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Change of thermal conductivity of polyurethane pre-insulated pipes as a function of time

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Summary

The increase of thermal conductivity was determined on pre-insulated district heating pipe composites which were exposed to an accelerated ageing. Two types of rigid polyurethane foams were used: a fully water blown and a cyclopentane blown foam system. The experimental results show that the thermal conductivity increase depends on the pipe ageing conditions. The results can be useful to check various models for the prediction of the thermal conductivity increase of pre-insulated pipes as a function of time.

Zusammenfassung des Berichts:

Veränderung der Wärmeleitfähigkeit als Funktion der Zeit und verschiedener Alterungsbedingungen bei Polyurethan vorgedämmten Rohren

Eine Vielzahl von Gründen sprechen für den Einsatz von Polyurethan-Hartschäumen bei vorisolierten Kunststoff-Mantelrohren im Fernwärmebereich, z.B. die ausgezeichnete mechanische Festigkeit, die hohe thermische Belastbarkeit, die geringe Wasseraufnahme sowie die vorzügliche Dämmeigenschaft. Allerdings verschlechtern sich die Dämmeigenschaften im Laufe der Zeit durch Gasdiffusionsprozesse und dadurch kann die Wirtschaftlichkeit eines Fernwärmenetzes beeinträchtigt werden. Daher ist es von allgemeinem Interesse, die Grössenordnung der Abnahme der Dämmeigenschaften, in anderen Worten, die Zunahme der Wärmeleitfähigkeit von Polyurethan-Schäumen in Fernwärmerohren zu untersuchen.

In einem Forschungsprogramm wurde die Zunahme der Wärmeleitfähigkeit von vorgedämmten DN50 Kunststoff-Mantelrohren bestimmt, die unter drei verschiedenen Bedingungen gealtert wurden. Dabei wurden zwei Schaumtypen untersucht: ein wasser-getriebenes System sowie ein cyclopentan-getriebenes System. Der Einfluss des Kunststoffmantels als Diffusionssperre wurde ebenfalls untersucht, indem die Änderung der Wärmeleitfähigkeit an Rohren mit und ohne HDPE-Mantelrohr gemessen wurde.

Die Zunahme der Wärmeleitfähigkeit wurde bei folgenden Bedingungen ermittelt: homogene Temperaturbelastung von 50°C Innen- und Aussentemperatur sowie 70°C Innen-und Aussentemperatur, und inhomogene Temperaturbelastung von 175°C Innen- und 25°C Aussentemperatur. Folgende Schlussfolgerungen können gezogen werden:

- **das HDPE Mantelrohr ist eine sehr wirksame Diffusionbarriere für Kohlendioxid, das durch Reaktion aus Isozyanat mit Wasser entsteht. Die Zunahme der Wärmeleitfähigkeit ist bei wasser-getriebenen Systemen in Gegenwart eines ca. 3 mm dicken HDPE-Mantels erheblich verzögert.**

- **bei cyclopentan-getriebenen Schaumsystemen ist das HDPE-Mantelrohr für den Erhalt der Dämmeigenschaften weit weniger wichtig. Im Vergleich zu Kohlendioxid und Luft diffundiert Cyclopentan sehr langsam durch den Schaum, so dass der Schaum selbst als Diffusionsbarriere angesehen werden kann.**

- **die anfängliche Wärmeleitfähigkeit eines wasser-getriebenen Schaumes erhöht sich um ca. 10 mW/m.K aufgrund von Gasdiffusion, d.h. Ersatz von Kohlendioxid durch Luft, das als Zellgas schlechtere Dämmeigenschaften aufweist als Kohlendioxid. Bei cyclopentan-getriebenen Systemen erhöht sich die anfängliche Wärmeleitfähigkeit um 4-5 mW/m.K.**

- **je höher die Alterungs-Temperatur, desto schneller erfolgt der Anstieg der Wärmeleitfähigkeit.**

