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A Preliminary Study of the Use of Magnetohydrodynamic Forces To Remove Impurities from Molten Metals

D. O. Hobson

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A PRELIMINARY STUDY OF THE USE OF MAGNETOHYDRODYNAMIC FORCES TO REMOVE IMPURITIES FROM MOLTEN METALS

D. O. Hobson

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A PRELIMINARY STUDY OF THE USE OF MAGNETOHYDRODYNAMIC FORCES TO REMOVE IMPURITIES FROM MOLTEN METALS*

D. O. Hobson

ABSTRACT

Experimental and modeling work on the use of magnetohydrodynamic forces for separating particulate impurities from molten metals is described. Several experimental systems are described, which use ac or dc electromagnets and, thereby, either induced or direct currents to produce the required forces. Recommendations are made for further optimization of the separators.

INTRODUCTION

In a recent issue of *News Report*, the National Research Council news magazine,[1] its director wrote about the need for new research in separation science. She quoted a Research Council committee's discussion of the importance of separation science and technology for U.S. economic competitiveness in a number of different fields. The committee stated, "Most separations use more than 50 times as much energy as is thermodynamically required." The article ended with the following statement:

> "The high priority research areas identified by the committee include improving the selectivity of separations at the molecular level, concentrating products from dilute solutions, understanding and controlling reactions that occur at interfaces between materials or solutions, increasing the rate and capacity of separations, improving separation equipment, and improving the energy efficiency of separation systems."

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The manufacture and fabrication of steel and other metallic materials are often complicated by the presence of nonmetallic particulates in the solidified metals. In the steel industry, for instance, the movement toward thinner castings requires more stringent control of the particulate content of the metal. Earlier casting techniques, that used large ingot molds and later continuous casting, required large numbers of hot- and cold-rolling reductions in order to produce sheet material of acceptable thickness and surfaces. This large amount of mechanical working was sufficient to break up and disperse the particulates and make them relatively harmless. Current trends toward near-net-shape castings do not require such substantial reductions. Therefore, the particulates remain as originally formed, with possible deleterious effects to the metal's properties.

Current commercial casting practice uses various methods for ridding the molten metal of its load of particulates. Filtration through ceramic foams, ladle spinning, and electromagnetic stirring are among the purification techniques used today. Depending upon the material being poured, these are all more or less efficient. Foam filtration, for example, works well with aluminum but is quite marginal for the much hotter steel alloys. Furthermore, such operations as ladle spinning are removed, both in distance and time, from the mold entrance, allowing time for reoxidation of the metal before it reaches the mold.

An ideal solution to the particulate problem would be a separator that could be installed in the final shroud tube and that would remove or divert the particulates from the main pouring stream before it enters the mold. Such a device has been developed on a bench scale. It uses magnetohydrodynamic (MHD) forces to increase the apparent density of the electrically conducting molten metal while the nonconducting impurity particles are unaffected. The seemingly much less dense particulates then "float" in a direction opposite to the applied force and at a much higher rate of speed than normal.

The application of MHD forces to liquids has been studied extensively by the Soviets during the last 30 years. An excellent review[2] was published in 1976 that discusses the use of those forces for various separation problems. Similarly, the French have studied MHD applications in recent years, particularly to quantify the forces involved.[3] Some aspects of their work are summarized in a report[4] of the Third Beer-Sheva Seminar on MHD flows and turbulence. Two papers in particular are of interest, one dealing in forces on particles[5] and the other on particle separation in a static MHD field.[6] The problems addressed by the French deal with static bodies of liquid metal. The problem addressed by the present work is a dynamic one. How does one apply body forces (artificial density increases) to a flowing liquid metal stream in such a way that vortices and other stirring actions are prevented?

THEORETICAL CONSIDERATIONS

Simplistically, a force is created on a conductor when the current flowing through that conductor is placed in a transverse magnetic field. Vectorially, this is represented by

$$\vec{B} \times \vec{J} = \vec{F} \quad ,$$

where

$\vec{B}$ = magnetic field (Wb/m^2),

$\vec{J}$ = current density (A/m^2),

$\vec{F}$ = force density (N/m^3).

This is equivalent to

$$(B)(J) \sin \theta = (F) \quad ,$$

corresponding to the diagram shown below:

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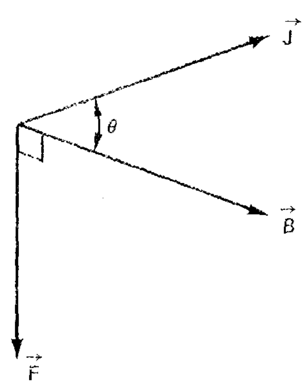

Either ac or dc currents and electromagnets may be used to generate the MHD forces properly known as Lorentz forces. The simplest experimental setup is one in which a dc electromagnet is positioned with its faces on each side of the conductor. A dc current flowing through the conductor will result in a force in the direction dictated by the relationship shown in the preceding diagram. In the case of ac power, an ac electromagnet induces a current in the conductor and crosses with that current to produce the Lorentz force. Careful attention must be paid to the phase relationships. The magnitude of the induced electromotive force, e, which drives the current, is dependent upon the rate of change of the magnetic flux, $d\phi/dt$. It follows that the induced voltage (and current) are normally 90° out of phase with the magnetic flux, which produces the drawback that when the current is at a maximum the magnetic flux is zero and vice versa. In order to obtain an optimum force, the phase angle must be shifted by some amount.

