DEVELOPMENT OF A VERSATILE ELECTROMAGNETIC LEVITATOR

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Abstract

A versatile electromagnetic levitator (VEL) for ground-based experiments is under development at the Jet Propulsion Laboratory. The VEL has two independent coils (one is for levitation and the other is for heating) which are advantageous for precise positioning and temperature control of a sample. The levitator can be operated in a vacuum of 10^{-7} torr as well as in an inert gas, which may be used for quenching purposes. The planned applications of the VEL include the total radiance measurement by a blackbody bolometer, the spectra emissivity measurement by an advanced division of the amplitude polarimetric pyrometer, the specific heat measurement by means of AC, DC and drop calorimetries, and undercooling and solidification experiments.

Introduction

Containerless techniques have been considered as novel techniques for material processing on earth and in space because they are free from contamination originating from the container walls (1-5). Among the containerless techniques, the electromagnetic levitation technique is particularly suitable for processing metallic materials. The advantages of electromagnetic levitation are its capabilities to levitate a sample against gravity relatively easily and to heat the sample simultaneously to high temperatures in vacuum as well as in a gas environment. The disadvantage is, obviously its incapability to levitate non-conductive materials. At the Jet Propulsion Laboratory (JPL) NASA Center for Containerless Microgravity Research, we have been developing a versatile electromagnetic levitator (VEL) to provide engineers and scientists with an opportunity to utilize the levitator for their experiments rather than building their own. In this paper, we describe the features, the capabilities and the scheduled applications of VEL.

VEL Features

Figure 1 depicts the schematic diagram of VEL. The heart of VEL is a vacuum chamber with four windows (one is on top and the others are at the side), two electrical feedthroughs and three motion feedthroughs (all are not shown). The VEL has some unique features which are separately described in the following sub-sections.

Levitation and Heating Coils

Figure 2 shows the side view of the levitation and heating coils (The top view can be seen in Figure 4). The levitation coil has an inverted conical shape which possesses some advantages over a conventional conical shape (6). The levitation coil is directly connected to a Lepel RF generator (maximum output: 5 kW) operated at 250 kHz. The heating coil has a spiral shape (two turns) and is placed at the spacing between the top and bottom turns of the levitation coil. The heating coil is connected to a general purpose function synthesizer whose output is amplified by a linear power amplifier (ENI A-500, Gain: 60 dB). In order to match the impedance between the amplifier and the coil whose impedance is very small, a coaxial step-down transformer (shown in Figure 3) is installed. The primary coil is wound on a water-cooled ferrite core (15 turns) and the secondary coil is the coaxial shell itself. The capacitors connected in series are rated at 0.001 μF. The use of the general purpose function synthesizer allows us to modulate the power output, which may be required for certain experiments.

The sample visibility from the side is generally poor in electromagnetic levitation because of the tight winding of the coil. We have succeeded in improving it with the present configuration of the coils. The spacing between the Invitation coil and heating coil is approximately 4 mm, which is wide enough to observe the major portion of the side view of the sample. An example of the side view of the sample appears in figure 5.

Stability Control

A levitated sample is not stationary but acquires the oscillatory anti rotational motions. The degree of the motions seems to be related to the sample geometry and the induction field. It is known that a permanent magnet is a good velocity damper of the motions (7). Figure 4 shows three magnets which are arranged in a circle and separated by 1200. For each magnet, the top face is the north pole and the bottom face is the south pole. Thus, the magnetic field is parallel to the axis of the levitation coil at the sample position. The temperature rise of the magnets due to eddy current hinting seems tolerable for most applications.

Temperature Measurement

The sample temperature can be measured by an optical pyrometer which is aimed at the sample through the top window. In [Figure 1, we also show an advanced division of the amplitude polar imetric pyrometer (DAPP) developed by INTERSONICS for JPL. The DAPP can measure the spectra emissivity and utilize it for the temperature determination.

