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State of the Art of Numerical Modelling for Electromagnetic Processing of Metallic Material

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Abstract

The characteristics of electromagnetic processing systems for materials are discussed with a view to determining the requirements for state of the art numerical modeling tools. Available numerical methods are reviewed to indicate where present numerical simulation tools stand relative to state of the art requirements.

Introduction

Electromagnetic processing of metallic material dates back to at least 1887 when Sebastian de Ferranti patented an induction process to be used for the melting of metal [1]. That same basic phenomenon today forms the basis for the many modern processes that are termed EPM, or **E**lectromagnetic **P**rocessing of **M**aterials. Essentially, with EPM, a time varying magnetic field induces the flow of electric current in the conducting material to be processed, thus causing energy transfer for the purpose of heating, and/or Lorentz forces to be exerted for the purpose of causing motion, deformation or confinement.

Numerical modeling today provides an essential component in the development and design of EPM systems. From the early beginnings of numerical simulation, dating from 1960 or so, to the present date, software tools that are capable of modeling the various aspects of an EPM system have reached an advanced state of sophistication.

The purpose of this paper is to asses the present state of the art regarding the numerical modeling of EPM systems. The paper compliments material that was presented at HES-07, the *2007 International Symposium on Heating by Electromagnetic Sources*, and subsequently published in *COMPEL* [2]. The purpose of the latter paper was to provide a comprehensive review of the literature relating to the numerical modeling of induction processes. The review had two principle components: (a) classical papers that were among the first to describe the numerical treatment of a class of induction problems, and (b) the most recent papers in the same area. In taking this approach, it was felt to be very important that some of the early work in various areas relating to induction be recognized.

The present paper provides an assessment of current modeling methods as they relate to typical EPM applications. The case of a modern electromagnetic stirring (EMS) system, used during the continuous casting of steel, provides a focus for a discussion of current modeling needs for such applications.

EPM Modeling Case Study: Electromagnetic Stirring for Continuous Casting

Electromagnetic stirring (EMS) is widely used during the production of steel billets and blooms by continuous casting. A typical dual stator in-mold EMS system is shown in Fig. 1. In this system, both of the stators are supplied from a low frequency, three phase power source. The coils shown for each stator are mounted on salient poles and typically surround a relatively thick copper mold containing molten steel. The Lorentz forces created by the interaction of the rotating magnetic fields with the molten steel produce a fluid flow that can be quite turbulent. The flow is primarily in the azimuthal direction, but does contain a nontrivial poloidal component as well. Not shown in the figure is an entry nozzle that continuously feeds molten steel to the mold from a tundish. The combination of the entry jet and the fluid flow induced by EMS can have a distorting effect on the molten metal free surface.

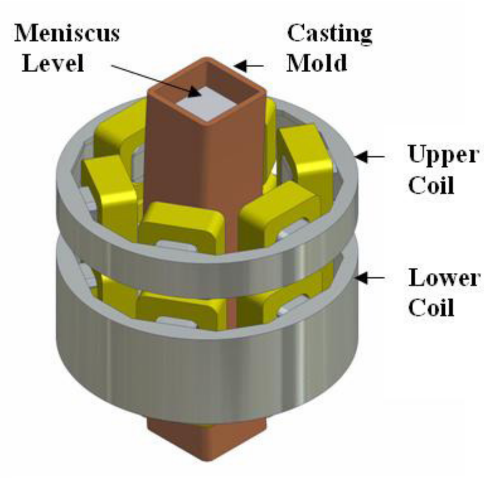

Fig. 1. Typical dual stator EMS system to provide stirring while continuously casting steel billets or

The continuous casting EMS system incorporates many of the key features that characterize modern EPM applications and thus require treatment if state of the art numerical modeling methods are to be employed during design or development stages. These features include the following:

1. *Electromagnetic Fields and Induced Current*

When modeling any EPM system, it is critically important that the electromagnetic fields be properly represented, in all the complexity that the system may involve. In the case of the EMS system shown in Fig. 1, the excitation is time harmonic and the geometry is fully 3-dimensional. There is no possibility that an equivalent 2-dimensional geometry can be devised for this system. State of the art electromagnetic modeling almost always involves the representation of a 3-dimensional geometry. The excitation of conventional EMS systems, and indeed that of many EPM applications, involves coil currents that are time harmonic. In the case of EMS, the excitation is generally low frequency involving relatively low ratios for conductor dimensions vs. penetration depth. For many other EPM applications, however, the penetration depth may be quite shallow relative to conductor dimensions, thus requiring special treatment when defining solution grids or indeed modeling methods. Additionally, more modern EMS and EPM systems may involve more complex forms of excitation, involving multiple frequencies or special waveforms, for which conventional software may be inadequate.

