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Parametric Study of Electromagnetic Characteristic of Liquid Metal Level Sensor

Jewhan LEE[1*], Yong-Bum LEE[1], Chung-Ho CHO[1], Byeongyeon KIM[1], Ji-Young JEONG[1]
Eunsil HAN[2]
[1]*Korea Atomic Energy Research Institute, 989-111 Daedeok-Daero, Yuseong-gu, Daejeon, 305-353, Korea*
[2]*Taesung S&E, Inc., 27 Seongsui-ro 7-gil, Seongdong-gu, Seoul, 04780, Korea*
[*]*Corresponding author: leej@kaeri.re.kr*

1. Introduction

The instrumentations for the measurement of various properties of liquid metal, especially chemically reactive metal such as potassium and sodium, are very different from those of water and air. For many purposes, the representative properties(temperature, flowrate, pressure) need to be measured to control the system[1]. The level measurement in the tank or large vessel is one of the above importance in liquid metal system[2]. The safety alarm and system protection set point is linked to the level signal of an expansion tank at the most top of the system and a storage tank at the most bottom. However, in Korea, the understanding on the level sensor is yet not enough to develop a product and also the industry is immature.

In this paper, the most widely used level sensor using electromagnetic induction was analyzed with various design parameters by commercial computer code (ANSYS Maxwell). The main purpose of this analysis is to deepen the understanding as well as to develop an improved/enhanced sensor with consideration of both engineering and manufacturing.

2. Liquid Metal Level Sensor

For liquid metal, the electromagnetic induction type sensor is most widely used for various reasons[3]. The liquid metal is electrically conductive and therefore the electromagnetic force can be induced by supplying the alternating current[4]. Due to its characteristic, the sensor itself does not directly contact with the liquid metal. In the sealing point of view, this is very good advantage. Moreover, the possibility of mal-functioning due to the residual liquid metal on the sensor surface is much less than other types of sensor. Although the cost for manufacturing this type of sensor is high, the other advantageous aspect compensates the loss.

2.1 Basic Principles

The Maxwell's equation is as follows. It is Faraday's law of induction, Ampere's law, and Gauss's law of magnetism and electricity, respectively.

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$
$$\vec{\nabla}\times\vec{H} = \vec{J} + \frac{\partial\vec{D}}{\partial t}$$
$$\vec{\nabla}\cdot\vec{B} = 0$$
$$\vec{\nabla}\cdot\vec{D} = \rho$$

According to the Faraday's law of induction, the change of magnetic flux with time induces the electromotive force in negative direction. The AC current supplied in the primary coil induces the magnetic flux and the alternating magnetic field induces the electric voltage on secondary coil. In this way, the electrical signal is produced in the sensor.

The magnetic field can be calculated by Ampere's law and is proportional to the number of coil turns and intensity of the current as follows.

$$\left|\vec{H}\right| \propto \mathrm{N}\cdot\mathrm{I}$$

The B field and H field is related with the permeability (or magnetic constant) as follows.

$$\vec{B} = \mu_0\mu_r\vec{H}$$

In the case of liquid metal instrumentation, there is no magnetic substance and thus the permeability is assumed to be 1.

The liquid metal is conductive and therefore the magnetic field induces the Eddy current on the surface. This Eddy current again induces the magnetic field in the opposite direction and making the total magnetic field weaker. Eventually the induced voltage on secondary coil is reduced. As liquid metal level rises, the signal from sensor (coil) decreases and it reaches the least value when the liquid metal is fully charged in the tank.

2.2 General Design and Layout

The liquid metal level sensor has two coils and in Fig. 1, the general layout of primary and secondary coil is shown. The coils are wound in bifilar way and installed inside the guide tube to protect from direct contact of liquid metal. The length of sensor ranges from less than 2 m to over 10 m, but the manufacturing issue comes up as it gets longer. The guide tube is usually installed with flanges at the top nozzle of the tank and bolt-fixed with appropriate sealing material.

2.3 Design Parameters

The main design parameters are the coil diameter, the core diameter, the coil pitch and the distance between coil and liquid metal. Other parameters can be all converted into the above 4 parameters and therefore excluded. In Fig. 2, the detailed design parameters are illustrated.

