1. Introduction

EMBR and argon gas injection as the concerned molten steel flow-control technologies in the mold for improving the quality of continuous casting slab at high casting speed are of great helpful and significant. The flow in the mold for applying the flow-control technologies is a complex multiphase flow process, and it is almost impossible to study these multiphase flow behaviours and molten steel temperature distribution in actual continuous casting mold directly. Furthermore, it is hard to simulate these complex phenomena on the basis of water model experiment. Numerical simulation is one of the useful and practicable means for understanding the motion behaviours of molten steel, argon gas and inclusions, and temperature distribution of molten steel.

Man et al. developed a 3-D model for the flow and heat transfer with EMBR and studied the magnetic field effects on turbulent flow field and heat transfer in the mold. Takatani et al. analysed the molten steel flow and the effects of argon gas injection and EMBR on the meniscus behaviour in the continuous casting mold using a 3-D and unsteady mathematical model. Ishii et al., Yamamura et al., Harada et al. and Kubo et al. performed the numerical simulations to examine the effects of different types of magnetic fields utilized in the EMBR technique on the electromagnetic braking efficiency and also analysed the changes of molten steel flow field and inclusion distribution in the mold when the magnetic field was imposed with the argon gas bubble injection. Li et al. developed a numerical estimation to analyse the motion of inclusion considering the effects of argon gas injection and magnetic field application in the slab continuous casting mold. All their models considered the effect of EMBR by imposing a fixed value of magnetic induction intensity on the solution region directly or a changing magnetic induction intensity according to a certain type of relationship with coordinates. The treatment of the magnetic field could not keep the consistency with the practical magnetic field distribution and would make a significant effect on the accuracy of numerical calculation results, so a better method to enhance the results accuracy of the simulation was suggested.

In the effort understanding the EMBR and argon gas injection effects on the molten steel flow and temperature and
inclusion trajectories, a new code for 3-D flow simulation in the conventional slab continuous casting mold has been developed and studied the multiphase flow phenomena with the EMBR and argon gas injection on the basis of the finite element and the finite volume codes ANSYS and FLUENT in this study. The former used to calculate the magnetic induction intensity distribution produced by the EMBR device for different current intensity of coils. The latter used to calculate the coupled solution for the magnetic field, turbulence model, energy equation and discrete phase model on the basis of imposing the magnetic field data files of the mold region calculated by the former in a certain data format on the corresponding nodes of the mold geometry model through its own magneto-hydrodynamics (MHD) module. So the simulation results of the magnetic field distribution and the coupled calculation of multi-physics fields are more in line with the actual production situation and more accurate.

2. Mathematical Model

Figure 1 shows the schematics of the mold geometry model with EMBR device are used for ANSYS and FLUENT calculation respectively and the detailed geometry and simulation parameters are shown in Table 1. The following assumptions for the molten steel flow and temperature, argon gas bubbles and inclusion particles in the mold are made in this model.

(1) The molten steel flow in the mold is a steady state, incompressible and viscosity flow process. The additional magnetic field produced by the molten steel flow in the mold is ignored.

(2) The influence of the solidified shell and the oscillation of mold on the molten steel flow and temperature distribution are ignored; the heat transfer at the free surface and the inclination effect of the mold wall are ignored.

(3) The effect of coalescence and break up between bubbles and inclusion particles is not considered, the gas bubbles and inclusions are assumed to be spherical with a uniform size. Inclusions move with molten steel flow and its motion does not affect the molten steel flow field, which is treated to be removed if it floats to the free surface and to be coagulated into the solidified shell if it moves to the outlet with molten steel flow.

2.1. Electromagnetic Force Equations

The key is how to solve the current density produced by induction between the flow field and the electromagnetic field interaction process. We assume that the induced magnetic field is much less than the external imposed magnetic field for a static magnetic field, so the induced magnetic field is neglected and the approach of solving electric potential equation is applied to solve the induced current density.

