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ELECTROMAGNETIC, HEAT AND FLUID FLOW PHENOMENA IN LEVITATED METAL DROPLETS BOTH UNDER EARTHBOUND AND MICROGRAVITY CONDITIONS

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INTRODUCTION

The purpose of this investigation is to develop an improved understanding of the electromagnetic, heat and fluid flow phenomena in electromagnetically levitated metal droplets, both under earthbound and microgravity conditions. In the following, we shall discuss the main motivation for doing this work, together with the past accomplishments and the plans for future research.

MOTIVATION

The main motivation for this work lies in the following:

(1) The electromagnetic, heat transfer and mass transfer problems in levitated metal droplets pose important fundamental scientific issues; here we are concerned with both laminar

and turbulent recirculating flows in a spherical (or distorted spherical) system driven by an electromagnetic force field. Due to the curvilinear nature of the system, significant damping of the turbulence will occur in the vicinity of the free surface; furthermore, there are important issues of velocity transients and the laminar/turbulent transition which are little explored. Finally, in levitation melting there are important problems of surface stablity and surface wave formation. A fundamental understanding of these phenomena could well provide the key to electromagnetic near net shape casting--a topic of very great current interest.

(2) Electromagnetically driven flows are of great technical importance in materials processing, including induction furnaces, electromagnetic stirring, welding, plasmas, electromagnetic casting, and confinement. An improved fundamental understanding of these phenomena could greatly improve the efficiency and effectiveness of these operations.

(3) The Electromagnetic Levitator is a key item in materials processing in space, because it allows containerless processing and ready heating and quenching of specimens. The numerous research projects using the EML for undercooling and alloy development studies would greatly benefit from a precise, quantitative description of the transient velocity, tempera-

ture and composition fields in these systems. Indeed, the availability of this information could be an important component of these studies.

THE NEED FOR MICROGRAVITY

In studying levitation melting under earthbound conditions, quite high currents have to be employed in order to levitate the specimens; this will necessarily lead to turbulent flow conditions and frequently to flow instabilities. Furthermore, when performing levitation melting studies on earth, significant deformation of the specimen will occur due to the force of gravity. In fact, levitation-melted specimens are never spherical on earth, but have an "inverted teardrop" shape. On performing levitation under microgravity, much lower currents will suffice to position the specimen, once it has been melted, so that one can study the laminar flow regime and the turbulent-laminar transition as well as turbulent conditions. Furthermore, the specimen will retain its spherical shape, which will make the analysis of both flow and instability phenomena much more straightforward.

ACCOMPLISHMENTS TO DATE

The purpose of the research has been to perform mathematical model development and to carry out ground-based experiments in order to allow rational planning of the in-flight studies.

The principal accomplishments to date may be summarized as follows:

(1) Through the statement and numerical solution of Maxwell's equations and the laminar/turbulent Navier-Stokes equations for a system with spherical symmetry, we were able to represent the temperature, velocity and concentration fields in levitated metal droplets under both earthbound and microgravity conditions (1,2,3,6,8). The theoretical predictions for the lift force and for mass transfer were in excellent agreement with the experimental measurements.

Here Fig. 1 shows the computed lift as a function of position; also shown is the weight of the droplet used in the experiment. The conditions depicted represented the threshold of the onset of levitation--in agreement with the measurements.

Fig. 2 shows the computed velocity fields in levitation melted specimens for earthbound conditions, while Fig. 3

shows a comparison between experimentally measured carburization rates and those predicted on the basis of the model.

Finally, Fig. 4 shows the computed circulation field for μg conditions. It is seen that under these conditions, the nature of the circulation is quite different, because of the symmetry; i.e. the droplet does not "sag" due to gravity.

(2) As part of this work, we have developed a general technique for calculating the electromagnetic force field and the corresponding velocity fields in inductively stirred vessels. The theoretical predictions were found to be in very good agreement with measurements (7,9,10,11,12,13).

Of the many possible examples, Figs. 5, 6, and 7 show a comparison between the experimentally measured and the theoretically predicted velocity fields in inductively stirred vessels. The excellent agreement is readily apparent.

(3) Work has also been done to represent the damping of convection that is attainable using an externally imposed magnetic field, and it was shown that convection cannot be readily damped under these conditions (5).

(4) Work has also been done to develop the technique of velocity measurement in molten Woods metal using hot film anemometry (4).

