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INTERFACE SCIENCE

High-speed imaging and CFD simulations of a deforming liquid metal droplet in an electromagnetic levitation experiment

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Abstract Electromagnetic levitation of a liquid metal droplet is of great interest to study gas–liquid metal reactions. An important prerequisite for the evaluation of the overall mass transfer between the gas and metal is to characterize the geometry of the deforming molten droplet, which determines the interfacial reaction area. In this article, the free surface shape and dynamics of a molten 80%Ni–20%Cr droplet is investigated both experimentally and numerically. The frequencies associated to the oscillatory translational motions of the drop and to the vibrations of its free surface are measured using high-speed video image analysis. A 2D transient model is then presented, in which three interacting phenomena are considered: electromagnetic phenomena, the turbulent flow of liquid metal in the drop and the change in the drop shape. The numerical results presented demonstrate the capabilities of the model.

Introduction

The levitated drop method has proved to be a useful laboratory technique to perform experiments on liquid metals, because it provides a contamination-free environment, without any crucible or substrate and allows high processing temperature [1]. In this respect, it is particularly appropriate for investigating reactive and refractory metals (e.g. Ti, Zr, Nb, V and Cr). Currently, an important application field of levitated drop experiments is the measurement of thermophysical properties of liquid metal alloys (such as the density, surface tension and viscosity). Other applications include fundamental studies on nucleation and solidification processes, and investigations of gas–liquid metal reactions. The present study is concerned with this latter application. The use of electromagnetic levitation to study gas–liquid metal reactions offers several advantages. First, any influence of a container wall is suppressed. Second, this technique makes it possible to quickly reach gas–liquid equilibrium, as a result of an important contact surface and an efficient stirring of the molten metal. The levitated drop method is used at the E.O. Paton Institute to investigate the nitriding and denitriding of various liquid metal alloys, including reactive alloys (Ti, Zr, Cr) and nickel–chromium alloys (representative of nickel-based superalloys). A levitation experiment involves exposing the levitated molten sample, maintained to a constant temperature, to a nitrogen gas flow during a controlled time interval. The gas content in the metal is obtained from chemical analysis after solidification of the sample. Such experiments give access to the equilibrium solubility of the gas in the metal at a given temperature and enable to determine kinetic data of the overall nitrogen reactive transfer at the gas–liquid metal interface.

The obtained experimental data are however insufficient to establish precisely the limiting step for the transport of nitrogen. For this reason, a numerical modelling work of the levitated drop experiment has been undertaken in parallel at the School of Mines in Nancy. The general objective of this model is to predict the time evolution of

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the nitrogen content in the metal sample during a nitriding or denitriding experiment. This requires modelling the flow of liquid metal induced by the mixing electromagnetic forces within the droplet. Such an approach has already led to a fair description of nitrogen pick-up and removal during a Sieverts' experiment [2]. Moreover, to quantify the overall mass transfer between the drop and surrounding gas, it is essential to accurately evaluate the interfacial area, which implies to carefully characterize the deformation of the drop free surface. This task is made particularly difficult due to the strong coupling of the free surface deformation with both the electromagnetic field and internal flow. As part of the effort to achieve a complete modelling of a levitation experiment, the present work concerns more especially the characterization of the geometry of the levitated drop. It combines high-speed visualizations and computational fluid dynamics (CFD) modelling of the dynamics of the drop and transient deformation of its free surface.

Experimental

The experimental set-up is presented in Fig. 1. The experiments are carried out in a quartz glass tube, 17.4 mm in diameter. A six-turn induction coil is installed around the tube, with two counter-turns at the top. The coil is supplied by a generator with a frequency of 66 kHz and an output power of around 7 kW. The alloy used in the present study is 80%Ni–20%Cr. The samples weigh approximately 1 g and have an initial diameter of 3 mm. The motion and shape of the levitated sample is recorded using a high-speed video camera (1,000 frames/s, 768 × 768 pixels) located in front of the levitation facility. A mirror is positioned laterally with a 45 degree angle in order to visualize simultaneously both frontal and transversal views of the sample. This allows to obtain some information about the 3D nature of the drop geometry. The temperature of the molten metal is measured using a pyrometer located above the sample. During the melting process, a flowing inert gas (Ar) atmosphere is maintained around the sample in order to prevent introduction of impurities in the molten metal by reaction with the ambient air. The metal temperature during the reported experiment was 1,700 °C. In order to quantify the geometry and dynamics of the levitated sample, an in-house computer program was developed for post-processing the video images. This program enables to detect automatically on each digital image the drop edges and to calculate the area and the coordinates of the centre of gravity of the surface bounded by the detected edges (i.e. the apparent cross-section of the drop in the observation plane). A spectral analysis of the time evolution of the latter parameters is then performed, in order to identify characteristic frequencies of the system dynamics (translational and oscillation frequencies).

