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Tao Wang, En-Gang Wang, Yves Delannoy, Yves Fautrelle, Olga Budenkova. Effect of vertical electromagnetic stirring on solute distribution in billet continuous casting process. *Journal of Iron and Steel Research International*, 2022, 29 (1), pp.132-143. 10.1007/s42243-021-00685-0 . hal-03738777

HAL Id: hal-03738777

<https://hal.science/hal-03738777>

Submitted on 26 Jul 2022

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1 **Effect of vertical electromagnetic stirring on solute distribution in**
2 **billet continuous casting process**

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17 **ABSTRACT:** A volume averaged **columnar** solidification model, which couples the flow,
18 temperature and solute concentration fields, is applied to simulate experimental casting cases with
19 and without vertical electromagnetic stirring (V-EMS). The calculated distribution of
20 electromagnetic intensity and final macrosegregation maps are consistent with the experimental
21 results. Calculation results reveal that the V-EMS promotes longitudinal melt flow, accelerates
22 heat dissipation, shortens the solidification end and reduces the central segregation of carbon.
23 However, when V-EMS is applied, the solute distribution becomes asymmetric because the melt
24 flow shows opposite directions between the near and far sides from stirrer. An obvious positive
25 segregation band is observed at about 1/4 width of the billet near the stirrer in both calculated and
26 experimental results. The position and degree of such positive segregation could be affected by
27 installation height of stirrer, as demonstrated by additional simulation cases.
28
29 **KEY WORDS:** vertical electromagnetic stirring; macrosegregation; volume averaged method;
30 continuous casting

31 **Declarations**

32 **Funding**

33 The authors gratefully acknowledge financial support from the National Nature Science
34 Foundation of China (Grant No. U1760206), the National Key R&D Program of China (Grant No.
35 2017YFE0107900), the 111 Project 2.0 of China, No. BP0719037). The SIMAP laboratory
36 acknowledges the financial support provided by the ESA-MAP MICAST project contract
37 14347/01/NL/SH.

38 **Availability of data and material**

39 The datasets used or analysed during the current study are available from the corresponding
40 author on reasonable request.

41 **Code availability**

42 Not applicable.

43 **Author Contributions: Conceptualization**

44 Conceptualization, E.W.; literature search, O.B. and T.W.; development of numerical code,
45 T.W., O.B. and Y.D.; calculation and production of figures, T.W.; data analysis, E.W., Y.D., and
46 O.B.; mathematical description, Y.F.; original draft preparation, T.W. All authors have read and
47 agreed to the published version of the manuscript.

48 **Ethics approval**

49 Not applicable.

50 **Consent to participate**

51 Not applicable.

52 **Consent for publication**

53 Not applicable

54

55 **Article Highlights**

56 Predicted macrosegregation map of continuous casting billet correlates well with experimental
57 results.

58 Vertical electromagnetic stirring promotes longitudinal melt flow and reduces central
59 segregation.

60 Installation height of electromagnetic stirrer affects the shape of positive segregation band.

61

62 **1 Introduction**

63 Electromagnetic stirring (EMS) is often applied during solidification to homogenize the
64 solidification structure and to limit the extent of macrosegregation and a proper application of EMS
65 can help improving the quality of continuous cast product^[1-4]. There exist various types of EMS,
66 among which rotational electromagnetic stirring (R-EMS) and linear electromagnetic stirring (L-
67 EMS) are most commonly applied in continuous casting processes. In general, R-EMS is used in
68 round or bloom caster^[5] while L-EMS is often used at wide face of slab caster^[6]. A R-EMS always
69 generates electromagnetic force which act in the plane perpendicular to the casting direction while
70 for L-EMS, the direction of generated electromagnetic force depends on the arrangement of
71 magnetic poles. Particularly, if the poles of L-EMS are arranged along casting direction, axially
72 moving magnetic flux will be imposed on melt in or against the casting direction. Such type of EMS
73 in vertical continuous casting is called V-EMS^[7,8]. Depending on casting configuration, the fluid
74 flow may strongly depend on the direction of the electromagnetic force, consequently, solidification
75 process can be also affected in various ways^[9]. In principle, the R-EMS generates peripheral flow
76 in stirring region while the V-EMS generates longitudinal flow, and combination of R-EMS and L-
77 EMS can produce spiral flow of melt^[10-11]. Many theoretical and experimental investigations have
78 been made regarding the effect of R-EMS or L-EMS in continuous casting process^[6,12-15]. However,
79 multiple industrial examples demonstrate that effect of the EMS depends on actual configuration of
80 the casting process and that of the stirrer, as well as on the positioning of the latter^[16,17]. In order to
81 have an in-depth understanding of the mechanism how V-EMS affects solidification during
82 continuous casting process, recently a series of experiments with casting of high carbon bearing
83 steel were carried out by Xu et al.^[7,8]. In those works, the effect of V-EMS on microstructure and
84 macrosegregation of cast products has been presented in detail. However, due to constraints, usual
85 for industrial process in harsh, in-situ observation was not realised, and only post-mortem analysis
86 was made for samples from casts, which provides information only about the final state of
87 solidification. Therefore, numerical simulation is indispensable for having clearer and
88 comprehensive understanding on such topic.

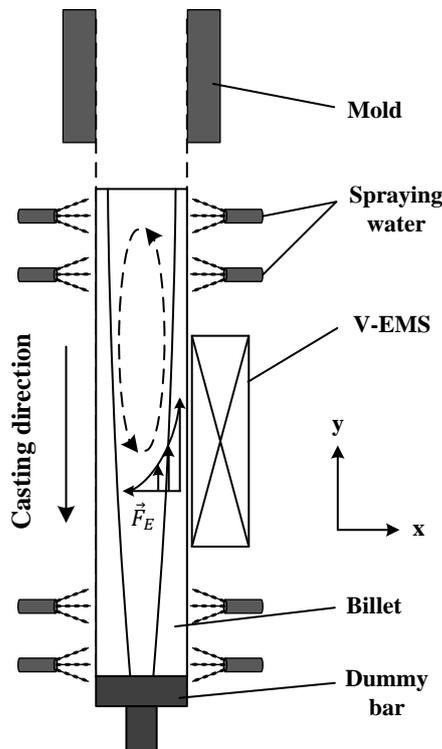
89 Numerically, the effect of the EMS on the flow in bloom caster was analyzed by Dubke^[17], but
90 without considering the solidification. Barman et al.^[15] simulated the solidification of aluminum
91 alloy ingot under EMS by coupling the heat transfer, fluid flow, solute transport, and multiphase
92 evolution. However, in that research, segregation of elements during solidification was estimated
93 simply by Scheil equation. It can be assumed that a more detailed description of grain growth can
94 provide more information regarding formation and development of macrosegregation. The up do
95 date solution is to apply the volume averaged method, which introduces a representative elementary
96 volume to embed the microscopic phenomena into a larger macroscopic system. Since first proposed
97 by Rappaz et al.^[18] and Beckermann et al.^[19], this modeling method has been developed quickly
98 during past decades^[20]. Compared with continuum media model or porous media model, volume
99 averaged model introduces the growth kinetics through its averaging process over microscale