CURRENTLY ONGOING RESEARCH

Research is currently proceeding in the following areas:

(1) We are developing the computational algorithm to represent the electromagnetic force field produced by induction coils in the presence of a metallic body hav ing unbounded (free) surfaces. This will allow us to represent accurately the deformation and the onset of surface instabilities, important not only in the accurate analysis of the levitation measurements, but also in the electromagnetic deformation processing of metals in general.

(2) We are developing techniques for the measurements of surface velocities by means of tracers and time-lapse photography for levitation-melted specimens. Here, the streaklines will give us both the magnitude and the direction of the velocities. This work is a crucial component of the planned in-flight experiments.

Here, Fig. 8 shows a photograph of an inductively heated specimen in an induction coil; the picture was taken by Dr. H. Edgerton. Figs. 9 and 10 show the streaklines obtained on the surface of a silver specimen at two different current levels.

Analysis of the streaklines has shown that at the lower current, velocities were of the order of 1-2 cm/s, while at the higher current, velocities were of the order of 6-7 cm/s.

(3) We are continuing with our work to study electromagnetically driven flows in molten Woods metal, as produced by a diverging current path between two electrodes, to compare theoretical predictions with measurements. This research is helpful for the independent testing of the model predictions.

THE PROPOSED FLIGHT EXPERIMENTS

The proposed in-flight experiments would involve levitation melting of a silver or gold alloy specimen about 1 cm in diameter, and tracking the path of tracer particles by using time-lapse photography. A major attraction of this technique is that the tracers would not have to be deposited on the surface, but would be contained in the sample prior to the flight. This has been proven in the laboratory. As per the results of the ground-based laboratory experiments, exposure times of the order of 1/10-1/30 of a second would give good streaklines.

Experiments would be carried out under conditions when the flow is quite turbulent, and upon reducing the current we would trace the trajectory of the system through the turbulent-laminar transition. Furthermore, the photographs taken will also provide information on the presence of surface waves and on the time-dependent shape of the metallic specimens.

The mathematical models predicting the steady state electromagnetic, temperature and velocity fields for an idealized spherical metal droplet are in place and may be run routinely, providing a first-level interpretation of the measurements. More refined models, allowing for deformation and transient behavior, are currently under development, and will be ready well before the time of the proposed in-flight experiments.

SUMMATION

The proposed in-flight experiments have both fundamental significance and important applications, earthbound and within the context of materials processing in space. Significant preparatory work has been carried out which in its own right has made major contributions to the understanding of electromagnetically driven flows. The preparatory ground-based work has been completed or is shortly to be finished; thus, the project has an excellent chance of success. Furthermore, the proposed work relies critically on the unique attributes of the microgravity environment. More specifically:

-- The proposed research addresses the fundamental issues of electromagnetically driven flow in spherical or near-spherical droplets, and the associated deformation and surface stability.

-- This work is important within the space processing context, because electromagnetic levitation is a standard tool of materials preparation in microgravity. Our research will allow precise definition of the flow and temperature conditions under which these experiments are carried out.

-- The work done to date, and the future work planned, have had, and will have, significant "fallout," helping the earthbound materials and metals processing industry through an improved understanding of electromagnetically driven flows and electromagnetic containment.

-- Microgravity is essential for this work, as laminar flow or turbulent/laminar transitions could not be achieved under earthbound conditions; furthermore, the nature of free surface behavior and free surface stability would be very different in the presence and the absence of gravity.

Significant, well-documented accomplishments have been made as part of this research to date, including computational methodology for handling the electromagnetically driven flow of molten metals. These calculations, together with ground-based experiments, provide an excellent basis for planning the in-flight research.