The levitated drop exhibits a complex dynamic behaviour. The drop is significantly distorted from a sphere and undergoes continuous free surface oscillations, translational motions in several directions and, under certain conditions, rotations. This section presents the main results of our study regarding the free surface behaviour and translational motions of the drop. Figure 2 displays the frequency spectrum associated with the fluctuations of each coordinate of

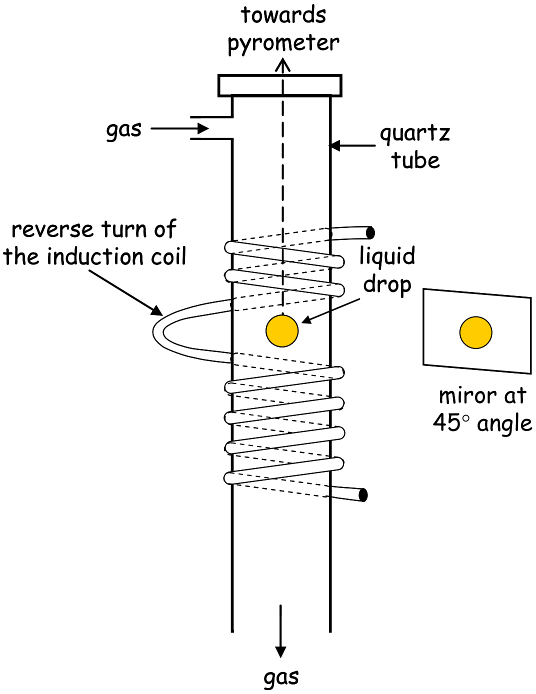

Fig. 1 Experimental set-up

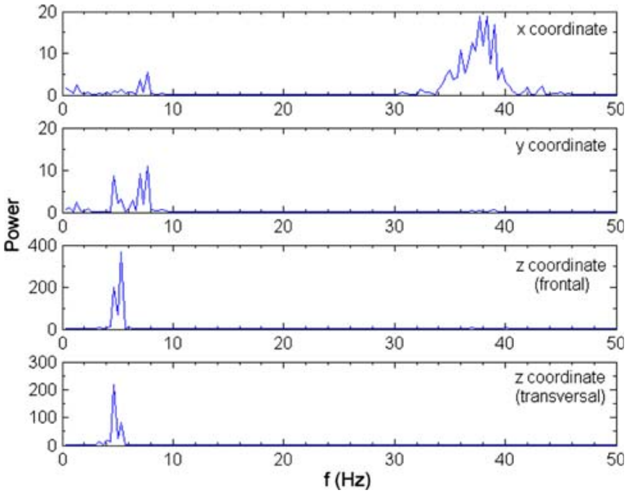

Fig. 2 Fourier power spectra for the fluctuations of the coordinates of the drop centre of gravity

the centre of gravity of the drop cross-sectional area. The centre of gravity is subjected to a predominant oscillating motion in the vertical direction, whose frequency is about 5 Hz. The centre of gravity is also oscillating in the horizontal plane (x and y coordinates), yet with a much lower intensity. The motions in the horizontal plane are characterized by a frequency of 7.7 Hz. The peak at 39 Hz observed on the x coordinate spectrum is linked, as shown below, to the surface oscillations.

Figure 3 shows the temporal variations of the frontal and transversal cross-section area of the drop. Also presented are video images of the transversal and frontal views of the drop at various time instants. Note that the bottom fraction of the drop on the frontal image is missing, due to the blockage of the view by the coil.

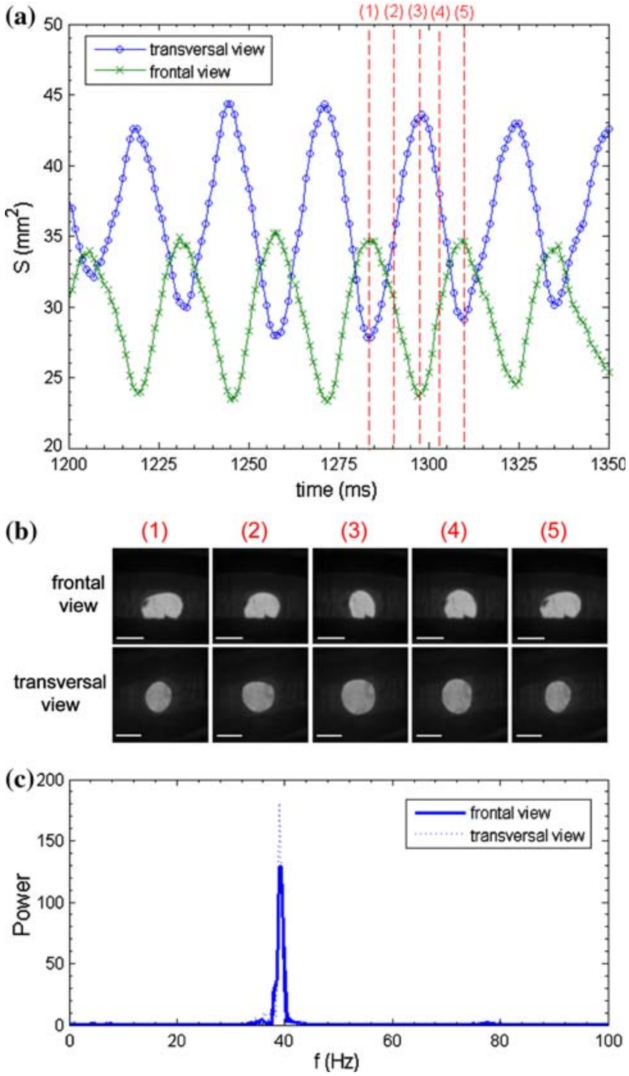

Fig. 3 Frontal and transversal cross-sectional area of the droplet: (**a**) fluctuations with time, (**b**) video images at different instants (the scale bars on the images are 5 mm) and (**c**) Fourier power spectra of the fluctuations

