Cavitation of multigrade oils under dynamic stressing at elevated temperatures

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Abstract

In many flow situations, liquids which are subjected to negative pressures (or 'tension') also experience a range of temperatures. In typical organic liquids, homogeneous nucleation theory predicts that the cavitation threshold or effective tensile strength of a liquid, F_c , decreases with increasing temperature by *ca.* 1 bar/°C. But in the case of common engineering liquids such as lubricants, cavitation is likely to involve heterogeneous nucleation due to the availability of nuclei for bubble growth. This being the case, it is necessary to measure F_c under pertinent conditions. This paper reports a technique which permits measurements of the effective tensile strength, F_c, of *degassed* samples of a commercial 'multigrade' engine oil over a range of temperatures, T, representative of those encountered under its operating conditions (in the range $20^{\circ}C \leq T \leq 140^{\circ}C$). In the experiments reported herein, samples of liquid are subjected to dynamic stressing by a rapid pressure-tension cycle, this being a feature of the conditions experienced by a lubricant within a dynamically-loaded journal bearing. The method used herein to estimate F_c avoids reliance upon direct measurements of substantial dynamic negative pressures using transducers which are designed for use in the range of positive pressures.

Introduction

In many flow situations, liquids which are subjected to negative pressure, or 'tension'[1], also experience a significant variation of temperature. An example is provided by the flow of lubricants within fluid film bearings in which case the liquid's effective tensile strength (or 'cavitation threshold', F_c) is an important

consideration in the assessment of flow boundary conditions, load bearing capacity and cavitation damage potential [1–4]. It is important to recall that a liquid under negative pressure is metastable (being superheated with respect to liquid vapour). In typical organic liquids, homogeneous nucleation theory predicts that F_c decreases with increasing temperature by *ca.* 1 bar/°C [5] but in the case of common engineering liquids cavitation is likely to involve heterogeneous nucleation, due to the availability of nuclei for bubble growth. This being the case, it is necessary to *measure* F_c under pertinent conditions. In many flow processes of scientific, industrial or biomedical concern, this involves measurements made under *dynamic* stressing by tension and over a range of temperatures representative of a liquid's operating conditions. The pertinent rates of tensile stress development can be very large, often exceeding 1 bar/μs. A liquid's effective tensile strength is an important factor in ultrasonics, in which bubbles may form (or grow from pre-existing nuclei) during the negative part of an acoustic cycle in an alternating pressure field. Such bubbles may be short lived and collapse to produce extreme intracavity temperatures and pressures. This 'transient cavitation' is required in processes such as industrial ultrasonic cleaning, the dispersion of solid particles in liquids, depolymerisation and microbial cell disruption. Elsewhere, sonochemistry relies on ultrasonically induced cavitation, which initiates reactions, changes reaction pathways or increases reaction rates and/or yields.

Experimental techniques for the study of liquids under quasi-static tension are well-documented and date back to the mid-19th century by Berthelot [1]. His technique exploited differences in the differential rates of contraction between a liquid and its container (the 'Berthelot tube') and was capable of inducing significant tensions, albeit at a very low rate (typically 1 bar/minute). Various improved forms of the Berthelot tube have been reported but, until very recently, no single dynamic stressing technique capable of inducing large rates of stressing and of handling a wide range of temperatures was available as a reliable means of measuring F_c [6,7]. As a result, virtually no reliable data exists for such basic factors as the temperature dependence of the effective tensile strength of liquids under dynamic stressing, or its dependence on the rate of stress development. The work reported in this paper describes the development of an experimental technique which addresses this paucity of data. This technique, which has antecedents in studies of F_c prompted by G.I. Taylor during World War II, involves a fluid in a vertical steel cylindrical tube fitted with a piston at its lower end [2]. A pressure pulse, generated in the liquid by a bullet striking the piston, travels up the liquid column to be reflected at the free surface as a pulse of tension. By varying the peak pressure, P, in the incident pulse, the values of P and the peak tension, F, of the reflected pulse are recorded. The (F, P) curve shows a limiting value which provides an estimate of F_c [1] by this so-called 'bullet-piston' (B-P) technique.

