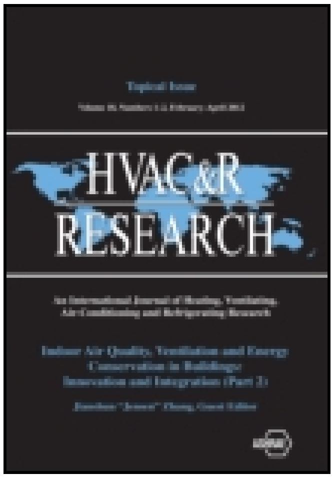


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# Pipe insulation thermal conductivity under dry and wet condensing conditions with moisture ingress: A critical review

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# Pipe insulation thermal conductivity under dry and wet condensing conditions with moisture ingress: A critical review

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Condensate that appears on mechanical pipe insulation systems might deteriorate the insulation thermal performance and lead to failure of the pipelines. An optimized solution that accounts for cost and system energy efficiency must consider the rate of moisture absorption at various operating conditions, and how the pipe insulation thermal conductivity varies with moisture content. This article reviews the most up-to-date work available in the public domain and observes that a controversy may exist about the similarities and differences of thermal conductivity of pipe insulation systems and flat slab configurations. Since the dissimilar behavior can be associated with the testing methodology from which the thermal conductivity values are originally derived, this article first discusses the methodologies for measuring thermal conductivity of pipe insulation systems with the intention of providing some clarification about such controversy. Steady-state and transient methods are discussed, and the measurements from these two methods are critically compared. The thermal conductivities of several pipe insulation systems are also summarized under dry operating conditions. For wet insulation, four main methods for preparing the wet samples during laboratory measurements have been identified, and it was observed that they yielded very different results. The advantages and shortcomings of each moisturizing strategy discussed at length, and the thermal conductivities of a few available pipe insulation systems in wet conditions are compared. To date, challenges still exist with the measurement of actual thermal conductivity of pipe insulation systems with moisture ingress, and future research needs in this area are discussed.

## Introduction

In several industrial and commercial buildings, cooling and heating pipelines are typically insulated to maintain process conditions, to prevent excessive heat losses from the system to the surroundings, and to promote safety and health of the occupied space. When a cold surface at a temperature below the dew point is exposed to air, moisture in the air will condense on that surface. When a chilled fluid pipe is inadequately insulated, such condensate will occur, and water will drip onto other building surfaces, possibly causing growth of mold, rotting of wood, and rusting of steel. Currently, engineers design pipe insulation systems with the aim of preventing such condensation. Ideally, vapor barriers that are installed on the exterior of the pipe insulation should prevent moisture ingress, but field experience with chiller pipelines that are used to cool large buildings shows that small holes in the insulation jacket, or the presence of inadequate sealed joints allow water vapor to permeate through the insulation toward the cold surface, leading to condensation within the insulation system. This can contribute to saturated insulation as the cold pipe surface draws moisture from the air and into the insulation. This condensation releases the latent heat from the vapor to the pipe surface and, ultimately, to the pipe's fluid contents. In addition, a wet insulation is a poor insulation, whereby more energy must be spent to pay for the heat gains through the pipelines. This reduces the energy efficiency and increases the parasitic energy consumption. Wet insulation will contribute to pipe corrosion and water dripping off the pipes may degrade the performance of other building components and cause mold to grow where dripping occurs. The moisture accumulation affects the economics of the building energy performance and can lead to system failure and downtime, which causes great economic implications when considering shutdown and replacement. An optimized solution that accounts for cost and system energy efficiency must consider the rate of moisture absorption at various operating conditions, and how the pipe insulation thermal conductivity varies with moisture content. An accurate characterization of the thermal conductivity and moisture transport in pipe insulation systems would enable mechanical system designers to choose the right insulation system for the specific application and better estimate the actual heat gains during the life cycle of the insulation system. For example, if water vapor condensate on the pipelines is a vital aspect of the design, then it is helpful to know that closed-cell insulation systems are typically more resistant to the

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water and vapor transport compared to fibrous and open-cell insulations. Vapor barriers are required on fibrous and open-cell insulation to prevent water accumulation in the insulation systems. However, it is also important to realize that studies in the literature have reported that some closed-cell insulation systems were not completely impermeable to water vapor, and the thermal conductivity of the insulation was affected by water content, such as polyurethane and extruded polystyrene (Kaplar 1974; McFadden 1986; Chyu et al. 1997a).

Because there are limited experimental data of thermal conductivity of pipe insulation systems at below ambient temperature, mechanical HVAC engineers often extrapolate the thermal conductivity and moisture ingress rates of pipe insulation systems in wet operating conditions from experimental data originally obtained on the same type of insulation material but in flat slab configurations. Two studies (Wilkes et al. 2002; Cremaschi, Cai, et al. 2012) have reported a measurable difference on the effective thermal conductivity when considering flat slab and pipe insulation systems. In addition, this approximation might not be suitable for all pipe insulation systems, as will be explained in more detail later in this article. Considering that the dissimilar values of thermal conductivity and moisture ingress rates are partially due to the method of testing, the test methodologies for measuring thermal conductivity of pipe insulation systems were critically reviewed with the intention to clarify the concept of apparent thermal conductivity associated with pipe insulation systems. To date, there are not any standard methods of testing pipe insulation systems for below ambient applications. Research was conducted to extend test methodologies that were originally developed for flat slab configurations to pipe insulation systems. We will also present standard methods of testing used specifically for pipe insulation systems for above ambient applications, that is, heated pipes with outward heat flow. For cold pipes commonly used in building HVAC systems, an inward heat flow occurs through non-homogenous and anisotropic materials, and selecting the thermal conductivity for this application based on measurements with outward heat flow is another point of debate among engineers, practitioners, and building owners. The first objective of this article is to critically discuss all these aspects by an extensive literature review. The thermal conductivities of pipe insulation systems measured at various laboratories were compared with the data in the literature for flat slab configurations. The second objective is to highlight the differences and similarities between these two sets of data. In addition, the direction of heat flow is key when considering wet conditions; that is, when the pipe surface temperature is below the dew point temperature of the surrounding atmosphere. This is often the case in the building's air conditioning, in which the occupied zone is set to 20°C to 25°C (68°F to 77°F), when the relative humidity of 40% to 50%, and the chilled water pipe surface temperatures are about 3.3°C to 5.6°C (38°F to 42°F). In these conditions, water vapor enters the insulation systems and condenses on the pipe surfaces. The impact of moisture ingress on the actual pipe insulation thermal resistance is still an unresolved question. For wet insulation, four main methods for preparing the wet samples during laboratory measurements are identified in this article. The third objective is to evaluate the impact of each method on the measured apparent thermal conductivity of the pipe insulation system. The advantages and shortcomings of each moisturizing strategy are discussed at length, and the thermal conductivities of a few available pipe insulation systems in wet conditions are compared. The literature review presented in the following sections should assist system designers in selecting appropriate pipe insulation systems based on the thermal performance and operating conditions because, as it will be highlighted later, some materials may perform very well under dry conditions, but condensate can easily accumulate leading to a fast degradation of the thermal performance.

## Experimental methodologies for measurement of pipe insulation thermal conductivity under dry conditions

In the current open domain, literature of experimental data involving thermal conductivity of cylindrical pipe insulation at below ambient conditions is scarce and mostly restricted to a few insulation systems. Because there is debate on whether the thermal conductivity of pipe insulation systems can be derived from measurements on flat slabs, it is helpful to highlight some of the similarities and differences in the thermal conductivity measurements of these two forms. A comparison between measured thermal conductivity data from the various test methodologies on pipe insulation systems and flat slab systems may also illuminate this debate.

### *Brief background on the methodologies for thermal conductivity measurements of flat slabs*

For flat slab insulation systems, steady-state and transient test methodologies are commonly used. The guarded hot plate (GHP) is one of the most widely used steady-state methodologies for thermal conductivity measurement on flat slab materials and (ISO 8302 [1991b]; American Society for Testing and Materials [ASTM] Standard C177-10 [2010a]). In the GHP methods, the edge effect is minimized by the end guards. The heat flow meter methods (HFM), which are mainly represented by ISO 8301 (1991a), as well as ASTM Standard C518-10 (2010b) and British Standard European Norm (BS-EN) 12667 (2001), are also commonly used due to their simple concept and low requirements for the application of test specimens. The basic principles of both GHP and HFM methods are applicable to pipe insulation systems. Compared to the GHP method, which is normally applied below 200°C (392°F), there is no upper temperature limitation for the thin heater apparatus (THA) that is typically used for refractory bricks and insulation panels. With considerably less mass than the combined central heater and guard heaters used in the GHP methods, the THA is able to shorten the time to reach steady-state and may also minimize drift errors (ASTM Standard C1114 [2006]). However, currently this method is only available for testing flat slab configurations. Another method commonly used under steady-state is the hot box method (ASTM Standard C1363-11 [2011]). Considering the severe requirements of the two temperature controlled boundary conditions on both sides of the test specimen, the same apparatus is not suitable to be used with material of cylindrical shapes because controlling the inner side might not be feasible in practice.

The transient hot wire (THW) and the transient hot strip (THS) methods are common techniques applied in transient conditions, and they are able to provide fast measurements of the thermal conductivity for small size test samples (Gustafsson et al. 1978; Ohmura 2007). The transient plane source technique (TPS), also referred to as "hot disk" or "hot square," is developed for evaluating anisotropic thermal property values by replacing the heating element with a very thin, double metal spiral heater (Gustafsson et al. 1994; Sabuga and Hammerschmidt 1995; Rides et al. 2009). The thermal conductivity probe is a practical method used in the field and it provides measurements of the thermal conductivity of regions of the insulation in which it is installed. It is generally viewed as a trade-off between accuracy and cost (Tye 1969).

Compared to transient test methods, thermal conductivity values from steady-state methods are simpler to be derived from the measured data if the uniform heat flux throughout the test specimen is a reasonable assumption. However, providing a uniform heat flux in the entire test section is the main challenge for most steady-state methods. Pratt, as cited in Tye (1969), mentioned that the steady-state methods are limited to only homogeneous materials with a thermal conductance of at least 6000 $W/m^2$-K (1060 Btu/hr-$ft^2$-°F). In order to prevent end edge effects, the test samples normally need to be very large, and it takes a considerable amount of time for the test specimen to reach complete thermal equilibrium. Due to the large surface area, the surface contact resistances should not be neglected especially when the material thermal resistances are of the same order. For example, Salmon and Tye (2010) pointed out that the material thermal conductivity, measured by transient methodologies, are about 3% higher than the values derived from the GHP due to the effects of surface thermal contact resistance between the test specimens and the guarded plates. Transient methods are also not affected by the conditions of the surrounding environments, which may cause the test specimens to become chemically unstable or contaminated with long testing periods required by steady-state methods (Tye 1969).