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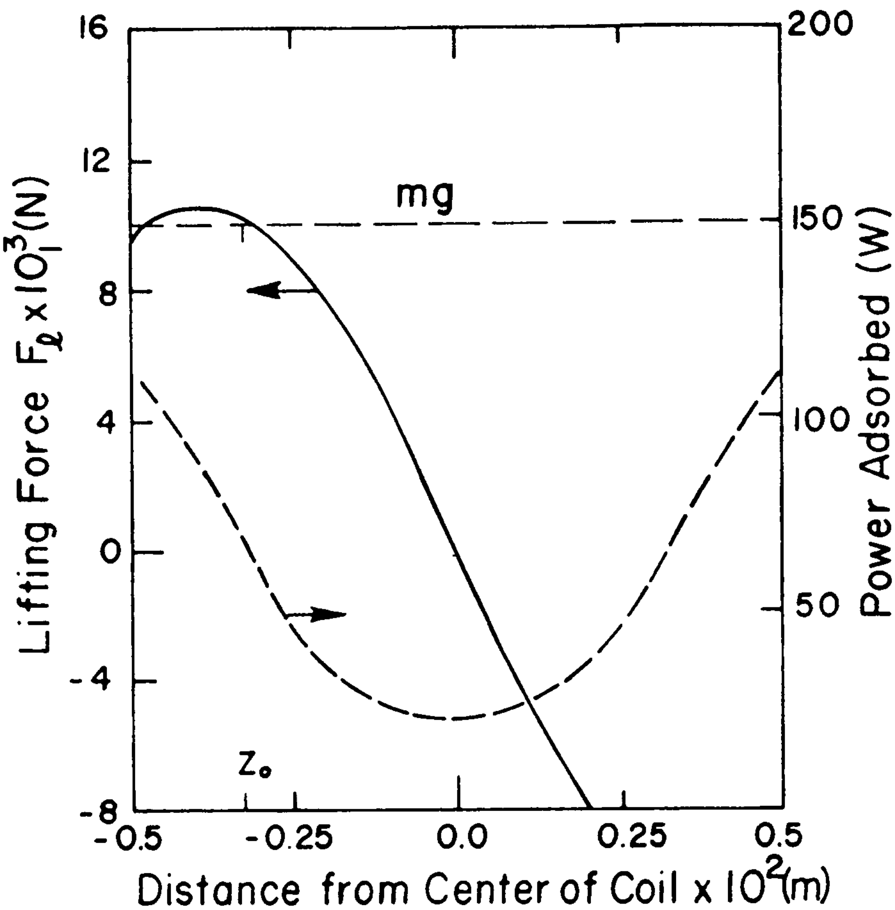

Fig. 1—Computed lifting force and power adsorption for a molten iron droplet along the axis of the coil. Coil current 250 Amp.

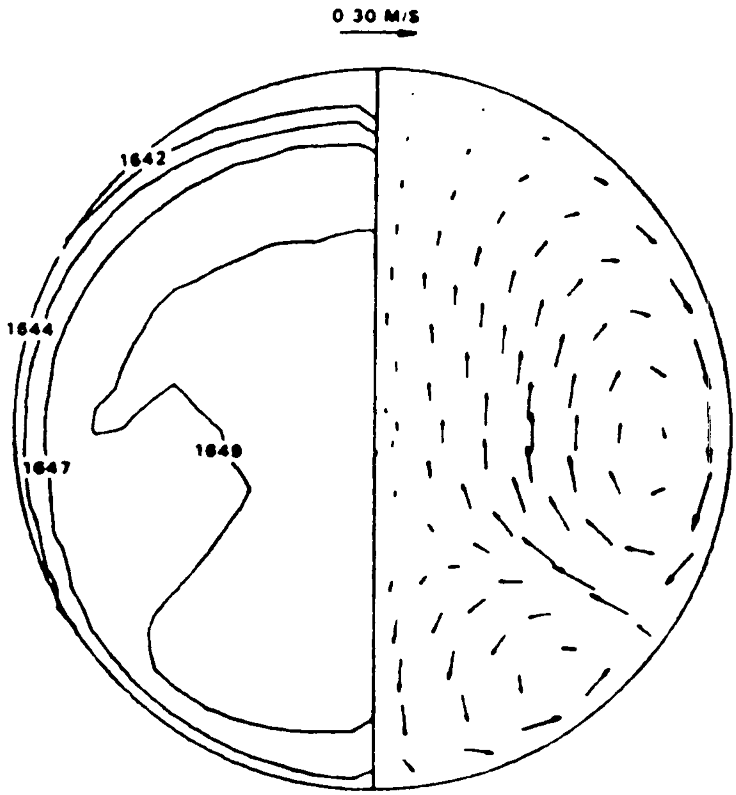

Fig. 2 Computed velocity field and temperature for a 6 mm iron droplet in earthbound gravity force (coil current = 250 A).

