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Original Article

RADAR level measurement in Joule heated ceramic melter: A novel technique

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ABSTRACT

The current study relates to RADAR (RAdio Detection and Ranging) application for level measurement of vitrified radioactive liquid nuclear waste. The vitrification of radioactive liquid waste is carried out in special equipment called ‘Melters’. The study is directed towards the design and frequency modulation used in the level measurement of vitrified waste. More specifically, the RADAR design and frequency used for level measurement in a melter. This level measurement technique can also be used for dynamic vitrification process and can be used to measure the level variations without using any external medium/material and using only electromagnetic waves. Also, this technique is durable and accurate even under the high radioactive environment present inside the melter.

1. Introduction

The operation of nuclear power plants produce spent nuclear fuel. These spent fuels are reprocessed to extract important and scarce elements such as Uranium and Plutonium which can be reused as a nuclear fuel. After extraction of useful elements, the remaining nuclear waste cannot be directly disposed into the environment due to its radioactivity. Hence, this waste is immobilised in a glass matrix by a process known as ‘vitrification’. Vitrification is carried out in equipment known as ‘Melter’ which operates at 1273–1373 K. There are different types of melters such as Joule Heated Ceramic Melter (JHCM), Cold Crucible Induction Melter (CCIM), Metallic Melter (MM), etc. The vitrified waste is poured into a canister. These canisters are then finally stored in engineered facilities. Accurate measurement of level inside the melter is crucial due to many reasons. The pouring of vitrified waste depends on the level inside the melter. High level in the melter can cause pressurisation of the melter that can release radioactive gases into the radioactive hot cell where the equipment is housed. Besides, a high level in the melter can give rise to other problems like non-uniform mixtures, the formation of dead zones, non-uniform distribution of cold cap, trapping of air bubbles in the glass, etc [1]. Operational data obtained from actual JHCM, CCIM, MM used in nuclear industries is limited given the high temperature and highly radioactive environment [2].

Measurement of level in an industrial furnace is essential for the controlled and safe operation of a system. Level measurement devices are categorized into two groups; contact type and non-contact type. Contact type devices include float type, electrical resistance type and dip tapes, that are used for liquid and solid level measurement. However, these cannot be used in highly radioactive, corrosive, and, high-temperature conditions present in heating furnaces. This is due to the low withstanding capacity of the materials used and the high possibility of point measurement errors due to dynamic surface [3]. Non-contact type includes capacitance-based [4–7], millimetre waveguide [8], thermal imaging techniques [9], ultrasonic waveguide [10,11], and RADAR [12,13]. Although the use of Ultrasonic/acoustic and RADAR techniques in high-temperature conditions are reported, none of these methods were reported to be implemented in a radioactive furnace.

Radar level measurement systems are often used in process applications for level measurement as they can effectively measure level in varying process media conditions like dielectric or specific gravity, and corrosive environments. The level measurement is not affected by changes in temperature, pressure, vapour composition & density above the medium. Radar level measurement comes in

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two forms: non-contact (through the air) and contact (guided wave). It is based on measuring the transit time of high frequency (GHz) electromagnetic energy transmitted from an antenna at the top of the tank and reflecting off the surface of the medium (the higher the dielectric of the medium, the stronger the reflection). The transmitted energy travels freely over long distances (greater than 66 m).

Radar pulses emitted by a transmitter are reflected by the product surface and detected by a receiver. From the Time-of-Flight of the pulse, the distance between the transmitter and the surface is determined using the known velocity of propagation. The level is determined from this value. The transceiver converts this signal electrically into distance/level and presents it as an analogue and/or digital signal. Pulse radar has been widely used for distance measurement since the very beginning of radar technology. The basic principle of pulse radar is purely time of flight measurement. Short pulses, typically of a millisecond or nanosecond duration, are transmitted and the transit time to and fro from the target is measured.