For the thermal conductivity measurement of insulating building materials, it seems that the steady-state heat flow techniques yield more accurate measurements than the transient techniques (Log 1993). Using a calibrated insulation sample (McFadden 1986), the accuracy of steady-state heat flow techniques can be significantly improved, and anisotropic materials, such as fiber materials with low bulk densities, can be successfully tested. Wulf et al. (2007) measured the thermal conductivities of both isotropic and anisotropic materials based on the GHP technique, the guarded heated pipe technique (which will be discussed in the next section), and the THW technique. These three techniques showed excellent agreement for isotropic materials, but some discrepancies were observed in anisotropic materials. It was observed that the position of the heated wire in the THW technique affected the measured thermal conductivity of anisotropic materials. When dealing with low thermal conductivity materials, Woodbury and Thomas (1985) pointed out that probe wires could become highly conductive and created an alternative path for the heat losses. This would affect the accuracy of the measurements, and Suleiman (2006) provided recommendations to avoid such phenomenon. On the other hand, GHPs show large differences when compare to other techniques at a temperature above 100°C (212°F; Albers 2002; Salmon and Tye 2010). This is because the radiation heat transfer cannot be neglected at high temperatures. Tritt (2004) observed that in using a standard steady-state method for temperatures above 150°C (302°F), radiation loss became a serious problem, and a correction method to account for radiation was proposed based on Wiedemann-Franz law (Johns and March 1985). To minimize the radiative heat transfer component, the surfaces need to be very emissive, especially for the low density materials (Miller and Kuczmarski 2009).

Since the GHP and HFM methods measure an overall thermal conductivity on a relatively large area, they do not allow one to probe the insulation for a measurement of the thermal conductivity at specific identifiable locations in the sample, which can be considered as a shortcoming of these techniques in some cases (McFadden 1988). By inserting the probe into the insulation, it is possible to check the uniformity of the heat flux within the insulation and to determine if the moisture is absorbed uniformly in the insulation for wet conditions.

### *Review of the thermal conductivity measurements of pipe insulation systems*

For pipe insulation systems, the heat transfer is in radial direction, due to the cylindrical shape, and heat conduction, which happens in radial symmetric geometries, was studied in the early literature (Glazebrook 1922). Because of the cylindrical geometry, the heat transfer area varies from interior surface to the exterior surface, and this leads to a range of thermal resistances. The definition of mean insulation temperature is not clear in most reported studies. In some studies, it is reported as the arithmetic average temperature between the interior and exterior surfaces; in other studies, it is defined as the temperature of a center layer of insulation obtained by volume-weighted averages on the insulation samples. During the application of the pipe insulation systems, joint sealant is usually required between the top and bottom shells. The presence of longitudinal joints and of joint sealant affects the measured thermal conductivity of pipe insulation systems if compared to corresponding thermal conductivity data, which is obtained from flat slab configurations. All the mentioned differences help to explain the reasons why the apparent thermal conductivity of the pipe insulation systems differs from the measured thermal conductivity of the insulation material, which is typically measured for flat slab configuration. In recent years, limited published work in the literature reported the comparison of the thermal performance and measurement methodologies between the pipe insulation systems and flat slabs of the same materials. Wilkes et al. (2002) concluded that for polyurethane insulation, the flat slab configuration had 2% to 5% higher thermal conductivity than the pipe insulation configuration. Cremaschi, Cai, Ghajar et al. (2012) and Cremaschi, Cai, Worthington et al. (2012) observed that the joint sealant applied on pipe insulation during the installation might cause a non-negligible effect on the apparent insulation thermal conductivity. Moore et al. (1985) pointed that measuring the thermal conductivity of pipe insulation systems would be easier than measuring flat slabs since very long test specimens could be used. Tritt (2004) disagreed because radial flow methods were relatively more difficult to apply when compared to the linear measurements, especially when the materials were tested below room temperature. However, Tritt (2004) agreed that the radiative heat loss, which was severe in the traditional longitudinal heat flow method under high temperatures, could be minimized when the heating source was placed internally.

From the standards of testing methods and literature reviews, the methodologies for measuring the thermal conductivity of pipe insulation systems were critically reviewed, and they are summarized next. The guarded heated pipe method, which was developed from an early radial flow test apparatus designed by Flynn in 1963 (as cited in Tye 1969), can be considered as a modification from the GHP method where the test pipe insulation shells are installed around a heated pipe. The entire test apparatus is required to be placed in a temperature controlled chamber (Kimball 1974; Whitaker and Yarbrough 2002; Wilkes et al. 2002), or a test enclosure (Zehendner 1983) to provide constant temperature boundary conditions. The main assumption of heat flux in the radial direction is reasonable only if the edge effects, at both ends of pipes, are minimized. ISO Standard 8497 (1994) and several studies in the literature provided guidelines on how to account for the end edge effects (ISO 8497 [1994]; ASTM Standard C335-05 [2005]; BS-EN 253 [2009]). The calibrated hot box method, which was first presented by Musgrave (1979), is designed for testing pipe insulation systems around cold pipes. For this method, it is critical to reduce the humidity inside the box before the test, either by vacuuming or by dehumidification. In addition, proper sealing with vapor barrier systems are required, but achieving complete vapor barrier during the test conditions is critical. The radial heat flow meter method (concentric cylinder comparative method) is a modification of the HFM method, and it is applicable for testing pipe insulation with both inward and outward heat flux. Because of ease of installation, researchers used small pads as heat flux meters, substituting them for sleeve flux meters (Ramsden 1985; Rawlins 2005). However, the application of the heat flux pads seems to affect the shape of the test specimen—either by compressing the insulation in some locations or by creating gaps of air between the test insulation and cold surface in other locations. This variation of the contact resistance should be properly accounted for when measuring the thermal performance of the pipe insulation systems.

While the guarded heated pipe method is only suitable for the thermal conductivity measurement with the outward heat flow, the calibrated hot box method is used for cold pipe with inward radial heat flux. For achieving accuracy, it is critical to design appropriate thermal guards at the ends, and water vapor condensate might be an issue during the thermal conductivity measurements. Radial heat flow meters are suitable for both heated and cold pipes, but these flow meters suffer similar issues when applied to cold pipes. When using the radial heat flux meter technique, the flow meter materials should either be designed as insensitive to the water vapor in the air and potential moisture accumulation on the meter or the ambient has to be controlled such that the dew point temperature is below the surface temperature of the cold pipes. Another challenge with the radial heat flux meter is the possibility of forming thermal bridges between the two concentric pipes in the test apparatus. Cremaschi, Cai, Ghajar et al. (2012) and Cremaschi, Cai, Worthington et al. (2012) pointed out that in order to obtain better accuracy during the measurement, the materials made for supporting sleeves in between the two concentric pipes need to be selected with a thermal conductivity of the same magnitude as the one of test specimen.

There are also some techniques that employed transient methods to measure the thermal conductivity of pipe insulation systems. Transient methods are suitable for the measurement of pipe insulation thermal conductivity under non-destructive testing and in the field. The THW method is applied for the measurement of thermal conductivity in the range from 0.08 to 2.0 W/m-K (0.55 to 13.9 Btu-in/hr-ft$^2$-°F; Kulkarni and Vipulanandan 2006). Adl-Zarrabi (2005) tested the pipe insulation thermal conductivity by using the TPS method. By comparing to the results measured from the guarded heated pipe method, all the values derived in the TPS apparatus were slightly higher. When considering the joint sealant and vapor jacketing of pipe insulation systems, it is clear that transient methods provide a measurement of the local thermal conductivity in the material, instead of the system thermal performance.

A summary of interlaboratory/laboratory comparison results between steady-state and transient measurements is given in Table 1. Table 1 summarizes the recent work in thermal conductivity measurements for pipe insulation systems, and the work is grouped into two main categories: steady-state techniques and transient techniques. Due to the lack of the reported uncertainty in some of the published data for pipe insulation systems, the range of application and corresponding accuracy for some of the studies are selected based on data published on flat slabs.

## Review of thermal conductivity variation in pipe insulation systems

In this section, a comparison of the thermal conductivity of both flat slab and pipe insulation is presented with the aim of documenting the methodologies discussed in the previous section. The differences in material properties, such as density, thickness, porosity, internal structure, anisotropy, blowing agent, manufacturing time, handling, and installation methods, may affect the results of the experimental measurements. However, there are no studies that provided detailed information on the materials being tested for the thermal conductivity of both pipe insulation systems and flat slabs. In one research study, the authors compared these two configurations and pointed out the differences come from the material density and geometry between the pipe insulation and flat slabs (Wilkes et al. 2002). In order to provide a general

**Table 1.** Summary of interlaboratory/laboratory comparison between steady-state and transient measurements.

| | | Uncertainty steady-state measurement | | Uncertainty transient measurement | |
|---|---|---|---|---|---|
| | Temperature range, °C | GHP, % | HFM, % | Hot wire, % | Hot disk, % |
| Zehendner (1983) | −60–80 | Pipe, <±3 | — | — | — |
| McCaa and Smith (1991)[a] | 24 | 1.3%–5.5 | — | — | |
| Albers (2002)[a] | 0–100 | <2.5 | — | — | — |
| | 100–1000 | 24 | — | — | — |
| Wilkes et al. (2002) | 5–45 | Slab, ±0.8<br>Pipe, ±0.8 | — | — | — |
| Ohmura (2007)[a] | −120–25 | <±10 | >±10 | ±10 | |
| | 200–800 | — | — | ±10 | — |
| | 100–1300 | ±10 | — | — | |
| Wulf et al. (2007)[a] | 0–1200 | GHP, radial flow and hot wire/disk method with test results within ±10 | | | |
| Rides et al. (2009)[a] | 20–180 | HFM, hot wire/disk method with test results within ±7 | | | |
| Hay et al. (2009)[a] | 10–23 | <2 | — | — | — |
| Salmon and Tye (2010)[a] | 10–3 | ±1.5 | ±2, if test on individual specimens (density differences) the difference up to 5% | ±3 (3 percent higher than GHP) | |
| Bezjak and Zvizdic (2011)[a] | 10–30 | <0.5 | — | <3.6 | — |
| Cremaschi, Cai, Ghajar et al. (2012); Cremaschi, Cai, Worthington et al. (2012) | 10–25 | — | Pipe, < ±6 | — | — |

[a]Literature review results on flat slabs.

idea of how the thermal performance of the insulation system varies with the methodologies applied for thermal conductivity measurement, as well as with different types of materials and material densities, the reported values in the open literature are summarized in the following sections. The material properties, such as configurations of the test samples, densities and thicknesses are documented in Appendix A–E. The thermal conductivity of both pipe insulation systems and flat slabs are compared between the materials with similar densities. Based on these criteria, nine insulation materials applied in HVAC field are discussed, and the data have been grouped in Figures 1–5.

