ACOUSTIC STREAMING AND HEAT AND MASS TRANSFER ENHANCEMENT

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ABSTRACT

A second order effect associated with high intensity sound field, acoustic streaming has been historically investigated to gain a fundamental understanding of its controlling mechanisms and to apply it to practical aspects of heat and mass transfer enhancement. The objectives of this new research project are to utilize a unique experimental technique implementing ultrasonic standing waves in closed cavities to study the details of the generation of the steady-state convective streaming flows and of their interaction with the boundary of ultrasonically levitated near-spherical solid objects. The goals are to further extend the existing theoretical studies of streaming flows and sample interactions to higher streaming Reynolds number values, for larger sample size relative to the wavelength, and for a Prandtl and Nusselt numbers parameter range characteristic of both gaseous and liquid host media. Experimental studies will be conducted in support to the theoretical developments, and the crucial impact of microgravity will be to allow the neglect of natural thermal buoyancy. The direct application to heat and mass transfer in the absence of gravity will be emphasized in order to investigate a space-based experiment, but both existing and novel ground-based scientific and technological relevance will also be pursued.

I. INTRODUCTION

The active control of the rates of heat and mass transfer in non-isothermal systems is often a desired capability associated with many industrial and technological practices. In general, this is accomplished by varying the interfacial area and by inducing appropriate flow fields in the medium through which transport takes place. For example, the control of gas and melt flow rates, atomizing gas pressure, initial melt temperature, and host medium conductivity are used to change the quenching rate in gas atomization processes of powder metallurgy . In the case of multi-component or multi-phase disperse systems dealing with direct contact heat transfer, distillation, or liquid extraction, some enhancement of transport or reaction rates has been obtained through the use of electric fields which induce drop oscillations as well as internal flow within the fluid particle. Thus, even for Earth-bound activities for which natural convection is often important, the control of *flow fields* in the vicinity of the contact interfaces is of significant practical value.

In a low gravity environment, the drastic reduction of natural buoyancy will make the contribution from any externally imposed flow field even more important. For example, heat transfer processes involving change of phase (such as boiling) are drastically affected by the elimination of buoyancy-driven removal of vapor bubbles. In the *absence* of artificially induced flows, heat or mass transfer in microgravity is expected to be dominated by radiation, conduction, or diffusion processes. A minor contribution may also come from thermocapillary flows (Marangoni convection) in the case of free liquid-gas interfaces. In currently utilized manned spacecraft, however, another source of *steady-state or time-varying convective flows* arises from the residual fluctuating acceleration background (the so-called "g-jitters"). The appearance of *steady-state* flows have been predicted, and under certain conditions involving a range of values for the Prandtl number, the vibration frequency, and for a large enough Rayleigh number, these flows could significantly impact heat transport processes (Kamotani, Prasad, and Ostrach (1981)[1] and Farooq and Homsy (1994)[2]).

Although the frequencies associated with the microgravity g-jitters are centered around relatively low values (0.1 to 10 Hz), the physical mechanism responsible for the creation of the steady convective flows is very similar to the case of higher frequency *acoustic streaming*. In both situations, time-varying Reynolds stresses generate vorticity in a thin Stokes boundary layer at the interface between the fluid and an object. As a result, a thicker steady-state flow boundary layer is generated. In both situations, the resulting convective velocity at the edge of this steady-state flow layer induces steady fluid motion which is propagated into the *bulk* of the fluid medium. There is a difference, however, in the characteristics of the steady-state flow outside the Stokes boundary layer in the two cases: for acoustic streaming this flow remains irrotational, while it is rotational in the case of a fluctuating gravitational field (g-jitter driven). In the latter situation, the time-varying body force (buoyancy) responsible for the flow is not conservative but is rotational, and the steady-state convective flow *outside* the Stokes layer is *directly* driven by the Reynolds stresses (Amin (1988)[3]). This difference, however, does not affect the impact of the steady-state convective flows on the heat and mass transport properties, and to a large extent, information gathered by studying acoustic streaming will be relevant to the case of a time-varying gravitational acceleration.