The ac electromagnet, with induced current, is of great interest because no electrical leads are needed to carry current from an external source. Such an ac electromagnet is of particular importance in the case of high-temperature melting where electrode erosion would be a problem.

A further consideration in the use of MHD forces for impurity removal is the minimum size of particles that can be moved by the conductor body force. As will be shown later, particles that are larger than ~250 μm will move, even with vortex motion in the conducting liquid. Smaller particles and, to some degree, nonspherical particles are less susceptible to the MHD force environment. To be truly effective, the MHD device must be capable of moving particles that range from 1 to 20 μm in size.

The goals for further study are, therefore, to limit vortical motion of the liquid conductor (caused by the curl of the vector forces) and to lower the particle size limit for reaction with the MHD forces.

EXPERIMENTAL PROCEDURE AND RESULTS

Two electromagnets were available for this study. A dc electromagnet (with 152-mm-diam pole faces, a 25- to 36-mm gap, and a rating of 1 tesla at 20 A) was used for the dc experiments. The ac tests have been conducted in a three-phase 25-kVA transformer modified by machining the center core leg to obtain a 28.6-mm air gap and rewiring the other legs into a series circuit to convert the whole frame into an ac electromagnet. A bank of capacitors was wired in parallel with the windings to bring the magnet to resonance conditions. The faces are 95 × 140 mm and generate a peak field of just under 0.5 tesla (5 kGauss) at 60 Hz.

A number of separation experiments with each magnet used a variety of liquid conductive media and several different particle types and sizes. Table 1 lists the various experimental setups used.

Table 1. Magnet types and experimental materials used in separation studies

Magnet type	Separator body material	Conducting liquids	Particle	
			Material	Size
dc	PVC	Hg	W (painted)	~4 mm
dc	Pyrex	Hg	Pyrex (beads)	~2 mm
dc	Lavite	Hg	W (painted)	~1 mm
ac	Lavite	Al	SiC	~250 μm
ac	Lavite	Al	Al_2O_3	~2-10 μm
dc	Pyrex	H_2SO_4/H_2O[a]	Pyrex (beads)	~2 mm
dc	Pyrex	H_2SO_4/H_2O[a]	Pyrex (particles)	~0.5 mm
ac	Lavite	Al-Mg-SiC[b]	SiC	~177 μm

[a]48 wt % H_2SO_4.

[b]2 wt % Mg, 1 wt % SiC.

The first series of tests was run in a (15.9-mm) (5/8-in.) PVC plumbing tee with copper plugs epoxyed into the ends of the cross tube to serve as current leads. The tee was installed upside down between the faces of the dc electromagnet, and the small volume between the electrodes was filled with mercury. Several cubes of tungsten metal were painted with lacquer to make them nonconducting and then placed in the mercury pool. It was necessary to push them beneath the surface because of the high surface tension. Current was then applied to the electromagnet, and dc current was also applied between the electrodes to produce a downward force on the mercury. The painted tungsten particles popped to the top and floated, buoyed by the apparent density increase in the mercury. This increase was readily noticeable when the PVC tee was held in place manually—a force of several pounds on the tee was apparent.

This set of experiments pointed out a problem that was to recur throughout the experiments. The surface tension of the conducting liquid creates a problem with mixing particles into that liquid. Calculations showed that only a fraction of the available magnet power and dc current would be needed to overcome the density difference between the mercury conductor (13.5 g/cm^3) and the painted tungsten particles (19.3 g/cm^3). Actually, it took full magnet power (1 tesla) and approximately 50 A to break the particles loose from the bottom of the tee. Once broken loose, the particles popped through the mercury surface and floated.

The surface tension problem was most acute when mercury was used as the conductor. The problem continued, however, when aluminum or aluminum alloys were used, and with the H_2SO_4 solution as well. Particles and beads all tend to adhere and agglomerate in the liquid, and a uniform dispersion is very difficult to achieve.