For fiberglass insulation, the thermal conductivities are linearly correlated with insulation mean temperatures (Wilkes et al. 2002; Abdou and Budaiwi 2005; Hay et al. 2009; Cremaschi, Cai, Worthington et al. 2012). McCaa and Smith (1991) and Salmon (2001) also correlated the thermal conductivity with material density. From the data given in Figure 1 and Appendix A, it appears that for fiberglass, the thermal conductivity of flat slabs and pipe insulation systems are fairly similar if one does not include the samples with low densities, which are shown as the solid and hollow triangle symbols. However, if one considers the samples with similar densities, by comparing the data reported by Wilkes et al. (2002) on the pipe insulation with a density of about 33 kg/m$^3$ (2.1 lbm/ft$^3$), and the data published by Al-Hammad et al. (1994) on the flat slab with a density between 32 and 37 kg/m$^3$ (2.0 and 2.3 lbm/ft$^3$), the measured thermal conductivity values on flat slab was about 10% higher than the pipe insulation, shown as group 1 in Figure 1. The reported uncertainty is ±0.8% for the guarded heated pipe method (Wilkes et al. 2002) and ±2% to ±4% for the GHP (Al-Hammad et al. 1994). When considering material samples with low densities, ranging from 12 to 27 kg/m$^3$ (0.75 to 1.7 lbm/ft$^3$), as shown in Appendix A, the thermal conductivity seems to increase as Langlais et al. (1982) pointed out. In this range, by selecting two

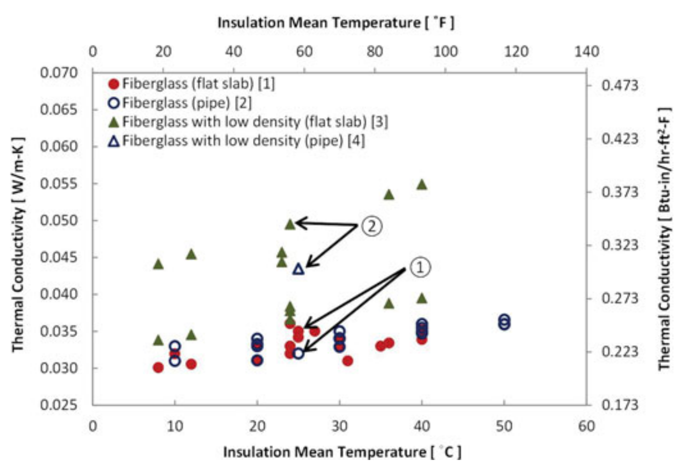


**Fig. 1.** Thermal conductivity of fiberglass insulation. ① = group 1; ② = group 2. [1] = Modi and Benner (1985), Moore et al. (1985), McFadden (1988), Wijeysundera and Hawlader (1988), Al-Hammad et al. (1994), Salmon (2001), Abdou and Budaiwi (2005); [2] = Chyu et al. (1997b), Wikes et al. (2002), Whitaker and Yarbrough (2002), Cremaschi, Cai, Ghajar et al. (2012), Cremaschi, Cai, Worthington et al. (2012); [3] = McCaa and Smith (1991), Abdou and Budaiwi (2005), Bezjak and Zvizdic (2011); [4] = Moore et al. (1985).

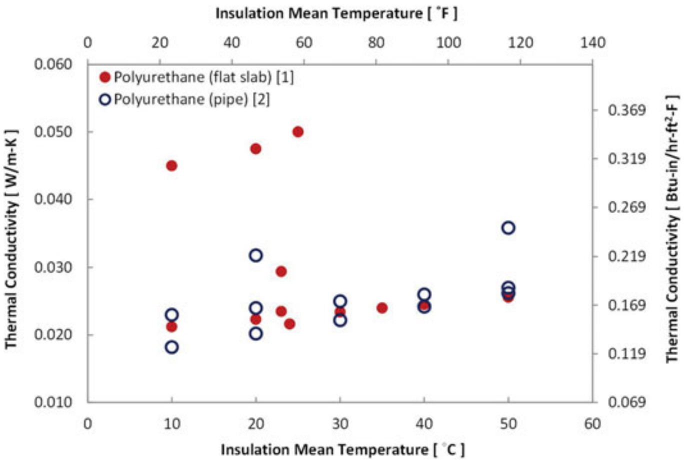


**Fig. 2.** Thermal conductivity of polyurethane insulation. [1] = McFadden (1988), Al-Hammad et al. (1994), Abdou and Budaiwi (2005), Ohmura (2007), Bezjak and Zvizdic (2011); [2] = Zehendner (1983), Adl-Zarrabi (2005), Chyu et al. (1997a).

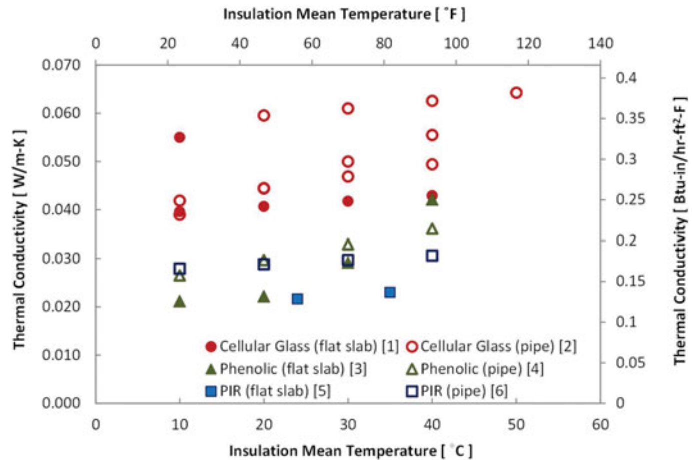


**Fig. 4.** Thermal conductivity of cellular glass, phenolic and PIR insulation. [1] = Kaplar (1974), Pittsburgh Corning Co. (2014); [2] = Whitaker and Yarbrough (2002), Cremaschi, Cai, Ghajar et al. (2012), Cremaschi, Cai, Worthington et al. (2012); [3] Tseng and Kuo (2002); [4] = Cremaschi, Cai, Ghajar et al. (2012), Cremaschi, Cai, Worthington et al. (2012); [5] = McFadden (1988), Al-Hammad et al. (1994); [6] = Cremaschi, Cai, Ghajar et al. (2012), Cremaschi, Cai, Worthington et al. (2012).

samples with similar densities, 15 kg/m$^3$ (0.9 lbm/ft$^3$) (Moore et al. 1985; McCaa and Smith 1991) and shown as group 2 in the figure, the flat slab seems to be more conductive than the pipe insulation. The mean error for the measurement of thermal conductivity on the flat slab was reported with an imprecision around 3% (McCaa and Smith 1991), and the uncertainty on the pipe insulation tester was not clarified in the literature.

For polyurethane, the density effect on the thermal conductivity seems not so significant as on fiberglass (Zehendner 1983). The data summarized in Figure 2 suggest that the polyurethane insulation has different thermal conductivity when measured from flat slabs and pipe insulation systems; however, a measurable difference was only reported for one group of data by Ohmura (2007). Although this group of data was validated by both steady-state and transient methods, within ±10% deviation, the material is affected by "aging" process since the blowing agent slowly diffuses out, and it is gradually replaced by air that fills in the cells. Kellner and Dirckx (1999) found that the thermal conductivity

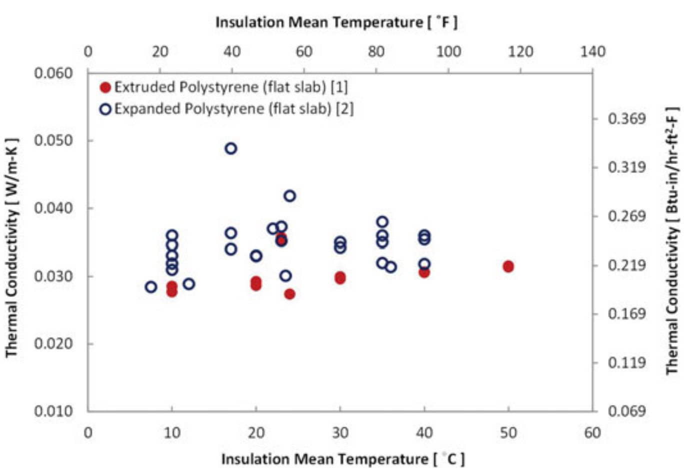


**Fig. 3.** Thermal conductivity of extruded polystyrene (XPS) and expanded polystyrene (EPS). [1] = McFadden (1988), Abdou and Budaiwi (2005), Bezjak and Zvizdic (2011); [2] = Pratt [as cited in Tye (1969)], McFadden (1988), Al-Hammad et al. (1994), Salmon (2001), Abdou and Budaiwi (2005), Mar et al. (2008), Bezjak and Zvizdic (2011), Lakatos and Kalmar (2013), Jerman and Cerny (2012).

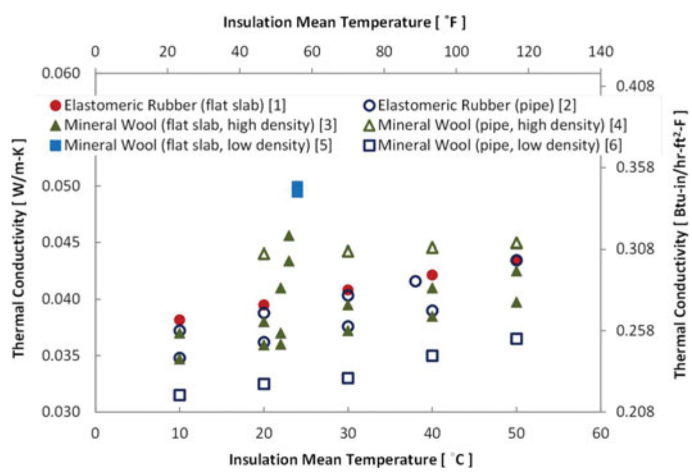


**Fig. 5.** Thermal conductivity of elastomeric rubber and mineral wool. [1] = Wilkes et al. (2002); [2] = Wilkes et al. (2002), Cremaschi, Cai, Ghajar et al. (2012), Cremaschi, Cai, Worthington et al. (2012); [3] = Abdou and Budaiwi (2005), Bezjak and Zvizdic (2011), Jerman and Cerny (2012); [4] = Whitaker and Yarbrough (2002); [5] = McCaa and Smith (1991); [6] = Zehendner (1983).

was increased by 7% to 30% depending on different aging methods. Blowing agent is another aspect that also needs to be considered during a critical comparison. Bhattacharjee et al. (1991) investigated both blowing agent and aging effects by comparing 20 specimens and concluded that different gas composition would vary the sensitivity on the thermal conductivity to the insulation mean temperatures. Biedermann et al. (2001) compared in detail the effect on thermal conductivity of 12 gas compositions, and the differences in the 6 closed-cell specimens were found within 10%. Therefore, during the comparison of polyurethane insulation, both the fabricating time of these test samples and gas composition in the cells need to be critically considered. All the ranges on the measurements of polyurethane thermal conductivity are reported in Appendix B.

Extruded and expanded polystyrene are two forms of foamed polystyrene insulation. Both extruded and expanded polystyrene are closed-cell foam insulation and for expanded polystyrene there are some small empty pockets in between the expanded beads (McFadden 1988). Free convection in foams was shown to be negligible for the cell sizes to be less than 1.5 mm (0.06 in.), which includes most polystyrene foams, and the main heat transfer in foams is due to coupled conduction and radiation (Yainik and Roux 1990). Air fills in these pockets, and the overall thermal conductivity is higher than the one of extruded polystyrene. This is probably caused by a higher infrared heat transfer due to a lower extinction coefficient (sum of the absorption and scattering coefficients) within the material. These findings are summarized in Figure 3. For extruded polystyrene, based on the current data collected from the open literature, with densities varying from 35.8 to 49.3 $kg/m^3$ (2.2 to 3.1 $lbm/ft^3$), there was not an obvious pattern between the system apparent thermal conductivity and material density. This material is also subjected to an "aging" process (Stovall 2009). Expanded polystyrene, on the other hand, is more sensitive to the material density, because the overall thermal conductivity of the material is affected by the radiative heat transfer within the material. Less dense materials are composed of more air pockets, which promote convective heat transfer and result in higher thermal conductivity. The numerical values are provided in Appendix C.