100 structure and transport phenomena. Compared with cellular automaton method^[21], phase field
 101 method^[22] or recently proposed needle network model^[23], volume averaged model demands less
 102 dense calculation mesh i.e. consumes less computational resources. Based on volume averaged
 103 method, simulations for ingot solidification have been carried out to investigate the mechanism of
 104 macrosegregation formation^[24-25] and the effect of electromagnetic stirring^[26]. Recently, such class
 105 of models were introduced to the computer simulation of continuous casting processes^[27-29].

106 In the current work, the solidification process of casting experiment is simulated using a
 107 volume averaged solidification model. Simulation is conducted in the 2D vertical central symmetric
 108 plane of a small billet. The interaction between the fluid flow and the grain growth, as well as the
 109 formation of the macrosegregation are investigated in detail. The characteristic of V-EMS and its
 110 role in a casting process is revealed through the comparison between cases with and without V-
 111 EMS.

112 2 Experiment introduction

113 The continuous casting experiment to be simulated was made in EPM laboratory of
 114 Northeastern University^[7,8]. The experimental system concerns apparatuses including mold,
 115 electromagnetic stirrer, water spraying system and dummy bar. Simulation is made in 2D in xy-
 116 plane, as schematically presented in Fig. 1.



117
 118 **Fig. 1** Schematic representation of the continuous casting system

119
 120 Before the continuous casting started, the weighted GCr15 (liquidus temperature: 1726 K) ingot
 121 was melted in an induction furnace and held with the overheat of 40 K for 2 hours. Then the molten

122 steel was poured into the mold and pulled down due to the displacement of the dummy bar with
 123 constant velocity of 0.6 m/min. The molten steel firstly formed a shell due to strong cooling in the
 124 mold, and then the shell with inside melt was cooled down from surface by spraying water during
 125 the following section with height of 1.25 m. An electromagnetic stirrer was set at 0.4 m below the
 126 end of mold, which generated the Lorentz force pointing upwards in billet in the spraying water
 127 cooling region. After that, the billet with length of about 0.6 m was pulled out of spraying water
 128 region and finished its solidification in air. Related experimental parameters are summarized in
 129 Table 1.

130 **Table 1** Process parameters of continuous casting experiment

Parameters, units	Values
Cross sectional size, m	0.1×0.1
Mold cooling length, m	0.4
Spraying water cooling length, m	1.25
Cooling water flux, m ³ /h	3.4
Cooling water temperature, K	300
Cast speed, m/min	0.6
Superheat, K	20
V-EMS electric current/frequency, A/Hz	250/12

131 3 Model description

132 3.1 Basic assumptions

133 A two-phase **columnar** solidification model was established coupling electromagnetism, fluid
 134 flow, heat and solute transport with the following assumptions:

135 (1) The two phases in the model are the liquid melt (*l*- phase) and the columnar dendrite trunks
 136 (*s*- phase) that gives for the corresponding fractions: $f_l + f_s = 1$. Solid phase always attaches to
 137 the boundary walls and grows from casting surface into the center of melt.

138 (2) Permeability of *s*- phase is calculated according to the Kozeny-Carman equation^[30] that
 139 assumes solid phase as porous media.

140 (3) Considering that the carbon is the main concern element in high carbon steel solidification,
 141 the equilibrium solute concentration is calculated upon binary Fe-C phase diagram. Model
 142 neglects the segregation behaviors of Si, P, Mn which should be similar to that of solute element C
 143 according to Choudhary and Gauguly^[31].

144 (4) The oscillation of mold and the nozzle structure are neglected. The hot metal was assumed
 145 to be poured into the mold slowly with a constant rate.

146 (5) Both liquid and solid phases have same mass density in conservation equations. For the
 147 buoyancy force calculation, Boussinesq equation^[32] is used, i.e. the liquid density is linearly
 148 dependent on temperature and solute concentration.

149

150 3.2 Governing equations of solidification model

151 3.2.1 Mass transfer

152 The mass conservation equations for liquid and solid phases are expressed as follows:

$$\frac{\partial(f_l \rho_l)}{\partial t} + \nabla(f_l \rho_l \vec{u}_l) = -M_{ls} \quad (1)$$

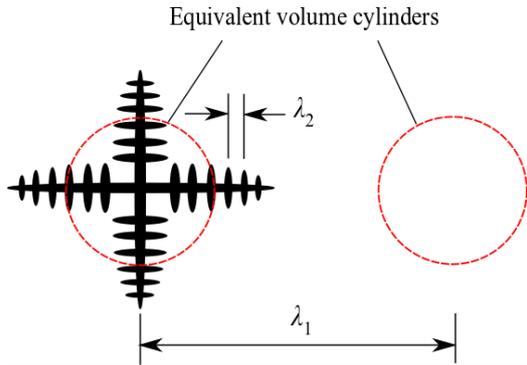
$$\frac{\partial(f_s \rho_s)}{\partial t} + \nabla(f_s \rho_s \vec{u}_s) = M_{ls} \quad (2)$$

153 where $M_{ls} = f_l \cdot \rho_l \cdot S_i^M \cdot v_i$ is mass transfer rate from liquid phase to solid phase. The dendritic
 154 trunks are assumed as cylinders (Fig. 2) and the interface movement is driven by diffusion of the
 155 solute in the interdendritic liquid. Therefore, the surface area concentration S_i^M and the lateral
 156 growth velocity of the columnar trunks v_i can be obtained by^[33]:

$$S_i^M = \frac{2d_c \pi}{\sqrt{3}\lambda_1^2} \quad (3)$$

$$v_i = \frac{2D_l}{d_c} \cdot \frac{c_l^* - c_l}{c_l^* - c_s^*} \left[\ln \left(\frac{2\lambda_1}{\sqrt{3}d_c} \right) \right]^{-1} \quad (4)$$

157 where $d_c = \lambda_1 \cdot \sqrt{12f_s/\pi}$ is the diameter of columnar trunks; λ_1 is primary arm spacing,
 158 interface concentration is given according to thermodynamic equilibrium: $c_l^* = c_s^*/k = (T_l -$
 159 $T_0)/m$, k is partition coefficient.



