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Thermal Performance and Moisture Accumulation of Mechanical Pipe Insulation Systems Operating at Below Ambient Temperature in Wet Conditions with Moisture Ingress

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ABSTRACT

When pipes are used for chilled water, glycol brines, refrigerants, and other chilled fluids, energy must be spent to compensate for heat gains through the wall of the pipes. Higher fluid temperature at the point of use decreases the efficiency of the end-use heat exchangers and increases the parasitic energy consumption. Mechanical pipe insulation systems are often used to limit the heat gains and save energy in commercial buildings. Pipe insulation systems play an important role for the health of the occupied space. When a chilled pipe is uninsulated or inadequately insulated, condensation might occur and water will drip onto other building surfaces possibly causing mold growth. The critical issue with cold pipes is that the temperature difference between the pipe and its surrounding ambient air drives water vapor in to the insulation system and condensation commonly occurs when the water vapor comes in contact with the chilled pipe surface. This paper experimentally studies this issue for pipe insulation systems operating at below ambient temperature. The moisture content and the associated thermal conductivity of several pipe insulation systems were measured at various wet condensing conditions with moisture ingress. Accelerated type tests in laboratory showed the propensity of moisture accumulation in several insulation systems due to the cylindrical configuration, split joints, and micro-imperfections in the jacketing system. The data in the present work showed that the thermal conductivity increased systematically when water vapor entered the pipe insulation system.

1. INTRODUCTION

Chiller pipes are often used in space conditioning systems for large commercial building applications and mechanical pipe insulation systems are commonly installed around cold pipelines to limit the heat gain. When the surface temperature of these pipes is below the dew point temperature of the surrounding ambient, water vapor condensation might occur. Insulation jackets, vapor retarders, and vapor sealing of the joints and fittings are usually installed to limit moisture ingress into the permeable pipe insulation. When a cold pipe is not adequately insulated, water vapor might enter into the insulation system and it might condense on the pipe surface. If this event occurs, the effective thermal conductivity of the insulation system is affected by the moisture that accumulates in the insulation material and by the water that is trapped on the small gaps between the exterior surface of the pipe and the interior surface of the pipe insulation system. Water might also start to drip from the chiller pipelines onto the building surfaces, possibly causing mold growth and bacteria growth in the occupied zones. The water condensate on the exterior of the pipe surface might also cause corrosion of the pipelines and of the joints.

Data of overall thermal conductivity of mechanical pipe insulation systems when these systems are exposed to operating conditions of below ambient air temperature in chilled water applications support the design, installation, service, and maintenance of mechanical pipe insulation systems. A standard method of test for the overall thermal conductivity of pipe insulation systems exists but it is based on a hot pipe test method, that is, the heat flow is outward. This method is used for pipe insulation systems in rigid, flexible, and loose fill types. This technique, which is summarized by the standard ASTM C335/C335M (2011), allows obtaining an estimated value for the pipe insulation system thermal conductivity in dry non-condensing conditions under two assumptions: (i) the pipe insulation has linear characteristic of thermal resistance or conductance; (ii) the thermal conductivity of the pipe insulation does not depend on the direction of the radial heat flux. Unfortunately this standard might be inadequate for pipe insulation system operating at below ambient temperature. The critical issue with cold pipes is that the temperature difference between the pipe and its surrounding ambient air drives water vapor into the insulation system and condensation commonly occurs when the water vapor comes in contact with the chilled pipe surface. This condensation increases the overall thermal conductivity of the pipe insulation systems. This phenomenon inevitably leads to degradation of thermal performance and service life of the insulation. It affects the economics of performance, promotes corrosion of piping and leads to system failure and downtime. A standard method for testing pipe insulation thermal conductivity at below ambient temperature in wet conditions with moisture ingress is missing in the open domain literature. An ASTM International task group focused on the issue and recognized that this issue has been hindered by a lack of experimental facilities capable of measuring the thermal conductivity of pipe insulation systems in wet conditions. For this reason, a pipe insulation test apparatus, referred in this paper as Pipe Insulation Tester or PIT, was designed, constructed, and calibrated and the details can be found in authors' previous work Cremaschi, Cai et al. (2012b).

To date, there are limited experimental data of thermal conductivity of pipe insulation systems operating at below ambient temperature in wet condensing conditions and the estimation of the thermal conductivity is often extrapolated from experimental data obtained from the same type of insulation material but in flat slab configurations. However, a paper from Wilkes et al. (2002) observed that the thermal conductivity of pipe insulation systems might be different from that obtained by extrapolation of the data of the same insulation material in flat slab configuration. This is due to the radial configuration and the presence of split joints in pipe insulation systems, which are necessary for the installation of these insulation systems around pre-existing pipelines. Several techniques for measuring the pipe insulation thermal conductivity at below ambient temperature under dry non-condensing conditions and various methods for measuring pipe insulation thermal conductivity and moisture ingress under wet condensing conditions were summarized in authors' review paper (Cai, Cremaschi et al. 2014). The present paper provides new data of pipe insulation thermal conductivity at below ambient temperatures in wet condensing conditions and advances the understanding of moisture transfer in mechanical pipe insulation systems. The PIT was used in the present study to measure the thermal conductivity of the pipe insulation systems summarized in Table 1 below in both dry and wet conditions at below ambient temperature.