Cellular glass, phenolic, and polyisocyanurate (PIR), which has a similar thermal conductivity as polyurethane, are typically closed-cell insulation, and all these three materials require joint sealant during the installation on pipes. As summarized in Figure 4 (and Appendix D), the densities of these closed-cell insulation materials are typically in a narrow range, and the thermal conductivity seems not to be sensitive on the material density. For cellular glass and phenolic pipe insulation systems, the thermal conductivity is about 20% higher than the thermal conductivity measured from flat slabs. Cremaschi, Cai, Worthington et al. (2012) explained that the difference might be due to the longitudinal joints and the sealant that was applied on these joints. For both phenolic and PIR insulation, the deterioration of self-performance in the test samples need to be considered since they are subjected to the aging process (Christian et al. 1998; Stovall 2009). Thus, the result reported in Figure 4, in which pipe insulation systems have 20% to 30% higher thermal conductivity than flat slabs, must be carefully gauged due to different manufacturing time between the test samples. Similar to polyurethane insulation, different blowing agents are applied for PIR insulation, and the effect also needs to be accounted for during the comparison on the effective thermal conductivity (Zarr and Nguyen 1994). For most closed-cell insulation, one critical issue that needs to be considered is some blowing agents, such as pentane and propane, which are defined as natural gas liquids, can be easily turned into liquid with the application of moderate pressure or freezing and dramatically reduce the thermal conductivity of the insulation.

Elastomeric rubber insulation has either open-cell or closed-cell structure when present as foam insulation. Compared to the closed-cell, the open cell structure is affected by the portion of air pockets within the material. During the installation of elastomeric rubber pipe insulation, either a very thin layer of sealant is applied on the longitudinal joint, or a self-seal lap (SSL) tape is manufactured for the joint. Wilkes et al.'s (2002) results on the thermal conductivity of the elastomeric pipe insulation system are about 6% to 7% higher than Cremaschi, Cai, Worthington et al.'s (2012) measurements on a similar specimen with a higher density. The uncertainty for each test methodology is summarized in Appendix E. According to Wilkes et al.'s (2002) findings, pipe insulation systems showed 1.5% to 2.5% lower thermal conductivity when compared to flat slabs with similar densities and thicknesses, as shown in Figure 5 and they considered it as a good match because the materials were not identical. Mineral wool is another type of fibrous insulation, and its thermal conductivity is quite sensitive to the material density. From the values summarized in Appendix E, it seems that with similar densities, the cylindrical shaped mineral wool insulation has a thermal conductivity 20% higher than the flat slab configuration (Whitaker and Yarbrough 2002; Abdou and Budaiwi 2005). It is noted that one group of pipe insulation (the hollow rectangles in the Figure 5) showed lower thermal conductivity than the flat slab which has a similar density. This is because during this group of tests, the test specimen is mineral fibers bound with synthetic resin (Zehendner 1983).

## Methodologies for measurement of pipe insulation thermal conductivity under wet condition and with moisture ingress

To date there are no set criteria for the testing methods of pipe insulation under wet conditions. In wet conditions, liquid water and water vapor will accumulate in the insulation by filling the air gaps between the cells, or replacing the gas in the cells if the cell wall is permeable. Water will be distributed in the insulation due to the gravitational effect and capillary force, and the partial pressure difference will be the driving force for the water vapor diffusion. Based on the present literature review, it is found that the method of testing depends on the technique used for preparing the moist insulation sample. Four methodologies for the measurement of insulation

**Table 2.** Common methodologies for insulation thermal conductivity measurements with moisture ingress.

| Experiments | Moisturization | Materials | Moisture content, % | Method | Uncertainty on thermal conductivity, % |
|---|---|---|---|---|---|
| Batty et al. (1981) | Immersion/squeeze | Fiberglass | 1.8–6.2 | Probe | — |
| Hay[a] | Injection | Extruded polystyrene | | GHP | — |
| Modi and Benner (1985) | Conditioned ambient with cold surface | Fiberglass | 18 | GHP | — |
| | | Cellulose | 19 | | |
| McFadden (1988) | Laboratory pre-conditioning and materials from field | Fiberglass | 8 | GHP | — |
| | | Polyurethane and polyisocyanurate | 7 | Probe | |
| | | Extruded expanded polystyrene | 21 | | |
| | | Molded expanded polystyrene | 10 | | |
| Kumaran (1987) | Injection | Fiberglass | 12–19 | HFM | — |
| Chyu et al. (1997a) | Immersion | Polyurethane | 70 | HFM | 9 |
| Kehrer et al. (2002) | Chamber | Fiberglass | 11.6 (by mass) | GHP | — |
| Cremaschi, Cai, Ghajar et al. (2012); Cremaschi, Cai, Worthington et al. (2012) | Conditioned ambient with cold surface | Fiberglass | 12 | Radial HFM | <±6, considered axial distribution |
| | | Phenolic | 5 | | |

[a]As cited in McFadden (1986).

thermal conductivity with moisture ingress are defined for the first time as shown in Table 2.

The first group, flooded methods, consists of completely immersing the test specimens in water to provide a certain amount of moisture and uniform distribution. By controlling the water temperature in the reservoir, the thermal conductivity can be measured under isothermal conditions. The water absorption is determined directly from the water volume variation in the reservoir (Kaplar 1974; Chyu et al. 1997a, 1997b). Several more or less cumbersome techniques are proposed to control the desired amount of water content in the test specimen (Batty et al. 1981; Langlais and Klarsfeld 1984; Kumaran 2006). Full immersion, partial immersion, and immersion under pressure may lead to different internal moisture distribution (Kaplar 1974; Chalumeau and Felix-Henry 2006). In addition, it has been pointed out that the temperature of the water reservoir might affect the moisture ingress and the apparent thermal conductivity of the test sample. This is due to surface tension effects (Chye et al. 1997a) and heat transfer processes that are caused by the natural convection phenomenon. The convection heat transfer is particularly relevant for fiberglass and mineral wool insulation. The flooded method is more appropriate on testing insulation systems applied around pipelines below ground or in deep sea application. However, in the HVAC field, the insulation systems are applied around pipelines which are normally placed in either indoor or outdoor environment. Flooded methods create different boundary conditions on the test samples from the actual field applications and, thus, it is difficult to extrapolate the data from these methods of wet testing.

Spraying or injecting water into pipe insulation systems and flat slabs belong to the second group of methodologies for measuring the thermal conductivity in wet conditions (Langlais et al. 1982; Wijeysundera et al. 1996). The moisture distribution inside the insulation might be in transient conditions since water at the hot surface will be vaporized and transported to the cold surface (Kumaran 1987). During the transient conditions, the insulation thermal conductivity is a function of the location of the high moist regions (McFadden 1986), and the thermal conductivity of pipe insulation systems depend on whether the high moist regions are closer to the hot side or to the cold side. This group of methodologies requires a great amount of time to reach steady state when the moisture content, both in the form of liquid and gas, is completely redistributed to the cold surface. Once it reaches steady state, the thermal conductivity of insulation systems is independent of the initial moisture distribution of the test samples. Results show that when the water content is less than 1% by volume, the heat flux through the material is 3 to 4 times higher than the dry insulation during transient conditions, but the material will perform as dry insulation under steady state when the moisture is completely transported to the cold surface (Kumaran 1987). Considering the sensitivity of the positions of the high moist regions to the thermal conductivity of pipe insulation systems, spray/injection methods would fail in simulating the water distribution in the pipe insulation systems applied in the HVAC field.

The third category, defined as laboratory preconditioning methods, consists of placing the insulation test specimens in the air with very high humidity before the thermal conductivity measurements. Several researchers have pointed out that the moisture content accumulated inside the insulation is lower than the moisture content in the actual operating conditions (Langlais et al. 1982; Batty et al. 1984;

Kumaran 1987; McFadden 1988; Kehrer et al. 2002). This is due to a weak vapor driving potential during the preconditioning process of the insulation test specimens. The other disadvantage of these methods is that water distribution in the insulation systems is different from the real field, and any water redistribution will affect the thermal conductivity measurements.

The fourth group includes methods that adopt a temperature, humidity, and air speed controlled ambient and simultaneously impose a cold surface/cold pipe on one side of the insulation test specimen (Modi and Benner 1985; Mumaw 2002; Peuhkuri et al. 2008; Cremaschi, Cai, Ghajar et al. 2012; Cremaschi, Cai, Worthington et al. 2012). Cremaschi, Cai, Ghajar et al. (2012) tested several pipe insulation systems in a psychrometric chamber. Their approach required a large amount of equipment, and it had a very high capital cost. The psychrometric chamber is able to better replicate the actual operating conditions of the pipe insulation systems as those of real service in the chiller applications. Moisture is driven into the insulation due to a gradient in the water vapor partial pressure across the insulation specimen, and the water vapor ultimately condenses when it reaches the cold pipe surface. A great amount of time is required to achieve measurable moisture contents, but accelerated type of tests can be conducted by increasing the temperature and humidity gradients to help drive water vapor ingress into the insulation specimen (Mumaw 2002; Cremaschi, Cai, Ghajar et al. 2012).

If the test samples are prepared according to the two techniques previously mentioned (spray/injection methods and preconditioning methods), steady-state methods are not suitable for the thermal conductivity measurements with moisture ingress. Kehrer et al. (2002) measured the thermal conductivity of fiberglass insulation by placing the sample, which had moisture content of about 11.6% by mass, in a GHP test apparatus. The insulation thermal conductivity was approximately 5% to 6% higher when compared to that of the dry sample. The reason is due to the latent heat convection effects with moisture that evaporates at the hot plate and condenses at the cold surface. They concluded that "the real thermal conductivity of the insulation material in equilibrium with 80% RH is not higher than in the dry state" (Kehrer et al. 2002). Langlais et al. (1983) tested a fiberboard with moisture sprayed on the cold and hot surfaces. The thermal conductivity was measured using the GHP method; it increased rapidly in the first two hours and gradually dropped in the following five hours. The similar phenomenon was observed by other researchers (Benner and Modi 1986; Wijeysundera et al. 1993, 1996). Langlais et al. (1983) explained that the redistribution of the moisture inside the insulation led to a water vapor enthalpy flow, which was interpreted as heat conduction by the thermal conductivity test apparatuses. Thus, the steady-state methods yield to overestimation of the material thermal conductivity under wet conditions. Sandberg (1995) highly recommended that with redistribution phenomenon, the measurement should not be taken with a large temperature difference or in a long time, which are the steps required for both GHP and HFM methods. These observations suggest that steady-state methods are not suitable for the thermal conductivity measurements of moist insulation with low heat fluxes. Only if the test sample is continuously in contact with a cold surface, then steady-state methods can be successfully applied (Cremaschi, Cai, Ghajar et al. 2012). In this method, the water distribution in the pipe insulation is fairly similar to the real chilled water application. Water redistribution is minimized because a continuous driving force for the moisture is established during the tests by the water vapor pressure difference between the cold surface and the ambient.

