A New Test Setup for Testing Polyethylene Tubes under Constant and Cyclic Internal Pressures

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Abstract

A test system was designed to evaluate the failure behavior of a thin-wall small-diameter polyethylene tube under internal pressure. The test setup was capable of delivering constant (static) and cyclic (dynamic) pressure patterns as well as maintaining an elevated testing temperature to accelerate the failure. Desired pressure patterns were obtained by controlling the opening/closing duration of the solenoid valves accordingly. A water-sensing system was used to detect the failure time, particularly for small brittle failure. A data acquisition system based on LabView™ was used to control and record the applied pressures and the failure times. The constant pressure tests were performed at 65 and 75°C and the cyclic pressure tests were performed at 75°C. The test data obtained from the constant pressure tests exhibited two distinguishable linear regions in a log-log plot of hoop stress versus failure time. Slope values of -0.034 and -0.113 were obtained for ductile and brittle regions, respectively. A brittle failure curve with slope of -0.039 was obtained under the cyclic pressure testing condition. The slow crack growth (SCG) failure was considerably accelerated by the cyclic loading.

Introduction

Small-diameter polyethylene tubes are widely used as flow lines for fluids and gases in pneumatic, hydraulic, medical and many other applications [1]. One of the areas in which polyethylene tubes have recently received significant attention is development of heat exchangers using polymeric components [2]. While the service life of traditional metal based heat exchangers can be significantly decreased by corrosion and biofouling, polyethylene offers a good resistance against these parameters. In addition, polyethylene is considerably cheaper and lighter than metal [3].

In the biomedical field, polyethylene tubes have been used as catheters for accessing different parts of human body to obtain data or administrate fluids. Polyethylene is easy to fabricate and provides properties such as flexibility, inhibition of infection, and non-thrombogenicity that make it a proper candidate for this application [4].

In many applications, polyethylene tubes are subjected to internal pressures throughout their service life. This requirement, together with the fact that polyethylene, particularly high density polyethylene (HDPE) is susceptible to stress cracking [5] justifies a thorough evaluation of the time-dependent failure of polyethylene tubes under internal pressure. Under internal pressure, the time-dependent failure of polymer tubes can take place as a result of strain accumulation or SCG [6, 7]. In some applications, such as in heat exchangers, polyethylene tube can be subjected to cyclic internal pressure which is known to accelerate the SCG process, shortening the service life [8].

Although stress cracking of HDPE has been well studied, particularly for gas and fluid transmission pipes and geomembranes, there is no test standard for thin-wall and small diameter HDPE tube. This paper introduces a new test design for both constant and cyclic pressure patterns.

Material and Test Specimen

A thin-wall small-diameter tube with wall thickness of 0.2 mm and outer diameter of 3.175 mm was extruded using a HDPE resin with a density of 0.946 g/cm³ and a melt index of 0.55 g/10 min at 190°C under 2.16 kg load. The tensile strength at yield was 22 MPa while the secant modulus at 2% was 690 MPa. Burst pressure values at 65 and 75°C were 1.22 MPa and 1.03 MPa, respectively. Test specimens with length of 150 mm were cut from the product for testing.

Test Setup Design

The test system presented in this paper was influenced by the test setup presented in ASTM D2143-15 “Standard Test Method for Cyclic Pressure Strength for Reinforced Composite Thermoset Plastic Pipe” [9] in which the applied pressure is generated by a pump. The pressurized fluid is alternatingly transmitted to two sets of pipe specimens to achieve cyclic pressure in each set of the specimens. During the period when the set of specimens is not pressurized, heated water is circulated through them to keep their temperature within ±2°C of the target temperature.

However, this standard test setup could not be directly implemented for testing thin-wall small-diameter HDPE tube without making some necessary modifications. In ASTM D2143-15, the test temperature is controlled by circulating heated water through the pipe. The outer surface
of the specimen is exposed to the ambient temperature. This leads to a temperature gradient across the thickness of the test pipe that can influence the failure time. During the circulation of hot water, small internal pressure may also be created inside the pipe, subsequently affecting the failure time. In the test standard, the pressure inside each set of the specimens is controlled by a single pressure regulator but is not measured and monitored individually. The pressurized fluid can experience a pressure drop while flowing through transmission tubing and connections before reaching the test specimens. As a result, the pressure inside each test specimen will be different from the pressure indicated by the regulator. Finally, upon failure of a specimen, the pressurized fluid can quickly escape through the failure location leading to a sudden pressure drop in the adjacent non-failed specimens.