Table 1: Pipe insulation systems tested under dry and wet-condensing conditions in the present paper

Test Samples (Ref. Name)	**Thickness in (mm)**	**Longitudinal Joint Sealant**	**Radial Cross Section End Seal**	**Vapor Retarder / Insulation Jacketing**
Fiberglass (P2-FG1)	2 (50.8)	N/A	Chil-Perm CP-30*	N/A
Fiberglass (P2-FG2)	1.5 (38.1)	N/A	Foster 90-66*	ASJ vapor retarder
Fiberglass (P2-FG3)	1.5 (38.1)	N/A	Chil-Perm CP-30*	ASJ vapor retarder
Cellular Glass (P2-CG)	1.5 (38.1)	Boss 368*	Boss 368*	N/A
Polyisocyanurate (P2-PIR)	1 (25.4)	Chil-Joint CP-70*	Chil-Joint CP-70*	PVDC

*: This designation is common in the pipe insulation industry to characterize commonly used joint sealants.

2. TEST APPARATUS

The experimental test apparatus consisted of three parts: the pipe insulation tester (PIT), a refrigeration system and a psychrometric chamber as shown in Figure 1. Details of the experimental set ups and test procedures can be found in authors' previous paper Cremaschi, Cai et al. (2012b). Two samples were installed on the two identical PITs, and they were exposed to the same temperature and humidity boundary conditions with similar radial inward heat flux. One sample was used to measure the overall thermal conductivity with moisture ingress (installed on the

1st PIT), while the other sample was used to measure the moisture accumulation rate at different time intervals during the wet test period. The test insulation specimen dedicated to the moisture data was installed on the 2nd PIT.

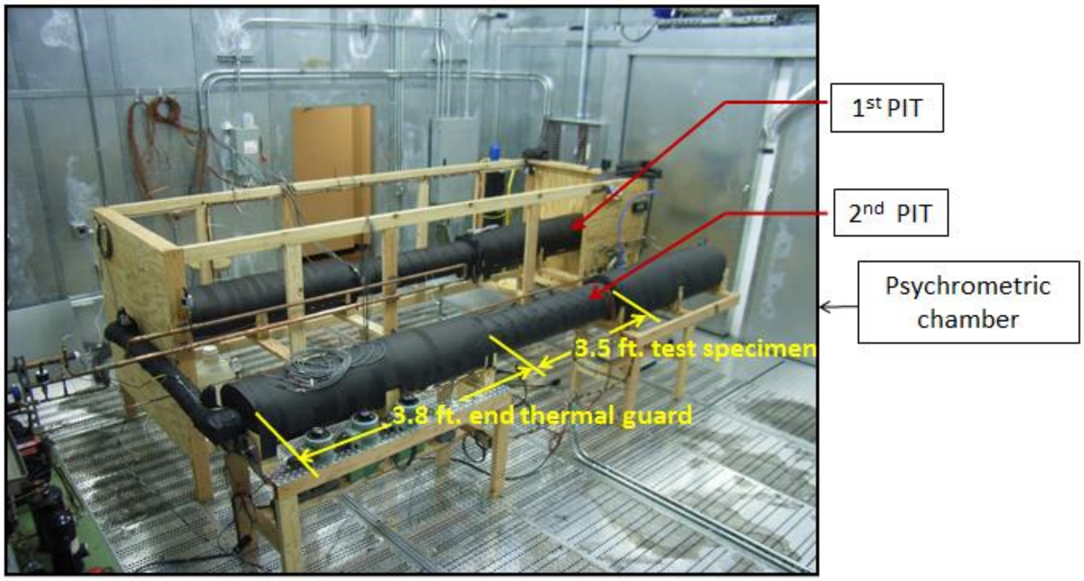


Figure 1: Photo of two PITs: the first PIT is used to measure the thermal conductivity of the insulation test specimen and the second PIT is used to measure the moisture content of the insulation test specimen

3. MOISTURE TEST RESULTS AND DISCUSSION

3.1 Moisture Test Results of System P2-FG1 in medium humidity environment (R.H. = 55%)

In this wet condensing test, the 50.8mm (2 inches) nominal wall thickness fiber glass pipe insulation system P2-FG1 was tested at the 25.6°C (78.1°F), 54.8% R.H. condition for 55 days. Photos of wet regions during the tests are shown in Figure 2(a). By the end of the moisture test period, only two small wet regions were observed on the exterior surface of the bottom shell and next to the insulation ends of the test sample. The wet regions, showed inside the red dashed circles in the photo, were observed during the fifth day of the moisture test, and the wet regions remained almost the same size for the remaining period of the test. The figure also shows that a large amount of water was trapped on the exterior layer of the fiberglass pipe insulation system due to possible preferential paths for water vapor ingress near to the insulation end cross sections. Figure 2 (a) shows the interior surface of the fiberglass insulation that was wrapped around the Aluminum pipe. The interior surface of the top shell was basically dry, with only few water droplets on the surface layer of the fibers. On the bottom shell, larger wet regions were present next to the insulation end cross sections. This observation supported the hypothesis that preferential paths for moisture ingress were established at the end cross sections of the pipe insulation test specimen. The experimental results on the system thermal conductivity and moisture content are shown in Figure 2(b) and (c). By the end of the moisture test, the system thermal conductivity in wet condition was 1.5 times higher than the thermal conductivity in dry condition at the same temperature. The maximum moisture content was about 1.7 percent by volume. From Figure 2(b), it is observed that the system thermal conductivity followed a two-step variation with time. This trend was observed in authors' previous work (Cai 2013) and it was due to transitory phases of water vapor redistribution within the insulation system. The system thermal conductivity ratio increased to 1.5 with the moisture content less than 0.3 percent by volume at the beginning of the test. Then the thermal conductivity ratio was 1.5 for a long period during which the moisture content increased from 0.3 to 1.7 percent by volume. Both the top and bottom shells of this insulation system had similar moisture content. It should be noted that the uncertainty was above 20 percent when the moisture content was below 2 percent by volume. The authors concluded that the moisture content was very small in this case and speculate that gravity had minor impact on the water redistribution between the top and bottom shells when the total amount of moisture content in the fiberglass insulation system was below 2 percent.

