Technical Report

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Performance Estimation of Molten-Iron Storage Equipment with a Magnetohydrodynamic Calculation Scheme

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Abstract

This report describes a magnetohydrodynamics calculation scheme, acquired through computation application to steelmaking processes, which is applied to a world-top-class inductor producing heated-molten-iron flows in an 'Iron Reserve Barrel' (IRB). The inductor has two staple functions: one is to heat molten iron in channels of the inductor, the other to initiate loop iron flows in the channels for heat transfer from the channels to all the molten iron. However, there is no means to observe the phenomena in the inductor directly; thus estimation of the functions is difficult. The magnetohydrodynamics calculation is an effective method for reducing the difficulty of function estimation, and its effectiveness is demonstrated in an example.

1. Introduction

The modern steelmaking industry has long been advanced by computerization, which has been developing and spreading internationally mainly in three ways—machine controlling and maintenance-monitoring in process operations, quality analysis of products, and designing machines with performance estimation—the first two are examined by other authors in this issue; the latter in this report.

Nippon Steel Corporation started application of computational design to equipment in steelmaking processes at the beginning of the 1980s; at that time, the capabilities of computers were extremely inferior to those of today, hence we could not develop models of the application in their actual stages. By minimizing the models to toy level, we were only just able to acquire the slightest essence of the equipment's performance. This century, therefore, the design and estimation of the performance has been realized by the progress of computational capability. Here we describe an example of the application to an inductor of molten-iron storage equipment.

Functional storage systems of molten iron are required for improvement of scheduling in the upstream steelmaking processes. Standardization of the systems, such as those for torpedo cars, converters, and mixers, have been introduced worldwide, and have concurrently developed for the control of material components of molten iron in their storage periods. Nippon Steel introduced a world-top-class molten-iron storage kiln, the 'Iron Reserve Barrel' (IRB), in 1998 at Yawata works. It not only has a storage function for molten iron, but also a dissolution function for steel scraps charged into it to increase its volume. The dissolution is conducted with six electromagnetic inductors on the IRB and realized with molten-iron flows using the Lorentz force of the inductors.

This report, the additionally revised paper of ours,[1] presents a scheme of the simulation for these phenomena—magnetohydrodynamics, its application to the inductors of IRB, and remarks on the simulation results and the inductors' functions.

2. Iron Reserve Barrel and Inductors

Figure 1 illustrates the construction of the IRB, into which molten iron is put through a charging mouth and stored, and steel scraps are periodically added into the molten iron through the three mouths with scrap doors. After dissolution of the scraps by induction heating, the grown-mass molten iron is poured out from a spout into a ladle, trundling its cylindrical body on four rolling guide pedestals. Its 2000-ton effective storage capacity has reduced that of torpedo cars by half.[2]

Six inductors are attached on the bottom of IRB like the legs of a beetle, and each has a complicated structure as shown in **Fig. 2** illustrating its symmetrical half region. A core with two coils intersects a steel case plugged up with refractory in which three channels

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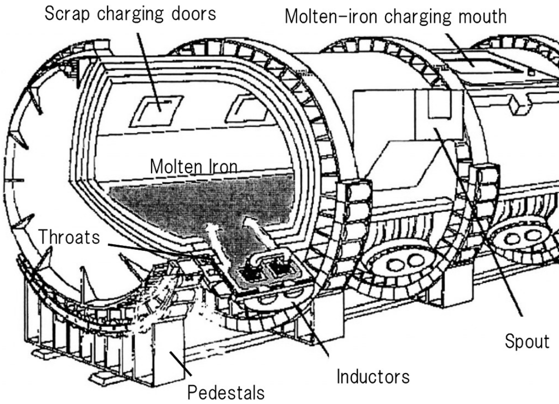

Fig. 1 Construction of Iron Reserve Barrel (IRB)

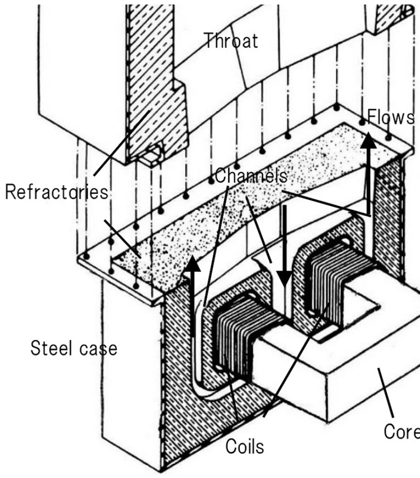

Fig. 2 Structure of an inductor

are cast: the main one in the center and thinner ones on the right and left sides respectively, connected to each other and molding loops. The inductor is attached to the body on the throat, through which the molten iron comes and goes. Each inductor makes 4.5 MW of AC power at 60 Hz, and the total power of IRB is 27 MW, the largest molten-iron storage-heating in the world to date.

