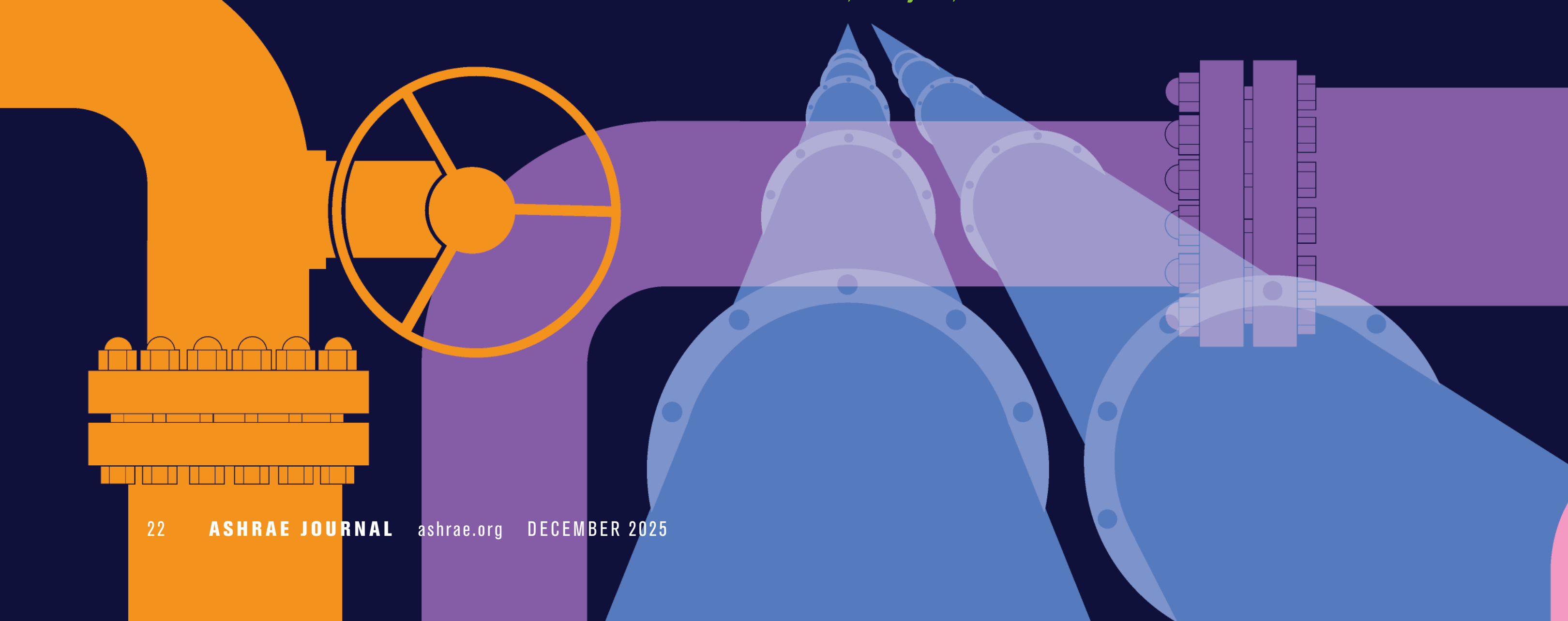
Darrell Peil is specifications/business development manager, commercial and industrial, Knauf Insulation North America, Shelbyville, Ind.



International System units (SI or metric).

The insulation can be provided as a preformed material produced to the correct size for the pipe, or a flat, flexible product that is formed to the pipe size at the project site. The insulation material is also formed with a specific wall thickness that varies to create the level of heat energy control desired. This combination of inside diameters and wall thickness determines the outside diameter of the insulating material.

Why Use Pipe Insulation?

