Feasibility of *In-Situ* Process Monitoring of Glass Melt in Industrial Furnace using Microwaves

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Abstract

Non-contact measurement of the level of molten glass is demonstrated in an engineering scale induction-heated glass melter using microwaves. The microwave sensor is a corrugated horn used in mono static RADAR (RAdio Detection and Ranging) mode operating over 20 to 24 GHz with 20 dB gain. The ability to measure the level of the glass melt is demonstrated using an off-centered port in an induction glass melting furnace.

Keywords - glass melt, level, microwave, process monitoring, industrial furnace

1. Introduction

Level measurement in glass melting furnace is an important requirement which is currently accomplished using visual inspection, dip stick or thermocouple sensor array depending upon the sophistication of the furnace and end application. Figure 1 shows a typical batch process for industrial glass melting. The level of the material inside the crucible is continuously monitored during different stages in a batch process. Current level measurement techniques are vulnerable to error due to the very high operating temperature (1500 ℃). As microwave is not significantly influenced by temperature and pressure variations, and the presence of cover gas, it was proposed for measuring the displacement in the level of the molten glass [1]. Acoustic sensors are also proposed for high temperature level measurement of molten glass [2-3]. However, they are contact type sensors and need periodic replacement.

Recently, we proposed an air cooled corrugated horn antenna operating over 20-24 GHz for non-contact sensing of the absolute level of molten mass in a furnace [4]. The demonstration was limited to a laboratory scale Joule-heated furnace. Preliminary measurements indicated the ability to measure the level of the molten glass in an 1100 ℃ furnace using the microwave sensor and non-contact level measurement technique. In this work we assess the ability of the proposed sensor to measure the absolute level of the glass melt in an engineering scale induction-heated glass melting furnace.

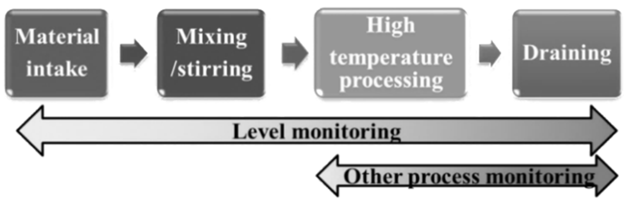

Figure 1. Typical batch process in industrial glass melting furnace.

2. Microwave level sensor

The accuracy of the proposed microwave based range measurement was assessed using physical measurement and commercial optical sensor (GLM 80 Professional, BOSCH) with ± 1.5 mm accuracy. A fine polished aluminium sheet of dimensions, 600 mm × 600 mm × 5 mm at room temperature was placed at a distance, R in the line of sight of the horn antenna as illustrated in Figure 2. The optical sensor was positioned on the same plane as the horn as shown in Figure 2.

The location of the metal plate from the antenna aperture, $\boldsymbol{R}$ was determined by processing the frequency domain continuous wave (CW) reflections gathered by the antenna using a microwave signal analyzer following the procedure explained in [4]. The time of arrival of the echoes in the measurement setup processed using the CW reflections was translated to space using the velocity of EM wave propagation in free space. The range of the metal plate detected from the processed microwave reflections is shown in Figure 2. The first reflected peak in Figure 2 indicates the antenna aperture and the second peak corresponds to the estimated location of the metal plate, $\boldsymbol{R_m}$. Table I compares the range measured by the microwave sensor ($\boldsymbol{R_m}$) with the optical sensor ($\boldsymbol{R_o}$) and the actual range, $\boldsymbol{R}$. The distance of the metal plate was varied

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over the measurement range expected in the induction glass melting furnace. Table I indicates close agreement between the microwave range measurement ($\boldsymbol{R_m}$) and the actual range ($\boldsymbol{R}$). Furthermore, the range measurements of the proposed sensor are comparable to commercial level sensor ($\boldsymbol{R_o}$).

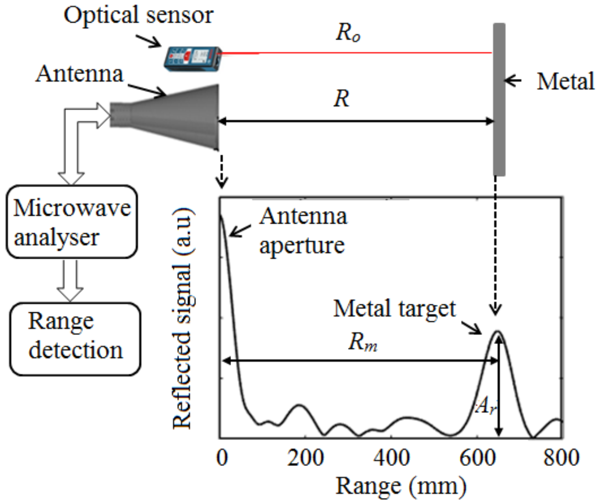

Figure 2. Illustration of the experimental set up for assessing the accuracy of the range detected by the microwave sensor. The optical sensor was positioned adjacent to the horn antenna and in the same plane for measurement comparison.

TABLE I – COMPARISON OF RANGE MEASURED FOR A METAL PLATE AT ROOM TEMPERATURE.