The cross-sectional areas fluctuate rapidly with time, with the areas of the frontal and transversal views oscillating in phase opposition. The amplitude of the fluctuations is relatively important. Such fluctuations of the cross-sectional area reflect oscillations of the drop free surface, which result from surface tension forces, magnetic pressure effects and convection of the molten metal. The spectral analysis of the fluctuations (performed taking into account 3,000 frames) shows the same dominant peak at around 39 Hz for the frontal and transversal views. Note that a close observation of the frequency spectrum reveals in fact the existence of a series of closely spaced frequency peaks around 39 Hz (eight peaks for both the frontal and transversal views). The existence of these multiple peaks indicates a complex dynamics of the drop oscillations. As observed on the images presented in Fig. 3, the instantaneous geometry of the drop deviates significantly from a sphere and is non-axisymmetric. Both frontal and transversal cross-sections may be approximated as an ellipse. During a half-time period, the major axis of the frontal cross-section oscillates between two inclined perpendicular directions.

Although being not the main purpose of our study, it is of interest to estimate the surface tension of the liquid metal from the measured frequencies, using the formula derived by Cummings and Blackburn [3]:

$$\frac{8\gamma}{3\pi m} = \frac{1}{5}\sum_{n=1}^{5} \nu_n^2 - \nu_{\mathrm{tr}}^2 \left[1.9 + 1.2\left[\frac{g}{8\pi^2 \nu_{\mathrm{tr}}^2 a}\right]^2\right] \qquad (1)$$

In the above expression, γ is the surface tension, m is the drop mass, ν_n denote the various frequencies of surface oscillations, ν_{tr}^2 is the mean of the squares of the three translational frequencies, g is the gravitational acceleration and a is the radius of the drop. Considering only the five most prominent peaks of the surface oscillation spectrum (which may be disputable since the above formula is strictly valid only for five peaks spectra), application of this formula yields a surface tension value of 1.70 N/m from the frontal view and 1.61 N/m from the transversal view. These two values are consistent with each other and are within 10% of the prediction obtained using the ideal solution model ($\gamma = 1.75$ N/m) [4]. Unfortunately, to our knowledge, no experimental data for the surface tension of a 80%Ni–20%Cr alloy is available in the literature.

Numerical modelling

The simulation of the behaviour of electromagnetically levitated droplets has been the subject of numerous investigations in the literature, which have been based on a large variety of analytical and numerical techniques. A comprehensive description of the system, including the coupling between the electromagnetic field, change in the liquid metal shape and fluid flow within the drop, is a challenging task. Most of the studies were focused on certain restricted aspects of the problem and/or rely on some simplifying assumptions. In particular, only a few studies have taken into account the dynamic effect of the melt flow on the free surface shape [5–7]. The most prominent and complete work is the recently reported model of Bojarevics and Pericleous [7], which calculates, using a spectral solution technique, the thermal and flow fields within an axisymmetric levitated drop, simultaneously with free surface oscillations.

The work presented here represents a first contribution to the development of a complete numerical model of a levitation experiment with the final aim of investigating gas–liquid metal reactions. From the experimental images shown in the previous section, the instantaneous geometry of the drop is not axisymmetric due to intense fluctuations of its free surface. Nevertheless, as it will be demonstrated later in this paper (see Fig. 8), the geometry of the drop averaged over several periods of fluctuations is relatively close to axisymmetry. To make the numerical problem tractable at a reasonable computational cost, the following assumption is made. Since our final interest lies in simulating the transfer of chemical species between the gas and metal and because the time scale of those transfer processes (at least a few seconds [2]) is much greater than the time scale of free surface fluctuations (about 25 ms), we decide to consider an axisymmetrical drop based on the above comment about time-averaged drop geometry. The methodology adopted to build a complete model is as follows. In a first step, i.e. the purpose of the present paper, we simulate the flow field in the drop generated by the electromagnetic forces and the associated deformations of the free surface. In a second step, we plan to derive a time-averaged shape of the levitated drop from the detailed simulation results of the free surface fluctuations obtained in step 1. Finally, we will simulate in a last step the transport of chemical species and the chemical reactions at the gas–metal interface in the fixed time-averaged geometry of the drop.

Model description

The model developed in this article focuses on the simulation of the flow field of the metal in the drop and the transient changes in the drop shape. The model addresses in a fully coupled way the following three aspects:

i. the calculation of the distribution of the electromagnetic field produced by the coil inside and outside the drop, and distribution of Lorentz forces acting on the liquid metal,
ii. the determination of the turbulent liquid metal flow induced in the drop by the Lorentz forces,
iii. the analysis of the deformation of the free surface shape of the drop.

