Moisture Accumulation and its Impact on the Thermal Performance of Pipe Insulation for Chilled Water Pipes in High Performance Buildings

ShanshanCai[1,]*, Lorenzo Cremaschi, Ph.D.[1],Afshin J. Ghajar, Ph.D.,P.E.[1]

[1] *Oklahoma State University, School of Mechanical and Aerospace Engineering Stillwater, OK, USA*

* *Corresponding author: phone:(405)744-0389; email: shanshc@okstate.edu*

Keywords: pipe insulation, thermal conductivity, heat transfer, moisture accumulation, chiller pipelines

ABSTRACT

Mechanical pipe insulation systems are commonly applied to cold piping surfaces in most industrial and commercial buildings in order to limit the heat losses and prevent water vapor condensation on the pipe exterior surfaces. Due to the fact that the surface temperature of these pipelines is normally below the ambient dew point temperature, water vapor diffuses inside the pipe insulation systems and often condenses when it reaches the pipe exterior surfaces. The water droplets accumulated in the pipe insulation system increase its overall thermal conductivity by thermal bridging the cells or the fibers of the insulation material. The moisture ingress into pipe insulation threatens the thermal performance and the overall efficiency of the building mechanical system. This phenomenon is also responsible for the mold growth inside occupied spaces and causes the pipelines to be more vulnerable to corrosion. Although a wide range of vapor barriers are used for preventing water vapor penetration into pipe insulation, common experience in the field shows that water vapor will inevitably ingress into the insulation materials from the end joints or from the cracks created during insulation installation. How to account for the moisture ingress on pipe insulation service life and thermal performance is still an open question.

Thermal conductivity is one of the most important properties for evaluating the thermal performance of the pipe insulation systems. Using a new test apparatus, the thermal conductivity of pipe insulation systems below ambient temperature and in wet conditions with moisture ingress was measured. Fiberglass and phenolic pipe insulation were tested to investigate the moisture effects on the material thermal conductivity. The data showed that these two types of pipe insulation systems had quite different water absorption rates due to different characteristics of the material and its structure. A serious degradation of fiberglass pipe insulation thermal performance was observed and the thermal conductivity increased by as much as 3 times when the moisture content was about 12 percent in volume. Tested at a different condition, the thermal conductivity of phenolic pipe insulation increased to 1.6 times of the original value and the moisture content was 5% in volume. Considering the gravity effect, the moisture content on the top and bottom C-shells were separately measured and discussed in this paper.

1. INTRODUCTION

Mechanical insulation systems applied to cold piping for refrigeration and de-humidification systems aim to prevent extra heat transfer and water vapor condensation on the pipe exterior surfaces. When a chilled fluid pipe is inadequately insulated, condensate occurs and keeps accumulating in the materials to threaten insulation thermal performance. The water condensate may also drip onto the building surfaces, causing mold growth, while the moisture filmed around the pipe surfaces may lead to corrosion on the pipelines, as well as deterioration on the service life of the insulation systems. Since cold piping is often used year-round, even with vapor retarder, insulation jackets, vapor sealing on the joints and fittings, or the proposed wicking action of hydrophilic fabrics (Crall, 2002; Korsgaard, 1993), it is not completely vapor tight and moisture will inevitably accumulate in the permeable insulation.

As the cold pipe cools down the surrounding air, moisture infiltrates into the insulation material via two thermodynamics processes. Since the saturation vapor pressure decreases with air temperature, there is a water vapor pressure gradient from the pipe insulation-air (higher temperature) interface to the aluminum pipe-pipe insulation (lower temperature) interface. It is the pressure gradient that drives a flux of vapor from the outside ambient through the insulation material to the low temperature side. If the temperature of the cold surface is lower than the air dew point temperature, condensate appears and the water droplets will accumulate next to the cold surface.

Chilled water pipe is one of the most common applications for mechanical pipe insulation systems. It is estimated that chilled water piping makes-up 15 to 25% of the piping in the United States. Measurements of the effective thermal properties of pipe insulation, by exposing to the same conditions as the field service for chilled water applications, have a positive effect to the system design, maintenance and life service. Currently the standard ASTM C335 (ASTM, 2010d) is used for measuring the thermal conductivity of cylindrical pipe insulation systems. However, this standard is based on a heated pipe, with the heat flow outward, and it is generally applied for measurements at above room temperature conditions. When this is applied to an ambient below the room temperature, the direction of heat flow should be controlled to be in the opposite direction to that of the flow around a cold pipe (Wilkes *et al.*, 2002). In addition, if the pipe is above the room temperature, moisture accumulation and water vapor condensation phenomena are virtually absent since the water vapor might be driven outward, that is, from the pipe surface to the ambient. Another approach in the literature is to consider the effective thermal conductivity of the materials used in pipe insulation systems as the property of the same materials used for insulation panels. The thermal conductivity of flat slab materials can be tested based on a number of methods stated in the standard (ASTM, 2005a, 2005b, 2010a, 2010b, 2010c). However, due to the effect of the radial configuration and split joints (Cremaschi *et al.*, 2012b), it is predicted that the pipe insulation systems would perform differently from the flat slab materials.

In the previous work, a novel test apparatus was designed and calibrated to measure the thermal conductivity of mechanical pipe insulation systems (Cremaschi *et al.*, 2012b). Fiberglass, elastomeric rubber and phenolic pipe insulation were tested on the developed pipe insulation testers (PITs) for temperature effects and linear correlations were developed between the insulation thermal conductivity and the insulation mean temperature. The effects of joint sealant and of the material wall thickness were also investigated in previous study and it was found that the joint sealant augmented the overall thermal conductivity of the pipe insulation system by as much as 15%.

