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Ultrasonically triggered ignition at liquid surfaces

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ABSTRACT

Ultrasound is considered to be an ignition source according to international standards, setting a threshold value of 1 mW/mm^2 [1] which is based on theoretical estimations but which lacks experimental verification. Therefore, it is assumed that this threshold includes a large safety margin. At the same time, ultrasound is used in a variety of industrial applications where it can come into contact with explosive atmospheres. However, until now, no explosion accidents have been reported in connection with ultrasound, so it has been unclear if the current threshold value is reasonable. Within this paper, it is shown that focused ultrasound coupled into a liquid can in fact ignite explosive atmospheres if a specific target positioned at a liquid's surface converts the acoustic energy into a hot spot. Based on ignition tests, conditions could be derived that are necessary for an ultrasonically triggered explosion. These conditions show that the current threshold value can be significantly augmented.

1. Introduction

Ultrasound is considered to be an ignition source according to international standards, setting a threshold value of 1 mW/mm^2 [1]. It was derived in the 1970s on the basis of conservative estimations in analogy to other ignition sources but it has never been experimentally verified. Therefore, it probably includes a large safety margin.

The variety of technical applications of ultrasound in liquids covers a range from medical diagnostics and therapeutics, to level and flow measurements, and to the cleaning and processing industry, to mention just the most prominent. Especially in the cleaning industry where burnable solvents are used, or in the processing industry, ultrasound can come into contact with explosive atmospheres. However, no explosion accidents in connection with ultrasound have yet been reported.

This situation results in the following conflict: On the one hand, in general, explosion proof devices have to satisfy safety and health requirements in consideration of potential errors, incorrect use, maintenance, and present or predictable environmental conditions. Thus, hazards posed by ultrasonic energy have to be considered. On the other hand, though, a threshold value including an exaggeratedly large safety margin can turn into a burden for innovations.

Therefore, within a research project at PTB the current threshold value is being revised. Ignition tests with airborne ultrasound have shown that it is indeed capable of igniting dust-air atmospheres when a target suspended in the pressure anti-node of a standing wave field heats up due to acoustic absorption [2] being revised. Ignition tests with airborne ultrasound have shown that it is indeed capable of igniting dust-air atmospheres when a target suspended in the pressure anti-node of a standing wave field heats up due to acoustic absorption [2].

Thus, the purpose of this paper is to present conditions that provoke an ultrasonically triggered ignition at liquid surfaces and to discuss whether the current threshold value is reasonable. For ultrasound coupled into a liquid, two mechanisms are critical. First, high intensity ultrasound could lead directly to an ignition of an explosive atmosphere above the liquid's surface. Second, collapsing cavitation bubbles filled with explosive vapors could cause an explosion due to extreme temperatures and pressures at the moment of the collapse. The objective of this paper is to address the first mechanism, while cavitation will be considered in future investigations.

In order to reassess the ignition source ultrasound in liquids, a worst-case situation has to be developed which provokes ignition. Therefore, in the following Section 2, theoretical considerations have to be taken. Subsequently, this worst-case situation will be transformed into an experimental setup for analysis.

2. Theoretical considerations for a worst-case situation for ultrasound-triggered ignition

The aim of this section is to theoretically derive a worst-case situation for ultrasound in liquids that provokes an ignition. To

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attain high intensities, focused ultrasound at MHz frequency is used. At this frequency, the wavelength in water at room temperature is of the order of 1 mm. Therefore, it is possible to sharply focus the ultrasonic wave by application of a concavely curved source. From theory, the half maximum width can be approximated by:

$$w = 0.71 \cdot \frac{cF}{fa} = 0.71 \cdot \frac{\lambda F}{a}, \quad (1)$$

where c is the speed of sound, f the frequency, and λ the wavelength in the medium of propagation, F the focal length of the transducer, and a the radius of the transducer [3]. Moreover, the acoustic absorption coefficient in general increases with frequency [4,5]. Consequently, at MHz frequencies the acoustic energy will be transformed more effectively into heat than at lower ultrasonic frequencies. Finally, kHz frequency ultrasound excites strong cavitation that consumes a large part of the acoustic energy. Clusters of cavitation bubbles also scatter the sound field and shield the target from the ultrasonic wave. At MHz frequencies, the threshold for cavitation creation is higher and cavitation bubbles smaller (typical radius $\leqslant 3$ m at 1 MHz [6]). Consequently, its influence will be negligible.

Since the liquid itself cannot ignite but only the vapor above the surface, the focus has to be placed into or above the phase interface between the liquid and an explosive atmosphere at its surface. However, as the impedance ratio is of the order of 0.0001 ($Z_{\text{vapor}} \approx 100 \text{Pa} \cdot \text{s/m}$ and $Z_{\text{liquid}} \approx 1000 \text{kPa} \cdot \text{s/m}$ [7]) at this interface the reflection coefficient is [8]:

$$R = \frac{Z_{\text{vapor}} - Z_{\text{liquid}}}{Z_{\text{vapor}} + Z_{\text{liquid}}} = 0.99. \quad (2)$$

Thus, 99% of the ultrasonic wave is reflected. Moreover, the acoustic radiation pressure scatters the liquid surface into droplets.

