SB^{3}C2016
Summer Biomechanics, Bioengineering and Biotransport Conference
June 29 –July 2, National Harbor, MD, USA
SB^{3}C2016-765

CONTRIBUTION OF ULTRASOUND ABSORPTION IN NANOPARTICLES FOR HYPERTHERMIA APPLICATION

V. Kumar (1), S. B. Devarakonda (2), R. K. Banerjee (2), A. K. Ganguli (1, 3), C. Bera (1)

(1) Institute of Nano Science and Technology,
Mohali, Punjab 160062, India

(2) Mechanical and Materials Engineering
Department, University of Cincinnati,
Cincinnati, OH, USA

(3) Department of Chemistry, Indian Institute
of Technology, New Delhi 110016, India

INTRODUCTION

There is a renewed interest in the thermal properties of ferrofluids due to the biomedical application of heating effect of magnetic nanoparticles (mNPs) [1] and application of focused ultrasound therapy for ablation of malignant tumors [2]. The ultrasound based treatment is a non-invasive alternative to conventional surgical procedures. However, one of the major problem in the field has been controlling accurate delivery of heat (energy) to the disease site, while minimizing collateral damage to the surrounding healthy tissue. One of the most important requirement for ultrasound therapy for clinical planning is to determine heat generated in tissue due to acoustic energy transfer to heat energy. These lead us to investigate the reason of temperature rise in mNPs in presence of ultrasound. Although most of the experimental investigations have predicted that the main reason behind the temperature rise is ultrasonic attenuation [3-6], there is a lack of fundamental knowledge based on either experimental or theoretical investigation on the contribution of attenuation to temperature rise in media such as ferrofluids or mNPs infused tissue mimicking materials (TMM). Few theoretical investigations have been made based on fluid dynamics and “streaming theory” to study acoustic attenuation [6-9]. Following Ref. [10], we develop a simple model based on acoustic mean free path to calculate temperature rise due to ultrasound attenuation in ferrofluids. From this model it is possible to calculate contribution of different media on temperature rise by changing volume fraction (x) of nanoparticles, viscosity of ferrofluid medium, etc.

METHODS

Acoustic wave propagated in a medium interacts with the thermal phonons and as a result of this acoustic wave is absorbed [10]. Due to this absorption, the momentum of thermal phonons increase which tends to set up heat flow in the direction of ultrasound propagation and generates a temperature gradient. Following Ref. [10], the increase in temperature with time is given by,

$$\Delta T = \int_0^t \frac{3N\hbar\omega v_{nf}}{\lambda_{nf} C_{nf} V} dt \qquad (1)$$

where λ_{nf} is the acoustic mean free path for ferrofluids, C_{nf} is the heat capacity, v_{nf} is the velocity of ultrasound, V is the total volume of medium, N is the number of phonons in acoustic mode, $(N\hbar\omega/V)$ is the energy density in the medium which we can calculate from the power of ultrasound wave, $\hbar$ is the reduced Planck constant and ω is the ultrasound frequency.

Acoustic mean free path of the media is calculated from absorption coefficient, $\lambda_{nf} = ((\frac{x\alpha_{np}}{\rho_{np}} + \frac{(1-x)\alpha_f}{\rho_f})(\rho)^{-1}$ where ρ is the total density. Absorption coefficient α_f of ultrasound for fluid is calculated using theory of Stokes [11]

$$\alpha_f = \frac{2\eta\omega^2}{3\rho_f v_f^3} \qquad (2)$$

Where η is the viscosity of base fluid, ρ_f is density of fluid, v_f is the speed of sound in base fluid

The absorption coefficient, α_{np} for nanoparticle can be written as, [12]

$$\alpha_{np} = 1.1\frac{\gamma^2\omega^2\tau C_{np} T}{v_{np}^3} \qquad (3)$$

C_{np} is the heat capacity of nanoparticle, v_{np} is the speed of ultrasound in nanoparticle, ρ_{np} is the density of nanoparticle at absolute temperature, γ is the Gruneisen parameter, τ is the phonon relaxation time which is calculated as, $\tau^{-1} = (\frac{1}{\tau_b} + \frac{1}{\tau_{np}}$. τ_b is the bulk phonon relaxation time, $\tau_b = \frac{3\kappa}{C_{np}\rho_{np}v_{np}^2}$, where κ is the heat conductivity and

$\tau_{np} = \frac{l}{v_{np}}$ is the relaxation time for boundary scattering, $l=10nm$ is the nanoparticles diameter. The values of different physical parameters for Eqn. 1-3 are listed in Table. 1.

Table 1: List of physical parameter used in Eqn. 1-3.

	Water	**Fe_2O_3**
Specific Heat, C_p	4175 J/Kg-K [13]	650.6 J/Kg-K [14]
Density, ρ	995.64 Kg/m^3 [15]	5.26×10^3 Kg/m^3 [16]
Thermal Conductivity, κ		11.3 W/m-K [17]
Velocity, v	1509 m/s. [18]	6273 m/s [19]
Bulk Modulus, B		2.07×10^{11} Pa [19]
Gruneisen parameter, γ		1.51 [20]
Viscosity, η	797.3×10^{-6} Pa-s [21]	

RESULTS

Fig. 1 represents the acoustic wave mean free path calculated for different volume fraction (x), and Fig. 2 represents the temperature rise due to ultrasound attenuation. Supplied power (P) to the ferrofluids medium is calculated from experimental temperature rise as, $P = \frac{dT}{dt} MC_{nf}$, where M is the total mass, $\frac{dT}{dt}$ is calculated from the linear region of experimental temperature rise(Fig.2). The calculated P for x values of 0.5%, 1% and 2 % is 1.8 J/s.