2. METHODOLOGY, EXPERIMENTAL APPARATUS AND TEST CONDITIONS

2.1 Methodologies

According to the literature, guarded hot plate (GHP) and guarded heat flow meter (HFM) are two most common and accurate methods designed for the thermal conductivity measurement of flat slab insulation materials (Albers, 2002; Bezjak & Zvizdic, 2011; Ohmura, 2007; Salmon & Tye, 2010). For pipe insulation, the methodology is modified according to ASTM C335 (2010d), which was published based on radial flow method by considering the flow direction and sample orientation. Instead of sandwiched test specimen between guarded hot plate and isothermal cold plate, in C335 the test pipe insulation shell is installed around a heated pipe, with thermal guards at the two ends of the test section to eliminate the edge effect. In order to measure the thermal conductivity of pipe insulation at below-ambient conditions, the heated pipe was replaced with a cold pipe to provide an inward heat flow.

During the measurement of pipe insulation thermal conductivity with moisture ingress, four common strategies exist in current research field for providing test specimen with different moisture content. These strategies included: 1) immersing the test specimen under flooded conditions with water filling in the gaps and cells among the material interior structure and forming a uniform distribution (Chyu *et al.*, 1997a, 1997b; Kaplar, 1974). However, the underwater strategy provides a different boundary condition from the real field, and may result in inaccurate prediction of the thermal conductivity variation. 2) Spray or inject water directly on the insulation surfaces. Although it is true that these two methods provide convenient and fast ways to prepare insulation with certain amount of water, the location of wet area which are determined by the specific injection and spray positions would become an issue during the thermal conductivity measurement (Kumaran, 1987, 2006; McFadden, 1986; Wijeysundera, 1996). 3) Conditioning test specimen in a high humidity ambient. Without temperature and pressure gradients between the interior and exterior surfaces of the insulation, the vapor transportation movement is insignificant and the moisture accumulation is normally lower than the real application. 4) Simulating condensing conditions with temperature and humidity regulated chamber during the thermal conductivity measurement. By maintaining the cold surface temperature below the air dew point, pressure gradient drives water vapor from the ambient to the cold surface, with water condensate accumulating and diffusing inside the insulation material. This strategy is considered as an effective way to simulate real application in the field in spite of the high cost on the equipment control and maintenance. In this paper, the moisture test was processed in a high humidity chamber with condensing conditions created across the test specimens.

2.2 Experimental Apparatus

The experimental apparatus consists of three parts: pipe insulation tester (PIT), refrigeration system and psychrometric chamber. Details on the experimental setups and test procedures for dry conditions can be found in a previous paper (Cremaschi *et al.*, 2012b). The experimental procedures for wet test were similar to those of dry tests. Two pipe insulation samples were installed separately on two pipe insulation testers (PITs) inside the psychrometric room at the same time. These two samples were exposed to the identical ambient conditions and similar inward heat flux: one sample provided the values of the apparent thermal conductivity with moisture ingress (installed on the first PIT) while the other sample provided the moisture content in real time during the period of exposure (installed on the second PIT) (Cremaschi *et al.*, 2012a). In order to determine the variation on moisture content in the insulation, the test sample on the second PIT was divided evenly into six small pieces so that the moisture variation can be determined from six time periods.

2.3 Test Conditions

To simulate a real chilled water pipe application, the aluminum pipe surface (cold surface) temperature was designed to be maintained around 5°C (40.5°F). During the wet test, the ambient was controlled at a high temperature and humidity to accelerate the moisture absorption in the pipe insulation specimens. The ambient temperature was set between 36 to 42°C (96 to 107°F), with a relative humidity that ranged from 81 to 87%. Different from dry conditions, the uniformity of test specimen surface temperatures was decreased gradually by the formation of the wet regions inside the materials, which was caused by the condensate accumulation and distribution. The maximum axial temperature difference on the insulation exterior surface increased from 0.5 to 5.5ºC (1 to 10ºF). Both aluminum pipe and copper tube also showed an increase on the maximum axial temperature differences, of 1.7ºC (3ºF) and 0.56ºC (1ºF), respectively.

3. MOISTURE TEST RESULTS

3.1 Moisture Test on 50.8 mm (2 inch) Nominal Wall Thickness Fiberglass Pipe Insulation

The fiberglass test specimen selected for the moisture test was prepared in a full length of 0.9m (3 ft), with 50.4 mm (2 inch) nominal wall thickness. The dry material density was around 80 kg/m^3(4.4 lbm/ft^3). In order to accelerate water vapor intrusion and moisture accumulation into the material, the vapor barrier attached to the exterior surface of the fiberglass was removed before installation. Due to the fibrous structure and light-weight characteristic of the material, the test specimen was installed in the test section of the first PIT device by placing plastic zip ties around the outer shell, instead of applying any joint sealant in the longitudinal direction between the two C-shells. Among the 0.15 m (6 inch) sample sections on the second PIT device, the vapor barrier was selected to be plastic film sheets, which was expected to prevent any longitudinal moisture diffusion from one sample to the adjacent one. However, this plastic film proved to create a preferential path for moisture radial transfer in and out of the fiberglass insulation.

