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Application of Multi-Physical Model to Process Solution in Electromagnetic Field Technique

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Abstract

Since the actual on-line process in steel making plant consists of a kind of the combined multi-physical phenomena, multi-physical model taken into account of each physical phenomenon as a numerical calculation model is has been developed. The multi-physical model taken into account of electromagnetic field, fluid dynamics, heat transfer, solidification, steel quality and process control expresses the real process phenomena qualitatively and/or quantitatively. It is a useful process solution tool to solve such technical problems as casting, plasma heating, microwave heating, color coating line and free surface level control system.

1. Introduction

As quality improvement and cost reduction are increasingly required in the process development of the steel industry, technologies of electromagnetic field application are attracting more attention than ever as new key technologies to meet the requirements[1)]. When applying electromagnetic field technology to steel processes, however, magnetic coils does not always fully perform in an object material by simply arranging them near the material, because a magnetic field diverges and electromagnetic field is a complicated phenomenon. On the other hand, a steel process is composed of combinations of complicated phenomena and for this reason, when applying an electromagnetic field technology to a steel process, it is imperative to deeply understand the characteristics of both.

An actual steel process is a complicated system in which physical models involving material flow, heat, their control are tangled with each other. Therefore, it is difficult to understand the whole phenomena of a steel process from the viewpoint of only one physical model. On the other hand, thanks to the recent remarkable advance of numerical analysis technology, a combined analysis of two or more physical models has been made viable.

This paper outlines a multi-physical model[2)] reflecting physical phenomena of an actual steel process to the maximum possible extent that includes an electromagnetic field analysis technique as one of the main components. The paper also presents some examples of electromagnetic process solutions to solve various technical problems of real steel production processes through application of the multi-physical model technologies.

2. Multi Physical Model

Fig. 1 shows a structural diagram of a multi-physical model that includes an electromagnetic field model as one of the main components. Here, each of the blocks representing an electromagnetic field, fluid dynamics, heat transfer and product quality analysis, and process control, respectively, constitutes a physical model independent from each other, and each model is coded according to a numerical analysis method such as the finite element or finite difference method.

It is very important for actual application of a multi-physical model to thoroughly understand the characteristics of the object process and analyze the process through modeling of the interactions between the physical models in consideration of the nature of the object material. For example, in the case of a combined analysis of an electromagnetic field and fluid dynamics having a free surface, the shape of the free surface changes under the influence of fluid flow

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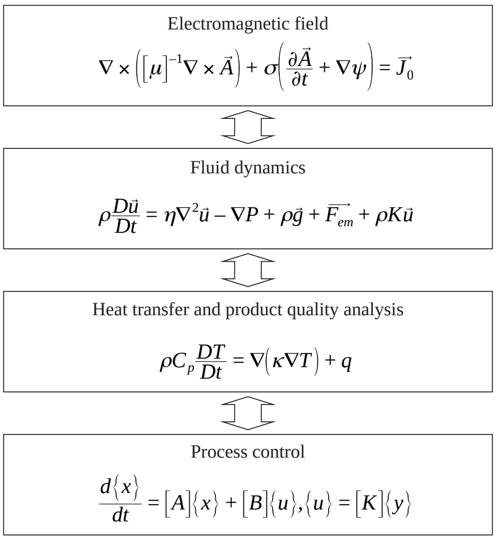


Fig. 1 Multi-physical model including electromagnetic field as one of main elements

induced by the electromagnetic force. From the standpoint of the electromagnetic field, this means a change in boundary conditions; as a consequence, a great amount of calculation time is required for accurately evaluating by large-scale numerical analysis method the distribution of the electromagnetic field in relation to the shape of the free surface that changes from time to time. Therefore, in order to carry out the numerical analysis efficiently, it is necessary to model the interaction by some method or other. In the above case, the magnetohydrodynamic analysis of a free surface can be modeled by a shadow method[3]. On the other hand, the influence of the speed electromotive force in an electromagnetic field is negligible in the case of an analysis object such as an electromagnetic stirrer for a continuous caster, in which the molten steel flow is far slower than the synchronous speed of the traveling magnetic field. In these cases, a simple model structure such as a one wherein electromagnetic force is added as an external force in the fluid dynamics can be adopted[4].

