

IMPROVING THE THERMAL STABILITY OF 1-3 PIEZOELECTRIC COMPOSITE TRANSDUCERS MANUFACTURED USING THERMALLY CONDUCTIVE POLYMERIC FILLERS

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Abstract: *With a view to improving the thermal stability of ultrasonic transducers prepared using 1-3 piezoelectric composites, the use of front face layers manufactured from thermally insulating and partially thermally conductive polymeric materials has been investigated. Experimentally, heat dissipation was investigated, in air and in water, using different transducer configurations and the advantage of including a front face layer manufactured from thermally conductive polymeric material is demonstrated. The PZFlex finite element modelling package was utilised to assess the thermal diffusivity of each polymer in the different transducer configurations and was found to compare well with experiment.*

I. INTRODUCTION

Avoiding temperature increases during operation of an ultrasonic transducer comprising a 1-3 piezoelectric composite as the active element is an important issue. Previous work has concentrated on improving the thermal stability of 1-3 piezoelectric composites by studying the effect of changing the polymer used as a filler material during manufacture of the device. By increasing the glass transition temperature (T_g) of the polymer used as the filler material and by introducing thermally conductive particles into this high T_g polymer, improved thermal stability was demonstrated [1].

In this current paper, the potential benefit of preparing front face layers from thermally conductive materials, in preference to their thermally insulating counterparts, is explored. In this paper, an ultrasonic transducer whose active element comprises a 38% volume fraction piezoelectric composite, is studied. Electrical impedance measurements were conducted on the active element in an oven as a function of temperature. Air-backed transducers were prepared with front face layers manufactured from a thermally insulating and a thermally conductive polymer. Heat dissipation was investigated using the different transducer

configurations. Studies were carried out in air and in water and experimental results were compared with data determined using the thermal solver of the PZFlex finite element modelling package.

II. MATERIALS AND CHARACTERISATION

The polymers we have been investigating are all based on the thermosetting epoxy resin MY750/HY906/DY062 (A), a polymer with T_g measured at 151°C [1], supplied by Vantico [3]. Previous work highlighted that commercially available polymers containing thermally conductive particles tend to demonstrate high longitudinal and shear velocities, low Poisson's Ratio and very low longitudinal and shear attenuation values [1]. As a result, these commercial materials are not ideal for use in preparing ultrasonic transducers. Preparation of polymers containing thermally conductive particles within CUE allowed materials with more desirable properties to be developed. Within the CUE laboratory, A was modified with thermally conductive additives. Sample B contained 30vol% aluminium oxide (Aldrich, 99.7%) and sample C contained 24vol% aluminium nitride (Aldrich, 98+%). Both additives have a particle size of less than 10 micron.

In order to assess the effect of the particulates on the elastic properties and to provide data for finite element modelling, acoustic properties were measured using a through transmission time-of-flight technique [2]. The longitudinal, V_l , and shear, V_s , acoustic wave velocities were measured at 500kHz, allowing calculation of Poisson's Ratio (ν), Young's modulus (E), the shear modulus (G) and the specific acoustic impedance (Z) of each material. The attenuation of each wave type, α_l and α_s , was also determined. In addition, thermal conductivity (k) was calculated from thermal diffusivity values measured using a laserflash technique and heat capacity values (C_p) determined using differential scanning calorimetry. The T_g for each material was measured as the temperature of maximum damping,

corresponding to the maximum $\tan \delta$, in dynamic mechanical thermal analysis. These results were discussed in detail previously [1] and the salient mechanical and thermal properties are shown in Table 1.

Polymer	A	B	C
Vl (m/s)	2342	2813	2636
Vs (m/s)	1094	1464	1345
ρ (kg/m ³)	1150	2007	1673
ν	0.360	0.314	0.324
E(GPa)	3.75	11.3	8.01
B(GPa)	4.47	10.14	7.60
G(GPa)	1.38	4.30	3.03
Z (Mrayl)	2.69	5.65	4.41
α_l (dB/m)	174	174	174
α_s (dB/m)	243	400	382
Tg	151	154	145
k (W/mK)	0.15	0.38	0.41

Table 1 Acoustic and Thermal Characterisation

From Table 1, materials B and C exhibit increased stiffness as a result of adding thermally conductive particles and this is demonstrated by the increased longitudinal and shear wave velocity values, increased density and decreased Poisson's Ratio values. The shear attenuation value was also higher in samples containing thermally conductive particles. Increased scattering from the particles in the sample could cause this effect. On introduction of the thermally conductive particles, the thermal conductivity increased from 0.15W/mK measured for A to 0.38W/mK and 0.41W/mK respectively measured for B and C. In this study polymer A is considered thermally insulating and polymers B and C are considered thermally conductive.