With the consideration of commercially manufactured tube size and MI cable, the test matrix was selected. Each parameter has 3 cases and the coil pitch has one extra case to consider the different winding option (layered type). Therefore the total case is 3 x 3 x 3 x 4 = 108.

Additionally, existence of sheath/guide tube was tested for 2 cases and liquid metal level change was tested for 5 cases. The final test cases were 115 cases in total. The test matrix is shown in Table 1.

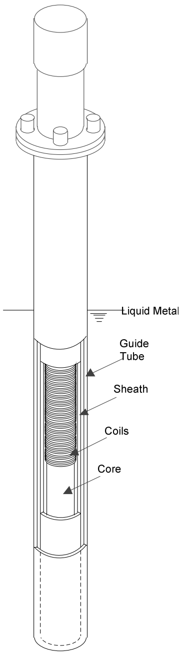

Fig. 1 General layout of liquid metal level sensor

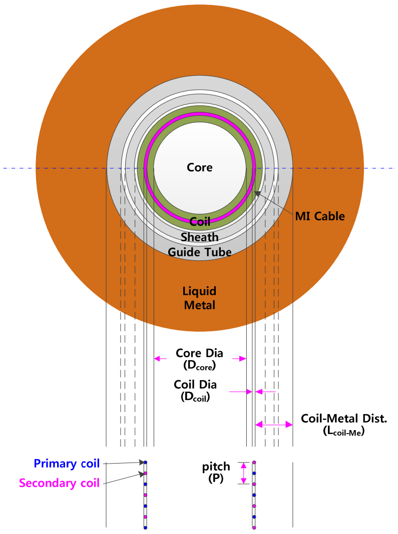

Fig. 2 Design parameters in detail

Table 1 Test matrix for analysis

	Coil Dia (D_{coil} , mm)	Core Dia (D_{core} , mm)	Coil-Me Dist ($L_{coil\text{-}Na}$, mm)	Pitch (P, mm)		Sheath/ Guide tube	Liquid metal height
1	0.18 0.56 1.02	10.00 16.90 25.50	5.26 6.77 8.04	4.00	bifilar	No	0.5H
⋮				12.00	bifilar		
⋮					layered		
108				24.00	bifilar		
	※ 3X3X3X4=108 case, H: model height						
109	0.56	16.90	6.77	12.00	bifilar	Yes	0.5H
110	0.56	16.90	6.77	12.00	bifilar	No	0.00
111							0.25H
112							0.75H
113							1.00H

3. Electromagnetic Analysis

The commercial tool, ANSYS Maxwell, was used to analyze the electromagnetic characteristic. The target value was the induced electric potential (Voltage) at the secondary coil and the parameters were changed to see the effect on this voltage.

3.1 Model

The analysis was conducted with the 2D simplified model as shown in Fig. 3. Due to limited calculation capability with computer resources, it was unable to conduct 3D model analysis (possible max. length was only 100 mm) and it required too many mesh for reasonable calculation. However, the comparison result of 2D and 3D model was less than 2 %.

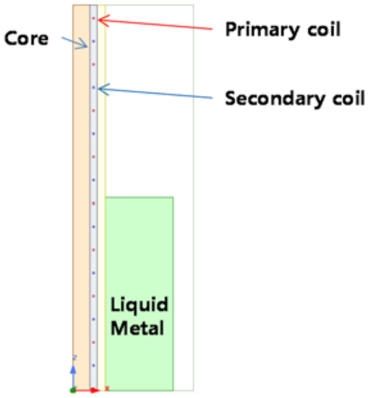

Fig. 3 2D simplified model for analysis

3.2 Results

The analysis results of coil and core diameter change are shown in Fig. 4 and the trend indicates that the larger the diameter, the stronger the output voltage is. Therefore, the coil diameter of 1.02 mm and the core diameter of 25.5 mm give the strongest output.

