Lambda-value aging

The λ-value of PU foam increases with time because blowing agents diffuse out and air diffuses in. The carbon dioxide diffusion rate through the foam is high, intermediate for air, and low for physical blowing agents.

The differences in partial pressures of the gases in the cells and the environment drive the diffusion processes. This process continues until the partial pressures of the gases in the cells and the environment are equal. Carbon dioxide escapes completely as its partial pressure in air is close to zero. Air migrates into the cell until its partial pressure reaches 1 bar. The physical blowing agent has a very low diffusion coefficient; it diffuses out, but the process may take decades [4].

Let us consider the aging characteristics of a PU foam produced from a recipe containing 1.5 p.b.w. of water and 14 p.b.w. of n-pentane on 100 p.b.w. of polyol. This yields a foam with a density of 35 kg/m^3 and an initial cell gas composition of 30:70 molar ratio of carbon dioxide and n-pentane. At the end of the rise, the foam temperature and the cell gas pressure were measured to be 160 °C and 1.2 bar. Using the ideal gas law and assuming that the cell volume remains constant upon cooling yields a cell gas pressure at 20 °C of 0.81 bar. Multiplying the molar ratio of the two gases yields their partial pressures: 0.24 bar for carbon dioxide and 0.57 bar for n-pentane.

The diffusion processes in a foam are complex and involve multiple factors. A simplified model consisting of a single isolated PU foam cell surrounded by air (N_2) was used for the calculations to demonstrate the basic principles of foam aging [5]. The advantage of this model is that the diffusion processes only depend on the partial pressure differences between the gases in the cell and the environment. The calculations used the gas diffusion coefficients from reference [5], which were normalized to 1 for air to demonstrate the relative differences [Tab. 7.5].

Tab. 7.5: Gas diffusion coefficients for PU polymer at 20 °C.

Gas	Diffusion coefficient (m^2/s)	Diffusion coefficient (normalized)
Air (N_2)	$4.66 \cdot 10^{-12}$	1
Carbon dioxide (CO_2)	$1.20 \cdot 10^{-10}$	25.75
n-Pentane	$3.17 \cdot 10^{-14}$	0.0068

The time axis in the model is dimensionless, but the calculated pressures are real. The calculation results are given in Fig. 7.9. The effusion of carbon dioxide occurs fast. Because air diffuses in at a slower rate, a minimum in the total cell gas pressure is reached after a relatively short time. As more air diffuses in, the total pressure increases and, over time, reaches a plateau value of approximately 1.5 bar. The partial pressure of n-pentane does not decrease significantly over the given time interval. Therefore, the gas pressure increment is the direct consequence of air ingress.

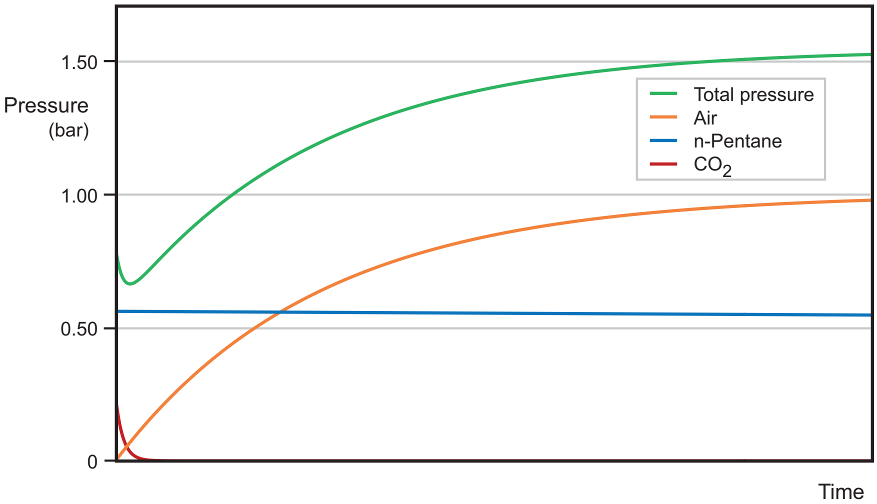

Fig. 7.9: Partial cell gas pressures of carbon dioxide, air (N_2), and n-pentane and the total gas pressure with time of the example pentane-water blown rigid PU foam.