A previous study of cooled water under dynamic stressing involved work in a B-P apparatus [6]. In that work estimates were made of the tensile strength of water at temperatures in the range 0°C to 70°C. The values of F_c so obtained indicated a maximum (13 bar) at a temperature close to that at which the density

of the liquid is a maximum (*ca.* 5 °C) and were virtually independent of temperature (at a value of 8 bar) at temperatures in the range 40 °C to 70°C. However, a feature of previous B-P research was the anomalously low value of F_c obtained for water - *ca.* 10 bar [3], considerably less than that obtained by static stressing in the Berthelot-tube experiment. Temperley and Trevena [4] proposed an explanation for the anomalously low values of F_c recorded in B-P experiments which invokes the concept of a transition layer between liquid and vapour. This involves the idea that at a free surface the density falls off with height with a characteristic distance of the order of a few intermolecular distances, as confirmed experimentally by Als-Nielsen [5]. The transition layer makes the free surface an imperfect reflector, and accounts for the distortion of reflected pulses found by Sedgewick and Trevena [6] in their B-P work. This implies *inter alia* that the amplitude of these pulses reflects the coupled effects of velocity dispersion and attenuation within the transition layer, and not necessarily the tensile strength of the bulk liquid. Thus, pressure transducers are unable to reliably measure F_c *directly* in pulse reflection experiments of this kind [4]; hence the anomalously low values of F_c recorded in such experiments. Following a re-evaluation of the B-P technique, the present authors showed [7] that the probable explanation for the low values of F_c is the combination of slow pressure transducer response and low data sampling rates. Following that work, an improved version of the B-P apparatus has been developed and adapted to permit measurements on samples of multigrade engine lubricants over a range of temperatures ($20^{\circ}C \leq T \leq 140^{\circ}C$) pertinent to their operating conditions.

Experimental

The bullet-piston apparatus used in the present work (see Figure 1) consists of a vertically mounted stainless steel tube (length: 1·4m; internal diameter: 0·0243m; pressure rated to 200bar) closed at its lower end by a steel piston (#3 in Figure 1) whose lower surface is coupled to the projecting face (#2 in Figure 1) of a 0.25" calibre cartridge-driven 'cosh'-type cattle stun-gun (Shelby and Vokes, UK, 'Magnum' model 7000).

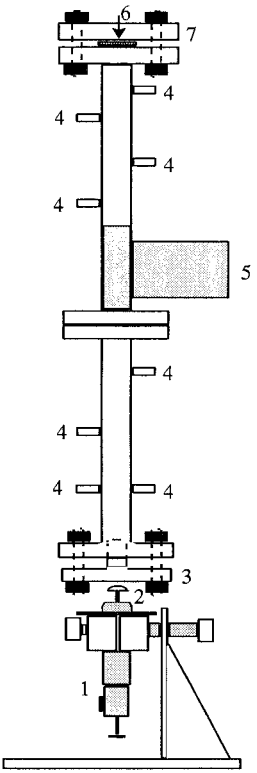
The tube is locked to restraining lugs and is supported by the support arm (#5 in Figure 1) on a counter-weighted aluminium stand. The piston is forced upwards relative to the tube by the action of the cosh, thereby generating a compressional pulse in the liquid. The pressure changes occurring within the test liquid are monitored by dynamic pressure transducers (Kistler model 603B; Kistler Instruments, UK) mounted in the walls of the tube (#4 in Figure 1). These (200 bar) pressure transducers, which have rapid rise-times (1 μsec) and high natural frequency (> 450 kHz), have been used previously in cavitation damage studies [8]. The output voltages of the transducers were recorded by a high speed data acquisition system (Microlink 4000; BioData UK Ltd) specifically designed for the capture of rapid transient signals. The transducer output voltage was sampled at 1 MHz by a 12-bit analogue to digital convertor with an 8 MB memory buffer. The pressure records were transferred to a PC-AT

microcomputer for analysis using signal processing software (DADiSP; DSP Corp., USA).

