Princeton Plasma Physics Laboratory

PPPL-5286

An IR-camera based particle-tracking technique to measure free-surface velocity in liquid metal systems

M.G. Hvasta, E. Kolement, A. Fisher

September 2016

Prepared for the U.S.Department of Energy under Contract DE-AC02-09CH11466.

An IR-camera based particle-tracking technique to measure free-surface velocity in liquid metal systems

M. G. Hvasta[a] E. Kolemen, and A. Fisher

Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

(Received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing here are provided by the Editorial Office)

Measuring free-surface liquid metal flow velocity is challenging to do in a reliable and accurate manner. This paper presents a non-invasive, easily-calibrated method of measuring the surface velocities of open-channel liquid metal flows using an IR camera. Unlike other spatially-limited methods, this IR camera particle tracking technique provides full field-of-view data that can be used to better understand open-channel flows and determine surface boundary conditions. This method could be implemented and automated for a wide range of liquid metal experiments, even if they operate at high-temperature or within strong magnetic fields.

I. INTRODUCTION

Flowing liquid lithium plasma facing components (FLL-PFC's) provide an attractive alternative to solid PFC's traditionally used in fusion reactors. FLL-PFC's possess excellent heat-transfer and power-removal characteristics, permit PFC exposure to large heat-fluxes, provide a self-healing surface that is immune to both thermal stresses and radiation damage, and facilitate tritium breeding[1]. Additionally, several experiments have shown that FLL-PFC's improve plasma performance within tokamaks by increasing energy confinement, reducing particle recycling, and suppressing impurity emissions[2,3,4].

The Liquid Metal eXperiment (LMX)[5,6] was created to study free-surface liquid metal flows and magnetohydrodynamic effects relevant to full-scale FLL-PFC development. During LMX operation, an alloy commonly known as 'galinstan' ($Ga^{67}In^{20.5}Sn^{12.5}$ wt. %) was pumped into the bottom of a rectangular open-channel and then circulated through the rest of the system, as depicted in Figure FIG. **1**. For this paper, a weir (approx. 0.6 [cm] tall) was used to maintain a minimum depth in the open-channel before allowing the galinstan to overflow, drain into the pumped portion of the system, and then return to the channel.

There are several well-known techniques for measuring liquid metal flows through pipes and tubes[7]. However, measuring free-surface liquid metal flow velocity is challenging to do in a reliable and accurate manner. Therefore, this paper will focus on the development of a particle tracking technique that uses an infrared (IR) camera to take measurements relevant to galinstan or other liquid metal experiments. This method could be implemented and automated for a wide range of liquid metal experiments, even if they operate at high-temperature or within strong magnetic fields.

[a)] Author to whom correspondence should be addressed. Electronic mail: MHvasta@pppl.gov

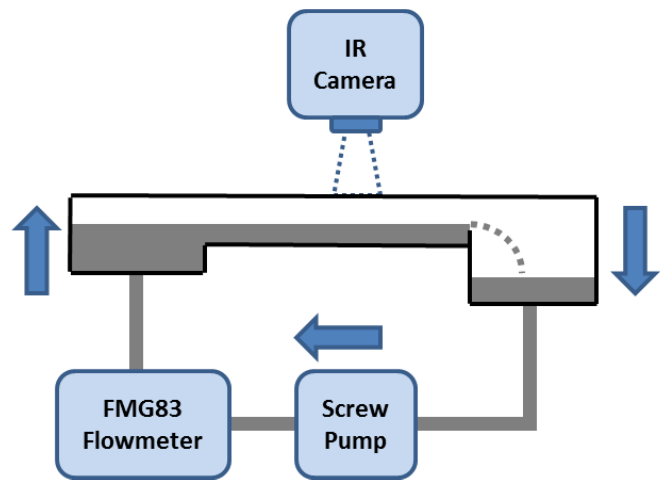

FIG. 1. A simple depiction of the LMX flow path and instrumentation layout.

II. PUMP & FLOWMETER

Galinstan was pumped through LMX using a custom-made, Archimedes-style screw pump. The pump was powered by a 2 [HP] Leeson DC motor while RPM was monitored using an Extech 461950 tachometer. Liquid metal flow through the tubes feeding the open-channel was measured using an FMG83 electromagnetic flowmeter from Omega Engineering. As shown in Figure FIG. **2**, the pump was able to reliably generate flow rates ranging from 4-10 [liter/min].