The induced current density equation

\[ \tilde{j} = \sigma (\tilde{E} + (\tilde{u} \times \tilde{B}_0)) \] ..........................(1)

\[ \tilde{E} = -\nabla \phi \] ..........................(2)

The induced current satisfies the conservation law for steady state

\[ \nabla \cdot \tilde{j} = 0 \] ..........................(3)

Substituting Eq. (2) into Eq. (1) and using Eq. (3) gives the following Poisson equation

\[ \nabla^2 \phi = \nabla \cdot (\tilde{u} \times \tilde{B}_0) \] ..........................(4)

The electromagnetic force equation

\[ \tilde{F} = \tilde{j} \times \tilde{B}_0 \] ..........................(5)

2.2. Discrete Phase Model Equations

The trajectories of argon gas bubble and inclusion discrete particle in the Lagrangian discrete phase model
(DPM) are predicted by solving the force balance equation with the forces acting on the particle,\(^{(12)}\) and the equation can be written as

\[
\frac{du_p}{dt} = F_D (u - u_p) + \frac{\partial (\rho_p - \rho)}{\rho_p} + F_i \quad \text{(6)}
\]

where \( F_D (u - u_p) \) is the drag force per unit particle mass and

\[
F_D = \frac{18 \mu C_D R_e}{\rho_p d_p^2} \frac{d}{24} \quad \text{(7)}
\]

\( C_D \) represents the drag coefficient of spherical bubble/particle and is determined by the following

\[
C_D = \begin{cases} 
0.424 & \text{if } R_e > 1000 \\
\frac{24}{R_e} \left( 1 + \frac{1}{6} R_e^{2/3} \right) & \text{if } R_e \leq 1000 
\end{cases} \quad \text{(8)}
\]

\( R_e \) is the relative Reynolds number and is defined as

\[
R_e = \frac{\rho d_p |u_p - u|}{\mu} \quad \text{(9)}
\]

\( F_i \) represents the additional other forces including the virtual mass force, the pressure gradient force of liquid phase and the lorentz force acting on the particle. The concrete forms of the virtual mass force and the pressure gradient force of liquid phase are expressed in Ref. \(^{12} \), and the lorentz force acting on the particle as a “used-defined function” is applied in the “Used-Defined Functions” of MHD directly.

### 2.3. Fluid Flow Model and Energy Equations

**Continuity equation**

\[
\frac{\partial (\rho u_j)}{\partial x_j} = 0 \quad \text{(10)}
\]

**Momentum equation**

\[
\rho \frac{\partial (u_j u_i)}{\partial x_j} = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu_{\text{eff}} \frac{\partial u_i}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( \mu_{\text{eff}} \frac{\partial u_i}{\partial x_j} \right) + F_{m,j} + F_{\text{other}} \quad \text{(11)}
\]

\( F_{m,j} \) is the momentum change quantity of bubble and incorporated in the molten steel flow calculation as a momentum sink.\(^{(12)}\)

\[
F_{m,j} = \sum \left[ \frac{18 \mu C_D R_e}{\rho_p d_p^2} \frac{d}{24} (u_p - u) + F_{\text{other}} \right] m_i \text{d}t \quad \text{(12)}
\]

The standard \( k-\varepsilon \) two-equation turbulence model is used to determine the effective viscosity \( \mu_{\text{eff}} \).

**Energy conservation equation**

\[
\rho \frac{\partial (u T)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\lambda}{c_p} \frac{\partial T}{\partial x_j} \right) + S_T + Q \quad \text{(13)}
\]

### 2.4. Boundary Conditions

For three-dimensional calculation, the calculation domains are shown in Fig. 1. Only a quarter of the EMBR device and mold are analysed because of the twofold symmetry of the mold and the static magnetic field is produced by the EMBR.

For the boundary conditions of electromagnetic field calculation based on ANSYS, the boundary conditions are simple because the interfaces between regions are automatically satisfied in ANSYS. So the boundary conditions in the symmetry planes and the air surfaces need only be set with the magnetic flux parallel condition.\(^{(13)}\)

For the boundary conditions of flow fields and heat transfer based on FLUENT, the inlet of the SEN and the outlet of the mold as the velocity-inlet to have the same mass flow rate corresponding to the specified casting speed, the temperature across the inlet plane is fixed to the casting temperature\(^{(14)}\); the top surface as a free surface is assumed to be flat where the symmetry plane condition is applied, normal gradients of all variables are set to zero; the wall are set to non-slip boundary condition with zero normal velocity and the standard “wall functions” near the wall are used to capture the steep gradients with accuracy on a coarse grid.\(^{(12,15)}\) the mushy zone is not considered and a fixed temperature with equal to the liquid temperature is imposed along all the mold walls.\(^{(14)}\)

For the boundary conditions of discrete phases based on FLUENT, the bubbles and inclusion particles are assumed to “escape” at the free surface and the outlet of the mold, and to “reflect” at the walls of the mold.\(^{(12,15)}\) The initial locations of bubbles/particles are assumed to be uniformly distributed within the inlet surface and the initial velocity is the same as the inlet velocity of molten steel.