Primary Benefits

Pipe insulation provides five primary benefits:

- **Slow heat loss or heat gain of the contents of a pipe system, or process control.** Control of heat loss or heat gain is the function of energy conservation. If heat loss in the case of heated contents, or heat gain in the case of cooled contents is reduced, less energy needs to be applied to the contents, either by adding or removing heat energy. When a process must be kept within a specific operating range of temperatures, pipe insulation is used to reduce energy flow.
- **Economical facility operations.** Saving energy costs is probably the biggest driver for using pipe insulation and is a direct outcome of slowed heat transfer. Less energy used to heat or cool the contents of the pipe results in cost savings associated with lowered energy consumption.
- **Control the formation of condensation on the exterior of piping having cooled or chilled contents.** The proper thickness of insulation will keep the surface temperature of the insulated pipe system above the dew-point temperature of the surrounding environment. In addition to the correct thickness of insulation, a high-performance vapor retarder system must be applied to the exterior of the system to slow water vapor transmission.
- **Personnel protection/safety.** A particularly key role of pipe insulation is safety in the workplace. Many piping systems operate at high temperatures—typically above 120°F (49°C)—that can present a burn hazard to personnel. Using a sufficient thickness of pipe insulation reduces the temperature of the surface of the system to a level where contact with the system will not cause burns, or it slows the time to cause burns.
- **Slow the freezing of pipe systems contents.** Many times, pipe systems are installed in locations that are subject to freezing temperatures that can cause significant trouble and expense if the contents freeze during periods of low or no-flow operation. The most common case is water piping that is subject to freezing. If the pipe breaks, and water flows uncontrolled, significant facility damage usually results.

In the case of municipal water distribution systems, it is imperative to protect pipes from developing frozen water (ice) to maintain system reliability and operation in all conditions. Pipe insulation can be used to slow the time it takes for the pipe's contents to freeze. It will not stop

*Statistic is derived from calculations using 3E Plus, an industry thickness calculator, supported by NAIMA.

freezing but will extend the time by slowing heat loss. Quite often, a method of adding heat to the pipe—electric or steam heat tracing—is used in combination with pipe insulation to stop freezing. Pipe insulation keeps the added heat energy directed to the pipe and keeps the required amount of added energy to a minimum.

Important Secondary Reasons for Pipe Insulation

A few secondary reasons for installing pipe insulation are becoming more important:

- **Acoustical control.** Many thermal energy insulation materials effectively control the transfer of sound energy. Pipe insulation can reduce the sound transmitted by piping systems, such as storm water or wastewater systems, into occupied spaces where these noises reduce acoustical comfort.
- **Fire safety.** Some pipe insulation materials have very low rates of flame spread and smoke generation when subjected to fire. Fire response properties are highly important to the overall life safety of the occupied structure. A key example of this is building cavities that are used for air distribution spaces, typically return air plenums. Polymer piping systems may be installed in these spaces, and a material needs to cover them to provide the proper fire resistance properties. Some pipe insulation materials can provide this resistance and are certified by using a method of system assembly testing developed and conducted by Underwriters Laboratories that includes the insulation material and polymer samples that are commonly used for pipe.

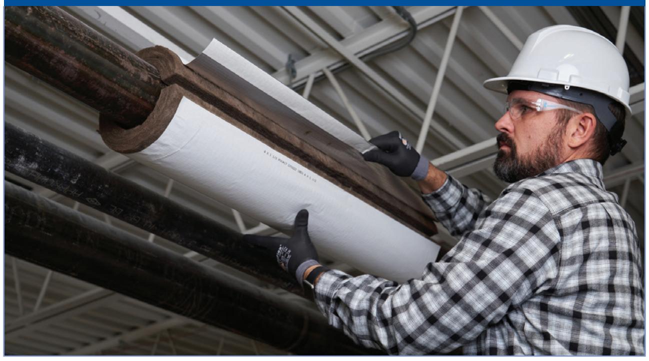
Carbon sequestration/decarbonization. Pipe insulation is an effective material for reducing operational carbon emissions from the built environment. The reduction in carbon emissions is a direct relationship to the reduced energy use that insulation affords. Information on this topic has been published in the *2025 ASHRAE Handbook—Fundamentals*.

Types of Pipe Insulation Materials

Pipe insulation comes in various materials, each suited for specific applications:

- **Mineral fiber.** Includes fiberglass and rock/slag fiber, the most widely used insulation types.
- **Mineral-based.** Cellular foamed glass, calcium silicate and alkaline earth silica offer durability and fire resistance.

PHOTO 1 Fiberglass pipe insulation fit to pipe.