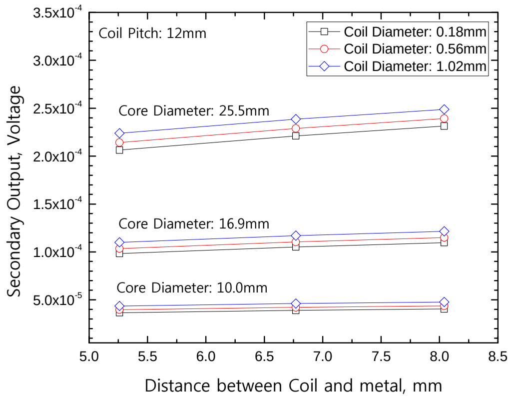

Fig. 4 Coil/Core diameter effect on output voltage

In Fig. 5, the coil pitch effect is shown and it can be seen that the y-axis scale is larger than in Fig. 4. The output signal of coil pitch 4 mm was much larger than others. This means that the dominant factor for output voltage is the coil pitch.

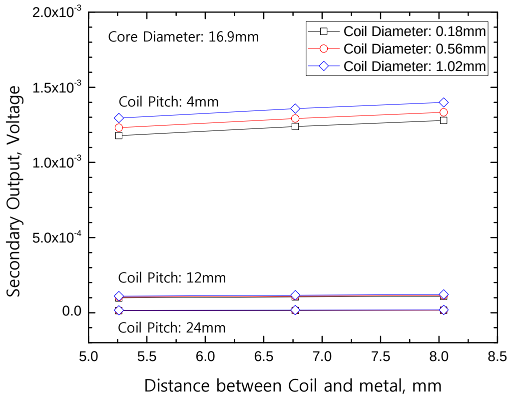

Fig. 5 Coil pitch effect on output voltage

The coil pitch decides whether there will be a proximate effect and the Eddy current effect. In Fig. 6 and Fig. 7, the H-field vector is illustrated for different pitch and it can be seen in Fig. 7 that the H-field is circular around the coil. Due to this Eddy current effect, the output signal in Fig. 7 is much less than that of Fig. 6. Therefore, it can be concluded that the optimum pitch will exist between 4 mm and 12 mm.

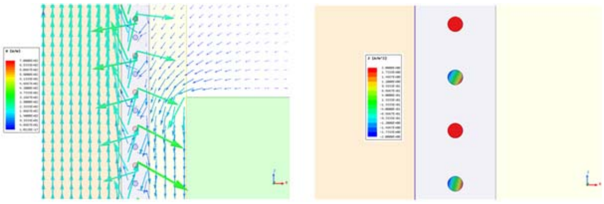

Fig. 6 H-field vector distribution of pitch 4 mm case

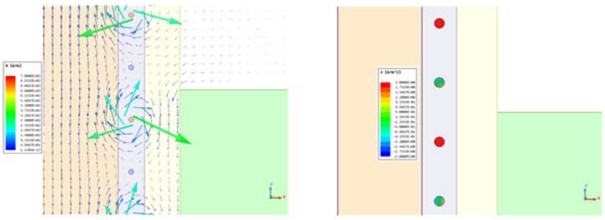

Fig. 7 H-field vector distribution of pitch 12 mm case

Regarding the effect of coil winding method (bifilar or layered), the output from layered type was higher than bifilar. But, this is because the secondary coil is simply closer to the primary coil in layered type. It can be considered same as the smaller pitch coils in bifilar type. Therefore this does not conclude that the layered type is better. When there is a need of maximum turns of coils with setting two coils as close as possible, the layered type will be the solution.

4. Conclusion

The instrumentation for the liquid metal is essential to monitor and control the system. One of the required measurements is the level in the tank or vessel. Most widely used type of level sensor is based on electromagnetic induction and yet the related knowledge is at low stage. In this paper, the electromagnetic characteristic of the level sensor with various design parameters was analyzed and the effect of each parameter was discussed. The dominant factor for the output voltage was coil winding pitch and the estimated optimum value was in between 4 mm and 12 mm. The optimized pitch will have the least Eddy current effect and proximate effect to put out the strongest signal. For other design parameters, it was preferred to have the largest diameter of coil and core. For further work, additional analysis for optimization of the coil pitch will be needed.

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