160

161 **Fig. 2** Schematic of the cross-section of growing columnar trunks

162 3.2.2 Multiphase flow

163 Momentum conservation for liquid phase can be described through Navier-Stokes equation.

$$\frac{\partial(f_l \rho_l \bar{u}_l)}{\partial t} + \nabla(f_l \rho_l \bar{u}_l \bar{u}_l) = -f_l \nabla p + \nabla[(\mu_l + \mu_{t,m})f_l(\nabla \bar{u}_l + (\nabla \bar{u}_l)^T)] \quad (5)$$

$$- \bar{u}_l M_{ls} + \vec{F}_{Bl} + \vec{U}_{sl}^D + f_l \vec{F}_E$$

164 where $\mu_{t,m}$ is turbulent viscosity calculated with a mixture realizable $k - \varepsilon$ turbulent model^[34]
 165 Eqs. (6-7) give expressions for the thermo-solutal buoyancy force \vec{F}_{Bl} as well as the drag force
 166 from solid dendrites \vec{U}_{sl}^D that is calculated by Kozeny-Carman equation. The calculation for
 167 electromagnetic force \vec{F}_E is detailed in section 3.3.

$$\vec{F}_{Bl} = f_l \rho_l \vec{g} [\beta_T (T_l^{ref} - T_l) + \beta_C (c_l^{ref} - c_l)] \quad (6)$$

$$\vec{U}_{sl}^D = \frac{20\pi^2 \mu_l f_s^2}{f_l \lambda_2^2} \quad (7)$$

168 3.2.3 Solute transport

169 Average solute concentration for each phase can be calculated through the following equations:

$$\frac{\partial(f_l \rho_l c_l)}{\partial t} + \nabla(f_l \rho_l \bar{u}_l c_l) = \nabla(D_l f_l \nabla c_l) - k c_l^* M_{ls} \quad (8)$$

$$\frac{\partial(f_s \rho_s c_s)}{\partial t} + \nabla(f_s \rho_s \bar{u}_s c_s) = k \cdot c_l^* \cdot M_{ls} \quad (9)$$

170 where D_l is the diffusion coefficient and can be expressed as $D_l(T) = D_0 \exp(-Q/(RT))$ ^[12].

171 3.2.4 Enthalpy conservation

172 The energy conservation is treated in two-phase form, implying that the temperatures of solid
 173 and liquid phases are solved separately. They can be expressed with the following equations:

$$\frac{\partial(f_l \rho_l h_l)}{\partial t} + \nabla(f_l \rho_l \bar{u}_l h_l) = \nabla(k_l f_l \nabla T) + L M_{ls} f_l + H^* (T_s - T_l) \quad (10)$$

$$\frac{\partial(f_s \rho_s h_s)}{\partial t} + \nabla(f_s \rho_s \bar{u}_s h_s) = \nabla(k_s f_s \nabla T) + L M_{ls} f_s + H^* (T_l - T_s) \quad (11)$$

174 where $h_l = \int_{T_{ref}}^{T_l} c_p^l dT + h_l^{ref}$; $h_s = \int_{T_{ref}}^{T_s} c_p^s dT + h_s^{ref}$; $H^* = 10^9$ W/(m²K) is an “infinite”
 175 volumetric heat exchange rate between two phases.

176 3.3 Electromagnetic force

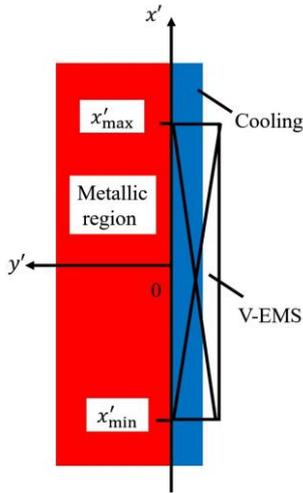
177 Solution for the electromagnetic problem can be obtained for the system shown in Fig.3, where
 178 the electromagnetic field generated by the inductor penetrates the metallic region. For the
 179 subsequent equations the y' -direction points into the metallic medium with the origin $y' = 0$ at its
 180 surface. Based on Maxwell equations, the analytical solution for time averaged electromagnetic
 181 force \vec{F}_E is given as^[35]:

$$F_{Ex'} = \delta(x') \frac{\sigma\omega}{2k} B_0^2 e^{-2y' \sqrt{\frac{k^2}{2} + \frac{1}{2}\sqrt{k^4 + \sigma^2\mu^2\omega^2}}} \quad (12)$$

$$F_{Ey'} = \delta(x') \frac{\sigma\omega}{2k^2} B_0^2 \sqrt{-\frac{k^2}{2} + \frac{1}{2}\sqrt{k^4 + \sigma^2\mu^2\omega^2}} e^{-2y' \sqrt{\frac{k^2}{2} + \frac{1}{2}\sqrt{k^4 + \sigma^2\mu^2\omega^2}}} \quad (13)$$

182 where $i = \sqrt{-1}$ is imaginary unit; σ is electric conductivity; μ is magnetic permeability; $\omega =$
 183 $2\pi f_0$ is the angular velocity of current; $k = \pi/\tau$ is the wave number and $\tau = 0.15$ m is the pole
 184 pitch; B_0 is the amplitude of \vec{B} at $y' = 0$. $\delta(x')$ represents the distribution interval of
 185 electromagnetic field.

$$\delta(x') = \begin{cases} 1 & \text{if } x'_{\min} < x' < x'_{\max} \\ 0 & \text{else} \end{cases} \quad (14)$$