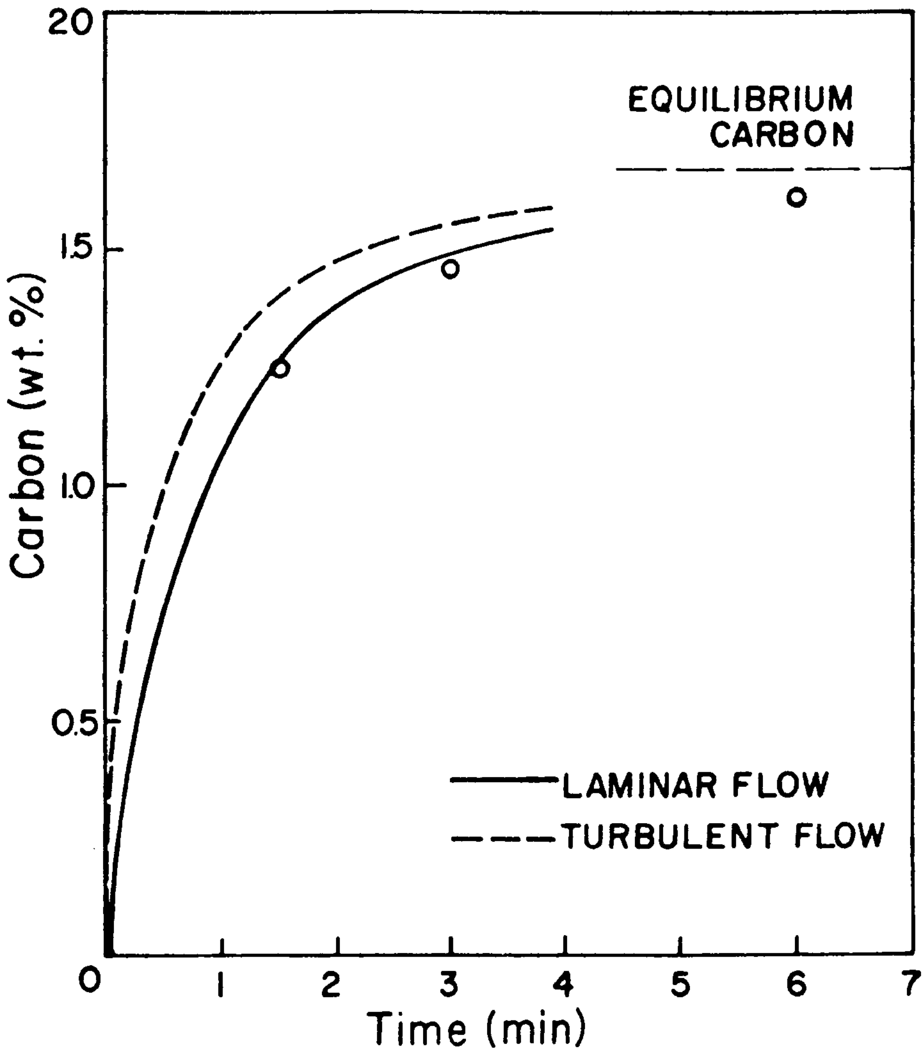

Fig. 3 —Experimental carburization results (CO 2.15/CO_2 at 38.9 atm and 1650 °C)[■,■] compared with the theoretical predictions for turbulent and laminar flow in the levitated drop.

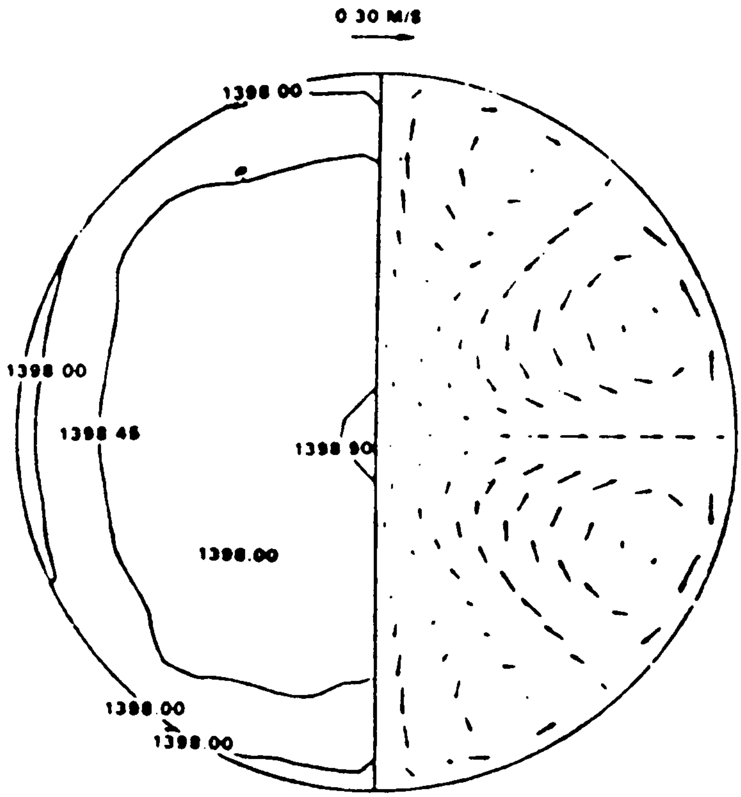

Fig. 4 Computed velocity field and temperature distribution for a 9 mm beryllium drop at zero-g.