Mechanism of moisture diffusion in fibrous insulation

The test specimen applied on the first and second PIT devices showed different appearances according to the observation during the moisture test. For the second PIT device, on which the test specimen was separated to six equal length sections for moisture content measurement, a preferential path was formed due to the less dense areas between every two 0.15 m (6 inch) samples, together with the partially unsealed gaps and gravity effect. These preferential paths played an important role in leading more condensate flow through and drip out from the insulation. This mechanism can be validated by the appearance of two wet regions at the ends of the bottom shell for each 0.15 m (6 inch) sample. For the first PIT device, the full length test specimen was installed in the test section without that many preferential paths in between. Since less portion of the condensate dripped out from the insulation, the overall moisture absorption rate determined from the first PIT device is higher than the second PIT device. Figure1 shows the development of the wet region on the bottom shell of the fiberglass pipe insulation from the first PIT device. Two wet regions appeared in the bottom shell of the test specimen on the 1st day of the moisture test and the wet area increased quickly in the following three days. This is because after water vapor penetrates through the insulation material and condenses on the cold aluminum pipe surface, the condensate transferred to the exterior surface through the preferential paths based on gravity and material non-uniformity. Due to the surface tension effect (Modi & Benner, 1985), instead of dripping out from the pipe insulation, the condensate was stayed on the exterior surface and diffused along the fibers which were aligned in the longitudinal direction, forming a visible increasing wet area. From the 5th day to the end of the test, that is the 12th day, although it seemed that the area of these wet regions did not change significantly from Figure1 (b to d), the moisture was accumulated inside the insulation material because the weight of the moisture insulation samples increased. It is postulated that with the fibers aligned in the longitudinal direction, moisture would spread horizontally from wet to dry areas preferentially via the layers until a quasi-steady state equilibrium was achieved. In this moisture test, the equilibrium was expected to reach around the 5th day based on the observation of the wet region formation. Then, instead of a longitudinal diffusion, the moisture diffused from the exterior surface to the interior layer of the insulation. However, this procedure was difficult to be observed based on current test facilities since there was no visual access along the radial direction of the pipe insulation test specimen. Compared to the bottom shell, the top shell showed a much lower water amount and none of the visual wet regions was observed on the insulation exterior surfaces. Only several condensate droplets were appeared on the interior surface attached to the cold aluminum pipe. This suggested that moisture diffused from the cold surface to the interior layers of fibers by gradually coating the fiber stands and filling the air gaps of the insulation material along the radial direction.

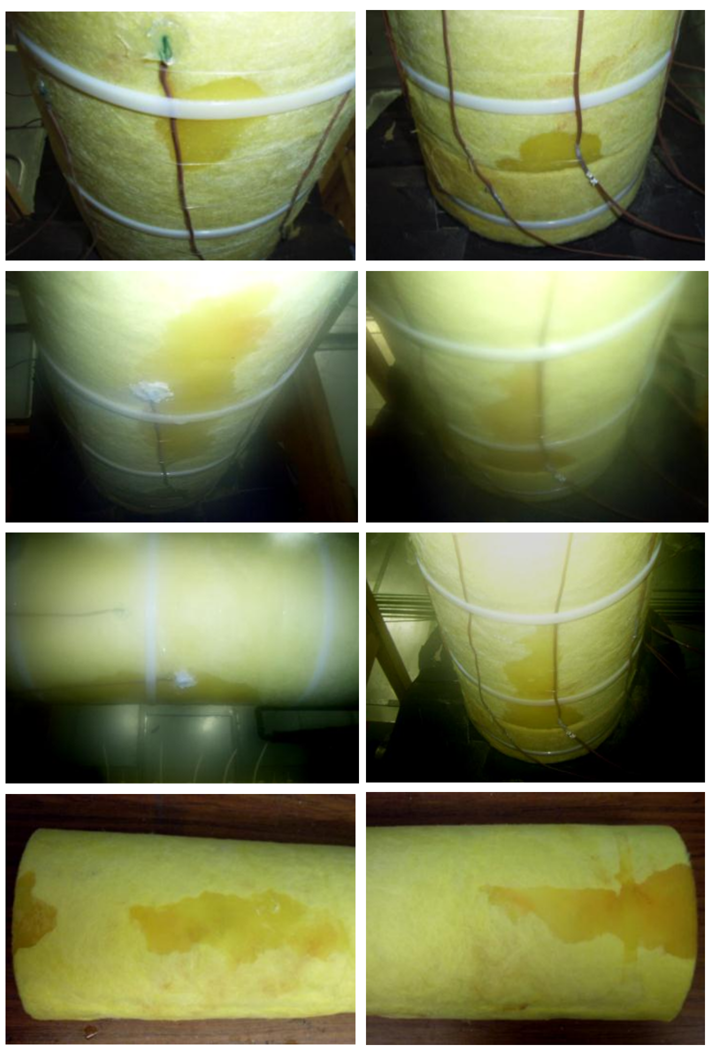

Figure1: Photos of the development of the wet region on the exterior surface of the fiberglass pipe insulation test specimen from the first PIT device

Thermal conductivity variation with moisture ingress in fibrous insulation

During the moisture test, visible water droplets were observed dripping onto the floor on the 12th day after the test began. With a larger temperature gradient and water vapor pressure gradient applied during the moisture test, this result matches with the time length referred in the literature (Modi & Benner, 1985) that the maximum moisture content for flat slab fiberglass insulation was estimated to be about 20% of water by volume within 600 hours (15 days). Once the insulation became partially saturated, the moisture test terminated since the pipe insulation thermal conductivity increased so rapidly that the current experimental apparatus was not able to maintain the aluminum pipe surface temperature at 4.5°C (40°F).