Environmental Control

The attainable vacuum level is in the 10^{-7} torr range, which should be adequate for most experiments. The chamber can be backfilled with a high purity inert gas. An oxygen remover can be installed to remove the residual oxygen in the gas. It is possible to adopt a closed loop oxygen removal system developed at JPL (8). The system is based on a metal loaded zeorite or carbon molecular sieves as the oxygen sorbents.

Operational Capabilities

The operational capabilities are strongly dependent on the configuration of the levitation and heating coils. A slight change in the configuration drastically affects the capabilities. The capabilities also vary depending on the properties of the sample such as the electrical conductivity. The following qualitative description of the capabilities is observed during an experiment with aluminum samples in an Ar environment.

Sample Choice

With the current setting, VI I can easily levitate Al and Al based alloys because of their low density and high conductivity. It is possible to levitate Ni and Fe samples but the sample stability is not satisfactory. We are working on this problem in order to enhance the levitation capability.

Sample Shape

Figure 5 shows the side view of a liquid Al sample. The sample is slowly rotating at an undetermined velocity. We may claim that the sphericity of the sample is better than that of the drop produced by the conventional conical shape coil.

Temperature Range

The power required for levitation is sufficient to melt a sample of Al in vacuum. In an Ar atmosphere, heating by the levitation coil is not sufficient to melt the Al sample; thus, we can melt and resolidify the sample by controlling the power to the heating coil.

Sample Stability

The magnets can stop oscillation and rotation of the solid sample, especially when the sample shape is irregular. The magnets are less effective for the liquid sample. The rotation of the liquid sample considerably slows down when the magnets are placed but it does not stop completely. The liquid sample near the melting point is more stable than that at higher temperatures. This observation indicates that the viscosity plays an important role in the stability of the liquid sample.

Applications

The VEL system is designed to accommodate a variety of experiments. If necessary, it is possible to make minor modifications to accommodate specific requirements. The planned applications using the system includes the following:

Total Hemispherical Emissivity

Professor W. L. Johnson at the California Institute of Technology (Caltech) has proposed to measure the total hemispherical emissivity by means of a blackbody bolometer. This quantity is necessary for his experiment on the AC specific heat measurement with the TEMPUS facility scheduled to fly on the Space Shuttle in 1994. The basic idea of the bolometer is to collect all of the radiation which can be translated into the total hemispherical emissivity if the sample geometry is known. The bolometer is under fabrication at Caltech and will be mounted on the top of the VEL system. The accuracy of the measurement will strongly be dependent on the stability and sphericity of the sample.

Spectra Emissivity

For radiometric pyrometry, the **spectra** emissivity must be independently obtained and provided for determining the sample temperature. Dr. A. Abatahi at JPL is interested in order to determine the emissivities of various metals and alloys to create a database for general use. The DAPP system will be utilized for this measurement.

Specific Heat

Levitation of a liquid is an effective way to achieve a significant level of undercooking because there is no contact with the container, which is usually a highly active heterogeneous nucleation site for a solid. The specific heat of the levitated undercooked liquid can be determined if it is measured by a noncontact method. A drop calorimeter developed at JPL has been successfully utilized to measure the specific heat of a undercook glass forming alloy (9). This method is time consuming and can only determine the specific heat indirectly. Alternative calorimetric methods that measure the specific heat directly are noncontact AC (10) and DC (thermal relaxation) calorimetry methods. We will explore the feasibility of these methods using the VEL system

Surface Tension

The surface tension of a levitated liquid drop can be determined by oscillating the drop about its equilibrium shape (11). The oscillation frequency can be related to the surface tension according to Rayleigh's law (12). An alternative method is simply to spin the drop until it is bifurcated. The bifurcation point has been theoretically predicted to be 0.56 ω_0, where

$$\omega_0 = \left(\frac{8\sigma}{\rho r}\right)^{1/2} \qquad (1)$$

is the fundamental axisymmetric mode of the shape oscillation of a non-rotating drop, σ is the surface tension, ρ is the density and r is the radius of the spherical drop (13). We have observed that the levitated sample naturally spins in an accelerated manner and sometimes it eventually bifurcates. We may utilize this phenomenon to determine the bifurcation point. We may also actively apply a torque by generating a rotating magnetic field (14).