For the boundary conditions of electric potential calculation based on FLUENT, the walls of the mold are set to insulating wall boundary condition with zero normal component of current density; the normal gradient of current density to be zero at the inlet and outlet surfaces.\(^{(2,11)}\)

### 2.5. Solution Procedure

Solution process is divided into two parts. First, during the calculation procedure of electromagnetic field based on ANSYS, a magnetic vector potential method is used to solve the electromagnetic field for different current intensity of coils. Then, the data files of the magnetic induction intensity in the mold region are exported according to a certain form.

Second, all other fields are solved by FLUENT. For one thing, except the trajectories calculation of inclusion particles, all other coupled fields including flow field and temperature field of molten steel, trajectories of argon gas bubbles and magnetic field are solved as a steady state process, in which its own MHD module needs to be activated and the magnetic field data file is loaded to the flow region in mold with a certain required data format. It gets a steady state convergence solution in this section. Then, it contin-
ues to solve all coupled fields including the trajectories calculation of inclusion particles based on the steady state solution as a transient state process until the end of 60 s. The pressure-velocity coupling algorithm in steady state and transient state process is SIMPLEC and PISO algorithm respectively. The trajectories of bubbles and inclusion particles are solved using the Random Walk model of DPM,\textsuperscript{12,15} which consider the effect of turbulent fluctuation of velocity field on the turbulent diffusion effect of bubbles and particles.

3. Results and Discussion

3.1. Simulation Results Verification of Magnetic Field

The predicted and measured results of magnetic field are compared in order to verify the numerical model of magnetic field. Figure 2 shows the comparison of magnetic field at the centerline along the length direction of mold for the lower coil current of 850 A and the upper coil current of 100 A and 200 A respectively. It is found that there is a good agreement between the measured and the predicted results including the changing tendency and numerical value of magnetic field.

3.2. Magnetic Field Characteristics with EMBR

Figure 3 shows the characteristics of magnetic field at the centre symmetry planes of mold for the lower coil current of 700 A and the upper coil current of 200 A and the casting speed of 1.8 m/min. Figure 3(a) shows the strongest areas of magnetic induction intensity exist in the regions of mold with corresponding to the upper and lower magnetic poles, and the weakening areas is formed between the two strongest regions of magnetic field, which is the transition region of the magnetic induction intensity changing the direction. Figure 3(b) shows that the induced current density displays the vortex distribution. The electromagnetic force distribution as shown in Fig. 3(c), which is agreement with the flow field of molten steel as shown in Fig. 4(a) and the direction is opposite to the flow direction of molten steel, and its magnitude is proportional to the flow velocity of molten steel.

Fig. 2. Comparison between the measured and predicted for the magnetic field B.

Fig. 3. The distributions of magnetic field at the half thickness symmetry planes of the mold. (a) Magnetic induction intensity, (b) induced current density, and (c) electromagnetic force.

Fig. 4. The velocity and temperature (K) at the half thickness symmetry planes of mold. (a) Without argon gas injection and EMBR, (b) with argon gas injection, (c) with EMBR, and (d) with argon gas injection and EMBR.
3.3. Effects of the EMBR and Argon Gas Injection

