

## Electromagnetic sensor just below CC mold by using magnetic transformation of steel

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### Abstract

Electromagnetic sensor to detect the unbalanced flow in CC strand by using the magnetic transformation just below CC mold has been proposed, noticing that the narrow face of slab has been cooled at beneath of mold and surface temperature rapidly decreases to Curie temperature ( $T_c$ ). Laboratory experiments have been performed to verify the principle of the proposed sensor, which is composed of primary and secondary solenoid coil. The obtained experimental results showed that the relationship between the surface temperature of slab and induced electric voltage could be explained by Curie-Weiss law, when AC magnetic field has been imposed on the slab surface. Moreover, plant tests have been conducted by installing the sensor just below the narrow face of mold. It can be found that the proposed sensor have potential to measure surface temperature under severe conditions and detect the unbalanced flow in CC strand.

**Key words :** magnetic transformation, Curie temperature, continuous casting, unbalanced flow, solidification

### Introduction

Molten steel flow in CC mold largely affects the cast slab quality and the productivity of CC. In CC mold, unsymmetrical discharged flow from submerged entry nozzle causes unbalanced flow in CC strand and local remelting of solidified shell at the impinging points of the discharged flow, as shown in **Fig.1**. Additionally, the unbalanced flow leads to the entrapment of mold powder at meniscus and the inner defects due to deeply transported Ar bubbles. Therefore, suitable control of the discharged flow and the entire flow pattern in CC strand are necessary. At the same time, the detection of the unbalanced flow becomes important in order to escape from serious casting troubles and slab defects. Several detection methods of the unbalanced flow in CC mold have been reported <sup>[1] [2]</sup>. However, it is impossible to directly detect the unbalanced flow in CC strand. Harada et al. <sup>[3]</sup> proposed electromagnetic sensor just below CC mold by utilizing magnetic transformation of steel, noticing that strong cooling beneath the mold causes magnetic transformation of steel. In this study, noticing that the unbalanced flow forms the large differences of surface temperature of slab just below the mold, the electromagnetically detecting methods of unbalanced flow in CC strand have been developed.

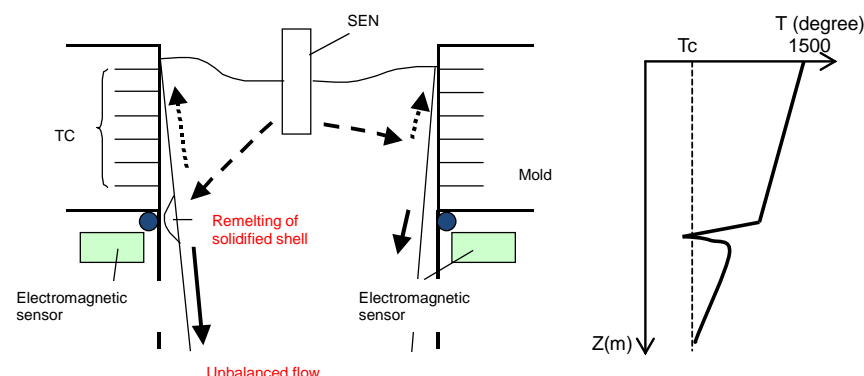


Fig.1: Schematic view of unbalanced flow in CC strand and surface temperature change during casting.



### The principle of electromagnetic sensor and laboratory experiment for verification

**Fig.2** shows the principle of the proposed electromagnetic sensor <sup>[3]</sup>. When AC magnetic field is applied normal to the slab surface, the distribution of magnetic field in the slab is dependent of magnetism of slab surface. When surface temperature ( $T_s$ ) is much higher than  $T_c$ , the distribution of magnetic field line is the same as the one in vacuum. On the contrary, when  $T_s$  approaches to and pass through  $T_c$ , the applied magnetic field is distorted by the magnetism of slab surface, in other words, slab surface temperature. By measuring the induced electric voltage due to the change of imposed magnetic field line, surface temperature can be estimated. The sensor is composed of primary coil and secondary coil. A set of coils is mounted into the cylinder made of stainless steel. AC electric current is supplied to primary coil by using a constant current power amplifier, AC magnetic field is imposed normal to the slab surface. The noise in secondary coil is minimized with low pass filter. Moreover, only the signal with same frequency as imposed electric current, is elucidated by using Lock in amplifier.