KNAUF INSULATION

- **Synthetic rubber foam.** Flexible, expanded foam made from synthetic rubber, available in closed- and open-cell forms.
- **Polymer-based foams.** Includes expanded/extruded polystyrene, polyisocyanurate, polyolefin, phenolic resin and melamine, each offering unique thermal and moisture-resistance properties.

Choosing the right material depends on the project's specific needs, including temperature control, moisture resistance and fire safety. The application must be understood for directing the proper choice of material(s) for a project.

Basic Forms of Pipe Insulation

Pipe insulation is most commonly supplied in factory-preformed tubes (*Photo 1*), in either rigid or flexible forms, with a set diameter and wall thickness. This ensures fast, accurate installation. These preformed sections may be one-piece or multiple-piece, with the latter being more complex and costly to install.

Pipe insulation can also come as a flat sheet that is meant for field fitting to the pipe. The flat sheets may be provided in a highly flexible sheet or a more rigid form, with a production practice that allows for wrapping/forming around pipes. This is normally reserved for larger pipes, typically 8 in. (203 mm) diameter or larger. It is important to understand this characteristic of the form supplied to arrive at the best combination of availability, performance and cost.

Key Performance Properties of Pipe Insulation

Key performance properties for pipe insulation are largely standardized, with some variation caused by properties unique to a particular material or class of materials. These properties are detailed in the ASTM standard specification for each product type.

The properties discussed here are basic to all pipe insulation products. These characteristics have standardized industry test methods, most commonly ASTM tests, to validate these essential properties.

Thermal conductivity. Basic measure of how much heat energy a material will conduct based on a standard thickness over a specific time with a given mean temperature between the system operating temperature and the outer surface temperature of the insulation. This is tested per ASTM C335.

Continuous service/use temperature range. The upper limit is tested per ASTM C411. The lowest temperature and intermittent "spike" limits are producer-determined, with no industry standard. Continuous service temperature is the key metric.

Water and water vapor transport properties. Water absorption, adsorption and water vapor transmission are the typical measures used to indicate how effective a material is in resisting the movement and retention of liquid and vapor water forms through the material.

- **ASTM E96.** The primary test for water vapor transmission.
- **ASTM C1104.** Measures the amount of water vapor absorbed by mineral fiber insulation in high-humidity conditions.
- **ASTM C1763.** Evaluates a material's liquid water retention by immersing it under specific conditions.

Fire Response Properties

Two primary tests evaluate fire resistance:

- **ASTM E84.** The most common standard for assessing a material's fire response, which measures flame spread (how quickly fire travels along a material's surface) and smoke developed (the amount of smoke produced during combustion).

Low ratings in both flame spread and smoke developed are essential as they enhance evacuation safety and minimize damage in case of a fire. Although ASTM E84 does not have a pass/fail criterion, most building codes require a flame spread index of 25 or lower and a smoke developed index of 50 or lower. Notably, a product cannot "pass" this test; it simply receives a rating based on measurements.

- **ASTM E136.** Another significant test, though not applicable to all materials. It identifies materials that do not contribute to combustion or significantly increase an ambient fire's heat. This test does have a pass/fail outcome, and materials that pass are typically classified as noncombustible.

Dimensional Characteristics

Dimensional properties of finished pipe insulation are key to the effective and correct performance of an installed system. The insulation must fit the pipe with a close fit for many reasons that maintain system integrity and performance.

Wall thickness is vital for controlling heat or sound energy flow as designed. If the thickness is below the specified value, desired energy control and performance cannot be achieved. Most factory molded or fabricated pipe insulation materials use the dimensional standards detailed in ASTM C585. However, field-applied flexible materials may not meet these dimensions. Therefore, verifying the thickness through field inspection is essential for systems using flexible materials. These properties, although not an exhaustive list, are fundamental to selecting and installing effective, safe and durable pipe insulation.

Pipe Insulation Sizing

Pipe insulation is designed to fit specific pipe or tube sizes and is available in a wide range of dimensions. The inside diameter of the insulation matches the outside diameter of the pipe, with sizes ranging from as small as 0.25 in. (6.4 mm) to as large as 36 in. (914 mm).

Wall Thickness Options

Single-layer thicknesses range from 3/16 in. (4.8 mm) to 6 in. (152 mm).