The following conductor/particle combinations did not work, either because the density differences were too great or because of the surface tension problem: Hg/Pyrex beads, Hg/painted tungsten (dynamic), and Al/SiC. The first system to work successfully was a casting made in the ac magnet with high-purity (metallic elements only) aluminum. This metal, although rated to be 99.99% pure, contained a large amount of oxygen in the form of 2- to 10-μm particles of Al_2O_3. A lavite box was machined with a partition partially dividing one side from the other. The partition left an opening at each end so that the incoming metal could form a continuous path around the annulus created by the partition and the walls of the box. The lavite was then fired at 950°C to harden it. Lavite is a commercial silicate material that is machinable as received and that hardens into a ceramic body when fired.

The aluminum was melted and poured at approximately 725°C (60°C) superheat. The magnet was turned on as soon as the aluminum reached the top of the mold and was left on for 30 s. The cooled aluminum casting was removed from the mold and resembled a thick-walled letter "O" approximately 12 mm thick. The casting was sectioned, and pieces were removed from each side and from the top and bottom for metallographic examination. These were polished on the cross section and photographed near the outer and inner edges. Each visible oxide particle was circled and then counted.

A similar casting was made with the magnet power off. This was sectioned, polished, and examined similarly to the previous casting. Table 2 shows the results for both castings.

Table 2. Results of particle count for castings made with and without magnet power

Sample position	Particle count		Ratio (Outside/ inside)		Number of particles
	Inside	Outside			
		Magnet power on			
Mouth	155	399	2.57		554
Side	178	277	1.56		455
Side	138	191	1.38		329
Bottom	116	192	1.66		308
		Average	1.54	Total	1646
		Magnet power off			
Mouth	230	285	1.24		515
Side	183	125	0.68		308
Side	207	225	1.09		432
Bottom	167	216	1.28		385
		Average	1.07	Total	1640

The casting made with no magnet power showed, on the average, no pattern of particle movement toward the outside of the casting. The test of the casting made with the magnet on, however, showed a consistently higher number of particles located near the outside of the casting. This confirmed the prediction that when an ac electromagnet induces an ac current in a conductor with a circular path, the vector forces will always cross so that the body force on the conductor will be directed inward, even as the current fluctuates from negative to positive. This test also confirmed that separation can be achieved.

While the $Al\text{-}Al_2O_3$ system is a very realistic subject for separation studies, it has several drawbacks:

1. It is destructive of the lavite molds and, therefore, relatively expensive.
2. It is difficult, if not impossible, to achieve steady-state, dynamic separation runs on a reproducible basis.
3. The time during which the aluminum is liquid is not readily controllable.
4. Quantitative measurements of separation require metallographic techniques and, therefore, a delay in evaluation of each run.

Because of these drawbacks, a decision was made to go to an aqueous-base system contained in glass.

A 48 wt % H_2SO_4 solution in water was chosen as the electrolyte, and 2-mm-diam Pyrex beads were used as the particles. The intent was to develop an experimental setup that would allow parametric studies of the separation process, with each variable being amenable to control. Figure 1 is a schematic of the experimental setup. Unfortunately, for several reasons, this design did not accomplish the goals set for it. It did, however, demonstrate that the concept toward which the experiments were directed was valid.

As first set up, 1-mm-thick teflon sheets were inserted into the 35-mm-OD Pyrex tube and placed so that each sheet protruded into the magnetic flux region, one in the liquid inlet region and the other, longer one extending from the liquid exit region back to the point where the two tube drains were positioned. The teflon strips were to serve two purposes: (1) to prevent the curl of the forces from setting up vortices

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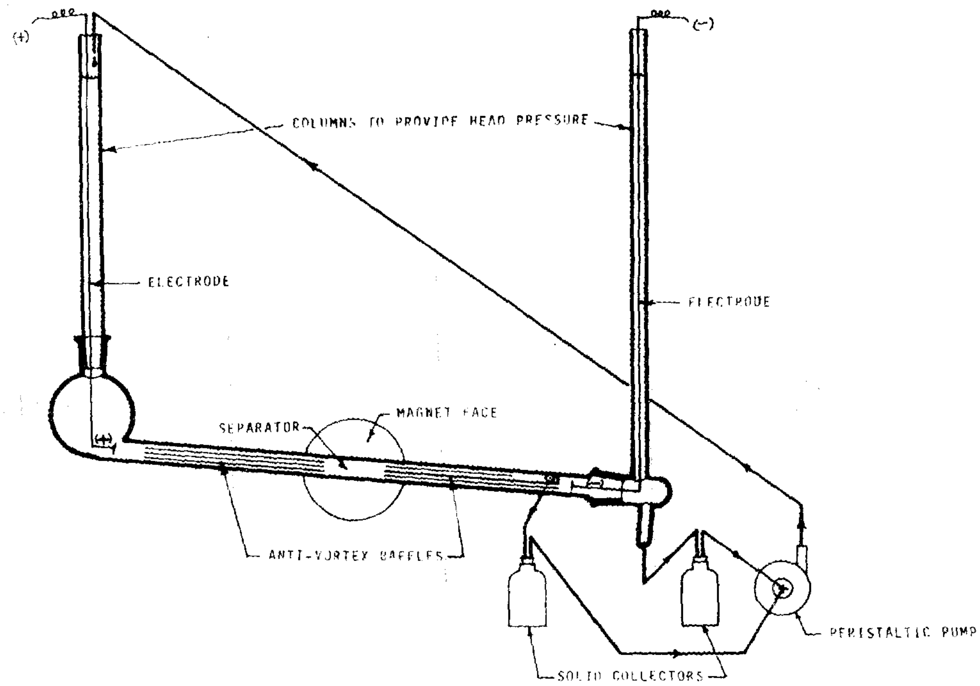