- **Gasdiffusionsprozesse in vorgedämmten Rohren laufen rascher ab bei einer homogenen Alterung, d.h. wenn Innen- und Aussentemperaturbelastung gleich sind, als bei einer inhomogenen Alterung, d.h. wenn die Aussentemperatur ist deutlich niedriger ist als die Rohr-Innentemperatur.**

Im Vergleich zu der beschriebenen forcierten Alterung im Experiment ist die Gasdiffusion in der Praxis bei erdverlegten Rohren erheblich reduziert. Folglich ist auch die Zunahme der Wärmeleitfähigkeit deutlich langsamer.

- **Erde selbst fungiert als Dämmmaterial und reduziert die Gasdiffusion. Ausserdem ist die Konzentration von Luft, die in die Zellen diffundieren kann, in der Erde deutlich geringer.**

- **in diesem Forschungsprojekt wurden DN50-Rohre verwendet. Bei einem grösseren Rohrdurchmesser kann man davon ausgehen, dass die Diffusionsvorgänge verlangsamt ablaufen, da sowohl das Mantelrohr als auch die Dämmschicht dicker sind.**

- **da es sich hier um eine forcierte Alterung handelt, sind die im Experiment verwendeten Alterungstemperaturen deutlich höher als die Bedingungen in der Praxis.**

Bei der Abnahme der Langzeitdämmfähigkeit von erdverlegten Fernwärmerohren handelt es sich um einen sehr langsamen Prozess. Die hier beschriebenen Ergebnisse können von Nutzen sein, verschiedene mathematische Modelle zu testen, um eine durch Diffusionsprozesse bedingte Verschlechterung der Dämmeigenschaften von Polyurethan-Hartschäumen in Kunststoff-Mantelrohren abzuschätzen.

Introduction

There are a number of reasons why rigid polyurethane foam is used as insulation material in the district heating area, e.g. the high mechanical strength, the high thermal resistance, the ability to fill narrow cavities, the low water absorption, the good adhesion to service and casing pipe and foremost, the excellent thermal insulation property.

The excellent insulation will efficiently minimise the heat loss during the transport of hot water or steam in pre-insulated pipes in a district heating network. The insulation performance however will deteriorate during the service life of a pipe, due to gas diffusion processes leading to changes in the cell gas composition. This is referred to as thermal conductivity ageing and results in an increased energy loss during transport of hot water which may reduce the profitability of a district heating network. Therefore, an assessment of the increase of the thermal conductivity as a function of time is of paramount importance for pipe producers and district heating network owners.

We have carried out thermal conductivity measurements on polyurethane pre-insulated DN50 pipes which were aged at three different temperatures. Two types of foam were evaluated, a fully water blown foam system and a water/cyclopentane dual blown system. The ageing was done on pipes with and without HDPE casing to evaluate the effect of the casing pipe as a diffusion barrier. The results obtained are described in the following. We believe that they are useful to validate mathematical models for the prediction of the thermal conductivity change of pre-insulated pipes over time.

Why is rigid polyurethane foam a good insulating material

Rigid polyurethane foam is a good insulator because it consists of 92 to 98% of closed cells which are filled with insulating gases. Only 8 to 2% of the foam is solid polyurethane polymer. The percentage of solid polymer is determined by the density of the foam: the higher the density of the foam, the higher the percentage of solid polymer. The closed cells are filled with several gases released by blowing agents during the manufacture of the polyurethane foam.

The cell gas composition can be influenced by using different blowing agents. This has a major impact on the thermal conductivity of the foam, as the composition of the gas determines more than 60% of the final thermal conductivity of the foam at the applied density. One can lower the thermal conductivity of the foam by choosing blowing agents that have lower vapour thermal conductivity, see also Table 1 which compares typical foam systems with different blowing agents used for pipe insulation. Table 2 lists the thermal conductivity of various gases [1].