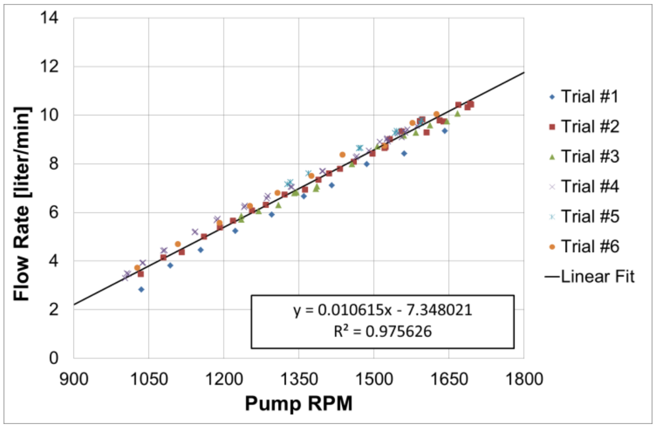

FIG. 2. (Color online). Pump output as measured by the electromagnetic flowmeter. The flowmeter data closely agrees with a linear fit. Pump data was collected over several weeks of operation.

III. DEPTH MEASUREMENT

The depth of the flowing galinstan was measured using the electrical contact probe method[8]. An Aerotech ATS-300 translation stage was used to precisely move the electric contact probe above the surface of the liquid metal. A vernier scale was used to measure where the probe came into contact with the surface of the galinstan with 0.1 [mm] resolution. As shown in Figure FIG. **3**, above 1000 RPM the galinstan began to smoothly flow over the weir and the depth could be accurately modeled using a polynomial fit.

During these tests, the width of the channel (w) was held at a constant 10.9 [cm]. Since both liquid depth (h) and flow rate (Q) were known as a function of pump RPM, the average velocity (v_{avg}) of the galinstan could be calculated using the following equation:

$$Q = v_{avg}\, h\, w \quad (1)$$

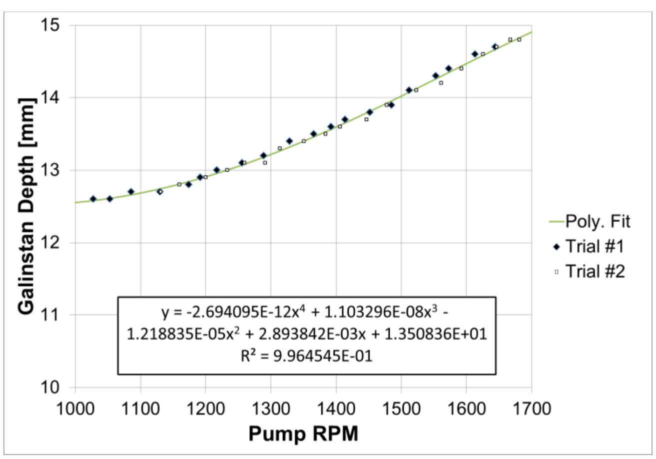

FIG. 3. Depth of galinstan as a function of pump RPM. Data collected using the electrical contact method. Above 1000 RPM the galinstan begins to flow over the weir and circulate through the system. The surface of the galinstan rises above the weir before beginning to flow due to surface tension effects ($\gamma = 0.533$ [N/m])[5,6].

IV. INFRARED PARTICLE TRACKING

During LMX operation, oxidation of the galinstan was minimized by keeping the gas-space above the open-channel inerted with ultra-high purity argon. However, despite efforts to maintain cleanliness, small amounts of impurities would develop and float along the surface of the galinstan[5]. While the galinstan was flowing, it was challenging to see the small (< 1[mm]), intermittently occurring oxide particles with the naked eye or capture them with a CCD camera unless they were illuminated with a high-intensity light source, such as a laser-sheet[12], which is spatially limited and can be difficult to aim exactly where needed. However, due to the thermal and optical differences between the matte oxides and the mirror-like galinstan[a], an IR camera could be used to resolve and track the impurities being carried by the flowing galinstan, as shown in Figure FIG. **4**.

A FLIR SC5000 (640 x 512 pixels, 60 [Hz]) IR camera was used to film the surface of the flowing galinstan over the full range of flow rates. The average velocity of the impurity tracer particles was calculated using the pixel data embedded in the videos with the following equation:

$$v_{surf} = K(x_1 - x_0)/\,(t_1 - t_0) \quad (2)$$

where K is a coefficient to scale from pixels to actual distance, x is the pixel location of the tracer particle, and t is the time stamp on the IR camera footage. As shown in Figure FIG. **5**, the IR camera particle tracking data yielded consistent results between test runs.

