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Abstract

Theory indicates that water has a high tensile strength. This paper synthesizes the results of a number of studies conducted on the tensile strength of water. The conditions under which water is able to sustain high tensions were examined. An experimental study was performed to investigate the behavior of water when subjected to high tensions. An apparatus was built which contained a high range pressure transducer, a high air-entry ceramic disk, and a small volume of water between the transducer and the ceramic disk. Cyclic pre-pressurization was found to enhance the ability of the water in the apparatus to withstand tensions much in excess of 100 kPa without cavitation. A high tension could be sustained by the pre-conditioned water for a relatively long period of time.

Introduction

Conventional tensiometers can only measure matric suction less than 100 kPa because water normally has no tensile strength and will cavitate at a pressure approaching -100 kPa. On the other hand, physicists have found that the tensile strength of water can be greater than several atmospheres under the right conditions.

This paper synthesizes some important concepts about the tensile strength of water and the results of a number of studies conducted by physicists. An experimental study was conducted to investigate the behavior of water subjected to high tensions. High tensions were generated in the water contained in a small chamber below a high air-entry ceramic disk. The tensions in the water were measured using a pressure transducer. The primary purpose of this research was to identify factors that may affect cavitation, and the durability and stability of water under a high tension.

Tensile Strength of Water

Cavitation commences as gas or vapor bubbles start to form in water. The vapor bubbles are triggered at gaseous or other hydrophobic surfaces which are commonly called potential cavitation nuclei. The net normal stress at the surface of a potential cavitation nucleus is equal to the vapor pressure, u_v, minus the hydrostatic pressure, u_w. The value of the net normal stress, at the inception of bubble formation, measures the tensile strength of water, S_w. The tensile strength, S_w, may be related to the surface tension, T_s, of a sphere of a gas bubble with a definite radius, r,

$$S_w = (u_v - u_w)_c = \frac{2T_s}{r} \tag{1}$$

where the subscript "c" refers to the value at cavitation.

The tensile stress in water can also be understood from the phase diagram of water shown in Fig.1. Curve OA, gives the vapor pressure at any temperature between 0°C and 374°C. The fact that water normally cavitates or boils at zero stress on curve OA indicates that water normally does not exhibit any tensile strength.

Eq. (1) indicates that if the cavitation nuclei are sufficiently small, water will not necessarily cavitate when the pressure is lower than -100 kPa. Figure 1 also illustrates two ways by which liquid water changes to a state below curve OA without changing its liquid phase. One is to reduce the hydrostatic pressure to a negative value; the other is to increase the temperature at a constant hydrostatic pressure (e.g., the atmospheric pressure). The latter approach is called "superheating".

Since the highest temperature at which liquid water and vapor can co-exist is about 374°C, the maximum tensile strength of water according to Fig. 1 is about 22,000 kPa.

Thermal methods, hydrostatic methods, and dynamic methods have been used to apply a tensile stress to liquid water. The thermal methods can be further divided into the superheating method and the thermal contraction method.

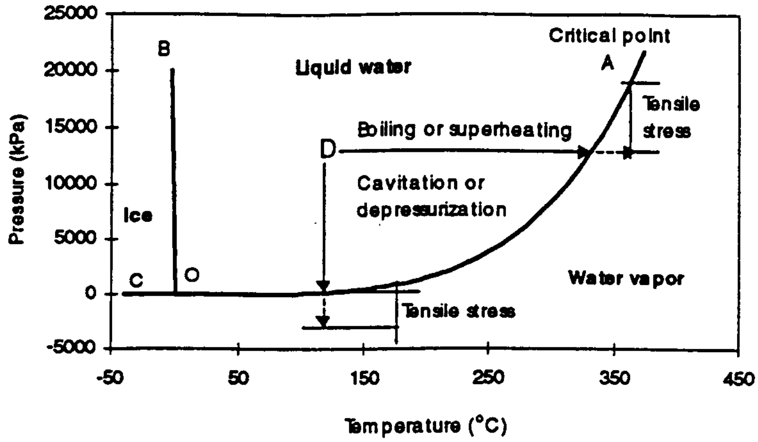

Fig. 1 Phase diagram and tensile stress in water

Briggs [1] superheated water contained in clean capillary glass U-tubes and calculated the maximum tension in water to be at least 5,000 kPa. Knapp [2] found that pressures as high as 133,000 kPa applied to water samples before the water samples were subjected to superheating could significantly increase the tensile strength of water.