Because of the issues described above, a modified test system is required to precisely measure the applied pressures and failure times of thin-wall small-diameter polyethylene tubes. The picture and schematics of the new test setup introduced in this paper are shown in Figures 1 and 2. The system can determine failure times of the test specimens under a constant pressure and a cyclic pressure. Water was selected as the pressurizing fluid due to its incompressibility to ensure a uniform distribution of pressure throughout the tube specimen. Water was reserved in a bath heated to a constant test temperature and was then pressurized by a pump to the desired level. Pressurized water was then directed to two distinct sections: constant pressure testing section and cyclic pressure testing section. The pressure level in each section was controlled by a pressure regulator. Desired pressure patterns were obtained by controlling on/off duration of solenoid valves using Arduino™ based electronic platforms. Up to five tube specimens were tested simultaneously in each section. The test tube specimens were connected to compression fittings inside a heated chamber and were conditioned at the test temperature before being pressurized. Pressure inside each test specimen was measured and monitored by an in-line pressure transducer, which was connected to a data acquisition system. LabView™ software was programmed to record the pressure values every 200 milliseconds.

Failure Detection

Challenge in detecting failure of small-diameter polyethylene tube was experienced for brittle cracking, particularly under cyclic pressure. It was initially anticipated that failure in the test specimen will induce a rapid pressure drop that can be used as an indication of failure. However, crack resulted from SCG was very small, and thus the pressure drop was too small to be detected. Therefore, a water-sensing failure detection system was
designed and integrated into the system. Figure 3 shows a schematic diagram of the sensing system installed around a test specimen. This system consisted of four wires that were bonded to the lower inner surface of a Plexiglas casing with spacing of 1 mm between them. The Plexiglas casing was 175 mm long and had a diameter of 25 mm. It enclosed the entire test specimen without touching. Upon failure, water (could be a small amount, depending on the type of failure) escaping through the tube wall under the test pressure was confined within the Plexiglas casing. The water then flowed to the bottom of the casing and bridged the wires, causing a change in voltage which was monitored by LabView™ software every 200 milliseconds. When the abrupt change in voltage was detected, a signal was sent to the Arduino™ board that was programmed for closing the solenoid valve in front of the specimen, stopping water from entering the failed tube. This sequential action took place within milliseconds, preventing pressure drop in adjacent specimens.

Figure 3. Failure detection system around the test specimen

Constant Pressure Testing Section

In the constant pressure testing section, a solenoid valve was installed in front of the test specimen and a ball valve after it. Initially, both valves were opened to remove all the air from the test specimen as water flowed through it. Then, the ball valve was closed manually while the solenoid valve was kept open. A constant pressure was maintained and monitored in each specimen by the pressure regulator and transducer until failure, when a signal was sent to the programmed Arduino™ to close the solenoid valve.

Cyclic Pressure Testing Section

In the cyclic pressure testing section, solenoid valves were installed in front of and after each of the specimens. Arduino™ based platforms were programmed to alternatingly energize the two solenoid valves every 1 second (this duration can be modified according to the desired test frequency). The maximum internal pressure was reached when the valve in front of the specimen was open and the one after the specimen was closed. Once the opening/closing functions of the valves were switched, pressurization was stopped by closing the front valve while the pressurized fluid inside the tube was released by opening the valve after the specimen. The internal pressure immediately dropped to zero. The on/off procedure took place every 2 seconds to achieve a frequency of 30 cycle/min. The sequence of controlling the two solenoid valves for producing cyclic pressure is shown in Figure 4. This cyclic pressure was applied to each test specimen until failure, when the programmed Arduino™ platform closed the solenoid valve in front of the test specimen.

Figure 4. Solenoid valve sequence for generating cyclic pressure

Experimental Design

For the constant internal pressure testing, the test was performed at 65 and 75°C. Testing was performed at pressures ranged from 0.71-1.07 MPa at 65°C and 0.62-0.96 MPa at 75°C. The maximum applied pressure at 65°C was approximately 88% of the burst strength while it was 94% for the tests performed at 75°C. The failure time was recorded in ± 0.2 second.

Cyclic pressure testing was conducted at 75°C. The applied pressure was characterized by the mean pressure value, calculated using Eq. (1):

\[ P_{\text{mean}} = \frac{P_{\text{max}} + P_{\text{min}}}{2} \]  

where \( P_{\text{mean}} \) is the mean applied internal pressure (MPa), \( P_{\text{max}} \) and \( P_{\text{min}} \) are the maximum and minimum internal pressures during each cycle.

