CONTRIBUTION OF ULTRASOUND ABSORPTION IN NANOPARTICLES FOR
HYPERTHERMIA APPLICATION

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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
time 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,
\[ \Delta T = \int_0^t \frac{3NkT}{\lambda_{nf}} C_{nf} \frac{\omega}{V} dt \]

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

Acoustic mean free path of the fluid is calculated from absorption
coefficient, \( \lambda_{nf} = \left( \frac{\rho_f}{\rho_f + (1-\rho_f)} \right) (\omega \nu_f)^{-1} \) where \( \rho \)
is the total density.

Absorption coefficient \( \alpha_f \) of ultrasound for fluid is calculated using
theory of Stokes [11]
\[ \alpha_f = \frac{2\pi\omega^2}{3\nu_f} \]

Where \( \eta \) is the viscosity of fluid, \( \nu_f \) is density of fluid, \( \nu_f \) is the
speed of sound in fluid.

The absorption coefficient, \( \alpha_{np} \) for nanoparticle can be written as, [12]
\[ \alpha_{np} = 1.1 \frac{\gamma \nu_{np}}{\rho_{np}} C_{np} \frac{\nu_f}{\nu_{np}} \]

\( C_{np} \) is the heat capacity of nanoparticle, \( \nu_{np} \) is the speed of ultrasound
in nanoparticle, \( \rho_{np} \) is the density of nanoparticle at absolute
temperature, \( \gamma \) is the Gruneisen parameter, \( \tau \) is the phonon relaxation
time which is calculated as, \( \tau^{-1} = \frac{1}{\tau_b} + \frac{1}{\tau_p} \) and \( \tau_b \) is the bulk phonon
relaxation time, \( \tau_p = \frac{4k}{C_{np} \rho_{np} \nu_{np}^2} \), where \( k \) 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>
<thead>
<tr>
<th>Parameter</th>
<th>Water</th>
<th>FeOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Heat, ( C_p )</td>
<td>4175 J/Kg-K [13]</td>
<td>650.6 J/Kg-K [14]</td>
</tr>
<tr>
<td>Density, ( \rho )</td>
<td>995.6 Kg/m^3 [15]</td>
<td>5.26x10^3 Kg/m^3 [16]</td>
</tr>
<tr>
<td>Thermal Conductivity, ( k )</td>
<td>11.3 W/m-K [17]</td>
<td></td>
</tr>
<tr>
<td>Velocity, ( v )</td>
<td>1509 m/s [18]</td>
<td>6275 m/s [19]</td>
</tr>
<tr>
<td>Bulk Modulus, ( B )</td>
<td>2.07x10^11 Pa [19]</td>
<td></td>
</tr>
<tr>
<td>Gruneisen parameter, ( \gamma )</td>
<td>1.51 [20]</td>
<td></td>
</tr>
<tr>
<td>Viscosity, ( \eta )</td>
<td>797.3x10^-6 Pa-s [21]</td>
<td></td>
</tr>
</tbody>
</table>

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 \( P = \frac{dP}{dt} M C_p \), 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.

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.

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REFERENCES