The thermal contraction method utilizes the thermal properties of expansion and contraction. Results from some earlier thermal contraction tests using the Berthelot tubes ranged from 1,300 to 15,000 kPa[3]. Richards and Trevena [4] directly measured tensions as high as 3,000 kPa in an enclosed liquid using a diaphragm-type transducer. Using an improved Berthelot tube, Jones et al. [5] pre-pressurized water up to 20,000 kPa and obtained tensions consistently higher than 500 kPa.

In the hydrostatic methods, tension is directly applied to a liquid without flow occurring [6]. In contrast, the dynamic methods involve either flow or kinetic impact in the testing liquid [7][3]. Tensions up to 1,450 kPa were directly measured using piezoeletric transducers in a dynamic stressing test [8].

The mechanism of cavitation is generally explained using a gas-trapping model [7]. This model identifies tiny crevices on the surfaces of undissolved dust particles and container walls as the most important potential cavitation nuclei. The gas-trapping model has been used to explain why pre-pressurization of a water-container system can effectively remove a significant portion of the potential cavitation nuclei, thus increasing the ability of the system to resist cavitation [9].

Experimental Study of Tensions in Water

The studies presented in this paper included the following investigations:
(a) Effect of pre-pressurization on sustainable tensions for water, and
(b) Durability and stability of water under high tensions.

(1) Apparatus and Procedures

The apparatus consisted of a high range pressure transducer and a stainless steel shroud (Fig. 2). The sensing area of the transducer was a smooth, circular surface with a diameter of 7.0 mm. A 15 bar ceramic disk was fitted into the shroud. Several shrouds were manufactured to allow for a range of depths from 0.1 mm to 2.5 mm for the measuring water chamber between the transducer and the ceramic disk.

Pre-pressurization was found to be effective in reducing potential cavitation nuclei. A manual pressurization system, able to supply pressures varying from -85 kPa to 15,000 kPa was constructed. Four (i.e., No. 1 to No. 4) 15 bar ceramic disks were tested. The ceramic disk in the shroud was saturated using distilled and de-aired water. The transducer was then assembled into the shroud under distilled de-aired water. The water in the system was then conditioned using a few cycles of vacuum and high positive pressure. Each cycle was consisted of a vacuum of -85 kPa followed by a positive pressure of 1,000 kPa to 12,000 kPa. The positive pressure in each pre-pressurization cycle was applied for 1 to 30 hours.

(a) Free Evaporation Tests

After the water in the system has been conditioned, free evaporation was allowed to generate a tension in the water until cavitation occurred. Several groups of tests were performed to identify the factors affecting the sustainable tension and the optimal procedure for pre-pressurization. These factors included the ceramic disk, the water, and the magnitude, duration, and the number of cycles of pre-pressurization pressure.

(b) Impeded Evaporation Tests

The surface of the ceramic disk was covered after a specific tension in the water was developed. The tension could be maintained essentially constant. The duration that the tension could be sustained is important for the application of the tensile strength of water for measuring high soil suction. The impeded evaporation tests were performed using ceramic disk No.1.