The duration of the pressure (and corresponding tension) pulses generated in the present experiments is typically 200μs to 500μs, with a risetime to peak amplitude of 50μs to 100μs. The characteristic time of these pulses is an important feature of the B-P technique in terms of its application to lubrication within a dynamically-loaded journal bearing. One example of the relevance of the B-P technique to this area is evident from a rheological study of multigrade oils in an extensional flow field conducted by Gupta *et al* [9]. In an attempt to relate their results to the performance of oils at engine operating conditions, the latter workers estimated the maximum rates of extensional deformation experienced by an oil within the main front bearing of a typical automobile engine. For engine speeds between 2000 r.p.m. and 6000 r.p.m., the characteristic times corresponding to these extension rates are commensurate with the timescales of stressing associated with the action of the present B-P apparatus (200μs to 500μs).

The upper steel flange connects the tube to (i) a high pressure steam line; (ii) a vacuum line and (iii) a regulated static pressure line, the latter being connected by a valve to an oxygen-free nitrogen supply and a pressure gauge. The lower flange houses the piston which, when removed, provides a connection to a steam condensation system and a liquid drain point. Prior to experiments, superheated (110°C) steam is blown through the tube. Periodically, steel plugs which are screwed into the transducer ports in the tube walls, and whose ends are mounted flush with the inner tube wall, were removed for inspection and replaced. The walls of the open tube were subsequently heated and allowed to dry at 100°C. Following this procedure the tube was allowed to cool prior to being refilled to the required depth with a fresh sample of liquid which was subsequently heated to the test temperature. The liquid was then thoroughly degassed *in situ* by connecting the upper flange to a vacuum line (−1bar). The temperature of the liquid in the range 20 °C to 140°C was regulated by means of a variac-controlled, 3m heating tape (100w/m at 230 volts) and an 'Armourflex'-lagged (IPS Ltd., UK) insulating jacket wrapped around the tube's external surface. The temperature at the tube's inner surface was measured using a thermocouple (Jenway, UK).

In the present work, preliminary dynamic stressing experiments were conducted on samples of degassed deionised water, followed by a series of experiments involving samples of commercial multigrade engine oils in the SAE 10W-40 category. In each experiment, the free surface was 0.945m above the face of the piston at the base of the liquid column. All samples were degassed *in situ* for 90 minutes prior to measurements. In the case of the oil samples, the degassing procedure was conducted at a temperature of 90°C due to their relatively high shear viscosity, the samples being subsequently brought to the requisite test temperature. The shear viscosity of the liquids was measured using an ARES controlled-strain rheometer (Rheometric Sci., USA) fitted with a cone-and-plate geometry (50mm diameter, 0.04radians and 46μm truncation).



1 Magnum model 7000 cattle stun gun
2 Mushroom-headed cosh
3 Steel piston
4 Transducer ports
5 Support arm
6 Sealing gasket
7 Sealing flange

Figure 1: Bullet-piston apparatus

In all measurements made under applied *static* pressure, the sample was subjected to the applied pressure (using pressurised "oxygen-free" nitrogen) for a few seconds prior to measurement, to minimise any pressure loading affects.

Results

The main features of a typical experimental pressure record obtained from a 603B transducer are shown in Figure 2, in which the data are presented in terms of transducer output in unscaled analogue to digital convertor, ADC, units (positive values correspond to positive pressure and vice versa). A pressure pulse (feature '*1*' in Figure 2) is followed immediately by a tension pulse (feature '*2*')

and the cycle '*1–2*' is referred to herein as the 'primary' pressure-tension cycle. Thereafter, the record comprises 'secondary' pressure-tension cycles ('*3–4*', '*5–6*' etc.) which are associated with cavitational activity within the liquid [10].

