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Lifetime modeling of polypropylene absorber materials for overheating protected hot water collectors

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Abstract

For the utilization of polymeric materials in high-demanding applications like solar thermal systems it is of utmost importance to define the performance requirements and to investigate the applicability of components for defined systems under service relevant conditions. This paper deals with the lifetime estimation of black-pigmented polypropylene (PP) absorber grades for overheating protected solar thermal collector systems for hot water preparation in five representative climate zones. Based on experimental aging data in hot air and heat carrier fluid at elevated temperatures (95 °C, 115 °C and 135 °C) and climatic input data, as well as deduced loading conditions and absorber temperature distributions, the lifetime was calculated using a theoretical and an empirical extrapolation approach and assuming cumulating damages in service relevant temperature intervals. Depending on the PP grade, the extrapolation method and the location, endurance limits ranging from 8 to 50 years were obtained. The PP grade with ß-spherulithic structures and less carbon black exhibited a superior performance (factor 2) compared to a well-established grade which is currently widely used for swimming pool absorbers.

Keywords: Polypropylene; Solarthermal collector; Absorber; Lifetime

1. Introduction

The combination of research in the fields of polymer engineering and solar energy science offers a high potential for further developments in solar thermal technologies regarding costs, processing and collector design (Wallner and Lang, 2005; Lang et al., 2013). For polymeric solar thermal absorber materials a long-term stability in hot heat carrier fluid or hot air environment is of prime importance (Kahlen et al., 2010a,b). Aging and degradation of polymeric materials decisively influence the physical performance properties and subsequently the lifetime (Celina, 2013). According to Köhl et al. (2005) for solar thermal collectors a service lifetime of 20 years is required. For the currently market-dominating, cost-efficient thermo-siphon hot water systems also shorter lifetimes ranging from 5 to 20 years are quoted by manufactures (Meyer, 2009; Sessler, 2014).

To assess the lifetime of pressurized polymeric components (e.g. pipes) internal pressure tests (EN ISO 9080) at elevated temperatures are carried out (Lang et al., 1997). By performing long-term tests on pipes at different pressure levels, creep rupture curves are generated, showing three different failure regions. When large defects are absent ductile failures are obtained at high hoop stresses (Region I). At lower stresses (Region II) mechanical phenomena (slow

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crack growth) and chemical degradation (thermo-oxidative aging) compete, resulting in quasi-brittle failures. The end of lifetime in Region III has been reached when extreme brittleness occurs and the lifetime is nearly independent on the hoop stress (Leijström and Ifwarson, 1998; Lang et al., 1997, 2005).

Solar collectors are commonly used in pressurized pumped or non-pumped systems. For polymeric materials based absorbers special attention has to be given to the control of the pressure level, but also the maximum stagnation temperature. Within the collaborative research projects *SolPol-1/2* (Solar thermal systems based on polymeric materials) an overheating controlled (OHC) glazed plastic collector has been developed, which is operated at a maximum pressure level of 1.5 bar (Lang et al., 2013). For functional model collectors it was shown that it is possible to limit the maximum stagnation temperature by back-cooling on the backside of the collector to 95 °C (Thuer et al., 2013). At elevated temperatures some polyolefin pipe grades (e.g. polypropylene) do not exhibit the stress dependent Region II characterized by quasi-brittle failure (Ifwarson and Leijström, 1992). Hence, it is of utmost importance to investigate and characterize primarily the Region III of large scale aging and brittle failure.

The absorber of a solar thermal collector is exposed to varying temperature levels depending on the application (domestic hot water preparation or space heating in single- or multi-family houses), the plant types (pumped systems or thermo-siphon systems) and the climate zone. Kaiser et al. (2013) carried out a comprehensive theoretical study on the loading conditions for collector components used in various solar thermal system types. Five climatic conditions representing different climate zones were considered. The derived loading conditions on the absorber level were used to perform comprehensive aging investigations on two black-pigmented, commercially available polypropylene grades for solar thermal absorbers (Povacz, 2014). The main purpose of this paper is to assess the lifetime for PP based absorbers of overheating protected glazed flat plate collectors for hot water preparation. Therefore the theoretically determined loading profiles (Kaiser et al., 2013) and the experimental aging data on specimen level (Povacz, 2014) were combined assuming cumulating damages at various temperature levels. This approach is commonly termed Miner's rule and is also used for the lifetime assessment of hot water pipes (Leijström and Ifwarson, 1998).

2. Methodology and procedure

2.1. Modeling of service relevant loading conditions

Based on the study by Kaiser et al. (2013) and prevalent market potentials, five different climatic conditions (continental (Graz/Austria), Mediterranean (Athens/Greece), hot and dry (Pretoria/South Africa), hot and humid (Fortaleza/Brazil), moderate climate (Beijing/China)) were taken into account for this work regarding the requirements for polymeric materials in solar thermal absorbers. Based on Meteonorm-data, relevant climatic parameters (e.g. air temperature, relative humidity, global radiation) were established on an annual basis. In a further step for all five climate zones market-based polymeric overheating controlled collectors for hot water preparation in multi-family houses were defined and evaluated. By theoretical modeling, annual time/temperature distributions for the absorber were obtained, which were significantly dependent on the location and the associated climatic conditions.

2.2. Aging characterization of black-pigmented PP grades and time/temperature extrapolation

Since the thickness dependency of the aging behavior of the investigated black-pigmented PP grades is limited (Povacz, 2014), results of the aging behavior of 100 μm thick micro-sized specimens (MSS) were selected as database for lifetime predictions. Based on compression molded 2 mm thick plates of two black-pigmented PP grades PP-B1 and PP-B2, 0.1 mm thick micro-sized specimens (MSS) were automatically manufactured using an adapted CNC-milling technique (Wallner et al., 2013). While the grade PP-B1 is established and widely used for unglazed swimming pool absorbers, PP-B2 is a novel grade characterized extensively in the collaborative research project *SolPol-1/2*. Both grades are black-pigmented polypropylene block copolymers. PP-B1 is an extrusion grade with 2.0 m% carbon black and a melt flow rate of 0.3 g/10 min (230 °C/2.16 kg) manufactured by LyondellBasell, Houston, USA. The stabilizer package of PP-B1 is based on 0.2 m% tri-functional primary antioxidants, 0.2 m% tetra-functional primary antioxidants and 0.1 m% secondary antioxidants (Beissmann et al., 2013). The grade PP-B2, provided by Borealis Polyolefine GmbH, Linz, Austria, is a ß-nucleated, heterophasic copolymer grade developed especially for hot-water compression fittings with a carbon black content of 0.8 m% and a melt flow rate of 0.3 g/10 min (230 °C/2.16 kg). PP-B2 contains an antioxidant mixture of 0.25 m% tetra-functional primary antioxidants and 0.05 m% secondary antioxidants (Beissmann et al., 2013).

After predefined aging times in hot air and hot heat carrier fluid at 95 °C, 115 °C and 135 °C at least 3 specimens were removed and characterized. As most relevant aging indicators describing the end of induction period and ultimate failure the associated carbonyl index and the strain-at-break values were evaluated.

To determine the carbonyl index FT-IR spectroscopy in transmittance mode was performed. The carbonyl index (C.I.) was calculated by the ratio of the absorbance peaks at 1715 cm^{-1} (carbonyl-peak) to 974 cm^{-1} (Horrocks et al., 1999). C.I. change of more than 0.1 indicated a significant carbonyl build-up at the end of the aging induction period of polyolefins (Schwarzenbach et al., 2009).

To obtain strain-at-break values tensile tests were carried out at 23 °C using a screw-driven universal testing