Application of a multi-physical model makes it possible to develop and design a steel production process focusing on product quality, because it is now possible to directly evaluate a field of physical phenomena that govern the process using the model and combine the evaluation results with steel quality models for non-metallic inclusions, cracking, segregation, etc.

3. Electromagnetic Process Solutions

Since a multi-physical model precisely expresses a certain aspect of an actual steel production process, it is often useful for solving various technical problems encountered in field production activities. **Fig. 2** schematically shows an electromagnetic process solution utilizing a multi-physical model that includes an electromagnetic field as one of its main elements. Such a multi-physical model is capable of proposing equipment specifications, visualizing process behaviors, suggesting optimum solutions and so forth, and thus it is instrumental in finding solutions to operation troubles and other technical problems encountered in production fields as well as process design and development. Some examples of process solutions applying multi-physical models are presented below.

3.1 Electromagnetic casting of steel billets[5]

Electromagnetic casting (EMC) is a technique to control the initial solidification of molten steel in a continuous casting mold by applying alternating currents to solenoids coil provided around the mold. It is viewed as a technique to improve the surface quality of cast billets and stabilize the lubrication between the mold and cast billets.

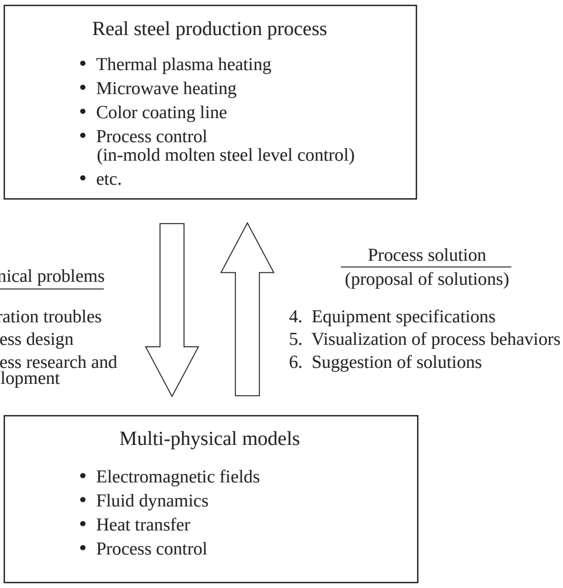


Fig. 2 Electromagnetic process solution by multi-physical model including electromagnetic field as one of main elements

Fig. 3 schematically illustrates the principle of the EMC. Alternating magnetic fields of the magnetic coils arranged around the meniscus of a mold act on the molten steel in the mold, and the Lorentz force is generated by the interaction between the alternating magnetic fields and eddy currents induced by them in the steel. Since the Lorentz force acts as a pinching force, the molten steel surface bulges upward to widen the flux channel between the solidification shell and the mold. As a consequence, the pressure fluctuation in the flux channel caused by mold oscillation is reduced to stabilize mold lubrication and improve billet surface conditions.

However, unless the magnetic fields are applied to the molten steel meniscus appropriately, an excessive steel flow is induced by the electromagnetic force, and as a consequence the molten steel surface may become unstable and mold powder be entrapped in the steel. For this reason, in order to obtain a sound initial solidification shell, it is important to adequately control the strength of the electromagnetic pinching force and the application pattern of the magnetic fields. In order to quickly find out an optimum solution, the dynamic behavior of the molten steel meniscus was analyzed, using a multi-physical model and changing the electric current application pattern