As reported previously [1], the thermal stability of a 1-3 piezoelectric composite was enhanced when both polymers B and C were used as filler materials in the device. The potential for these thermally conductive materials to further improve the thermal stability of an ultrasonic transducer when configured as front face layer materials is investigated here.

III. TRANSDUCER EVALUATION

A piezoelectric composite devices of 38% volume fraction was constructed employing polymer B as the filler material. Details of the microstructure are shown in Table 2. Three K-type thermocouples were embedded

in the polymer kerf, at half the pillar height, in order to monitor the temperature changes in the composite.

Polymer	B
Ceramic (PZT)	5A
Kerf (mm)	0.61
Pitch (mm)	1.68
Thickness (mm)	4.89
fe (kHz)	313
fm (kHz)	360

Table 2 Constructional Parameters of the Piezoelectric Composite Device

Front face layers were manufactured from thermally insulating polymer A and thermally conductive polymer C. Heat dissipation studies in air and water were undertaken on the unmatched transducer and on the two other transducer configurations. Temperature rises were induced in the transducer by electrically driving the device at a range of relatively low input powers. The temperature rise was monitored in the air and water loaded cases over a five minute period. Experimentally measured results are presented for each transducer configuration operating at 315kHz with average input power levels of 0.4W, 0.8W and 1.4W. As expected, it was found for all transducer configurations, that temperature increases became correspondingly greater as average input power levels increased and the temperature increases recorded in air were always greater than those recorded in water. In this study, the behaviour of the three different transducer configurations in water is of most relevance and are summarised in Table 3.

Average Input Power	0.4W	0.8W	1.4W
Unmatched	0.9°C	1.8°C	2.9°C
Polymer A Layer	5.8°C	11°C	22.4°C
Polymer C Layer	3.3°C	5.9°C	10.8°C

Table 3 Measured temperature increases after 5 minutes for the three transducer configurations operating into a water load

In the unmatched configuration the electroded face of the 1-3 piezoelectric composite is directly in contact with the water load. Water has the ability to operate as a very efficient heat sink and is able to provide effective cooling. Recorded temperature increases are, therefore, relatively small at all average power levels.

When both polymer A and polymer C are included as front face layer materials, the direct contact between the

front face of the 1-3 piezoelectric composite and the water heat sink has been lost. A finite time is required for the heat to pass through the front face layer to the water and temperature increases are recorded. At all average input power levels, a more pronounced temperature increase was recorded using polymer A because the front face layer material is less thermally conductive.

Since transducer manufacture typically includes use of a front face layer, these results suggest that it is more beneficial to use a front layer manufactured from a thermally conductive material in preference to that prepared from a thermally insulating material.

IV. FINITE ELEMENT MODELLING

FE models were constructed using the PZFlex code [4] to investigate the thermal response. The unit cell of the device was modelled in 3D using quarter symmetry with air or water as the load medium. The temperature profile was recorded at the position of the thermocouple; i.e. centre of the kerf at half the device height. Figure 1 shows the theoretical and experimental temperature response for the unmatched transducer operating in air and water with an average input power of 0.4W. Figures 2 and 3 show the response of the transducer with thermally insulating and thermally conductive layers respectively, operating with an average input power of 0.4W. In all cases, the correlation between theory and experiment is good.

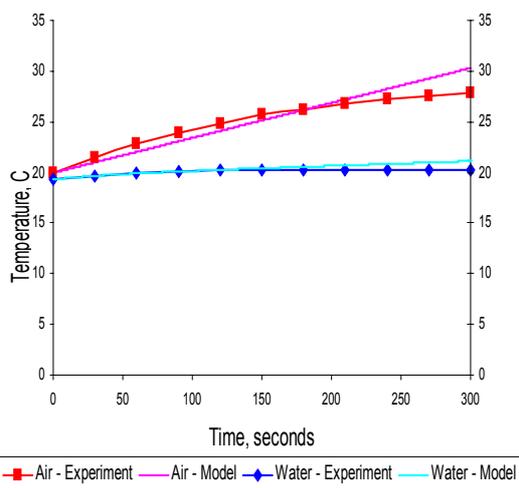


Figure 1 Comparison of Experimental and Theoretical Behaviour for unmatched transducer at 0.4W

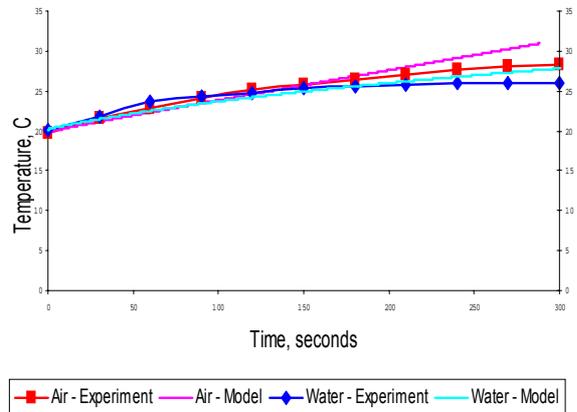


Figure 2 Comparison of Experimental and Theoretical Behaviour for the transducer with front face layer of polymer A at 0.4W