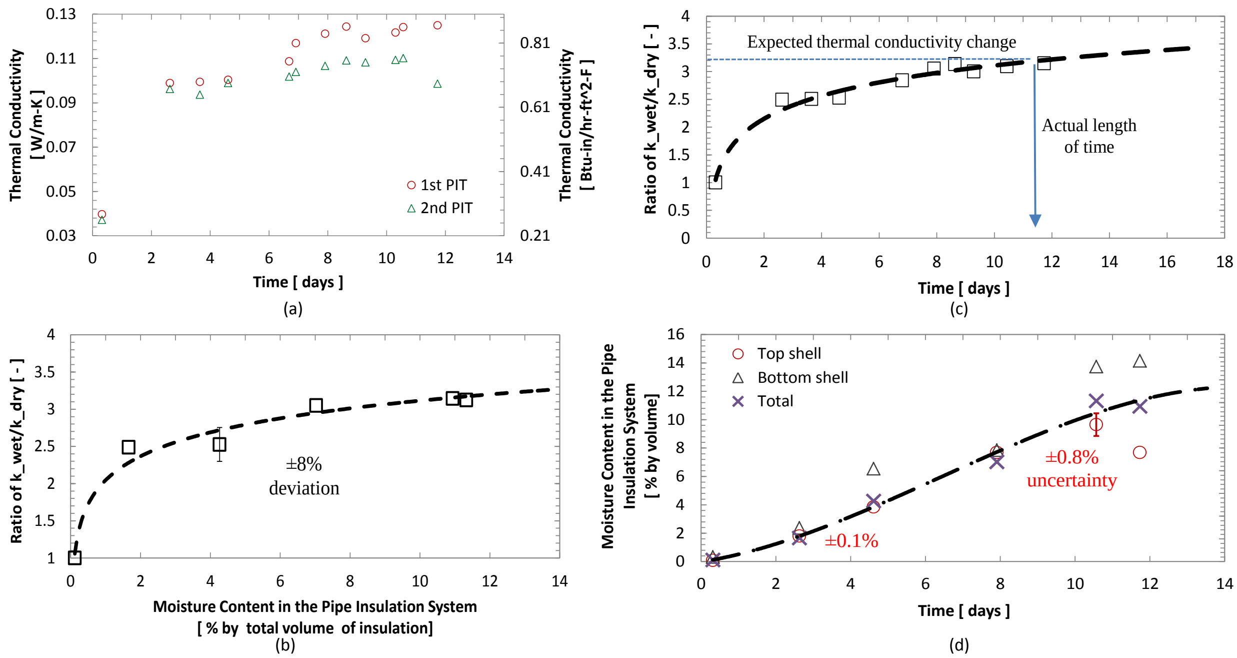

Figure 2: Test results on fiberglass pipe insulation systems: a) thermal conductivity variation with time b) thermal conductivity ratio (k_{wet}/k_{dry}) with moisture content; c,d) ratio and moisture content with time

Figure 2a shows the variation of moisture content on both first and second PIT devices with the experimental time length. It is noted that the two values of thermal conductivity were quite close during the first 5 days of wet test. Then the thermal conductivity for the test specimen on the first PIT device increased faster and gradually deviated from the data provided by the second PIT device. This behavior suggested that water condensate accumulation in the first PIT device was easier than the accumulation in the second PIT device because certain amount of water would drip out from the second PIT device, via the preferential radial cuts with plastic film in between, in the pipe insulation test specimen. The first PIT device, for which there was no radial cuts present, absorbed the water condensate completely in the pipe insulation specimen and performed as more conductive. Figure 2b shows the ratio of fiberglass pipe insulation thermal conductivity under wet condensing conditions to the corresponding thermal conductivity in dry conditions versus the moisture ingress. The thermal conductivity of test specimen increased with moisture content and gradually reached an asymptotic value during the first 15 days. This suggests that during the diffusion process in fibrous insulation, the water vapor first fills the voids between the stands with water (Ogniewicz & Tien, 1981) and leads to a gradual increase on the material thermal conductivity. After filling the air gaps around the strands of glass that lay perpendicular to the heat flux, the water condensate might accumulate on the exterior surface in the bottom shell due to surface tension and gravity effects (Modi & Benner, 1985). Water gradually coats the exterior fiber surfaces and increases the intersect areas among the strands. The macroscopic effect is higher thermal bridging phenomenon that promotes larger heat losses and increases the thermal conductivity of the pipe insulation system. The authors postulate that once a quasi-steady state equilibrium is achieved at the exterior surfaces, the water that diffuses toward the adjacent inner layer of fibers would decrease to a lower rate because of a lower local temperature of the insulation (Langlais *et al.*, 1983). At 12 days after the beginning of the wet test, the overall thermal conductivity of fiberglass pipe insulation increased by more than 3 times of the dry thermal conductivity and the moisture content was about 12% in volume. Figure 2c shows the thermal conductivity values versus time, in days. The wet test was terminated when there was a visual observation on the large wet regions on the exterior surface of the pipe insulation and the test specimen became partially saturated with water droplets dripping out onto the floor.