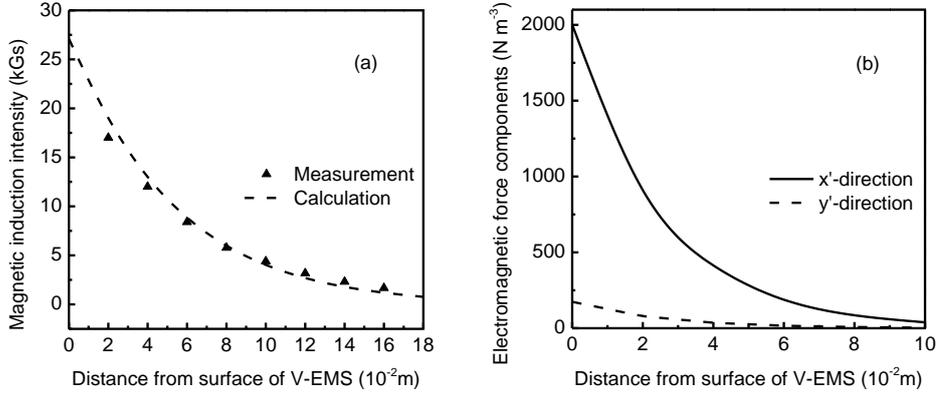
186
 187 **Fig. 3** Coordinate system for calculation of electromagnetic field

188
 189 **It should be noted that the expression of the electromagnetic forces neglected the presence of**
 190 **the mold wall and the end effects in the frame of a heuristic model.** In order to verify the calculation
 191 results, distribution of magnetic induction intensity B_{eff} is compared with the values measured in
 192 space without the metal charge using Lake Shore-475 Gauss meter counter.

$$B_{eff} = \frac{B_0 e^{-ky'}}{\sqrt{2}} \quad (15)$$

193 As shown in Fig. 4(a), the calculated distribution of B_{eff} agrees well with measured values
 194 obtained under the offline state. Both calculation and measurements show that the magnetic
 195 induction intensity decreases exponentially from the surface to the geometry center of the setup.
 196 The maximum value of B_{eff} (0.32 kGs) appears at the place nearest to the V-EMS surface, then it
 197 decreases to 0.12 kGs at about 0.06 m from surface of V-EMS. Distribution of calculated
 198 electromagnetic force at different directions are presented in Fig. 4(b). Results show that the

199 electromagnetic force in y -direction is much smaller than that in x -direction, in other words, the
 200 EMS mainly acts along the vertical direction.



201

202 **Fig. 4** Calculated and measured distribution of electromagnetic induction intensity (a) and
 203 calculated time averaged distribution of electromagnetic force components (b)

204 3.4 Boundary condition

205 During the solidification of continuous casting, the heat transfer process comprises of the
 206 mold cooling, secondary cooling and air cooling, all of which can be described by effective heat
 207 transfer coefficients. In copper mold cooling zone, the heat transfer rate from the billet is less
 208 intense at lower region because of the widening of air gap between mold and billet induced by
 209 solidification shrinkage. The heat transfer coefficient in the mold h_m is calculated according to
 210 Yamazaki et al.^[36]

$$h_m = 1256 e^{1.31z/(60v)} \text{ W}/(\text{m}^2\text{K}) \quad (16)$$

211 where z is the distance from the top of the mold, and v is casting speed.

212 In the secondary cooling zone, the heat is extracted from the billet surface by spraying water.
 213 According to Nozaki et al.^[37], the heat transfer coefficient h_w can be expressed as:

$$h_w = \frac{1570W^{0.55}(1 - 0.0075T_w)}{\beta} \text{ W}/(\text{m}^2\text{K}) \quad (17)$$

214 where W is spraying water density, T_w is the cooling water temperature, and β is an empirical
 215 coefficient.

216 In the air cooling zone, the heat radiated from strand surface is calculated by the Stefan–
 217 Boltzmann law, correspondingly, the heat transfer coefficient h_{rad} is written as:

$$h_{rad} = \sigma\varepsilon(T_{surf}^2 + T_{amb}^2)(T_{surf} + T_{amb}) \text{ W}/(\text{m}^2\text{K}) \quad (18)$$

218 where σ is Stefan–Boltzmann constant, ε is steel emissivity, T_{surf} and T_{amb} are the strand
 219 surface temperature and the ambient temperature respectively.

220 The whole model employs two different time steps. Microscale evolution, including the grain
 221 growth and solute transport between phases, is calculated with a smaller step size. Macroscale
 222 physical fields, like multiphase flow, transport of energy, solute and nuclei density, are solved by
 223 ANSYS FLUENT® software with a larger step size. The physical properties used in the numerical
 224 simulation are collected in Table 2.

225 **Table 2.** Material properties

Parameters	Value
Density, kg m ⁻³	7200
Electric conductivity, A V ⁻¹ m ⁻¹	7.14 × 10 ⁵
Latent heat, J kg ⁻¹	2.72 × 10 ⁵
Viscosity kg m ⁻¹ s ⁻¹	0.006
Thermal conductivity of solid, W m ⁻¹ K ⁻¹	26
Thermal conductivity of liquid, W m ⁻¹ K ⁻¹	39
Specific heat, J Kg ⁻¹ K ⁻¹	725
Emissivity	1
Primary arm spacing, μm	50
Secondary arm spacing, μm	20
magnetic permeability, V s A ⁻¹ m ⁻¹	1.2566 × 10 ⁻⁶

