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Deflection of a liquid metal jet/drop in a tokamak environment

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HIGHLIGHTS

- We model steady flow of a liquid metal jet inside an electromagnetic field in the presence of inertia and capillary forces.
- Similar analysis is performed for the motion of a liquid metal spherical drop.
- The deflection of the trajectory is predicted as a function of the intensity of the externally imposed magnetic and electric fields.
- The analysis is used as a proof of principle study in reference to experimental observations of jet/drop deflection due to $\vec{j} \times \vec{B}$ effects in the ISTTOK tokamak.
- We discuss the possibility of using liquid metal flows as an alternative approach toward enhancing power exhaust in tokamak facilities.

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ABSTRACT

The interaction of a liquid gallium jet with plasma has been investigated in the ISTTOK tokamak. The jet was observed to remain intact during its interaction with plasma, within a certain length beyond which drop formation was observed. Significant deflection of the jet was detected as soon as plasma production was started. Furthermore, a strong dependency of the deflection magnitude on plasma position was observed that could be correlated with plasma potential gradients. As a means to capture and, possibly, quantify this effect, a preliminary magnetohydrodynamic analysis was performed in order to predict the trajectory of a jet that is traveling inside an electromagnetic field. The effect of Lorentz forces, gravity and pressure drop are accounted for in a unidirectional model that assumes a small jet radius in comparison with the trajectory length. The effect of external electric potential gradients on jet deflection was ascertained in conjunction with the importance of electric stresses in modulating the jet speed and radius. Analysis of the results reported in the ISTTOK experiments identifies the process of jet break-up as a capillary instability. The trajectory of the ensuing droplets is modeled and intensification of the deflection process is predicted in the presence of Lorentz forces.

1. Introduction

Employment of plasma facing components (PFCS) constitutes one of the most critical technological challenge of future fusion reactors since they should have the ability to withstand power densities of the order 5–10 MW/m^2 and up to 100 MW/m^2 for off-normal events such as edge-localized modes (ELM) and disruptions. The plasma–wall interaction that is generated by such events is expected to cause problems such as erosion, thermal stresses, thermal fatigue and Tritium retention, that are difficult to deal with.

In order to circumvent the above problems liquid metals are considered as alternative plasma facing components (PFCS) [1]. The self-cooling and self-annealing properties of flowing liquids increase their life cycle as they interact with the core plasma of the fusion reactor. The flow pattern of liquid metals employed for protection of the divertor region and the blanket first wall is characterized by the formation of a free surface that is subjected to the electromagnetic field generated by the plasma. The supply of the liquid metal can be via, a continuously flowing film that coats the divertor walls [2], an array of jets that decay into a stream of drops thus curtaining the divertor walls [3,4], or a porous system that acts as a capillary pump pushing liquid metal through a porous medium [5]. In the latter case capillary action is of central importance for renewing the liquid metal, typically lithium, that is in contact with the plasma [6]. As an alternative to lithium, liquid gallium is envisioned as PFC, due to its low reactivity and much wider liquid state temperature range, that provides much higher extracting power from fusion plasmas.

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The concept of employing a jet–drop curtain was among the first to be investigated as a means to assist power exhaust from fusion reactors. The drop motion was employed as a means to minimize ponderomotive forces arising due to spatial and time variations of the electric field [4]. Furthermore, experimental studies focusing on the magnetic field induction effect [7] showed that even a mild intensity magnetic field could suppress spraying of the liquid metal flow. A representative drop curtain configuration is that of T3-M which was tested with a gallium alloy [4], with encouraging preliminary results in terms of plasma contamination. However, especially when a liquid metal sheet was employed in a plasma environment, the reactor's chamber walls were sprayed by small drops.

Recent experiments at the ISTTOK tokamak [8,9] validate the negligible effect that gallium has on plasma operation as well as its high heat removal capacity. Beyond a certain length drop formation was observed as a result of what seemed to be a capillary instability, based on the available measurements of the jet breakup length. Once plasma was turned on jet break-up was seen to be postponed over a longer distance, possibly as a result of magnetic braking and, more importantly, the emerging drops were deflected from their original trajectory as a result of their interaction with the surrounding plasma. The deflection increased with increasing magnetic field intensity and drops were observed to hit the collector walls. Several interpretations of this effect were conjectured [9] in relevance to (a) the mechanical stress on the injector due to chamber compression, which was ruled out, (b) the shift due to magnetic induction and the 3d magnetic field gradient along the jet length which was also ruled out [7] and (c) the plasma kinetic pressure change along the jet width which was also negligible. Consequently, the interaction between electric currents generated along the advancing jet, in response to electric potential gradients within different plasma regions, and the toroidal magnetic field – identified as $\vec{j} \times \vec{B}$ effect in the literature – seems to be the most plausible explanation for the observed jet/drop deflection. The aim of the present study is to provide a first principle justification of this mechanism, assuming a simplified model of the jet motion that incorporates electromagnetic forces.

In Section 2 the problem formulation is presented along with the major simplifying assumptions for the case of a jet, Section 2.1, and a drop, Section 2.2. Finally, in Section 3 a parametric study is presented, based on the numerical solution of the model equations, that highlights the major factors affecting jet and drop deflection, Section 3. Conclusions are drawn and directions for future research are proposed.