The major advantages of RADAR level measurement technique are non-contact, maintenance-free measurement, can accurately measure both liquid and solid media. Typical applications include corrosive and non-corrosive liquid level monitoring, sanitary environments, caustics, small tank or process vessel, freely adjustable measuring range. Radar instrumentation can have accuracy up to ±2 mm. Besides, the instrument will not need recalibration after initial configuration and will not experience zero point drift or fluctuations due to change in specific gravity, temperature, or pressure. Non-contacting radar provides a top-down, direct measurement as it measures the distance to the surface.

For non-contacting radar level measurement, there are two main modulation techniques; Pulse radar technique and Frequency Modulated Continuous Wave (FMCW) radar technique. The pulsed radar transmits a pulse and then is silent for a period. During this period of silence, it can listen for the small returns reflected from the target surface unlike CW radar, which is always transmitting, and so has to detect returns against a background of its transmission. This can be challenging and so will limit the detection range. The main advantage of pulse radar is greater sensitivity in a monostatic configuration.

M. Pieraccini et al. [14], studied and tested a microwave technique for level measurement of molten glass in glass furnace using RADAR inferometry which works at around 10 GHz frequency. The study concluded that this technique can be used in very harsh and high temperatures conditions. Y.R. Yadam et al. [15], presented a level measurement technique using a non-contact wideband microwave sensor for low lossy, lossy solid, and fluidized bed with a frequency band of 10–16 GHz. The study includes the improvement in measurement accuracy with phase-based signal processing. The study concluded that wideband Step Frequency Continuous Wave RADAR sensor can be used at higher temperatures, variable pressure conditions, and in the presence of a cover gas. Balamurugan et al. [3], presented a compact corrugated horn antenna which has superior radiation characteristics in terms of low Side Lobe Level (SLL), with an excellent beam symmetry and high gain compared to the standard horns used in industrial level gauging.

Level measurements of the RADAR sensor in monostatic mode indicate its ability to measure the average level of the fluctuations in the target surface even for a very low angular displacement of 1°. Stable level measurements inside the closed furnace for long durations (11 h) demonstrate the ability of the proposed RADAR sensor for in-situ, non-contact level measurement at high temperatures. Stelzer et al. [16] demonstrated a precise level gauging sensor based on Radar for fuel tank level measurement with a waveguide to avoid multi-targets and multi-wave path. Gulden et al. [17] studied a novel Radar-based tank level gauging system with 24 GHz frequency implementation with an adaptive model-order estimation algorithm. But the studies did not put any light on its applications in the nuclear industry, the durability of the sensor on very high-temperature usage, the accuracy of measurements during dynamic changes in the level, and impact of long-time usage in radioactive conditions.

Yoshioka et al. [18] used a glass level detection based on the electrical resistance measurement between a common probe and the detection probe. The system used is a direct contact method which increases the chances of failure. The method if deployed will not give accurate measurement due to various characteristics of the cold cap along the height on the top of glass pool [1]. Woskov et al. [19] deployed a 137 GHz heterodyne receiver with hollow ceramic waveguides for measuring surface temperature and flow velocity during pouring.

The measurement of process parameters inside a JHCM requires all the electronic parts to be located outside hot-cell. Also, the level measurement technique must be remote as the operation involves highly radioactive solution and very high and harsh temperature conditions. Thermocouples placed inside a thermowell, and electrical resistance methods are the only methods deployed for measuring level in glass furnaces used for vitrification of radioactive waste. The accuracy of the level measurement using thermal sensors is low and the point accuracy is least obtained due to continuous fluctuation of the surface. The electrical resistance method is contact type and the probes require frequent replacement due to the highly corrosive nature of the molten glass. The current study mainly probes the feasibility of the usage of the RADAR level measurement technique in vitrification furnace.

2. Experimental

The basic objective of the current study is to provide a selective frequency band of RADAR to aid the level measurement in melters operated under highly corrosive, highly radioactive, and high-temperature environment. Another object of the study is to provide the dimension of the RADAR equipment used viz., horn antenna, waveguide, pulse generator, transceiver, and electrical parts. The dimensions of the antenna and horn used for the study are shown in Fig. 1.