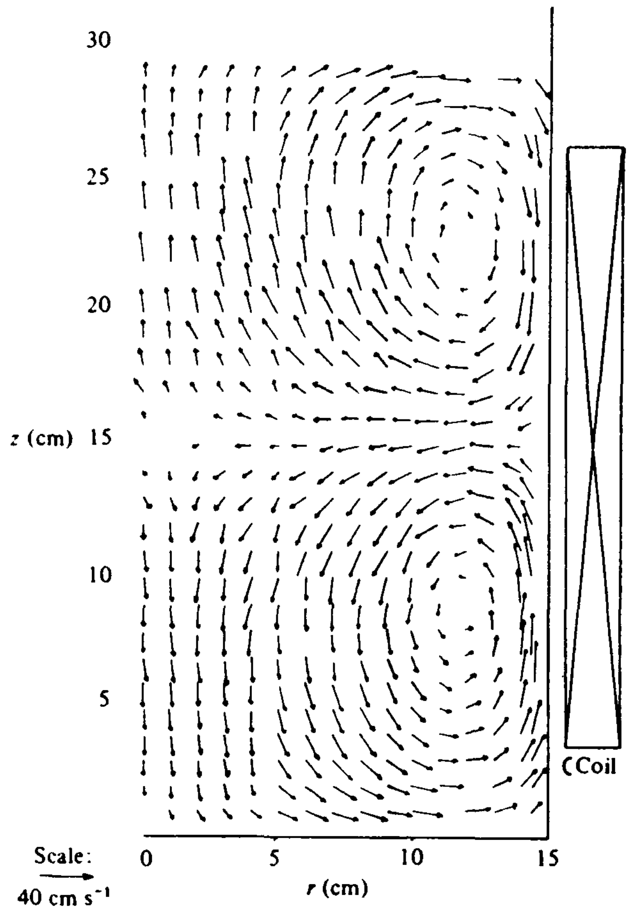

Fig 5a Experimentally measured velocity field for 1900 A coil current.

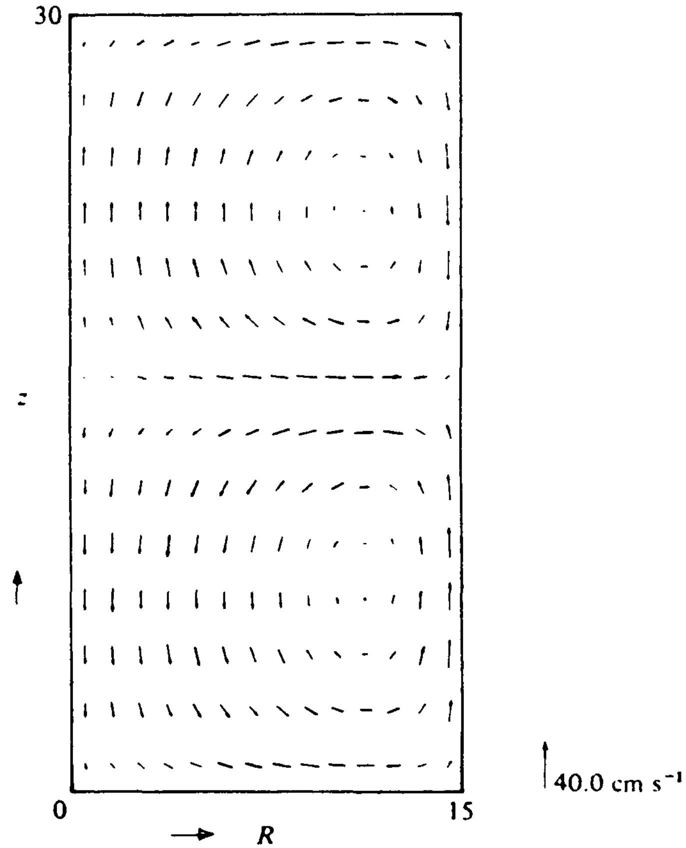

Fig 5b Computed velocity field for 1900 A coil current.