The compression hardness of rigid PU foams is measured on 50 mm cubes cut from a larger block. The compression hardness of (partially) water-blown foams shows a minimum after approximately 10 days. This minimum results from the minimum in gas pressure of the foam.

Fig. 7.10 illustrates the corresponding development of the λ-value with time based on the calculated cell gas compositions shown in Fig. 7.9. The combined contribution of solid conduction and radiation was taken as 6.5 mW/(m·K), whereas the gas contribution was calculated using simple molar proportions. The thermal conductivity curve follows essentially the air ingression curve of Fig. 7.9 and reaches a plateau value. The predicted initial and final λ-value were 20.7 and 27.2 mW/(m·K), incrementing 6.5 mW/(m·K).

Given sufficient time, PU foams not protected by facers typically exhibit an increase in thermal conductivity between 4 and 7 mW/(m·K). In practice, however, foams for insulation applications are sandwiched on both sides by substrates, which will retard the aging process. Impermeable facings can effectively prevent aging during the panel's service life.

7.4.3 Dimensional stability

The foam's dimensional stability over a wide range of temperatures is relevant for many applications, such as in the construction industry, where the operating temperature for PU rigid foams can range from well below 0 °C to above 80 °C.

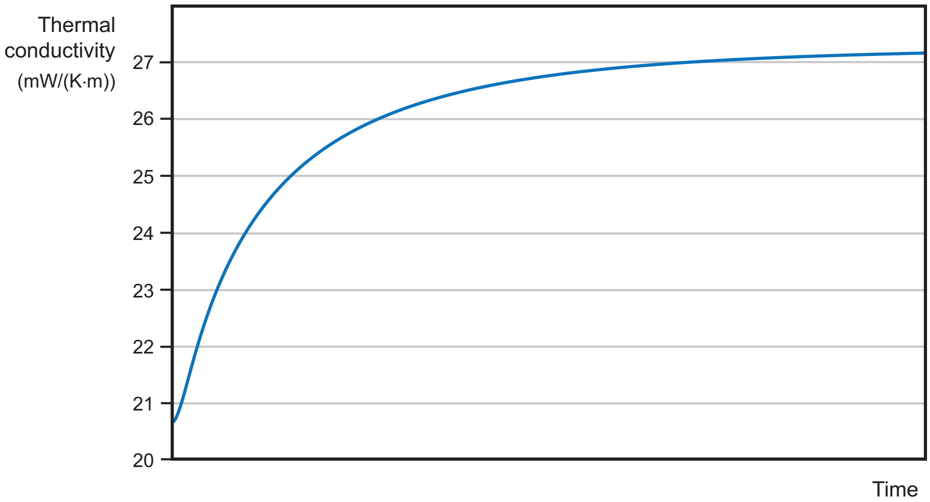

Fig. 7.10: Development of the λ-value with time for the example pentane-water-blown PU rigid foam.

The dimensional stability test measures the tendency of the foam to swell or shrink under service conditions. Foam slabs (100 mm × 100 mm × 25 mm) are subjected to specified temperatures for a given duration, after which the changes in the three orthogonal directions are measured. The samples are typically held at low (-18 °C) and high temperatures (+70 °C or + 100 °C) for 24 h (ISO 2976) and the dimensions of the slabs are measured when the foam has reached room temperature. Some shrinkage (≤1%) in each direction is acceptable.

When the pressure difference between the gas pressure in the cells and the atmospheric pressure exceeds the strength of the polymer, it will deform. This can happen at both high and low testing temperatures. At higher temperatures, the gas pressure increases. The foam slab may swell when the polymer has a low crosslink density and a low glass transition temperature. The physical blowing agent may condense at low temperatures, reducing the cell pressure. Although the polymer is rigid at those temperatures, it may shrink during the test.

7.4.4 Mechanical properties

The mechanical properties of PU foams, including flexural, tensile, and compressive strength, primarily depend on the crosslinking of the polymer matrix, the cell structure, the cell gas pressure, and the foam density. Compressive strength is the most important of the three properties and is measured according to ISO 844. The flexural and tensile properties are measured per ISO 1209 and ISO 1922, respectively. The