Fig. 1. Schematic of aqueous H_2SO_4/glass particle separator.

at the entrance and exit to the magnetic field, and (2) to serve as a barrier and conduit at the exit end to prevent the separated beads from returning to the main stream.

The goal of the separation was for the liquid stream to carry the beads into the magnetic field where the apparent increased density of the conducting liquid would cause them to float upward onto the top of the teflon partition and, thence, into the sidearm of the tube. Figure 2 illustrates what happened to prevent the separation from taking place. It was anticipated that rotational flow would occur at the entrance and exit to the magnetic field. This problem was studied by the Soviets,[7] and it was found that separation of the flow streams into smaller cross sections, along with an increased flow rate, would cancel out most of the vortical motion. It was soon apparent that the subdivision of the flow cross section (in half) was not sufficient to prevent a backflow along the bottom of the tube. This backflow was enough to prevent the beads from entering the flux region. The pump capacity was insufficient to overcome that flow.

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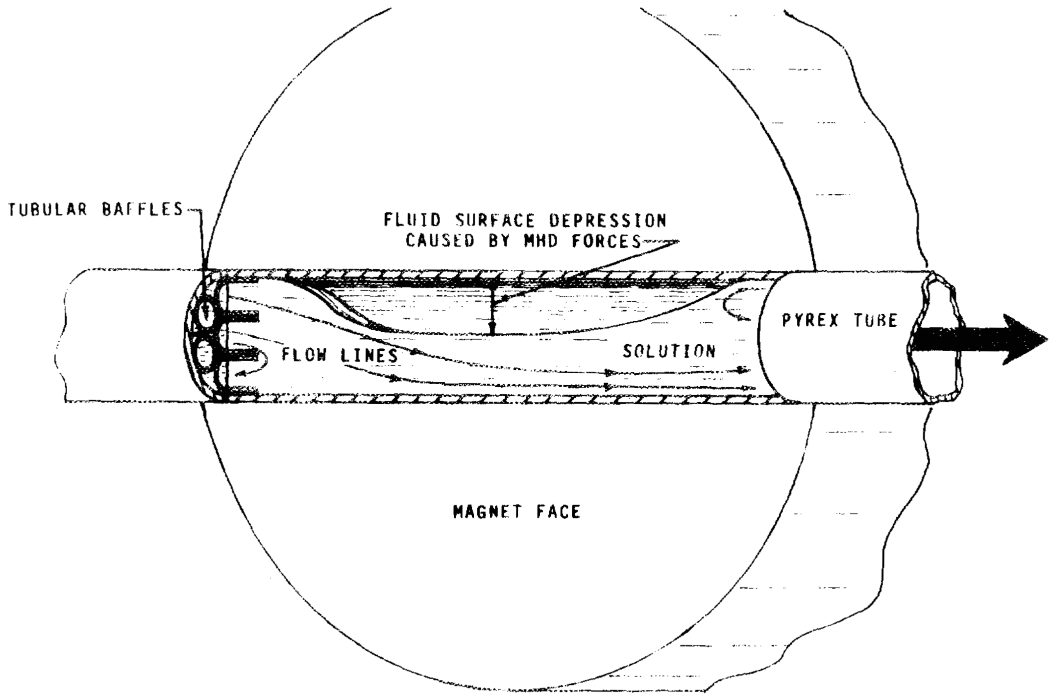

Fig. 2. Liquid instability and flow reversals caused by MHD forces. The solution between the magnet faces exhibits an apparent increased density due to the forces.

The baffle arrangement was redesigned so that a bundle of 6-mm-OD Pyrex tubes (seven tubes in a hexagonal configuration) was inserted in place of the teflon sheet at the entrance to the flux region. A second, longer bundle was substituted for the exit strip. The fluid entering the top three tubes was diverted to a side drain, while the bottom four tubes drained back into the main pump stream. Ground Pyrex particles (approximately 0.5 mm) were substituted for the Pyrex beads.