Heat transformation from electric power into all the molten iron involves the following: the electric power creates eddy currents that heat the molten iron in the channels, and also generates a special distribution of the Lorentz force on the gateways of the channels; the distribution moves the molten iron into the main channel, pushes it out through the side channels, and thus gradually mixes and heats all the molten iron. The heat transfer mechanism will be described in detail later.

3. A Magnetohydrodynamic Scheme

For the functionality of IRB the inductors are vital, but phenomena stemming from them are complicated because the phenomena involve interaction of the electromagnetic, thermal, and fluid fields with each other; thus numerical approaches to the phenomena require coupled simulations of the fields. Those field calculations, however, are not directly applicable to each other and further techniques and modelling are required.

Let us, hereupon, consider the characteristics of the fields and reconcile their calculations. Electromagnetic field analysis involves not only the inductor but the air region surrounding it; on the contrary, fluid dynamics and thermal analysis handle practically only the molten iron. Those division-scale differences impede direct coupling of the field calculations.

There are two principal techniques to facilitate connecting values of the fields from the perspective of time-scale and space-scale; without the techniques the calculations would continue for the duration. One of the techniques here is an interpolating conversion between space divisions of the fields. Fluid dynamics, owing to turbulence especially around the channels, requires the largest number of divided cells. Heat transfer typically takes place with coarser division by its gradual change that differs from the others, and is fully imported in the governing equation for the molten iron. The second largest is that of electromagnetic field analysis whose division has great variation because there is a steel case, molten iron, refractory, and voluminous air in its region. The steel case has to be divided in proportion to its ferromagnetic-conductivity more than molten iron in the channels. The case itself is also inductively heated, but by the cooling system its thermal effect is negligible compared to that of the molten iron.

The other technique is time-component selection of physical quantities. Let us consider changing the rapidity of each physical field. The thermal phenomenon generally is the steadiest. The most rapid phenomenon is electromagnetic, whose field varies at 60 Hz in this application in which fluids cannot follow it due to the incomparably large inertia. All of the alternating components of the electromagnetic field can be disregarded in the motion of fluids; hence we treat only the steady components as external quantities to be imposed on the fluids. The influence of the fluid flows to the electromagnetic fields can also be disregarded for the same reason. The characteristics of the fields allow our scheme to operate in one-way from the electromagnetic fields to the fluids, and significantly reduce computation times.

In summary, first, we solve the 60 Hz-AC electromagnetic field of the inductor to acquire the Lorentz force and thermal density distributions in the molten iron; then, transfer them into the fluid equation of the molten iron as the external quantities; finally, the molten iron flows are solved by the fluid dynamics. We employ the finite element method for the electromagnetic field analysis, and the finite difference method for the fluid dynamics including thermal effects (**Fig. 3**).

4. Numerical Models of Inductor and Molten Iron

We constructed a realistic model of the inductor (**Fig. 4**) for electromagnetic analysis, which is based on its draft as shown in Fig. 2; **Fig. 5** presents an image without the steel case. In this model the throat area is not designed because the eddy currents can be disregarded in it. For fluid dynamics, our model of molten iron is shown in **Fig. 6**; a free surface is introduced, and the complex shape of the molten iron is molded by placing obstacles into the entire box area including some molten iron in the body of the barrel. The cross section of the main channel is double that of the side channels.

