Introduction

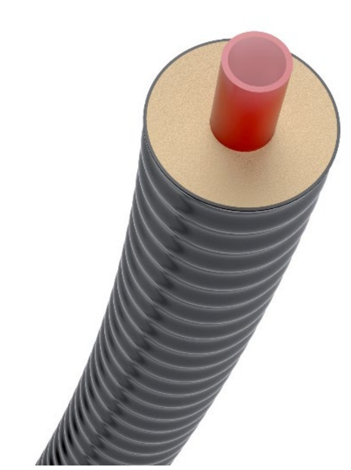
Numerous different pipe systems are used in local and district heating. As well as conventional insulated steel pipes, in recent years many manufacturers have brought insulated plastic pipes to the market. The following summary describes the extensive historical development of the insulation and the propellants that are used. This account is intended to explain the background for the latest generation of physical propellants, hydrofluoroolefins (HFOs), as well as helping to categorise this substance class.

1. Main types of insulated pipes for local and district heating

The insulated pipes needed for transporting hot water can be divided into two broad categories: rigid and flexible pipe systems. Both have their advantages and disadvantages, and the decision about which pipe system should be used in each individual case depends on the specific technical requirements.

Rigid pipe systems (plastic sheath pipes, PSPs) consist of steel carrier pipes, thermal insulation (insulating material) and an outer casing made of polyethylene (PE), which protects the insulation. These pipe systems are designed to withstand high temperatures and operating pressures and are used as main lines in larger district heating networks. These pipes are delivered in rods and the carrier pipes must be welded on site. The connection points must be insulated with sleeves and foam. The underlying standard is EN 253.

Flexible pipe systems usually consist of polymer carrier pipes, thermal insulation and an outer casing made of PE (polymer carrier pipe, PCP). The maximum operating temperatures and operating pressures are lower than with PSPs. However, they have the advantage that long lengths can be laid in one piece, because this type of pipe is produced in a coil and can be delivered like this to the construction site; lengths of several hundred metres are common. This considerably reduces the amount of connection work involved. The underlying standard is EN 15632.



CALPEX PUR-KING

Flexible pipe system

PREMANT

Rigid pipe system

Thermoplastic and thermosetting insulating materials

In terms of flexible pipe systems with plastic carrier pipes, there are currently two systems on the market: those which use a PE foam as an insulating material, and those which feature a chemically cross-linked insulating material, i.e. a thermoset (PUR/PIR).

PE insulating materials are normally prefabricated and are placed around the carrier pipes as part of the process of manufacturing the insulated pipes. PE foams have relatively coarse pores, while their cells are comparatively large. In addition, the density of PE foams is relatively low, which means that the insulating material only offers limited resistance against gas diffusion, and so the cell gases can easily reach a state of equilibrium with the surrounding air. This means that both nitrogen and oxygen can be found in the cells. It is therefore not possible to change the cell gas composition in a targeted way in order to reduce the thermal conductivity. An additional characteristic of PE foams is the fact that they do not adhere to the carrier pipes by themselves. As a result, there is no force-locking bond (non-bonded system EN 15632-3).

Thermosetting insulating materials are usually polyurethane (PUR) or polyisocyanurate (PIR) foams. The foams are produced from a two-component mixture (2K) during the process of manufacturing the insulated pipe. These insulating materials are therefore not prefabricated, but are created through a chemical reaction during the production process. During the formation of the foam, the carrier pipes are wetted very effectively by it, resulting in a firm adhesion and a force-locking bond. These insulating materials have a closed-cell structure and also have a higher density than PE foams. The type and quantity of the cell gases can be manipulated in a strategic way during the production process. The diffusion of air gases into the pores of the foam happens very slowly, which means that the thermal insulation can be improved considerably via the cell gas composition.

Thermosetting PUR and PIR systems

Both PUR and PIR-based foams are formed when polyols and isocyanates react with one another. These are generic terms: in practice, many different polyols and isocyanates are offered by different suppliers. This results in a variety of foams with different properties, depending on the basic materials and the proportions they are used in.

For a deeper understanding, the following chemical equations are important:

a) Polyol + isocyanate → polyurethane
b) Polyol + isocyanate (excess) → polyisocyanurate
c) Water + isocyanate → carbon dioxide (CO_2)

More PUR or more PIR will be formed depending on the quantity of isocyanate used. For PIR systems, relatively more isocyanate is needed (in addition to other reaction control measures). The advantage of PIR systems is their greater resistance to temperature and their lower combustibility. However, manufacturing them in a continuous process comes with significant challenges.

