Magnetic Nanofluids in Ultrasonic Testing

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ABSTRACT

The use of the magnetic nanofluid as the bonding medium find an ever increasing application in ultrasonic non-destructive testing method.A thin layer of magnetic nanofluid which is adhered on the transducers face with a permanent magnet enhance the ability of movement and provide good bonding for transducers. Using the results of the hydrodynamical analysis and these experimental data we evaluated the magnetic fluid losses when the transducer is moving along the tested surface. Measurements of the temperature dependence of the ultrasonic velocity, density, viscosity and surface tension of water-based, dodecane-based, kerosene-based, antifreeze-based magnetic nanofluids have been made. The obtained results can be use for the choice of an optimum type of magnetic nanofluid in the design of ultrasonic transducers.

Keywords: magnetic nanofluid, ultrasound, acoustic impedance, ultrasonic testing

1 INTRODUCTION

Ferroflud, also called magnetic nanofluid is synthesized colloidal mixture of non-magnetic carrier liquid containing single domain permanently magnetized particles, typically magnetite, with diameters of order 10 nm. To prevent particles agglomeration due to dipole– dipole interaction, they are coated with a stabilizing layer, for instance, a surfactant, the choice of which is determined by the type of carrier liquid [1] .

Ultrasonic defectoscopy is one of the non-destructive testing methods. When setting the tasks for calculating and designing ultrasonic defectoscopes, one also considers the problem of how to ensure maximal stability of the acoustic contact of the ultrasonic sensor with the control subject. Water, alcohol, mineral oils, glycerine and various special multicomponent liquids serve as a coupling medium [2]. The quality of the acoustic contact, which to a greater extent determines the sensitivity of an ultrasonic defectoscope, depends on the following parameters and physical properties of the coupling fluid: the thickness of the contact layer, acoustic resistance of the coupling fluid, the ultrasound absorption ratio in the coupling fluid, the wettability of the working surfaces by the coupling fluid and continuity of the contact layer. The authors of patent [3] enjoy the privilege of first using magnetic nanofluids to ensure acoustic contact in ultrasonic spectroscopy. The main advantage of this contact is associated with an opportunity to hold magnetic nanofluid in the working gap with the help of a magnetic field specific configuration created by constant magnets. Besides, there is an opportunity to scan the surfaces controlled, e.g. those of a pipeline, with the given advance speed of ultrasonic sensors. It is also a matter of great import to study the influence of a magnetic field on the velocity of ultrasound propagation in a magnetic nanofluid. However, it is historical that in one of the first experimental works on measuring the impact of a magnetic field on the ultrasound propagation velocity in a water-based magnetic nanofluid [4] there crept in a procedure error. According to [4], the change of ultrasonic velocity on the exposure to relatively weak fields (of several hundreds of gausses) amounted to $30 - 50\,\%$. These data served the basis for a number of inventions, e.g. various delay lines; they also provided grounds for critique of theoretical research on ultrasound propagation in magnetic nanofluids. Paper [5] pointed at the procedure error committed by the authors of work [4] when the latter were processing the experimental data. In paper [4] in order to determine the changes of phase ultrasonic velocity in a magnetic nanofluid when exposed to a magnetic field, they used a phase method, which essentially means measuring the phase shift between two harmonic signals, one of which passes through an acoustic cell with the studied magnetic nanofluid, whereas the other passes through a delay line. However, while processing the experimental data, the authors of [4] did not take into account the phase advance at the length equalling the distance between the piezoelectric converters, which led to as is shown in [5] an upward bias of the relative change in ultrasonic velocity by two orders. Thereafter, this result was proven experimentally and theoretically [6].

2 EXPERIMENTAL DATA

One of the major requirements for the coupling fluid is for it to provide a reliable acoustic contact when carry-

Table 1: Experimental data

Sample	$\rho, kg/m^3$	$c, m/s$	$\eta \cdot 10^3$, $Pa \cdot s$
A1	1103	1718	7.73
A2	1119	1695	8.17
A3	1259	1572	25.91
K1	956	1228	1.78
K2	1064	1165	3.23
K3	1325	1132	7.60
K4	1565	1094	19.85
H	1101	1186	3.41
D	1135	1112	5.07
W1	1022	1473	1.11
W2	1058	1464	1.23
W3	1100	1440	1.39
W4	1135	1420	2.12
W5	1197	1416	2.43

ing out ultrasonic control in a wide temperature range,as well as to minimise the magnetic nanofluid waste when scanning the object at a fixed speed. In this regard, there have been studied magnetic nanofluids based on: the antifreeze (A1,A2,A3), the kerosene (K1,K2,K3,K4), the heptane (H), the dodecane (D), and the water (W1, W2, W3, W4). The antifreeze was the mixtures of ethylene glycol and water with ratio 2/3 and 1/3 of volume parts respectively.