The radar antenna length used for the experiment was 4500 mm and the bend of 90° was chosen. This was done to minimize any radiation leakage from the antenna to the electronic parts of the radar equipment as the antenna end was fixed on the top of the melter. The length of the horn was 233 mm and the experiment was conducted using simulated waste and the glass pool is maintained at a temperature of around 1273 K. The load cell weight was measured during pouring of the vitrified product into a canister. The schematic of the experimental setup is presented in Fig. 2(a). The setup consisted of an electric furnace and a RADAR transmitter with an antenna along with an extension pipe. A feasibility study and equipment qualification was carried out in an 18 kW modular electric furnace as shown in Fig. 2(b) in which glass forming studies were carried out. During the simulated trials, the level inside the melter was also measured with a dipstick and the values were compared with those measured by RADAR.

3. Results and discussion

Pulse Radar uses a single antenna for both transmitting and receiving signals with the help of duplexer. The block diagram of Pulse Radar is shown in Fig. 3. Non-contacting pulse radar sends out a microwave signal that bounces off the product surface due to a change in the dielectric constant of medium and returns to the

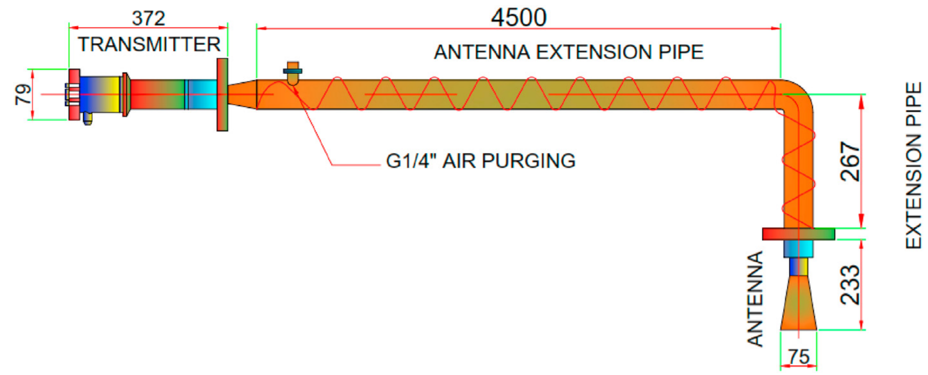
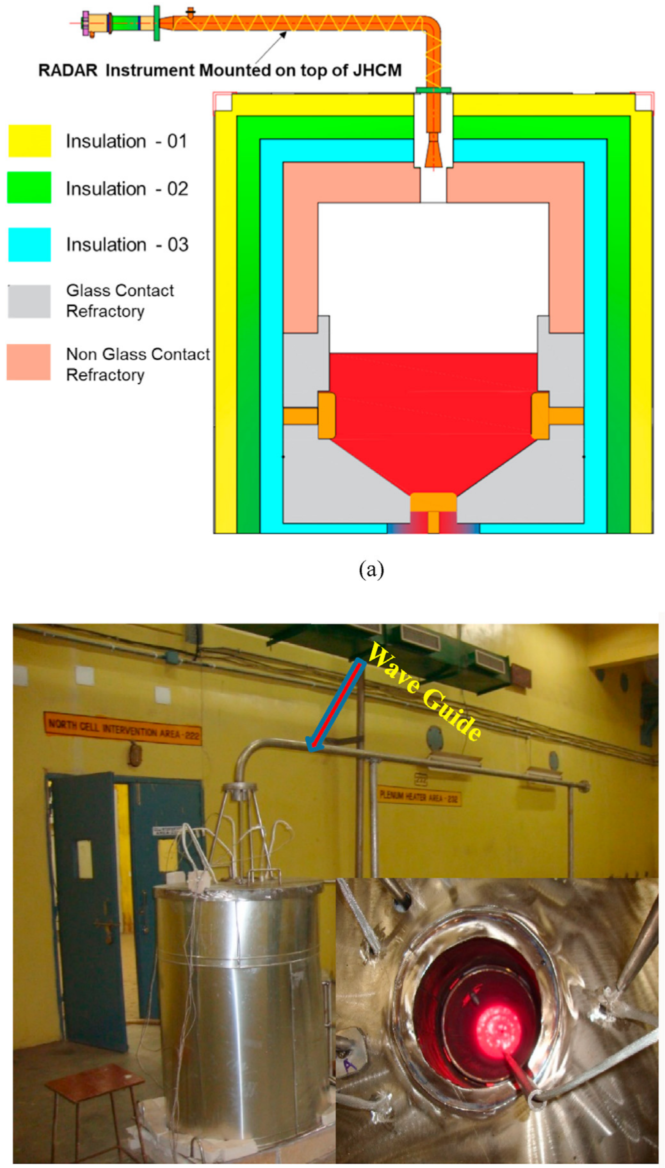