Actual range, R (mm)	Optical sensor measurement, R_o (mm)	Microwave measurement, R_m (mm)
324	324.7	324.1
635	635.4	635.2
890	889.1	890.2

3. Level measurements in CCIM

Figure 3 shows the illustration of the Cold Crucible Induction Melter (CCIM) with capacity of about 100 kg of molten glass [5]. The crucible is a contiguous arrangement of water-cooled stainless steel tubes. The cylindrical metal crucible of inner diameter, 500 mm containing the glass feed was inductively heated using an outer inductor coil. The eddy current induced by the inductor in the metal crucible creates an electromagnetic field inside the crucible which in turn melts the glass. The details of the cold crucible induction melter used for level measurement can be found in [5]. The challenges with this measurement set up are the presence of the steel tubes and the offset port for level measurement. Thus, the ability of the proposed microwave sensor to measure the level of the high temperature glass melt through an off-centered port located 35 mm away from the inner periphery of cylindrical metal crucible was assessed in this work. The antenna was fitted in the sensor port provided on the roof of the furnace as shown in Figure 3. Level measurement experiment was carried out using borosilicate glass beads. Initial batch of ~98 kg glass beads were fed to the cold crucible induction melter and measurements were gathered once the glass reached the molten state. The molten state of the glass (1100 ℃) was confirmed using a pyrometer. Microwave CW reflections were gathered continuously for 80 minutes using the air cooled corrugated horn antenna. During the in-situ microwave level measurements, a batch of 2.5 kg of glass beads was added at the end of 60 minutes. The measurements were processed to extract the time variation in the absolute level of the glass melt, L in the induction melting furnace. With the knowledge of the furnace dimensions and sensor location, the absolute level of the glass melt given by,

$$L = D - R_m, \qquad (1)$$

was estimated from the range measurement, R_m. In Eqn. (1), D denotes the distance between the furnace bottom surface and the sensor aperture.

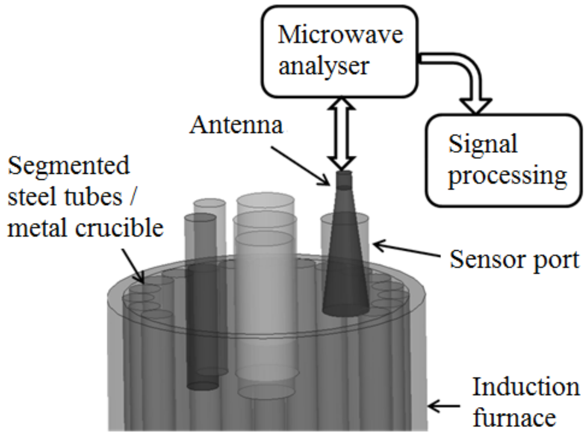

Figure 3. Illustrations of the induction glass melting furnace with off centered port for level measurement.

Figure 4 shows the in-situ measurement of the absolute level of the molten glass, L extracted from the processed microwave reflections. The initial level of the glass melt was measured as 201.5 mm with small fluctuations indicating bubbling of the high temperature glass melt. The level of the glass melt gradually reduced to 196.5 mm due to the volume reduction due to complete melting of glass beads. Upon addition of 2.5 kg of raw glass beads, the level increased to 209.5 mm from 196.5 mm. The sudden rise in the level indicates material addition. The level of the molten mass gradually settled and reached the final state of 201 mm. The difference in the steady state level before and after material addition was measured as 4.5 mm by the microwave level sensor. This difference is comparable to the estimated increase of 5 mm per 2.5 kg of glass for the induction melter calculated based on the mass and density of the glass. The measurements clearly demonstrate the ability of the proposed microwave sensor for level measurement in industrial furnace with tight space constraints.

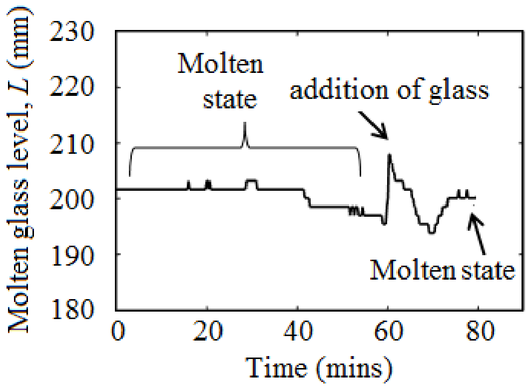

Figure 4. In-situ measurement of the level of the molten glass at 1100 ℃ extracted from the non-contact microwave sensor.

5. Conclusion

A microwave based non-contact level sensor is proposed for in-situ measurement of high temperature molten glass in industrial furnace. The measurements at the off centered port 35 mm away from the inner periphery of the metal cylindrical crucible indicate the antenna is highly directive. The sensor is a compact air cooled corrugated horn antenna with narrow half power beam width and symmetric radiation profiles in the E and H planes. The preliminary measurements of the level of the glass melt in an engineering scale cold crucible induction melter indicate the ability of the proposed microwave sensor and measurement technique to faithfully measure the level and also indicate the change in the process such as material addition from the processed signals.

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