Rigid Polyurethane foam is used in pipe insulation since it provides

excellent mechanical strength combined with

excellent thermal insulation properties

Thermal conductivity ageing of polyurethane foam

A fresh foam is characterised by a certain insulation value: the initial thermal conductivity value. According to the EN 253 norm for polyurethane pre-insulated pipes, the thermal conductivity should be maximum 33.0 mW/m.K at 50°C [2]. However, this initial value will not be maintained over time because gases are able to migrate into or out of the foam. This causes changes in the cell gas composition and hence in the insulation value of the foam. The result is a gradually increasing thermal conductivity value of the foam.

Each gas has its own diffusion rate through polyurethane foam:

- **In the short term, carbon dioxide will diffuse out of the foam and will be replaced by air. An effect on the thermal conductivity can be seen because air is characterised by a higher thermal conductivity compared to carbon dioxide. A net increase of the thermal conductivity of the foam system will occur.**

- **In the long term, the physical blowing agent will again escape out of the cells. However, in general the physical blowing agents are considered to be permanent gases and have very low diffusion speeds. Due to their long term presence in the cells, though the concentration will drop, the thermal conductivity of foams expanded by physical blowing agents will increase at a much slower rate.**

The gas diffusion phenomena occurs until the gases partial pressures inside and outside the foam are equal. The processes are accelerated by higher temperatures and are decelerated when making use of diffusion barriers that are impermeable or semi-permeable for gases.

There is limited experimental data available concerning gas diffusion processes in district heating pipe composites and thus the thermal conductivity ageing of district heating pipes.

This prompted us to initiate a research project where pipe samples were subjected to accelerated ageing. Pipe segments with fully water blown and water/cyclopentane dual blown foams were homogeneously aged in ovens at 50°C and 70°C, and in-homogeneously on a pipe rack with an outside temperature of 25°C and an inside temperature of 175°C, i.e. by circulation of steam in the service pipe. To quantify the effect of the HDPE casing, the ageing was carried out with and without casing and the thermal conductivity change was recorded as a function of time. The density of the polyurethane foam was ca. 85 kg/cm^3.

The thermal conductivity of DN50 pipe composites was measured at an average temperature of 50°C with a so-called Kapapipe, designed and made by A.L.B. Instrumentation, St.-Ismier, France. One metre long DN50 pre-insulated pipe segments were used to record the thermal flux in the middle 35cm of the pipe, after a stable temperature gradient between inner and outer pipe was established, i.e. 80°C inside and 20°C outside. This temperature gradient causes a heat flow from the higher temperature to the lower temperature. This heat flow is proportional to the insulating performance of the pipe as well as to the magnitude of the temperature gradient. The thermal conductivity of the pipe can be calculated if the energy needed to maintain the inner steel pipe at the higher temperature and the temperature of inner and outer pipe are known:

$$\lambda = \frac{\phi \ln (D_2/D_0)}{2\pi L(T_0 - T_2)}$$

with:
- **ϕ the power needed to maintain the temperature of the steel pipe**
- **D_2 and D_0 respectively the inner and outer diameter of the pipe**
- **T_2 and T_0 respectively the temperatures of inner and outer pipe**
- **L the length of the pipe segment**

The equipment was calibrated by means of a DN50 pipe filled with expanded polystyrene, for which the thermal conductivity value was determined at different temperatures by the Department of Building Physics at the University of Chalmers, Gothenburg in Sweden.