Figure 4 shows flow fields and temperature distributions at the center symmetry planes and Fig. 5 shows flow fields in the horizontal sections under the free surface 20 mm of mold for different flow-control technologies respectively, and Fig. 6 shows the velocity of centreline along the mold width direction under the free surface 20 mm. It is very influential on the flow pattern when the argon gas flow rate is 6 NL/min, most of molten steel from the SEN port directly flow to upwards with the argon gas bubbles due to the buoyancy effect of gas bubbles, the eddy eye of the upper re-circulation zone disappears and the re-circulating velocity is obviously reduced as shown in Fig. 4(b) and Fig. 5(b) compared with Fig. 4(a) and Fig. 5(a), the maximum velocity at the free surface decreases from 0.26 m/s without argon gas injection to 0.13 m/s. It is obvious that the appropriate argon gas injection may also play a braking effect for the molten steel flow. Figure 4(c) and Fig. 5(c) show the case with EMBR, there is an obvious change in velocity magnitude and pattern of flow field, the flow velocity of molten steel as a whole reduced, especially near the free surface and at the meniscus, and the areas of re-circulation zones also reduced, the velocity are more smooth and the maximum velocity reduces to 0.03 m/s; it forms a small vortex flow at the free surface near the side of SEN and the vortex flow direction is opposite to the upper re-circulating flow direction; the molten steel of lower re-circulation zone do not re-circulate to a rounded loop, which turn to flow downwards after re-circulating a certain distance with the decreasing of the re-circulating momentum. Figure 4(d) and Fig. 5(d) show the case with the double action of EMBR and argon gas injection where the re-circulating velocity of upper re-circulation zone and the vortex velocity of vortex flow zone near the SEN increase evidently, and the molten steel near the free surface appear a wavy flow pattern. The maximum velocity at the free surface appears in the vortex flow zone near the SEN and increases from 0.02 m/s with EMBR to 0.12 m/s. Obviously, argon gas injection can aggravate the vortex intensity, thus the appropriate argon gas flow rate is crucial for keeping the stability of free surface and preventing the occurrence of slag entrapment.

The changes of temperature are also obvious as shown in Fig. 4. It is visible that temperature in the upper re-circulation zone increases when argon gas injected, especially near the meniscus as shown in Fig. 4(b). The superheating molten steel is moved up when EMBR applied as shown in Fig. 4(c), temperature in all re-circulation zones increases and its distribution is more uniform, temperature gradient is reduced in molten steel zone, and so the temperature gradient at the front line of solidified shell increases, it means that the freezing speed of molten steel is reduced and the heat transfer at the front line of solidified shell is improved, and it is helpful for removing the surplus superheat and reducing the superheat temperature. The temperature pattern with the double action of EMBR and argon gas injection is similar to the case of EMBR, however, it is clearly seen from Fig. 4(d) that temperature in the upper re-circulation zone is more higher than the case of EMBR, especially the temperature near the meniscus and the vortex flow zone near the nozzle is up to 1 816 K. It is in favour of improving the solidification near the meniscus and reducing the formation of slag rim and the occurrence of quality problems such as deeper oscillation marks, which later form transverse cracks of slab. Figure 7 shows the temperature contours at vertical sections distance from the narrow wall 20 mm of mold. It also indicates that the superheat region of molten steel moves up when EMBR and argon gas injec-
tion applied; temperature distribution and the change of temperature gradient along longitudinal direction near the narrow wall are smoother, it has helpful for forming a uniform thickness solidified shell.

3.4. Effects of Argon Gas Flow Rate on Flow Field with EMBR

Figure 8 and Fig. 9 show the flow fields at the center symmetry planes and in the horizontal sections under the free surface 20 mm of mold for different argon gas flow rate with EMBR. The re-circulating velocity of molten steel in the upper re-circulation zone increase with the increasing argon gas flow rate as a result of the increasing bubbles buoyancy, and lead to the vortex velocity and intensity of the vortex flow zone near the SEN becoming larger and larger; especially when the argon gas flow rate up to 8–10 NL/min, it besides forms a stronger vortex flow near the SEN side of free surface, a secondary eddy flow also appears at the middle position of free surface as a result of the molten steel with larger vortex velocity colliding with the molten steel with weakening re-circulating velocity which flow from the narrow wall of mold. The intensity of these vortex flows would directly determine the fluctuation range of free surface and the occurrence of slag entrapment. Figure 10 shows the horizontal velocity of centreline along the mold width direction under the free surface 20 mm. The maximum horizontal velocity increases from 0.06 m/s with the argon gas flow rate of 4 NL/min to 0.15 m/s with the argon gas flow rate of 10 NL/min. Obviously, the increasing argon gas flow rate would result in a larger vortex velocity at the free surface and weaken the effect of EMBR under a certain casting speed and current intensity.

