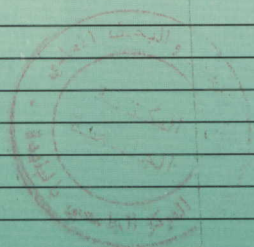


TRANSACTIONS OF THE ASME

**JOURNAL
OF
VIBRATION
AND
ACOUSTICS**



EXCLU DU PRIX



An Experimental Investigation of the Behavior of Droplets in Axial Acoustic Fields

R. I. Sujith

G. A. Waldherr

J. I. Jagoda

B. T. Zinn

School of Aerospace Engineering,
Georgia Institute of Technology,
Atlanta, GA 30332

EXCLU DU PRBT

This paper describes an experimental investigation of the behavior of water droplets in axial acoustic fields. It was motivated by the increasing interest in the use of pulsations to improve the performance of energy intensive, industrial processes. The presence of an acoustic field is believed to enhance heat and mass transfer to and from the droplets, probably because of the relative motion between the droplets and the gas phase. This relative motion is characterized by the ratio of the amplitude of the oscillatory droplet velocity to that of the acoustic velocity (entrainment factor), and by the phase between the droplet and gas phase oscillations. An experimental set-up was developed to investigate the effect of acoustic oscillations on the motion of individual droplets. In these experiments a droplet produced by a piezo-ceramic droplet generator is allowed to fall through a transparent test section in which an acoustic field has been set up using a pair of acoustic drivers. Images of the droplets in the test section acquired at consecutive instants using a high speed, intensified imaging system were used to determine the time dependent droplet trajectory and velocity. The acoustic velocity was calculated from measured acoustic pressure distributions. The entrainment factor and the phase difference were then determined from these data. The results show how the entrainment factor decreases and the phase difference increases with increasing droplet diameter and frequency, indicating that larger diameters and higher frequencies reduce the "ability" of the droplets to follow the gas phase oscillations. The measured data are in excellent agreement with the prediction of the Hjelmfelt and Mockros model. Both theoretical predictions and measured data were correlated with the Stokes number, which accounts for the effects of droplet diameter and frequency. It was also shown that acoustic oscillations decrease the mean terminal velocity of the droplets.

Introduction

This paper describes an experimental investigation of the behavior of water droplets in axial acoustic fields. The study is motivated by the increasing interest in the use of sound waves to improve the performance of energy intensive industrial processes such as spray drying and calcining. In such processes, the rate controlling mechanisms are the heat and mass transfer between the gas phase and the droplets. For instance, the performance of a spray dryer depends upon the rate of heat transfer from the hot gas to the spray droplets and the rate of mass (i.e., moisture) transfer from the droplets to the gas. If these rates can be increased by, for example, acoustic oscillations, the time required to dry a typical droplet will decrease. This, in turn, will permit pumping more material through an existing dryer, thus increasing the dryer productivity. Alternately, the reduced drying time will reduce the required size of a new dryer, which will reduce capital investment costs. Furthermore, increasing the rate of heat transfer from the gas to the droplets will increase the fraction of input energy that will be transferred to the wet material, resulting in fuel and operating costs savings. Finally, reducing the fuel consumption will reduce emissions such as CO₂ and NO_x, which may help combat global warming.

The realization that the performance of energy intensive processes could be improved if means for increasing the rates of mass, momentum, (i.e., mixing) and heat transfer within these processes could be found has stimulated interest in developing

practical means for enhancing these transport processes. The possibility of using sound or vibrations to increase convective heat transfer rates has recently received increased attention. It has been shown that pulsations (which, for example, can be established in industrial processes using pulse combustors) increase the heat and mass transfer from stationary objects (Bayley et al., 1961; and Richardson, 1967) where relative motions between the gas phase oscillations and the objects exist. These findings suggest that pulsations could also increase the rates of transport processes between gases and small particles when relative motions exist between the two phases. This conjecture is supported by additional studies (Richardson, 1967; Al Taweel and Landau, 1976; Lyman, 1977; and Padmanabha and Ramachandran, 1970) showing that pulsations increase the rates of heat and mass transfer to or from solid spheres or droplets.

In order to understand the effect of pulsations on sprays, it is important to understand their effect on individual droplets. This would require quantitative determination of the ranges of particle sizes and pulsation amplitudes and frequencies for which relative oscillatory motions can be established and whether such relative motions increase the rates of transport processes between the two phases.

A number of related studies of the effect of axial acoustic oscillations on droplets and particles can be found in the literature. The equation describing the unsteady motion of a rigid particle was developed by Basset (1961) assuming creeping flow (i.e., $Re < 0.01$, where Re is based on the relative velocity of the droplet with respect to the gas phase and the droplet diameter). Here, the drag on the droplet is linear and is given by the Stokes drag. An analytical solution for this equation was obtained by Hjelmfelt and Mockros (Hjelmfelt and Mockros, 1966; Clift et al. 1978).

This work was supported by the Gas Research Institute under contract number 5089-260-1839. Mr. James Kezerle is the contract monitor.

Contributed by the Technical Committee on Vibration and Sound for publication in the JOURNAL OF VIBRATION AND ACOUSTICS. Manuscript received July 1994. Associate Technical Editor: C. Fuller.