In order to predict that moisture absorption happened in the first PIT device, where only the initial and final values of the moisture content were measured based on the experiment strategy, the intermediate values of moisture content in the pipe insulation were required to provide a curve for the water content variation. These values were extrapolated from the measurements of the test specimen around the second PIT device based on a correction factor (CF), which represents the moisture content difference between the two PIT devices with time. On the 12th day of the test in wet condition, the maximum moisture absorption in the first and second PIT devices were measured with water content about 11% and 8% by volume, respectively (CF=11%/8%=1.4). By assuming a zero moisture content for both PIT devices at the beginning of the test (CF=1 at day 0), CF was developed as a linear function according to the time (days). It should be noted that this linear format was selected based on the assumption that the moisture absorption behaviors of the two test specimens were similar since geometry, temperature boundary conditions, and water vapor pressure boundary conditions were identical. The corrected moisture content in the fiberglass pipe insulation system that operated in wet, condensing conditions with moisture ingress is shown in Figure 2d. This plot provides the data of the moisture content in the top C-shell (circle data points), bottom C-shell (triangle data points), and the overall cylindrical section (cross data points). Due to the gravity effect, the moisture content in the bottom shell was always higher than the one in the top shell. Water accumulated in the bowl shape of the bottom C-shell and large wet regions were visually observed at the bottom surface of the pipe insulation.

3.2 Moisture Test on 50.8 mm (2 inch) Nominal Wall Thickness Phenolic Pipe Insulation

Phenolic pipe insulation is a closed-cell foam insulation composed of cells with small diameter. For this cellular type of insulation, conduction, convection, and radiation heat losses are inhibited from the micro air pockets that surround the cells and from the thin cell walls, which decrease the cross-sectional flow path areas (McFadden, 1988). The phenolic test specimen was tested in a full length of 0.9 m (3 ft), nominal wall thickness of 50.4 mm (2 inch), and with a density of 50 kg/m^3 (3.121 lbm/ft^3). Joint sealant was applied along the longitudinal joints of the C-shells during the installation of phenolic pipe insulation. Considering the rigid surface of phenolic, instead of using plastic film as adopted for fiberglass, another type of non-adhesive vapor sealant was applied in between each 0.15 m (6 inch) long samples, and also at the two ends of the test specimen. Similarly to the previous test, the thermal conductivity was measured from the first PIT device while the moisture content was measured from the six small test specimens installed on the second PIT device. It need to be noted that moisture measurement was always on a pure insulation sample to eliminate the water content in the sealant chemicals, which means that both the joint sealant and vapor sealant layer must be removed before weight measurement.

Mechanism of moisture diffusion in cellular insulation

Figure 3 illustrates the development of the wet regions in phenolic pipe insulation tested on the second PIT device at three locations of the bottom shell. Similar to the fiberglass, from the beginning of the test, the wet regions on the bottom shell appeared next to the cross sections, near the edges of the vapor sealant, and then slightly increased in sizes during the following days. After the 7th day of the test, these wet regions remained unchanged till the end of the moisture test (day 24). This phenomenon suggested that moisture was accumulated first next to the cross sectional cuts of the insulation. Due to the application of the vapor sealant, instead of dripping out from the test samples, the moisture started to diffuse into the insulation systems from these locations. The top shell gradually appeared wet around the vapor sealant mastic at about the 10th day of the moisture test. The authors postulate that besides condensate, the phenolic insulation also absorbed a small amount of the water from the sealant itself. Both vapor sealant and joint sealant are water based and typically need 24 hours to release their moisture content and dry out. During this process, the insulation adjacent to the joint sealant might have absorbed part of the moisture released by these chemicals. For the phenolic insulation of the first PIT device without cross sectional cuts, there were no visible regions of moisture accumulation on the outer surface of the insulation. However, the thermal conductivity increased gradually during the wet test, suggesting that moisture did enter the insulation material. At day 24, a small wet spot was observed at the bottom surface next to the end side of the insulation specimen which might also be caused by the water through the cross sectional cuts and the water released from the joint sealant, as shown in Figure 4.