In particular, the proposed model accounts for the influence on the free surface shape of both the electromagnetic field and internal flow dynamics in the droplet. As a first step towards the development of a complete model, heat and mass transfer phenomena are not considered in the present work and the droplet is assumed to be isothermal.

Calculation of the electromagnetic force

The electromagnetic force in the molten droplet results from the interaction between the induced current and magnetic field. The magnetic field can be obtained in terms of the vector potential $\vec{\mathrm{A}}(\vec{\mathrm{B}} = \nabla \times \vec{\mathrm{A}})$, which is purely azimuthal $(\vec{\mathrm{A}} = A_\theta \vec{\mathrm{e}}_\theta)$ in the axisymmetrical case. The vector potential must satisfy the following equation derived from Maxwell's equations (with the Coulomb gauge condition):

$$\nabla^2 A_\theta - \frac{A_\theta}{r^2} = \mu\sigma \frac{\partial A_\theta}{\partial t} - J_{\mathrm{ex}} \qquad (2)$$

where μ is the magnetic permeability, σ is the electrical conductivity of the metal and J_{ex} is the current density circulating in the coil. Note that in the above equation, the convective term associated to the flow velocity $(\vec{\mathrm{A}} \times \vec{\mathrm{u}})$ has been neglected, which is justified for high enough frequencies. In the case of a sinusoidal source current, it is convenient to express the field quantities using the phasor notation. For example, the vector potential is represented by the complex exponential function $\underline{A_\theta} e^{\mathrm{j}\omega\mathrm{t}}$, where the complex amplitude $\underline{A_\theta}$ has only a spatial dependence and ω is the angular frequency.

Using the phasor notation, Eq. 2 can be rewritten in terms of the complex amplitude:

$$\nabla^2 \underline{A_\theta} - \frac{\underline{A_\theta}}{r^2} = j\mu\sigma\omega \underline{A_\theta} - \underline{J_{\mathrm{ex}}} \qquad (3)$$

The decomposition of the above equation into its real and imaginary parts leads to two coupled diffusive transport equation for the real part $(A_\theta = \mathrm{Re}(\underline{A_\theta} e^{\mathrm{j}\omega\mathrm{t}}))$ and imaginary part $(\mathrm{Im}(\underline{A_\theta} e^{\mathrm{j}\omega\mathrm{t}}))$ of the complex vector potential.

Given a solution for $\underline{A_\theta}$, the induced current density in the molten droplet $\underline{J_\theta}$ can be obtained by combining the Maxwell–Faraday equation and Ohm's law:

$$\underline{J_\theta} = -j\sigma\omega \underline{A_\theta} \qquad (4)$$

Finally, the resulting electromagnetic force acting on the liquid metal, time-averaged over a period of the AC current, is given by:

$$\vec{\mathrm{F}} = \langle \vec{\mathrm{J}} \times \vec{\mathrm{B}} \rangle = \frac{1}{2}\mathrm{Re}(\underline{\vec{\mathrm{J}}_{\theta}} \times \underline{\vec{\mathrm{B}}^{*}}) \tag{5}$$

where the superscript * stands for the complex conjugate. Note that the fluctuating part of the electromagnetic force can be ignored, since the time scale associated to the inertia of the liquid metal is much higher than the coil current frequency.

Flow modelling

Flow phenomena are described by turbulent Navier–Stokes equations. The choice of a suitable turbulence model for levitated drop systems still remains an open question in the literature and the application of a traditional RANS turbulence model (like the k–ε or k–ω model), although being the most frequently reported approach, is questionable. In this study, we employed the well-known Renormalization Group (RNG) version of the k–ε model, following the recommendation of Berry et al. [6, 8] who, from a comparative numerical study, have concluded in the superiority of the RNG model over the standard k–ε model for representing the internal flow in a levitated droplet. The Navier–Stokes and turbulence transport equations can be written in the general form of a convection–diffusion equation for the variable ϕ, which reads in an axisymmetric cylindrical coordinate system (r, θ, z):

$$\frac{\partial}{\partial t}(\rho\phi) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u_{\mathrm{r}}\phi) + \frac{\partial}{\partial z}(\rho u_{\mathrm{z}}\phi) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_{\phi}\frac{\partial \phi}{\partial r}\right) + \frac{\partial}{\partial z}\left(\Gamma_{\phi}\frac{\partial \phi}{\partial z}\right) + S_{\phi} \tag{6}$$

The expressions of the diffusion coefficient Γ_{ϕ} and source term S_{ϕ} are given in Table 1 for each variable of the flow. μ_{eff} is the effective dynamic viscosity given by $\mu_{\mathrm{eff}} = \mu + \mu_{\mathrm{t}}$, where μ and μ_{t} are, respectively, the molecular and turbulent dynamic viscosity. F_{r} and F_{z} represent the radial and axial components of the electromagnetic force in the liquid metal, and g is the gravity.

