Piezoceramic Ultrasonic Transducer for Preventing the Calcarous Depositions on the Inner Walls of Heat Exchangers

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Abstract. An ultrasonic sandwich type transducer was designed for preventing and cleaning the undesired calcarous depositions on the inner walls of heat exchanger and pipes. It uses as active elements two piezoceramic rings sandwiched between a cylindrical back end part of stainless steel and a front end piece of duraluminum, terminated with a convex shaped stainless steel tip. The whole construction is clamped by a hardened steel bolt at a prestressed pressure of about 25 MPa. The transducer works in immerse regime being tightly screwed in a flange of the heat exchanger. The ring shaped piezoceramic active elements are made of a special lead titanate zirconate material, whose main piezoelectric properties do not change significantly up to temperatures of 200 ^{o}C, so that the transducer can be effectively used in hot water with high efficiency. The ultrasonic vibrations produced by the piezoactive elements, when excited by an electric signal from a high frequency high power generator, are transmmited and amplified by the front end cap and diffused within the water by the convex shaped stainless steel tip, so that one prevents, to a high percentage, any undesired deposition on the metallic wall because both water and walls are in permanent vibration. The transducer can be easy used with any type of heat exchanger just by changing and adapting the screwed part of the front end piece.

Introduction

At present the piezoelectric transducers have become the most important electromechanical type of transducers that convert high frequency electrical oscillations into mechanical vibrations or vice versa by the use of the direct or converse piezoelectric effect. Such devices have a great variety of forms and sizes depending on the specific field of applications, such as cleaning, welding, non-destructive testing, medical imaging, automotive industry, or domestic appliances [1,2]. During the last years there was an increased demand for high intensity high efficiency piezoelectric ultrasonic transducers for industrial use in high capacity cleaning tanks, ultrasonic treatment of liquids in large scale, disintegrating sludge or deaglomerating and reducing germs. Such transducers require high quality piezoceramic materials, since sometimes they work at temperatures above room temperature and the properties of ceramics active elements must not be irreversible altered.

For this purpose we developed a hard type piezoceramic material with rather stable properties up to nearly 250 ^{o}C, to be used for a high power ultrasonic transducer, designed to prevent the calcarous depositions on the walls of heat exchangers, in the petroleum industry. The present paper describes the results obtained on the material and transducer.

It is known that pure PZT type materials can be tailored to a great variety of materials with special and desired properties by using different ions to partially replace any of the basic ions of PZT on both A and B positions of the perovskite lattice. Generally, the effect of most additives on the material properties is already known [3] so that by a proper choice of additives one can obtained materials with desired properties.

1. Experimental results and discussion

1.1. Piezoceramic material

The starting raw materials we used in this investigation were oxides and carbonates of p.a. purities. They were weighted to match the following chemical stoichiometric formula: $Pb_{0.98}Sr_{0.01}Bi_{0.01}Mn_{0.02}Sb_{0.03}Ni_{0.03}Zr_{0.45}Ti_{0.47}O_3$. The reasons to chose this composition consisted in the known enhancing effect of these additives on the piezoelectric properties of the basic PZT material. Thus Sr and Ni increases the dielectric permittivity and charge constant d_{33} [4, 5]. Sb is effective in suppressing the grain growth [6] and Mn increases the electromechanical coupling coefficient and decreases the dissipation factor tanδ [7, 8]. In order to produce high dense material with a rather uniform fine grains microstructure, some supplementary additives like CeO_2, SiO_2 and PbO were added to the basic composition in a total amount of 3%. This glassy like phase forms a liquid phase which helps to enhance the densification degree [9-12]. In addition, the excess PbO and the other sintering aids helps to lowering the sintering temperature [13-15] and sometimes control the grain growth process.

The stoichiometric amounts of oxides were mixed together for 6 h in a planetary ball mill in methanol media, and then were calcined at 850 ^oC for 3 h. The calcined product was subjected to a rather prolonged wet milling for 24 h in a planetary ball mill, in agate vessels, at a ball/powder weight ratio of 2:1, in order to produce a fine submicronic powder with an increased reactivity. The microscopic examination of this powder showed, indeed, rather spherical grains with a mean diameter of about 0.15 μm. Disc shaped samples of 15 mm diameter and 1mm thick were uniaxially pressed from this powder and sintered at 1200 ^oC for 6 h, in order to characterize the ceramic material.

The density of sintered samples was determined by the Archimede method and then the samples were mechanically processed and electroded with a silver paste and poled at 220 ^oC in a silicon oil bath under an electric field of 3kV/mm. The main piezoelectric properties at room temperature were determined by the resonance-antiresonance method by means of an impedance analyzer HP 4194A, after a 48 h relaxing period following poling. The results are shown in table 1.