In what follows we seek to provide a complete explanation of the pressure record and begin by establishing that cavitation may result from the development of the 'primary' pressure-tension cycle. That the response of a bubble nucleus to a single pressure-tension cycle, such as that generated in the present experiments, can result in several cycles of cavitational activity may be illustrated as follows. We begin by considering the collapse of a cavity in a large mass of incompressible liquid, in which case the cavity boundary $R(t)$ obeys the relation

$$R\ddot{R} + \frac{3}{2}(\dot{R})^2 = \frac{1}{\rho}\{p_i - p_\infty - \frac{2\sigma}{R} - \frac{4\mu}{R}\dot{R}\} \qquad (1)$$

in which ρ is the liquid density and p_∞ is the pressure in the liquid at a large distance from the bubble. The generalized 'Rayleigh-Plessett' equation (equation (1)) includes the effects of surface tension, σ, and shear viscosity, μ, and the pressure in the gas at the bubble wall, p_i (and p_∞) may be a function of time [11]. Figure 3 shows the result of an integration of equation (1) (using a fourth-order adaptive Runge-Kutta method) in which $p_\infty(t)$ takes the form of a 'primary' pressure-tension cycle such as '1-2' in figure 2 and is represented by :

$$P(t) = \frac{d}{dt}\left[a_0 / \{1 + \frac{(t - a_1)^2}{a_2^2 a_3}\}^{(a_3/2+1/2)} \right]$$

in which a_0 is the amplitude, a_1 is the center, a_2 is the width, and a_3 is a shape parameter. In this example the representative values of σ, μ, ρ and p_i are taken to be those of water at 20 °C [12], the vapour pressure of the liquid at this temperature representing p_i and the initial radius of the cavity (at rest) being 10 μm. The resulting change in the cavity radius, $R(t)$ in response to the 'primary' pressure-tension cycle involves a series of oscillatory cycles of bubble growth followed by rapid collapse and rebound, as shown in Figure 3 in which time is made dimensionless by the appropriate value of the 'Rayleigh' collapse time, τ [13] where:

$$\tau = 0.915 R_m \left(\frac{\rho}{p_0 - p_v} \right)^{\frac{1}{2}}$$

and the cavity radius is represented by R/R_m where R_m is the maximum radius of the cavity (note that the pressure p_0 is atmospheric pressure, the values of pressure in the 'primary' cycle being made dimensionless by the peak pressure, P, in the incident pulse). In the corresponding experiments, the hydrodynamic pressure variation produced about the oscillating cavitation bubble(s) is recorded as the 'secondary' pressure-tension cycles shown in pressure records, such as

Figure 2. The upward travelling pressure wave generated by the motion of the piston, recorded as the pressure pulse '*a*' (P_1) in Figure 2, is subsequently reflected (as tension) at the free surface, recorded as the downward travelling pulse denoted '*b*' (F_1) in Figure 2. This tension pulse is then reflected from the plane face of the piston at the base of the fluid column, thus doubling the magnitude of the tension in the liquid.

