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Polyethylene-Based Pipe (PEX)

Design Considerations For Underground Hot Water Piping

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It is important to understand available pipe materials when direct-burying pipe underground. Pre-insulated crosslinked polyethylene-based pipe (PEX) has gained acceptance as a cost-effective alternative to ferrous pipe in direct-bury applications for certain heating hot water systems. These systems can also be used on cooling systems but there are many other non-ferrous cost-effective solutions as discussed in a previous column.[1] While steel pipe can deliver unmatched temperature and pressure service levels, properly designed PEX pipe can deliver corrosion-free and leak-free operation.

There are some unique challenges requiring special design considerations due to PEX piping's visco-elastic nature, very low material allowable stress, large coefficient of thermal expansion, and relatively thick pipe walls. This month I will review these considerations in order to design and specify underground hydronic heating hot water PEX piping systems.

Underground Piping Objectives

In the past, most direct buried heating hot water systems used either carbon steel, ductile iron (DI) or copper pipe. These systems and modes of failure were presented in a previous *ASHRAE Journal* column.[2] Ductile iron is typically joined using gasketed push-on joints. These joints are restrained with either concrete thrust blocks or external bolted-on mechanical couplings. The author has found monthly and annual allowable leakage through push-on joints on large distribution systems can be substantial and will result in loss of treated water. Excessive makeup water can also lead to loss of adequate levels of corrosion inhibitor in the circulating water. One objective is to design and install distribution piping that will not leak.

Pre-insulated carbon steel and copper piping are also commonly used in direct-buried heating hot water systems. The piping has unmatched temperature and pressure ratings but is subject to both internal and external corrosion. According to NACE International,[3] corrosion of ferrous metals buried underground is a naturally occurring process and is the leading cause of underground piping system failures. Pre-insulated and jacketed steel pipe is protected from soil corrosion by providing a continuous physical and vapor barrier over the insulation. Insulation joint installation errors or

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damage from subsequent excavation can cause the insulation jacket to be penetrated, leading to external corrosion and eventual pipe failure. An underground distribution piping that will not experience corrosion and will provide a long service life (>50 years) is one of the most important design and installation objectives.

PEX Piping

Engineering Properties

Crosslinked polyethylene (PEX) is a flexible plastic pressure pipe with over 40 years of successful use in the European market in hot water applications, including extensive testing for durability and material performance. It was first introduced in North America in 1984 and is widely used for plumbing, water service, fire protection, hydronic heating and cooling (particularly radiant floors), snow and ice melting and ground source geothermal piping systems. PEX began being used in the 1990s for underground applications.

PEX is a polyethylene material, which has undergone a change in molecular structure using a chemical or a physical process whereby the polymer chains are chemically linked. The primary reason for cross-linking PE is to increase the material's elevated temperature internal pressure performance. Crosslinking also improves the pipe's environmental-stress crack resistance, resistance to slow crack growth, chemical and corrosion resistance, toughness, and abrasion resistance. Finally, crosslinking makes PEX a "semi-thermoset" polymer, providing good long-term stability.

In general, 140°F (60°C) is the maximum service temperature for thermoplastic high-density polyethylene (HDPE) pressure pipe applications. With PEX, however, the in-service temperature can be raised to at least 180°F (82°C) and sometimes as high as 200°F (93°C), depending on the starting density, degree of crosslinking, type of crosslinking and operating pressure. PEX pipes are also tested to ensure short-term exposure to a temperature of 210°F (99°C) is also tolerated.

PEX-a tubing with an oxygen diffusion barrier is most commonly used for underground heating hot water applications. The oxygen diffusion barrier limits oxygen permeation through the tubing wall in hydronic heating applications, which prevents corrosion of ferrous metal parts in the heating system. PEX-a tubing is produced using the Peroxide (or, "Engel") method, named after the inventor Thomas Engel. During the manufacturing process, free radicals are created when HDPE polymer is melted and cross-links between molecules occur at temperatures that exceed the decomposition temperature of the polymer. *Table 1* shows physical and mechanical properties comparison of PEX-a and carbon steel. The PEX-a coefficient of thermal expansion is substantially higher than steel pipe.

TABLE 1 Carbon Steel and PEX-a physical and mechanical properties.