Table 1. The main piezoelectric properties of material at room temperature

Parameter	Symbol	Unit	Value
Density	**ρ**	g/cm^3	7.74
Mechanical quality factor	$\mathbf{Q_m}$	-	1050
Electromechanical planar coupling coefficient	$\mathbf{k_p}$	-	0.61
Piezoelectric charge constant	$\mathbf{d_{33}}$	10^{-12} C/N	405
Piezoelectric voltage constant	$\mathbf{g_{33}}$	10^{-3} Vm/N	28
Relative dielectric permittivity	$\mathbf{\varepsilon_r}$	-	2300
Dielectric loss factor	**tanδ**	10^{-3}	2.8
Curie Temperature	$\mathbf{T_C}$	^oC	292

The data shown in table 1 illustrate that the material is rather fully densified (about 97.5% of theoretical density [11]) this being due to the increased degree of reactivity of the initial submicronic powder obtained by a prolonged milling and to the presence of the liquid glassy phase [9, 15] which assure a better wettability and presumable solubility of the solid phase into the liquid, followed by reprecipitation. The sintered ceramic shown in figure 1 shows a rather pore free structure and hence a high density. The other mechanoelectrical data indicate that such a material is a “harder” type material that can be successfully used for high power ultrasonic transducers.

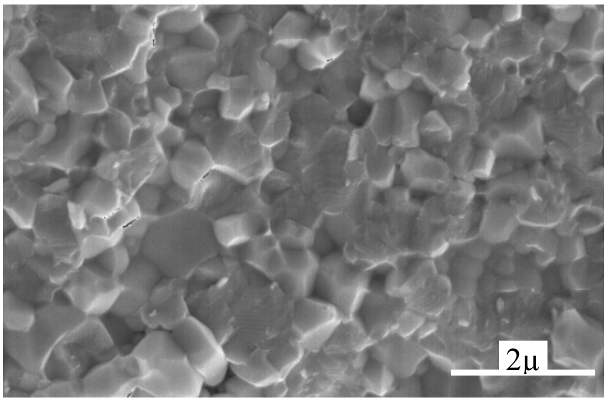

Fig. 1. Fracture SEM image of a typical material sample sintered at 1200 ^{o}C for 6 hours

In order to see how efficient should be this material over a larger temperature interval, we have measured the temperature dependence of the main parameters between room temperature and the Curie point. The results are shown in figures 2 *a)-f)*. The most remarkable thing about these results is that nearly all piezoelectric parameters, except charge and voltage constants, show a rather constant and steady variation with temperature over a large temperature interval up to nearly 250 ^{o}C after which their values drop much more rapidly to zero ($\mathbf{k_p}$, $\mathbf{Q_m}$, $\mathbf{d_{33}}$ and $\mathbf{g_{33}}$) or increase to very high values ($\boldsymbol{\varepsilon_r}$ and **tanδ**) by approaching the Curie temperature, due to the sudden depoling effect of ceramic. Such a behavior is benefic for transducers in that they can be safety and efficiently used up to 250 ^{o}C, without any major risk to alter their functionality, but the most secure and recommended upper limit of working temperature must be taken at 200 ^{o}C.