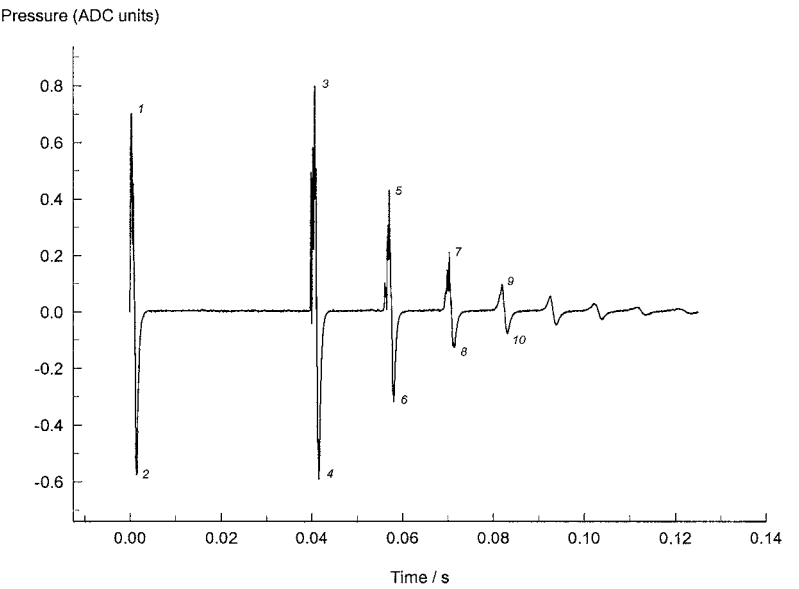


Figure 2: A typical pressure record obtained from a 603B transducer in an experiment on a sample of oil. The pressure transducer output is in ADC units, positive values of which correspond to positive pressure and vice versa. The record contains the 'primary' ('1—2') and 'secondary' pressure-tension cycles ('3—4', '5—6' etc.)

As explained above, the B-P technique used in previous work has the disadvantage that the means by which P is varied (using different combinations of piston mass, piston length and bullet momentum) necessitates frequent dismantling of the apparatus and removal of the liquid. This was overcome in the present work by a new method which allows F_c to be estimated with the same liquid sample remaining *in situ* throughout. This method involves regulating a static pressure, P_s , in the space above the liquid column, P_s being increased gradually in a series of dynamic stressing experiments. From the dynamic pressure records obtained in these experiments a record is made of the time delay, τ_i, between the peak incident pressure and the first pressure pulse arising from cavitation bubble collapse. It is useful to recall here that, under tension, cavitation bubbles grow from pre-existing nuclei within the liquid and eventually collapse and rebound, emitting a pressure wave into the liquid as they do so. Hence the interval τ_i , which encompasses the attainment of maximum cavity

radius and its subsequent decrease to a minimum value, is reduced by increasing P_s (τ_i therefore provides a convenient measure of cavitational activity). The B-P experiment involves the transmission of a pulse of tension by the liquid to the face of the piston; and that cavitation may result from this pulse. It follows that in the case of experiments in which cavitational activity is detected, the magnitude of the tension transmitted by the liquid is sufficient to result in the development of a transient net negative pressure in the presence of a background static pressure (P_s). Thus an estimate of the magnitude of tension capable of being transmitted by the liquid can be obtained from a knowledge of P_s.

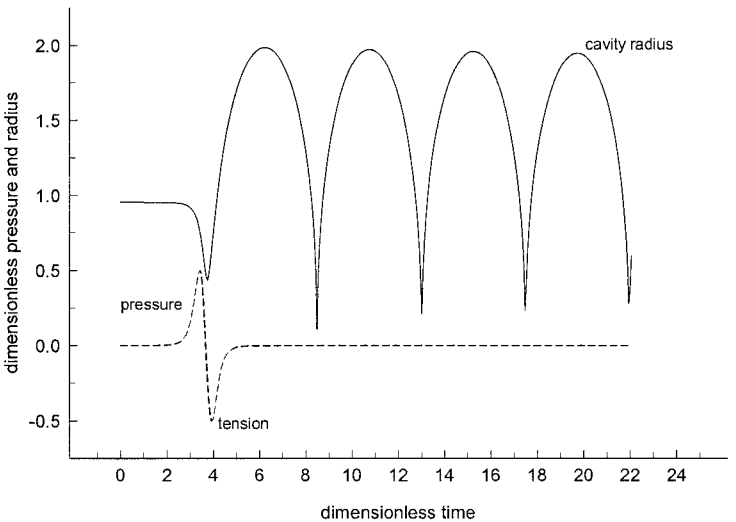


Figure 3: Results of a numerical integration of equation (1) illustrating the response of a cavity nucleus (initially at rest) to a pressure variation which represents the 'primary' pressure-tension cycle generated in the experiments. The resulting change in cavity radius involves several oscillatory cycles, of gradually diminishing amplitude and period.