Acoustic streaming-induced convective flows have also been shown to substantially enhance heat and mass transfer, even under the full action of the Earth gravitational field. A detailed understanding of this effect is not yet available, however, because *natural convection* interferes with accurate heat and mass transport measurements under most experimental conditions found in Earth-based laboratories. The exception might be found at very high acoustic pressure at which stage the second order streaming flow becomes turbulent and theoretical analysis is even more complicated. We plan to carry out a ground-based research program to experimentally and theoretically examine both the configuration and stability of acoustically induced streaming flows in order to advance the understanding of the physical mechanisms responsible for their generation, and to develop a predictive model for the observed enhancement in the rates of heat and mass exchange. The capability to virtually eliminate steady natural convection in microgravity will be examined to assess the possibility of performing experimental measurements that are not possible on Earth, but that could impact the understanding of both Earth-based and microgravity problems. We thus believe that the problem of controlling heat and mass transfer through induced external flow is important to technological applications both on Earth and in microgravity, that acoustic streaming-modulated transport processes are of current scientific interest, and that this phenomenon could be better understood by carrying out microgravity studies. Further, we think that the similarity between acoustically and g-jitters-induced streaming is significant enough to be useful in the investigation of the microgravity streaming problem. The specific objectives are:

(1) To quantitatively characterize the acoustically-induced flows and thermal fields in fluid-filled enclosures and around freely suspended (levitated) spherical particles which are at the same as well as at higher temperature than the surroundings. Of particular interest are the causes and conditions for the onset of instability of these flow fields in 1 G and in low gravity.

(2) To measure the effects of these flows on the *rate of heat transfer* in 1 G as well as in reduced gravity using *finite-size* enclosures.

(3) To compare the experimental results with an *analytical and numerical model* developed for the case of zero gravity.

(4) To assess the validity and desirability of potential *long duration* microgravity investigations to gain new information in a parameter range not accessible to Earth-based experiments.

These studies will be carried out for finite Prandtl numbers ($0.1<Pr<10$) to cover the cases of gaseous and liquid host media, for a range of streaming Reynolds number, R_S, typical of currently relevant systems ($1< R_S< 10{,}000$), and for Grashof numbers ranging between 0 (zero G or isothermal system) and values reflecting temperature differences up to 500 ^{0} C in gas and liquid media in 1 G. The range of the Peclet ($Pe= R_S.Pr$) and of the Rayleigh ($Ra=Pr.Gr$) will be determined by the other non-dimensional numbers listed above. Radiative effects will be experimentally assessed, but not theoretically modeled as the temperature will be restricted to moderate values ($T < 500^{0}$ C). The heat transfer measurement approach will involve the usual correlation between the Nusselt (Nu) and Reynolds and Prandtl numbers, i.e. $Nu = F(R_S).G(Pr)$, where F and G are functions to be determined.

II. SPECIFIC OBJECTIVES AND IMPLEMENTATION

In general, for the problem of streaming and heat transfer from an *isolated spherical or cylindrical object immersed in an infinite fluid medium*, the analytical solution of the complete set of equations for a wide range of the relevant non dimensional numbers is not possible. Even if it was available, a single solution would not be valid over the entire space because of the existence of viscous and thermal boundary layers. Matched asymptotic expansion methods using the non-dimensionalized amplitude(ε) of the acoustic wave as expansion parameter have been used, and solutions have been obtained for the problem of the heat transfer from spherical and cylindrical objects in limited ranges and under certain limiting values of the characteristic Reynolds ($Re_s = U_s^2/\omega\nu$, where U_s is the characteristic streaming velocity, ω is the acoustic angular frequency, and ν is the fluid medium kinematic viscosity), Prandtl (Pr), Grashof (Gr), and Strouhal ($S=1/\varepsilon$) numbers. This expansion approach allows the general equations of motion to be decomposed into a set of independent linear and nonlinear equations of increasing order in the parameter ε (Riley (1965)[4], Davidson (1973)[6], Amin (1988)[3]) .