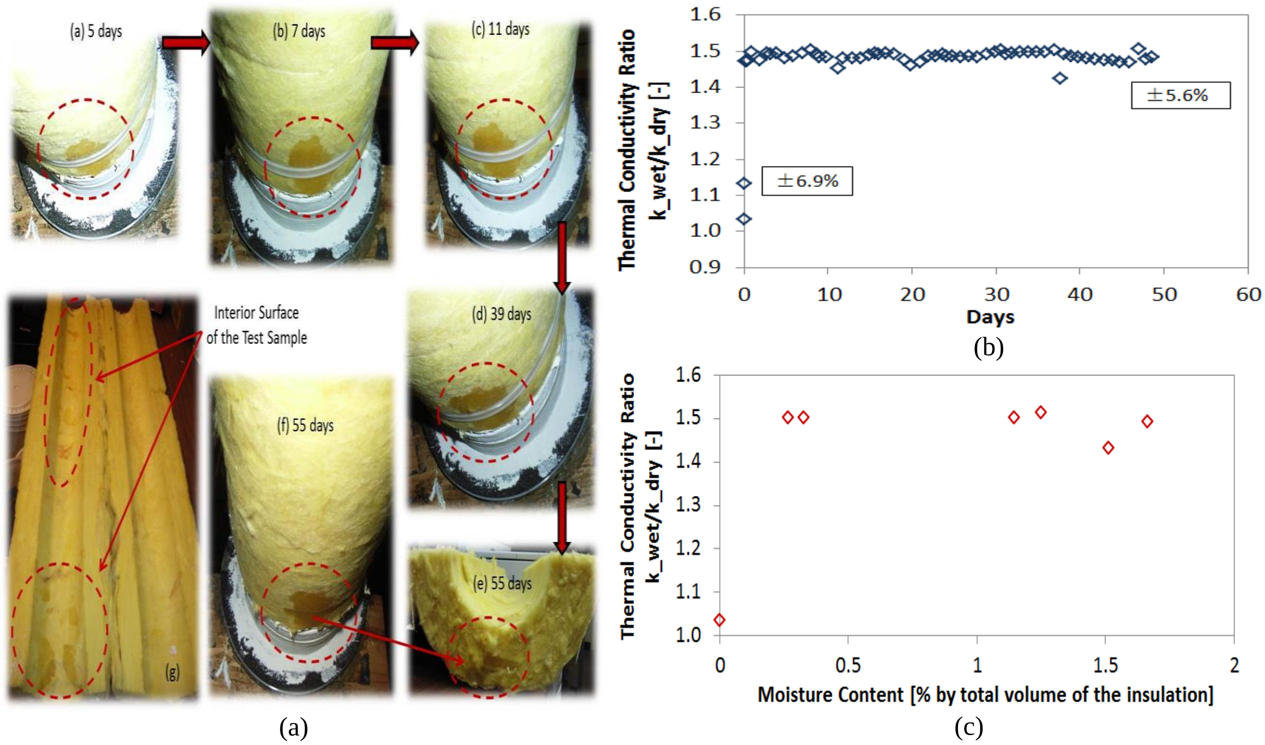


Figure 2: Test results on system P2-FG1: (a) moisture absorption on the bottom shell (b) thermal conductivity ratio with time and (c) thermal conductivity ratio with moisture content

3.2 Moisture Test Results of System P2-FG1 in high humidity environment (R.H. = 84%)

This fiber glass pipe insulation system P2-FG1 was tested under severe conditions with a high temperature of 32.3°C (90.1°F) and a high relative humidity of 84% for 53 days. In these conditions, the dew point temperature was 29.2°C (84.6°F), and the insulation surface temperature of the P2-FG1 system ranged from 31.2°C (88.2°F) to 31.6°C (88.9°F). The nominal wall thickness was 50.8mm (2 inches). Only one small wet region was observed on the exterior surface of the bottom shell, and the wet region remained almost of the same size for the remaining period of the test. One possible reason for the formation of the wet region might be the effect of sealing of the end joint, that is, the radial cross sections at the end of the pipe insulation test section. These end joints affected the water vapor distribution in the longitudinal direction of the insulation system. Another possibility might be the denser insulation near the surface for this particular system, which might have limited water moisture diffusion on the exterior surface. The experimental results on the system thermal conductivity and moisture content are plotted in Figure 3(b) and (c). After 53 days of wet test, the system thermal conductivity ratio, defined as wet over dry thermal conductivity at the same temperature, increased up to 3.5 with the total moisture content of about 15 percent by volume. Figure 3(a) shows the interior surface of both top and bottom shells of the fiberglass test sample in this system P2-FG1. There were not any visible water marks on the top shell, and the water droplets only coating along the surface of the fibers. For the bottom shell, a large region of water marks was observed at the location indicated inside the dashed red line circles in the Figure 3 (a). This location might be a less dense region for the insulation material and water ingress was locally promoted. The performance on the system thermal conductivity was similar to the results observed in medium humidity environment, and showed a two-step variation process. The system thermal conductivity changed almost simultaneously with the ambient condition at the beginning of the moisture test. The thermal conductivity ratio increased to 2.5 during the first several hours and then gradually increased to 3.5 during the remaining of the wet test period.