Experimental results and conclusions

The results of our thermal conductivity measurements on polyurethane pre-insulated pipes subjected to homogeneous ageing at 50°C and 70°C and in-homogeneous ageing at 25°C outside temperature and 175°C inside temperature are shown in Tables 3-5 and Figures 1-3. The following general conclusions can be drawn:

- **the HDPE casing is a very efficient diffusion barrier for air and carbon dioxide: the thermal conductivity ageing rate of water blown pipes stored at 70°C is significantly lower when a 3mm thick HDPE casing is present. The HDPE casing is therefore crucial for maintaining the insulating performance of a pipe with a water blown foam.**

- **the HDPE casing is less important for the cyclopentane blown foams: the physical blowing agent migrates extremely slowly through the foam, compared to air and carbon dioxide. Hence, the foam itself can be regarded as a diffusion barrier. The thermal conductivity ageing rate is only marginally lower when a 3mm thick casing is applied.**

- **the initial thermal conductivity value of a water blown pipe will increase by approximately 10 mW/m.K due to diffusion. For the physical blown pipes this increase is 4 to 5 mW/m.K.**

- **the higher the temperature, the faster the thermal conductivity ageing.**

- **the diffusion processes in pipes exposed to in-homogeneous ageing are slower compared to the pipes which were homogeneously aged in an oven.**

Our experimental results are similar to accelerated pipe ageing results obtained at DTI, Denmark [3]. However, it should also be noted that these measurements, both from DTI and ourselves, reflect a higher thermal conductivity ageing rate than is encountered in reality:

- **the fact that polyurethane pre-insulated pipes are buried in the ground considerably reduces the speed of the diffusion processes as the soil acts as an insulation layer but also as the presence of air is limited.**

- **for the research project DN50 pipes were used. For bigger diameter pipes, the diffusion will be decelerated as there is usually a thicker HDPE casing and a thicker foam layer present.**

- **the ageing conditions as applied in the research project are much more severe than in reality, i.e. a higher temperature gradient was used.**

This is also confirmed by measurements carried out on a pre-insulated pipe with a water blown foam which was buried in the ground. The temperature of the transported water was 50-60°C during summer and 80-90°C during winter. The thermal conductivity value after 8 years service increased only slightly by 2.3 mW/m.K, from 31.6 mW/m.K to 33.9 mW/m.K which is an increase of 7% [4].

In reality, the thermal conductivity ageing is a very slow process which takes years. Therefore it is interesting to predict the ageing profiles with computer models. We believe that this experimental data for the thermal conductivity change as a function of ageing temperature and time can be of value to assess various mathematical models for the prediction of the thermal conductivity change over time in pre-insulated pipes.

HDPE is a very efficient diffusion barrier for air and carbon dioxide

Blowing agent	Average initial thermal conductivity of DN50 pipe composites at 50°C (mW/m.K)
Water blown	31
Cyclopentane/water dual blown	28
HCFC-141b/water dual blown	28

Table 1: Typical thermal conductivity of pipe insulation foam systems

Tabelle 1: Typische Wärmeleitfähigkeit von Hartschaumsystemen eingesetzt im Fernwärmebereich

Gas	Gas thermal conductivity at 25°C (mW/m.K)
Air	25.9
Carbon dioxide	16.2
Cyclopentane	13.0
HCFC-141b	10.0

Table 2: Thermal conductivity of typical cell gases at 25°C

Tabelle 2: Wärmeleitfähigkeit typischer Zellgase bei 25°C

Ageing time at 50°C (days)	water blown, no HDPE casing (mW/m.K)	water blown (mW/m.K)	c-pentane blown, no HDPE casing (mW/m.K)	c-pentane blown (mW/m.K)
0	29.3	29.1	28.0	27.1
40	31.0	29.8	29.5	27.8
83	32.2	30.3	29.6	28.1
114	33.7	31.1	30.7	29.0
151	36.3	31.8	30.1	28.1
201	37.1	32.5	31.4	28.4
270	39.4	33.9	–	29.3

Table 3: λ-increase for DN50 pipe composites homogeneously aged at 50°C

Tabelle 3: λ-Zunahme bei DN50-Rohren gealtert bei 50°C Innen- und Aussentemperatur