The fundamental assumption at the basis of all the approaches based on series expansions of the stream function and temperature field around a heated sample in a streaming flow field is invalid in the case of higher amplitude time-varying fluctuations found high intensity sound fields. Such high levels are encountered in ground-based ultrasonic levitation of liquid and solid samples at ambient and high temperature. The steady streaming velocity reaches very high values, and neither the flow or thermal fields can be described by available theories. Experimental evidence (Trinh and Robey (1995)[5]) shows the appearance of new configurations and instabilities in the flow fields which are not theoretically predicted. In addition, real physical systems are characterized by *finite dimensions and large temperature differences* which cannot yet be simulated by theories that assume a fluid medium of infinite extent, no attenuation, and small differences in temperature in order to preserve the Boussinesq approximation, and to avoid the complications of a high temperature theory.

Time-independent streaming is one of the nonlinear effects associated with the propagation of high intensity acoustic waves in a fluid medium. This *steady* flow generated by a sound field has been extensively analyzed by Nyborg and other modern researchers (Nyborg (1965)[7], Zarembo (1971)[8], Lighthill (1978)[9]), but Rayleigh was once again an early investigator of this phenomenon (Rayleigh (1896)[10]). As a result, the principal physical mechanisms responsible for the generation of the flows have been identified, and a fairly good general understanding has been obtained. Streaming flows are generally divided into two separate classes: in the first category they are generated in a free acoustic plane wave propagating into the bulk of a fluid medium, sometimes called volume streaming or "Quartz wind" (Eckardt (1948)[11]), and in the other category they arise because of the interaction of the sound wave with boundary walls or objects in its path. In this research project we are mostly concerned with the streaming flows in the second category, and we concentrate on the streaming fields due to standing acoustic waves inside *enclosures of finite dimensions*, and on the flows induced around single spherical samples suspended at the velocity antinodes.

1. EXPERIMENTAL OBJECTIVES

(1) Isothermal streaming around a freely suspended solid sphere. Quantitative and qualitative flow field measurement will be carried out in order to establish a baseline condition. The orientation of the cell will be changed from parallel, to perpendicular, and to anti-parallel to the gravity vector in order to filter out any gravitational bias. Quantitative velocity measurements will be performed using PIV for low sound pressure levels. The flow fields should be very similar to those shown in figure 1. The position of the attached eddies will be above or below the sample equator depending upon the velocity direction of the outer primary streaming. The measurements will be carried out for increasing sound pressure level (or Reynolds number R_s) in order to record the evolution of the attached eddies. The uniform temperature condition will be established by enclosing the test chamber in a temperature controlled environment. Air (Pr=0.7), water (Pr=7), and silicone oil (Pr=5) will be initially selected because they have been well characterized in the past and they will also allow a range in the streaming Reynolds number R_s. The size of the sample will range between 0.1 and 0.5 cm in radius. This is translated into $k_{ac}.R$ parameter between 0.4 to 0.9 (where k_{ac} is the acoustic wave number).

(2) Streaming around a heated spherical sample. Flow field mapping will first be carried out for varying Grashof number ($Gr=gD^3\beta(\Delta T)/\nu^2$, where g is the gravitational acceleration, β is the thermal expansion coefficient, ν the fluid kinematic viscosity, and D is the sphere diameter), or Rayleigh number since Ra=Gr.Pr. The mapping of the stability regions of the various flow configurations will be done in the parameter space involving the streaming Reynolds number, the Rayleigh number, and to a limited extent

the Prandtl number. This will cover the three cases of sound field orientation with respect to the Earth-based gravitation acceleration vector: parallel, normal, and anti-parallel.

Short duration low-gravity tests will also be performed aboard NASA airplanes flying parabolic trajectories. This will provide 15 to 20 seconds of 0.01 to 0.05 G steady background acceleration with varying amount of transient acceleration superposed. This noisy acceleration background does not allow extensive quantitative measurements, but it provides both qualitative results as well as a test bed for low-gravity experimental techniques development.