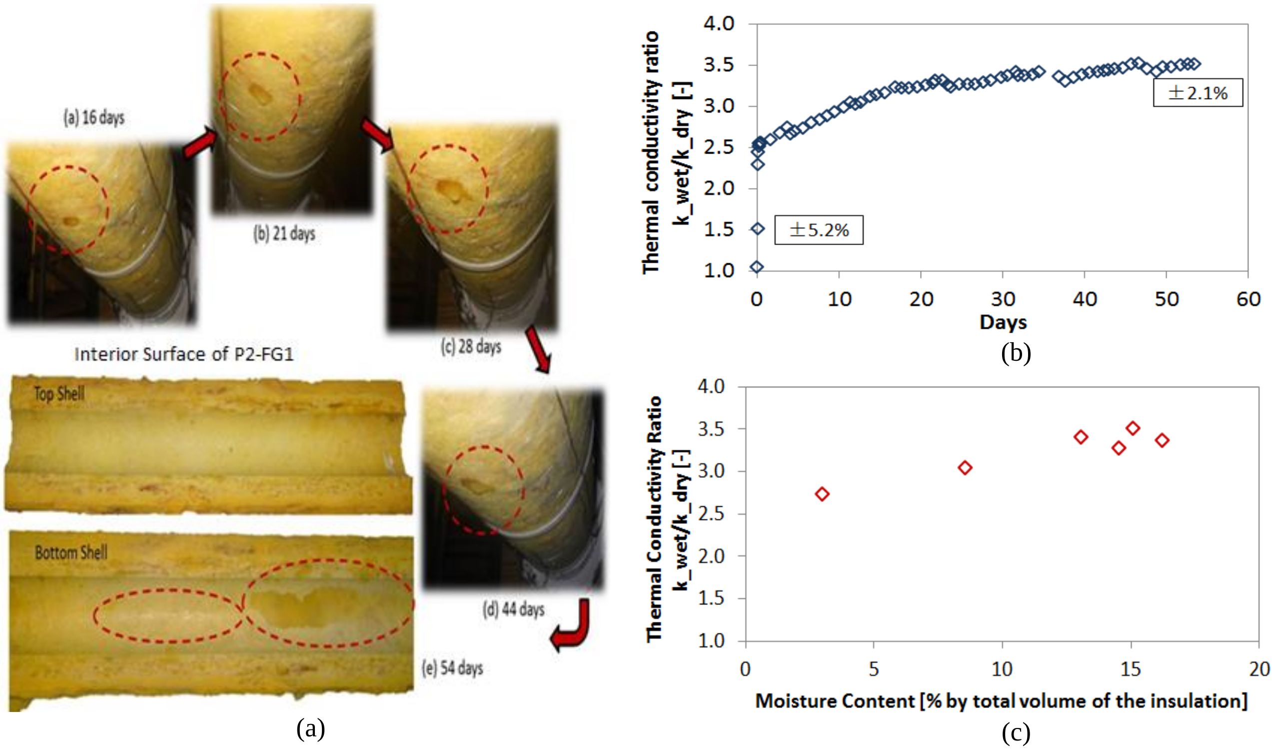


Figure 3: Test results on system P2-FG1: (a) photos of moisture absorption in the bottom shell; (b) thermal conductivity ratio with time; and (c) moisture content with time

3.3 Moisture Test Results of P2-FG2 in high humidity environment (R.H. = 83%)

Different from the previous fiberglass systems, this system P2-FG2 was tested with a water vapor retarder jacket on the exterior surface of the fiberglass pipe insulation. This system had a nominal wall thickness of 38.1mm (1.5 inches) and was tested at 32.3°C (90.1°F), 83% R.H. for 66 days. The dew point temperature of the ambient air was 29.0°C (84.2°F) and the pipe insulation surface temperatures ranged from 30°C (86°F) to 31.4°C (88.5°F). It can be observed from Figure 4(b) and (c), that at day 66 the thermal conductivity increased by about 7 percent. The final moisture content of the test specimen on the 2nd PIT was about 0.2 percent by volume. During the moisture test, wet regions and some water droplets were observed on the exterior surface of the ASJ vapor retarder, specifically on the bottom C-shell near the end sections as shown in Figure 4(a). The formation of these condensation regions were due to lower local temperature of the joints, in which joint sealant was used to fill the micro gaps along the radial cross sections of two adjacent joints, with respect to the average surface temperature of the insulation system. As moisture accumulated on the exterior surface of the ASJ vapor retarder, the jacketing material became gradually wet and it darkened with time. A hypothesis is that, water condensation around the insulation joints might have entered the system through the micro-gaps of the ASJ butt joint strips. The water vapor trapped inside the insulation system during the installation stage could also contribute to the increase of the system thermal conductivity. It should be noted that due to the low moisture content, the uncertainty was very high, and there was no specific correlation between the moisture content and thermal conductivity variation on the 1st PIT.