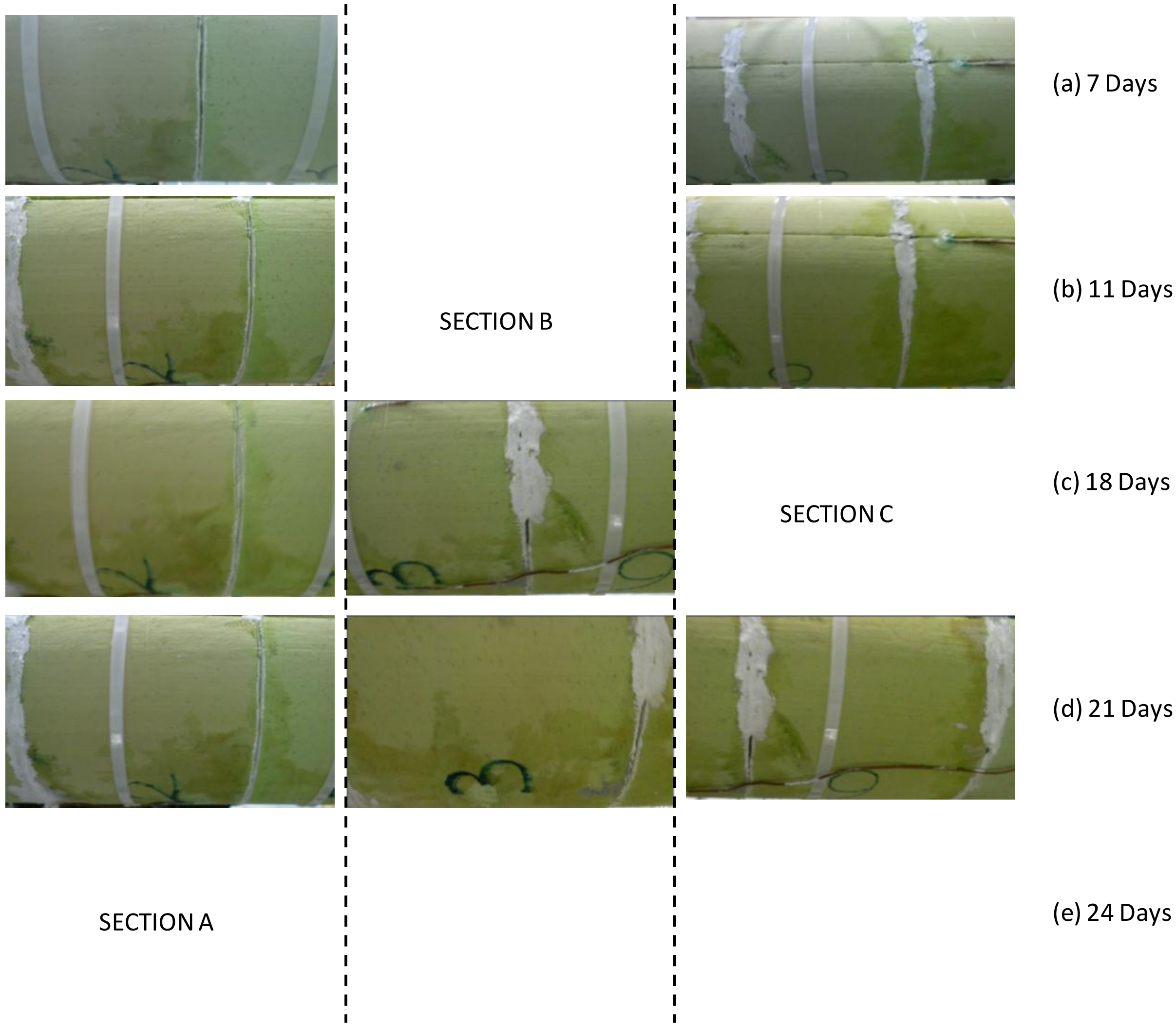

Figure 3: Photos of the progression of the wet regions on the exterior surface of phenolic pipe insulation test specimen during the wet test

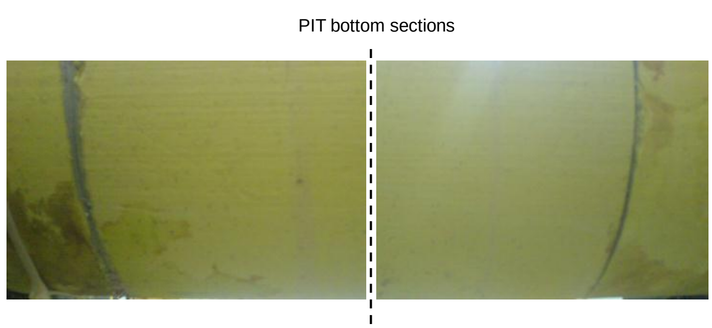

Figure 4:Photos of the wet regions at the bottom surface of the phenolic pipe insulation specimen installed on the first PIT and at the day 24 since the wet test