Heat transfer measurements will be carried out for spot-heated, stably held samples in different locations in the ultrasonic standing wave in air. Once again, the measurements will be carried out as a function of the streaming Reynolds number (which carries information on the sound pressure level), and of the Grashof number (which involves ΔT). The Nusselt number ($Nu = Q / kD\Delta T$, where Q is the total energy transferred, and k is the thermal conductivity of the fluid) will be measured, and a correlation in the form $Nu=F(Pr).(R_S)^{1/2}$ (where F(Pr) is a function of the Prandtl number) will be sought. Earth-based measurements will be carried out in detail, and short-duration low-gravity measurements will be attempted. Another, more standard correlation between the Nusselt and Grashof number $Nu = G (Gr)$ will be investigated for fixed streaming Reynolds numbers.

(3) Steady and oscillatory streaming flows in closed cavities. The stability of streaming flow fields in empty chambers will also be investigated by flow visualization methods in isothermal and non-isothermal systems. Earth-based experiments will investigate the coupling between the natural buoyancy-driven motion with the acoustically driven flows in *air* and in the Ra-R_S parameter space, and low gravity tests will reveal the most glaring flow field differences. Amplitude modulation of the ultrasonic field can be precisely controlled, and the investigation of the frequency response of such a system to singly and multiply periodic excitation will be initiated. Once again, the construction of a bifurcation diagram to represent the various stability regions and transition points will be attempted. Similar experiments will be also initiated for liquid-filled cavities similarly driven through ultrasonic standing waves.

2. THEORETICAL OBJECTIVES

(1) Superposition of an axisymmetric steady convection on the streaming flow around an isolated spherical sample in a uniform temperature cavity.

Earlier analyses using higher order boundary-layer theory was used by Riley (1975)[12] to study the streaming problem around a cylinder, and later extended to the case of a sphere in a non homogeneous pulsating sound field (1980)[13] will be further modified by including a superposed uniform convective flow field of the type observed at ultrasonic frequency and in a closed cavity (see figure 1). Axisymmetric configuration and isothermal conditions will be used, and this additional imposed flow field will be modeled as a large scale vortex flow with appropriate boundary conditions away from the sample. In the vicinity of the sample, the flow is nearly one-dimensional with a weak shear component due to the gradient along the radial direction. Under these circumstances standard techniques used in sound propagation in moving media can be applied.

(2) Superposition of streaming flow solution to the free convection problem.

A numerical treatment of the free convection boundary-layer problem around a heated sphere for large Grashof number was authored by Potter and Riley (1980)[14]. Essential characteristics of the plume around the sphere were reproduced, and a reasonable agreement with experimental results was observed. Two simple extension to this analysis can be envisioned: a steady convective circulation opposite to, or in the same sense as the natural buoyancy flow can be added as a background , or the case of an oscillating heated sphere can be treated. In both cases, major characteristics of the realistic streaming problem can be simulated and flow fields predicted, at least within the boundary layer approximation.

(3) Extension of the theory for the heat transfer from heated sphere due to acoustic streaming.

Gopinath and Mills (1993)[15] have presented an analytical and numerical treatment of the problem of acoustic streaming and heat transfer from a free sphere under the assumption of small and large Reynolds numbers and for small values of the $k_{ac}.R$ parameter. Additional restrictions were small ΔT and the absence of free convection. Under these circumstances, the experimental validation of the theoretical predictions remains problematic, but it could be attempted by performing initial short-duration low-gravity measurements with very small levitated samples. In order to extend the applicability of this work, however, a simplistic approach will be to try to extend this approach by relaxing the constraint $R_s >> 1$ and by extending the approximation to larger values for $k_{ac}.R$.