The turbulent viscosity is expressed in terms of the turbulent energy k and its dissipation rate ε by the relation:

$$\mu_{\mathrm{t}} = C_{\mu}\rho\frac{k^{2}}{\varepsilon} \tag{7}$$

In the case of a swirling flow, the k–ε RNG model corrects the value of viscosity given by Eq. 7, by means of a weighting function of the form $f(\Omega, k/\varepsilon)$, where Ω is the fluid angular velocity.

The term G_{k} representing the production of turbulent kinetic energy due to the mean velocity gradients is expressed as a function of the modulus of the mean strain rate tensor S:

$$G_{\mathrm{k}} = \mu_{\mathrm{eff}}S^{2} \tag{8}$$

The main modification with respect to the standard k–ε model, except the correction of the turbulent viscosity, is the presence of an additional term R_{ε} in the transport equation of the dissipation rate ε.

$$R_{\varepsilon} = \frac{C_{\mu}\rho\eta^{3}(1-\eta/\eta_{0})}{1+\beta\eta^{3}}\frac{\varepsilon^{2}}{k} \tag{9}$$

where $\eta = S\frac{k}{\varepsilon}, \eta_{0} = 4.38, \beta = 0.012$.

All the above defined constants of the turbulence model (C_{μ}, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, α_{k}, α_{ε}) are taken equal to the recommended values in the user guide of the FLUENT code [9].

Calculation of the free surface deformation

The well-known volume of fluid (VOF) method is employed to represent and track the moving free surface of the droplet. This method, first introduced by Hirt and Nichols [10], is a surface capturing type technique, which uses a fixed Eulerian mesh. The position of the interface between the liquid metal and surrounding gas is represented by means of a local function F representing the fractional volume of the mesh cell occupied by the metal. The value of F is 1 in any cell filled with metal, 0 in any cell filled with the gas and between 0 and 1 for any cell containing the interface.

The motion of the interface is tracked by solving a pure advection equation for the volume fraction:

Table 1 Expressions of the diffusion coefficient Γ_{ϕ} and source term S_{ϕ} in Eq. 6 for the different variables ϕ

	ϕ	Γ_{ϕ}	S_{ϕ}
Continuity	1	0	0
Conservation of momentum (radial)	u_{r}	μ_{eff}	$-\frac{\partial P}{\partial r} + \frac{\partial}{\partial z}(\mu_{\mathrm{eff}}\frac{\partial u_{\mathrm{z}}}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial r}(r\mu_{\mathrm{eff}}\frac{\partial u_{\mathrm{r}}}{\partial r}) - 2\mu_{\mathrm{eff}}\frac{u_{\mathrm{r}}}{r^{2}} + \rho\frac{u_{\theta}^{2}}{r} + F_{\mathrm{r}}$
Conservation of momentum (axial)	u_{z}	μ_{eff}	$-\frac{\partial P}{\partial z} + \frac{\partial}{\partial z}(\mu_{\mathrm{eff}}\frac{\partial u_{\mathrm{z}}}{\partial z}) + \frac{1}{r}\frac{\partial}{\partial r}(r\mu_{\mathrm{eff}}\frac{\partial u_{\mathrm{r}}}{\partial z}) + \rho_{0}g + F_{\mathrm{z}}$
Conservation of momentum (azimuthal)	u_{θ}	μ_{eff}	$-\frac{u_{\theta}}{r^{2}}\frac{\partial}{\partial r}(r\mu_{\mathrm{eff}}) - \rho\frac{u_{\mathrm{r}}u_{\theta}}{r}$
Conservation of k	k	$\mu_{\mathrm{eff}}/\alpha_{\mathrm{k}}$	$G_{\mathrm{k}} - \rho\varepsilon$
Conservation of ε	ε	$\mu_{\mathrm{eff}}/\alpha_{\varepsilon}$	$C_{1\varepsilon}\frac{\varepsilon}{k}(G_{\mathrm{k}} + C_{3\varepsilon}G_{\mathrm{b}}) - C_{2\varepsilon}\rho\frac{\varepsilon^{2}}{k} - R_{\varepsilon}$

$$\frac{\partial F}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(ru_{\mathrm{r}}F)+\frac{\partial}{\partial z}(\rho u_z F)=0 \qquad (10)$$

Reconstruction of the interface from information on the volume fraction field is performed using the piecewise-linear interface calculation (PLIC) method of Youngs [11]. A single set of equations is shared by the metal and the gas. In the computational cells containing the free surface, the physical properties of the fluid mixture (density, viscosity) appearing in the equations are expressed as an average of the properties of the mixture components, weighted by the volume fraction of each fluid. Surface tension effects along the interface are modelled using the continuum surface tension (CSF) model proposed by Brackbill et al. [12], which consists in expressing the surface tension as a volume force added as a source term in the momentum equation.