However, if an object that is fixed to the liquid's surface impedes the liquid surface from scattering and if this object transforms the acoustic energy into heat, an explosive atmosphere could be ignited by its hot surface. In this respect, the investigations are similar to those carried out with optically irradiated particles [9,10].

This ignition mechanism, however, sets certain requirements for the material characteristics of the object at the liquid surface: First, its acoustic impedance has to be close to the one of the liquid so the major part of the sound is transmitted into it. Second, it has to absorb the ultrasonic wave and, therefore, a high absorption coefficient and a size of at least one wavelength in the direction of sound propagation are necessary. Third, the material of the absorber has to be temperature resistant in order to attain temperatures exceeding the auto-ignition temperatures of easily ignitable combustibles. Finally, its thermal conductivity has to be low so the heat can accumulate and is not dispersed into the liquid. These conditions tremendously limit the number of suitable materials. They are in accordance with recently published investigations on the thermal behavior of different ultrasonically insonified materials [11].

The acoustic impedance of liquids is of the order of 0.5–3 MNs/m^3 [4,7,8,12]. For instance, at room temperature, pentane has an acoustic impedance of 0.6 MNs/m^3, water and carbon disulfide of 1.5 MNs/m^3 and glycerin of 2.5 MNs/m^3. For the target to be insonified, a material of similar impedance is needed. Ceramics and metals (except for alkaline metals) which are very temperature resistant are inappropriate because their impedance is of the order of 25–50 MNs/m^3 [7,12], so reflection will be high at the phase interface between liquid and target material. Plastics have impedances of the order of 2.5–4 MNs/m^3 [7,12] and therefore closely match the impedance of liquids. The ability of glues, resins and plastics to transform acoustic energy into heat has been made use of in thermistor probes to measure ultrasonic intensity distributions [13]. According to experience, many plastics such as polymethyl methacrylate (PMMA) even melt in the focus of focused ultrasound. As their melting point is at approx. 150 °C, ordinary plastics do not seem suitable for ignition tests with vapors and gases. However, there are some plastics specifically designed for high temperature applications that endure temperatures of several 100 °C, which therefore are appropriate.

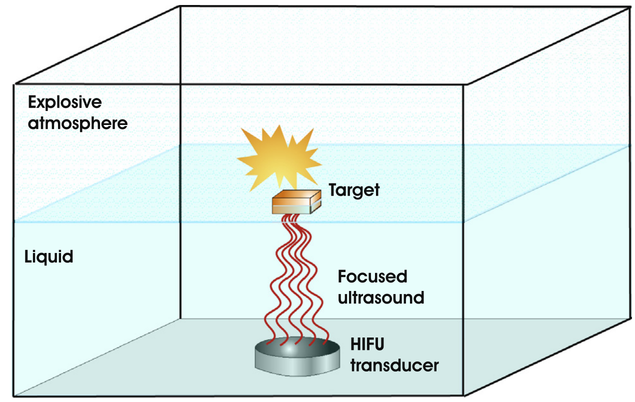

Fig. 1. Worst-case situation for the incendivity of ultrasound coupled to liquids with respect to an explosive atmosphere at the liquid surface.

As mentioned above, focused ultrasound is used to create a hot spot on an insonified target material which is fixed at the liquid surface. Hence, for ignition, an explosive atmosphere with a low auto-ignition temperature is needed at the liquid surface. Vapors and gases are grouped into temperature classes of similar standardized auto-ignition temperatures [14]. Thus, for the analysis of the incendivity of ultrasound at liquid surfaces, representatives of these temperature classes can be selected.

The standard auto-ignition temperature is a value determined in a standardized apparatus. The actual ignition temperature in a specific setup can differ significantly since it depends, among other things, on the size of the hot surface, concentration, turbulence and humidity. However, it helps to classify vapors and gases with respect to their hazardousness in connection with hot surfaces.

On the basis of these considerations, the worst-case situation for the incendivity of liquid-borne ultrasound at a liquid surface can be summarized. It consists of a focusing MHz ultrasound source whose focus is placed on a target at the liquid. The target is made of a temperature-resistant material that closely matches the acoustic impedance of the liquid and has a high acoustic absorption coefficient.

Generally, a wave propagating in the direction of $\vec{x}$ can be described by $p(\vec{x}, t) = p_0(\vec{x}, t) \cdot e^{-\alpha \cdot \vec{x}}$ [8], where p_0 is the undisturbed pressure wave and α the absorption coefficient of the medium. Thus, concerning the target's dimensions, it has to be larger than the acoustic wavelength to effectively absorb the sound wave and wide enough to stabilize the liquid surface against scattering. Moreover, it has to be mechanically fixed at the surface so it will not be pushed away by the acoustic radiation pressure. Adjacent to the target at the liquid surface, an explosive atmosphere at an easily ignitable concentration with a low auto-ignition temperature is needed. Schematically, this worst-case situation is depicted in Fig. 1.

3. Experimental setup, metrological equipment and procedure of ignition tests

In chapter 2, a worst-case situation for ignition triggered by liquid-borne ultrasound was derived at the liquid–gaseous phase