For improving the accuracy of the measurement in presence of moisture ingress, the end sections of the test specimens must be given special considerations in order to avoid longitudinal moisture ingress that can skew the measurements (Simonson et al. 1996). Batty et al. (1984) concluded that the traditional GHP methods were impractical for the thermal conductivity measurements of moist insulation due to moisture redistribution, and they proposed using a line-source thermal conductivity probe. With this transient method, the short measuring time and small temperature gradient overcome the limitation of vapor redistribution that exists in most steady-state methods. Woodbury and Thomas (1985) concluded that when measuring with a thermal conductivity probe, the moisture content was quite sensitive to the thermal conductivity at low concentration, and the thermal conductivity increased dramatically when the insulation becomes slightly wet. Yu et al. (2009) derived a similar conclusion on the thermal conductivity probe when using the device to determine the effects of moisture content on the uncertainty during sand thermal conductivity measurements. They found that when the moisture content was higher than 25% (by volume), the thermal conductivity could be accurately measured by the probe because the evaporation rate and capillary forces were low. However, when the moisture content was low, such as in pipe insulation systems, the regions adjacent to the heating tip of the probe might be easily dried out; this local dry out phenomenon could bring a large error in the measurement of the actual thermal conductivity of the wet insulation. Some other challenges include the heat loss from the high conductive probe wire (Woodbury and Thomas 1985), the limitation of the sample size based on the probing length (Suleiman 2006), and the estimation of the bulk thermal conductivity measured at a finite number of specific locations.

In order to correlate the thermal conductivity with moisture content in the insulation systems, scale method is the most common way to measure the water content in the systems (Mumaw 2002; Vrana and Bjork 2008). Other techniques for quantifying the moisture content in the test insulation specimen exist but are costly and require extensive calibration, such as computing the water volume from the immersion in a tank (Chyu et al. 1997a), using gamma-ray attenuation phenomenon (Freitas et al. 1991), and measuring the electric capacitance of the test samples (Rywotycki 2003).

## Review of the thermal conductivity variation with moisture content in pipe insulation systems

Variations of the thermal conductivity with water content are shown in Figure 6 for four types of insulation systems. A summary of the data is provided in Tables 3 and 4.

**Table 3.** Comparison among experimental methods and test results for fiberglass insulation with moisture ingress.

| Fiberglass | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean temperature | Thermal conductivity wet | Thermal conductivity dry | Thermal conductivity ratio | Moisture content | Type | Method | Thickness | Description |
| | °C | W/m-K | W/m-K | - | % by volume | | | mm | |
| Kaplar (1974) | | | | | 29.7% | Slab | - | 101.6 | - |
| Langlais *et al.* (1982) | 24 | 0.0320 | 0.0320 | 1.00 | 0.0% | Slab | Spray, GHP, HFM (spray on cold surface) | 25.4 | Dry density: 70kg/m$^3$ |
| | | 0.1000 | 0.0320 | 3.13 | 1.0% | | | | |
| | | 0.1100 | 0.0320 | 3.44 | 5.0% | | | | |
| | | 0.1200 | 0.0320 | 3.75 | 8.0% | | | | |
| | 24 | 0.0320 | 0.0320 | 1.00 | 0.0% | Slab | Spray, GHP, HFM (spray on cold surface) | 25 | Dry density: 70kg/m$^3$ |
| | | 0.0350 | 0.0320 | 1.09 | 3.2% | | | | |
| | | 0.0360 | 0.0320 | 1.13 | 5.0% | | | | |
| | | 0.0400 | 0.0320 | 1.25 | 8.3% | | | | |
| Jesperson [a] | 10 | 0.0360 | 0.0360 | 1.00 | 0.0% | Slab | - | - | Dry density: 65.6kg/m$^3$ |
| | | 0.0830 | 0.0360 | 2.31 | 5.0% | | | | |
| | | 0.0950 | 0.0360 | 2.64 | 10.0% | | | | |
| | | 0.1060 | 0.0360 | 2.94 | 15.0% | | | | |
| Modi and Benner (1986) | 20 | 0.0540 | 0.0330 | 1.58 | 8.1% | Slab | Conditioned ambient with cold surface, GHP | 51 | Dry density: 45.8kg/m$^3$ |
| | 27 | 0.0590 | 0.0330 | 2.00 | 16.0% | | | | |
| Wijeysundera and Hawlader (1988) | 28 | 0.0580 | 0.0330 | 3.73 | 1.4% | Slab | Spray, GHP | 25.4 | Dry density: 131kg/m$^3$ |
| | 29.5 | 0.0520 | 0.0330 | 1.80 | 0.5% | | Spray, probe | | |
| | 28.7 | 0.0560 | 0.0350 | 2.38 | 1.8% | | | | |
| | 30 | 0.0650 | 0.0350 | 2.81 | 2.2% | | | | |
| | 29 | 0.0700 | 0.0350 | 2.72 | 4.0% | | | | |

*(Continued on next page)*

**Table 3.** Comparison among experimental methods and test results for fiberglass insulation with moisture ingress. *(Continued)*

| Fiberglass | Mean temperature | Thermal conductivity wet | dry | ratio | Moisture content | Type | Method | Thickness | Description |
|---|---|---|---|---|---|---|---|---|---|
| | ℃ | W/m-K | W/m-K | - | % by volume | | | mm | |
| McFadden (1988) | 24 | 0.0700 | 0.0350 | 1.01 | 0.1% | Slab | Laboratory pre-conditioning or from field, GHP and probe | >3.2 | $k=k_0+0.03\%M$ ($0<\%M<2$) |
| | | 0.0700 | 0.0350 | 1.24 | 2.0% | | | | |
| | | 0.1230 | 0.0330 | 3.21 | 3.0% | | | | $k=0.73+0.024\%M$ ($3<\%M<8$) |
| | | 0.0557 | 0.0310 | 3.69 | 8.0% | | | | |
| Kehrer *et al.* (2002) | 10 | 0.0739 | | | 11.6% by mass | Slab | Laboratory pre-conditioning, GHP | - | - |
| | 35 | 0.0870 | | | 11.6% by mass | | | | |
| Abdou and Budaiwa (2013) | 14 | 0.0340 | 0.0333 | 1.02 | 0.1% | Slab | Spray, HFM | 50 | Dry density: 27kg/m$^3$ |
| | | 0.0343 | 0.0333 | 1.03 | 0.3% | | | | |
| | | 0.0346 | 0.0333 | 1.04 | 0.5% | | | | |
| | 34 | 0.0375 | 0.0371 | 1.01 | 0.1% | | | | |
| | | 0.0377 | 0.0371 | 1.02 | 0.3% | | | | |
| | | 0.0380 | 0.0371 | 1.02 | 0.5% | | | | |
| | 14 | 0.0323 | 0.0313 | 1.03 | 0.4% | | | | Dry density: 84kg/m$^3$ |
| | | 0.0329 | 0.0313 | 1.05 | 0.9% | | | | |
| | | 0.0335 | 0.0313 | 1.07 | 1.5% | | | | |
| | 34 | 0.0344 | 0.0336 | 1.02 | 0.4% | | | | |
| | | 0.0350 | 0.0336 | 1.04 | 0.9% | | | | |
| | | 0.0357 | 0.0336 | 1.06 | 1.5% | | | | |
| Cremaschi *et al.* (2012a) | 40 | 0.0397 | 0.0360 | 1.10 | 0.1% | Pipe | Conditioned cold pipe, HFM (cold pipe) | 50.8 | Dry density: 70kg/m$^3$ |
| | | 0.0989 | 0.0360 | 2.75 | 1.7% | | | | |
| | | 0.1004 | 0.0360 | 2.79 | 4.3% | | | | |
| | | 0.1212 | 0.0360 | 3.37 | 7.0% | | | | |
| | | 0.1242 | 0.0360 | 3.45 | 11.3% | | | | |
| | | 0.1250 | 0.0360 | 3.47 | 10.9% | | | | |

[a]: As cited in Batty *et al.* (1981)
Note: $k$ and $k_0$ = Btu-in/hr-ft$^2$-åF; %M = the percent by volume of moisture in the sample.

**Table 4.** Comparison among experimental methods and test results for other common insulations with moisture ingress.

| | Mean temperature, °C | Thermal conductivity | | | Moisture content, % by volume | Type | Method | Thickness, mm | Description |
|---|---|---|---|---|---|---|---|---|---|
| | | Wet, W/m-K | Dry, W/m-K | ratio | | | | | |
| **Polyurethane** | | | | | | | | | |
| Kaplar (1974) | — | — | | | 1.6 (14 days) | Slab | — | 50.8 | Dry density: 35.9 kg/m$^3$ |
| Chyu et al. (1997a) | 23.89 | 0.3462 | 0.0190 | 16.26 | 70.0 | Pipe | Flooded, radial HFM | 38.1 | Dry density: 46.5 kg/m$^3$ |
| | 60 | 0.3462 | 0.0242 | 16.26 | 70.0 | | | | Dry density: 140 kg/m$^3$ |
| McFadden (1988) | 24 | 0.0229 | | | 0.1 | Slab | Laboratory preconditioning or from field, GHP and probe | > 3.2 | $k = k_0 + 0.085\%M$ ($0 < \%M < 0.5$)[b] |
| | | 0.0265 | | | 0.4 | | | | |
| | | 0.0410 | | | 1.1 | | | | $k = 0.27 + 0.013\%M$ ($1 < \%M < 7$)[b] |
| | | 0.0490 | | | 0.1 | | | | |
| **Extruded polystyrene** | | | | | | | | | |
| Kaplar (1974) | 4.4 | 0.0360 | | | 1.0 | Slab | — | 50.8 | Dry density: 53.8 kg/m$^3$ |
| Hay[a] | | 0.0229 | | — | 3.2 | Slab | Spray/injection | — | $k = 0.17 + 0.03W$[b] |
| | | 0.0265 | 0.0245 | 1.53 | 9.6 | Slab | | | |
| | | 0.0410 | 0.0245 | 1.88 | 16.0 | Slab | | | |
| McFadden (1988) | 24 | 0.0427 | 0.0290 | 1.47 | 1.0 | Slab | Laboratory preconditioning or from field, GHP and probe | > 3.2 | $k = 0.29 * \exp(0.014\% * \%M)$ |
| | | 0.0484 | 0.0290 | 1.67 | 10.0 | | | | |
| **Expanded polystyrene** | | | | | | | | | |
| McFadden (1988) | 24 | 0.0314 | 0.0290 | 1.08 | 2.0 | Slab | Laboratory pre-conditioning or from field, GHP and probe | > 3.2 | $k = k_0 + 0.0089\ \%M$[b] |
| | | 0.0229 | 0.0290 | 1.47 | 21.0 | | | | |
| Jerman and Cerny (2012) | — | 0.0265 | 0.0290 | 1.67 | 1.0 | Slab | Immersion, IM | 20 | $k = -0.4757*\%M^2 + 0.2198*\%\ M + 0.0394$ |
| | | 0.0410 | 0.0290 | 1.08 | 10.0 | | | | |
| **Phenolic** | | | | | | | | | |
| Cremaschi, Cai, Ghajar et al. (2012) | 35 | 0.0369 | 0.0345 | 1.07 | 0.8 | Pipe | Conditioned cold pipe, HFM (cold pipe) | 50.8 | Dry density: 50–60 kg/m$^3$ |
| | | 0.0407 | 0.0345 | 1.18 | 1.6 | | | | |
| | | 0.0438 | 0.0345 | 1.27 | 2.4 | | | | |
| | | 0.0473 | 0.0345 | 1.37 | 4.8 | | | | |
| | | 0.0484 | 0.0345 | 1.40 | 4.9 | | | | |

[a]As cited in McFadden (1986). $\%M$ = the percent by volume of moisture in the sample; $W$ = weight ratio.
[b]$k$ and $k_0$ = I-P unit, Btu-in./hr-ft$^2$-°F.
[c]$k$ = SI unit, W/m-K.