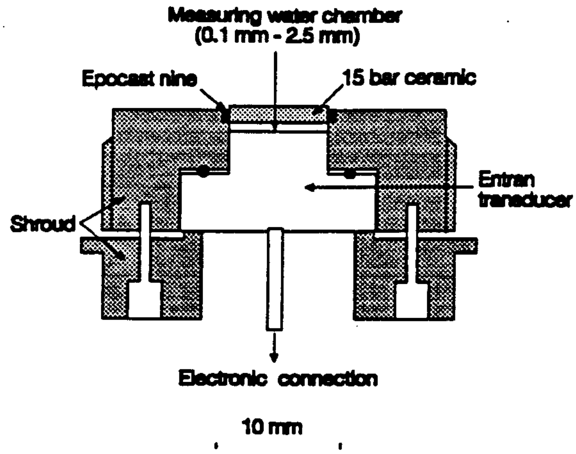

Fig. 2 The design of the apparatus to measure the tensile strength of water

(c) Tension Reversibility Tests

When a chosen tension was reached during an evaporation test, a small water droplet was placed onto the ceramic, causing the tension to drop. As evaporation continued, the tension was restored and would continue to rise. Such cyclic evaporation and wetting tests were conducted to determine if the apparatus could possibly respond to environmental changes. The tests were conducted using ceramic disk No. 1.

(2) Presentation of Results

Figure 3 shows typical results of free evaporation tests. Each pre-pressurization cycle was consisted of a positive pressure of 8,000 kPa for about 18 hours, followed by a negative pressure of -85 kPa for about 5 hours. Tension developed quickly during evaporation. When no pre-pressurization was used, cavitation occurred when the negative pressure reached -100 kPa. In contrast, pre-pressurization increased the tension that could be sustained without cavitation. At the moment of cavitation, the negative pressure instantaneously dropped to about -100 kPa. If the water in the chamber was pre-pressurized again, the ability of the water to sustain tension could be almost fully restored. Increasing the number of cycles of pre-pressurization increased the tensile strength of water. The highest sustainable tension was 540 kPa, where 12 cycles of pre-pressurization were applied. The increase in tensile strength with pre-pressurization pressure was significant for pre-pressurization pressures up to 5,000 kPa. The increase became less significant when the pre-pressurization pressure exceeded 5,000 kPa. The tensile strength of water seemed to reach an upper limit at a pre-pressurization pressure of about 12,000 kPa.

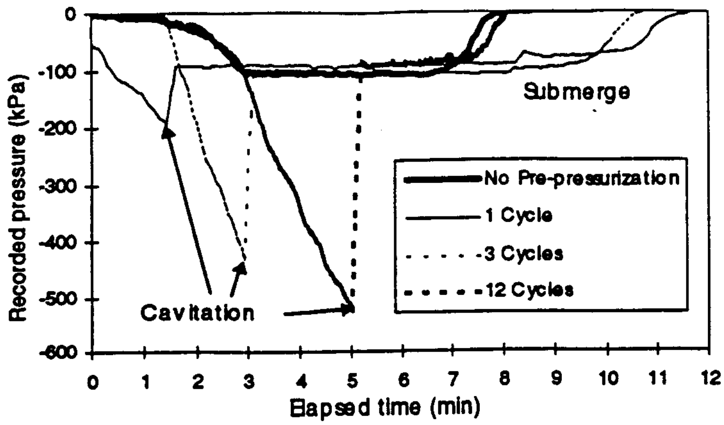

Fig. 3 Tension by free evaporation and effect of pre-pressurization

Tests indicated that the duration of pre-pressurization is less important than the number of cycles. Pre-pressurization longer than one hour did not produce superior results compared with one hour pre-pressurization. When the number of pre-pressurization cycles exceeded 6, the benefit of using more cycles became less significant. It was found that 6 cycles of pre-pressurization consisting of 12,000 kPa for one hour followed by -85 kPa for another hour is optimal.