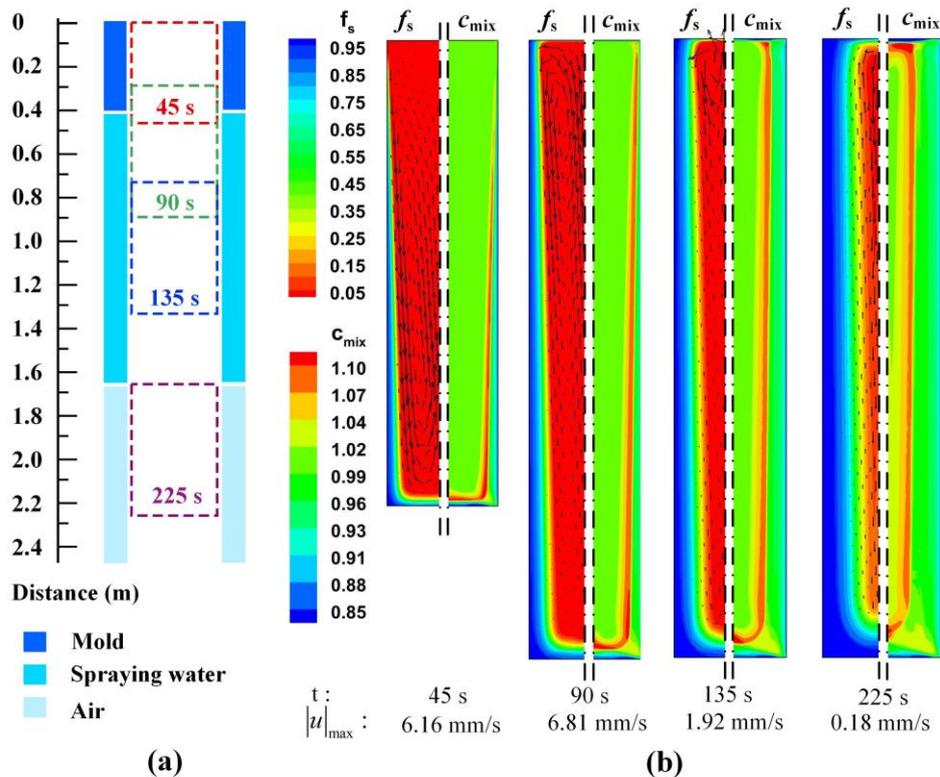
226 **4 Results and discussion**

227 Below, the simulations that are made for casting cases with and without EMS are presented in
 228 the section 4.1 and 4.2, respectively. Then, to demonstrate the effect of V-EMS on the solidification,
 229 a detailed comparison of the obtained results is presented in the section 4.3. In section 4.4 effect of
 230 the stirrer position and size on macrosegregation is considered through numerical simulations.

231 **4.1 Solidification Process without V-EMS**

232 During vertical continuous casting process, the billet experiences three distinguished cooling
 233 stages, which happen in mold, spraying water zone, and air cooling zone, respectively. The
 234 evolution of flow field, phase distribution and solute distribution are presented with snapshots at
 235 four representative times (45 s, 90 s, 135 s, 225 s). The schematic of the position of billet is provided
 236 in Fig. 5(a) where the dark blue color represents the strong cooling condition in the mold, the light
 237 blue color represents the water spray cooling zone, and the even lighter color represents the air
 238 cooling zone. Calculated results are presented in Fig. 5(b) with indication of time. Due to the
 239 symmetrical nature of the billet, only half of each physical field is given. The left half division is
 240 the solid phase fraction overlaid with liquid flow velocity vectors, while the right half shows the
 241 distribution of averaged mixture concentration: $c_{mix} = (f_l \rho_l c_l + f_s \rho_s c_s) / (f_l \rho_l + f_s \rho_s)$. It should
 242 be noted that the velocity vectors presented in Fig. 5(b) indicate the moving speed of the liquid
 243 phase relative to the solid shell, which continuously moves downwards under the pulling of the
 244 dummy bar.

245 An initial shell of small thickness quickly forms at the surface of strand in the mold own to the
 246 strong cooling condition. The molten steel near the solidified shell has a large temperature gradient
 247 pointing inwards. As the colder molten steel near the shell is heavier, it flows downwards to the
 248 bottom, resulting in an upward return flow at the melt center. At $t = 45$ s, the maximum velocity in
 249 liquid is about 6.16 mm/s and a front part of billet has been pulled out of mold and enters the
 250 spraying water cooling zone. The downward flow continuously transports the solute to the lower
 251 end region, therefore, an enriched layer appears near the bottom. At $t = 90$ s, the billet has entered
 252 into the water spray cooling zone and the shell thickness increases. Temperature gradient and the
 253 thermal buoyancy force in the melt decrease due to the decrease of the cooling intensity and also to
 254 the increase of the shell's heat resistance. Finally, the melt flow velocity is significantly reduced. At
 255 $t = 135$ s, the slab completely enters into the spray water cooling zone. The flow direction of molten
 256 steel near the shell gradually reverses from downward to upward because the melt at the
 257 solidification frontier is getting carbon enriched and becomes lighter. Due to the flow resistance in
 258 the mushy zone, the flow velocity of liquid is greatly reduced. At $t = 225$ s, the billet enters into air
 259 cooling region and the surface cooling intensity gets weaker. The solute element continues to be
 260 rejected by the growing solid phase and pushed by the solidification front into the liquid phase,
 261 eventually forming a strong central segregation.

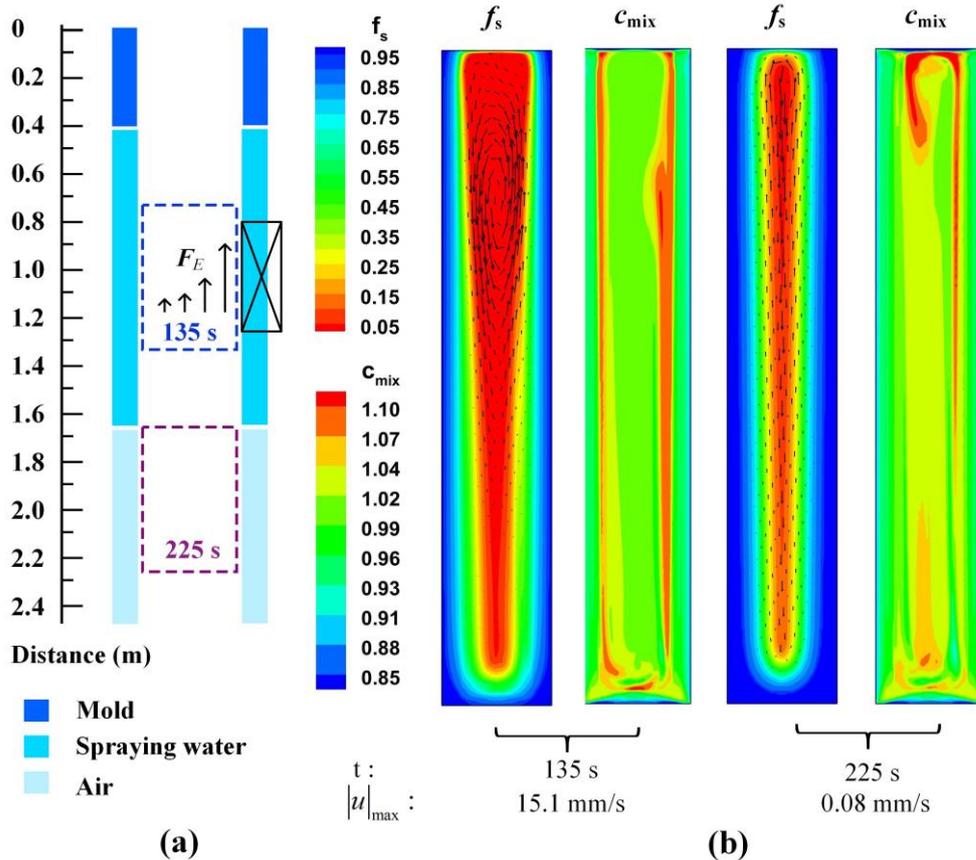


262

263 **Fig. 5** Schematic position of billet at each solidification time (a), and flow field, solid phase
 264 fraction distribution and solute distribution at different solidification time of vertical continuous
 265 casting process without V-EMS (b)