2. Problem formulation

We are interested in obtaining a prediction on the trajectory of a jet or drop that move inside an electromagnetic field. The latter is taken to be fixed in time, whereas the jet cross-section and drop shape are taken to be circular and spherical, respectively, as a first approximation. Due to the small size of the jet/drop the magnetic Reynolds is quite small and consequently we can neglect magnetic induction.

2.1. Formulation for jet propagation

The trajectory of a liquid metal jet of circular cross-section is investigated. The jet enters a region, $z<0$, at a speed of $\vec{u}_0 = -u_0\vec{e}_z$, where a uniform magnetic field $\vec{B} = B_0\vec{e}_x$ exists along with an externally imposed electric potential gradient, $\vec{\nabla}\varphi_\mathrm{p} = d\varphi_\mathrm{p}/dz\vec{e}_z = -a\vec{e}_z$, where $u_0>0$, $B_0>0$ and $a>0$, as illustrated in Fig. 1a; subscript p stands for plasma.

This is a first attempt to capture the jet/drop motion in the plasma–jet interaction region of the ISTTOK experiments, Fig. 1b. Once the jet enters the aforementioned area, where fluctuations of the electric potential are present due to the surrounding plasma, a net current is induced within it which interacts with the magnetic field generating a Lorentz force.

As a first approximation, we treat both the jet and the surrounding medium as perfect dielectrics, i.e. no bulk or surface electric charges. Thus the following conditions hold at their interface:

$$\varphi = \varphi_\mathrm{p} \qquad \in \frac{\partial \phi}{\partial n} = \in_\mathrm{p} \frac{\partial \phi_\mathrm{p}}{\partial n} \tag{1}$$

with $\in$ and φ denoting the electric permittivity of Ga and the electric potential, respectively. For a sufficiently thin jet the flow inside it can be assumed to remain unidirectional and electric potential variations can be neglected in the direction normal to the interface, $d\phi/dn \ll d\phi/ds$, with s signifying the arc length along the jet trajectory and n the unit normal pointing out of the surface. Consequently, electric potential variations along the jet passively follow variations in the surrounding medium based on its trajectory, with $\vec{e}_s$ its unit vector:

$$\vec{\nabla}\phi = \frac{\partial \phi}{\partial s}\vec{e}_s = \frac{\partial \phi_p}{\partial s}\vec{e}_s = -a\frac{dz}{ds}\left(\frac{dy}{ds}\vec{e}_y + \frac{dz}{ds}\vec{e}_z\right) \tag{2}$$

In the above equation we assume that the jet cross-section remains circular with its center of mass inscribing a trajectory within the yz plane and $z(s)$, $y(s)$ constituting its parametric representation. The resulting Lorentz force is of the form:

$$\begin{aligned} &\vec{F} = \sigma(-\vec{\nabla}\phi + \vec{u} \times \vec{B}) \times \vec{B} \rightarrow \\ &\vec{F} = \sigma B_0 a \frac{dz}{ds}\left(-\frac{dy}{ds}\vec{e}_z + \frac{dz}{ds}\vec{e}_y\right) - \sigma u_0 B_0^2 \vec{e}_s \end{aligned} \tag{3}$$

The second term in the last equation represents the jet deceleration due to the part of the Lorentz force that arises because of the induced electric currents in the jet, whereas the first term corresponds to the part of the Lorentz force that arises due to the interaction between the external magnetic and electric fields. It is the latter term that is responsible for the jet deflection. Thus, based on the constant volumetric flow rate Q and assuming a circular cross section of radius R, mass and momentum conservation within the jet read for unidirectional flow:

$$Q = u\pi R^2, \quad \vec{u} = u\vec{e}_s \tag{4}$$

$$\rho\frac{du}{dt} = \rho u \frac{\partial u}{\partial s} = -\frac{\partial p}{\partial s} + \rho\vec{g}\cdot\vec{e}_s + \vec{F}_L\cdot\vec{e}_s \tag{5}$$

When the radius of curvature of the trajectory is much larger than the jet radius $\Re \gg R$ pressure variations within the jet cross-section can be neglected and pressure in the jet is determined by the interfacial stress balance.

$$[-\Delta p\underline{\underline{I}} + (\underline{\underline{\tau}}_e - \underline{\underline{\tau}}_e^p)]\cdot\underline{n} + 2\gamma H\underline{n} = \underline{0} \quad \text{at} \quad \vec{r} = \vec{r}_s(s, n, \varphi) \tag{6}$$

In the aforementioned equations σ, γ and ρ denote the electrical conductivity, the surface tension and the density of Ga, respectively, H the mean curvature, Δp the pressure difference, $\underline{\underline{I}}$ the unit tensor and $\underline{\underline{\tau}}_\mathrm{e}$, $\underline{\underline{\tau}}_\mathrm{e}^\mathrm{p}$ the electric stress tensors of Ga and plasma, respectively.

Averaging around the periphery of the jet cross-section and accounting for capillary and electric stresses, electric potential variations along the tangential, φ, and normal, n, direction cancel out and the pressure drop across the interface reads:

$$p - p_\mathrm{p} \approx 2\gamma\frac{1}{R} + \frac{(\in_p - \in)}{2}\left(\frac{d\phi}{ds}\right)^2 \tag{7}$$