3.5. Influence of EMBR and Argon Gas Injection on the Removal of Inclusions

The removal rate of inclusion particles in the mold is calculated by tracing the particle numbers floating up to the free surface that trapped into the liquid slag and moving to the outlet that trapped into the solidified shell within the time period of 60 s for different flow-control technologies. In analog calculation, inclusion particles are divided into two groups, one group is 90 particles including the particle size of 5, 10, 20, 30 and 50 μm with each size involving 18 particles and the other group also includes 90 particles with only the particle size of 150 μm. The initial position of all inclusions is at the inlet area uniformly when starting to trace the inclusions. The removal rates of each group inclusion particles in the steady state flow field of molten steel within a period of 60 s for four cases are observed and the statistical results are shown in Fig. 11. In the Figure, the floated out numbers namely is the removal numbers of particles, the exited domain numbers namely is the trapped numbers of particles by solidified shell, and the inclusion particles remaining in the mold domain are possible to float up sequentially and also possible to be coagulated into the solidified shell with molten steel. The following analysis results are obtained.

(1) When without EMBR and argon gas injection, the floating up rate for small inclusions with the size of 5–50 μm and relative big inclusions with the size of 150 μm is 6.7% and 14.4% respectively. The rate to be trapped into solidified shell for small inclusions and big inclusions is 70% and 58.9%.

(2) When with argon gas injection, the floating up rate for inclusions with the size of 5–50 μm and the size of 150 μm is 8.9% and 27.8% respectively. In the same way, the rate to be trapped into solidified shell for small inclusion...
sions and big inclusions is 65.6% and 42.2%.

(3) When with EMBR, the floating up rate for inclusions with the size of 5–50 μm and the size of 150 μm is 3.3% and 27.8% respectively. Similarly, the rate to be trapped into solidified shell for small inclusions and big inclusions is 76.7% and 45.6%.

(4) When with EMBR and argon gas injection, the floating up rate for inclusions with the size of 5–50 μm and the size of 150 μm is 12.2% and 22.2% respectively, and the rate to be trapped into solidified shell for small inclusions and big inclusions is 64.4% and 38.9%.

The above statistical results show that argon gas injection can increase the floating up rate of inclusions, mainly because the buoyancy effect of gas bubbles lead to the upper re-circulating molten steel move to upwards and inclusion particles also move to upwards with molten steel. EMBR has no helpful for the removal of small inclusions, because the majority of molten steel in the upper re-circulation zone have not yet arrive at the free surface and already begin to form re-circulating loop, and the direction of re-circulating velocity is relative horizontal so much as flow downwards; the molten steel of lower re-circulation zone has not form a rounded loop, which turn to flow downwards after re-circulating a certain distance (e.g. Fig. 4(c)), and in addition, the specific surface area of small inclusion particle is bigger than that of large inclusion particle, thus the small inclusions are difficult to float up; on the contrary, the buoyancy of large inclusion particle can resist the drag motion effect of molten steel flow velocity completely because of the smaller specific surface area of large inclusion particle, and so the large inclusions remove to the free surface more easily than small inclusions. The removal rate of small inclusions can be improved obviously under the double action of EMBR and argon gas injection.

The trajectories of argon gas bubbles as shown in Fig. 12. More gas bubbles from the SEN directly flow to upwards near the SEN when EMBR applied, and lead to the larger buoyancy acting on the molten steel of upper re-circulation zone, so the argon gas injection increases the upward movement tendency of molten steel in the upper re-circulation zone with EMBR, which results in the molten steel to move up and forms a wavy flow pattern at the free surface (e.g. Fig. 4(d)), although it has no helpful for stabilizing the fluctuation of free surface, but is actually in favour of inclusions floating up to the free surface and to be trapped by liquid slag easily. Figure 13 shows the trajectories of 90 inclusion particles in diameter of 150 μm in the mold. (a) Without argon gas injection and EMBR, (b) with argon gas injection, (c) with EMBR, and (d) with argon gas injection and EMBR.
molten steel in the mold (e.g. Fig. 4(a)). The particles from the SEN impinge on the narrow wall along with the mainstream of molten steel and are divided into two directions, one part moves to the upper re-circulation zone and the other part flow into the lower re-circulation zone. The case of argon gas injection applied as shown in Fig. 13(b), it is very obvious that more particles enter the upper re-circulation zone and these particle trajectories are more turbulent, and relative fewer particles flow into the lower re-circulation zone. Thus, the particle numbers exited the mold domain are more than the case without argon gas injection. The cases of EMBR and argon gas injection are shown in Figs. 13(c) and 13(d). The particle trajectories for two cases are very similar, most particles move into the upper re-circulation zone and these particle trajectories are more turbulent, especially in the latter case. The results of particle trajectories for four cases are in agreement with the statistical results (diameter 150 μm) as shown in Fig. 11.