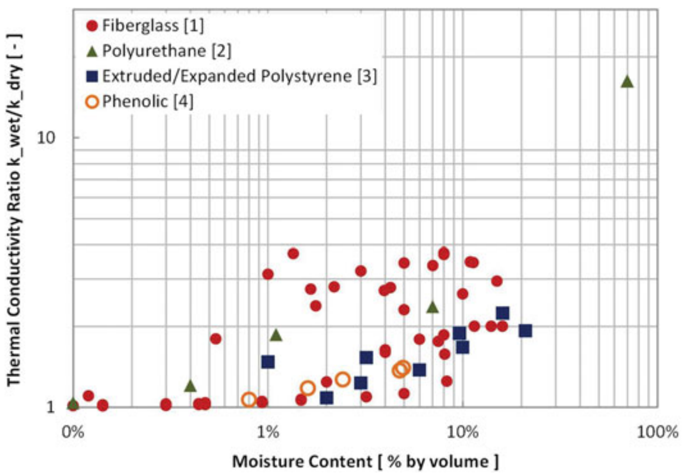


**Fig. 6.** Thermal conductivity of four common insulation materials with moisture effect. [1] = Kaplar (1974); Batty et al. (1981); Langlais et al. (1983); Modi and Benner (1986); Wijeysundera and Hawlader (1988); McFadden (1988); Kehrer et al. (2002); Cremaschi, Cai, Ghajar et al. (2012); Abdou and Budaiwa (2013).

Fiberglass becomes fairly conductive at the room temperature if a certain amount of water accumulates in the insulation. This is because when the strands are gradually covered by water, the conduction heat transfer is intensified through larger surface areas along the fiber strands and the intersection regions among the strands (McFadden 1988). If considering the density and temperature effects, most of the results published for either flat slabs or pipe insulation showed similar trends (solid circles in Figure 6). When the moisture content reaches about 12% by volume, the thermal conductivity of fiberglass insulation increases up to 2∼3 times of the corresponding thermal conductivity in dry conditions (in which moisture content is less than 0.1% by volume). As more water accumulates in the fibrous material, an excess amount of water drains out from the insulation (Cremaschi, Cai, Ghajar et al. 2012). Comparing the published data on denser fibrous materials to the fibrous materials with lower densities, the thermal conductivity of the insulation at lower densities performs less sensitive to the amount of water. This can be explained by the presence of a smaller number of fiber strands and intersections among the fibers. Because smaller internal surface areas are coated with water, the heat conduction results are less sensitive to the moisture content in fibrous insulation. The density also affects the convection heat transfer during condensing conditions, but this is a secondary mechanism when compared to the conduction in fibrous insulation.

For the three types of closed-cell insulation reported in Table 4, the thermal conductivity of the test specimens increased with moisture ingress because (1) water accumulates on the cell walls, which increases the wall thickness and offers a better heat flow path and (2) water fills in the small air gap and therefore enhances the heat conduction. It should be noted that at one point of the polyurethane pipe insulation (solid triangle in Figure 6), the moisture content reached 70%, and its thermal conductivity was measured almost 16 times higher than the dry condition. However, this point was measured by flooded method, and researchers prepared the moist test specimen by immersing it in the water tank (Chyu et al. 1997a). It was the only data that reported a very large increase of the thermal conductivity for wet polyurethane insulation. Extruded polystyrene shows an increase on the system thermal conductivity in moist conditions by about 2.2 times with respect to the values in dry conditions (McFadden 1988). This increase is reported for a moisture content of 16% by volume. For expanded polystyrene, the water content is around 21% by volume, and the thermal conductivity increases up to 1.9 times of the value in dry conditions. Phenolic is tested as pipe insulation, and it shows that the thermal conductivity increases by 1.6 times when the moisture content is about 4.9% by volume (Cremaschi, Cai, Ghajar et al. 2012; Cremaschi, Cai, Worthington et al. 2012).

Tables 3 and 4 provide a brief summary of the experimental methods and test results for insulation systems with moisture ingress. Most of the published data are for flat slabs, and the thermal conductivity of pipe insulation systems with moisture ingress are reported in only two studies in the open domain literature, Cremaschi, Cai, Ghajar et al. (2012) and Chyu et al. (1997a). Expanding the database for pipe insulation systems at below ambient temperatures in wet conditions with moisture ingress is a natural extension of the current efforts in this field and should be considered for future research. Developing thermal conductivity correlations with moisture content as the correlations published for flat slab configurations might also be helpful. Since pipe insulation systems have more complex geometries than flat slabs and consist of multiple C-shell sections and various materials (e.g., the presence of joint sealant and vapor retarder at the butt joints), a generalized correlation that works for all the systems, even for only the ones with the same insulation material, might not be possible. These questions should be addressed by future research in this field.

## Challenges with the current methodologies for measuring the pipe insulation apparent thermal conductivity with moisture ingress and future research needs

Some challenges are identified for moist tests: (1) how to prepare the test specimen with controlled and uniform moisture and (2) what the appropriate techniques are that can replicate similar boundary conditions across the test specimen as the ones observed during pipe insulation systems field service. Flooded, spray/injection and laboratory conditioning methods are the most common methodologies adopted for inducing moisture ingress. However, all of these methods have some trade-off and, ultimately, the laboratory conditions deviate from the actual field conditions. Conditioned ambient with cold surface/pipe method provides a more reliable measurement on the apparent thermal conductivity of pipe insulation systems. The temperature and humidity regulated psychrometric chamber, together with a low temperature maintained at the pipe insulation interior surface, would provide appropriate pressure gradients to help vapor condensate on the cold surface and lead to water accumulation in the insulation materials. This will help simulate the moisture distribution in the real application fields. However, the entire test apparatus, including the psychrometric chamber and the thermal conductivity sensors, may require a large space and a considerable amount of time for construction, control, and calibration. The equipment maintenance is also a high cost and large capital investment. It is believed that a compact, easy to install, and inexpensive sensor is still needed in future research.

Any inhomogeneity that exists in the material interior structure would create preferential paths for moisture transportation and would form wet regions around those preferential paths. The formation of the wet regions affects the moisture test due to the following two reasons. First, the preferential paths lead more water to pass through. In this case, when the weight of the water that accumulates around the surface of the wet spot overcomes the material surface tension, the water condensate drips out of the insulation material, and some of the water condensate is lost to the ambient. Once this phenomenon occurs, the experiment has to be terminated since the partial loss of water condensate makes it difficult to correlate the true accumulated moisture content in the insulation test sample with time. A second reason is that when the test material becomes partially wet, the thermocouple sensors, which are evenly placed on the insulation surface, read larger temperature differences due to higher thermal conductivity around the wet regions. For example, for fiberglass pipe insulation, after 10 days of test in the moist ambient, the temperature difference on the insulation surface increased from 1.7°C (3°F) to 6.1°C (11°F; Cremaschi, Cai, Ghajar et al. 2012). The nonuniformity of the temperature distribution may affect the direction of the heat flow, and the assumption of one-dimensional flow becomes arguable. For pipe insulation systems, large temperature variations along the cylindrical surfaces imply that axial heat transfer has to be considered. This is the same consideration typically made for flat slabs in which large variations of the insulation surface temperatures produce longitudinal heat transfer in the slab, and the assumption of unidirectional heat conduction is no longer valid.

For most pipe insulation systems, it is required to use joint sealant or adhesive during the installation procedure. Joint sealant, which serves as a thermal conductive chemical, may increase the apparent thermal conductivity of the insulation material. The joint sealant may also absorb moisture and can create preferential paths for water accumulation (Cremaschi, Cai, Ghajar et al. 2012). Both effects deteriorate the apparent insulation thermal performance. This can be an explanation as to why most of the manufacturers' data, which are tested on flat slabs, under predict the thermal performance and water absorption of pipe insulation systems. Mumaw (2002) measured the moisture content in the pipe insulation by using the calibrated hot box method and pointed out that the measured moisture content was much higher than the value predicted from the simplified model because the model neglect the effects of the joints and lap seals in the vapor retarders. By dissecting the specimens, he observed that water absorption, lack of curing, and shrinkage of insulation materials away from the joints occurred near the sealed joints. Two technical challenges should be addressed in future studies on joint sealant effects. The first challenge is that joint sealant is usually applied as a thin layer on the cross section of one or both half shells, and then the two half shells of the pipe insulation are compressed tightly to make a good contact between the insulation materials. In this case, it is not feasible to accurately measure the thickness of the joint sealant. One way to determine it is to first measure the perimeter of the pipe insulation before applying the test specimen around the cold pipe. Once the insulation is installed on the cold pipe, the perimeter of the test specimen with joint sealant will be measured again. The joint thickness is computed from the difference between the diameters before and after the installation procedure. The second challenge is that there are no accurate data for the thermal conductivity of joint sealants in the open literature.

In future research, there are other areas that potentially can be investigated on the effects of apparent thermal conductivity of pipe insulation systems. These areas include the split joints, insulation bulk densities, wall thicknesses, insulation jacketings, contact resistances between pipe and insulation, interior structures, and types of fillers and aggregates (Kulkarni and Vipulanandan 2006). For some closed-cell insulation, aging is a common phenomenon that degrades the thermal performance of the pipe insulation systems, and very limited work is reported in the literature on this process (Christian et al. 1998; Kellner and Dirckx 1999; Biedermann et al. 2001; Stovall 2009). Insulation thickness affects the volume available for the storage of the gas and, thus, it directly impacts the deterioration of the insulation thermal performance during aging (Eriksson and Sunden 1998). The impacts of the exterior water vapor jacketing systems, as well as of the split joints and seams, are not clear, and the results are sporadic and sometimes contradictory. The previously mentioned additional features of the pipe insulation systems and the anisotropic features of the pipe insulation material on the radial and angular directions seem to affect the behavior of the pipe insulation systems during dry and wet operating conditions.

In wet condensing conditions with moisture ingress, the moisture migration inside pipe insulation systems can result in a temperature redistribution on the radial and angular directions. What are the predominant forces that drive the moisture from one region to another in different types of pipe insulation systems, and what are the geometric inner structures that promote or prevent microscopic water vapor mass transfers inside the pipe insulation are still open questions. Some works that pioneered in this research topic were studied on a "wick" concept, and they focused on the methods to limit water moisture accumulation in pipe insulation systems (Korsgaard 1993; Guldbrandsen et al. 2011). These studies reported that the microscopic capillary actions inside fibrous pipe insulation systems were responsible for the removal of moisture from the inside of the material outward. It is believed that there are opportunities to improve their models for better prediction of the apparent pipe insulation thermal conductivity in wet conditions and to expand further their original models to other types of pipe insulation systems beside fibrous type insulation. A model that describes and predicts water accumulation in pipe insulation systems will advance the state-of-the-art knowledge of these mechanical insulation systems in cold pipe applications. It will also cause an enormous potential in the industry for developing sensors that can detect failure of the insulation systems and local moisture traps in the pipelines, and this technique can be used for operational and management of the building cooling system.