Solidification

Professor J. H. Perepezko at the University of Wisconsin has shown that the corr-elation between the onset eutectic spacing and the nucleation temperature of InSb-Sb (15) can be described by the eutectic growth theory of Kurz and Fisher (16). The theory is written as

$$\Delta T = A \lambda v + \frac{B}{\lambda} \qquad (?)$$

where Al is the undercooling at the interface, λ is the spacing, v is the interface velocity and A and B are constants. Trivedi, Magnin and Kurz have advanced the theory by taking into account the solute trapping which **might** happen at high interface velocities (17). It is of interest to test these theories with other eutectic alloys. We have chosen the Al-Cu eutectic alloy which is suitable for the VE 1 system.

Acknowledgments

This work represents one phase of research carried out at the Jet Propulsion laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). Special thanks to J. Watkins and J. Gatewood for their suggestions and help.

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Captions:

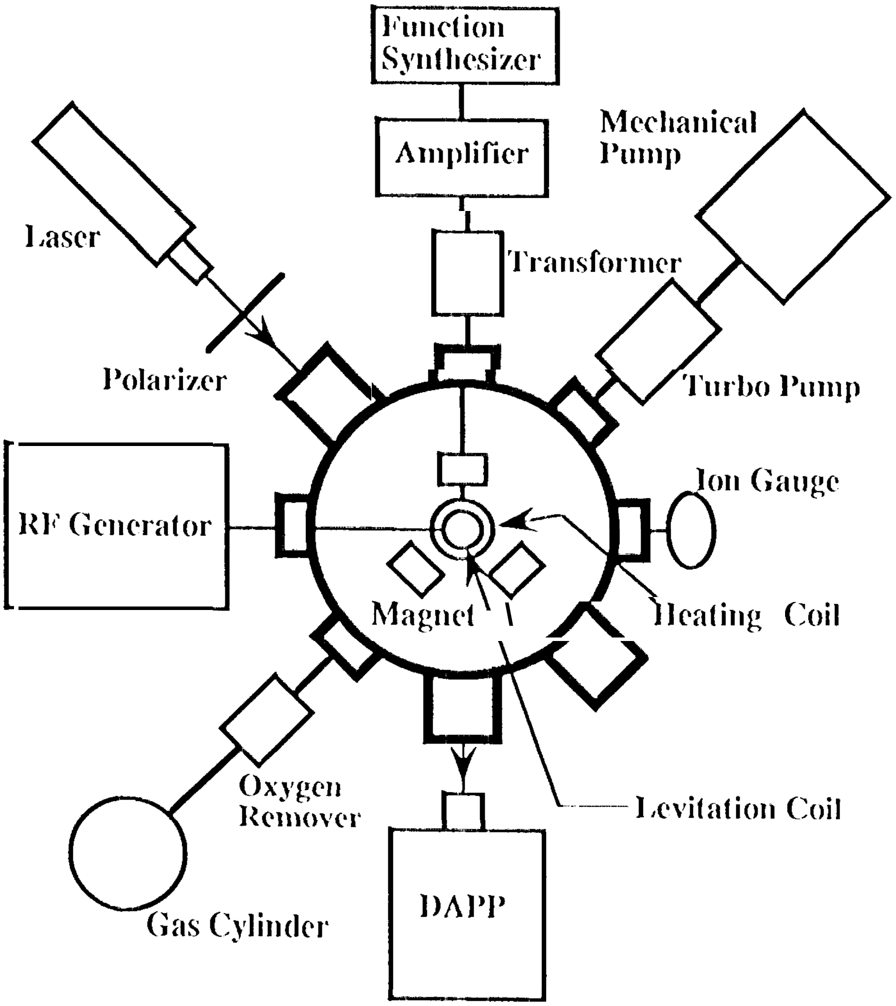
Figure 1. Schematic diagram of VE 1.