The results of such experiments on degassed, deionised water are shown in Figure 4, in which τ_i is plotted as a function of P_s (absolute, in p.s.i.) and from which F_c is estimated in the following way. The time delay, τ_o, between pulses corresponding to '1' and '3' in Figure 2 represents the time required for the upward travelling pressure wave to return, as tension, to the lower transducer's location: it also represents the smallest time interval for which a cavity growth-collapse cycle could occur given that a bubble would have to grow and collapse infinitely quickly in order that $\tau_i = \tau_o$. Thus F_c is estimated by extrapolation of the data in Figure 4 to that pressure P_s at which $\tau_i = \tau_o$, this condition representing the complete suppression of cavitation. This procedure yields a value of F_c of 96 bar ($\pm$ 5 bar).

It is clearly appropriate to compare our results with values obtained by other dynamic stressing techniques which do not rely upon the direct measurement of negative pressures using pressure transducers. Such a technique has been reported by Marston and Unger [14] and involved a compressive pulse of duration 1.7μs which was reflected at a flexible membrane to create a pulse of tension in the liquid. Their values of F_c (100-110 bar) for degassed, distilled water are in good agreement with the results of the present work which yield a value of 96 bar (± 5%). Our slightly lower value may be attributed to the longer time of stress development involved in the present work (50μs -100μs rather than 1μs -2μs). It is well established that in work involving the dynamic stressing of liquids by tension, the higher the rate of stress development, the higher the value of F_c obtained [1].

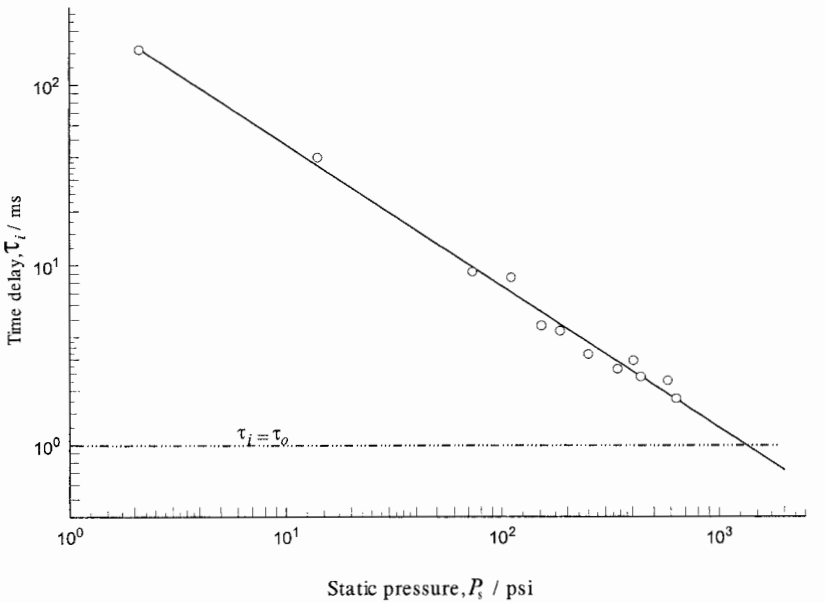


Figure 4: The time interval τ_i as a function of applied static pressure, P_s (in p.s.i.) for degassed, deionised water. Also shown is the value of the time internal τ_o used to estimate F_c.