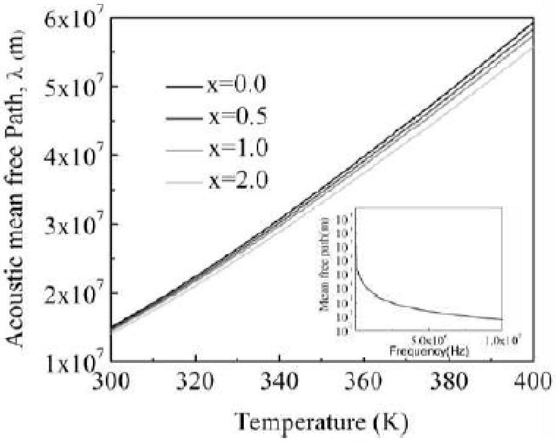

Figure 1: Acoustic mean free path for different volume fraction of ferrofluids for 20 KHz frequency. Here, x is the volume fraction of Fe_2O_3. (Inset) mean free path for different frequencies.

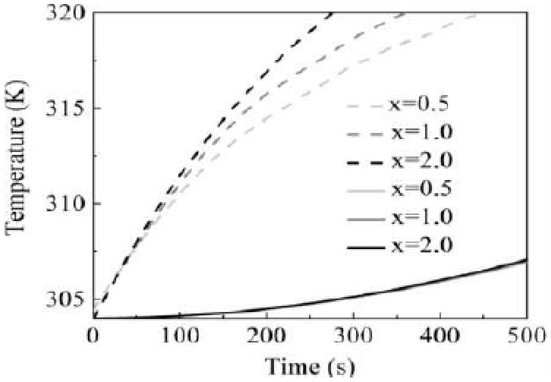

Figure 2: Temperature rise for ultrasound propagation time. Dashed lines are experimental values of total temperature rise for 20 KHz ultrasound frequency, solid lines are theoretical calculation for ultrasound attenuation. 'x' is the volume fraction.

DISCUSSION

Here, we have shown that the theoretical temperature rise in ferrofluids due to purely ultrasound attenuation is very low (1.7 °C after 400s at x= 0.5%). However, for highly viscous medium the temperature rise is faster and higher compared to ferrofluids. Only by changing the viscosity of base fluid to 3.4 cp and 10 cp, we observed temperature rise of 3.6°C and 10.2°C respectively for x =1%, after 300s. It has been observed that change in acoustic mean free path in ferrofluids is smaller after 1.5MHz frequency, so the change in frequency will not have a dominant effect on temperature change at very high frequencies. This model can also be used for the temperature calculations in TMM and it can be further improved by incorporating other phenomena for temperature increase such as phonon-electron interaction in NPs, viscous heating and temperature rise due to fluid momentum.

ACKNOWLEDGEMENTS

VK and CB acknowledge computing facility of PARAM Yuva-II. Also, partial financial support (time spent by co-investigators) from the National Science Foundation (Grant No. 1403356) is gratefully acknowledged.

REFERENCES

[1] Lee, L., Simon, C., Bove, E. *et al.*, Echocardiography, 17(6), 563-566 (2000).

[2] S. A. R. Dibaji et al, J Nanotechnology in Engineering and Medicine, 4: 041003, 2013.

[3] Curra, F. P., and Crum, L. A., Acoust. Sci. Technol., 24(6), 343–348, 2003.

[4] Ter Haar, G., Phys. Today, 54(12), 29–34, 2001.

[5] Wu, J., and Du, G., Ultrasound Med. Biol., 16(5), 489–498, 1990.

[6] Curra, F. P., Mourad, P. D., Khokhlova, V. A., Cleveland, R. O., and Crum, L.A., IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 47(4), 1077–1089, 2000.

[7] Soneson, J. E., AIP Conf. Proc., 1113(1), 165–169, 2009.

[8] Myers, M. R., and Soneson, J. E., J. Acoust. Soc. Am., 126(1), 425–433, 2009.

[9] Dibaji, S. A. R., Banerjee, R. K., Soneson, J. E., and Myers, M. R., J. Acoust. Soc. Am., 134(5), 3435–3445, 2013.

[10] Simons, S., Proc. Phys. Soc., 83, 645-657, 1964

[11] Pinkerton, J. M. M., Proc. Phys. Soc., 62, 129-141, 1949

[12]Brawer, Steven, Phys. Rev. B, 7(4), 1712-1717, 1973

[13]Bousfield, W. R., and Bousfield ,W. E., Proc. R. Soc. Lond. A, 85, 302-304, 1911.

[14]Lide D. R., CRC Handbook of Chemistry and Physics, CRC Press, 2009.

[15]Bigg, P. H., Br. J. Appl. Phys,18, 521-525, 1967.

[16]Schwertman, U., and Cornell, R. M., Iron Oxides in the Laboratory Preparation and Characterization, Wiley-Vch, 2nd Edition, 2000, pp. 7

[17]Toher, Cormac, Physical Review B, 90, 174107, 2014.

[18] Greenspan, Martin and Tschiegg, Carroll E., The Journal of the Acoustical Society of America, 31(1), 75-76 1959

[19]Anderson, Don L., and Anderson, Orson L., Journal of Geophysical Research, 75(17), 3494-3500, 1970

[20]Shim, Sang-Heon, and Duffy, Thomas S., American Mineralogist, 87, 318-326, 2001

[21] Kestin, J., *et al*, Phys. Chem., 7(3), 941-948, 1978.