3. EXPERIMENTAL APPROACH

A previously used ultrasonic standing-wave experimental apparatus used between 20 and 40 kHz and with air as a host fluid[21] will be adapted to this proposed research. Standard flow visualization methods using smoke tracers and laser sheet illumination has been shown to be very effective for this specific frequency range and for spherical samples between 0.1 and 1 cm in diameter. For streaming Reynolds number in the lower range ($R_s <50$) full field Particle Image Velocimetry techniques[16,17] can provide quantitative measurements of the particles velocities. A correction factor will be empirically derived to account for the inertia of the smoke particles. This correction will be very small because of the small size of the smoke particles used in air, but could become non-negligible for other tracer particles used in a liquid host. A schematic description is given in figure 2

The test chamber will be thermally controlled and the tracer particles will not react with the host liquid. The injected smoke for flow visualization in air will be cooled to ambient cell temperature prior to injection into the standing wave region. The temperature of the suspended sample will be measured using an IR thermal imaging camera with reference calibration. The crucial thermal measurements are really concerned with temperature changes due to the effects of streaming, and are less sensitive to absolute temperature measurement accuracy. A resolution of 0.01 ^{o}C in temperature is judged adequate for the heat transfer measurement considered. For a levitated sample, the heat transfer is strictly through the fluid phase, while in the case of mechanically suspended samples, we must consider conduction heat loss through the suspending thin wires. Radiation heat transfer will be evaluated for the higher temperature range measurements by using samples with well characterized emittance as a function of temperature.

Levitated samples will be heated by a focused laser source which must be calibrated. The energy absorbed by the sample will be calculated by using temperature dependent optical absorptance values at the relevant incident wavelength. Holographic interferometry methods previously developed and used at lower acoustic frequencies[18] will also be implemented to map the thermal field around the free samples. Both ultrasonic and electrostatic levitation of spherical samples will be used to allow the free suspension of heated as well as unheated spheres. The addition of electrostatic levitation requires the presence of free charges and an electric field, but it allows the investigation of streaming flow fields around a free sample at very low streaming Reynolds numbers. The levitation of the sample through ultrasonic means alone would require a minimum sound intensity which would already lead to a very high Reynolds number.

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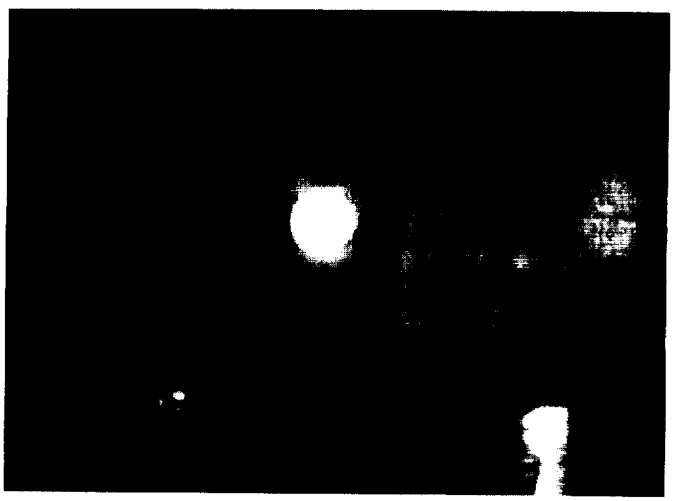

Figure 1

Photograph of streaming flow field in a closed cavity around a levitated sample

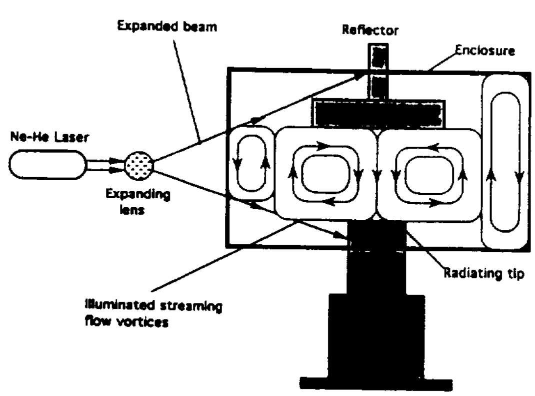

Figure 2

Schematic description of a basic experimental apparatus