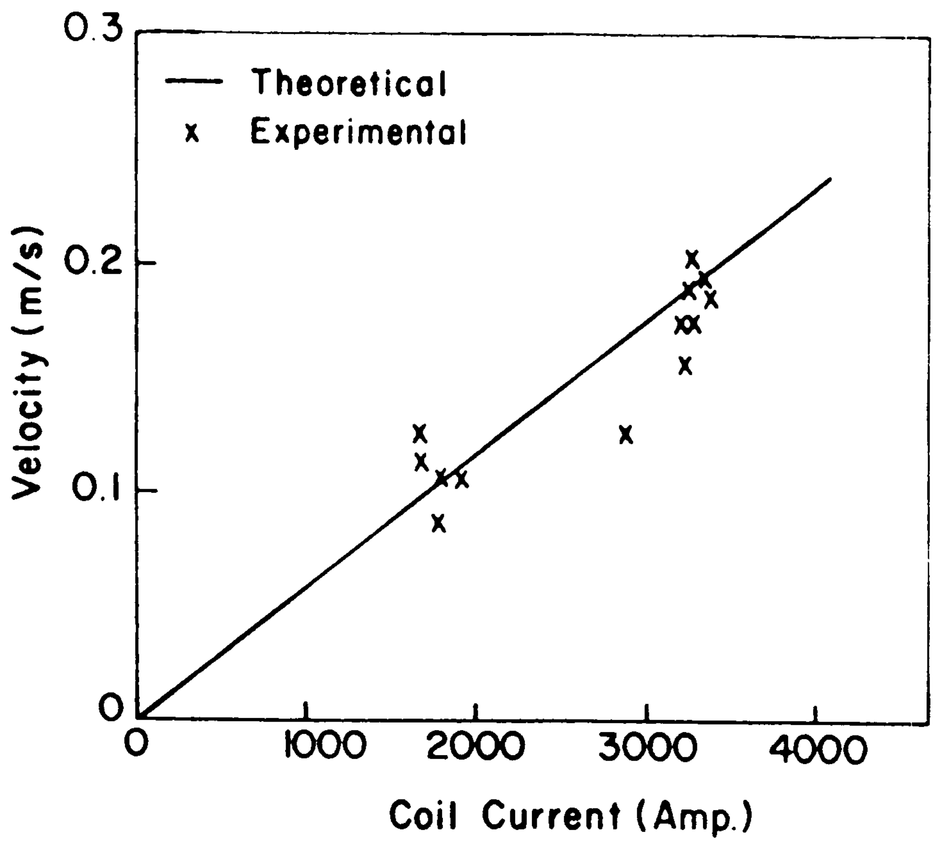

Fig. 6 Comparison between the measured and the computed near surface velocity for a four ton melt of steel as a function of the coil current .