Thermal conductivity variation with moisture ingress in cellular insulation

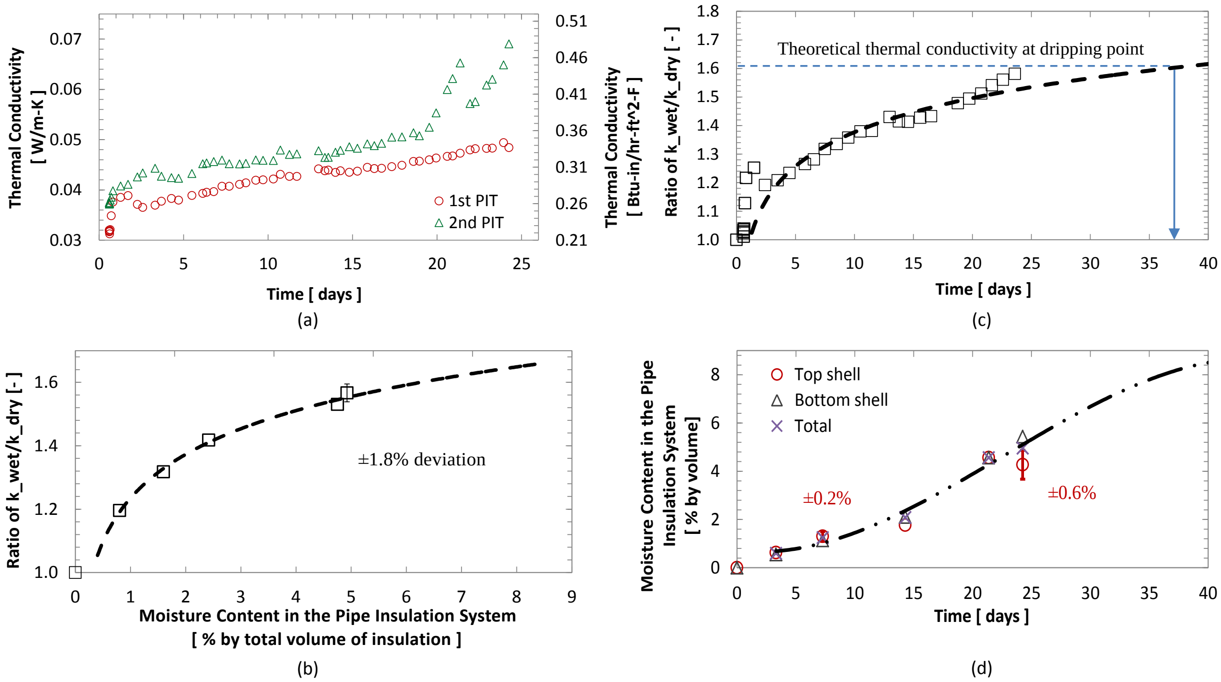

Figure 5: Test results on phenolic pipe insulation systems: a) thermal conductivity variation with time b) thermal conductivity ratio (k_{wet}/k_{dry}) with moisture content; c,d) ratio and moisture content with time

Figure 5a compares the thermal conductivity between the test specimens on the first PIT device and on the second PIT device during the moisture ingress test. Unlike the fiberglass pipe insulation, which showed a higher thermal conductivity in the first PIT device and lower in the second, the phenolic test specimen on the second PIT device was performed to be more conductive. The reason for this different behavior of phenolic pipe insulation detected by the developed test apparatus can be explained as follows. Phenolic might be a fairly homogenous insulation material and the preferential paths for moisture diffusion in the phenolic test specimen assembled in the apparatus was likely to be not as many as the ones observed for the fiberglass test specimen. Besides, due to the characteristic of the vapor sealant, it would not only prevent axial moisture diffusion in between two adjacent sections but also stop water condensate draining out from the radial cross section. Therefore, the moisture content in test specimen of the first PIT device was lower than the one in the test specimen on the second, and led to a lower thermal conductivity. Another reason to explain the different thermal behaviors on the first and second PIT devices is that the vapor sealant is more conductive, when compared to the insulation materials, and by placing the sealant parallel with the pipe insulation around the cold surface, the overall thermal resistance dropped to a lower value. With more thermal bridging introduced in the second PIT device, conduction heat loss was slightly promoted with respect to the test specimen on the first PIT device. Figure 5a shows a dramatic increase of thermal conductivity of the second PIT device around the 19th day of the wet test. This is caused by a sudden increase of heat gain in the refrigeration pipelines between the first and second PIT device sections, where the insulations all saturated in the high humid environment and resulted in deterioration on the thermal performance. As result of this heat transfer augmentation, the surface temperature of the aluminum pipe and copper pipe in the second PIT device increased. The average sand temperature (an intermediate medium filled in the aluminum pipe and considered as a heat flow meter with calibrated thermal conductivity, referred by Cremaschi *et al.* (2012a, 2012b)) increased to 8°C (48°F), for which accurate calibration curve of sand effective thermal conductivity were not available at that time. After day 24, the increase of the surface temperature was so high that the wet test was terminated.

The ratio of thermal conductivity measured at below ambient temperature in wet condensing conditions to the corresponding thermal conductivity in dry condition with moisture ingress is shown in Figure 5b. By following previous analysis on fiberglass pipe insulation, a correction factor (CF) between the first and second PIT devices was determined based on a similar moisture absorption behavior. However, due to an unexpected heat gain during the end of the test, the maximum moisture content in the phenolic test specimen on the first PIT device could not be accurately measured. Instead, a maximum value of moisture absorption was selected to be 8% according to the literature (ASTM, 2009). By extrapolating from the empirical correlation developed with the data of thermal conductivity and moisture content, as shown in Figure 5b, the ratio would be as high as 1.6 at the time the moisture content reaches 8% in volume. With a thermal conductivity ratio of phenolic pipe insulation at 1.55 after 24 days, the extrapolated experimental length to achieve a thermal conductivity ratio of at least 1.6 was predicted to be 37 days, see Figure 5c. Figure 5d shows the moisture content in the phenolic pipe insulation, both the top and bottom shells, at below ambient temperature and in wet, condensing conditions. Due to a homogeneous configuration, the moisture content was fairly uniform between the top and the bottom C-shell sections, with a moisture difference less that 10%, which was within the experimental uncertainty. Only for the last data point the bottom C-shell section of phenolic pipe insulation had moisture content that was measurably different than the top C-shell section.

6. CONCLUSION

This paper is a second part of the work on the measurement of pipe insulation thermal conductivity at below-ambient conditions with moisture ingress. Based on the test apparatus developed and validated in our previous work (Cremaschi *et al.*, 2012b), fiberglass and phenolic pipe insulation was continuously tested to investigate the moisture effect on the material thermal conductivity. In order to accelerate the moisture intrusion through the insulation materials, the ambient conditions were controlled at 42°C (107.6°F) and 35.7°C (96.3°F), with relative humidity between 81 to 87%. Based on two experiments with continuous operation for 12 and 24 days respectively, the overall thermal conductivity of fiberglass pipe insulation was measured to be increased by 3 times of the original dry value with maximum moisture content at 12% in volume. The thermal conductivity of phenolic pipe insulation was increased by 1.6 times of the original value and the water content reached 5% by volume. It is emphasized that the wet test conditions were intentionally different from each other because the objective was to show the apparatus capacities and limitations at various ambient conditions and radial heat flux. Thus a comparison of the thermal performance of the two pipe insulation systems tested in wet conditions should not be made due to the different test conditions. According to the gravity effect, larger wet regions were always observed on the bottom C-shell surface of the test specimen, while the top surface would show smaller or even no wet regions depending on the specific applications and material characteristics.