Incremental changes typically occur in 0.5 in. (13 mm) steps.

Multilayer Installations

ASTM C585 standards are designed to allow the correct fitting of multilayer insulation systems to achieve the desired total thickness using multiple layers. Note that not all materials are available in every combination of inside diameter and wall thickness, so understanding these specifications is crucial for effective product selection.

Basic Installation Practices

Warm Installations

When insulating pipes above ambient temperatures, the primary goals are reducing heat energy loss and ensuring a smooth, pleasing appearance. A finished pipe insulation system is installed for both function and appearance, as it is the visible and final part of an installed piping system.

- **Vapor retarders.** Less crucial compared to cold systems, but smooth and uniform joints are still important, especially in straight pipe runs.
- **Fittings installation.** Fittings like 90° and 45° elbows and tees need to have a full thickness of insulation. This can be achieved by field fabricating the pipe insulation to fit properly over them. The use of other accessories can help transition the insulation system effectively to these components.
- **Pipe supports.** Pipe supports can be encased by the insulation. Best practice is to have the pipe separated from the pipe support by high-compressive strength insulation inserts with load-distributing shields. This practice increases the energy conserving function of the insulation system.

Cold Installations

When insulating pipes below ambient temperatures, the focus is on preventing heat gain, controlling condensation and maintaining aesthetics. Proper vapor retarder application is critical to system performance and longevity. As with warm systems, the insulation should be functionally sound and visually appealing.

- **Vapor retarders.** Must be installed and sealed effectively to prevent condensation and vapor intrusion. Avoid stapling as it creates vapor pathways. Vapor retarder details and sealing are critical to effective function and system life.
- **Smooth transitions.** Maintain a smooth appearance and vapor retarder integrity during transitions between different pipe sizes or fittings.
- **Fittings.** Ensure complete insulation coverage on 90° and 45° elbows, tees, specialties like valves, traps, strainers, flanges, etc., using field-fabricated pieces for a precise fit.
- **Pipe supports.** It is imperative to separate pipes from supports with high-compressive strength insulation inserts and shields to prevent condensation and leaks.

Both warm and cold installations require meticulous attention to detail to ensure functional efficiency and a neat, professional appearance.

Insulation System Accessory Material Needs

When designing and installing pipe insulation systems, selecting the right materials is crucial for achieving optimal performance and longevity. Understanding the specific characteristics and applications of each material will help ensure the success of your project.

Attachments

The method used to attach pipe insulation varies based on standard practices, product recommendations and project conditions. Several common attachment methods exist, including the ones below.

- **Pressure-sensitive adhesives.** Some insulation materials come with adhesive closures for easy application.
- **Tie wire or banding.** Made from various metals and alloys, these are commonly used for securing insulation.
- **Pressure-sensitive tapes.** Frequently used with specific insulation materials.
- **High-performance adhesives.** Suitable for a wide range of temperatures, from extremely cold to very high.

Carefully consult product instructions and industry standards to determine the best attachment method for your specific project needs.

Sealants

Typically called coatings, adhesives and sealants (CAS), this category of accessories may be the most misunderstood and misapplied of this industry. These products serve several functions including bonding/attachment, vapor retarders, aesthetic finishing and protection from weather and contaminants.

As final finish materials, they are most commonly supplied in white, gray or black colors. Some are meant to be used in conjunction with reinforcing fabrics. Each has a specific set of performance characteristics that is important to their intended function. Similar to the other system components, understand these characteristics to decide what is right for the function and project.

Finishing Materials

This category, sometimes referred to as jackets or facings, typically consists of barriers applied to the outside diameter of the pipe insulation to prevent damage and contamination. Not all these materials serve

PHOTO 2 Representation of smooth, clean transitions between fittings.

PHOTO 3 Example of a finishing material (jacket).

as vapor retarders, although some do, such as the all service jacket/premium all service jacket (*Photo 2*), which is a commonly supplied factory-applied laminated vapor-retarder facing suitable for many installations as the final finish. Other finishing products include PVC, rubber, metal (*Photo 3*), coatings, fabric/mastic systems and fiber/glass reinforced plastic (FRP/GRP). Many of these can be provided in various colors or painted to achieve specific schemes. Again, understanding the characteristics of each material is crucial for selecting the right one for your project needs.