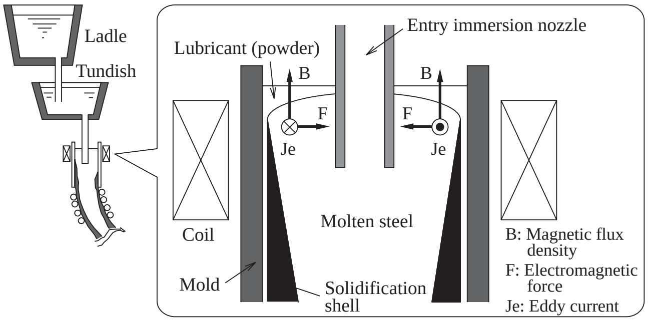


Fig. 3 Concept of electromagnetic casting (EMC) technique

of an analysis model for EMC equipment to cast square section billets. The research was carried out by the Japan Research and Development Center for Metals (JRCM) as one of the activities of the "Energy Use Rationalization Metal Production Processes", a national research project that the Center undertook from 1995 to 2000 under a subsidy of the then Ministry of International Trade and Industry.

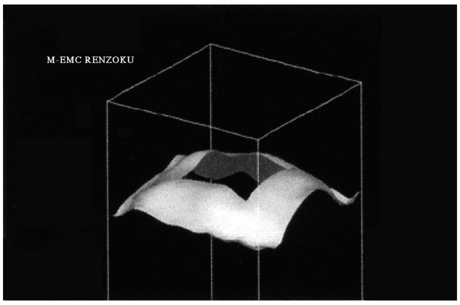
Fig. 4 shows molten steel surface shapes under different application patterns of electromagnetic force. When electromagnetic force was applied continuously as in conventional practice, the meniscus was so unstable as to fluctuate asymmetrically owing to the steel flow induced by the electromagnetic force. When pulsating electromagnetic force was applied at a cycle of 0.1 s, in contrast, the steel surface shape was a combination of a large bulge across the surface and small ripples having the same cycle of the pulses. Further, when the on/off of the electromagnetic force application was smoothed so that the waveform of the applied electromagnetic force was trapezoidal, regular bulges appeared on the steel surface in the same cycle as the pulses. Casting tests of EMC were carried out on a commercial continuous caster applying the most suitable pulsating condition identified using the multi-physical model, and an optimum solution to improve the surface characteristics of cast billets was obtained.

3.2 Electromagnetic stirring of molten steel in slab caster mold[6)]

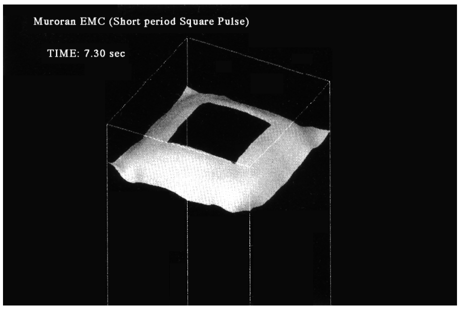
Electromagnetic stirring (EMS) equipment to stir molten steel in a slab caster mold has been successfully used in commercially operated casters to improve surface quality of steel slabs. However, a wide variety of problems had to be solved to realize optimum equipment design and operation under the hardware and software restrictions of each plant. In view of the situation, a multi-physical model was developed to analyze the electromagnetic fields, molten steel flow, heat transfer and product quality in an integrated manner, and it proved effective for solving problems encountered in actual field production activities.

In **Fig. 5**, the 3-dimensional distribution of magnetic flux density under application of the EMS calculated by the developed multi-physical model is compared with the actually measured distribution. It is seen in the figure that the electromagnetic field analysis well quantified the real process behavior. The technology can be effectively applied to the design of high-performance magnetic coils.

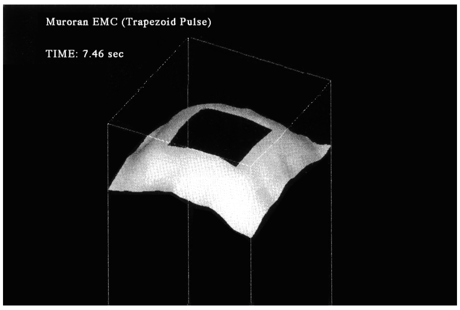
The molten steel flow under application of the EMS calculated by the multi-physical model is plotted versus actually measured steel flow in **Fig. 6**; a diagonal line is given to see if the calculated figures agree with the actually measured ones. It is concluded from the figure that the hitting ratio of the multi-physical model calculation is