We now turn to the results obtained in experiments on samples of a commercial multigrade oil (Shell 'Helix Plus' 10W-40) which were conducted at various temperatures, T, in the range $20^\circ C \leq T \leq 140^\circ C$. The values of τ_i recorded over a range of pressures P_s at three temperatures (20°C, 50°C and 90°C, respectively) are shown in Figure 5. A total of five sequential repeat dynamic stressing measurements were made at each value of the applied static pressure at each temperature, which procedure established the repeatibility of the results as being within ± 5% of the values reported herein. An example of the

pressure record obtained in an experiment at a temperature of 120°C (background static pressure atmospheric) is shown in Figure 6.

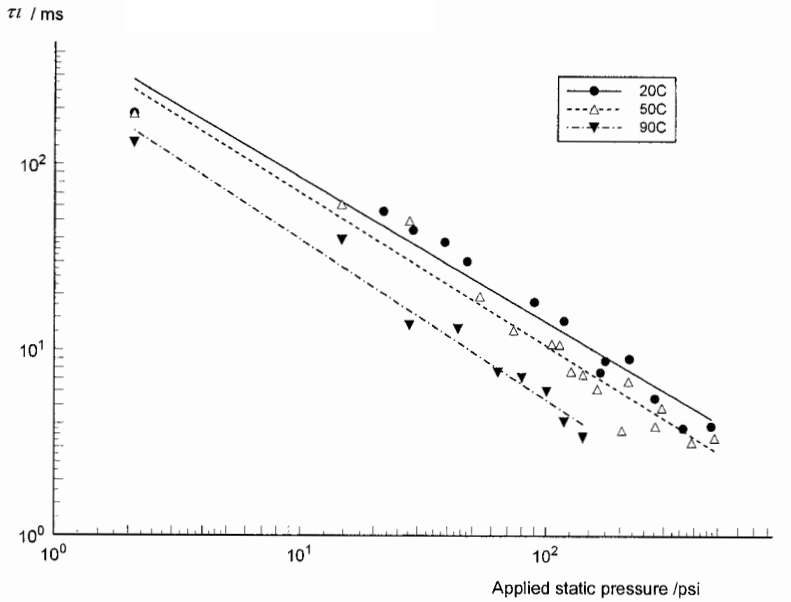


Figure 5: Results obtained in the dynamic stressing of a multigrade motor oil (SAE 10W40) at three temperatures, 20°C, 50°C and 90°C.

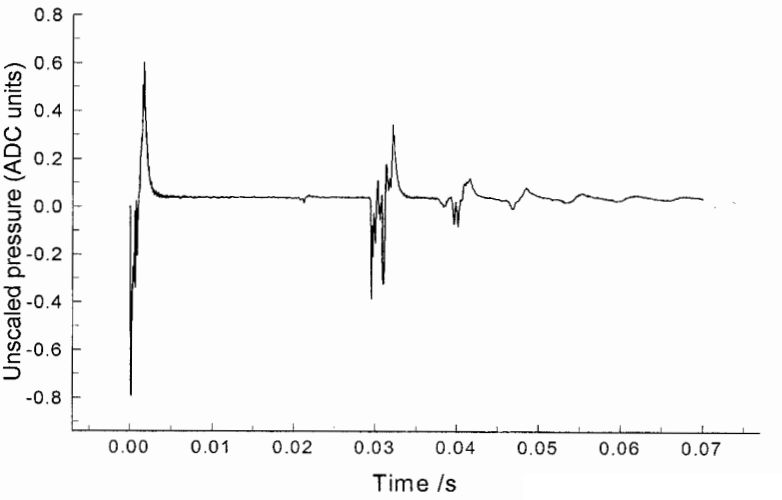


Figure 6: Pressure record obtained in the dynamic stressing of a multigrade motor oil (SAE 10W40) at 120°C and atmospheric pressure.