Under the above-described scheme, we have to select the calculation means. The governing equations are Maxwell's equation ($j\omega$ method)[3] with FEM (finite element method) and the Navier-Stokes equation with FDM (finite difference method). Nonlinearity of the magnetic permeability of the core and steel case is partly taken into account. The large eddy simulation (LES) is employed as a turbulence treatment method for the molten iron flows. We solve the models with the programs: our own codes for electromagnetic and

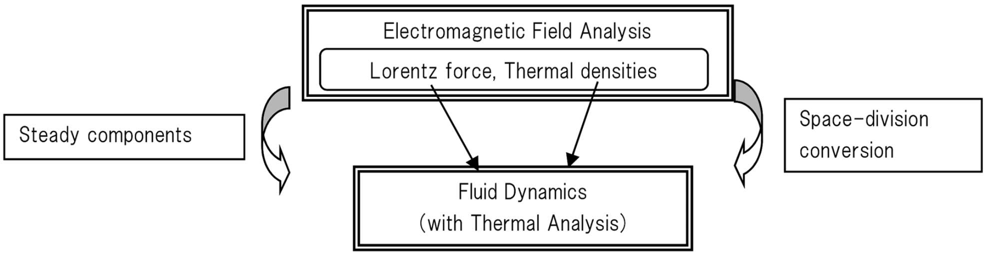

Fig. 3 Magnetohydrodynamics scheme

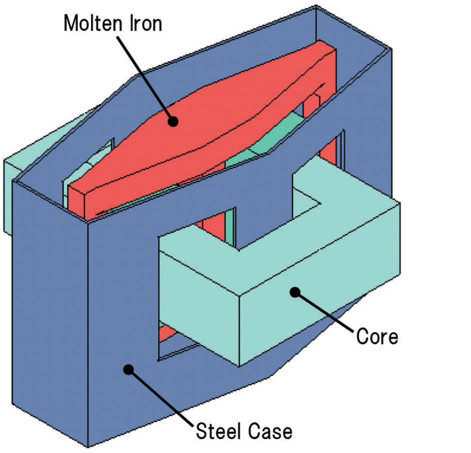

Fig. 4 Electromagnetic field analysis model of an inductor

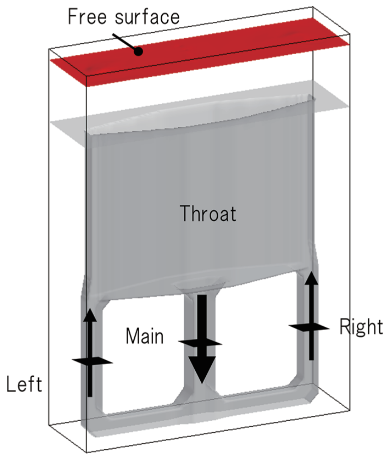

Fig. 6 Fluid dynamics model

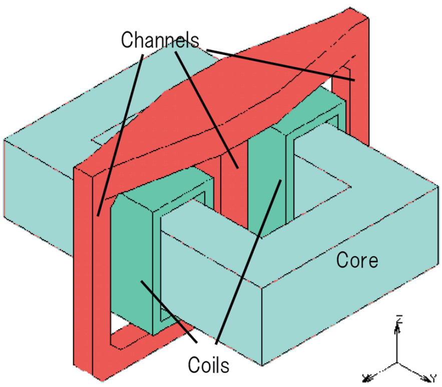

Fig. 5 Channels and an electromagnet

Table 1 Material constants of molten iron

Electric conductivity	7.22×10^{5} [S/m]
Thermal conductivity	25.1 [W/m/K]
Specific heat	837 [J/kg/K]
Density	6957 [kg/m^3]
Viscosity	4.73×10^{-3} [Pa·s]
Surface tension	1.58 [N/m]
Expansion coefficient	1.25×10^{-4} [1/K]

thermal analyses and a commercial code for fluid dynamics. We also implement the interpolating software. Material constants are summarized in **Table 1**.

5. Results and Discussions

5.1 Lorentz force distribution

Figure 7 shows bird's-eye-view graphics of the Lorentz force distribution on the channels' gateways by electromagnetic analysis. It reveals special vectors that are bigger at the gateways of side channels and smaller at the center. This gradient is caused by the rhombus configuration of the gateways and the difference of cross-sections of the channels in Fig. 5; the configuration directly varies eddy current densities, i.e. the gradient Lorentz force distribution. The very large forces at the side channels would drive the molten iron into the main channel, and therefore circulation flows in the throat would be produced.