Transactions of the ASME®

Technical Editor
DANIEL J. INMAN
Past Technical Editors
F. EHRICH
T. CONRY

DESIGN ENGINEERING DIVISION

Associate Technical Editors
M. AHMADIAN (1996)
L. A. BERGMAN (1996)
R. CLARK (1999)
R. IBRAHIM (1997)
G. H. KOOPMANN (1997)
J. E. MOTTERSHEAD (1996)
S. NOAH (1997)
C. PIERRE (1999)
S. C. SINHA (1999)
P. D. SPANOS (1996)
J. Q. SUN (1997)
A. VAKAKIS (1999)
K. W. WANG (1999)
B. YANG (1999)

BOARD ON COMMUNICATIONS

Chairman and Vice-President
R. MATES

OFFICERS OF THE ASME

President, **K. B. THAYER**

Exec. Director
D. L. BELDEN

Treasurer
J. A. MASON

PUBLISHING STAFF

Managing Director, Engineering
CHARLES W. BEARDSLEY

Director, Technical Publ.
PHILIP DI VIETRO

Managing Editor, Technical Publ.
CYNTHIA B. CLARK

Managing Editor, Transactions
CORNELIA MONAHAN

Production Coordinator
RAY RAMONAS

Production Assistant
MARISOL ANDINO

Transactions of the ASME, Journal of Vibration and Acoustics (ISSN 1048-9002) is published quarterly (Jan., April, July, Oct.) for \$185.00 per year by The American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017. Periodicals postage paid at New York, NY and additional mailing offices. POSTMASTER: Send address changes to Transactions of the ASME, Journal of Vibration and Acoustics, c/o THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, 22 Law Drive, Box 2300, Fairfield, NY 07007-2300. CHANGES OF ADDRESS must be received at Society headquarters seven weeks before they are to be effective. Please send old label and new address. PRICES: To members, \$40.00 annually; to nonmembers, \$185.00. Add \$40.00 for postage to countries outside the United States and Canada. STATEMENT from By-Laws. The Society shall not be responsible for statements or opinions advanced in papers or . . . printed in its publications (B7.1, Par. 3). COPYRIGHT © 1997 by The American Society of Mechanical Engineers. Authorization to photocopy material for internal or personal use under circumstances not falling within the fair use provisions of the Copyright Act is granted by ASME to libraries and other users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service provided that the base fee of \$3.00 per article is paid directly to CCC, 222 Rosewood Dr., Danvers, MA 01923. Request for special permission or bulk copying should be addressed to Reprints/Permission Department. INDEXED by Applied Mechanics Reviews and Engineering Information, Inc. Canadian Goods & Services Tax Registration #126148048

Journal of Vibration and Acoustics

Published Quarterly by The American Society of Mechanical Engineers

VOLUME 119 • NUMBER 3 • JULY 1997

TECHNICAL PAPERS

- 285 An Experimental Investigation of the Behavior of Droplets in Axial Acoustic Fields
R. I. Sujith, G. A. Waldherr, J. I. Jagoda, and B. T. Zinn
- 293 The Use of Wave-Absorbing Elements for the Evaluation of Transmission Characteristics of Beam Junctions
K. De Langhe, P. Sas, and D. Vandepitte
- 304 Application of Hybrid Frequency Domain Substructuring for Modelling an Automotive Engine Suspension
A. T. M. J. M. Huizinga, D. H. van Campen, and A. de Kraker
- 311 Dynamic Loosening and Tightening of a Single-Bolt Assembly
D. P. Hess and S. V. Sudhirkashyap
- 317 Three-Dimensional Vibrations of Cross-ply Laminated Hollow Cylinders With Clamped Edge Boundaries
J. Q. Ye and K. P. Soldatos
- 324 Resonant-Frequency-Distribution of Internal Mass Inferred From Mechanical Impedance Matrices, With Application to Fuzzy Structure Theory
A. D. Pierce
- 334 Extension of the Wittrick-Williams Algorithm to Mixed Variable Systems
Zhong Wanxie, F. W. Williams, and P. N. Bennett
- 341 Identification of Principal Rigid Body Modes Under Free-Free Boundary Condition
Masaaki Okuma and Qinzhong Shi
- 346 Prediction of Periodic Response of Rotor Dynamic Systems With Nonlinear Supports
Yu Wang
- 354 Relationship Between Improved Inverse Eigensensitivity and FRF Sensitivity Methods for Analytical Model Updating
R. M. Lin and M. K. Lim
- 363 Nonlinear Fluid-Structure Interaction in Propeller Aircraft Cabins
M. Alvelid
- 374 Nonlinear Piezothermoelasticity and Multi-Field Actuations, Part 1: Nonlinear Anisotropic Piezothermoelastic Shell Laminates
H. S. Tzou and Y. Bao
- 382 Nonlinear Piezothermoelasticity and Multi-Field Actuations, Part 2: Control of Nonlinear Deflection, Buckling and Dynamics
H. S. Tzou and Y. H. Zhou
- 390 Harmonically Forced Wave Propagation in Elastic Cables With Small Curvature
M. Behbahani-Nejad and N. C. Perkins
- 398 Analysis of a Polarization-Maintaining Optical Fiber Interferometer for Simultaneous Measurement of Acoustic Pressure and Temperature
B. Chiu and M. C. Hastings
- 404 Natural Frequencies and Stability of a Spinning Disk Under Follower Edge Traction
Jen-San Chen
- 410 Redesign of Ultrasonic Block Horns for Improved Vibration Performance
M. Lucas and A. C. Smith
- 415 Flexural Wave Propagation in a Fluid-Loaded Elastic Plate With Periodically Varying Rigidity
M. A. Hawwa and A. H. Nayfeh
- 420 Vibration Control of Rotor Systems With Noncollocated Sensor/Actuator by Experimental Design
S. M. Yang, G. J. Sheu, and C. D. Yang
- 428 Identification of Structural Parameters in Mistuned Bladed Disks
Marc P. Mignolet and Chung-Chih Lin
- 439 A Reduced Order Modeling Technique for Mistuned Bladed Disks
M. P. Castanier, G. Öttersson, and C. Pierre

(Contents continued on p. 323)