2. *Motion of Conducting Material*

A key feature of EMS is that the conducting material within the casting mold moves relative to the applied magnetic field. Consequently, in addition to the electric current induced by the time variation of the source field, there is an additional component due to conductor motion. This **v x B** component has a significant impact on the stirring that the system produces and cannot be neglected. As a consequence of motional effects, the electromagnetic fields in an EMS system cannot be treated in isolation from the stirring that the fields produce. The system is actually tightly coupled, and this coupling is one of the defining features for state of the art modeling software for EMS (and other EPM) systems.

3. Material Nonlinearity

In the EMS system, the stator is ferromagnetic steel, and the salient poles may incorporate solid ferromagnetic pole extenders. Thus, a complete electromagnetic simulation may require that the nonlinear B-H properties of these components be modeled appropriately. Accounting for the nonlinear B-H properties will have important implication on the electromagnetic field solution strategy. It may require the use of a transient solution, or alternatively, an appropriately defined, spatially dependent magnetic permeability.

4. Joule Heating and Heat Transfer

In an EMS system, Joule heating occurs primarily in the high powered coils where the current density is pushed to a limit that is determined by available cooling. Additionally, a system design constraint is the ability of the water cooled copper mold to effectively freeze a solid shell during the dwell time of the molten metal within the mold. Thus, when modeling an EMS system, a software module that accounts for heat transfer will also be required. For typically EMS applications, the heat transfer and electromagnetic effects may not be closely coupled. Such is not the case in other EPM applications, particularly any system that involves heating by induction, where it becomes critical that the nonlinear σ-T behavior of the conducting material be accounted for. In such applications, there will of necessity be close coupling between the electromagnetic and thermal software modules. When ferromagnetic materials are being heated, an additional B-H-T behavior must be accounted for.

5. Turbulent Fluid Flow

The key physical phenomenon in an EMS system, as well as in many others liquid metal applications of EPM, is the flow produced by the applied electromagnetic fields. The strong coupling between the source magnetic flux density and the resultant EMS flow was noted above. In and of itself, the flow in an EMS system is structurally complex. The primary flow is characterized by a swirling motion in the azimuthal direction. However, it also contains an important poloidal component that extends well beyond the immediate vicinity of the stator(s); i.e. the zone where the driving Lorentz forces exist. The flow also exhibits strong turbulence, the characteristics of which change significantly from the stator region to regions remote from the stators. The computational fluid dynamics (CFD) software that is used to model turbulent flow in EMS systems must provide a rich menu from which to select turbulence models, it must make available high order models to account for convective momentum transfer and, ideally, it should provide means to coupled with electromagnetic software modules in order to account for the **v x B** coupling.

The importance of the **v x B** coupling, as well as the need to have a rich assortment of turbulence models, is illustrated in Fig. 2 and Fig. 3, respectively. Fig. 2 shows the actual angular velocity produced by an EMS system, compared with the results predicted by various models. The importance of the **v x B** coupling is clearly evident; by not accounting for the coupling, the predicted velocities are at least 30% greater than the measured data. As noted in Fig. 2, the predicted values of angular velocity, at a radius that is distant from the center axis, are all relatively close to one another, regardless of the turbulence model that is used. This is not the case, far from the stirrer, when angular velocity as a function of radius is considered, as illustrated in Fig. 3. Due to the importance of momentum transfer effects far from the stirrer zone, upwinding and the choice of turbulence model have a significant impact on the predicted velocities. Considerable care must be taken when modeling such systems and the importance of having experimental data available for the purpose of validation cannot be under estimated.

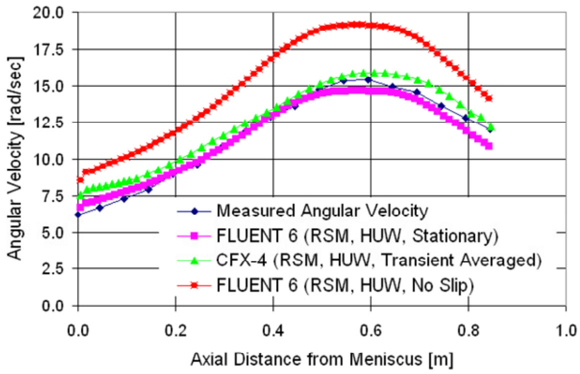

Fig. 2. Angular velocity as a function of axial displacement from the meniscus.

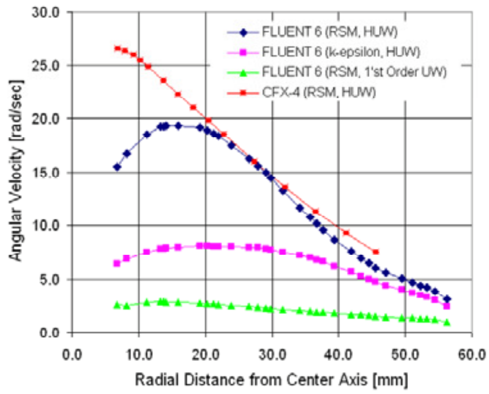

Fig 3. Angular velocity distribution predicted at the meniscus under various model assumptions

6. Transient vs. Steady State

Conventional EMS systems essentially operate in the steady state in that the flow results from time average, or DC, Lorentz forces. Nevertheless, when modeling the flow aspects of such systems, solution strategies that are based on a time stepping transient approach have proven to be significantly more robust than are strategies that attempt to directly determine the steady state flow. The latter have proven to be overly prone to instabilities and lack robustness. In addition, the availability of transient solvers for all aspects of EMS modeling, namely for both the electromagnetic fields and the resultant flow, becomes essential when considering most of the 'next generation' of stirrers that are presently being considered. These newer concepts seek to introduce additional turbulence in specific regions by exploiting specific forms of time variation in the Lorentz force distribution.