## Conclusions

This article discussed the experimental methodologies for measuring the apparent thermal conductivity of pipe insulation systems with the aim of providing some clarification on the existing thermal conductivity data for pipe insulation systems. Steady-state and transient methods were discussed, and the measurements from these two methods were critically compared. It was observed that steady-state methods for pipe insulation systems are commonly adopted for measuring an average thermal conductivity, which is defined as apparent thermal conductivity of the pipe insulation systems. Steady-state methods are simpler, more direct, and easier to make than transients methods in dry operating conditions. However, steady-state methods often need more time to reach thermal equilibrium, larger test sample sizes to eliminate edge effects, and a narrower temperature range to prevent radiation. In addition, when considering steady-state methods for pipe insulation systems, the flow direction seems to affect the apparent thermal conductivity. Transient methodologies provide fast measurements, simple installations, and they can be easily applied to pipe insulation systems. However, these methodologies are indirect measurements of the thermal conductivity and adopt more or less cumbersome models to reduce the data from the original measurements. Transient methodologies also provide local values of thermal conductivity in various regions of the test specimen, and the apparent thermal conductivity is strongly depended on the number and locations of the probing sensors. The accuracy and repeatability of transient methods for pipe insulation systems are not as well defined as steady-state methodologies.

During the measurement of the thermal conductivity of pipe insulation with moisture content, four moisturizing strategies used to prepare the wet samples were identified as flooded method, spray/injection method, laboratory preconditioning method, and conditioned ambience with cold surface/pipe method. The advantages and shortcomings of each moisturizing strategy were discussed at length. A main finding is that there is not one way to measure the apparent thermal conductivity of wet pipe insulation with moisture ingress. Most steady-state methods in wet conditions seem to be inadequate because the enthalpy flow occurs due to the redistribution of water condensate in the insulation systems. The recent methodology that uses a psychrometric chamber with a cold pipe test apparatus is one of the most accurate methods and close to the actual application. But the entire test apparatus takes a large space, a great amount of time for construction, control and calibration, and the equipment has a high maintenance cost and large capital investment. Transient methods applied to wet pipe insulation systems may be sensitive to the moisture content in the regions adjacent to the probe installed in specific locations of the insulation samples.

The thermal conductivities of several pipe insulation systems were compared under dry conditions, and some data were discussed for wet conditions with different water content. To date, challenges still exist in the measurement of apparent thermal conductivity of insulation with moisture ingress. The main aspects that must be properly considered are nonuniformity of the pipe surface temperatures, the lack of information on the thermal performance of joint sealants, and the moisture redistribution in radial configurations of the pipe insulation systems. These aspects can be investigated further in future research in order to develop reliable and predictive models that would estimate the pipe insulation apparent thermal performance in chillers for building air conditionings applications.

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**Appendix A.** Comparison among experimental methods and test results for fiberglass insulation (SI units).

| | Mean temperature, °C | Thermal conductivity, W/m-K | Type | Method | Uncertainty /deviation, % | Thickness, mm | Description |
|---|---|---|---|---|---|---|---|
| **Fiberglass** | | | | | | | |
| Modi and Benner (1985) | 20 | 0.0310 | Slab | GHP (sample between water and air space | — | 50.8 | Density: 45.8 kg/m$^3$ |
| | 27 | 0.0350 | | | | | |
| Moore et al. (1985) | 25 | 0.0342 | Slab | GHP | 1 | 15.9–36.3 | Density: 26 kg/m$^3$ |
| | 25 | 0.0435 | Pipe | — | — | | Density: 15 kg/m$^3$ |
| Wijeysundera and Hawlader (1988) | 30 | 0.0328 | Slab | HFM | — | 25.4 | Density: 131 kg/m$^3$ |
| | 35 | 0.0330 | | | | | |
| | 31 | 0.0310 | Slab | Probe | — | 25.4 | Density: 131 kg/m$^3$ |
| McFadden (1988) | 24 | 0.0361 | Slab | Probe and GHP | >3.2 | >3.2 | — |
| McCaa and Smith (1991) | 24 | 0.0384 | Slab | GHP, HFM, THA | 2.8∼3 | 152.4 | Density: 12 kg/m$^3$ |
| | 24 | 0.0378 | | | | | Density: 15 kg/m$^3$ |
| Al-Hammad et al. (1994) | 24 | 0.0330 | Slab | GHP | ±2∼±4 | — | Density: 48 kg/m$^3$ |
| | 25 | 0.0350 | | | | — | Density: 32–37 kg/m$^3$ |
| Chyu et al. (1997b) | 10 | 0.0310 | Pipe | Radial HFM | — | — | Density: 46.4 kg/m$^3$ |
| | 20 | 0.0330 | | | | | |
| | 30 | 0.0340 | | | | | |
| | 40 | 0.0355 | | | | | |
| | 50 | 0.0360 | | | | | |
| Salmon (2001) | 10 | 0.0319 | Slab | GHP and HFM | 1.83 | 25 | Density: 150–165 kg/m$^3$ $k = -7.7663 \times 10^{-3} + 5.6153 \times 10^{-5}\rho + 1.0859 \times 10^{-4}T^{a}$ |
| | 20 | 0.0330 | | | | | |
| | 30 | 0.0341 | | | | | |
| | 40 | 0.0352 | | | | | |
| Wikes et al. (2002) | 20 | 0.0311 | Pipe | Guarded heated pipe | ±0.8 | 54 | Density: 33 kg/m$^3$ $k = 0.000183T + 0.02742^{a}$ |
| | 30 | 0.0329 | | | | | |
| | 40 | 0.0347 | | | | | |
| | 50 | 0.0366 | | | | | |
| Whitaker and Yarbrough (2002) | 20 | 0.0333 | Pipe | Guarded Heated Pipe | −27.5 ∼ 9.6 deviation | 50.8 | Density: 86.5 kg/m$^3$ $k = 7.787 \times 10^{-7}T^2 + 1.921 \times 10^{-4}T + 0.2141^{b}$ |
| | 30 | 0.0341 | | | | | |
| | 40 | 0.0350 | | | | | |
| | 50 | 0.0359 | | | | | |
| Abdou and Budaiwi (2005) | 8 | 0.0441 | Slab | GHP | — | 5–100 | Density: 13.1 kg/m$^3$ $k = 0.0003368T + 0.041433$ |
| | 12 | 0.0455 | | | | | |
| | 24 | 0.0495 | | | | | |
| | 36 | 0.0536 | | | | | |
| | 40 | 0.0549 | | | | | |
| | 8 | 0.0338 | Slab | GHP | — | 5–100 | Density: 27 kg/m$^3$ $k = 0.000188T + 0.030677$ |
| | 12 | 0.0345 | | | | | |
| | 24 | 0.0367 | | | | | |
| | 36 | 0.0388 | | | | | |
| | 40 | 0.0395 | | | | | |
| | 8 | 0.0301 | Slab | GHP | — | 5–100 | Density: 56 kg/m$^3$ $k = 0.0001189T + 0.02913$ |
| | 12 | 0.0306 | | | | | |
| | 24 | 0.0320 | | | | | |
| | 36 | 0.0334 | | | | | |
| | 40 | 0.0339 | | | | | |
| Bezjak and Zvizdic (2011) | 23 | 0.0457 | Slab | GHP | 3.1 | 80 | Density: 13 kg/m$^3$ |
| | 23 | 0.0444 | | THW | 8.1 | | |
| Cremaschi, Cai, Ghajar et al. (2012); Cremaschi, Cai, Worthington et al. (2012) | 10 | 0.0330 | Pipe | HFM (cold pipe) | <±6 | 50.8 | Density: 70 kg/m$^3$ $k = 0.00010T + 0.0320$ |
| | 20 | 0.0340 | | | | | |
| | 30 | 0.0350 | | | | | |
| | 40 | 0.0360 | | | | | |

[a]SI units for $k$ = W/m-K and $T$ = K, $\rho$ = density, kg/m$^3$.
[b]I-P units for $k$ = Btu-in/hr-ft$^2$-°F and T = °F.
Unmarked correlations follow SI units as $k$ = W/m and T = °C.

**Appendix B.** Comparison among experimental methods and test results for polyurethane insulation (SI units).

| | Mean temperature, °C | Thermal conductivity, W/m-K | Type | Method | Uncertainty /deviation, % | Thickness, mm | Description |
|---|---|---|---|---|---|---|---|
| **Polyurethane** | | | | | | | |
| Zehendner (1983) | 10 | 0.0230 | Pipe | Guarded Heated Pipe | <±3 | 20–26 | Density: 39 kg/m$^3$ Blowing agent: $CFCl_3$; aging: 4∼6 months with 0.3mm PVC jacketing |
| | 20 | 0.0240 | | | | | |
| | 30 | 0.0250 | | | | | |
| | 40 | 0.0260 | | | | | |
| | 50 | 0.0270 | | | | | |
| McFadden (1988) | 24 | 0.0216 | Slab | Probe and GHP | — | >3.2 | — |
| Al-Hammad et al. (1994) | 35 | 0.0240 | Slab | GHP | ±2∼±4 | — | Density: 32–35 kg/m$^3$ |
| Chyu et al. (1997a) | 10 | 0.0182 | Pipe | HFM (hot pipe) | — | 38.1 | Density: 46 kg/m$^3$ |
| | 20 | 0.0202 | | | | | |
| | 30 | 0.0222 | | | | | |
| | 40 | 0.0242 | | | | | |
| | 50 | 0.0262 | | | | | |
| Abdou and Budaiwi (2005) | 10 | 0.0212 | Slab | HFM | — | 5–100 | Density: 44 kg/m$^3$ $k = 0.0001089T + 0.020132$ |
| | 20 | 0.0223 | | | | | |
| | 30 | 0.0234 | | | | | |
| | 40 | 0.0245 | | | | | |
| | 50 | 0.0256 | | | | | |
| Adl-Zarrabi (2005) | 20 | 0.0318 | Pipe | TPS | | | |
| | 50 | 0.0358 | | | | | |
| Ohmura (2007) | 10 | 0.0450 | Slab | Cyclic heat, THW, hot disk | ±10 (deviation) | 20 | Density: 119 kg/m$^3$ |
| | 20 | 0.0475 | | | | | |
| | 25 | 0.0500 | | | | | |
| Bezjak and Zvizdic (2011) | 23 | 0.0235 | Slab | GHP | 3 | 100 | Density: 42 kg/m$^3$ |
| | 23 | 0.0294 | | THW | 6.1 | | Density: 42 kg/m$^3$ |

Note: $k$ = W/m-K; $T$ = °C.