The results of free evaporation tests conducted on 4 ceramic disks are given in Table 1. Each ceramic disk appeared to have a particular range of sustainable tensions for a given pre-pressurization procedure. The No.4 ceramic disk was found to have the highest sustainable tension. The ceramic disk that had a quicker response time usually gave a higher sustainable tension. An exception was ceramic disk No.3 which showed the slowest response. The first test conducted on ceramic disk No.3 gave a cavitation tension of 1,600 kPa. Subsequent tests showed a cavitation tension of only 360 kPa. A clear "click" was heard whenever cavitation occurred at a tension above 800 kPa. A loud "click" was heard when the water cavitated at about 1,600 kPa for ceramic disk No. 3.

Table 1 Sustainable tensions of ceramic disks

Ceramic No.	Sustainable Tensions (kPa)
1	600 ~ 650
2	400 ~ 450
3	360, 1600 (only one occurrence)
4	1200 ~ 1250

The sustainable tension appears to depend on the cavitation history. The sustainable tension for ceramic disk No. 1 was reduced from about 600 kPa to about 300 kPa after undergoing about 20 cavitations.

Free evaporation tests using ceramic disk No. 4, with water chambers varying from 0.1 mm, 0.3 mm, and 0.5 mm in depth gave essentially the same cavitation tensions. The 2.5mm depth chamber gave a cavitation tension of about 925 kPa.

When the pressure in the water became lower than -100 kPa, a slight mechanical shock to the system could immediately cause cavitation. This is because water under tension is in a metastable state. External disturbance to the system under tension can trigger the growth of cavitation nuclei[10].

Typical results of impeded evaporation tests are given in Fig. 4. Test 1 was a free evaporation test using a new sample of water in the apparatus. Cavitation occurred at a tension close to 600 kPa. In the subsequent Tests 2 and 3, pre-pressurization was applied without replacing the water in the chamber. When the tension in the water rose to about 320 kPa during a free evaporation test, the ceramic disk was covered. The tension continued to rise and the water cavitated at a tension close to 600 kPa. The results indicated that a tension between 300 kPa and 500 kPa could be sustained for several hours. In most cases, cavitation occurred at tensions around 600 kPa, whether or not the water in the measuring chamber was replaced after the previous cavitation test, or whether the evaporation was free or impeded.

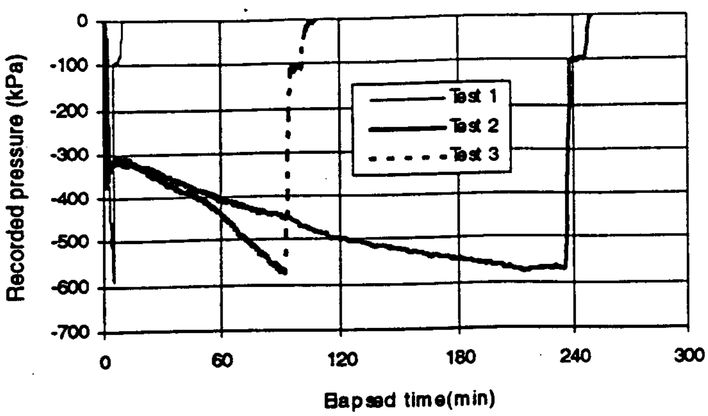

Fig. 4 Tension development after evaporation from the ceramic was impeded

The first series of reversibility tests was conducted over a 48-hour period. Cavitation did not occur even though many evaporation cycles were applied. The apparatus was intermittently submerged for periods varying from 0.5 hour to several hours. Figure 5 shows the results of one of the reversibility tests performed over a 6-hour period. At the end of the 48-hour test, the tension was allowed to reach 600 kPa and the water cavitated.

Another series of reversibility tests was performed over a period of 17 days. The apparatus was, for most of the time, submerged in water. Each reversibility test, which was repeated every one or two days, lasted about 60 minutes. After Day 9, the apparatus was submerged in a 2 molarity NaCl solution. The ability of the system to respond to environmental changes was maintained as long as the tension was kept lower than 600 kPa.