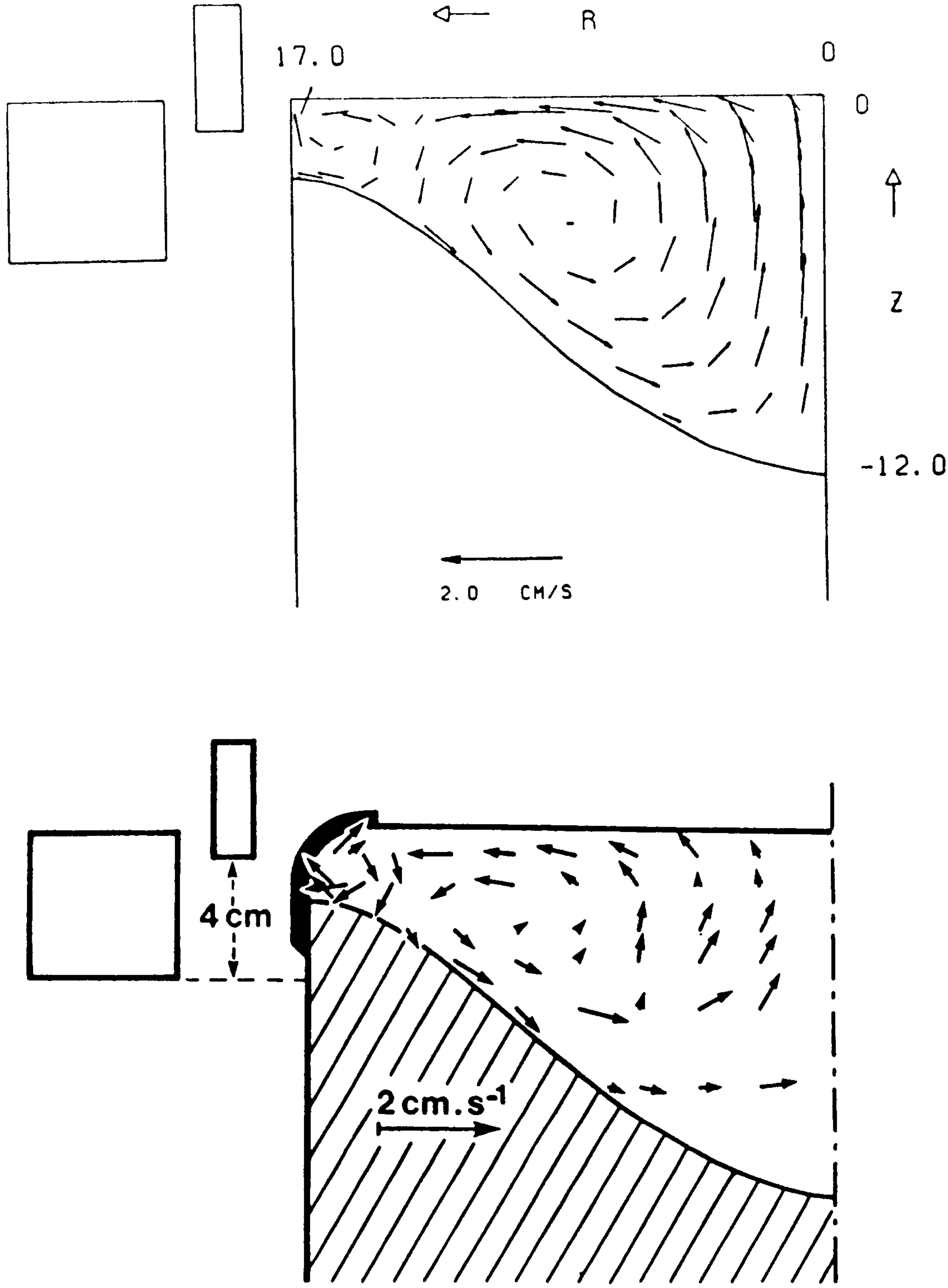

Fig. 7 Comparison between the computed (a) and the measured (b) fluid flow fields for the EM casting of Aluminum .