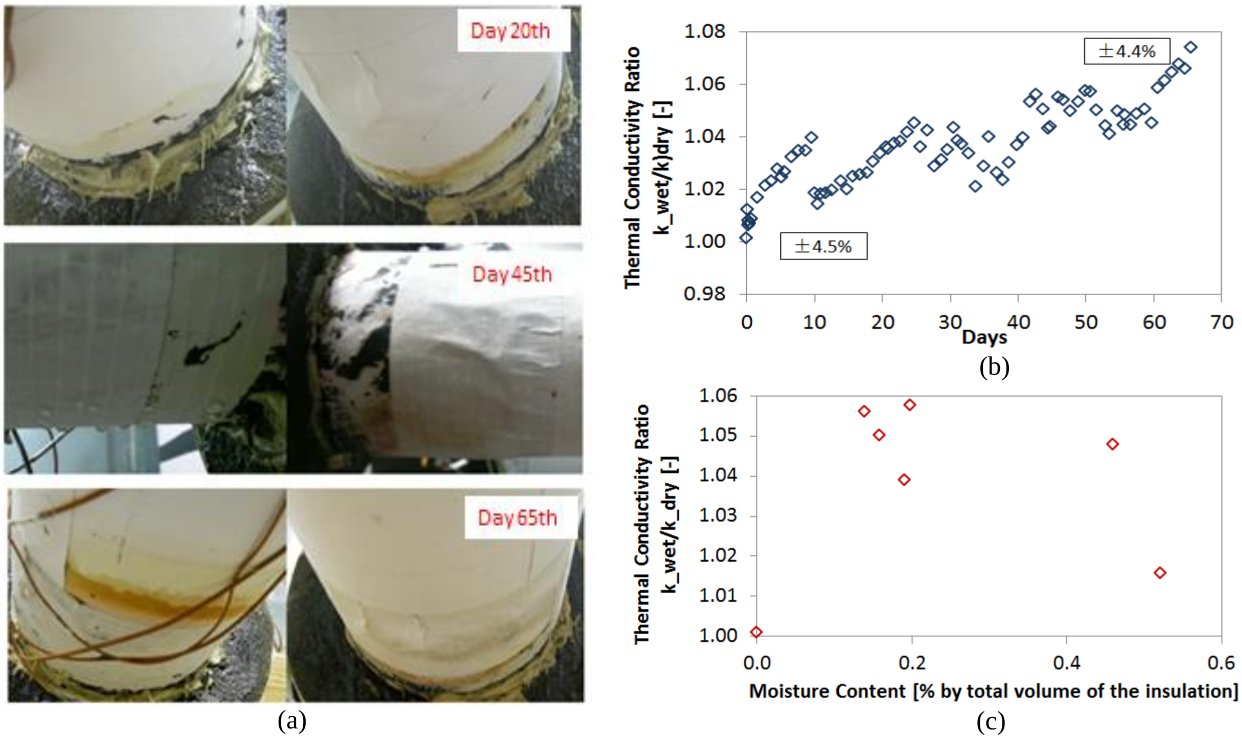
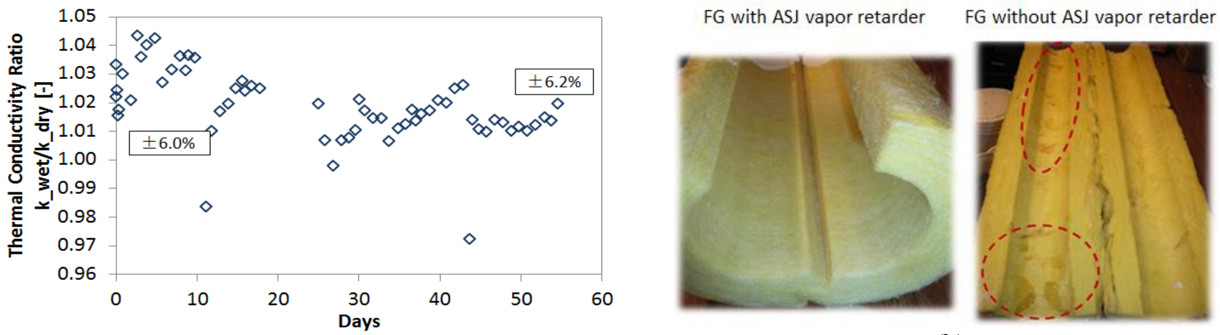


Figure 4: Test results on system P2-FG2: (a) development of condensation on the bottom shell on the ASJ vapor retarder surface, (b) thermal conductivity ratio with time, and (c) thermal conductivity with moisture content.