5.2 Molten iron flow distribution and particle tracing

Two imperative results are confirmed by fluid dynamics. The first is the gradient Lorentz force produces strong flows. **Figure 8** is a flow-speed contour of the molten iron on the longitudinal section of the model at the center. The contour shows that the side flows start at the side channels' gateways, along the throat wall, reach the free surface in 11.5 s, and slightly deform it. There are many regions where their flow speeds exceed 1 m/s. The second is that the flows circulate globally, not locally. The circulation could pull up the molten iron into the channels to the body region of IRB in a short time, so that heat transfer from the channels to the body area would be realized.

Now, to confirm this in practice, we placed 1000 imaginary particles uniformly and randomly in the molten iron except the channels and conducted computations of their motion. The particles are only markers of moving fluid and do not have any material properties (the Lagrange picture), therefore the particles cannot affect the molten iron flows. **Figure 9** illustrates that after some particles

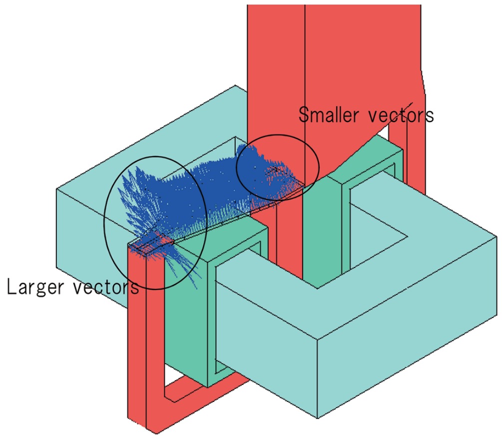

Fig. 7 Lorentz force distribution at gateways of channels

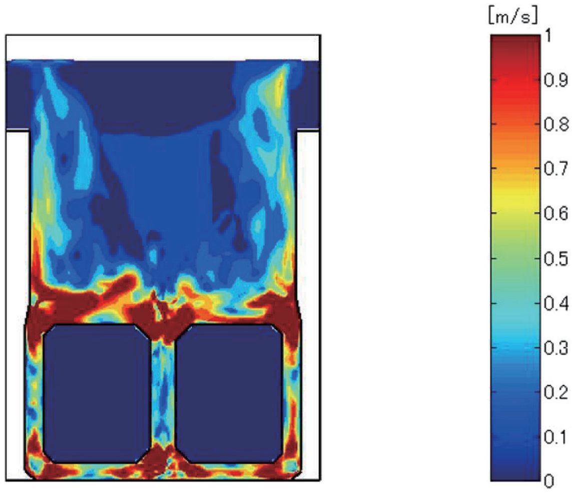

Fig. 8 Flow speed distribution on the central cross section (at 11.5 s)