Figure ?. Levitation and heating coils of VEL.

figure 3. Coaxial step-down transformer for the heating coil.

Figure 4. Permanent magnet assembly for motion damping.

Figure 5. Side view of levitated molten Al.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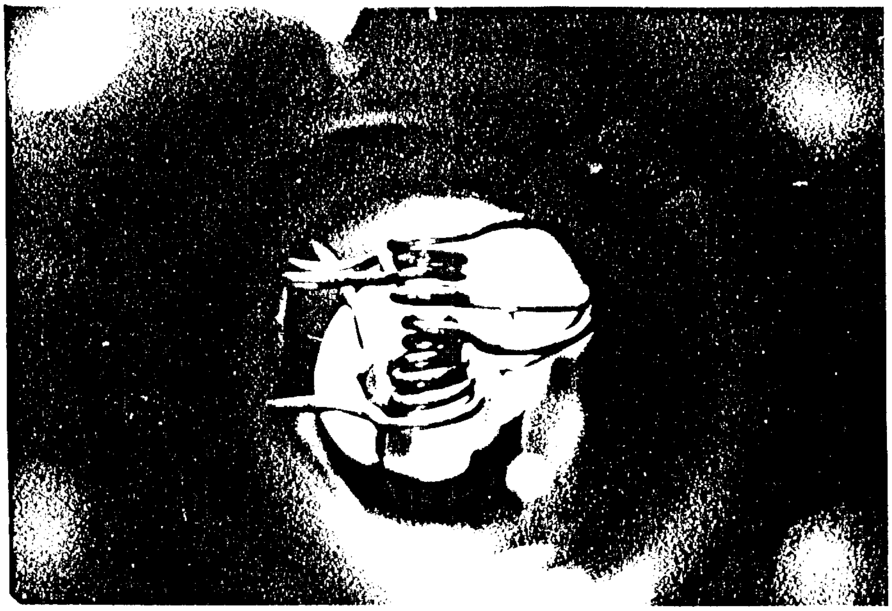
Oxygen Remover
Gas Cylinder
DAPP

Figure 1



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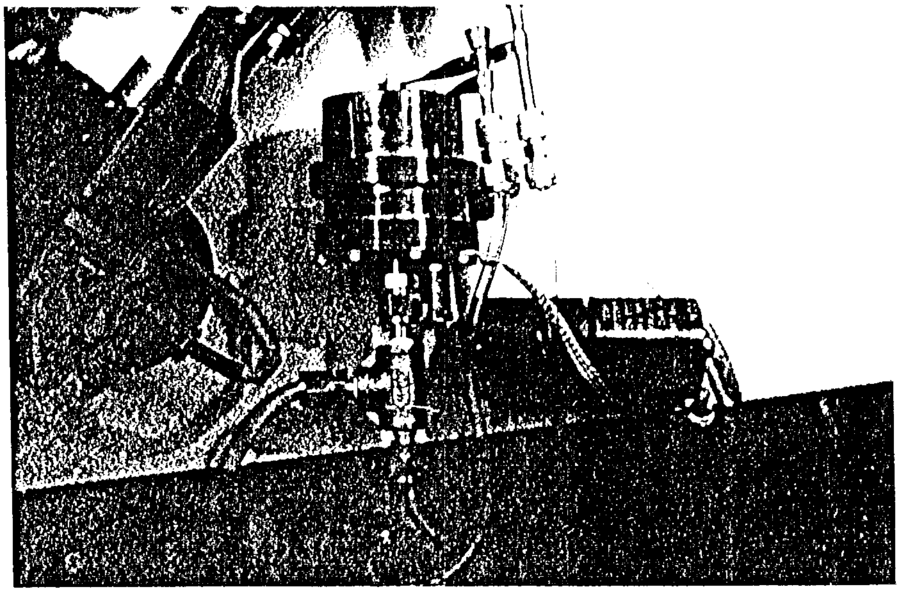