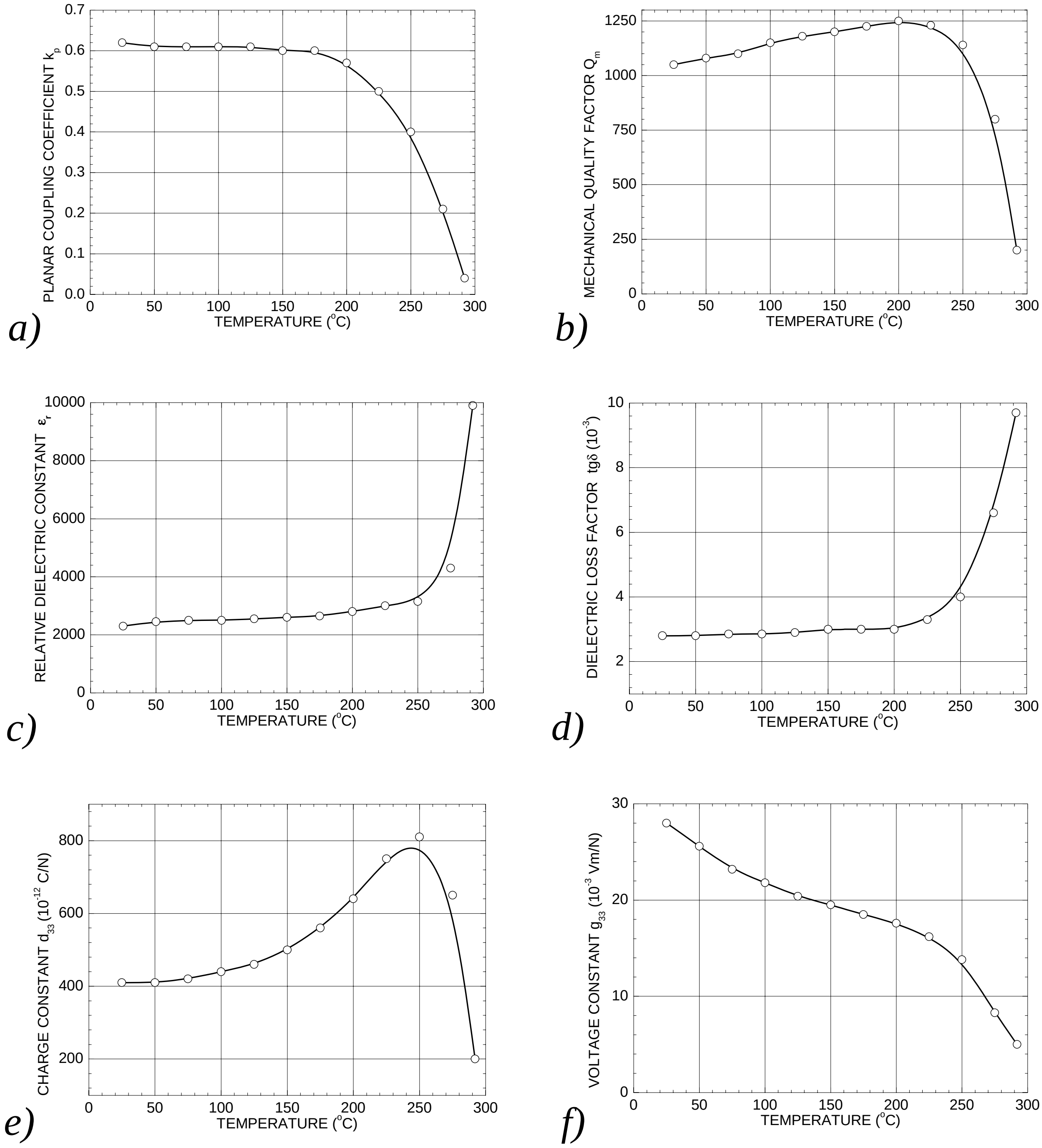

Fig. 2. The temperature dependence of the main piezoelectric parameters of the piezoceramic material: *a)* $\mathbf{k_p}$; *b)* $\mathbf{Q_m}$; *c)* $\boldsymbol{\varepsilon_r}$; *d)* **tanδ**; *e)* $\mathbf{d_{33}}$ and *f)* $\mathbf{g_{33}}$

1.2 The transducer

The transducer for high intensity applications has to be a narrow-band transducer of rather low frequency, around 20 kHz. Such a transducer is a sandwich type transducer of half-wave resonant length expander structure consisting simply of paired piezoceramic rings sandwiched and mechanically prestressed between two metal blocks in the axial direction by means of a bolt, at a typical compressive stress of the order of 25-30 MPa. For this purpose, using the material described in § 1.1, we have pressed rings with an outer diameter of 45 mm, inner diameter of 18 mm and thickness of 8 mm, and sintered them at 1200 °C for 6 h. These rings were then mechanically processed by polishing to the following final size: 40 mm outer diameter, 15 mm inner diameter and 6 mm thickness. Nickel electrodes were then applied by a chemical procedure, and the rings were poled in an electric field of 3 kV/mm at 220 °C in an silicon oil bath. These rings were piezoelectrically tested by means of the HP 4194A analyzer so as to fulfill the practical criterion requirement: $f_a/f_r > 1.06$ where f_a and f_r are the antiresonance and resonance frequencies respectively [17].

The construction of the transducer consists in the following: two active ceramic rings are sandwiched and prestressed by means of the bolt between a backing stainless steel block with a diameter of 42 mm and thickness of 40 mm and a front end structure of duraluminum having a rather complicated shape as can be seen in fig. 3*a)*.