Fig. 1. Structure of Antenna and Horn used in the experiment (all dimensions are in mm else otherwise mentioned).



(a)

(b)

Fig. 2. (a) Schematic of experimental set up (b) Experimental Set up.

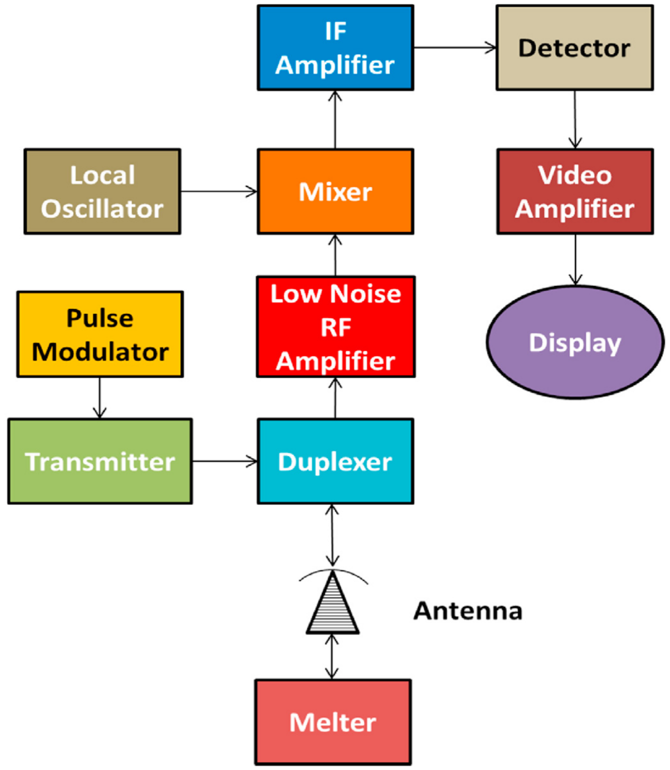


Fig. 3. Block diagram of Signal processing in Pulse Radar.

Duplexer. The pulse modulated microwave signal is produced in a Pulse Modulator and is applied to the Transmitter. The transmitter then transmits a series of repetitive pulses to the Duplexer. The Duplexer is a microwave switch, which connects Antenna to the transmitter and receiver alternatively. The antenna transmits the signal when the Duplexer is connected to the transmitter. Similarly, it sends the signal received from the antenna to the Low Noise Radio Frequency (RF) Amplifier.

Mixer compares the signal from Low Noise RF amplifier with the stable frequency produced by Local Oscillator. The difference of the frequencies is Intermediate Frequency (IF) type. IF amplifier amplifies the IF type signal obtained from Mixer and improves the noise ratio. The signal from the IF amplifier is demodulated by the Detector. The Video amplifier amplifies the video signal obtained from the Detector. The amplified video signal is displayed on the LCD screen.

