A New Experimental Technique for the Study of Turbulent Electromagnetically Driven Flows

DONALD R. SADOWAY AND J. SZEKELY

Turbulent electromagnetically driven flows play a major role in a broad range of metals processing operations which include induction furnaces, inductively stirred ladles, electro-slag refining, electro-slag welding, the operation of aluminum smelters, and the like. Because the nature of the fluid flow in the melt has a strong effect on the rate processes in these sytems there has been a growing interest in the mathematical modelling of these operations.[1-5] However, notwithstanding some of the ingenious measurement techniques that have been devised, the predictions based on these models have yet to be completely verified. A detailed comparison of predicted and measured velocity fields and turbulence patterns in such systems would be of considerable fundamental and practical interests. Of fundamental interest, in particular, is the interaction between the electromagnetic force field and the turbulence patterns. This is not well understood, and it is possible, indeed likely, that this interaction may produce nontrivial results.

Investigators of this problem have faced the following dilemma. One could either study the behavior of real molten metal systems, such as molten steel, woods metal or mercury but then settle for only partial results, such as surface velocity measurements or approximate values of the velocity field.[3,6,7-9] Alternatively, one could use transparent "model systems" such as water models,[10] the circulation of which must by necessity be mechanically driven, and obtain quite accurate measurements employing laser Doppler anemometry.[11] Under these conditions, however, the interaction between the electromagnetic and turbulence fields cannot be studied. The objective of the present work was to explore whether the powerful data acquisition capabilities of laser Doppler anemometry could be employed on a transparent fluid which could be put into motion electromagnetically.

The electrical conductivity of molten salts occupies an intermediate position between the values of aqueous electrolytes and molten metals; alkali halides are about 2 orders of magnitude more conductive than aqueous electrolytes. In addition, molten alkali halides are transparent to visible light. The questions to be resolved in the present work were whether such a melt could be put into motion by electromagnetic induction and whether a pair of low power helium-neon laser beams would penetrate the melt, interact with seed particles moving with the fluid, and emit a trackable Doppler signal. Fluid flow measurements in molten salt systems by laser Doppler anemometry had not been reported in the literature.

DONALD R. SADOWAY and JULIAN SZEKELY are Assistant Professor and Professor, respectively, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139.

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Figure 1 is a diagram of the apparatus designed to model an inductively stirred ladle and to measure the fluid flow patterns therein. The molten salt used as the working fluid was a binary solution of KCl and LiCl at the eutectic composition, 55 wt pct KCl. Some of the physical properties of this material are shown in Table I. The salts, which were of reagent grade, were treated prior to use by slowly heating in air to a temperature sufficient for fusion. The melt, the volume of which was about 700 ml, was contained in a beaker of borosilicate glass, 9.5 cm ID. The vessel was open to the atmosphere for the duration of an experiment, typically for 4 h. During this time hydrolysis of LiCl occurred as was evidenced by the gradual clouding of the initially clear melt due to the slow chemical attack of the glass walls by the oxychlorides which were thought to have formed. Power was furnished by a high frequency generator, nominal power 2.5 kW and frequency 2.5 MHz. In contrast, water cooled 3/16 in. OD copper tubing was made to circle the glass vessel four to six times with a turn diameter of 11 cm. The ratio of melt height/diameter was 1.25 and that of melt diameter/skin depth was 4.1. In contrast to industrial installations in which the coils carry current of two frequencies, one primarily responsible for heating the melt and the other for melt circulation, the apparatus used herein consisted of coils carrying electrical current of a single frequency. The magnetic field thus produced served both for stirring and heating of the melt. The temperature of the melt was measured by a radiation thermometer* and regulated by a proportional current adjusting type controller† connected directly to the induction power supply. Experiments were conducted at 500°C.

*Lepel Laboratories, Maspeth, NY.

†Ircon, Inc., Skokie, IL.

The fluid velocities were measured by a single channel laser Doppler anemometer* by using the so-called dual beam, forward scatter optical arrangement The light source was a 15 mW helium-neon laser. To eliminate directional ambiguity a frequency shifter consisting of an acousto-optical cell (Bragg cell) with an RF driver and electronic downmix circuit was mounted to fit between the beamsplitter and focusing lens. The photodetector was a photomultiplier tube which has a quantum efficiency of 13 pct for He-Ne lasers, frequency response of 100 MHz and overall sensitivity of 40 kV/lumen including amplifier. To convert the output frequency of the photodetector to

*Thermo-Systems, Inc., St. Paul, MN.