(a) Continuous electromagnetic force mode



(b) 0.1-s cycle pulse mode



(c) 1-s cycle trapezoidal-wave pulse mode

Fig. 4 Molten steel surface shape of EMC under different electromagnetic force application modes

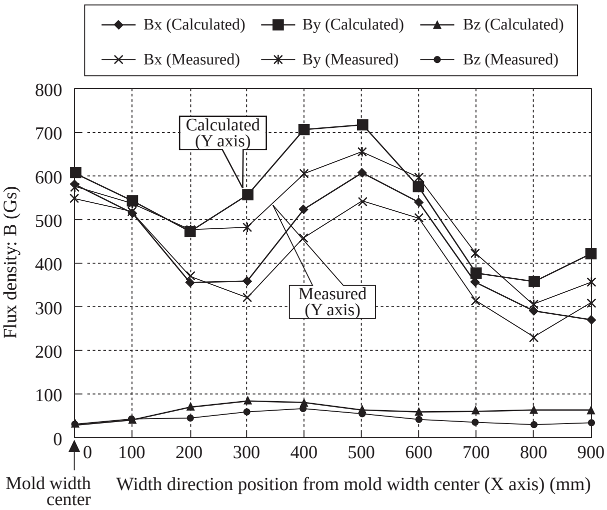


Fig. 5 Calculated and measured magnetic flux density distributions of EMS for slabs

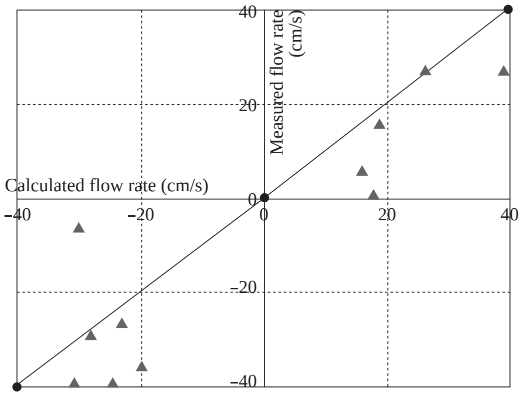
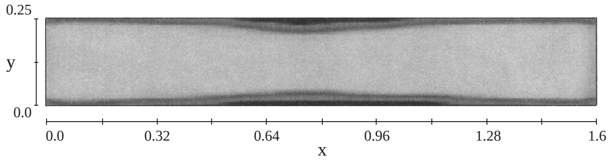
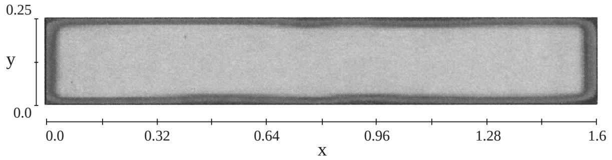


Fig. 6 Calculated and measured molten steel flow rates with EMS for slabs



(a) EMS off



(b) EMS on

Fig. 7 Calculated distributions of solidification shell thickness with and without EMS (Dark portion: Solidification shell; Light portion: Molten steel)

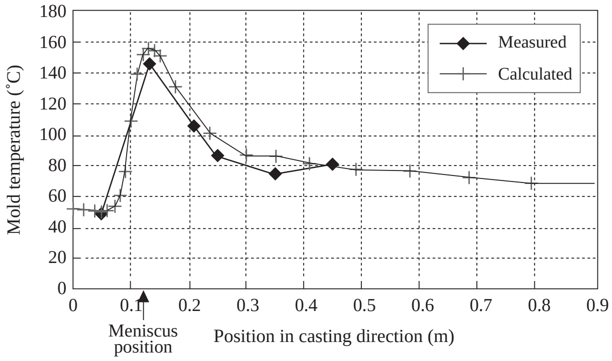
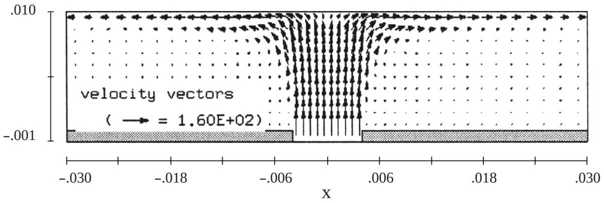
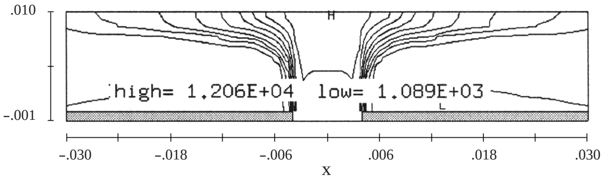