Functional principle of a chemical propellant

In the polyols that are used, there is always a small quantity of water, meaning that when the PUR or PIR foam is formed, CO_2 will also always be produced (see chemical equation above). During the chemical reaction, the molecular network of the polyurethane or polyisocyanurate also forms at the same time, and the further this reaction progresses, the more rigid the foam becomes. Because of its nature as a gas, the CO_2 that is produced tries to escape. As a result, the compound, which has not yet solidified, inflates, forming the foam.

For this type of foam formation, which is caused by the CO_2 produced during the reaction, we can use the term ‘chemical propellant’. The term ‘water-blown system’ is often used as well because the presence of water in the polyol is the determining factor in the production of CO_2.

Functional principle of a physical propellant

It is possible to further advance the foaming process with physical propellants, improving the end properties of the foam at the same time. A physical propellant is normally a liquid at room temperature. It is mixed with the foam-producing components. During the chemical reaction, heat is released. Because the physical propellant has a low boiling point, this causes it to evaporate and turn into a gas. This means that the reacting compound, which has not yet completely solidified, inflates and becomes a foam.

The product at the end of the production process is the finished foam. This is made up of many small pores, also called cells. The structure is formed by the polymer matrix. The cells contain cell gases. These partly consist of the physical propellants which are now trapped in the cells. As well as this, however, the cells also contain CO_2, which is always produced to a greater or lesser extent, as well as a small amount of the gases that make up the majority of the surrounding air: nitrogen and oxygen.

Types of physical propellants

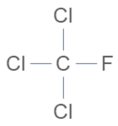
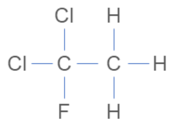
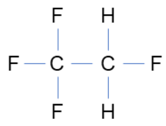
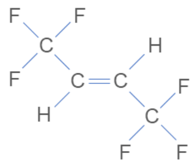
The main physical propellants for insulation foams are halogenated hydrocarbons/halocarbons or simple low-molecular-weight hydrocarbons.

Halogenated hydrocarbons/halocarbons

Following the invention of CFC-11 by American chemical engineer Thomas Midgley, halogenated hydrocarbons/halocarbons were first used as refrigerating agents in fridges from the 1930s onwards [1]. Their useful properties quickly made CFCs indispensable for a huge range of technical applications. From the 60s onwards, CFC-11 was also used to produce PUR foams [2].

A typical example of this class of substances, CFC-11, also known as Freon-11, has the formula shown in Table 1. Chlorofluorocarbons are distinguished by the fact that they consist only of chlorine (Cl), fluorine (F) and carbon (C) and only have single bonds. This is why they are known by the abbreviation CFC.

In response to a publication in 1974, the scientific community began to address the dangers that CFCs – which had been used extensively up to that point – posed to the ozone layer of the stratosphere [5]. This resulted in a reassessment of this class of substances. With the 1987 Montreal Protocol, an agreement was made on phasing out their use [6]. Subsequently, many replacement products were developed and marketed as alternatives.

Substanz-klasse	***C**F**C*** *Chlor Fluor Kohlenstoff*	***HCFC*** *Hydro Chlor Fluor Kohlenstoff*	***HFC*** *Hydro Fluor Kohlenstoff*	***HFO*** *Hydro Fluor Olefin*
Typischer Vertreter	CFC-11	HCFC-141b	HFC-245fa	HFO-1336mzz
Struktur-Formel				
ODP	1 [3]	0.11 [3]	0 [3]	2 [4]
GWP	3800 [3]	600 [3]	1430 [3]	8.9 [4]
Lebensdauer an der Atmosphäre	45 Jahre [9]	9.2 Jahre [15]	7.4 Jahre [8]	22 Tage [4]

Substanzklasse	Substance class
Typischer Vertreter	Typical example
Strukturformel	Structural formula
ODP	ODP
GWP	GWP
Lebensdauer an der Atmosphäre	Atmospheric lifetime
CFC Chlor Fluor Kohlenstoff	CFC Chloro Fluoro Carbon
HCFC Hydro Chlor Fluor Kohlenstoff	HCFC Hydro Chloro Fluoro Carbon
HFC Hydro Fluor Kohlenstoff	HFC Hydro Fluoro Carbon
HFO Hydro Fluor Olefin	HFO Hydro Fluoro Olefin
45 Jahre	45 years
9.2 Jahre	9.2 years
7.4 Jahre	7.4 years
22 Tage	22 days

Table 1: *Typical examples of halogenated hydrocarbons/halocarbons that were used as propellants.*

The ability of a substance to damage the ozone layer under the influence of UV light is known as Ozone Depletion Potential (ODP). This is a relative value based on CFC-11, which has been given a fixed ODP of 1. The goal of technical development was now to find propellants with an ODP significantly lower than that of CFCs.