Table I. Properties of Molten LiCl—KCl Eutectic at 500°C

			Reference
Density ρ	=	1.62 g cm^{-3}	12
Viscosity η	≅	2.6 cP	13
Electrical conductivity κ_{el}	=	1.85 ohm^{-1} cm^{-1}	12
Surface tension γ	=	126 dynes cm^{-1}	14,15
Thermal conductivity κ_{th}	≅	0.05 cal cm^{-1}s^{-1}K^{-1}	16,17*
Heat capacity C_P	≅	0.31 cal g^{-1}K^{-1}	18,19*

*Estimated from data reported on related molten salts.

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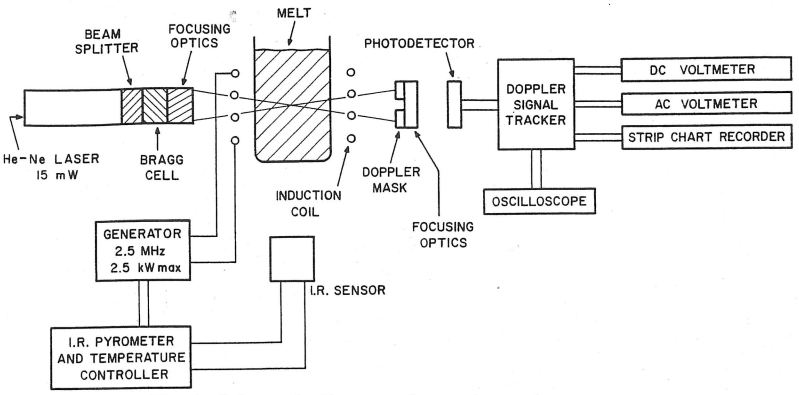

Fig. 1—Schematic diagram of experimental apparatus.

an analog voltage proportional to fluid velocity a phase and frequency locked loop tracker-type signal processor was used. DC and rms voltmeters continuously measured the output voltage from the signal processor. In addition, the results were plotted on a two pen strip chart recorder. To "fine-tune" the optical assembly an oscilloscope was connected in parallel with the tracker so that the signal from the photodetector could be optimized.

Figure 2(*a*) shows the "double loop" toroidal flow pattern which would be expected, given the axisymmetrical coil design and the single-phase, single-frequency coil current. Figure 2(*b*) shows the flow pattern observed in the present experiments, a "single loop" toroidal pattern. The flow velocities measured in the central region of the beaker were of the order of $\bar{v}$ = 1.0 cm/s downward for the time-averaged component and v' = 0.15 cm/s for the fluctuating component.

Clearly, this observed flow pattern is not consistent either with an electromagnetically driven flow produced by a single phase coil or with natural convection resulting from a temperature difference between the "cold walls" and the warmer bulk of the melt. However, if intense local heating were to occur at a distance in from the beaker wall equal to the skin depth, for example, the resultant temperature field would exhibit a maximum in the vicinity of the wall. A crude estimate of the velocities which could be expected can be made from the consideration of the equations for laminar natural convection along a vertical plate. A temperature difference of 50 K between the beaker's center and the "hot ring" just inside the wall would give a maximum velocity of the order of 0.3 cm/s. It is not unreasonable, then, to suggest that the observed flow pattern was the result of natural convection caused by localized induction heating. Had the flow been driven by the electromagnetic force field a rather different flow pattern would have resulted.[10]

Since the objective of the work was to produce an electromagnetically driven flow field in a transparent medium, attempts were made to change the apparatus to increase electromagnetic coupling and to decrease resistive heating in the melt. This was done by varying the vessel diameter and/or the operating frequency of the induction power supply over the range, 425 kHz to 8MHz. Unfortunately, under these conditions the mismatch between workpiece and power

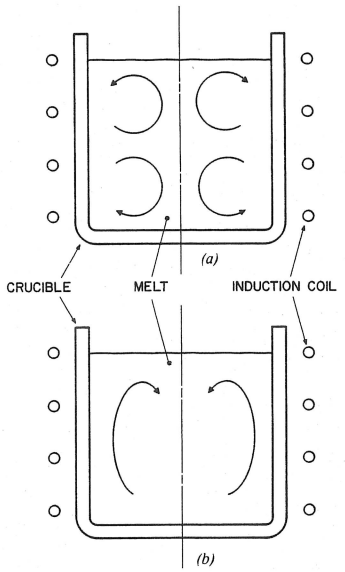

Fig. 2—(*a*) Flow pattern of a molten conductor in a vessel positioned in an axisymmetrical magnetic field. (*b*) Flow pattern of molten salt observed in the present study.

supply was too great, and the protective circuits of the latter prevented its operation. It appears that a more elaborate power supply would be necessary in order to produce an electromagnetically driven, rather than buoyancy driven, flow field in the transparent molten salt system. The development of such an arrangement is being explored at present.

In summary, it has been demonstrated for the first time that fluid velocities can be accurately measured in molten salts by laser Doppler anemometry. Furthermore, it appears that with modifications to the electrical hardware it should be possible to cause the coupling necessary to produce electromagnetically driven flow in molten salts, thereby making them very attractive as test materials for many metals processing operations.