The range of mean pressures was limited to the levels that will yield brittle failure according to the results of constant internal pressure tests. The highest mean pressure...
was 0.48 MPa and the tests were performed at 0.02 MPa intervals. The failure time was recorded in \pm 0.2 second.

**Results and Discussion**

The pressure value for each test specimen was measured by the pressure transducer and recorded by the LabView™ program. This program was also used to receive signals from the failure detection system to obtain the time-to-failure. The test result is presented by plotting hoop stress against failure time in a log-log scale. The hoop stress of the specimen was calculated based on the applied pressure using Eq. 2:

\[ S = \frac{PD}{2t} \]  

(2)

where \( S \) is the hoop stress (MPa), \( P \) is the applied internal pressure (MPa), \( D \) is the inner diameter (mm), and \( t \) is the wall thickness (mm).

Figure 5 shows the failure curve for the HDPE tube under a constant internal pressure testing condition. Two regions with different slopes were obtained which indicates separate mechanisms controlling the failure in each region. The region with a shallow slope indicates failure that is caused by strain accumulation (ductile region) while the failure in the region with a steep slope is attributed to SCG (brittle region) [6]. The slope values of ductile and brittle regions at two test temperatures are relatively similar; the average slope for the ductile region is -0.034 and the average brittle region slope is -0.113. Calculating the slopes from the data presented by Williams for un-notched HDPE pipes yields the values of -0.032 and -0.160 for ductile and brittle regions, respectively [10]. Similar slope values (-0.030 for ductile region and -0.190 for brittle region) were calculated for un-notched HDPE gas pipes from the study conducted by Tränkner, et al. [11]. Microscopic pictures of tubes failed under each failure mode are shown in Figures 6 and 7.

By comparing the failure times of a same hoop stress at 65 and 75°C, it is observed that an increase of 10°C in temperature significantly accelerated the failure, resulting in a decrease in failure times by a factor of 40.

Failure curve under cyclic pressure testing is presented in Figure 8. The highest mean hoop stress was 3.39 MPa which is below the onset of brittle region in the constant pressure test at 75°C. Figure 9 shows the microscopic picture of a tube specimen failed under cyclic internal pressure. The brittle nature of the cracking confirms a failure governed by SCG. The slope of the cyclic failure curve is -0.039 which is much lower than that of the brittle region under constant pressure condition. Abdelkader, et al. [12, 13] performed uniaxial fatigue tests on un-notched...
tensile specimens taken from the HDPE pipe and obtained slope values of -0.068 and -0.073. The discrepancy of the slope values may be caused by the test material and test conditions such as frequency and test setup.

Figure 8. Stress failure curve of HDPE tube under cyclic pressure

Figure 9. Brittle failure of HDPE tube under cyclic internal pressure

Comparing the result of cyclic and constant pressure test at 75°C, indicates that the cyclic pressure has accelerated the SCG mechanism (Figure 10). This effect can be derived from the microstructural aspects of crack initiation and growth. Initially, a porous zone (inside the craze) is formed at the point of imperfection which then transforms to a fibrillated zone that holds the crack surfaces together [14]. Eventually, fibrils begin to fail, a new fibrillated zone is formed and crack propagates through the material [15]. This process is shown in Figure 11. Under cyclic pressure, fibrils are stretched and compressed during each cycle. It causes buckling, bending, or crushing of the fibrils and therefore accelerates the process of fibril failure and crack growth, leading to shorter failure times and different failure mechanism than the SCG under constant pressure testing condition.

Figure 10. Cyclic and constant pressure test results at 75°C

Figure 11. Crack propagation mechanism

Conclusions

A new test system was designed for assessing the failure behavior of thin-wall small-diameter HDPE tube at 65 and 75°C under constant and cyclic internal pressures. The challenge of pressure variation within each test specimen and detection of small failures, particularly under cyclic pressures, were resolved. The failure curves obtained from the constant pressure testing clearly yielded two distinguished regions controlled by strain accumulation and SCG failure modes. An acceleration of SCG was observed under cyclic pressure loading, but the slope of the failure curve is much lower than that of the constant pressure testing. Failure times were found to be highly affected by temperature and pressure levels, hence a precise measurement of these two test parameters was emphasized in this new test system.
References