(3) Discussions

Dissolution of cavitation nuclei is dependent upon the magnitude of the positive pressure applied. Using the apparatus described, the tensile strength of water seemed to reach an upper limit at a pre-pressurization pressure of about 12,000 kPa. These results were similar to those obtained by Knapp [2] using the superheating method. Dissolution of cavitation nuclei is also a time-dependent process. The results of tests with different durations of pre-pressurization indicated that dissolution of most cavitation nuclei was complete within one hour of pre-pressurization.

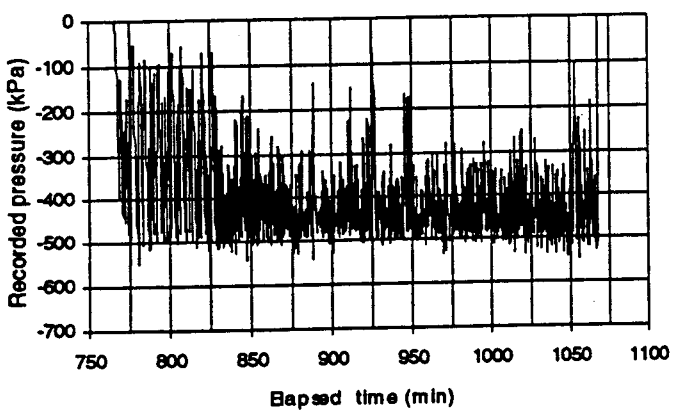

Fig. 5 Six-hour results of a tension reversibility test

Cyclic pre-pressurization was found to have a considerable effect on the sustainable tension. Ohde et al. [11] suggested that successive temperature cycles appeared to cause reduction of gases trapped in crevices on the container surfaces and increased the tensile strength of the water. In the present study, cyclic applications of a positive pressure and a vacuum may likely cause the reduction of cavitation nuclei in the system.

Pilot tests showed that ordinary tap water did not show an appreciable difference in tensile strength from distilled and de-aired water. High pre-pressurization pressures seemed to be effective in dissolving gases in water. On the other hand, the tensile strength of water seemed to be dependent on the ceramic disk.

There appeared to be a cavitation threshold for a particular system using a particular pre-pressurization procedure. As long as the tension did not exceed the cavitation threshold value, the tension could be sustained for a relatively long period of time. Cavitation threshold may be explained using the gas-trapping model for cavitation. In the gas-trapping model (Fig. 6), the gas-water menisci penetrate into the crevices under pre-pressurization. When the pressure in the water changes, the gas-water meniscus acts like an elastic membrane and deflects back and forth inside the crevice. If the tension in water increases to a level such that the receding contact angle, θ_r, is reached, the meniscus will retreat out of the crevice and cavitation will occur. The tension under which the meniscus deflects to reach the receding contact angle, θ_r, corresponds conceptually to the proposed cavitation threshold.

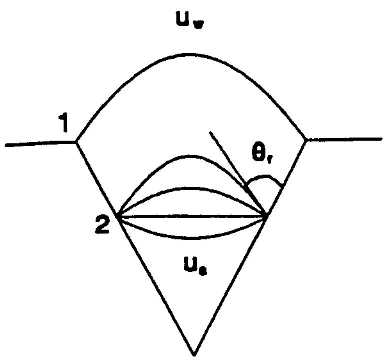

Fig. 6 Illustration of the cavitation threshold using the gas-trapping model

Conclusions

Pre-pressurization can effectively dissolve cavitation nuclei in a system, making the system capable of sustaining tensions much in excess of 100 kPa. The main factors that may affect the sustainable tension include the magnitude, the duration, and the number of cycles of pre-pressurization pressure. The sustainable tension is also affected by the ceramic disk. No special procedure, apart from cyclic pre-pressurization, was required to pretreat the water.

There appeared to be a cavitation threshold value for a given system and a given pre-pressurization procedure. Below the cavitation threshold value, a tension could be sustained for several hours and the system showed tension reversibility.

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