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# Investigations on the sound field between waveguide and counterpart induced by high-intensity focused ultrasound in thin polymer films

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ABSTRACT

The use of high-intensity focused ultrasound (HIFU) to heat polymer films is getting more in focus of interest in the industry due to some advantages e.g. low damages of thin polymer films during film processing or cost reduction of the processing tool. The capability to heat thin polymer films using a solid waveguide transducer was already reported in the literature. However, some significant hurdles persist: the physical principles responsible for the heating of thin polymer films are not fully understood. This study aims to investigate the sound field occurring in thin polymer films between a solid waveguide transducer (having a resonance frequency of 1.1 MHz) and a solid counterpart and compared it to the sound field in mm-thick polymer sample. An analogy between the sound field measured in water and the sound field inside polymer films during the heating process is done. The sound field between counterpart and solid waveguide is analyzed by means of membrane hydrophone sound field measurements and finite element simulations. The impact of the transducer-counterpart gap size is studied. This investigation reveals that the behavior and characteristics of the sound field in water in a transducer-counterpart gap differ considerably from each other depending on the gap size. When the gap is smaller than a wavelength, the sound cannot be focused within the waveguide-counterpart gap and complex interferences occur inside the small gap. Furthermore, the investigation showed that similarities occur between the sound field measured in water and the sound field calculated in polymer. These findings are relevant for the understanding of HIFU-based processes involving thin polymer films.



## 1. Introduction

High-intensity focused ultrasound (HIFU) has been used in medicine for tumor treatment since 1942 [1–3]. HIFU consists of the focusing of a sound beam of high intensity in a localized part of the human body using an ultrasonic transducer [2,3]. The focusing of the waves generates a high energy density in the body leading to tissues overheating and damage, due to the absorption of energy in tissue, without adverse effects on the surrounding regions [2,3]. Recently, HIFU has also been appeared in industrial applications like sonochemical applications for surface treatment and polymer heating [4–6]. Hallez et al. [4] investigated the thin layers surface treatment and preparation using ultrasound. The interaction between thin acrylic polymer films deposed on a stainless steel substrate and ultrasonic waves in a sonoreactor at 750 kHz and 3 MHz as well as the ultrasonic energy absorption ability of the polymers were analyzed [4]. Piezocomposite transducers with a resonance frequency of 750 kHz and 3 MHz were used to sonicate thin layers coated on stainless steel substrates inside a water filled sonoreactor. Using Sonochemiluminescence, Fricke dosimetry and Particle Image Velocimetry technique (PIV), the sound field of the transducer was characterized to allow for a good knowledge of the sound field properties in terms of cavitation and acoustic streaming in order to study the interaction between sound field and polymer films. Hallez et al. [4] showed that not-cross linked acrylic resin layers absorb the ultrasonic energy and fuse, whereas the cross linked samples were mechanically eroded due to cavitation. Liu et al. [5] presented a study about the impacts of polymer structures and ultrasonic power on the HIFU-induced heating behaviors appearing in different polymer materials (having thicknesses varying between 0.4 mm and 5 mm) in order to improve the knowledge about effects and mechanisms of HIFU on polymer matrix for the release of drugs from a polymeric stent. A transducer with a working frequency of 1.1 MHz irradiated

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polymer samples located at the surface of the water in a water tank. Recording the temperature inside the sample with infrared thermo-camera, Liu et al. [5] observed that the heating inside the sample occurs quickly but differs strongly, depending on the polymer structure (particularly on the macromolecular chains configuration) and the polymer thickness: the thicker the sample is, the higher the thermal equilibrium temperature is and the slower the temperature rise is.

All the investigations of the interaction between polymer films and HIFU described above were carried out in a water tank, whereas Oehm et al. [6] [7] investigated for the first time the HIFU-induced thermal effects in 320 μ m thick low density polyethylene films using a solid waveguide transducer surrounded by air. The ultrasonic transducer, composed of a curved piezoceramics and a solid waveguide, was used to sonicate two polymer films pressed between the transducer and a sapphire plate with a pressure of 4 N/mm$^2$. The temperatures inside the polymer films were recorded using an infrared thermography system and a 45° tilted mirror [6]. Oehm et al. [6] found that there is a major difference between the heating behaviors of low density polyethylene films induced by HIFU in water or with a solid waveguide. Whereas Liu et al. [5] found an homogeneous heating and structure of irradiated zone of the polymer, Oehm et al. [6] measured a temperature rise up to 680 K/s, however, in form of local temperature hot spots, localized mainly in the middle of the sonicated area, forming an inhomogeneous heating inside the polymer films. Observing the structure of the sonicated sample, Oehm et al. [6,7] identified air bubbles sited where the hot spots were measured. Additionally, the authors found that a secondary heating appeared at the border of the waveguide tip. Recently, Koo Sin Lin et al. [8] published that the polymer heating induced by HIFU using a solid waveguide depends strongly on the polymer thickness: when the polymer thickness is thinner than a wavelength in the polymer, the polymer heats quickly but the maximum temperature does not appear inside the theoretically calculated sound field focus of the transducer. O'Neil et al. [9] and Hamilton et al. [10] reported that the focusing of waves is the result of the overlapping of converging waves traveling in the same medium and having the same phase, leading to a constructive addition of the wave amplitudes. According to the literature [9–12], wave interference occurs when several waves travel in the same medium, where the medium extends in an area larger than a wavelength. In the case studied in [8], the focusing of waves is not possible in the thin polymer films, however, the polymer films are nevertheless heated. Regarding to [13], the area where the sound is focused is spread in a width $b_{fFZ}$ and a length $l_{fFZ}$ calculated with the following equations:

$$b_{fFZ} = 0.257 \frac{\lambda F_{geo}}{r_a} \quad (1)$$

$$l_{fFZ} \approx 1.8 \frac{{F_{geo}}^2}{r_a} \quad (2)$$

where $F_{geo}$ is the geometrical focal length, $\lambda$ the wavelength in the material and $r_a$ the transducer aperture radius [13]. These equations are only verified when the waves travel through the same material from the transducer to the focal area. The waves cannot completely focus in polymer films thinner than $l_{fFZ}$. Thus, the physical principles that are responsible for the phenomenon observed by [8] remains poorly understood: heating inside thin polymer films occurs despite the thickness of the films being smaller than a wavelength. It means that an ultrasonic energy is absorbed locally by the polymer films, even though no focused wave propagation can occur in such a small area. It is particularly interesting to investigate how the sound field is built in the thin polymer films and which mechanisms are responsible for the occurring polymer film heating.

There is currently no practical method available to measure the sound pressure inside a polymer film pressed between two solid non transparent parts. The only possibility is to measure the vibrations at the surface of the thin polymer films using vibrometry. However, this method does not allow to measure the sound pressure inside the polymer film. In this study, we propose to make an analogy between the sound field in polymer films having a thickness thinner than a wavelength and the sound pressure distribution in water between waveguide and counterpart, because the material properties of water and low density polyethylene (LDPE) like sound velocity and density have the same order of magnitude. The sound velocity was measured around 1480 m/s in water and was found to be 1030 m/s in LDPE [14]. The density is 1000 kg/m$^3$ and 923 kg/m$^3$ for water and LDPE respectively [14]. Moreover, the sound field investigation was carried out for different gap distances in order to understand the difference between the mechanism of heating induced by ultrasound in thin polymer films and in mm-thick polymer samples. Hence, the sound field induced by a transducer with a solid waveguide between waveguide tip and counterpart was measured using a membrane hydrophone in a water tank. In addition, a finite element simulation model was developed to calculate the radiated sound field and compare it to the experimental results. This study contributes to understand the effects and mechanisms of thin polymer films heating induced by HIFU. These findings are particularly relevant for packaging films processing, where the polymer films are typically thinner than 250 μm.

## 2. Methods

### 2.1. HIFU system

HIFU ultrasonic applicators, which consist of an ultrasonic transducer containing a spherically curved piezoceramics and an aluminum waveguide [6,8], are used for this investigation. The system is shown in Fig. 1. The diameter of the piezoceramics is 64 mm and the geometrical focal length 48.5 mm. The waveguide length is 48.4 mm. The focus of the sound beam is close to the waveguide tip surface as explained by Oehm et al. [6]. The waveguide coupling surface has a diameter of 3 mm. The nominal resonance frequency of the thickness mode is 1.096 MHz. Both parts of the ultrasonic applicator, the piezoceramics and the waveguide, are mounted with two components epoxy resin. The cw-signal is generated by a function generator coupled to a RF power amplifier as described in [8]. As mentioned by Oehm et al. [6] an impedance matching

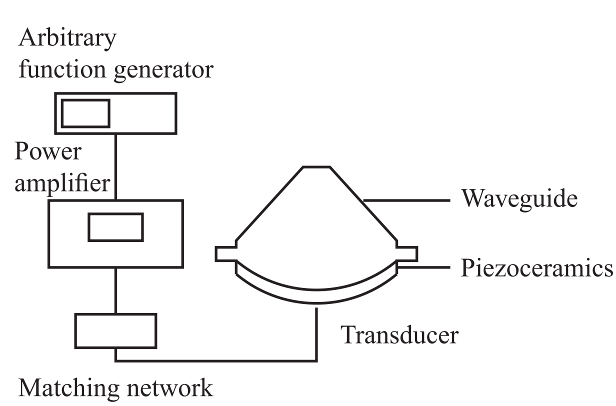


**Fig. 1.** HIFU system, the HIFU ultrasonic transducer consists of a spherical curved piezoceramics and an aluminum waveguide [6–8].