Ageing time at 70°C (days)	water blown, no HDPE casing (mW/m.K)	water blown (mW/m.K)	c-pentane blown, no HDPE casing (mW/m.K)	c-pentane blown (mW/m.K)
0	30.0	30.8	29.0	28.2
1	30.4	–	–	–
9	31.3	–	–	–
15	33.1	–	29.0	–
22	34.2	–	–	–
30	35.4	31.4	–	29.1
37	–	–	30.1	–
54	37.9	–	30.6	–
60	38.3	32.1	–	28.7
68	–	–	30.2	–
70	38.5	–	–	–
84	39.1	–	–	–
94	–	–	31.7	–
110	40.2	–	–	–
150	–	35.5	–	29.9
154	–	–	32.3	–
170	40.4	–	–	–
210	–	36.4	33.4	29.7
260	41.8	38.4	33.7	31.1
297	–	37.3	34.6	31.3
330	–	37.2	33.2	31.4
350	40.5	–	–	–
365	–	38.2	33.7	31.2
421	–	38.4	33.2	31.8
455	41.8	–	–	–
526	–	39.9	39.9	32.8

Table 4: λ-increase for DN50 pipe composites homogeneously aged at 70°C

Tabelle 4: λ-Zunahme bei DN50-Rohren gealtert bei 70°C Innen- und Aussentemperatur

The λ-ageing rate of **cyclopentane blown foams** is considerably slower compared to

water blown foams

Table 5: λ-increase for DN50 pipe composites homogeneously aged at an outside temperature of 25°C and inside temperature of 175°C

Tabelle 5: λ-Zunahme bei DN50-Rohren gealtert bei 25°C Aussen- und 175°C Innentemperatur

Ageing time at 25°C/175°C (days)	**water blown, no HDPE casing** (mW/m.K)	**water blown** (mW/m.K)	**c-pentane blown, no HDPE casing** (mW/m.K)	**c-pentane blown** (mW/m.K)
0	29.7	29.6	28.2	27.7
35	37.2	30.7	29.1	29.0
64	–	–	30.0	–
67	38.4	31.5	–	29.0
97	40.3	31.4	–	29.5
114	–	–	30.4	–
147	39.9	33.0	–	29.7
200	–	–	33.0	–
230	40.6	37.7	–	31.0
305	–	–	34.7	–
335	40.9	39.0	–	32.3