Hydrochlorofluorocarbons (HCFCs) were the first major advance with regard to ODP and demonstrated values that were significantly lower than 1. HCFC-141b, shown here, has a value of 0.11 [3]. HCFCs consist of hydrogen, chlorine, fluorine and carbon and only have single bonds.

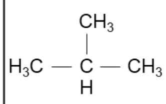
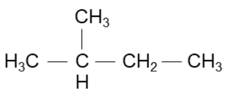
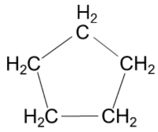
Development continued with hydrofluorocarbons (HFCs) which consist solely of hydrogen, fluorine and carbon and also only have single bonds. Their ODP is actually zero, providing a permanent solution to this particular environmental problem.

However, the substance classes described up to this point (CFCs, HCFCs, HFCs) all have another disadvantage: their effects as greenhouse gases. This value is usually denoted with the abbreviation GWP (global warming potential) [7], and is measured relative to CO_2 (GWP = 1). For all halogenated hydrocarbons/halocarbons, the GWP is far higher than that of CO_2. The factor known as atmospheric lifetime is a good indicator of the efficacy of a substance as a greenhouse gas. The lifetime of a substance in the atmosphere is the time that must pass before the substance will degrade naturally. For the substance classes under discussion, which only have single bonds, the typical time frames range from years to decades.

Hydrofluoroolefins (HFOs) are the most recent development. These now contain at least one double bond in each molecule, as suggested by the term 'olefin'. In the structural formula, the double bond is shown by the double lines between the two carbon atoms in the middle. They also contain hydrogen, fluorine and carbon as a minimum. This double bond is highly significant from a chemical perspective. It is at this point that the degradation of the molecule in the atmosphere begins, caused by exposure to UV light. Furthermore, water and oxygen cause further damage to this double bond, meaning that the lifetime of these substances in such conditions (UV light, moisture) is reduced to a few days. This means that they cannot be carried to the upper layers of the atmosphere, and so the global warming potential of HFOs falls to zero.

Simple hydrocarbons

A direct consequence of the findings regarding the damage to the ozone layer was the use of low-molecular-weight hydrocarbons (HCs) as propellants from the 1980s onwards [8]. These contain only carbon and hydrogen and are therefore free from halogen. The technical advantages of these substances for foam production were already well known, but for a long time their high combustibility prevented their technical use in this industry. However, this changed very quickly with the development of systems which allowed polyols and isocyanates to be safely processed in the presence of HCs. Table 2 shows the possible candidates – their thermal conductivity values explain why cyclopentane has become established as the preferred physical propellant for PUR and PIR foams. Once the investments in systems technology and storage for the propellant have been taken care of, it serves as a cost-effective propellant with low thermal conductivity and almost no environmental impact.

Substanz	*Iso-Butan*	*Iso-Pentan*	*N-Pentan*	*Cyclopentan*
Struktur-Formel			$H_3C - CH_2 - CH_2 - CH_2 - CH_3$	
ODP	0 [10]	0 [10]	0 [10]	0 [10]
GWP	11 [10]	11 [10]	11 [10]	11 [10]
Lebensdauer an der Atmosphäre	Wenige Tage [10]	Wenige Tage [10]	Wenige Tage [10]	Wenige Tage [10]
*λ - Wert [W/m*K]*	0.016 @ 25 °C [10]	0.014 @ 25 °C [10]	0.015 @ 25 °C [10]	0.013 @ 25 °C [10]

Substanz	Substance
Strukturformel	Structural formula
ODP	ODP
GWP	GWP
Lebensdauer an der Atmosphäre	Atmospheric lifetime
λ - Wert [W/m*K]	λ value [W/m*K]
Iso-Butan	Isobutane
Iso-Pentan	Isopentane
N-Pentan	N-pentane
Cyclopentan	Cyclopentane
Wenige Tage	A few days

Table 2: *Typical examples of simple hydrocarbons that are used as propellants.*

<u>Comparison of physical propellants</u>

Although cyclopentane is still the standard propellant for pipes in district heating, Table 3 shows that HFOs are currently the best compromise in terms of availability, thermal conductivity, environmental impact and reliability.