3.4 Moisture Test Results of System P2-FG3 in medium humidity environment (R.H. = 55%)

The fiberglass pipe insulation system P2-FG3 was operated in a wet condensing environment and it had a nominal wall thickness of 38.1mm (1.5 inches). It was tested at 25.6°C (78.1°F), 55% R.H. for 55 days. The temperature and humidity of the surrounding air were lower than the ones used for other wet tests because these conditions purposely simulated more closely the actual temperature and humidity of indoor spaces for mechanical insulation systems in commercial buildings. For this fiberglass system, both the 1st PIT and the 2nd PIT were used to measure the thermal conductivity of the fiber glass pipe insulation systems in order to confirm the repeatability of the data and to estimate the error due to operator installation. Only the initial and final moisture content were measured for both PITs. There were not any wet regions observed during the 55 days of wet test period and the insulation interior surfaces appeared to be completely dry after taking out the samples from the PITs. It can be observed from Figure 5(b), that the thermal conductivity ratio increased slightly during the beginning of the moisture test, and then it gradually decreased back to 1. Both systems P2-FG3 had moisture content lower than 0.3 percent by total volume and they showed identical behavior, confirming the repeatability of the measurements with the newly developed test apparatus. In this system, the water vapor that was trapped in the system during the installation phase might have condensed in the low temperature regions and formed the moisture beads at the contact points of the fibers. The presence of vapor barrier decreased the rate of moisture ingress. Therefore, less preferential paths were formed during the first stage of the wet test period and the system thermal conductivity increased only by a few percentages. In the second stage of the wet test period, instead of coating the fibers and filling in the voids, the small amount of moisture might have redistributed throughout in the insulation system. Some of the moisture beads were shifted from the contact points of the fibers. This moisture redistribution affected the heat flow paths and resulted in a reduced overall thermal conductivity of the insulation system (Cai 2013).

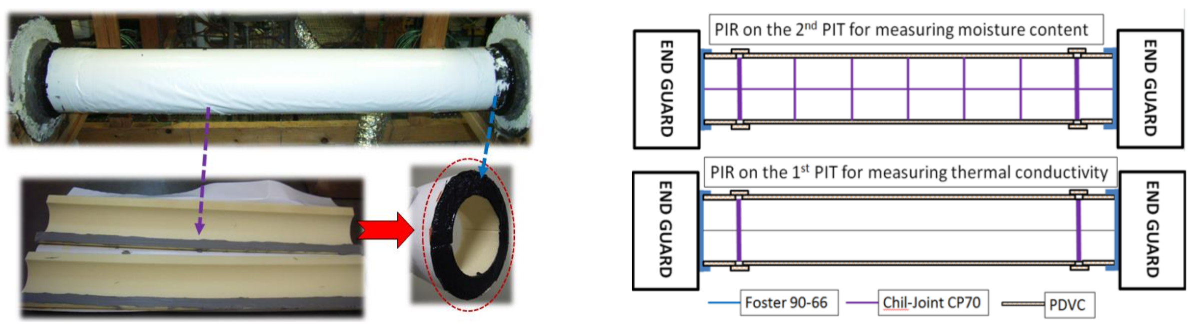


(a) (b)

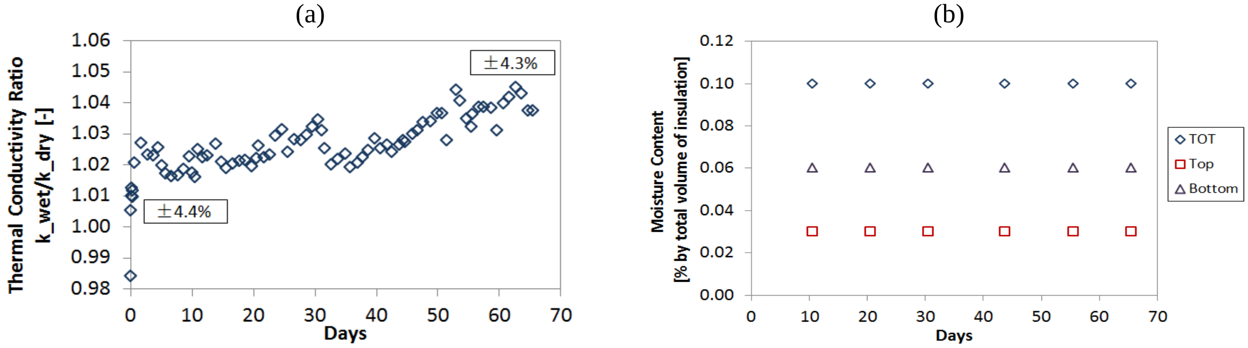
Figure 5: Test results on system P2-FG3: (a) thermal conductivity ration with time, (b) comparison of the interior surface of pipe insulation systems P2-FG1in medium humidity environment and P2-FG3

3.5 Moisture Test Results of System P2-PIR in high humidity environment (R.H. = 83%)

Polyisocyanurate (PIR) pipe insulation is closed cell insulation for mechanical pipe insulation system applications. The PIR pipe insulation system P2-PIR had a nominal wall thickness of 25.4mm (1 inch). A polymer polyvinylidene chloride (PVDC) vapor retarder jacket was used with PIR and it consisted of a film of barrier PVDC coextruded with other polymers that provided strength and support. Figure 6(a) shows the installation details of the PIR test specimen with the PVDC vapor retarder. Figure 6(b) is an overview of the PIR insulation systems around the first PIT and the second PIT. The thermal conductivity was measured from the first PIT and the moisture content was measured from the six small sections installed on the second PIT. It should be noted that Foster 90-66 vapor sealant was not used on the cross section areas of the six 6-inch sections. This is because each 6-inch section had to be taken out at regular intervals during the wet test period but without damaging the adjacent sections. Unfortunately Foster 90-66 was an adhesive vapor sealant compound and it was not possible to remove each section without damaging the adjacent ones when this adhesive sealant was used.