266 **4.2 Solidification Process with V-EMS**

267 For the case with the application of V-EMS, the flow motion of melt is greatly changed. After
 268 initial solidification process up to $t = 90$ s, the billet arrives at the region where V-EMS can have
 269 effect on it. An upward electromagnetic force is stimulated in the melt near the stirrer by the
 270 travelling electromagnetic field. A counterclockwise vortex is formed at the stirring region and the
 271 flow velocity of the melt is significantly intensified. For the sake of concision, only the results at t
 272 $= 135$ s and $t = 225$ s are provided (Fig. 6(b)). Note that the symmetry of the process is destroyed
 273 due to the stirring. At $t = 135$ s, the melt near the stirrer flows upwards, driving the colder and more
 274 enriched melt at the bottom to an upper place. On the contrary, the hotter and fresher melt at the
 275 other side moves downwards, causing the horizontal asymmetric solute distribution. This flow
 276 results in a higher solute concentration near the stirrer side. The maximum velocity occurs at upper
 277 part of billet and it is around 15.1 mm/s. After the billet has left the stirring zone, such melt flow
 278 continues for a while and then gradually disappears. At $t = 225$ s, the melt flow becomes very weak
 279 with the maximum velocity of only 0.08 mm/s, which is due to the quick growth of solid phase.



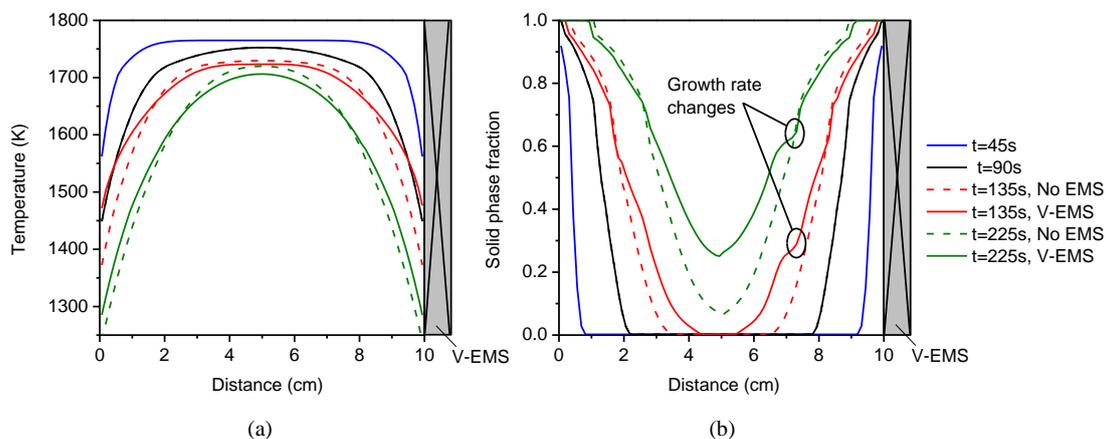
280
 281 **Fig. 6** Schematic position of billet at each solidification time (a), and flow field
 282 fraction distribution and solute distribution at different solidification time of vertical continuous
 283 casting process with V-EMS (b)

284

285 4.3 Comparison of results between cases

286 4.3.1 Temperature and solid fraction

287 In order to further analyze the effect of the V-EMS, the evolution of profile of temperature and
288 solid phase fraction along horizontal direction at middle height of billet are presented in Fig. 7.
289 Comparison shows that the application of V-EMS increases the temperature of about 100 K at the
290 surface of billet, which means the heat extraction from billet is promoted. Meanwhile, stirring
291 slightly decreases the temperature at the center for about 5.5 K. Consequently, the difference of
292 temperature between the surface and the center is diminished by V-EMS. According to Trindade et
293 al.^[14], smaller temperature gradient tends to promote the growth of equiaxed grains, which is
294 beneficial to the final cast quality. It is found (Fig. 7(b)) that V-EMS promotes the solid growth in
295 the billet, in particular, at $t = 225$ s, the solid fraction at the center of billet is 26% with use of V-
296 EMS, while it is only 6.7% without EMS. V-EMS also enlarges the distance between the two solid
297 fraction lines, indicating that the mushy zone is widened. Comparison between Fig. 5 and Fig. 6 shows
298 that the length of liquid core is shortened, which is beneficial to the liquid feeding in billet and to
299 reducing the shrinkage and porosity defects. An interesting observation is that the solid phase
300 fraction profile has a obvious turning points at distance of 7.2 cm, which implies that the local solid
301 growth rate is changed after the V-EMS is applied. Indeed, the stirring promotes the heat dissipation
302 and solid growth, which will further affect the macrosegregation distribution as will be discussed
303 below.



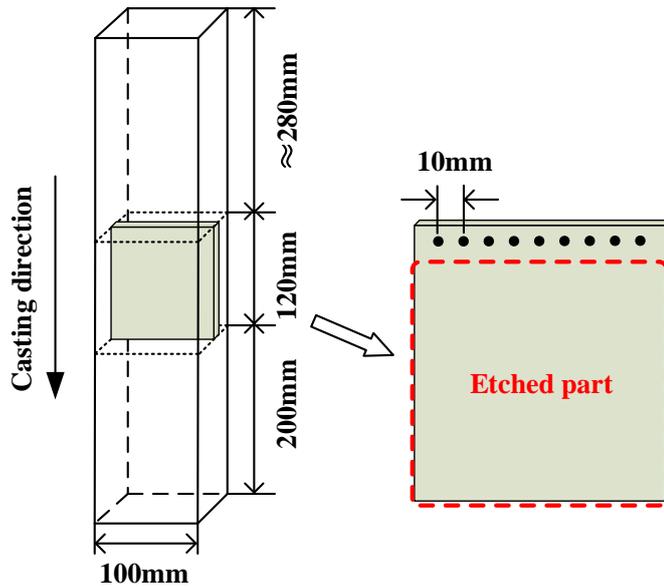
304

305 **Fig. 7** Distribution of temperature (a) and solid phase fraction (b) along cross section at middle height
306 of billet with and without V-EMS

307 4.3.2 Macrosegregation Formation

308 Samples from longitudinal section of billet products were polished and etched to show their
309 internal quality and macrosegregation either with or without V-EMS. As can be seen in Fig. 8, the
310 slice sample with side length of 100 mm was etched with mixture liquid: FeCl_3 , picric acid,

311 C_2H_5OH and H_2O . Obtained macrostructure of etched samples are shown in Fig. 9(a-b) with
312 calculated carbon segregation maps for the same region provided in Fig. 9(c-d).