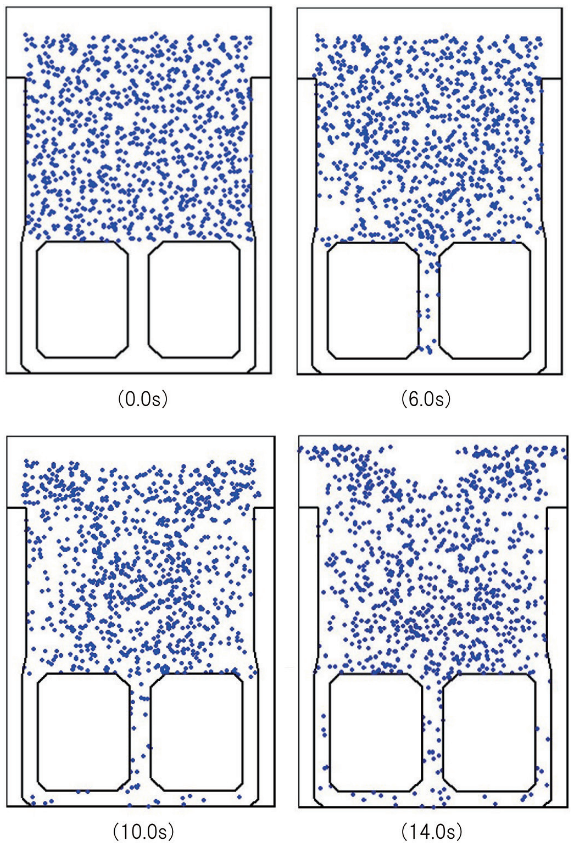

Fig. 9 Particle distribution in the molten iron

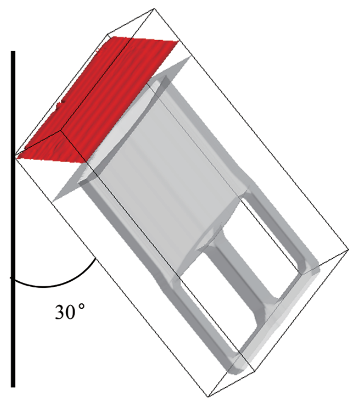

Fig. 10 Model for thermal and gravitational effects

move into the main channel (at 6.0 s), they are emitted from the side channels (at 14.0 s). It is clear that two circulations in all the molten iron occur, which means that they form a bridge between the channels and the body region on heat transfer. In this calculation, only the Lorentz force is considered.

5.3 Other effects on flows and heat transfer

Furthermore, to make the model even more realistic, gravitational and thermal factors are taken into account. **Figure 10** shows another model with the factors: incline of the inductor at 30 degrees to the vertical line, and thermal expansion of the molten iron by the eddy currents in the fluid equation. **Figure 11** indicates that the side flows arrive at the free surface in a shorter time of 9.5 s. This is because gravitation force on the circulations and loop flows becomes smaller by the body trundling and the thermal expansion of the heated molten iron levitates itself. By contrast, the particles take a longer time of 17.0 s to completely go through the channels (**Fig. 12**). These results mean that the molten iron can acquire higher speed under small gravitation; on the other hand, the levitation will hinder the loop flows, namely low heat transfer.

5.4 Transferring iron-volume

Moreover, we add anomalous conditions to the channels to examine the stability of the channel flows. We make the right channel thinner and its gateway narrower than those of the original in Fig. 6, as if a skull is stuck on the inside. **Figure 13** displays the flow distribution under the conditions: the flow speed on the right is superior to that on the left. It indicates that the superiority means an amount of molten iron through its cross-section will be conserved in total. However, that is not the case; the particle motion is unexpectedly very slow as shown in **Fig. 14**.

Thereupon, to reconsider the results from another perspective, we introduce an iron-volume transferring speed—the iron volume per second passing through each channel. The resulting values are shown in **Table 2**. The sum of the right and left thinner channels approximately equals that of the main channel in all cases, thus the loop flows conserve themselves. In addition, the values are stable under the gravitational and thermal changes. However, the thinner a channel becomes, the more inferior its value is to others. This indi-

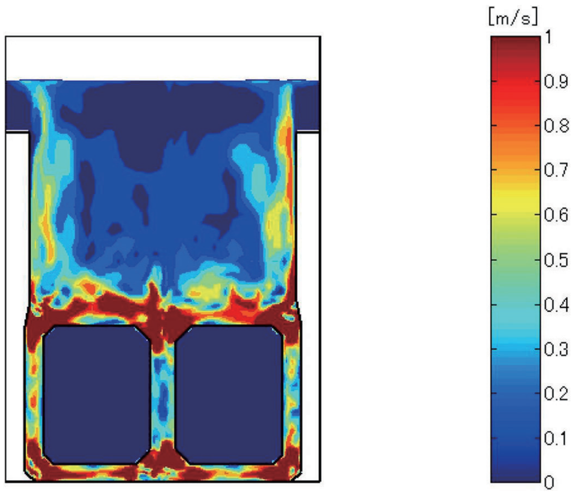

Fig. 11 Flow speed distribution on the central cross section (at 9.5 s)

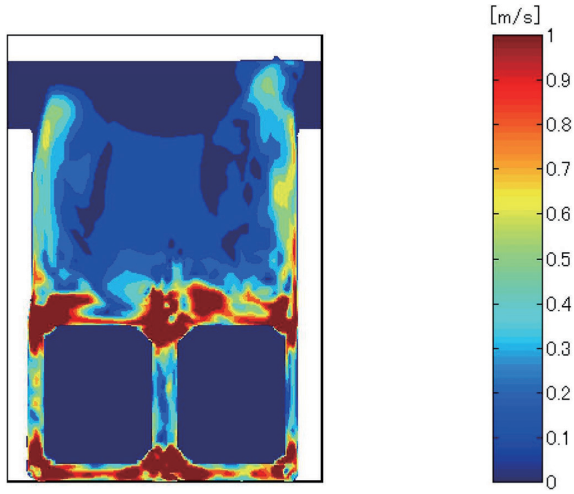

Fig. 13 Flow speed distribution on the central cross section (at 11.0 s)