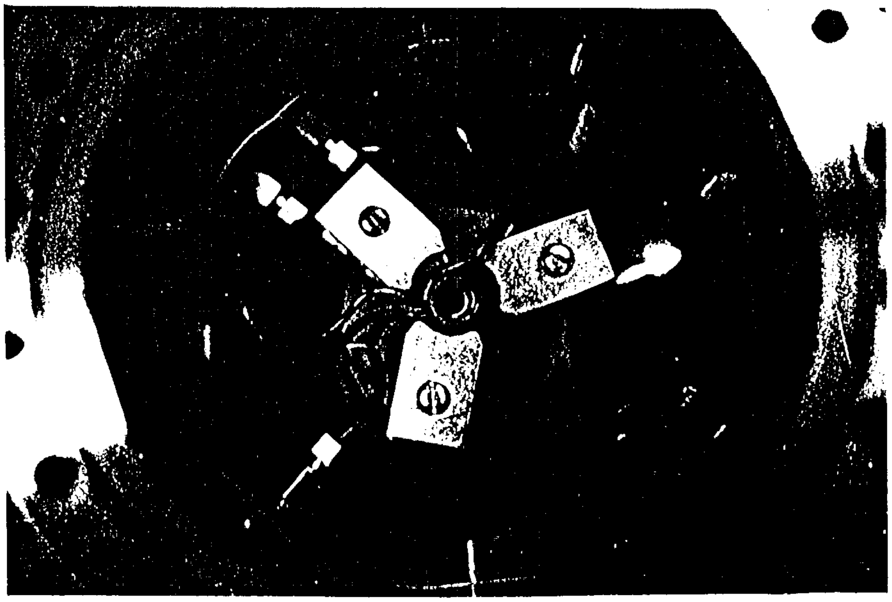

Figure 4.

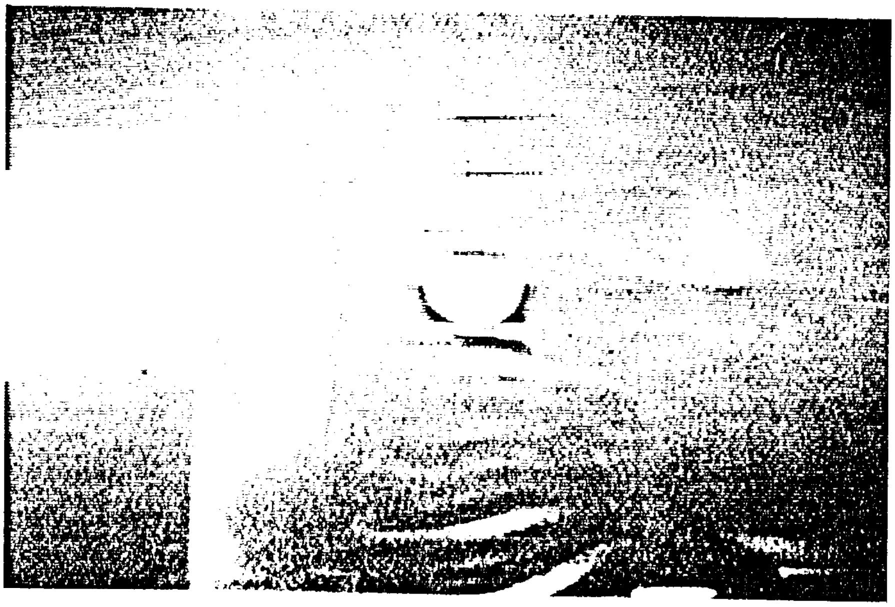

Figure 5