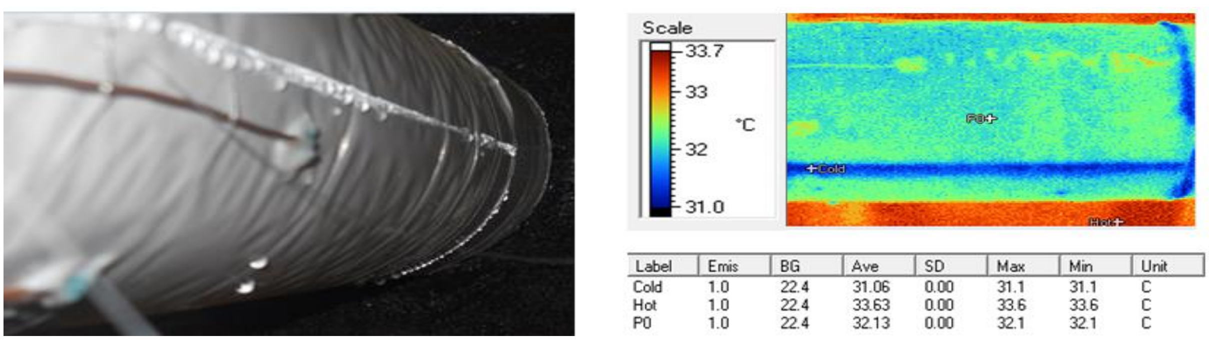
(a) (b)



(c) (d)

Figure 6: Installation details and test results of system P2-PIR: (a, b) installation pictures and schematic on the 1st and 2nd PITs, (c) thermal conductivity ratio with time, and (d) moisture content with time

To predict the moisture ingress on the long insulation test specimen installed on the 1st PIT, where only the initial and final values of the moisture content were measured, the intermediate moisture content data measured from the pipe insulation system installed on the 2nd PIT were used. The data were curve fit to generate a function of moisture content with time. For the 6 samples on the 2nd PIT, only the second and third sample showed total moisture content of 0.14 and 0.13 percent by total volume, while the other four samples showed basically 0 percent moisture content. This was due to the limitation of the sensitivity of the scale used for measuring the weight of the wet samples. It appeared that the moisture content inside the test specimen was sometimes below the sensitivity of the scale and thus it was defined to be 0 percent. At the 65th day of the wet test period, the moisture content on the 1st PIT was measured and resulted of about 0.1 percent by total volume. In this case, because the moisture content on the 2nd PIT was quite small and practically constant during the entire wet test period, we assumed that the moisture content in the PIR insulation on the 1st PIT was also small and practically constant throughout the wet test period. It should be also noted that, during the wet test period, condensation droplets were observed on the exterior surface of the jacket. The dew point temperature of the ambient was 28.9°C (84.0°F) and the pipe insulation surface temperature ranged from 30.5°C (86.9°F) to 30.7°C (87.3°F). However, as shown in Figure 7 (b), the presence of joint sealant decreased the local surface temperature by about 1°C with respect to the average exterior surface temperature of the pipe insulation system in areas clear of joints. This yielded to visible condensation regions covering exactly the joint lines of the pipe insulation system. It was possible that the condensation droplets on the exterior surface of the PVDC vapor retarder jacket entered the test specimen through micro-cracks and unsealed gaps in the jacket, causing the thermal conductivity of the test specimen on the 1st PIT to slightly increase with time. It was also postulated that the water vapor could have entered into the system during the installation phase. Once the vapor retarder jacket was wrapped around the pipe insulation system, then the water vapor remained trapped inside. These are the two possible reasons for the insulation thermal conductivity on the 1st PIT to gradually increase by 4 percent, as can be seen from Figure 6(c). It was finally observed that while the thickness of the pipe insulation system was purposely selected to avoid condensation on the exterior surface, the presence of joints and joint sealant caused significant water droplet condensation at the joints. Thus, the thickness of the pipe insulation system should be selected based on the lowest temperature on the insulation exterior surface in order to completely avoid condensation on the exterior surface of mechanical insulation systems when they are operating at below ambient temperature in high humidity environments.



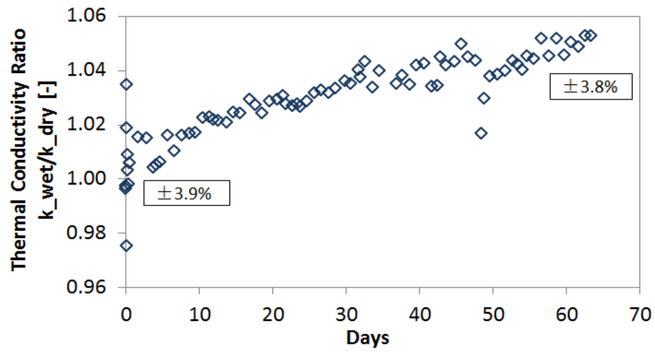
(a) (b)

Figure 7: (a) condensation following precisely the joint sealant areas on the pipe insulation system, (b) infrared image showing the temperature difference between the region near the sealed joints and rest of the insulation