In what follows, we attempt to set these findings in the context of lubrication and emphasise in so doing that the focus of the present study is upon *vaporous* rather than *gaseous* cavitation phenomena. We recognise that the latter represent an important (and probably dominant) feature of lubricant cavitation and it is important therefore to state our reasons for choosing to work, in this instance, with degassed liquids. Our aims in the present paper are to introduce a new technique in lubricant cavitation testing; and to explain its operation and the analysis of results. In so doing, as in other areas of cavitation work, it is important to compare the first such results of measurements made upon oil samples with those made on other liquids, some of which have also been studied by other, related techniques. In order to facilitate a meaningful basis for such comparisons the provision of degassed samples provides a convenient 'baseline', given the well-documented dependence of F_c on the presence of permanent gas bubbles within a liquid [1]. Our aim is to explain how the B-P apparatus enables the cavitation response of a lubricant to an alternate pressure-tension cycle to be investigated in a systematic manner, over an appropriate range of temperature: such a technique has been lacking in cavitation research until now. Our intention is that the values of F_c thereby established provide upper-bound estimates for the lubricant's tensile strength, these being particularly valuable in the case of comparisons of F_c at different temperatures (and hence gas solubilities). Moreover, it is important to point out that, although the samples of oil used in the present work were thoroughly degassed using a vacuum line prior to each measurement, the process of degassing is not, in fact, confined to the application of a vacuum to the sample. In work involving the dynamic stressing of liquids, the repeated application of tension results in the progressive liberation of dissolved gases, with a concomitant and progressive increase in F_c. This finding is well established in studies of water [1] and other liquids [15].

Table 1. Viscosity and tensile strength data for Shell Helix Plus 10W-40 oil at various temperatures.

Temperature /°C	F_c / bar	Viscosity / Pa.s
20	180	0.26
30	113	0.12
50	92	0.05
90	48	0.014
110	38	0.0096
140	30	N/A

As can be seen from Table 1, at 20°C samples of the degassed motor oil are capable of sustaining a substantial transient negative pressure (180 bar). Moreover, even at the highest test temperature attained (140°C), the oil was capable of sustaining a transient negative pressure of 30 bar. If the repeated application of tension (due to bearing action) to the recirculating oil were to progressively denude it of nuclei, then our findings suggest that during an engine's 'warming up' period, prior to the attainment of its normal operating

temperatures following a cold start, the lubricant may be substantially resistant to (vaporous) cavitation. This may have serious consequences in terms of the load-carrying capacity of fluid-film bearings, given the stabilising influence of cavitation on journal dynamics [16, 17] e.g. in the absence of cavitation it is well-established that a journal exhibits half-speed whirl for a constant viscosity lubricant: under full-film conditions the journal's trajectory spirals towards the bearing and, as it does so, the angular velocity of the path approaches half-speed whirl, resulting in zero load bearing capacity and, ultimately, failure of the bearing [18, 19]. The trend of the data suggests far lower (and possibly negligible) levels of F_c at temperatures in excess of 150 °C. This leads us to speculate that the eventual attainment of normal operating temperatures may correspond to an inability of the lubricant to resist vaporous cavitation.

Concluding remarks and acknowledgments

The work reported in this paper describes a technique in which lubricants (and other common engineering liquids) may be subjected to dynamic stressing by pulses of tension, at temperatures representative of those encountered in their normal operation. It is important to note that the present work does not represent an attempt to recreate the complicated flow field experienced by a lubricant within a bearing, this being a mixture of shear and extensional flow [10]: rather, it is concerned solely with isolating, for separate detailed study, the effects (nonetheless important) of subjecting a liquid to a pressure-tension cycle (which is also a feature experienced by a lubricant during its passage through a bearing). The results of cavitation experiments involving samples of degassed commercial multigrade oil at elevated temperatures suggest a substantial resistance to vaporous cavitation. The results obtained suggest that further experiments should now be conducted using this technique in an attempt to isolate the influence of viscoelasticity and the presence of dissolved (permanent) gases in the cavitation of lubricants under dynamic stressing by pulses of tension. Such work is planned and the results will be communicated in a future paper.

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