While the extremely low λ value of CFC-11 is still unmatched, that of the HFO given as an example is significantly lower than that of CO_2 or even cyclopentane.

In terms of cost, water-blown systems would be the best option; however, the insulation values that can be achieved with these have not kept up with market requirements or energy-saving targets in recent years (see also the comparison in the next section).

Zellgas	*λ - Wert*	*ODP*	*GWP*	*Kosten*	*Sonstiges*
	*[W/m*K]*				
CFC11	0.008 @ 25 °C [13]	1 [3]	3800 [3]	Mittel	Nicht mehr zugelassen
HCFC-141b	0.010 @ 25 °C [12]	0.11 [3]	600 [3]	Mittel	Nicht mehr zugelassen
HFC-245fa	0.013 @ 25 °C [11]	0 [3]	1430 [3]	Mittel	Nicht mehr zugelassen
HFO-1336mzz	0.011 @ 25 °C [4]	0 [4]	2.0 [4]	Hoch	Seit Kurzem kommerziell verfügbar
Kohlendioxid (CO_2)	0.016 @ 25 °C [9]	0 [9]	1 [9]	0	Hohe Wärmeleitfähigkeit
Cyclopentan	0.013 @ 25 °C [10]	0 [10]	5 [10]	Niedrig	Brennbar
Stickstoff (N_2)	0.026 @ 20 °C [14]	-	-	-	Aus der Umgebungsluft

Zellgas	Cell gas
CFC11	CFC-11
HCFC-141b	HCFC-141b
HFC-245fa	HFC-245fa
HFO-1336mzz	HFO-1336mzz
Kohlendioxid	Carbon dioxide
Cyclopentan	Cyclopentane
Stickstoff	Nitrogen
λ - Wert	λ value
[W/m*K]	[W/m*K]
ODP	ODP
GWP	GWP
Kosten	Cost
Mittel	Medium
Hoch	High
Niedrig	Low
Sonstiges	Other
Nicht mehr zugelassen	No longer legal
Seit Kurzem kommerziell verfügbar	Recently made commercially available
Hohe Wärmeleitfähigkeit	High thermal conductivity
Brennbar	Combustible
Aus der Umgebungsluft	From ambient air

Table 3: *Comparison of the propellants and cell gases under discussion including their thermal conductivity.*

Technical requirements

The technical requirements for insulated flexible pipe systems are laid out in the EN 15632 family of standards. There are quantifiable minimum requirements that must be met for the properties of the carrier pipes, the outer casing and the insulation. With regard to the performance capability of the insulating material, however, only the underlying calculation methods are described, and no minimum requirements are set. For this reason, the following is intended as a short explanation of the insulating performance.

Thermal insulation

Thermal conductivity is the physical variable that describes the insulating effect of thermal insulation in a quantitative manner. It is represented by the Greek letter λ (lambda). This variable is measured with the unit W/m*K (Watts per metre-Kelvin). The lower this λ value, the worse the material is at conducting heat. Accordingly, the value for insulated pipes should be as low as possible.

The total thermal conductivity (λ_{tot}) is calculated from the sum of the individual components:

$$\lambda_{tot} = \lambda_{con} + \lambda_{solid} + \lambda_{rad} + \lambda_{gas} \; / \; [W/m^*K]$$

Whereby

λ_{con}: the contribution from convection

λ_{solid}: the thermal conductivity of the actual matrix, i.e. the solid material which surrounds the pores

λ_{rad}: radiation

λ_{gas}: the thermal conductivity of the cell gases

The convection contribution (λ_{con}) can be disregarded for foam materials because of their small pores.

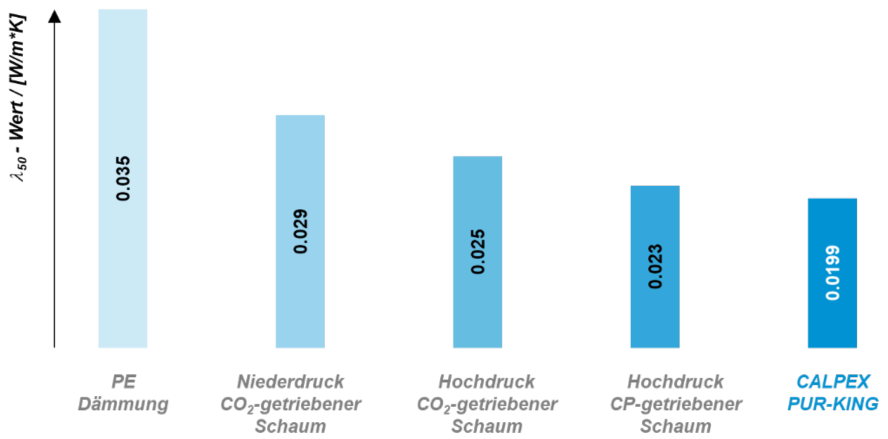
The contribution of the solid matrix (λ_{solid}) can be reduced for a given material by reducing the foam density. However, there are strict limits to this: the density cannot be reduced indefinitely due to considerations of the pipe’s overall stability.