In subsequent runs it was found that the peristaltic pump was unable to provide a flow rate that was high enough to sweep the particles through the flux region. An attempt was made to pour the solution through the device at a high rate; however, this was unsuccessful because it was not possible to sustain the hydrostatic head, and a discontinuity developed in the liquid in the flux region. Evidence of the development of such discontinuities was found in the earlier runs with this apparatus.

Figure 2, adapted from ref. 2, illustrates the discontinuity phenomenon. It is possible, by increasing the flux and/or the current, to pinch the liquid conductor completely apart. In the present experiments, a depression similar to that shown in Fig. 2 was seen. Assuming the depression reached the midpoint of the 2.4-cm-ID tube, that it was approximately 10 cm long, and that the end standpipes furnished a head of approximately 60 cm of solution of density 1.38 g/cm^3, the volume of liquid under the depression was exerting a force of approximately 2.0 kg to balance that head. This represents approximately 38 times the force of gravity or an apparent density of 52 g/cm^3.

It is apparent that, had the glass particles been able to penetrate the backward vortical flow, they would have been buoyed up into the upper exit tubes and into the side drain.

The discontinuity or depression could be eliminated by increasing the hydrostatic head, either by higher standpipes or by applying gas pressure over the liquid. This was believed to be too dangerous because of the high concentration of acid.

At this point preliminary results were received from a computer modeling study[8] done for ORNL by the University of Alabama. This study suggested a modification to the lavite/aluminum combination studied earlier. The modeling study will be discussed later. Lavite molds were machined to conform to the suggested new dimensions, and, in addition, a copper block was placed in the center of the annulus to effect a phase shift between the magnetic flux and the induced current in the conductor. Several runs were made with the mold using an Al-2 wt % Mg-1 wt % SiC (80 mesh) alloy mixture. The magnesium was added to increase the wettability of the SiC particles by the aluminum.

In a typical experiment two castings were made—one without magnet power and one with. In each case the alloy-SiC mixture was melted in a graphite crucible, superheated to approximately 715°C, stirred vigorously with a graphite rod, and poured into the lavite mold which was positioned in the air gap of the magnet. In the run with the magnet on, the power was adjusted to give a flux of approximately 0.27 tesla (rms) and the magnet was turned on as the liquid metal reached the top of the mold and was left on for 13 s. The induced current traveled around the rectangular path and interacted with flux (perpendicular to the plane of the paper) to produce an inward force on the aluminum. Each casting was sectioned in the middle of a side leg, a lower corner, and in the center of the bottom. Each section was then mounted and polished in cross section. The results are shown as montages in Figs. 3 and 4.

In Fig. 3, cast without magnet power, the SiC particles are distributed over most of the area of the three cross sections. Some reach almost to the inner edge. In Fig. 4, with magnet power, all except one of the visible particles are in the outer 50 to 60% of the cross sectional area. Considering that the magnet was on for 13 s and that the casting was solidifying during that time, the results are not surprising and do indicate the occurrence of separation.

To summarize the experimental results to date, we have strong evidence that separation of nonconducting particulates from a conducting liquid has been achieved and can be improved. Future work must take advantage of further computer modeling so that forces can be applied to the liquid without generating the large amounts of curl and, therefore, vortex formation in the liquid. The next section will discuss preliminary modeling work conducted on an early separator design and will discuss possible solutions to the vortex problem.

COMPUTER MODELING

It was recognized that a two-path investigation was needed to optimize the separator design. The experimental work has shown that the concept of applying MHD body forces to a conductor and thereby separating particulates is valid. It soon became obvious that experimental studies by themselves would not allow a classical investigation of the effects and interactions among the many variables. A parallel modeling study was initiated, therefore, to enable us particularly to study the effects of separator geometry and system dimensions on separator operation. A subcontract was established with The University of Alabama, Tuscaloosa, Alabama, for Dr. Nagy El-Kaddah to do the analysis. The results of his study were issued in a final subcontract report.[8]

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- Al-2 WT % Mg-1 WT % SiC (~280 μm PARTICLE SIZE)
- MELTED AND HEATED TO 726°C
- STIRRED TO MIX SiC PARTICLES AND POURED INTO LAVITE MOLD
- MAGNET OFF DURING POUR AND SOLIDIFICATION
- CROSS SECTIONS TAKEN AS SHOWN