MATERIAL	CARBON STEEL	PEX-A
Modulus of Elasticity (E)	27.9×10^6 psi	180°F: 87,000 to 130,000 psi
Pipe Roughness Value (e)	0.00015 ft	0.000002 ft
Coefficient of Thermal Expansion	6.5×10^{-6} in/in·°F	212°F: 2.72×10^{-4} in/in·°F
Thermal Conductivity (K)	25 Btu/h·ft·°F	2.86 Btu/h·ft·°F

TABLE 2 PEX elastic modulus versus temperature.

TEMPERATURE (°F)	ELASTIC MODULUS (PSI)	LONG-TERM MODULUS (PSI)	COEFFICIENT OF THERMAL EXPANSION, IN/IN·°F
220	6,815	889	2.94E-04
200	8,700	1,056	2.39E-04
180	11,165	1,260	1.89E-04
160	14,065	1,513	1.61E-04
140	19,720	1,827	1.28E-04
120	27,115	2,221	1.11E-04
100	36,540	3,612	1.00E-04
73	61,915	3,612	7.94E-06

PEX is not subject to galvanic action and does not rust or corrode. PE has no nutritional value and will not support microbiological induced corrosion and fouling as seen in carbon steel. PEX also has an extremely smooth surface compared to carbon steel, which provides minimal opportunity for the precipitation of minerals such as calcium carbonate onto the interior surface. This smoothness also reduces pressure drop and associated pump energy.

The modulus of elasticity is related to the Poisson ratio for plastic materials. It is the ratio of normal stress to corresponding strain. A material with a low modulus of elasticity is more flexible and expands with less force than a material with a higher modulus of elasticity. For PEX pipes, the Poisson ratio is 0.4. *Table 2* shows the effect of temperature on short-term and long-term modulus of elasticity, and the coefficient of thermal

TABLE 3 Hydrostatic design stresses and pressure ratings for SDR 9 PEX tubing for water at different temperatures.

RATED TEMPERATURE (°F)	HYDROSTATIC DESIGN STRESS (PSI)	PRESSURE RATING FOR WATER (PSI)
200	315	80
180	400	100
73	630	160

expansion from 220°F (100°C) down to 73°F (23°C) for a particular PEX pipe.

Hydrostatic Pressure Ratings

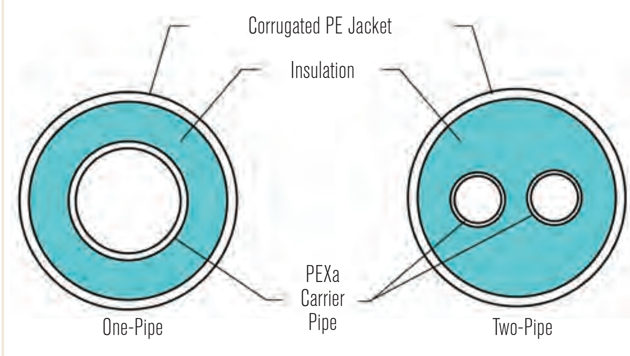
The pressure rating of PEX piping is obtained from the hydrostatic design basis (HDB) method as defined in ASTM D2837.[4] The HDB ratings have been shown to be useful indicators of relative long-term strength of thermoplastic materials. The Plastics Piping Institute (PPI) develops policies and procedures for the recommendation of the estimated long-term strength for commercial thermoplastic piping materials and includes this in its "PEX Pipe Design Manual (HDB-Based) for Water, Oil, Gas & Industrial Applications."[5] PPI also develops policies and procedures for the recommendation of the estimated long-term strength for commercial thermoplastic piping materials and includes this in Technical Report-3, TR3.[6] PPI Technical Note, TN-52,[7] provides guidance for determining appropriate design life calculations of PEX pipe and tubing in high-temperature applications, defined as operating temperatures above 180°F (82°C).

Table 3 shows the ASTM F876[8] minimum long-term hydrostatic design stress ratings and pressure ratings for SDR 9 PEX tubing for various temperatures, when determined in accordance with procedures no less restrictive than those of PPI TR-3. The pressure rating is the estimated maximum water pressure the tube is capable of withstanding continuously with a high degree of certainty that failure of the tube will not occur.