Figure 1

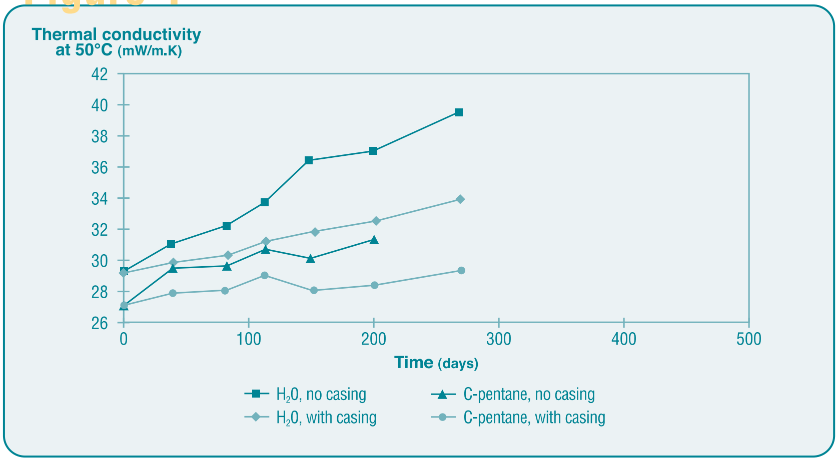

Figure 1: λ-increase for DN50 pipe composites homogeneously aged at 50°C

Bild 1: λ-Zunahme bei DN50-Rohren gealtert bei 50°C Innen- und Aussentemperatur

Figure 2

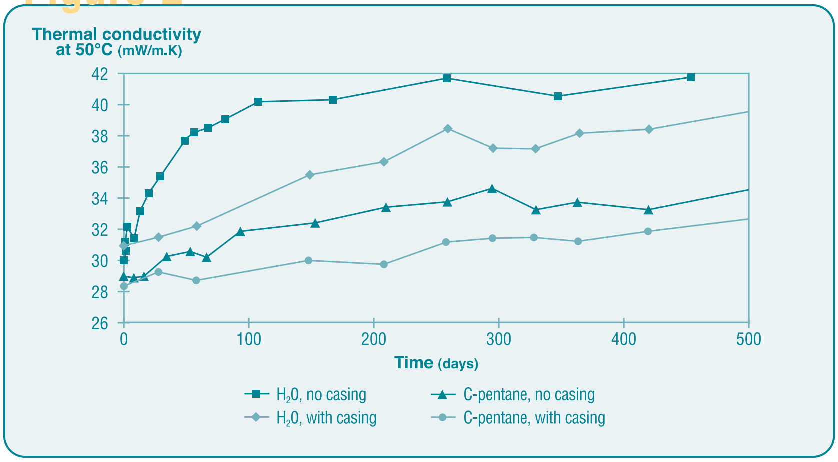

Figure 2: λ-increase for DN50 pipe composites homogeneously aged at 70°C

Bild 2: λ-Zunahme bei DN50-Rohren gealtert bei 70°C Innen- und Aussentemperatur

Figure 3

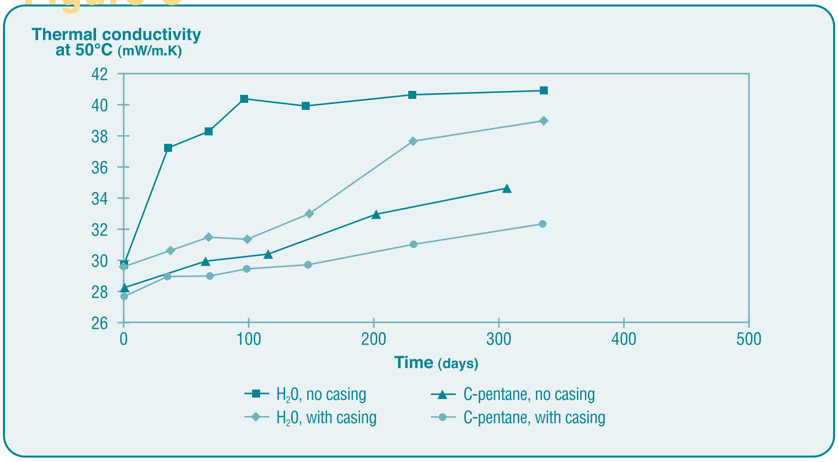

Figure 3: λ-increase for DN50 pipe composites homogeneously aged at an outside temperature of 25°C and inside temperature of 175°C

Bild 3: λ-Zunahme bei DN50-Rohren gealtert bei 25°C Aussen- und 175°C Innentemperatur

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Biographies

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Dr. Jürgen Kellner, Shell Research and Technology Centre, Louvain-la-Neuve in Belgium, responsible for the applicational research, development activities and technical service in rigid polyurethane foam insulated pipes. The author joined Huntsman Polyurethanes in 1999 following a strategic alliance in the area of rigid polyurethane between Shell Chemicals and Huntsman Polyurethanes.

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The information, technical data and recommendations in this paper are, to the best of our knowledge, reliable. Tests performed and referred to in the paper do not necessarily represent all possible uses or actual performance as this is very much dependent on the particular circumstances the product or foam is used in. Suggestions made concerning the products and their uses, applications, storage and handling are only the opinion of the Huntsman Polyurethanes group and users should make their own tests to determine the suitability of these products for their own particular purpose. Huntsman Polyurethanes makes no guarantee or warranty of any kind, whether express or implied, other than that the product conforms to its applicable Standard Specifications. Statements made herein, therefore, should not be construed as representations or warranties.

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