Non-contacting pulse radar sends out a microwave signal that

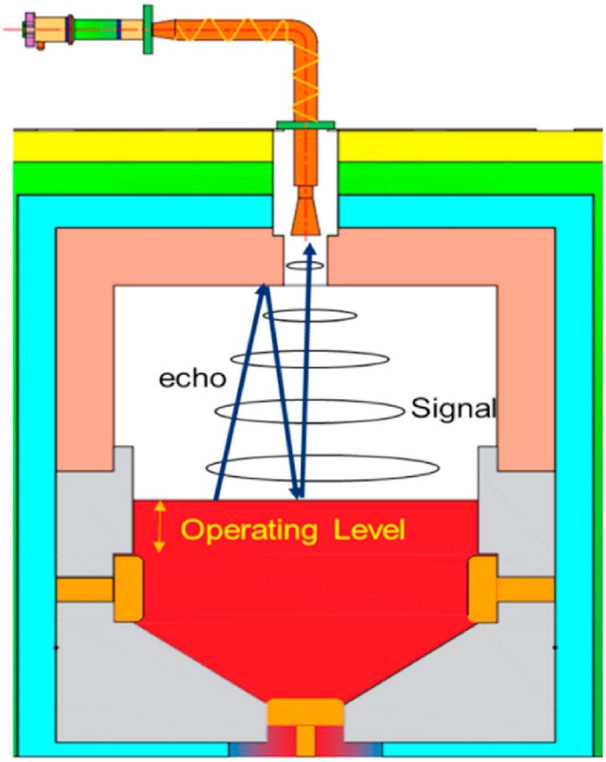


Fig. 4. Beam projection inside the experimental set up.

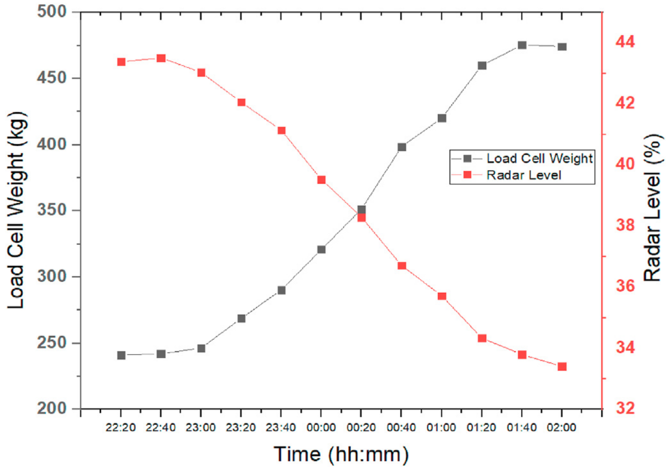


Fig. 5. RADAR Level measurement and other parameters variation in the experiment.

bounces off the product surface due to a change in the dielectric constant of medium and returns to the sensor. The transmitter measures the time delay between the transmitted and received echo signal as shown in Fig. 4. The on-board microprocessor calculates the distance to the liquid surface using the formula:

Distance = (Speed of light x time delay)/2.

Once the transmitter is programmed with the tank reference height of the application – usually the bottom of the tank or chamber – the liquid level is calculated by the microprocessor.

Level = Equipment Height – Distance.