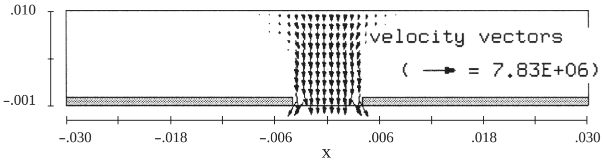
Fig. 8 Calculated and measured mold temperature distributions



(a) Flow rate distribution

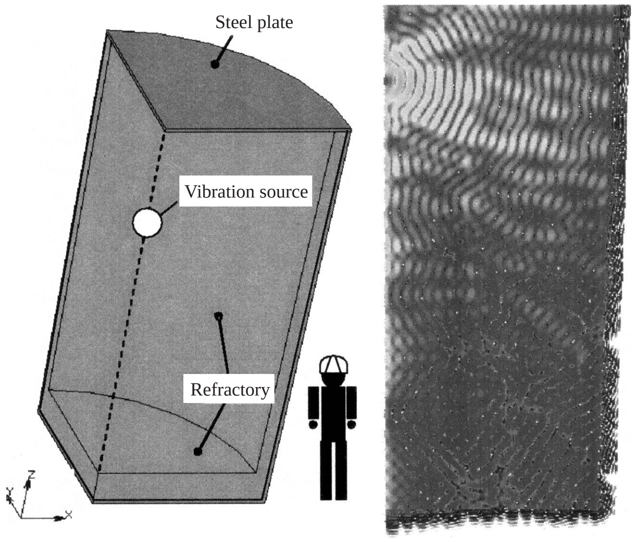


(b) Temperature distribution



(c) Eddy current distribution

Fig. 9 Magnetohydrodynamic analysis of 3-dimensional thermal plasma heating



(a) Microwave drying equipment (1/4 scale model)

(b) Electric field distribution

Fig. 10 Electromagnetic wave analysis of microwave drying process

about 30%.

Fig. 7 shows the calculated distribution of solidification shell thickness, and **Fig. 8** compares the calculated temperature distribution of a mold with that actually measured. It is seen in the figures that the multi-physical model can qualitatively and quantitatively reproduce what actually takes place.

This means that the multi-physical model constitutes a promising tool for magnetic coil design, process design, preparation of operation guidelines and analysis of process phenomena from the viewpoint of improving product quality, which is the very final objective.

3.3 Thermal plasma heating technology

Thermal plasma is commercially used in the steel industry as a heat source in a tundish of the steel plant, but its behaviors have not been well understood, and hence they have been studied using numerical analysis methods. **Fig. 9** shows some results of magnetohydrodynamic analysis of 3-dimensional thermal plasma. Here, a combined calculation covering an electromagnetic field, fluid dynamics and heat transfer was done by modeling a plasma torch as a conductive body having physical constants (density, heat conductivity, electrical conductivity, etc.) changing depending on temperature[7]. The behaviors and characteristics of thermal plasma have been made clearer as a result, and efficient thermal plasma heating methods have been worked out.