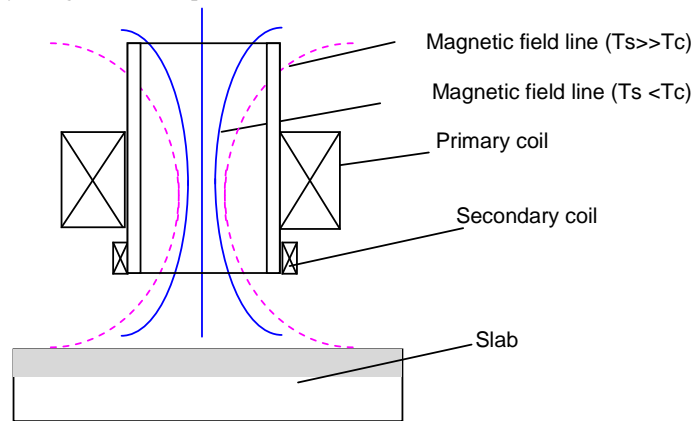


Fig.2: Schematic view of electromagnetic sensor and the change of magnetic field line due to magnetism of slab surface.

Laboratory experiment has been performed to clarify the relationship between sensor signals and surface temperature of slab. Slab samples are inserted into a heating furnace and heated into 1350 degree. A thermocouple is inserted into the slab, in which the position is 1mm from the surface of slab. After extraction of the heated slab, aforementioned sensor is set on the heated samples and the relationship between induced electric voltage of secondary coils and surface temperature of slab has been investigated. **Fig.3** shows the typical example of the obtained results. It can be found that the induced electric voltage is almost constant in high temperature and low temperature region. On the contrary, the electric voltage changes with temperature, when surface temperature approaches to Curie temperature. When magnetic field is applied to paramagnet whose temperature is changing with time, the change of magnetic flux and the induced electric potential of the coil is governed by Curie-Weiss law and Faraday law of induction as expressed by equations (1)-(4). After transformation of these equations, the relationship between electric potential and temperature of paramagnet can be finally obtained by using integral equation (5). The calculated results by using equation (5) and experimental results are plotted on **Fig.4**. It can be found that experimental results show good agreement with the calculated results based on Curie-Weiss law and that the proposed electromagnetic thermometer is the sensor based on magnetic transformation of steel.

$$V = -n \frac{d\Phi}{dt} \quad (1)$$

$$\Phi = B \cdot S \quad (2)$$

$$B = \mu_0(1 + \chi)H \quad (3)$$

$$\chi = \frac{c}{T - T_c} \quad (4)$$

$$\int V dt = \int \frac{\mu_0 n S H c}{(T - T_c)^2} dT \quad (5)$$

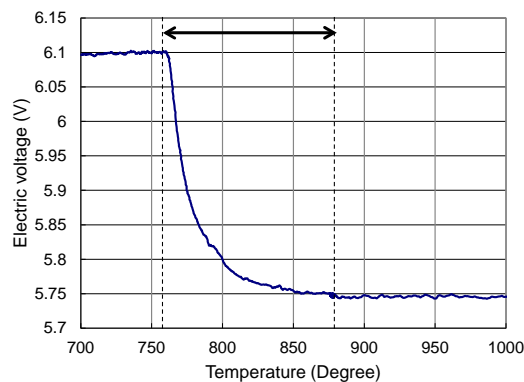


Fig. 3: Relationship between slab surface temperature and induced electric voltage of secondary coil.

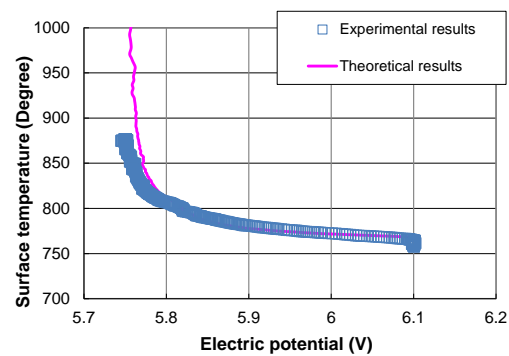


Fig.4: Comparison of experimental results with theoretical results based on Curie-Weiss law, about the relationship between slab surface temperature and induced electric voltage.