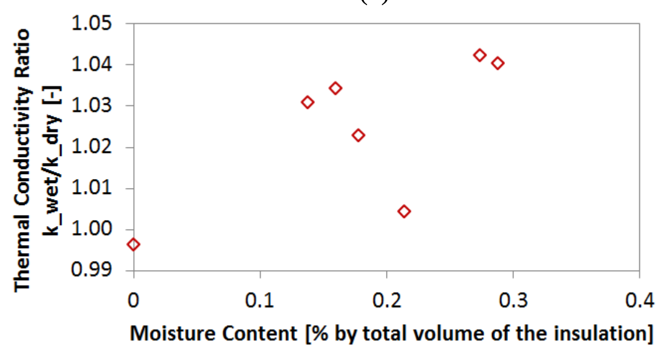
3.6 Moisture Test Results of System P2-CG in high humidity environment (R.H. = 83%)

Cellular glass insulation is a light weight, rigid insulating material containing millions of completely sealed glass cells. Because of the low permeability of cellular glass insulation, the thermal conductivity during the moisture test increased only by about 5 percent at day 63, as shown in Figure 8(b). The moisture content on the 1st PIT at day 63 was measured to be 0.3 percent. For the moisture measurements, due to the small amount of water measured from the insulation test specimens, the uncertainty in the moisture content was over 15 percent. Because of the low moisture accumulation amount, both the top and bottom C-shell sections had practically same moisture content. It should also be noted that similar to what occurred to system P2-PIR, water condensation was observed on both the longitudinal and cross sectional joints with joint sealant of the cellular glass pipe insulation system. Water droplets ran down visibly along the joints lines as illustrated in Figure 8(a) (see red solid circles).

(a)



(b)



(c)

Figure 8: Test results on system P2-CG: (a) condensation along the joint sealant on the cellular glass test specimen, (b) thermal conductivity ratio with time, and (c) moisture content with time

4. SUMMARY OF THERMAL CONDUCTIVITY IN DRY AND WET CONDITIONS

For each pipe insulation system investigated in the present work, Table 2 shows the measured ratio of thermal conductivity in wet conditions over the corresponding value of thermal conductivity in dry non-condensing condition at the same average insulation temperature. The maximum moisture contents measured for each system are also reported in Table 2. In addition, Table 2 includes the results from the dry non-condensing tests. In the temperature range from 12.8°C (55°F) to 40.6°C (105°F), the overall thermal conductivity of fiberglass pipe insulation systems (FG1 to FG3) increased linearly with the test insulation mean temperature. The coefficients of the linear functions are summarized in Table 2. For the same temperature range, the thermal conductivity of cellular glass (CG) and polyisocyanurate (PIR) pipe insulation systems was practically constant.

5. CONCLUSIONS

Six mechanical pipe insulation systems were tested at below ambient temperature in wet-condensing conditions with moisture ingress. The thermal conductivity increased with time when water vapor entered the insulation system and the ratio of the thermal conductivity in wet conditions over the thermal conductivity in dry conditions ranged from 1.04 to 3.51. The moisture content measured in the pipe insulation systems ranged from 0.1 percent by volume, which was the case of no moisture ingress and impermeable vapor retarder system, to 15 percent by volume. It was evident that proper installation of a vapor retarder jacket played a key factor in limiting the rate of vapor ingress into the fiberglass insulation system. Cellular glass had low water vapor ingress and its thermal conductivity during the wet test increased by 5 percent compared with its thermal conductivity in dry conditions. PIR pipe insulation system was tested with a water vapor retarder jacket, and the moisture content was less than 0.1 percent. The PIR system thermal conductivity increased by less than 5 percent. For both cellular glass and PIR pipe insulation systems, water droplets were observed on the exterior surface of the pipe insulation system, resulting from vapor condensation near the joints. Infrared thermal images confirmed that the regions on the exterior pipe insulation surface near the joints had about 1°C lower temperature with respect to the average pipe insulation surface temperature. Thus, it was concluded that the presence of joints and joint sealant was a factor that should be considered when designing a mechanical pipe insulation system that aims to avoid condensation on its exterior surfaces.

Table 2: Summary of the experimental results on the pipe insulation systems under dry and wet conditions

System	Dry Tests Conditions and Results			Wet Tests Conditions and Results				
	$k_{pipe,insulation}$ = a× T + b W/m-K (Btu-in/hr- ft2-F) a	b	Amb.Temp. range °C (°F)	Temp. °C (°F)	R.H. [%]	Max. Thermal Conductivity Ratio[-]	Max. Moisture Content [%]	Test length [day]
P2-FG1	0.00016 (0.0006)	0.0359 (0.2294)	24.9~38.8 (76.9~101.8)	25.6 (78.1)	55	1.48	1.7	55
P2-FG1	0.00016 (0.0006)	0.0359 (0.2294)	24.9~38.6 (76.9~101.5)	32.3 (90.1)	84	3.51	15.1	53
P2-FG2	0.00036 (0.0014)	0.0325 (0.1809)	25.1~41.8 (77.1~107.2)	32.3 (90.1)	83	1.07	0.2	66
P2-FG3	0.00014 (0.0006)	0.0345 (0.2212)	25.0~38.6 (77.0~101.5)	25.6 (78.1)	55	1.04	0.3	55
P2-PIR	-0.000086 (-0.0003)	0.0384 (0.2660)	25.1~41.9 (77.1~107.5)	32.2 (90.0)	83	1.04	0.1	65
P2-CG	-0.000057 (-0.0004)	0.0518 (0.3795)	25~38.9 (77.0~102.2)	32.1 (89.8)	83	1.05	0.3	63

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