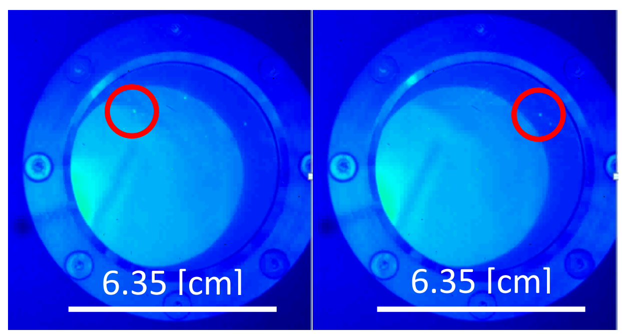

FIG. 4. (Color online). A sample of data collected using the IR camera pixel tracking method. IR compatible windows were installed above the free-surface flow. Left timestamp = 2.04 [s], Right timestamp = 4.20 [s].

[a] Pure galinstan has a very high reflectivity[9,10] and a very low emissivity[11] ($\varepsilon \approx 0.04$).

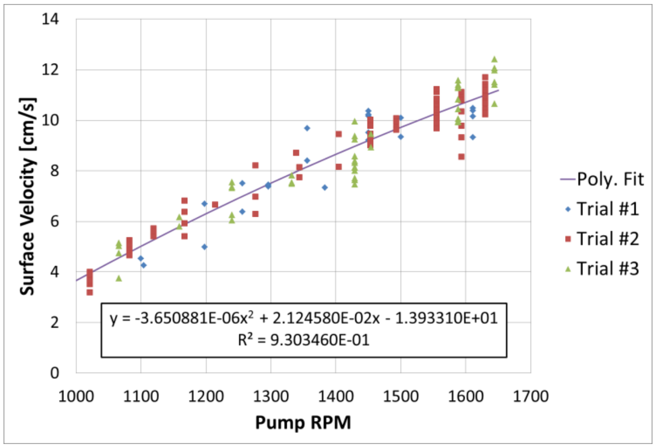

FIG. 5. (Color online). The surface velocity of the galinstan flow as measured using the IR camera particle tracking technique. Tracer particle velocities were measured towards the center of the channel.

V. VELOCITY MEASUREMENT COMPARISON

As shown in Figure FIG. **6**, the average velocity of the galinstan in the open-channel agrees closely with the surface velocity of the liquid metal. At higher pump speeds above 1300 RPM, the surface velocity becomes greater than the average velocity, as would be expected for most open channel flows[13,14]. At lower pump speeds, the surface velocity lags behind the average velocity, which is likely due to large surface tension effects across the open-channel. Evidence supporting this possibility was seen during numerous tests where the surface oxides on the galinstan did not move at all for small flow rates.

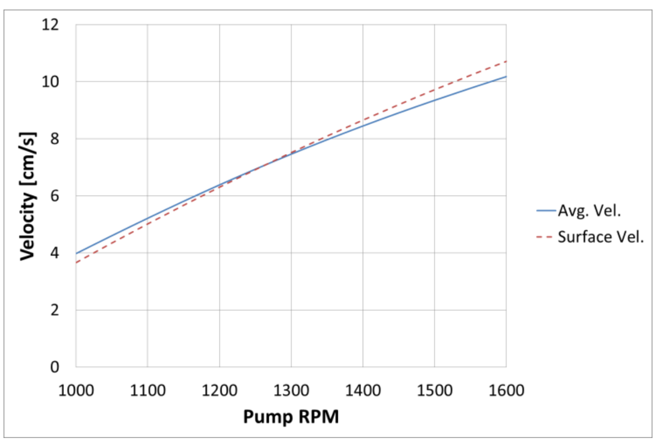

FIG. 6. (Color online). A comparison of the average and surface velocities. The values shown above were calculated using the linear and polynomial fits given in Figures FIG. 2, FIG. 3, and FIG. 5.

VI. SUMMARY

A non-invasive, easily-calibrated method of measuring the surface velocity of liquid metal flows using a commercially available IR camera was presented. Unlike spatially-limited laser-sheet methods, the IR camera particle tracking technique provides full field-of-view data that could be used to better understand open-channel flows. Additionally, unlike ultrasonic velocimetry techniques[15], this new technique is unaffected by oxide build-up or acoustic interface issues between the vessel wall, the liquid metal, and the air or argon in the gas-space.