7. Free Surface Deformation

One final aspect of the EMS system, and indeed of most EPM applications involving liquid metal, deserves mention. The free surface of the molten metal in the casting mold is subject to several forces that cause it to distort. In the case of EMS, the distorting forces predominantly result from momentum transfer from moving metal, either motion in response to Lorentz forces, or momentum transfer originating from the incoming stream feeding molten steel to the mold. Control of the free surface conditions at the meniscus is critical to achieving a high quality cast product. In other applications of EPM, for example the conventional crucible induction furnace or, alternatively, moldless casting of aluminum, the electromagnetic pressure developed by the interaction of the source magnetic flux and the liquid metal is sufficient to significantly distort the liquid metal free surface. Ideally, modeling software will have the capability to consider the free surface shape as a solution variable.

Current State of the Art

Recently, a comprehensive review of the literature relating to numerical modeling of induction processes was published [2]. This review not only covered the induction process, which is a key component in most EPM processes, but also touched on issues relating to heat transfer, electromagnetic stirring and turbulent fluid flow. The purpose of the paper was to not only provide an assessment of the current state of the art, but also to place the current methods within a historical context by citing important early papers in the field. The present paper covers many of the same research areas relating to EPM. Rather than cite once again many of the same references, the interested reader is referred to the earlier paper where he/she will find a detailed listing of technical literature.

Modeling requirements for typical EPM applications were outlined in the previous section by referring to an electromagnetic stirring system for the purpose of illustration. The modeling requirements for that system were discussed in terms of several broad categories. In what follows, the current state of the art relative to the modeling of EPM systems will be briefly discussed. The discussion will focus on software that is commercially available, although mention will not be made of particular software packages.

1. Electromagnetic Fields, Induced Current, Material Nonlinearity and Motion

Software is available from a number of vendors that has the capability to model the electromagnetic aspects of advanced EPM systems. The software easily treats 3-dimensional geometries of considerable complexity, subject to excitation by DC and time harmonic sources, as well as sources having relatively arbitrary waveforms. The solutions can be obtained in either the steady state or by time stepping through a transient, taking into account source impedance characteristics. The conducting media can be either magnetic or non magnetic. In the case of magnetic materials, some software may have the capability to include user defined material characteristics.

Electromagnetic software is most often based on the Finite Element Method, although software based on Boundary Element methods is also available. The FEM approach has the advantage of flexibility and may offers a wide range of elements that simplify the treatment of special geometrical features (e.g. thin shells, highly conductive media). Some software packages may also offer a choice of solvers, either direct or iterative. Some software may also link to models for other physical phenomena associated with EPM, the most common being to temperature rise models where the heat transfer side is tightly integrated to the electromagnetic.

There are two areas where the electromagnetic software remains weak. The first is the treatment of **v x B**. The case where motion is linear and well defined can generally be modeled with confidence (e.g. the motion of a solid plate near a linear induction stator). The case where the motion is more arbitrary, as in a liquid metal, remains generally an open question still. This problem has been solved at the research level, but commercially available solutions are not widely available, but some do exist.

The above noted **v x B** weakness is linked to the second area where all software, EM and CFD, requires improvement, namely the integration of modules so that real world coupled problems may be conveniently solved. At present, it is possible for the user to define linkages so that this can be achieved, but a tighter integration would be desirable.

2. Computational Fluid Dynamics and Heat Transfer

Software to model fluid flow and associated phenomena, including heat energy flow, is at a very sophisticated level of development. The software is capable of treating a broad range of real world problems, either in the steady state or transiently. From the fluid flow side, the software generally includes a number of turbulence models, ranging from the widely used k-ε, through the higher order Reynolds Stress model, to the computationally intensive Large Eddy Simulation (LES) model. As with EM software, a range of element types are available, as are steady state and transient solver modules. Most important, and more so that is the case with most EM software, CFD modules generally provide the user with the capability to link compiled, self generated, modules to that main software. Using this capability, there are instances where the full **v x B** problem has been incorporated.

Conclusion

This paper has attempted to provide an assessment the present state of the art in modeling EPM systems. The paper complements a previous paper in which a detailed literature review relating to induction processes was undertaken.

References

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[2] Lavers, J.D., *State of the art of numerical modeling for induction processes*, COMPEL, Vol. 27, 2008, No. 2, pp. 335-349.

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