The radiation contribution (λ_{rad}) can only be altered to a certain degree. This only applies at high temperatures. can

In practice, the thermal conductivity of the cell gases (λ_{gas}) and, hence, the propellants used are the most efficient means of reducing the λ_{tot}. There are considerable differences between the thermal conductivity values of the various cell gases. In the past, this was also the reason for the use of halogenated HCFCs and HFCs as physical propellants in PUR and PIR foams, until their use was limited or banned by statutory regulations.

U values for insulated pipes

U values and λ values are usually determined on the basis of a pipe with a nominal diameter of DN 50 because the measuring equipment is set up for this, and taking these measurements is rather complex. Together with the geometric parameters of the pipe, the thermal conductivity of the insulating material can be calculated. This thermal conductivity value is then used to calculate the U values of the other pipe diameters. Of course, this is only possible if they belong to the same product series: the insulating material must be exactly the same.



λ_{50} - Wert / [W/m*K]	λ_{50} value / [W/m*K]
PE Dämmung	PE insulation
Niederdruck CO_2-getriebener Schaum	Low-pressure CO_2-driven foam
Hochdruck CO_2-getriebener Schaum	High-pressure CO_2-driven foam
Hochdruck CP-getriebener Schaum	High-pressure CP-driven foam
CALPEX PUR-KING	CALPEX PUR-KING

Figure 2: *Comparison of the thermal conductivity of different insulating materials.*

Because the U values and the λ values depend on the temperature, the measuring temperature must be listed along with these values. In the construction industry, it is usual to refer to a temperature of 10 °C, while in district heating 50 °C is usual. As a general rule of thumb, raising the measuring temperature by 10 °C causes the λ value to increase by around 0.001 W/m*K.

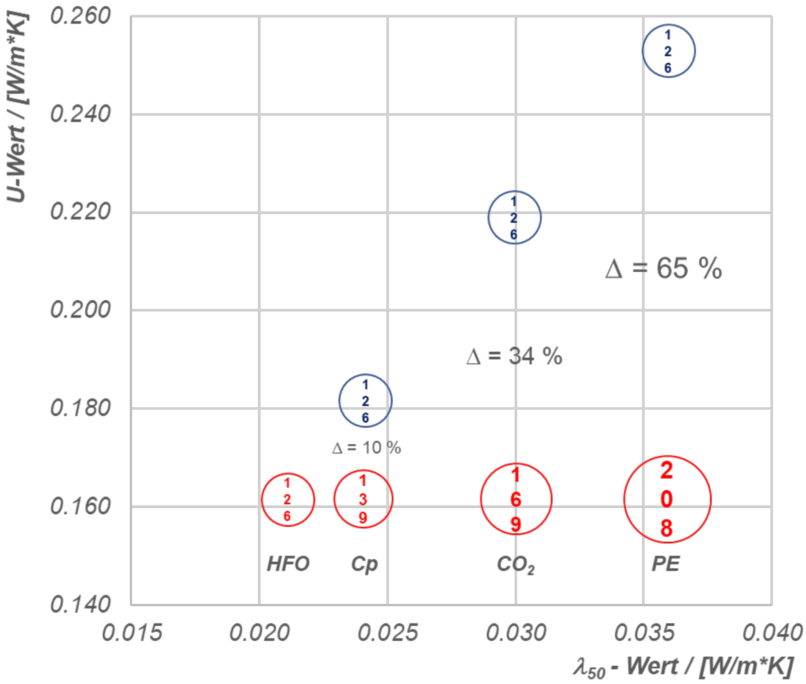
This is illustrated by the following example:

a) Smooth insulated pipe with a carrier pipe centrally aligned
b) Outer diameter of carrier pipe = 63 mm
c) Wall thickness of carrier pipe = 5.8 mm
d) Wall thickness of PE casing = 2.5 mm
e) Conductivity of carrier pipe = 0.38 W/m*K @ 50 °C
f) Conductivity of PE casing = 0.33 W/m*K @ 50 °C
g) Conductivity of PE insulation = 0.035 W/m*K @ 50 °C
h) Conductivity of CO_2-driven PUR foam (low-pressure) = 0.029 W/m*K @ 50 °C

i) Conductivity of CO_2-driven PUR foam (high-pressure) = 0.029 W/m*K @ 50 °C
j) Conductivity of cyclopentane (Cp)-driven PUR foam = 0.023 W/m*K @ 50 °C
k) Conductivity of HFO-driven PUR foam (PUR-KING) = 0.0199 W/m*K @ 50 °C