#### Plant test for verification of the proposed sensor

A pair of sensor was installed under the respective narrow face of mold at bending type of continuous casting machine and plant tests have been performed to investigate the effects of casting conditions on the sensor signals. **Table 1** shows the casting conditions. **Fig.5** shows the time-change of the measured surface temperature by using sensor, when casting speed changes in sequential casting. It can be found that surface temperature of narrow face of slab changes with casting speed and surface temperature always changes under the constant casting speed conditions. The difference in surface temperature measured by both sensors have been compared with the difference in the fluid flow velocity at solidification front at both narrow face of slab. The fluid flow velocity at solidification front can be estimated from the measured value of inclination angle of columnar dendrites and solidification speed by using experimentally obtained formula by Okano et al.<sup>[4]</sup> The difference in thus obtained fluid flow velocity at both narrow face has been compared with the difference in the measured surface temperature of both sensors. The obtained results are plotted in **Fig.6**. The good correlation between the measured temperature difference and the estimated fluid flow difference can be recognized. This means that the temperature differences increases with the fluid flow difference, in other words, the magnitude of the unbalanced flow. As a result, it can be found that the proposed sensor have potential to detect the unbalanced flow in CC strand by measuring surface temperature of cast slab just below CC mold.

Table1 Casting conditions of plant test.

Slab width	1000 ~ 1800mm
Casting speed	0.75 ~ 1.2m/min.
Steel grade	Middle Carbon Al-killed steel, Low Carbon Al-killed steel, IF steel
Sensor position	(i)Vertical position: just below the narrow face of mold (ii)Distance between sensor and narrow face of slab : 30mm

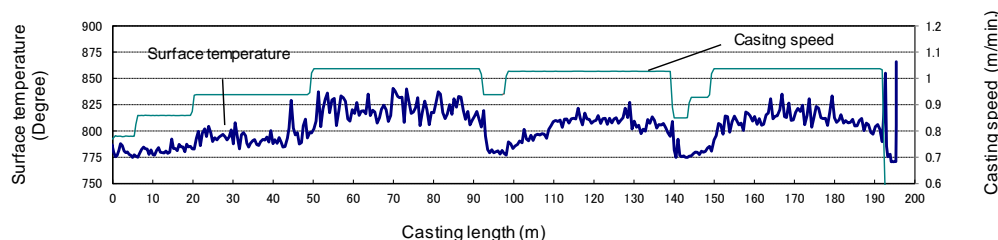


Fig.5: Successive change of surface temperature of slab with casting speed.

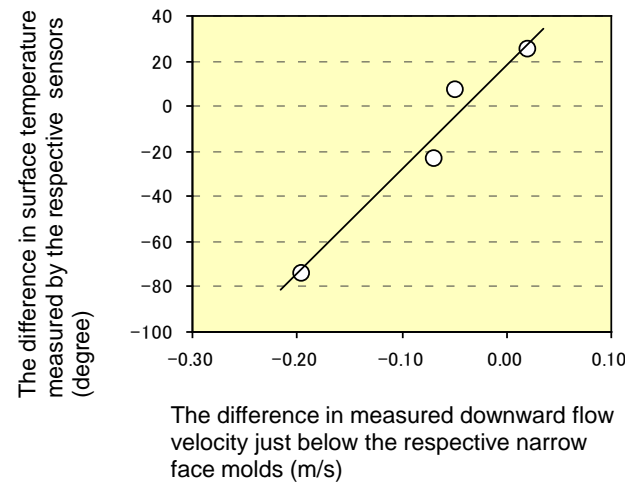


Fig.6: Correlation between temperature difference and fluid flow velocity difference.

### Conclusions

Electromagnetic sensor to detect the unbalanced flow in CC strand by using the magnetic transformation just below CC mold has been proposed. The obtained results are summarized as follows:

- (1) Noticing that the narrow face of slab has been cooled below Curie temperature at the beneath of mold, the sensing method to measure the change of imposed AC magnetic field due to slab surface temperature, has been constructed.
- (2) Laboratory experiments have been performed to verify the principle of the proposed sensor which is composed of primary and secondary solenoid coil. The obtained experimental results showed that the relationship between the surface temperature of slab and induced electric voltage could be explained by Curie-Weiss law, when AC magnetic field has been imposed on the slab surface.
- (3) Plant tests have been performed by installing the sensor under the respective narrow face mold to show that the proposed sensor could measure surface temperature under severe conditions and detect the unbalanced flow in CC strand.

### Nomenclature

$B$ : magnetic flux density,  $c$ : constant,  $H$ : magnetic field,  $n$ : turn number of electric coil,  $S$ : area,  $t$ : time,  $T$ : temperature,  $T_c$ : Curie temperature,  $T_s$ : Surface temperature of slab,  $V$ : electric voltage,  $\phi$ : magnetic flux,  $\chi$ : magnetic susceptibility,  $\mu_0$ : magnetic permeability

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