Numerical aspects

The model was built within the commercial software FLUENT version 6.2, which is a finite volume CFD package for simulating multiphase fluid flow. The FLUENT solver is supplemented by a set of user defined functions (UDF) developed at the EPM-Madylam Laboratory (package Induct2D) for the calculation of the electromagnetic field and Lorentz force using a magnetic vector potential formulation [13]. Numerical solution of the flow equations is obtained with the SIMPLEC algorithm. The main advantage of the present approach is to handle all aspects of the problem in a single computational framework, which allows a fully coupling and avoids possible interpolation issues when transferring data between different codes. Note, however, that the necessity to use a grid extending beyond the metal droplet domain may lead to an increased computational cost with respect to more specialized techniques for the electromagnetic field and free surface shape computations, which use a mesh covering only the metal domain.

Results

In this section, the capability of the model is tested on three cases. For the first two ones, analytical or numerical results are available and are compared to the model predictions. The third case is based on the levitation coil configuration used in the experimental study reported above.

First, in order to validate the treatment of surface tension effects, we simulate the small amplitude free oscillations of a liquid drop in the absence of gravity and levitation fields. We consider a spherical aluminium drop of radius $a = 5$ mm subjected to an initial deformation defined in polar coordinates (r, θ, φ) as $r_n(\theta) = a(1 + \varepsilon P_n(\cos\theta))$ where P_n is nth order Legendre polynomial and ε the amplitude of the initial deformation. The drop is then left free to oscillate. In the case of small amplitude deformations and assuming viscosity effects to be small, Lamb's theory provides analytical expressions for the angular frequency ω_n and damping coefficient b_n of the nth oscillation mode [14]: $\omega_n^2 = \gamma n(n-1)(n+2)/\rho_1 a^3$ and $b_n = \mu_1(n-1)(2n+1)/\rho_1 a^2$, where γ is the surface tension of the liquid, ρ_1 is its density and μ_1 is its dynamic viscosity. As an example, we present the oscillations of the drop for the fundamental mode (corresponding to $n = 2$), starting from an initial deformation $\varepsilon = 3.5\%$ (Fig. 4). The liquid metal properties are: $\gamma = 0.94$ N/m, $\rho_1 = 2{,}380$ kg/m^3 and $\mu_1 = 3.345 \times 10^{-2}$ kg/m/s. The computational time step is 1 μs.

Consistently with the theory, the drop exhibits a regular oscillation pattern that decays with time. The oscillation damping brings the drop progressively back to an equilibrium spherical shape. The angular frequency of the oscillations predicted by the model (22 Hz) corresponds closely to the analytical value (25.3 Hz). The relative discrepancy is about 13%. The computed amplitude decay is also in relatively good agreement with the theoretical exponential decay.

The second application is a test case computed by Bojarevics and Pericleous [15]. A 5 mm radius Al droplet is levitated under zero gravity conditions by a single current loop located in the equator plane. The effective current in the coil is 200 A and the coil current frequency is 9.6 kHz. The material properties are identical to those employed above, except for the viscosity, which is set equal to an artificial high value of 2.38 kg m^{-1} s^{-1}, in

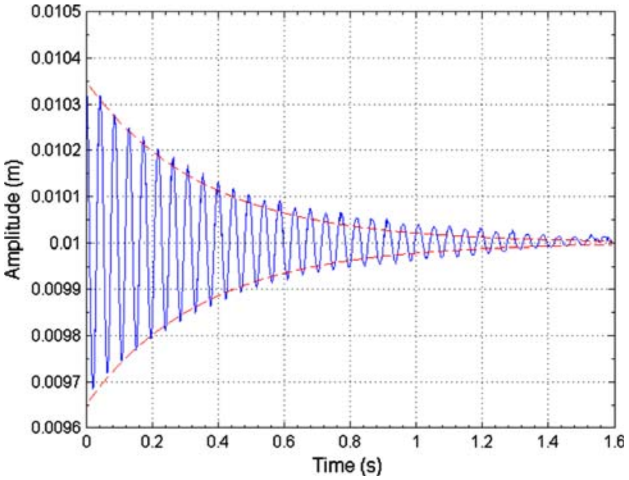

Fig. 4 Computed oscillations of the vertical diameter of a drop with an initial deformation corresponding to the fundamental mode $n = 2$. The exponential decay of the oscillation amplitude from the analytical solution is also shown

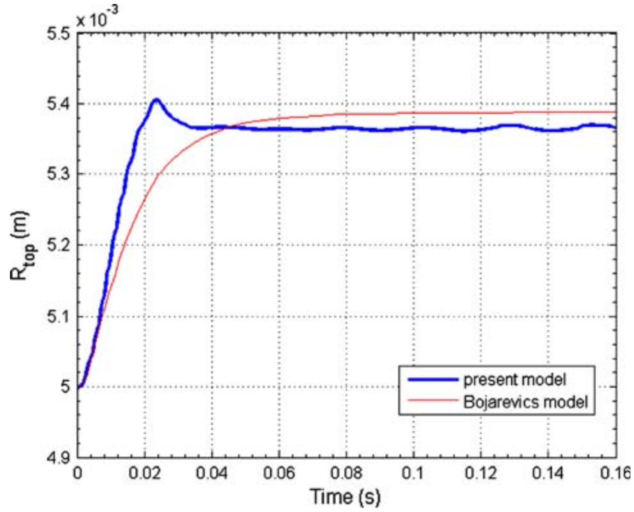

Fig. 5 Computed time evolution of the *z* coordinate of the top centre of a drop levitated in a single current loop and comparison with Bojarevics simulation results [15]