The thermal conductivity of the HFO-driven PUR foam was calculated as the mean of ten individual measurements carried out by an accredited body.

Figure 1 presents the U values that were calculated with this data. The blue elements show the U values for an outer diameter of 126 mm with the respective insulating material. It is now possible to achieve the same U value as that of the reference pipe, which has HFO PUR foam insulation, with any insulating material. However, this will only be successful if the outer diameter (i.e. the thickness of the insulating layer) is increased considerably. For example, the diameter of the PE-insulated pipe would have to be increased to 208 mm, i.e. by 65 %.



U-Wert / [W/m*K]	U value / [W/m*K]
HFO	HFO
Cp	Cp
PE	PE
λ_{50} - Wert / [W/m*K]	λ_{50} value / [W/m*K]

Figure 1: *U values for pipes with various insulating materials and the outer diameters that are needed to achieve the same U value with these pipes as with the reference pipe, which is insulated with HFO.*

One result of this measure is the increased quantity of materials needed to produce the pipes. A larger volume has to be filled with the insulating material, and more PE must be used for the outer casing.

A further detrimental effect of increasing the outer diameter is the shorter coil lengths. The length of the pipes can essentially be adapted to the customer's needs; however, as the outer diameter gets larger, there is also an increase in the feasible size of the winding radii. The resulting outer diameters of the pipe coils provide an ultimate limit, because only items with a diameter up to xx m can be transported in a lorry as standard.

With PUR, the most compact insulating material in the field of district warming, the longest delivery lengths can be achieved, meaning that transport costs can be considerably reduced (Table 4).

Ø dimension	***Coil length ****	***Bending radii***	***Weight***
[mm]	***[m]***	***[m]***	***[kg]***
76	1000	0.45	900
91	715	0.55	858
111	450	0.60	630
126	291	0.65	698
142	260	0.70	806
162	149	0.90	671
182	86	1.10	620
202	80	1.40	672

Table 4: *Feasible coil lengths and bending radii for flexible plastic pipes in relation to the outer diameter of the pipe. * Applies to outer coil diameters of 2.8 m.*

Longitudinally watertight pipes

Regarding flexible insulated pipe systems with plastic carrier pipes, standard EN 15632-1 makes a distinction between bonded pipes and non-bonded pipes.

In bonded pipes, the insulating material forms a force-locking bond with the carrier pipes and the outer casing. When these insulated pipes are produced, the insulating material is formed from a 2K mixture and adheres to the carrier pipes. The connection to the outer casing is formed when the film that carries the 2K mixture fuses with the outer casing as soon as the casing is extruded on. This type of insulated pipe is usually longitudinally watertight in accordance with EN 15632-2, section 6.4. The strength of the force-locking bond itself is also specified here in the form of a minimum value for the axial shear strength.

With non-bonded pipes, the insulation is generally only coiled around the inner pipe. There is no force-locking bond. This means that it is very difficult to achieve longitudinally watertight pipes, while axial shear strength is not required. In order to prevent any moisture that has penetrated the pipe from spreading throughout the entire pipe system, the sleeve area must be fitted with special components which will stop the moisture from proceeding past this point.

A further disadvantage of non-bonded pipes is the fact that the carrier pipes can move more or less freely, and can therefore fall out.

Summary

As far as technical performance is concerned, insulating materials based on PUR foams are currently the best solution for local and district heating. Using the latest technologies means that low thermal conductivity values can be achieved. This results in low U values with small outer diameters. Smaller outer diameters mean less space is required. This makes it easier to lay pipes in trenches, for one thing. It also means that coiled pipes can be longer so that a greater length of pipe can be transported per volume unit, reducing logistics costs.

Furthermore, the production process with a reactive 2K system guarantees that the foam will form a strong bond with the inner pipes. The use of propellants from the HFO class of substances is the latest advance, and means that the U values can be reduced even further while maintaining the same outer diameters.

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