The physical properties of samples, corresponding to temperature $T = 293\,K$, are given in Table 1.For the water-based magnetic nanofluids, the measurements were taken in the temperature range of $273 - 313\,K$, whereas for the antifreeze-based ones the measurements were conducted in the range of $233 - 313\,K$. Temperature dependence of the ultrasonic velocity c in water-based magnetic nanofluids qualitatively repeats a similar dependence for pure water. In antifreeze-based fluids, the ultrasonic velocity decreases linearly with the temperature growth. Temperature dependence of density ρ in all samples studied is close to linear one.

With the temperature increase, the shear viscosity η decreases nonlinearly, so, for instance, for A2 sample the shear viscosity reduced by more than two orders.

2.1 ACOUSTIC IMPEDANCE

The acoustic impedance Z of a material is defined as the product of its density ρ and sound velocity c,

$$Z = \rho c \qquad (1)$$

The attenuation does not contribute significantly to the acoustic impedance. Even in highly concentrated colloids at high frequency, when the attenuation becomes about $1000\,dB/cm$, it still contributes only 2% to the acoustic impedance. This allows us to approximate the acoustic impedance as a real number. Acoustic impedance is important in determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedance [7].

Basing on the obtained experimental results, we have calculated the acoustic impedance of samples. Figure 1 features the dependence of acoustic impedance on the antifreeze-based,kerose, magnetic nanofluids temperature.

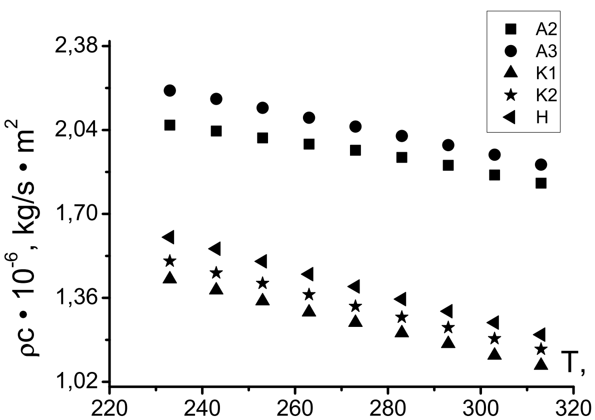

Figure 1: Acoustic impedance of different magnetic nanofluids *versus* temperature.

In the water-based magnetic nanofluids with the increase of solid-phase particles concentration, the temperature dependence of wave resistance is less pronounced (Figure 2), and is practically non-existent in sample W5.

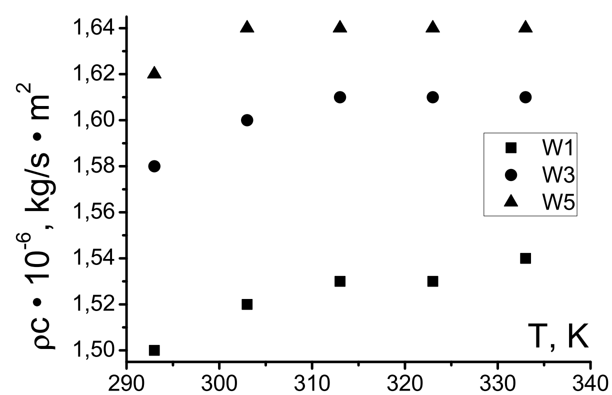

Figure 2: Acoustic impedance of water-based *versus* temperature.