Pre-Insulated Piping and Joining Methods

Pre-insulated PEX piping systems are available from several manufacturers. In North America, pre-insulated PEX piping comes in two primary configurations: single pre-insulated pipe is available up to 4 in. (100 mm) nominal pipe diameter while two-pipe systems in a single insulated jacket are available up to 2.5 in. (65 mm) nominal pipe diameter. *Figure 1* shows pre-insulated single pipe and two-pipe configurations. Two-pipe systems typically work best when the temperature differential between the two pipes is less than or equal to about 20°F (11°C) ΔT. Corrugated polyethylene jackets are used for the pre-insulated piping system to allow flexibility in bending and resistance to thermal expansion when buried.

FIGURE 1 One-pipe and two-pipe pre-insulated PEX.



Because the maximum diameter of available pre-insulated PEX pipe is relatively small, its use is limited to applications with lower flow requirements. In the author's experience, this has been in applications routing from local heating plants to nearby buildings and used in building connection branches from campus distribution vaults.

Different insulation materials and techniques are used by various manufacturers. Fully bonded polyurethane insulation is available by several manufacturers while another uses unbonded layered PEX insulation. The fully bonded polyurethane insulation is bonded to both the PEX pipe and jacket and is more rigid, and has a lower thermal conductivity requiring less insulation. The unbonded layered PEX insulation has different layers of PEX insulation that move independently for increased flexibility and tighter bending radiuses but requires a larger outside jacket diameter due to a higher thermal conductivity. For example, a 2 in. (50 mm) nominal pipe with the fully bonded polyurethane insulation system requires a 36 in. (914 mm) bending radius while the unbonded layered PEX insulation requires only 18 in. (457 mm).

An integral part of any pipe system is the method used to join the system components. PEX is typically joined with compression sleeve type fittings. The majority of systems use fittings made from either DZR (Dezincification Resistant) brass or offer poly PEX fittings, which are not subject to corrosion.

Selection and Design

PEX Design and Installation Considerations

PEX pipe diameter is typically specified by copper tubing size (CTS). This means PEX pipe will have a significantly smaller inside pipe diameter than nominal pipe size (NPS) steel pipe; therefore, it is sometimes oversized to achieve the desired inside pipe diameter. For example, 3 in. CTS (76 mm) SDR 9 PEX pipe has an inside diameter of 2.398 in. (61 mm), whereas A53 carbon steel pipe would have an inside diameter of 3.068 in. (78 mm). When sizing PEX piping, both the much lower pipe roughness value and the decreased inner diameter of nominal pipe sizes should be considered. In some cases, depending on butterfly valve dimensions used in the system, flange adaptors with tapered ID spacers may be required for the valve to open and close freely. In most cases, ball valves can be used for isolation due to the smaller pipe sizes.

PEX has a unique benefit of being shipped pre-insulated in lengths of 300 to 600 ft (91 to 182 m) coils to minimize field joints in trenches. In the author's experience, underground field joints on pre-insulated steel piping tend to be the single greatest risk of corrosion failure. These field joints and fittings are required every 20 ft (6 m) in addition to directional and tee fittings. In many cases, the long lengths and flexibility of PEX tubing eliminates the need for underground field joints between buildings and the flexibility allows the pipe to bend where normally 45- or 90-degree fittings would be used with rigid piping. The flexibility in the PEX system does not require trenches to be dug straight and level and also makes avoiding underground obstacles easier since the pipe can be installed to snake around the obstacles. If an underground field joint is required for tees, they should be provided in an accessible connection vault similar to *Photo 1* and not direct buried.

When determining the minimum depth to bury the pipe, the compressive wall stress on the pipe from exterior forces should be kept less than the allowable compressive stress of the PEX material. Generally, the American Association of State Highway and Transportation Officials (AASHTO) H-20 truck loading is met using SDR 9 pre-insulated pipe with 2 ft (0.6 m) of cover. Burying the pipe below the frost line can prevent heaving and improve thermal performance. As with most thermoplastic piping systems, do not install the

PHOTO 1 Typical underground PEX connection vault. Photo courtesy of Uponor.

pre-insulated PEX system in soil or groundwater conditions, which are thought or known to be contaminated with fuels, organic compound, or solvents, as these substances could permeate the pipe and contaminate the water or damage the integrity of the piping system. A minimum of 4 in. (100 mm) of sand should surround the pre-insulated PEX system in the trench.