**Appendix C.** Comparison among experimental methods and test results for extruded and expanded polystyrene insulation (SI units).

| | Mean temperature, °C | Thermal conductivity, W/m-K | Type | Method | Uncertainty /deviation, % | Thickness, mm | Description |
|---|---|---|---|---|---|---|---|
| **Extruded polystyrene** | | | | | | | |
| McFadden (1988) | 24 | 0.0274 | Slab | Probe and GHP | — | >3.2 | — |
| Abdou and Budaiwi (2005) | 10 | 0.0277 | Slab | HFM | — | 5–100 | Density: 35.8 kg/m$^3$ $k = 0.0000961T + 0.026741$ |
| | 20 | 0.0287 | | | | | |
| | 30 | 0.0296 | | | | | |
| | 40 | 0.0306 | | | | | |
| | 50 | 0.0315 | | | | | |
| | 10 | 0.0286 | Slab | HFM | — | 5–100 | Density: 49.3 kg/m$^3$ $k = 0.0000706T + 0.027846$ |
| | 20 | 0.0293 | | | | | |
| | 30 | 0.0300 | | | | | |
| | 40 | 0.0307 | | | | | |
| | 50 | 0.0314 | | | | | |
| Bezjak and Zvizdic (2011) | 23 | 0.0357 | Slab | GHP | 3.1 | 50 | Density: 40 kg/m$^3$ |
| | 23 | 0.0352 | | THW | 6.3 | | |
| **Expanded polystyrene** | | | | | | | |
| Pratt[1] | 10 | 0.0346 | Slab | — | — | — | Density: 16 kg/m$^3$ |
| | 10 | 0.0331 | Slab | — | — | — | Density: 24 kg/m$^3$ |
| McFadden (1988) | 24 | 0.0418 | Slab | Probe and GHP | — | >3.2 | |
| Al-Hammad et al. (1994) | 35 | 0.0380 | Slab | GHP | ±2∼±4 | | Density: 16 kg/m$^3$ |
| | 35 | 0.0360 | | | | | Density: 20 kg/m$^3$ |
| | 35 | 0.0350 | | | | | Density: 24 kg/m$^3$ |
| | 35 | 0.0320 | | | | | Density: 26 kg/m$^3$ |
| Salmon (2001)[b] | 10 | 0.0319 | Slab | GHP and HFM | 1.83 | 25 | Density: 40 kg/m$^3$ $k = 6.3054 \times 10^{-4} - 4.1993 \times 10^{-5}\rho + 1.1650 \times 10^{-4}T$ |
| | 20 | 0.0331 | | | | | |
| | 30 | 0.0343 | | | | | |
| | 40 | 0.0354 | | | | | |
| Abdou and Budaiwi (2005) | 7.5 | 0.0284 | Slab | HFM | — | 5-100 | Density: 32.5 kg/m$^3$ $k = 0.0001045T + 0.027658$ |
| | 12 | 0.0289 | | | | | |
| | 23.5 | 0.0301 | | | | | |
| | 36 | 0.0314 | | | | | |
| | 40 | 0.0318 | | | | | |
| Mar et al. (2008) | 10 | 0.0310 | Slab | GHP | — | — | Density: 40 kg/m$^3$ |
| | 20 | 0.0330 | | | | | |
| | 30 | 0.0350 | | | | | |
| | 40 | 0.0360 | | | | | |
| | 10 | 0.0360 | Slab | GHP | — | — | Density: 20 kg/m$^3$ |
| Bezjak and Zvizdic (2011) | 23 | 0.0373 | Slab | GHP | 3.1 | 60 | Density: 20 kg/m$^3$ |
| | 23 | 0.0352 | | THW | 6.8 | | |
| Lakatos and Kalmar (2013) | 17 | 0.0489 | Slab | HFM | — | 50 | Density: 10.2 kg/m$^3$ |
| | 17 | 0.0363 | | | | | Density: 21.4 kg/m$^3$ |
| | 17 | 0.0340 | | | | | Density: 26.0 kg/m$^3$ |
| Jerman and Cerny (2012) | 22 | 0.0370 | Slab | IM (impulse method, transient method) | ±5% | | Density: 16.5 kg/m$^3$ |

Note: $k$ = W/m-K; $T$ = °C; $\rho$ = kg/m$^3$.
[a]As cited in Tye (1969).
[b]$k$ = W/m-K, $T$ = K.

**Appendix D.** Comparison among experimental methods and test results for cellular glass, phenolic and PIR insulations (SI units).

| | Mean temperature, °C | Thermal conductivity, W/m-K | Type | Method | Uncertainty /deviation, % | Thickness, mm | Description |
|---|---|---|---|---|---|---|---|
| **Cellular glass** | | | | | | | |
| Kaplar (1974) | 10 | 0.0550 | Slab | GHP | — | 50.8 | Density: 148 kg/m$^3$ |
| Zehendner (1983) | 10 | 0.0545 | Pipe | Guarded heated pipe | <±3 | 50 | Density: 137 kg/m$^3$ Staggered joints with recommended joint sealant; Vapor barrier and sheet metal jacket were applied on the outside |
| | 20 | 0.0560 | | | | | |
| | 30 | 0.0575 | | | | | |
| | 40 | 0.0600 | | | | | |
| | 10 | 0.0600 | | | | 73 | Density: 140 kg/m$^3$ Staggered joints with recommended joint sealant; Vapor barrier and sheet metal jacket were applied on the outside |
| | 20 | 0.0625 | | | | | |
| | 30 | 0.0650 | | | | | |
| | 40 | 0.0660 | | | | | |
| Whitaker and Yarbrough (2002) | 20 | 0.0596 | Pipe | Guarded | −2.5∼4.4 | 50.8 | Density: 136.2 kg/m$^3$ $k = 1.316 \times 10^{-6}T^2 + 3.574 \times 10^{-4} \times T + 0.3825$[b] |
| | 30 | 0.0610 | | Heated | deviation | | |
| | 40 | 0.0626 | | Pipe | | | |
| | 50 | 0.0643 | | | | | |
| Pittsburgh Corning Co. | 10 | 0.0396 | Slab | GHP | — | 25.4 | Density: 120 kg/m$^3$ $k = 0.25 + 0.00054T + 4.6 \times 10^{-7}T^2 + 2 \times 10^{-11}T^2$[b] |
| | 20 | 0.0407 | | | | | |
| | 30 | 0.0418 | | | | | |
| | 40 | 0.0429 | | | | | |
| Cremaschi, Cai, Ghajar et al. (2012); Cremaschi, Cai, Worthington et al. (2012) | 10 | 0.0419 | Pipe | HFM (cold pipe) | ±6 | 25.4 | Density: 120 kg/m$^3$ $k = 0.00025T + 0.0394$[a] |
| | 20 | 0.0444 | | | | | |
| | 30 | 0.0469 | | | | | |
| | 40 | 0.0494 | | | | | |
| | 10 | 0.0390 | Pipe | | <±6 | 50.8 | Density: 120 kg/m$^3$ $k = 0.00055T + 0.0335$[a] |
| | 20 | 0.0445 | | | | | |
| | 30 | 0.0500 | | | | | |
| | 40 | 0.0555 | | | | | |
| **Polyisocyanurate (PIR)** | | | | | | | |
| McFadden (1988) | 24 | 0.0216 | Slab | Probe and GHP | — | >3.2 | — |
| Al-Hammad et al. (1994) | 35 | 0.0230 | Slab | GHP | ±2 ∼ ±4 | 50.8 | Density: 32–37 kg/m$^3$ |
| Cremaschi, Cai, Ghajar et al. (2012); Cremaschi, Cai, Worthington et al. (2012) | 10 | 0.0279 | Pipe | HFM (cold pipe) | <±6 | 50.8 | Density: 50 kg/m$^3$ $k = 0.00009T+0.0270$[a] |
| | 20 | 0.0288 | | | | | |
| | 30 | 0.0297 | | | | | |
| | 40 | 0.0306 | | | | | |

[a]SI units for $k$ = W/m-K and $T$ = °C.
[b]I-P units for $k$ = Btu-in/hr-ft$^2$-°F and $T$ = °F.

**Appendix E.** Comparison among experimental methods and test results for elastomeric rubber and mineral wool insulation (SI units)

| | Mean temperature, °C | Thermal conductivity, W/m-K | Type | Method | Uncertainty /deviation, % | Thickness, mm | Description |
|---|---|---|---|---|---|---|---|
| **Elastomeric rubber** | | | | | | | |
| Wikes et al. (2002) | 10 | 0.0382 | Slab | GHP | ±0.8 | 30.4 | Density: 61 kg/m$^3$ $k = 0.000133T + 0.03684$[a] |
| | 20 | 0.0395 | | | | | |
| | 30 | 0.0408 | | | | | |
| | 40 | 0.0422 | | | | | |
| | 50 | 0.0435 | | | | | |
| | 10 | 0.0372 | Pipe | Guarded heated pipe | ±0.8 | 25.4 | Density: 66 kg/m$^3$ $k = 0.000156T + 0.03567$[a] |
| | 20 | 0.0388 | | | | | |
| | 30 | 0.0404 | | | | | |
| | 38 | 0.0416 | | | | | |
| | 50 | 0.0435 | | | | | |
| Cremaschi, Cai, Ghajar et al. (2012); Cremaschi, Cai, Worthington et al. (2012) | 10 | 0.0348 | Pipe | HFM (cold pipe) | <±6 | 50.8 | Density: 86 kg/m$^3$ $k = 0.00014T + 0.0334$[a] |
| | 20 | 0.0362 | | | | | |
| | 30 | 0.0376 | | | | | |
| | 40 | 0.0390 | | | | | |
| **Mineral wool** | | | | | | | |
| Zehendner (1983) | 10 | 0.0315 | Pipe | Guarded heated pipe | <±3 | 20-40 | Density: 43–53 kg/m$^3$ Mineral fibers bound with synthetic resin |
| | 20 | 0.0325 | | | | | |
| | 30 | 0.0330 | | | | | |
| | 40 | 0.0350 | | | | | |
| | 50 | 0.0365 | | | | | |
| | 10 | 0.0370 | Slab (wrap around pipe) | Guarded heated pipe | <±3 | 20 | Density: 85 kg/m$^3$ Laminates glued to aluminum film |
| | 20 | 0.0380 | | | | | |
| | 30 | 0.0395 | | | | | |
| | 40 | 0.0410 | | | | | |
| | 50 | 0.0425 | | | | | |
| McCaa and Smith (1991) | 24 | 0.0494 | Slab | GHP, HFM, THA | 10.5 ~ 11 deviation | 14-21 | Density: 30 kg/m$^3$ |
| | 24 | 0.0499 | | | | | Density: 40 kg/m$^3$ |
| Whitaker and Yarbrough (2002) | 20 | 0.0440 | Pipe | Guarded heated pipe | —29.7~31.5 deviation | 50.8 | Density: 145.8 kg/m$^3$ $k = 1.059 \times 10^{-6}T^2 - 8.21 \times 10^{-5}T + 0.3060$[b] |
| | 30 | 0.0442 | | | | | |
| | 40 | 0.0446 | | | | | |
| | 50 | 0.0450 | | | | | |
| Abdou and Budaiwi (2005) | 10 | 0.0347 | Slab | HFM | — | 5–100 | Density: 145.4 kg/m$^3$ $k = 0.0001263T + 0.033425$[a] |
| | 20 | 0.0360 | | | | | |
| | 30 | 0.0372 | | | | | |
| | 40 | 0.0385 | | | | | |
| | 50 | 0.0397 | | | | | |
| Bezjak and Zvizdic (2011) | 23 | 0.0434 | Slab | GHP | 3 | 160 | Density: 142 kg/m$^3$ |
| | 23 | 0.0456 | | THW | 8.3 | | |
| Jerman and Cerny (2012) | 22 | 0.0370 | Slab | IM (impulse method, transient method) | ±5 | 25 | Density: 70 kg/m$^3$ |
| | 22 | 0.0360 | | | | 25 | Density: 100 kg/m$^3$ |
| | 22 | 0.0410 | | | | 25 | Density: 170 kg/m$^3$ |

[a]SI units for $k$ = W/m-K and $T$ = °C.
[b]I-P units for $k$ = Btu-in/hr-ft$^2$-°F and $T$ = °F.