2.2 SURFACE TENSION OF MAGNETIC NANOFLUIDS

When performing optimization calculations of magnetic fluid contact, alongside with the afore-listed values we must know the temperature dependence of surface tension coefficient. In order to define this dependence, there has been elaborated a new method taking into account the specific properties of magnetic nanofluids [8]. The very pinch of the method is to generate gravitational capillary waves on the magnetic nanofluid surface with the help of static and varying magnetic fields, orthogonal to the fluid surface. Gravitational capillary waves excited in such a manner have been recorded by holographic interferometry in the colliding beams with the time averaging. He -Ne laser with wavelength of $0.63mk$ was used as a source of coherent radiation. The physical reason for forming standing waves on the magnetic nanofluid surface is a parametric swing of the free surface by a varying magnetic field. A layer of magnetic nanofluid was submerged in homogeneous, orthogonal to the surface static and varying magnetic fields, i.e.

$$H = H_0 + h\cos\omega t \tag{2}$$

with the amplitude of varying magnetic field h being considerably smaller than the value of the static magnetic field H_0. When carrying out this method, we took into consideration the restriction for the upper limit of H_0 change in order to prevent appearing static monotonic instability. The fields mentioned were created by two pairs of Helmholtz coils that were placed on the alignment table, which allowed setting the magnetic nanofluid surface orthogonally to the magnetic field intensity vector every time prior to conducting the measurements. The frequency of varying magnetic field varied within $10 - 60\,Hz$ range. Magnetic nanofluid was placed in Petri dish with inner diameter of $61\,mm$, the fluid layer thickness was $20\,mm$. With the help of stroboscopic illumination, we discovered that the frequency of standing waves oscillations coincides with the frequency of variable component of a magnetic field. The recording of holographic interferograms was done on a photo plate, the exposition time was 1 2.5 minutes. Under these conditions, we registered high-quality holographic interferograms which confirmed the stability of surface waves.

The dispersion equation of gravitational capillary waves of a magnetic nanofluid layer resting between the poles of a magnet has the form [9]

$$\omega^2(k) = \frac{\sigma k^3}{\rho} + gk + \frac{(\mu-1)^2 H_0^2 k^3}{4\pi\rho(\mu+1)}, \tag{3}$$

where k is the wave number, σ is the required surface tension coefficient, g is the gravitational acceleration, μ is the permeability of magnetic nanofluid. The last term of this equation is negligibly small.Therefore we calculated the surface tension using the following expression

$$\sigma = \frac{\rho\omega^2}{k^3} - \frac{\rho g}{k^2} \tag{4}$$

To ensure usability of the data obtained in engineering designs, the latter were approximated by the following dependences. For water-based magnetic nanofluids the dependence of surface tension coefficient can be satisfactorily described by the following expression:

$$\sigma(T) = 18.8\left(2.73 - \frac{T}{273}\right)10^{-3}$$

in the temperature range of $288 - 313\,K$. Similar relations are true for antifreeze-based magnetic nanofluids:

$$\sigma(T) = 16.3\left(3.32 - \frac{T}{273}\right)10^{-3}$$

in the temperature range of $273 - 303\,K$.

3 CONCLUSION

During magnetic fluid acoustic contact, there arises a problem how to minimize the irreversible loss of magnetic nanofluid that occurs when the defectoscope ultrasonic head moves on the product surface. Theoretical studies connected with calculating the thickness of the layer left on the surface as a function of surface movement speed and the parameters characterising the properties of the fluid are based on the findings of paper [10] . The peculiarity of such thin films flow is a significant role of surface tension and fluid shear viscosity. According to [11], a customary mode of liquid viscous flow with the constant thickness of the film is realized with Reynolds numbers not exceeding $20 - 30$. With $Re > 30$ there occurs a wave flow in the fluid film, which becomes an additional source of disturbances for acoustic signal passage. Besides, with small thickness of the coupling liquid layer, it can decompose into single drops due to a prevailing role of capillary forces. Paper [10] singles out two limit cases covering high and low velocities. The latter case is more common for a magnetic fluid contact, which corresponds to low velocity of fluid flow v:

$$v \ll \frac{\sigma}{d} \tag{5}$$

In this approximation, paper obtained an expression defining the rate of magnetic nanofluid consumption from the drop held by a system of magnets in a flat gap between two mutually shifting surfaces. The analysis was conducted for a thin layer, when viscous and capillary forces play the main role in forming a fluid film carried by a moving border. Thereat, it was experimentally discovered that the thickness of the film drifting in a wide range of cross sectional dimensions turned out to be considerably less than the thickness of the contact layer. According to the authors of [11], the consumption of magnetic nanofluid per a unit of length due to the movement of one of the layers borders at velocity v is defined by the following expression:

$$Q = 0.66vd\left(\frac{\eta v}{\sigma}\right)^{\frac{3}{2}} \quad (6)$$

This expression shows that consumption of magnetic nanofluid entrained by the moving boundary of the layer increase with an increase in velocity $\backsim v^{5/3}$ and viscosity $\backsim \eta^{2/3}$ and decreases with increases in surface tension $\backsim \sigma^{-2/3)}$. We chose the contact layer thickness equal to half the length of an ultrasonic wave λ with frequency of $f_0 = 3MHz$. Therefore, Eq. 6 takes the form

$$Q = 0.66v\frac{c}{2f_0}\left(\frac{\eta v}{\sigma}\right)^{\frac{3}{2}} \quad (7)$$