After adding simulated waste, change in the level was observed

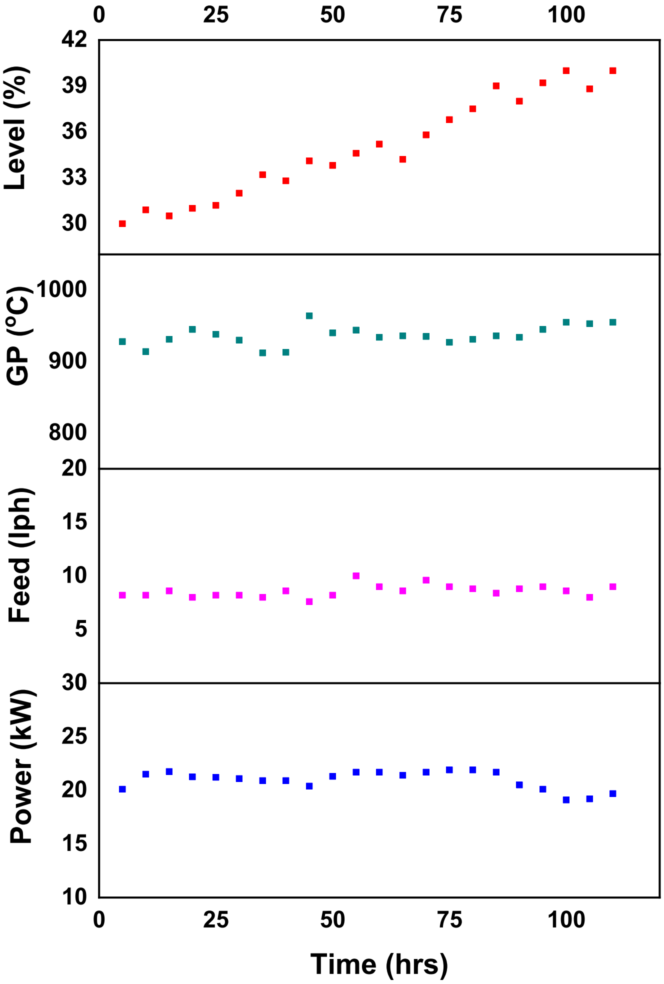


Fig. 6. Load Cell Weight & RADAR Level Vs Time during pouring.

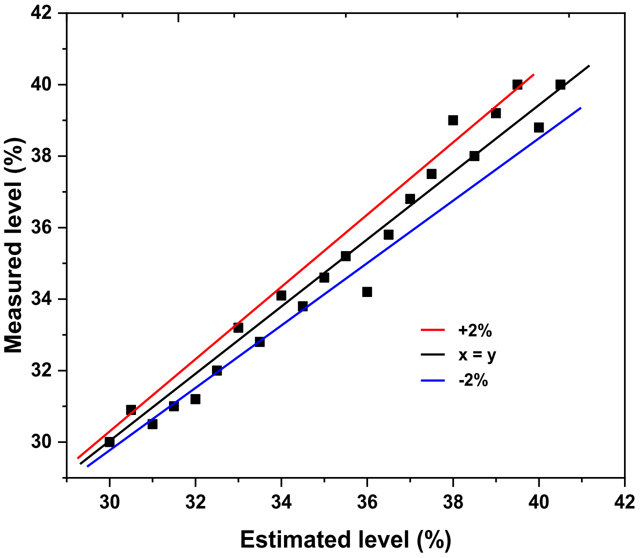


Fig. 7. Parity plot for RADAR level measurement.

(it was observed that level is fluctuating). The experiment was conducted for 120 h. The level measured by the radar was rising with the addition of feed. The rise in level was consistent with the theoretical level calculation from the calibration data of the melter as indicated in Fig. 5.

Also, the level measured during the pouring of the simulated waste product was compared with the Load Cell weight measurement. The radar level indication was in agreement with the increase in the Load cell weight. The performance of the RADAR Level probe during pouring is presented in Fig. 6.

The radar level measurements were compared with the theoretical level calculations and error was found to be about ±2% which is satisfactory for the radar to be used in the industrial scale. The parity plot is shown in Fig. 7. Yoshioka et al. [18] used a glass level detection based on the electrical resistance with reliability of ±10% within 100 mm range of operation.

4. Conclusions

Measurement of level in a radioactive industrial vitrification furnace is developed using a non-contact remotely placed real-time RADAR level measurement. The system till date has been exposed to more than 600 MRads and successfully performed continuous monitoring of level in JHCM. Although provision exists for remotely replacing the entire unit, till date no necessity has been felt and the RADAR has been performing satisfactorily. A frequency of 25–30 GHz is suitable for this application. Measurement in a radioactive furnace containing about 1 MCi of radioactivity was demonstrated and the instrument has functioned uninterruptedly for 21,000 h without drift in the sensor.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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