3.4 Microwave heating[8]

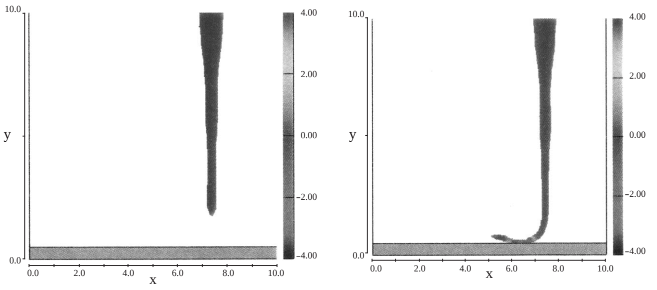
Microwave heating has been used in the steel industry for drying castable refractory. In such an application, electromagnetic wave analysis and heat transfer calculation based on the heat generation distribution of electromagnetic waves are indispensable for efficiently and adequately designing process factors such as the shapes of waveguides and applicators in accordance with the shape of the material to heat and heating conditions. In consideration of the displacement current term, which was neglected in the case of the analysis of an eddy current field (section 2), and the large size of materials to heat used in the steel industry, the FDTD method was employed for the electromagnetic wave analysis. **Fig. 10** shows the distribution of electric fields when microwaves are irradiated inside a molten steel ladle. The heat development of the refractory has been well understood thanks to the analysis, and methods of irradiation are being examined to realize an efficient heating process.

3.5 Color coating line[9)]

A color coating line is a processing line to apply a thin paint layer on a surface or surfaces of a thin steel strip, and it has to be capable of stable and homogeneous application of the paint. **Fig. 11** shows an example of numerical analysis calculation of the fluid behavior of paint when it lands on the surface of a travelling steel strip. Coating quality indices obtained using a multi-physical model analysis agreed well with the paint surface quality obtained through test coating. Here, a multi-physical model proved useful for efficiently selecting a suitable paint and an adequate operation method.

3.6 Process Control (Mold Level Control)[10)]

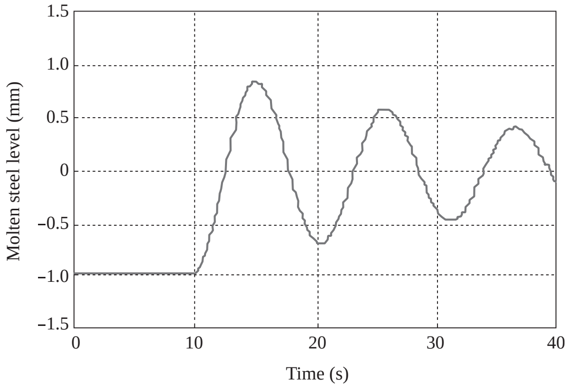
Multi-physical models can be applied also to process control. **Fig. 12** shows the multi-physical model analysis of the molten steel level in a continuous casting mold. Here, the calculation result by a distributed parameter model, which is used in multi-physical models, is compared with that by a lumped parameter model, which is used in conventional design models. It is seen in the figure that the calculation result by the distributed parameter model clearly shows small ripples that resulted from the influence of molten steel turbulence. As seen here, multi-physical models are used in the development of process control methods for analyzing detail internal conditions of a process.



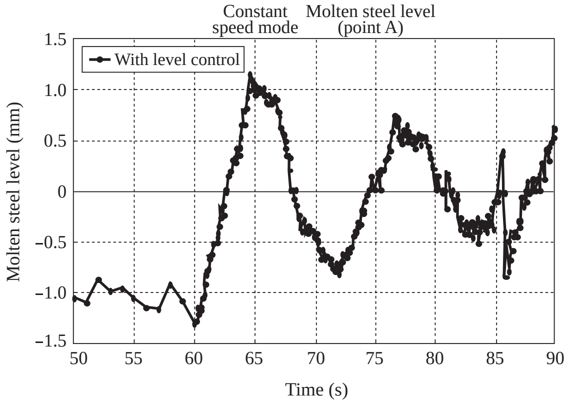
(a) t = 0.06s **(b) t = 0.07s**

(t: time after beginning of paint dropping)

Fig. 11 Paint fluidity analysis of color coating line



(a) Molten steel surface behavior calculated by conventional lumped parameter model



(b) Molten steel surface behavior calculated by distributed parameter model

Fig. 12 Example of application of multi-physical model analysis to molten steel level control

4. Closing

As described above, the electromagnetic process solutions based on multi-physical models have come to be widely practiced as the application of electromagnetic fields to steel production processes has steadily expanded.

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