NOMENCLATURE

CF: correction factor
k_{wet}: thermal conductivity at wet condition
k_{dry}: thermal conductivity at dry condition
PIT: pipe insulation tester

REFERENCES

Albers, M. A. (2002). *A round robin interlaboratory comparison of thermal conductivity testing using the guarded hot plate up to 1000C*, Charleston, SC, USA.

ASTM. (2005a). ASTM C 1363-05, Standard test method for thermal performance of building materials and envolop assemblies by means of a hot box apparatus. Philadelphia: ASTM International.

ASTM. (2005b). C1113/C1113M-09, Standard test method for thermal conductivity of refractories by hot wire (Platinum resistance thermometer technique). Philadelphia: ASTM International.

ASTM. (2009). ASTM C 1126-04 Faced or unfaced rigid cellular phenolic thermal insulation. Pheladelphia: ASTM Interational.

ASTM. (2010a). ASTM C177-10, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. Philadelphia: ASTM International.

ASTM. (2010b). ASTM C518-10, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. Philadelphia: ASTM International.

ASTM. (2010c). ASTM C1043-06(2010), Standard Practice for Guarded-Hot-Plate Design Using Circular Line-Heat Sources. Philadelphia: ASTM International.

ASTM. (2010d). ASTM C 335 05a, Standard Test Method for Steady-State Heat Transfer Properties of Pipe Insulation. Philadelphia: ASTM International.

Bezjak, M., & Zvizdic, D. (2011). Dynamic measurements of the thermal conductivity of insulators. *International Journal of Thermophysics, 32*(7-8), 1467-1478. doi: 10.1007/s10765-011-1025-8.

Chyu, M.-C., Zeng, X., & Ye, L. (1997a). *Effect of moisture content on the performance of polyurethane insulation used on a district heating and cooling pipe*, Philadelphia, PA, USA.

Chyu, M.-C., Zeng, X., & Ye, L. (1997b). *Performance of fibrous glass pipe insulation subjected to underground water attack*, Philadelphia, PA, USA.

Crall, G. C. P. (2002). *The use of wicking technology to manage moisture in below-ambient insulation systems*, Charleston, SC, United states.

Cremaschi, L., Cai, S., Ghajar, A., & Worthington, K. (2012a). ASHRAE RP 1356 final report: Methodology to measure thermal performance of pipe insulation at below ambient temperatures: ASHRAE, available by request to ASHRAE.

Cremaschi, L., Cai, S., Worthington, K., & Ghajar, A. (2012b). *Measurement of pipe insulation thermal conductivity at below ambient temperatures Part I: Experimental methodology and dry tests (ASHRAE RP-1356)*. Paper presented at the ASHRAE winter conference - Technical papers, January 21, 2012 - January 25, 2012, Chicago, IL, USA.

Kaplar, C. W. (1974). Moisture and freeze - thaw effects on rigid thermal insulations. *United States Army, Corps of Engineers, Cold Regions Research & Engineering Laboratory, Hanover, N.H. Technical Report*(249).

Korsgaard, V. (1993). *Innovative concept to prevent moisture formation and icing of cold pipe insulation*, Chicago, IL, USA.

Kumaran, M. K. (1987). Moisture transport through glass - fibre insulation in the presence of a thermal gradient. *Journal of thermal insulation, 10*, 243-255.

Kumaran, M. K. (2006). *A thermal and moisture property database for common building and insulation materials*, Quebec City, QC, Canada.

Langlais, C., Hyrien, M., & Klarsfeld, S. (1983). *Influence of moisture on heat transfer through fibrous-insulating materials*, Clearwater Beach, FL, USA.

McFadden, T. (1986). *Moisture effects on extruded polystyene insulation*, Anchorage, AK, USA.

McFadden, T. (1988). Thermal performance degradation of wet insulations in cold regions. *Journal of Cold Regions Engineering, 2*(1), 25-34.

Modi, D. K., & Benner, S. M. (1985). Moisture gain of spray - applied insulations and its effect on effective thermal conductivity - Part I. *Journal of thermal insulation, 8*, 259-277.

Ogniewicz, Y., & Tien, C. L. (1981). Analysis of condensation in porous insulation. *International Journal of Heat and Mass Transfer, 24*(3), 421-429.

Ohmura, T. (2007). *Study on comparison of thermal conductivities of thermal insulations using different measurement methods in wide range of temperature*, Vancouver, BC, Canada.

Salmon, D., & Tye, R. P. (2010). An inter-comparison of a steady-state and transient methods for measuring the thermal conductivity of thin specimens of masonry materials. *Journal of Building Physics, 34*(3), 247-261. doi: 10.1177/1744259109360060.

Wijeysundera, N. E. (1996). Effect of initial moisture distribution on the transient heat flow through wet porous insulations. *Journal of Thermal Insulation and Building Envelopes, 19*, 348-366.

Wilkes, K. E., Desjarlais, A. O., Stovall, T. K., McElroy, D. L., Childs, K. W., & Miller, W. A. (2002). *A pipe insulation test apparatus for use below room temperature*, Charleston, SC, USA.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding and support from ASHRAE as well as the help of the Project Monitor Subcommittee Members and ASHRAE Technical Committee TC 1.8 Mechanical Insulation Systems.

The authors would also like to thank you Kasey Worthington, a graduate student from Oklahoma State University, for the help with construction and calibration of the test apparatus and the service and maintenance of the psychrometric chamber facility.