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This is shown in Fig. 1, in which various strip cha recordings are reproduced for gas samples analyzed on a Fisher Model 1200 Gas Partitioner, using Mole ular Sieve 13X as the second column. Figure 1(*a*) is sample of atmospheric air; note that no peaks other than N_2 and O_2 are apparently present. Figure 1(*b*) i sample of combustion gas obtained by using atmosph air to burn charcoal at approximately 900 K in a tub furnace; note that peaks for N_2, CO_2, CO and *apparen* O_2 are present.

In Fig. 1(*c*), the conditions of sample (*b*) are the same except that instead of atmospheric air, a synthetic air was used, obtained by mixing N_2 and O_2 in an approximately 4.5:1 ratio from gas cylinders. Not that no peak is obtained in the oxygen/argon location To show that argon is responsible for the peak labele "A" in Fig. 1(*b*), an N_2/Ar mixture containing about 10 pct Ar was analyzed in the chromatograph. The r sults are shown in Fig. 1(*d*).

The calibration of peak height *vs* pct is about the same for O_2 and Ar, thus the presence of 1 pct Ar in the blast furnace gases analyzed by Chao *et al* would give a peak height equivalent to about 1 pct O_2, which is what they observed. If the O_2 peak height is corrected for the presence of Ar, the amount of O_2 in th

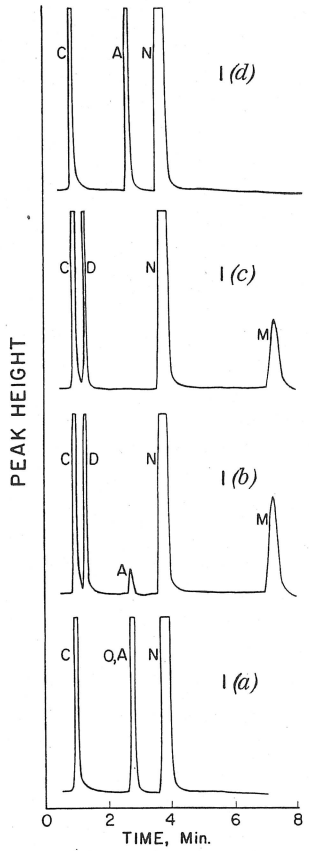

Fig. 1—Strip-chart recordings of gas analyses on Model 1200 Fisher Gas Partitioner. Zero time was taken at moment of sample injection into instrument. *C* is composite gas peak, *O* is oxygen peak, *A* is argo peak, *D* is carbon dioxide peak, *M* is carbon monoxide peak, and *N* i nitrogen peak. (*a*) Normal air sample; peak labeled *O, A* is superimposed peaks for argon and oxygen. (*b*) Combustion gas sample obtained by burning charcoal with normal air at about 900 K. (*c*) Combustion gas sample for conditions of sample (*b*), except that argon-fr synthetic air was used. (*d*) Sample of nitrogen/argon gas mixture con taining about 10 pct argon.

Discussion of "Gas Composition, Temperature, and Pressure Measurements in a Lead Blast Furnace"*

ARTHUR E. MORRIS AND JOHN R. KNOEPKE

Chao *et al* report on gas compositions and temperatures within a commercial lead blast furnace.[1] A particularly noteworthy occurrence was their observation of approximately 1 pct O_2 in the furnace gas, independent of position in the furnace. The authors were unable to account for the presence of this O_2 in a gas containing several pct CO. We offer proof that O_2 was actually not present in significant amounts in their blast furnace gas sample; the gas chromatograph peak ascribed by them to O_2 was actually Ar.

On various models of the Fisher Gas Partitioner or other gas chromatographs using Molecular Sieve 13X as the second column, O_2 and Ar elute from the partitioner at virtually the same time. This occurs for both H_2 and He as the carrier gas. Since atmospheric air contains about 0.93 Ar,[2] normal combustion gases always contain a bit less than 1 pct Ar. If combustion is carried out in the presence of excess carbon, the gases should contain negligible O_2. However, the Ar contained in combustion gases will give a small peak at the O_2 peak location, and thus falsely indicate the presence of O_2.

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*JOHN T. CHAO, PETER J. DUGDALE, DAVID R. MORRIS, and FRANK R. STEWARD: *Met. Trans. B*, 1978, vol. 9B, pp. 293-300.

ARTHUR E. MORRIS is Professor, Department of Metallurgical Engineering, University of Missouri-Rolla, Rolla, MO 65401 and JOHN R. KNOEPKE, formerly Graduate Student, Department of Metallurgical Engineering, University of Missouri-Rolla, is now Associate Scientist, Kennecott Copper Corp., Salt Lake City, UT 84147.

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