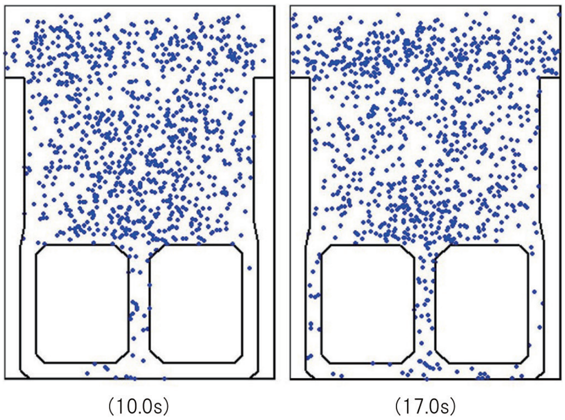

Fig. 12 Particle distribution in the molten iron

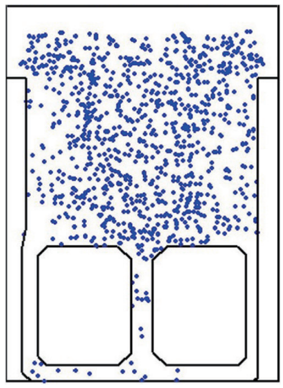

Fig. 14 Particle distribution in the molten iron (at 9.0 s)

cates that there is no direct correlation between flow speeds in the throat and iron volumes through the channels, which are separable. Due to the slow flows in the channels, the correlation can lower the efficiency of energy transformation from electric power of the inductors to molten iron heating, even when the electric power is constant. Thermal density rapidly increases, depending on the cross-sections of the channels; therefore, super-heated molten iron within the channels would attack the refractory and inflict adverse damage upon it.

We have observed steadily firm circulations (A) in the throat by the gradient Lorentz force, and it is seemingly natural that those and the channel flows (B) strongly correlate: i.e. $A \propto B$. Our results signify that the inductor steadily generates the circulations, but its connection with the channel loop flows is not always preserved, and also disclose that certain conditions could break the preservation and safety of the refractory.

6. Summary

We published a paper[1)] in 2006; with some limitations, the related results of our application were omitted in publication. Now we have revised our paper and include the new findings by reexamination in this report.

We described one of the applications in computerization for our steelmaking processes: the structures of IRB and its inductors, the mechanism of generating circulation and loop flows in the inductors. The magnetohydrodynamics scheme explained here is founded on physical philosophies and the solutions obtained through the scheme prove that the inductors have high performance to heat the molten iron, to create the loop flows in their channels, and to create a heat connection between the channels to the IRB body through the throat. The high-speed circulations have strong stability under various conditions: structural, thermal, and gravitational. These findings are helpful for stabilizing everyday operation, but when conditions of the channels change or the gravitational effect varies by the trundling of the body, a decline of its heat-transfer efficiency and damage by overheating in the refractory could occur and proceed en masse under a steady electric power supply to the inductor. This novel implication vindicates the usefulness of numerical analysis for performance estimation and state monitoring of equipment.

We have also applied this scheme and a more advanced version to continuous casting processes; for example, a national project

Table 2 Iron-volume transferring speed through each channel

[m^3/s]

Conditions	Left	Main	Right
Normal	4.28×10^{-3}	8.65×10^{-3}	4.38×10^{-3}
Thermal & gravitational	4.12	8.88	4.78
Thinner channel (right)	5.57	9.23	3.65

called 'Electromagnetic Casting: EMC'[4] with the New Energy and Industrial Technology Development Organization (NEDO), applications to electromagnetic molten-iron stirrers at a few Hz of frequency including the time-dependent components of the Lorentz forces with the effects of electromagnetic fields on molten iron flows.[5, 6] For particle tracing, though we introduced ideal types, another group realized particles of nonmetallic inclusions in a tundish.[7]

With the massive progress in more accurate computers, more varied calculations are feasible, which also enables us to not only estimate the performances of apparatuses, but also to design and ameliorate them; besides, numerical analysis is a powerful tool for troubleshooting. Even in our application of this report, the functionality of the inductor cannot be estimated by experiments alone. We consider that this report will contribute to further appreciation of the usefulness.

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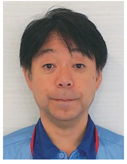

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