order for the computed flow to remain in the laminar regime. The electrical conductivity of liquid aluminium is $3.85 \times 10^6\ \Omega^{-1}\ \mathrm{m}^{-1}$. The time step is chosen as 1 µs and the grid size in the electromagnetic skin layer is equal to 90 µm. Initially, the metal in the molten droplet is at rest. Figure 5 shows the time evolution of the *z* coordinate of the top centre of the drop. During an initial transient phase, the drop stretches in the axial direction. Eventually, the drop shape stabilizes about a prolate ellipsoid at $t = 32$ ms. Our results are in good agreement with those reproduced from Bojarevics paper [15]. The final deformation amplitude of the drop predicted by the model is very close to that calculated by Bojarevics. Note, however, that the transient stage is slightly shorter in our simulation.

Finally, the model is applied to simulate the levitation experiment described in the previous section. A nickel–chromium alloy droplet is positioned under normal gravity conditions in the levitation coil presented in Fig. 1. The drop radius is 3.1 mm. The material properties are: $\gamma =$ 1.75 N/m, $\rho_1 =$ 8,400 kg m^{-3}, $\mu_1 =$ 5.10^{-3} kg m^{-1} s^{-1} and $\sigma = 10^6\ \Omega^{-1}\ \mathrm{m}^{-1}$. Initially, the molten droplet is at rest. The time step is 5 µs and the grid size in the electromagnetic skin layer is equal to 110 µm. An important input parameter into the model is the actual intensity of the electric current flowing in the coil. Unfortunately, this parameter is not shown by the instrumentation of the facility and could not be measured or calculated during the experimental campaign.

From a series of model runs, it was found that a coil current in the range of 1,250–5,625 A is required to levitate the drop. The evolution of the *z* coordinate of the centre of gravity of the drop is shown on Fig. 6 for different current values within this range. The centre of gravity retains the same qualitative behaviour for all current values. The drop undergoes a periodic translational motion in the axial direction. The amplitude of the motion decreases rapidly with time until the drop stabilizes around an equilibrium position. Note that the drop keeps on performing undamped small amplitude oscillations around this equilibrium in the case of low current values. The amplitude of the initial oscillations, as well as the time interval taken by the drop to reach an equilibrium, increase with decreasing current. The equilibrium height of the drop rises only slightly with increasing current (the drop is shifted only 2 mm up within the range of investigated currents).

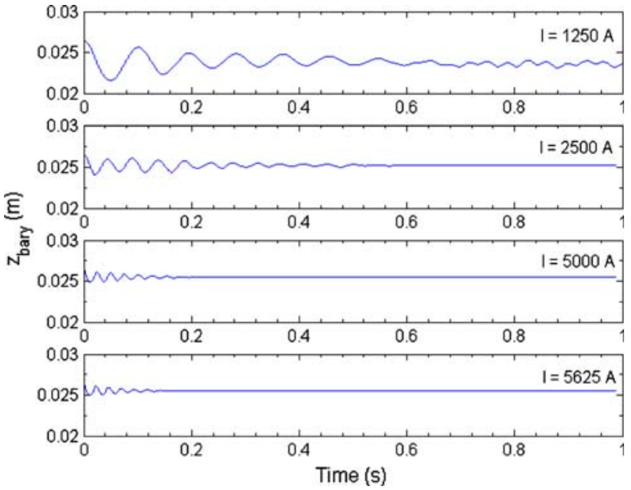

Fig. 6 Computed time evolution of the axial position of the drop centre of gravity for different values of the coil current

The value of the current plays a more significant role on the surface oscillations than it does on the dynamics of the centre of gravity of the drop. As illustrated in Fig. 7, the

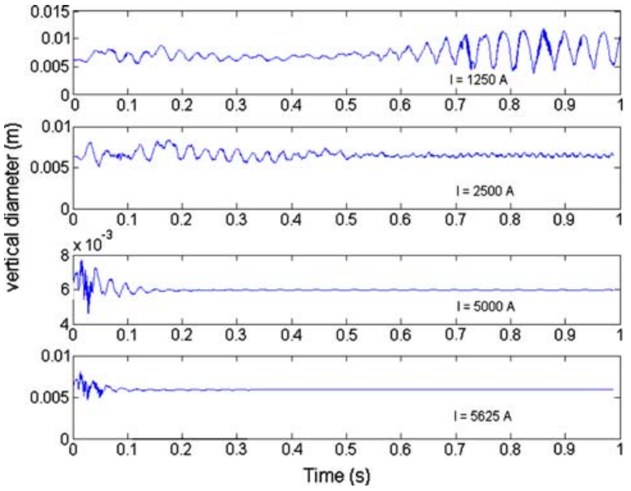

Fig. 7 Computed time evolution of the vertical diameter of the drop for different values of the coil current