313

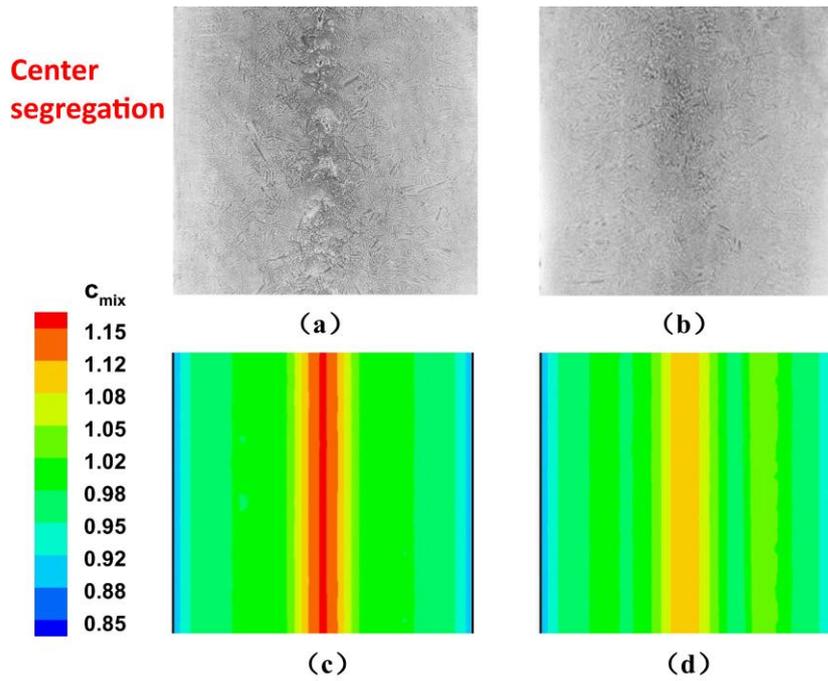
314 **Fig. 8** Sampling schematic diagram for the etching process and the carbon analysis

315

316 The morphology of etched samples and calculated macrosegregation maps are put together in
317 Fig. 9. Both experimental and calculated results show that the center segregation is decreased by
318 the V-EMS owing to the strengthened melt flow that accelerates the heat dissipation and solute
319 homogenization in the billet. Besides, the shrinkage and porosity defects are reduced or eliminated
320 because shortening of liquid core improves the feeding ability of liquid core. Another interesting
321 phenomenon is the positive segregation band appearing at the vicinity of the right 1/4 width region
322 (Fig. 9d) under the effect of V-EMS . On the one hand, the upward flow near the solidification
323 frontier brings up the enriched melt, increasing local solute concentration, on the other other hand,
324 electromagnetic stirring makes the melt near the right side solidify more quickly.

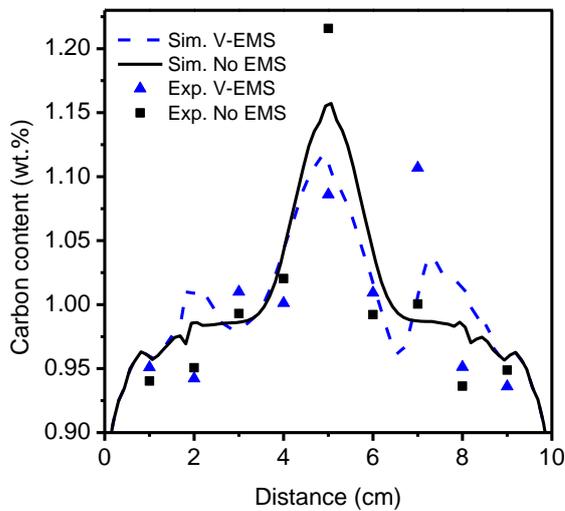
325

326 To have a more quantitative comparison for carbon segregation along the transverse direction,
327 different positions on the samples with an interval of 10 mm were drilled and chemically analyzed
328 by using Leco CS844 instrument. Measured carbon element at the points are plotted in Fig. 10,
329 where calculation results are added for comparison. The calculated central segregation is slightly
330 different from the experimental result. In experiment the center segregation ratio drops from 1.22 to
331 1.08 with the use of V-EMS while in simulation it drops from 1.16 to 1.12. According to the
332 experimental data, the segregation ratio in positive segregation band is nearly 1.11, while in
333 calculation, it is about 1.04. This difference can be attributed to the neglecting of shrinkage and
334 deformation of the solidified shell, which is believed to be important for the formation of central
segregation according to some other studies^[28,38].



335

336 **Fig. 9** Morphology of a part of the vertical section of billets and calculated macrosegregation
 337 distributions with (b, d) and without (a, c) V-EMS