Common Challenges in Pipe Insulation

For cold installations, achieving an effective vapor retarding system is often challenging and requires significant attention to detail. This involves the proper sealing of factory-applied vapor retarder facings with pressure-sensitive adhesive closures, ensuring both longitudinal and circumferential seams are correctly sealed.

Insulation Fit and Transition Issues for Fittings

Correct thickness of material is important. In both warm and cold installations, ensuring the insulation fits properly and transitions smoothly (*Photo 2*) to the pipe is a common concern. For hot systems, gaps at fittings can lead to heat leaks, causing discoloration or deformation of finishes, and even posing burn hazards to personnel. In cold installations, detrimental water vapor leaks may be formed.

Pipe Support and Hanger Insulation

The installation of pipe support and hanger insulation (*Photo 4*) is another critical area, as varied practices can lead to inconsistencies. This is a significant concern for design firms, as improper methods can compromise the system's effectiveness.

Design Considerations and Specifications

Design discussions often revolve around thickness and product selections, conflicting specification terms and ensuring adequate spacing for insulation when achieving compliance with ASHRAE/IES Standard 90.1 pipe insulation thickness requirements (*Photo 5*). These considerations are crucial for correct installation, optimal system performance and energy efficiency.

Innovations in Pipe Insulation

The pipe insulation market is a dynamic, evolving sector, far from one that some believe has become stagnant. Here are noteworthy advancements introduced in recent years:

- **Innovative vapor retarder facings.** Incorporating polymer film surfacing for enhanced performance.
- **Eco-friendly binders.** Using highly renewable plant-based technology for mineral fiber insulation.
- **Sustainable glass formulations.** Using increased amounts of pre- and post-consumer recycled content in fiberglass production.
- **Advanced vapor retarder systems.** Introducing new materials for improved finishing systems.
- **Improved standards.** Establishing new benchmarks that highlight a product's impact on indoor air quality (IAQ) and indoor environmental

PHOTO 4 Insulation installed through clevis hangers.

PHOTO 5 Ensuring adequate spacing for insulation between piping runs.

quality (IEQ).

- **Diverse manufacturing materials.** Expanding the range of materials used for pipe insulation.
- **Expanded size options.** Offering a wider variety of sizes for different pipe insulation materials.
- **Innovative insulating pipe support inserts.** Developing new products specifically for insulating pipe supports.

These developments are pushing the boundaries of what is possible in pipe insulation, ensuring the market remains vibrant and forward-looking. While this article is focused solely on piping insulation, all equipment associated with the piping system needs to be as well insulated as the piping to achieve system goals.

While the topic of pipe insulation may initially appear straightforward, it is, in fact, a complex and multifaceted field with significant impact across various industries. The design and installation of pipe insulation systems involves a deep understanding of thermal dynamics, materials science and environmental considerations. Understanding best practices in pipe insulation will undoubtedly enhance your expertise and contribute to more efficient and sustainable insulation solutions.

Ultimately, pipe insulation is not just about wrapping pipes—it is about enhancing energy efficiency, ensuring safety and contributing to the broader goals of environmental sustainability.

Resources for Further Learning

Many industry publications and organizations exist to provide information related to pipe insulation and installation.

Trade Associations, Standards Organizations and Associations

- ASHRAE. https://www.ashrae.org/
- ASTM International. https://www.astm.org/
- National Insulation Association (NIA). https://insulation.org/resources/
- North American Insulation Manufacturer's Association (NAIMA). https://insulationinstitute.org/tools-resources/

Publications

- *2025 ASHRAE Handbook—Fundamentals*. ASHRAE. https://tinyurl.com/yfrx8mjr
- 3E Plus Thickness Calculator. North American Insulation Manufacturers Association. https://www.3eplus.org/
- *Guide to Insulating Chilled Water Piping Systems with Mineral Fiber Pipe Insulation.* North American Insulation Manufacturers Association. https://tinyurl.com/ctd7jazw
- *North American Commercial and Industrial Insulation Standards Manual.* Midwest Insulation Contractors Association. https://tinyurl.com/msssdy2s
- "Standard Guide for Industrial Thermal Insulation." ASTM International. https://tinyurl.com/ysjkn8dj ■