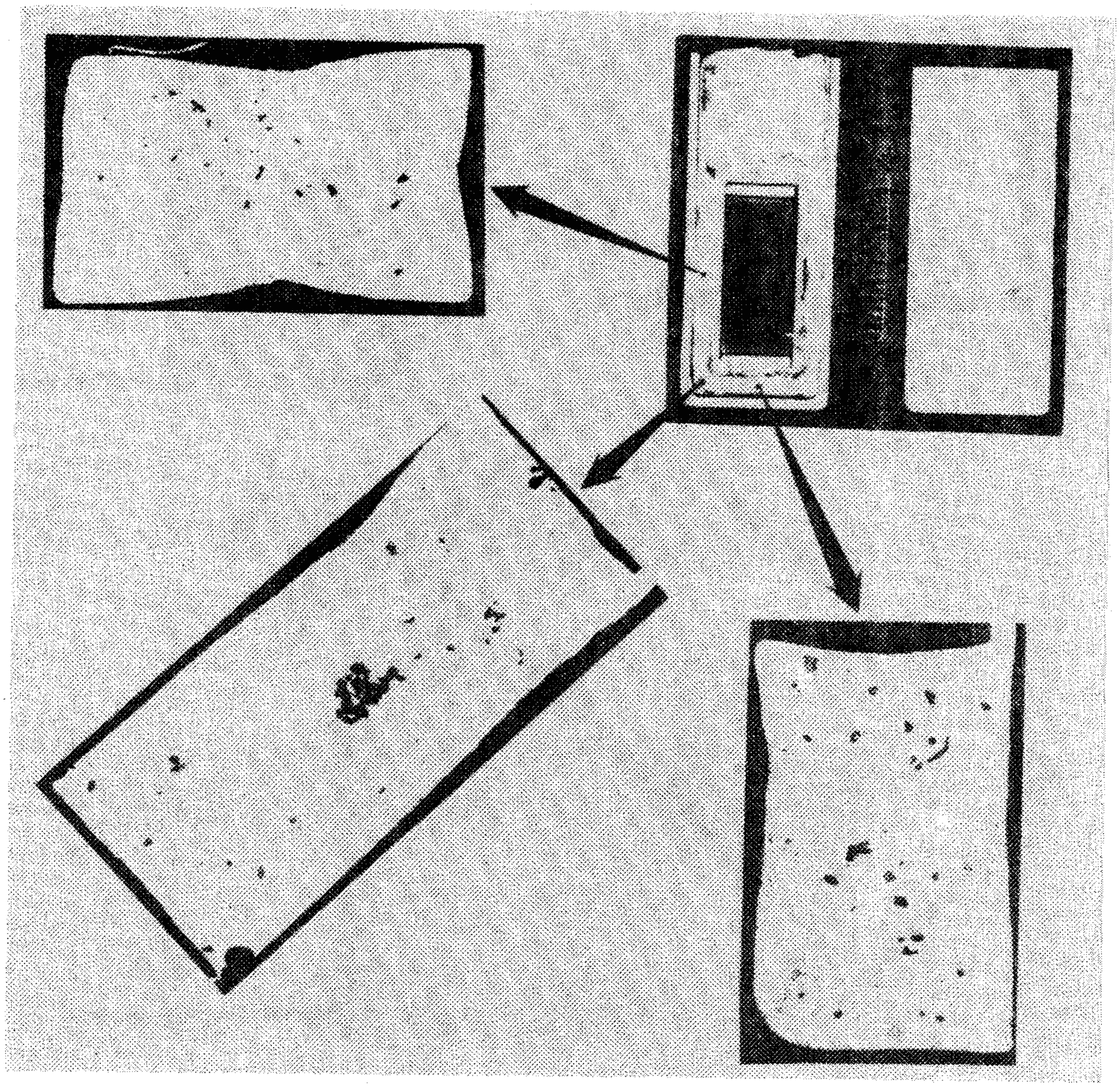

Fig. 3. Cross sections of casting poured with no MHD forces applied. Note particles covering entire cross sections. Arrows point to inside edges.

ORNL-DWG 88-6181

- Al-2 WT % Mg-1 WT % SiC (~280 μm PARTICLE SIZE)
- MELTED AND HEATED TO 706°C
- STIRRED TO MIX SiC PARTICLES AND POURED INTO LAVITE MOLD
- MAGNET ON FOR 13 s AFTER MOLD FILLED
- CROSS SECTIONS TAKEN AS SHOWN