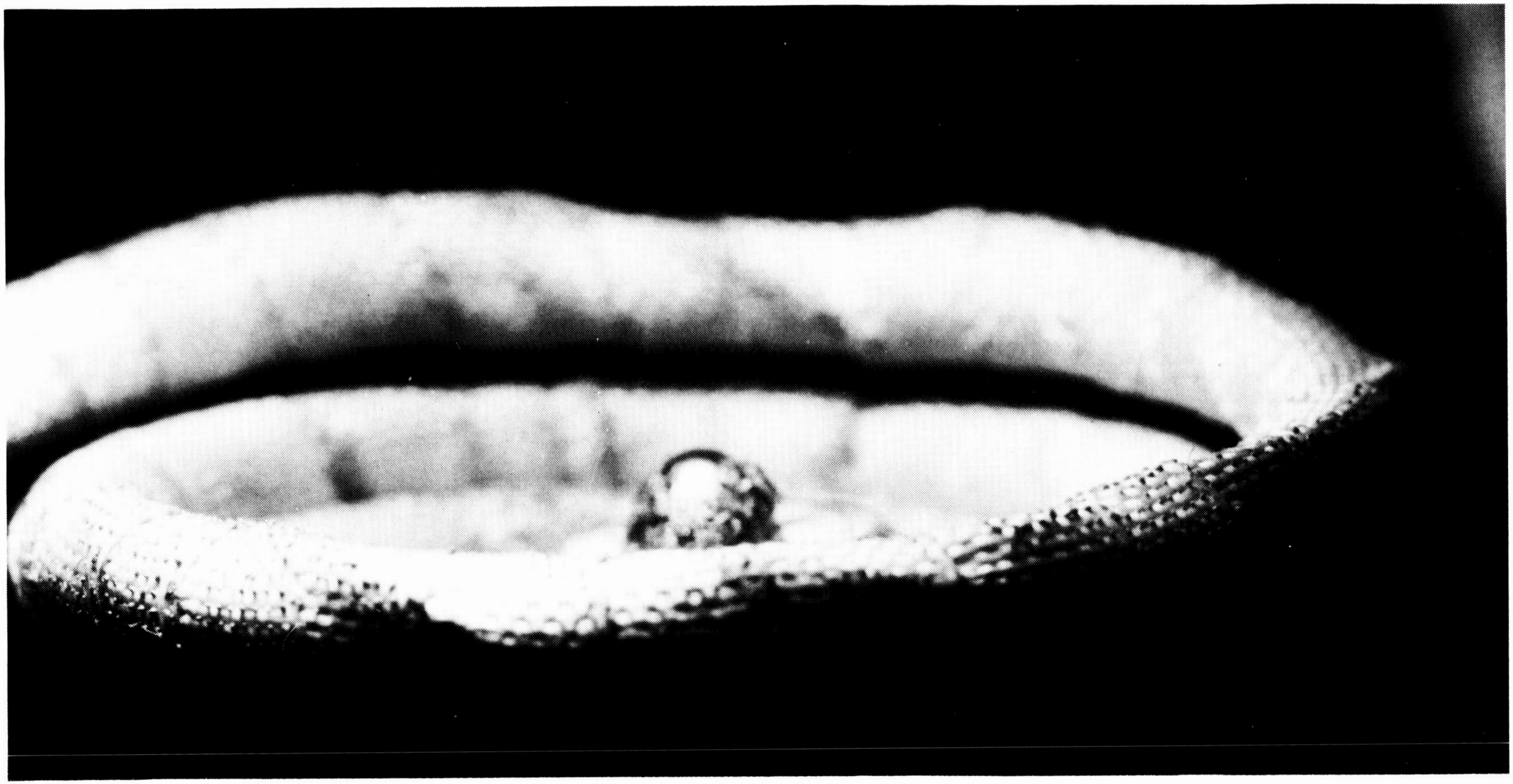

Fig. 8. The experimental set-up showing the coil, the sample and the quartz rod used to support the sample (photo by H. Edgerton).

Fig. 9. Silver droplet showing tracer particle paths. The current in the coil is about 600 A.

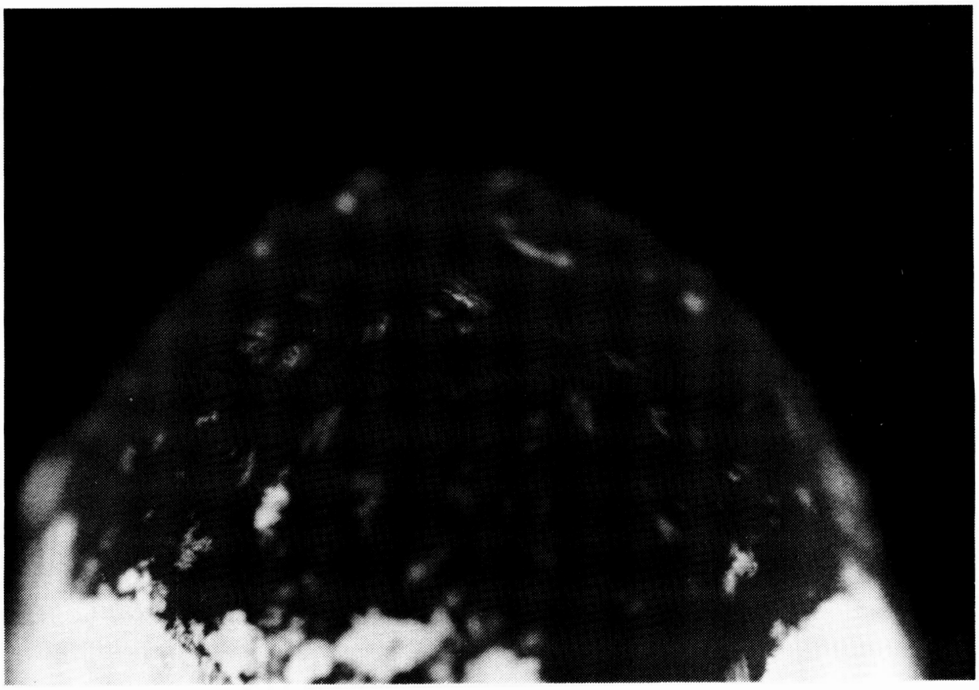

Fig. 10. Silver droplet showing tracer particle paths. The current in the coil is about 400 A.