The obtained array of experimental data enabled calculating irreversible losses with the help of this relation. The product scanning speed varied from $5\,mm/s$ to $10\,cm/s$. The outcomes of the calculations performed by the formula stated above allowed making the following conclusions. Irreversible losses sharply increase with the increase of the scanning speed in low temperatures range of $233 - 283\,K$. The antifreeze-based magneto-acoustic contact has the biggest losses.

For instance, at the scanning speed of $10cm/s$ the permanent loss amounts to , $10^{-4}m^2/s$, which is two orders more than in other types of magnetic nanofluids. The temperature dependence of irreversible losses is close to linear one at the aforementioned scanning speeds. An increase in magnetite concentration results in the increase of irreversible losses, moreover, this dependence most sharply manifests itself in the antifreeze-based magnetic fluid, which first and foremost is stipulated by high viscosity of the carrier fluid. Among the magnetic fluid samples studied, there is no universal working temperature range. In the temperature range of $233-273\,K$ it is optimal to use antifreeze-based magnetic fluid but with a small volume of magnetite content, not exceeding $0.5\,\%$. The main advantage of water-based magnetic nanofluids is connected with the independence of the wave resistance from the temperature, thus such fluids are reasonable to use when we control the products under conditions of varying surface temperature. It goes without saying, all the aforementioned presupposes the fluid to be aggregately stable. It is quite a tough requirement as the magnetic fluid is being held under the piezoelectric converter with the help of a nonhomogeneous magnetic field. In a production environment, one can evaluate the magnetic fluid quality with the help of an ultrasonic defectoscope. For this purpose, it is enough to record temperature dependence of the signal level at a fixed position of the converter. If the change of absorption meets the inequality $\Delta\alpha \leqslant dB/cm$, the magnetic nanofluid can be used as a coupling fluid.

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REFERENCES

[1] R. Rosensweig, "Ferrohydrodynamics," Cambridge University Press, 8-24, 1985.

[2] Charles J. Hellier "Handbook of nondestructive evaluation, " McGRAW-HILL, New York, 7.13, 2003.

[3] P. P. Prokhorenko and A. R. Baev "Method of creating acoustic contact for for ultrasonic measurements", Patent 697916 (USSR), 1979.

[4] D.Y.Chung and W.E. Isler, "Ultrasonic velocity anisotropy in ferrofluids under the influence of a magnetic field," J. Appl. Phys., 43, 1809-1811, 1978.

[5] V. V. Sokolov "Comments to the results of Chung and Isler,devoted magnetic field effect on the sound velocity in a magnetic fluid," Magnetogydrodynamics, 4, 136, 1986.

[6] V. V. Sokolov, "Wave Propogation in Magnetic Nanofluids (A review)", Acoustical Physics, 56, 972, 2010.

[7] Andrei S. Dukhin and Philip J. Goetz, "Characterization of Liquids, Nano- and Microparticulates, and Porous Bodies Using Ultrasound," second ed., Elsevier, New York, 95-97, 2010.

[8] V.M. Kondrachov, V.V. Sokolov "The Golographic Study of Surface Properties of Magnetic Fluids, " Abst. Six Int. conf. on Magn. Fluids, Paris, 288-289, 1992.

[9] R. E. Zelazo and Melcher, "Dynamics and stability of ferrofluds: surface interactions," ,J. Fluid Mech., 39, 1-24, 1969.

[10] L. D. Landau and V. G. Levich, "Entrainment of liquid by moving plate, " in L. D. Landau "Collected Works" , Gordon and Breach, Science Publishers, New York , 355-363,1965.

[11] V. M. Korovin and Yu. L. Raiker, "Entrainment of a magnetic fluid by the moving boundary of a plane- parallel layer", Magnetohydrodynamics, 23, 41-44, 1987.