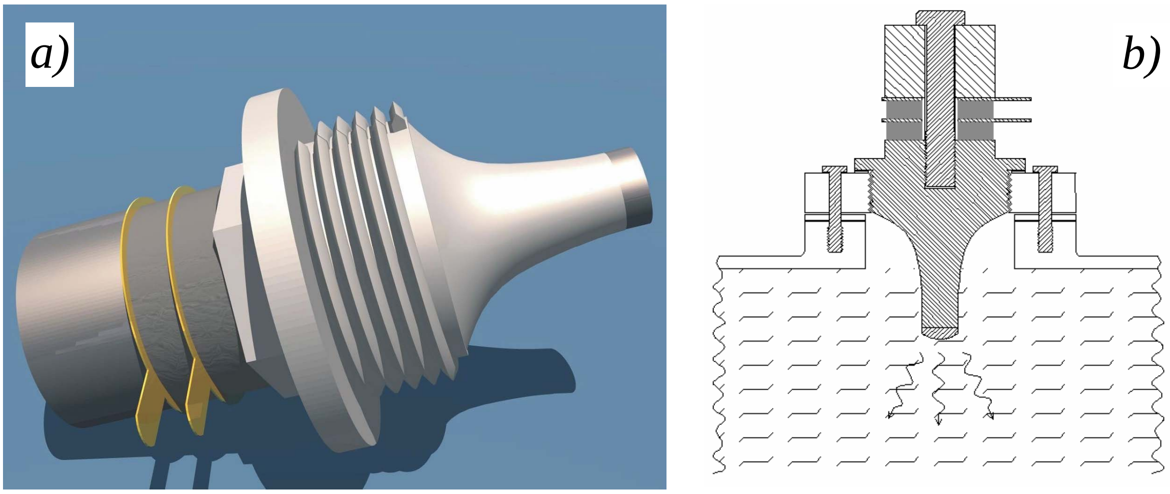

Fig. 3. Piezoceramic transducer: *a)* General view; *b)* Mounted in the heat exchanger

The particularities of this front structure are the screwed portion for fixing it in the flange of the tank of the heat exchanger and the horn like end amplifier, terminated with a small protection convex piece of stainless steel. The horn is thus immersed in the flowing water like in fig. 3*b)* and the amplified vibrations are spread within the circulating hot water and the pipes net of the exchanger. In this way the calcarous particles as well as any undesired particle agglomerations are continuously expelled from depositing on the tank and pipe walls and forced to flow through the water stream.

The role of the tiny stainless steel convex piece mounted at the end of the horn is important in preventing the erosion and corrosion of the duraluminum horn. Figure 4*a)* illustrates the effect of ultrasounds and hot water on the end of the horn. After about 500 h of functioning in a circulating water of about 200 °C throughout the heat exchanger. The water characteristics were on average the following: surface tension σ=66.5 N/m, dynamic vyscisity $\eta=1.34\cdot10^{-3}$ daP, dielectric permittivity ε_r=4.8 and loss tanδ=1.9 .

Fig. 4. Micrograph images of the surfaces of the horn like end piece after 500 h functioning: *a)* Duraluminum unprotected; *b)* Stainles steel protected

One may remark that the middle and the marginal areas of aluminum unprotected face are just a little less affected by the corrosion than the median zone. This indicates that the ultrasonic vibrations are more concentrated in the median zone than in the middle and the marginal side of the horn end. One may also notice the radial tendency of the corrosion for which we cannot find a pertinent explanation so far. All these erroding phenomena were avoided just by mounting the tiny convex piece of stainless steel at the end face of the horn. An inspection of its surface, after a similar functioning time, shows a good and clean surface without any trace of errosion on it as can be seen in fig 4*b)*.

As concern the efficiency of the ultrasounds in preventing the undesired deposition on the tank and pipe walls of the heat exchanger, the preliminary results of a laboratory experiment are very encouraging in that no deposition were found after 500 h of US applications in a tank of 500 liters capacity, with circulating hot water, compared with a similar one without US where some non uniform calcarous deposited strata were found on about 40% from the whole inner surface of the tank. Experiments on an industrial heat exchange are now in progress.

Summary

A hard type piezoelectric material was designed for a high intensity piezoelectric transducer to work in hot water of heat exchangers. The material properties remain practically unaltered up to 200 ^{o}C, but it can also work for shorter times up to 250 ^{o}C.

High quality rings from this materials were produced by sintering at 1200 ^{o}C for 6 h. These rings were used to produce a sandwich type US transducer, destined to prevent the calcarous depositions and undesired particle agglomeration in the heat exchangers from industry.

The preliminary experimental results obtained on a laboratory tank of 500 liters regarding the effect of ultrasound on the undesired deposition are very encouraging and the tests with an industrial heat exchanger are now in progress.

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