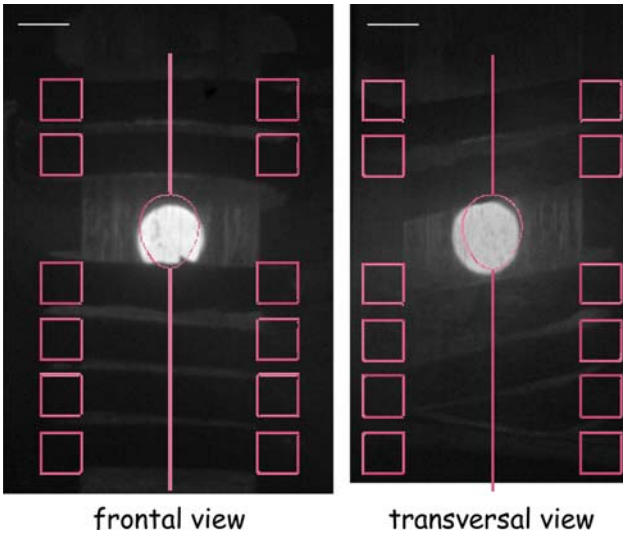

Fig. 8 Comparison of the computed and experimentally observed equilibrium shape of a Ni–Cr liquid droplet levitated in the experimental facility shown in Fig. 1. The simulation results have been obtained for a coil current equal to 1,250 A. The scale bars are 5 mm

drop surface oscillations show two different regimes depending on the coil current. At low currents (1,250 A and 2,500 A), the drop diameter keeps on performing long lasting oscillations of varying amplitudes. The amplitude of these oscillations increases with decreasing current. At high currents (5,000 A and 5,625 A), by contrast, the initial oscillations are found to be rapidly damped and vanish after 100–200 ms.

The equilibrium shape of the levitated drop predicted by the model (for the case $I = 1{,}250$ A) is compared on Fig. 8 to video images of the drop recorded during the experiment. The current value of 1,250 A was chosen here as it provides the best match between the experimental and numerical results. The computed equilibrium shape was obtained by averaging the various droplet shapes calculated over the first 3 s of the simulation. The video images are the results of averaging of 400 frames. It is interesting to note that once averaged, the frontal and transversal cross-sections of the drop are very similar. Good agreement is observed between the computed shape and both the frontal and transversal cross-sections observed experimentally. The equilibrium height of the droplet is also well predicted by the model.

Conclusions

An investigation on the free surface shape and dynamics of a molten Ni–Cr droplet levitated electromagnetically has been presented. Observations made using high-speed video have enabled to measure the frequencies of the translational oscillating motions of the drop and oscillations of its free surface. The experiments have revealed an instantaneous asymmetrical shape of the drop. A 2D transient model has then been developed, which involves the simultaneous simulation of the distribution of the levitation forces inside the drop, stirring of the liquid metal in the drop induced by the latter, and deformation of the free surface. The model has been tested successfully against analytical and numerical results of the literature. Finally, by adjusting the experimentally unknown value of the induction coil current, the model was able to provide a good representation of the equilibrium shape and position of the levitated Ni–Cr droplet observed in our experimental facility.

In the near future, a special effort will be put to measure the induction coil current in Kiev facility, in order to fully validate the present model. In the next step, the model will be extended to include both heat transfer and solute transport phenomena inside the molten droplet, so that it is suitable to simulate a complete levitated drop experiment applied to the investigation of gas–liquid metal interactions. In complement to the experimentally obtained data, the model developed will provide a better understanding of the limiting step for the mass transfer between the gas and liquid metal, as well as the transfer kinetics.

References

1. Bakhtiyarov SI, Overfelt RA (2003) Recent Res Dev Mater Sci 4:81
2. Petitnicolas L, Jardy A, Ablitzer D (1998) Rev Metall CIT/Sci Génie Mater 95:177 (in French)
3. Cummings DL, Blackburn DA (1991) J Fluid Mech 224:395
4. Egry I (2005) Int J Thermophys 26:931
5. Szekely J, Schwartz E (1994) In: Proceedings of the international symposium on electromagnetic processing of materials, Nagoya, Japan, p 9
6. Berry SR, Hyers RW, Racz LM, Abedian B (2005) Int J Thermophys 26:1565
7. Bojarevics V, Pericleous K (2003) ISIJ Int 43:890
8. Berry S, Hyers RM, Abedian B, Racz LM (2000) Metall Mater Trans B 31B:171
9. FLUENT Documentation (User's Guide, UDF Manual) version 6.2.16. Fluent, Inc., Lebanon, New Hampshire (2005)
10. Hirt CW, Nichols BD (1981) J Comput Phys 39:201
11. Youngs DL (1982) In: Morton KW, Baines MJ (eds) Numerical methods for fluid dynamics. Academic Press, New York, p 273
12. Brackbill JU, Kothe DB, Zemach C (1992) J Comput Phys 100:335
13. Delannoy Y, Pelletier D, Etay J, Fautrelle Y (2002) In: Proceedings of PAMIR conference, Ramatuelle, France
14. Lamb H (1932) Hydrodynamics, 6th edn. Cambridge University Press, p 473
15. Bojarevics V, Pericleous K (2001) Magnetohydrodyn 37:93