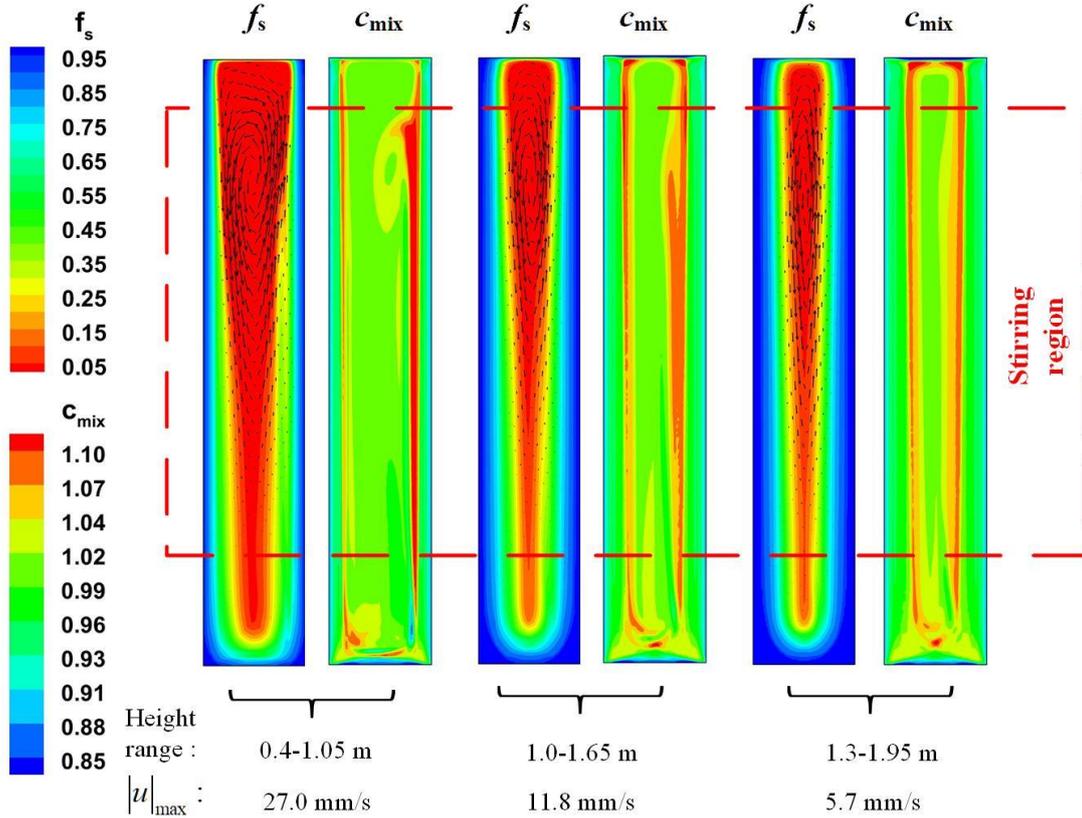
338

339 **Fig. 10** Comparison of the final macrosegregation distribution along along the transverse direction
 340 between simulations and experimental measurements

341 4.4 Effect of stirrer's installation height

342 One of the important parameter for cast quality and energy consumption is the installation
 343 height of the stirrer. In order to give some enlightenment to this problem, three additional
 344 simulation cases were conducted, in which the positions of the stirrer moves from 0.8 m to 0.5 m,
 345 1.1 m and 1.4 m below the meniscus, respectively. Casting speed, mold heat transfer coefficient and

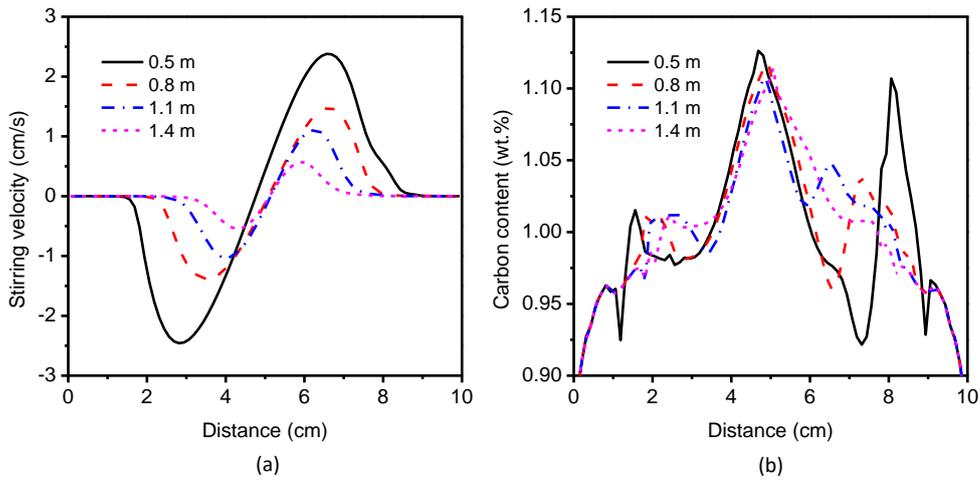
346 material properties are kept same for all cases. Simulated fields of solid fraction, liquid flow and
 347 solute concentration under new positions of electromagnetic stirrer have been presented in Fig. 11.
 348 For the convenience of comparison, the results in Fig. 11 have same relative position between billet
 349 and stirrer as in Fig. 6. In each case, flow velocity of melt in lower part of billet is smaller because
 350 of larger solid phase fraction and larger flow resistance. It is also observed that the liquid pool
 351 width and melt flow velocity decreases with the position of stirrer displacing downwards.



352
 353 **Fig. 11** Flow velocity vectors and solid fraction distribution at $t = 135$ s for the cases with different
 354 installation height of EMS

355

356 As illustrated in Fig. 12(a), when the installation height of EMS stirrer moves from 0.5 m to
 357 1.4 m below meniscus, the maximum velocity drops from 2.7 cm/s to 0.6 cm/s, the position of
 358 maximal velocity displaced from 2.2 cm to 0.5 cm to the center of billet. The macrosegregation
 359 distribution is also greatly influenced by the installation height of EMS stirrer (Fig. 12(b)). When
 360 the V-EMS is installed at 0.5 m below meniscus, the carbon content shows large value in the
 361 position 2 cm away from surface, indicating a severe segregation band at this distance. When V-
 362 EMS is installed at lower position, i.e. closer to the solidification end, the segregation band
 363 becomes less intense, while the central segregation is not obviously changed.



364

365 **Fig. 12** Comparison of liquid velocity profile(a) and macrosegregation profile(b) with different
 366 installation height of EMS

367

368 **5 Conclusions**

369 In this paper, a volume averaged columnar model is used to simulate the solidification process
 370 of GCr15 bearing steel continuous casting process. The evolutions of flow field, solid phase fraction
 371 distribution and solute concentration distribution have been presented for cases with and without V-
 372 EMS. Results show that V-EMS can promote the longitudinal melt flow, accelerate the superheat
 373 dissipation and relieve central segregation. However, vertical stirring leads to opposite moving
 374 directions of liquid between near and far sides from the stirrer, which causes positive segregation
 375 band near the stirrer and horizontal solutal inhomogeneity. Lowering the installation position of V-
 376 EMS helps relieving this kind of segregation band. In the future, more optimization has to be made
 377 for the structure and application parameters of V-EMS.

378

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