This method could be implemented and automated for liquid metal work to help accelerate the development of FLL-PFC's. Future plans for LMX will implement this technique to better understand the effects of magnetic fields and Lorentz forces on open-channel galinstan flows.

ACKNOWLEDGEMENTS

The research described in this paper was conducted under the Laboratory Directed Research and Development Program (LDRD) at Princeton Plasma Physics Laboratory, a national laboratory operated by Princeton University for the U.S. Department of Energy under Prime Contract Number: DE-AC02-09CH11466.

The authors would also like to thank E. Gilson, H. Ji, K. Caspary, and P. Sloboda for their expertise, assistance, and insights during these experiments.

[1]R. E. Nygren, T. D. Rognlien, M. E. Rensink, S. S. Smolentsev, M. Z. Youssef, M. E. Sawan, B. J. Merrill, C. Eberle, P. J. Fogarty, B. E. Nelson, D. K. Sze, and R. Majeski, Fusion Engineering and Design, **72**, 181 (2004).

[2]R. Maingi, D.P. Boyle, J. M Canik, S. M. Kaye, C. H. Skinner, J. P. Allain, M. G. Bell, R. E. Bell, S. P. Gerhardt, T. K. Gray, M. A. Jaworski, R. Kaita, H. W. Kugel, B. P. LeBlanc, J. Manickam, D. K. Mansfield, J. E. Menard, T. H. Osborne, R. Raman, A. L. Roquemore, S. A. Sabbagh, P. B. Snyder, and V. A. Soukhanovskii, Nuclear Fusion, **52** (2012).

[3]J. S. Hu, G. Z. Zuo, J. Ren, Q. X. Yang, Z. X. Chen, H. Xu, L. E. Zakharov, R. Maingi, C. Gentile, X. C. Meng, Z. Sun, W. Xu, Y. Chen, D. Fan, N. Yan, Y. M. Duan, Z. D. Yang, H. L. Zhao, Y. T. Song, X. D. Zhang, B. N. Wan, J G, Li, and EAST Team, Nuclear Fusion, **56**, 046011, (2016).

[4]J. Ren, J. S. Hu, G. Z. Zuo, Z. Sun, J. G. Li, D. N. Ruzic, and L. E. Zakharov, Physica Scripta, **T159**, 014033, (2014).

[5]M. D. Nornberg, H. Ji, J. L. Peterson, and J. R. Rhoads, Review of Scientific Instruments, **79**, 094501 (2008).

[6]J. R. Rhoads, PhD Dissertation, Princeton University, (2013). http://arks.princeton.edu/ark:/88435/dsp01rj430467r

[7]G. E. Turner, Liquid Metal Flow Measurement (Sodium) State-of-the-Art-Study, LMEC-Memo-68-9, Liquid Metal Engineering Center (1968).

[8]H. W. Slocomb, Liquid Metal Level Measurement (Sodium) State-of-the-Art-Study, NAA-SR-MEMO-12582, Liquid Metal Engineering Center (1967).

[9]L. A. Akashev and V. I. Kononeko, Technical Physics, **43**, 118 (1998).

[10]E. F. Borra, G. T. Tremblay, Y. Huot, and J. Gauvin, Astronomical Society of the Pacific, **109**, 319-325 (1997).

[11]A. Arthurs, J. Rhoads, E. Edlund, E. Spence, and H. Ji, *Measurement of the Emissivity of Liquid Gallium Alloy for Temperature Measurements of Free-Surface Flows*. 52nd Annual Meeting of the APS Division of Plasma Physics. Chicago, IL. (2010).

[12]M. Narula, A. Ying, and M.A. Abdou, Fusion Science and Technology, **47**, 564-568 (2005).

[13]N. Cheng, Advances in Water Resources, **30**, 1775-1784 (2007).

[14]C. Chiu, J. Hydraulic Eng., **5**, 576-594 (1989).

[15]D. Brito, H. Nataf, P. Cardin, J. Aubert, and J. Masson, Experiments in Fluids, **31**, 653-663 (2001).

PRINCETON PLASMA PHYSICS LABORATORY

Princeton Plasma Physics Laboratory
Office of Reports and Publications

Managed by
Princeton University

under contract with the
U.S. Department of Energy
(DE-AC02-09CH11466)

P.O. Box 451, Princeton, NJ 08543
Phone: 609-243-2245
Fax: 609-243-2751

E-mail: publications@pppl.gov

Website: http://www.pppl.gov