4. Conclusions

Three dimensional finite-element and finite-volume based numerical simulations for the multiphase flow phenomena in a slab continuous casting mold have been developed and modelled the cases of EMBR and argon gas injection applied. The following conclusions are summarized.

(1) The characteristics of magnetic field distribution with EMBR are predicted by numerical simulation, and the reliability of the numerical model for magnetic field is tested with the measured magnetic field data. Reasonable agreement between the predicted and measured results is observed.

(2) When argon gas injection applied, the eddy eye of the upper re-circulation zone disappears and temperature of molten steel increases in the upper re-circulation zone; when EMBR applied, the area of re-circulation zones and the re-circulating velocity of molten steel are reduced obviously, temperature distribution is more uniform; when the double action of EMBR and argon gas injection, the upper re-circulating molten steel increase the upward movement tendency and a wavy flow pattern at the free surface formed, temperature near the meniscus also increases obviously.

(3) The removal of inclusions is affected as a result of the changed flow field for different flow-control technologies. Argon gas injection can improve the removal rate of inclusion particles; EMBR has no helpful for the floating up of small inclusion particles; the floating up rate of small inclusions is up to 12.2% when the double action of EMBR and argon gas injection.

(4) Under a certain condition of casting speed and EMBR, the increasing argon gas flow rate results in the increasing re-circulating flow velocity of molten steel in the upper re-circulation zone obviously, and produces the stronger vortex flow near the free surface and also easily appears a secondary eddy flow; it would directly weaken the EMBR effect and cause them not compatible with each other.

Acknowledgements

The authors wish to express thanks to the National Natural Science Foundation of China and Bao Steel Co. and Program for New Century Excellent Talents in University, Ministry of Education for supporting this research project, Project No. 50674020 and No. NCET-04-0285, and are grateful to Northeastern University (Shenyang, China) for providing the comfortable work environment.

Nomenclature

\[ B_0 : \] Magnetic induction intensity (T)  
\[ j : \] Induced current density (A/m²)  
\[ \phi : \] Electric potential (V)  
\[ \sigma : \] Electrical conductivity (Ω⁻¹ m⁻¹)  
\[ F : \] Electric field intensity (V/m)  
\[ F_{\text{mag}} (F) : \] Electromagnetic force (N/m³)  
\[ \mu_{\text{eff}} : \] Effective viscosity (kg·s⁻¹ m⁻²)  
\[ \mu : \] Kinetic viscosity (kg/m·s)  
\[ \mu_t : \] Turbulent viscosity (kg·s⁻¹ m⁻²)  
\[ p : \] Pressure (N/m²)  
\[ u, u_p, u_i : \] Molten steel velocity (m/s)  
\[ u_p : \] Bubble/particle velocity (m/s)  
\[ g : \] Gravitational acceleration (m/s²)  
\[ F_i : \] Additional other force (N/m³)  
\[ C_D : \] Drag coefficient  
\[ R_e : \] Relative Reynolds number  
\[ \rho : \] Molten steel density (kg/m³)  
\[ \rho_p : \] Bubble/particle density (kg/m³)  
\[ d_p : \] Bubble/particle diameter (m)  
\[ F_p : \] Momentum sink (N/m³)  
\[ m_p : \] Mass flow rate of bubble/particle (kg/s)  
\[ \Delta t : \] Time step (s)  
\[ F_{\text{other}} : \] Other interaction forces  
\[ T : \] Temperature (K)  
\[ S_i : \] Viscous dissipation (W/m³)  
\[ \lambda : \] Thermal conductivity (W/m·s)  
\[ c_p : \] Specific heat (J/kg °C)  
\[ Q : \] Joule heating rate (W/m³)

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