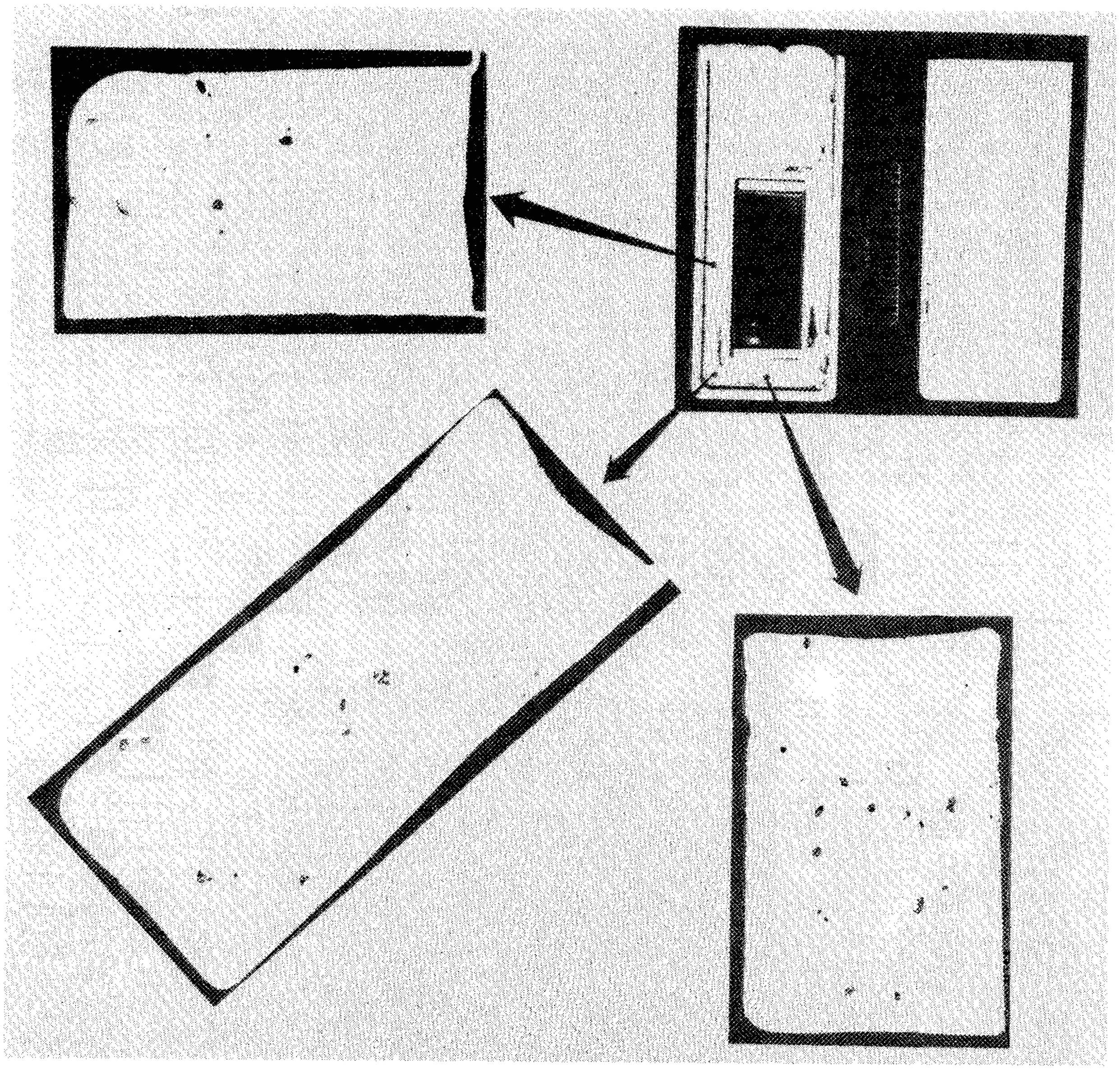

Fig. 4. Cross sections of casting poured with MHD forces applied. Note particles generally confined to outer two-thirds of cross sections. Rounded spots (particularily in corner section) are voids in the casting. Arrows point to inside edges.

The El-Kaddah study developed a mathematical model to describe the separation of inclusion particles and was able to quantify some of the effects of the process variables. The model was used to provide a more fundamental understanding of the electromagnetic and fluid flow phenomena and of the particle motion in the separator through the numerical solution of the Maxwell equations, the laminar Navier-Stokes equation, and the differential equation of particle motion.

Originally the modeling was based on design for a flow-through separator that was subsequently discarded in favor of studies on semi-static separators—where the molten metal was poured into the separator body, the MHD forces applied, and the metal allowed to solidify. The mathematical model developed for the dynamic separator was directly amenable to the semistatic case since it considered only two-dimensional forces and movements within the separator.

The El-Kaddah modeling study consisted of two parts: the distribution of forces in the channel cross section, and particle trajectories within the rotational flow caused by divergence of those forces. This was done by calculating the electromagnetic field present in the molten fluid, developing fluid flow equations, and deriving a particle history model. The computed results were obtained from the electromagnetic field calculations, the velocity field calculations, and the computed particle trajectories.

The initial separator design was immediately shown to have two serious problems: the coupling between the electric and the magnetic fields, and the divergence of the electromagnetic force field. The latter effect stirs the melt and causes the entrainment of the inclusion particles within the flow eddies. The purpose of the modeling development was to provide a fundamental understanding of the electromagnetic and fluid flow phenomena and of particle motion; the results were used to redesign the separator to optimize its operation.