Expansion loops that allow linear expansion and contraction for rigid piping are generally not required when using pre-insulated PEX piping. The unique nature of the service pipe encasement and the expansion absorption built into the pre-insulated PEX systems virtually eliminates the effects of linear expansion as long as the points of connections to buildings are anchored.

Once buried and backfilled, PEX piping cannot be located via metal detectors. Therefore, it is suggested PEX piping, as with all non-ferrous piping, should be buried with a 12 gauge (2.05 mm) tracer wire attached thereto, all the way back to an accessible manhole or indoor space at each end. This will allow a small electrical current to be used to assist a locator in finding the pipe route at some date in the future. A cautionary "underground buried piping" vinyl warning tape should also be located in the backfill above the pipe to warn future unsuspecting excavators.

Installed pre-insulated PEX piping systems are less expensive than installed pre-insulated A53 standard steel piping systems. The author has seen 20 to 35% construction cost savings when comparing pre-insulated PEX to pre-insulated steel piping systems for connections between buildings or heating distribution building branches. Most of these cost savings are a result of substantially less labor and shorter installation time due to the large reduction of field joints required in a pre-insulated steel piping system.

Transition to Building Service Piping

The pre-insulated PEX system can penetrate the building exterior wall or floor prior to connecting to other systems, such as mechanical room equipment or existing metal piping inside the building. Plastic pipes expand and contract dramatically with changes in temperature. To avoid damage to the pre-insulated PEX system and the connecting pipe components, the PEX system should be properly anchored to the wall or floor.

Temperature Control Limit

Maximum water temperature control is critical when using thermoplastic materials with heating hot water systems. The pre-insulated PEX systems typically come with a 25-year warranty on the PEX pipe as long as the system operates within the temperature pressure rating limits shown in *Table 3*. Hot water boilers have its operating control set for the desired hot water supply temperature. The limit control is set at a higher temperature than the operating control and typically requires a manual reset. If a boiler reaches its limit control setpoint, it usually means the operating control is not working. Since boilers can operate above their operating setpoints it is recommended to install controls to ensure the maximum allowable service temperature is not exceeded for the pressure rating. This is typically not an issue if the boiler limit control is set below the temperature pressure rating limit for the installed system.

Commissioning

PEX, like other piping materials, should be thoroughly flushed prior to testing to prevent damage to valves and other fittings from any material left in the pipe during construction. A minimum flush velocity of 3 fps (0.9 m/s) is recommended to move the material in the pipe. PEX leak testing is usually done with water at a pressure specified by the designer, typically 1.5 times the normal operating pressure but not higher than the temperature pressure rating limits shown in *Table 3*. It is worth noting that this is a field leak testing procedure since PEX pipe is a lower modulus visco-elastic material that dilates in diameter (creep-strains) when subjected to higher stress during hydrotest. This means that for a fixed volume of clean fill water, the hydrostatic pressure will decline slightly during the first 30 minutes, as the PE molecular chains stretch and align under high stress. During the test period, water is added to keep the pressure constant since the thermoplastic pipe will expand with pressure. Normally, if the pressure remains within 5% of the target value for 90 minutes, the leakage test passes.

Concluding Remarks

Based on decades of experience with direct-buried heating hot water systems, the author has found that piping materials that will not corrode and that prevent joint leakage will typically provide reliable service for close to 50 years. PEX has been slowly growing in popularity primarily due to high copper prices and increasing popularity of lower temperature underground heating hot water systems. It is flexible and therefore requires fewer fittings and allows for longer continuous pipe runs. PEX has an overall good track record and is cheaper, easier and faster to install than steel and copper. It also is much more resistant to mineral build-up (scale formation) than steel and copper.

PEX is another pipe material the design engineer should be familiar with when evaluating direct-buried piping systems. An understanding of PEX material characteristics is an inherent part of the design process for applying this material to underground piping systems. With such an understanding, the piping designer can use the properties of the material to design for optimum performance for the intended service.

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