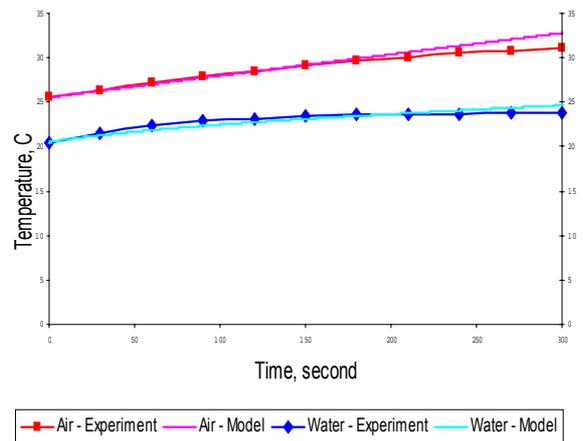


Figure 3 Comparison of Experimental and Theoretical Behaviour for the transducer with polymer C as the front face layer at 0.4W

V. DISCUSSION

Figure 4 illustrates the theoretical temperature profile across the thermally insulating and thermally conductive layers after a 5-minute period of transducer operation at 0.4W, as determined using PZFlex. The data has been normalised to the temperature at the front face of the piezocomposite element in each configuration.

From Figure 4, a lower temperature gradient for the thermally conductive layer has been predicted. This indicates that this material is efficiently conducting heat from the transducer into the load medium. This predicted enhanced flow of heat produces the lower temperature rise in the active piezoelectric element, as

discussed in Sections III and IV. Whereas, the lower thermal conductivity of the insulating material limits the transfer of heat across the layer, resulting in higher temperature effects in the transducer. Consequently, the thermal solver in PZFlex could be used in the design of matching layer materials when operation at higher input power levels is relevant.

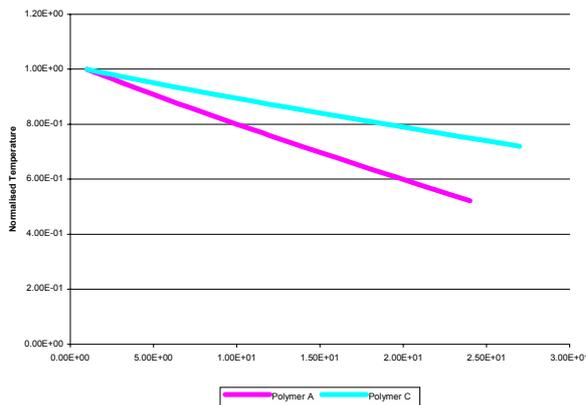


Figure 4 Thermal diffusivity recorded using PZFlex for the thermally insulating and thermally conductive layers operating at 0.4 W into a water load

Since these materials will be used in applications requiring high power, it is of interest to examine data recorded experimentally at higher power levels in this study. In Figure 5, the temperature profile for each of the transducer configuration operating into water at an average input power of 1.4W is shown. At this higher input power level, the improvement in the temperature stability when the thermally conductive layer is incorporated in preference to the thermally insulating layer is clearly shown.

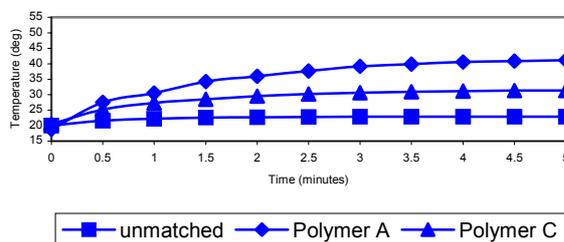


Figure 5 Temperatures recorded for the three transducer configurations operating at 1.4W

VI. CONCLUSIONS

The thermal stability of a 1-3 piezoelectric composite can be improved by using thermally conductive polymers as the filler material. By consideration of the properties of the front face layer materials, there is the potential to further improve the transducer thermal stability. It is a requirement with piezocomposite design to incorporate a front face matching layer for operation into a water load medium. The design of such layers is generally based on the acoustic impedance and attenuation properties of the material. This work has demonstrated that the thermal conductivity of the material must also be considered in the design process. Materials possessing high thermal conductivity have been shown to improve the thermal stability of a 1-3 piezocomposite transducer under a variety of drive conditions. Importantly for high drive applications, the thermal properties of a matching layer material will have a significant effect on the piezoelectric transducer performance. Good correlation was observed between experimental and theoretical values using the thermal solver in PZFlex. Hence, it is anticipated that the PZFlex finite element modelling package could be applied to predict thermal behaviour involving higher power levels and will be able to be used as a design tool for virtual prototyping in future work.

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