Acoustic streaming and temperature elevation in a high viscous fluid by irradiation of ultrasound beams

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Abstract: Two physical phenomena of cooling effect by acoustic streaming and thermal self-action of sound beams in a viscous fluid are discussed. Sound energy losses due to viscosity and heat conduction in the fluid induce temperature elevation locally and streaming globally in the beams. The streaming carries forcibly away the heated mass of the medium, then the temperature elevation is reduced. In a high viscous fluid, however, the streaming does not greatly grow up because of the viscosity. Since physical parameters such as sound speed depend on temperature in most fluids, sound beam changes its amplitude itself with irradiation time.

Theoretical model and discussion

The present study is concerned with two physical problems: one of them is temperature elevation by ultrasonic heating and cooling effect by acoustic streaming which occur near an interface between water and silicone rubber material. Sound absorption of the rubber is generally so great that temperature on the area irradiated by cw ultrasound is increased gradually with irradiation time of sound. It should be expected that acoustic streaming generated in the beam reduces the temperature near the locally heated area. The other problem is thermal self-action in a high viscous fluid. Physical parameters of castor oil vary with temperature. Therefore time-dependent changes should be observed in the beam profiles. This phenomenon is called the thermal self-action.1)

![Fig. 1 Theoretical model.](image1)

![Fig. 2 Temperature elevation near the interface.](image2)

Figure 1 shows a theoretical model, in which a planar sound source with circular aperture of radius $a$ radiates cw ultrasounds at high frequency in a tube of radius $b$ filled with water. The beams are terminated with a silicone rubber stopper which is located at $h_1$ from the source. The sounds in the rubber decay greatly with propagation distance. The acoustic impedance of the rubber is nearly equal to that of water, so sound reflection from the rubber can be neglected. Build-up profiles of the streaming velocity and temperature elevation are theoretically predicted by the hydrodynamic and forced convection heat transfer equations, which are described elsewhere.1,2) As these equations are intrinsically nonlinear and mutually coupled, it is not easy to obtain their analytical solutions. A numerical calculation method previously reported by two of the authors is helpful for a theoretical prediction of the velocity and temperature fields.2)
Figure 2 shows the axial profiles of the temperature elevation near the interface at 2sec and 20sec after the source begins to radiate cw beams. The source parameters are assigned to be $a = 9.1\text{mm}$, ultrasonic frequency $5\text{MHz}$, source pressure amplitude $116\text{kPa}$, and $b = 2.7\text{cm}$. Solid and dashed curves are numerically calculated solutions including acoustic streaming and excluding it, respectively. It is clearly demonstrated that the temperature is really reduced by the streaming immediately in front of and behind the interface.\(^3\)

In particular, the temperature in the front region is elevated by about $4{}^\circ\text{C}$ within the framework of the present source conditions. In order to testify the validity of the theory on the cooling effect an appropriate experiment is going on.

![Figure 3 On-axis pressure change with time.](image)

![Figure 4 Time-dependent beam patterns at $z = 20\text{cm}$.](image)

The next theoretical interest is thermal self-action in a high viscous fluid. Let the tube in Fig.1 to be filled with caster oil instead of water. Since the physical parameters such as the viscosity depend generally on temperature, sound field is changed with time. In addition to the viscosity, two other temperature-dependent parameters of sound absorption and sound speed are taken account in the theory. The temperature coefficients of three parameters are all negative in room temperature. The basic flow and heat equations mentioned above, and the wave equation which includes the terms of temperature-dependent sound speed and absorption are simultaneously solved by small time step by use of a finite difference scheme. Numerical examples of sound pressure amplitude along and across the acoustic axis as a function of time are given in Fig.3 and Fig.4 for a $2.5\text{MHz}$ beam emitted from a Gaussian source of effective radius $1\text{cm}$. The source pressure is assumed to be $300\text{kPa}$ and the tube radius to be $5\text{cm}$. It is seen that the sound pressure amplitude increases and the beam gets narrower and narrower with time; the generation of the self-action is numerically ascertained. A discernible pressure dip in the beam pattern appears at 10sec around the axis in spite of no dip in the initial Gaussian beam. The present method of numerical calculation is easily extended to more interesting situation in focusing system.

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References

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