Figure 5 is a generic sketch of a separator similar to those used later in the modeling study and is presented to show the coordinate system used. The study assumed that the separator was very long in the Z direction so that flow effects caused by the stirring action were confined

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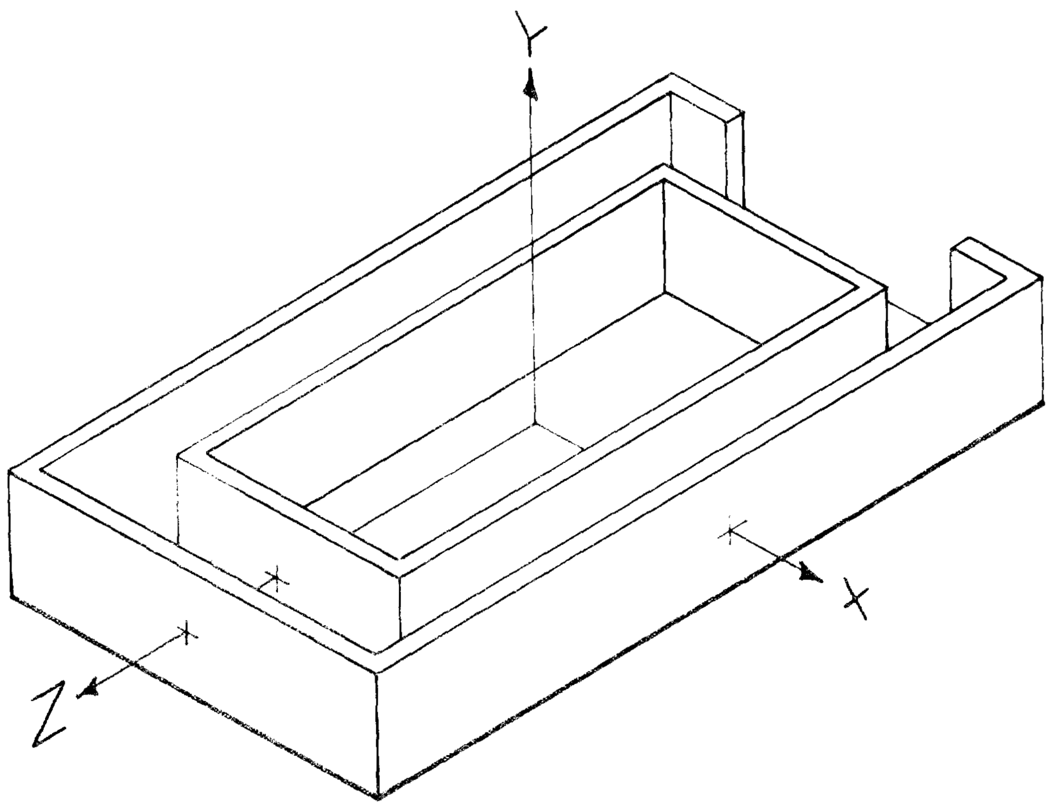

Fig. 5. Schematic of uncovered mold with reference directions indicated. Actual mold was fabricated of Lavite. The center section contained a copper block to effect a phase change in the electrical properties.

to the X-Y cross section. A second assumption was that the molten metal was static, in the sense that there was no flow-through—the mold was filled and the metal sat until it solidified.

Dr. El-Kaddah showed that 250-μm-diam particles were marginally separable, depending upon their initial locations in the liquid metal and that smaller particles were trapped in the vortical flow. He also showed that slight changes in the device dimensions enabled the 250-μm particles to be separated from any location in the cross section. The latter dimensions were used to machine a lavite mold which, with the addition of a copper center, was used to generate the successful run discussed earlier in the Experimental Procedure and Results section.

CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated through a series of experiments and modeling efforts that the separation of particles from molten metals is possible and, indeed, feasible. Conceptually, there is no reason the method cannot be applied to any molten metal (i.e., nonelectrically conducting particulate system) within the material capabilities of the separator body.

We have shown that a single ac electromagnet is capable both of supplying the magnetic field and of inducing the current in the molten metal that the field crosses to produce the required body forces.

Having proved the concept, there remains the problem of optimization. The following aspects of the process must be addressed and solved before the device becomes truly commercially useful.

1. Modeling studies must address the three-dimensional aspects of the problem.
2. Flow vortices must be minimized to decrease stirring effects.
3. The efficiency of the coupling between the magnetic field and the induced current must be increased.
4. The process must be optimized to remove particles in the size range peculiar to commercial materials.
5. The process must be optimized to handle the flow-through situation.

We are to the point where computer process modeling must address a dynamic, flow-through system, with realistic particle sizes, in which we can vary parameters and see the changes that result. Only this way can true optimization be accomplished.

ACKNOWLEDGMENTS

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Dr. Nagy El-Kaddah was instrumental in setting up and performing the initial phase of the modeling work, and we are grateful for his contribution to the study.

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