DETECTION OF EARLY STAGE GLASS PENETRATION AND WEAK REFRACTORY SPOTS ON FURNACE WALLS

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ABSTRACT

Erosion of the refractory lining in molten glass furnaces is a major problem for the glass manufacturing industry. When erosion on the walls is not detected early enough, it may lead to a molten glass leak through the refractory lining and may result in the suspension of production for several weeks. In some cases, a catastrophic accident may also result. The glass penetration typically starts small within the insulation layer and takes anywhere from a few weeks to several months to penetrate through the insulation layer and result in major catastrophic furnace leak. Therefore, detecting an early stage glass penetration within the insulation layer and identifying weak refractory linings will result in safer and longer furnace operation through preventive and proactive maintenance.

To address this major industry need, we are developing a non-destructive sensor technology for tomographic imaging of insulation and refractory lining. This sensor will identify early stage glass penetration into insulation and identify weak refractory spots for preventive and proactive maintenance. We have already developed a sensor that measures the residual AZS thickness on operational glass furnaces. We have also shown the feasibility of mapping interior walls of insulation layers for glass penetration in an operational furnace. Lastly, the same sensor technology is capable of detecting voids and defects in cold refractories.

In this paper, we will discuss the underlying fundamentals behind the proposed sensor technology, the measurement results pertaining to feasibility and in-situ tests on operational furnaces, and the path forward to an integrated sensor system for smart (self-sensing) furnaces.

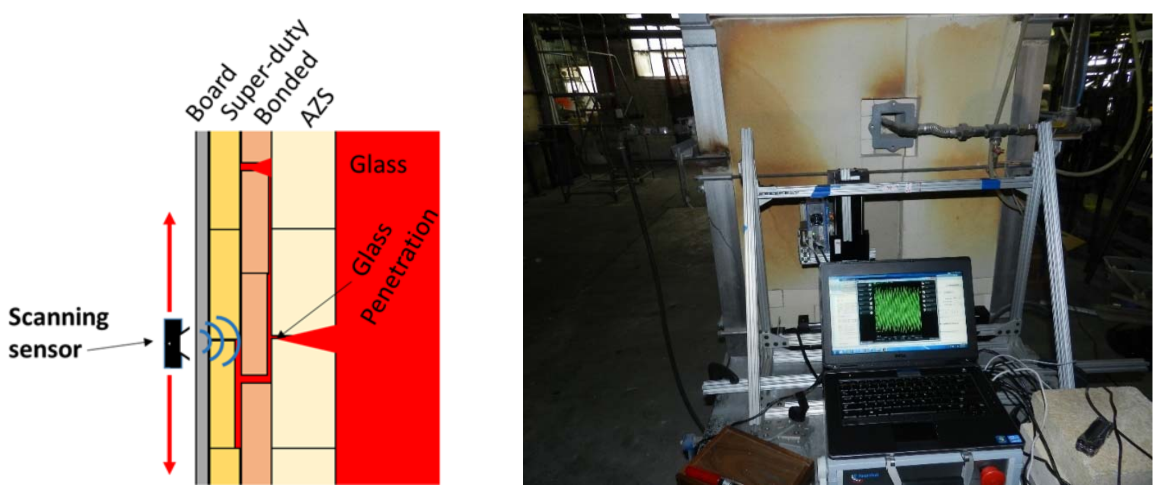
INTRODUCTION

Erosion of refractory lining of glass furnace walls is a major problem for the glass manufacturing industry. When erosion on the walls is not detected early enough, it may lead to a molten glass leak through the refractory lining and may result in the suspension of production for several weeks. Detecting early-stage glass penetration before a major leak occurs will result in safer and longer operation. These glass penetrations can be detected using a wireless non-destructive sensor technology, currently under development at PaneraTech, Inc. The technology is based on radar imaging of the internal wall structures and utilizes specialized imaging and mapping techniques. The hardware is designed to have a very low profile, allowing it to fit close to the furnace walls and out of the way of any structural or cooling elements. In this paper, we will discuss the underlying fundamentals behind the proposed sensor technology, the measurement results pertaining to feasibility, and the path forward to an integrated sensor system for smart (self-sensing) furnaces.

TOMOGRAPHIC SENSOR FOR EARLY STAGE GLASS PENETRATION DETECTION

The furnace tomographic sensor maps and identifies early stage glass penetration into the insulation layers backing the refractory lining of glass furnaces. This system is based on radar imaging of the insulation layers. The sensor is comprised of an ultra-wideband low-profile antenna specially designed to perform tomographic mapping of the insulation walls. The antenna is connected to radio-frequency (RF) hardware that generate and receive the RF signals into and from the wall. This whole package is designed to fit between structural, cooling, and other elements around the furnace and the furnace wall itself and does not touch the wall. The sensor is then scanned over the wall in a two-dimensional pattern. After the data is collected, it is processed and tomographic images of the internal structure of the wall are constructed. In this way, any glass penetration into the insulation material is identified and mapped.

A conceptual diagram of the scanning system is shown in Figure 1 (a). A common sidewall configuration is shown, consisting of the fused-cast AZS lining, bonded AZS, super-duty firebrick, and fiber board layers. This system will also work with other configurations, such as bonded AZS backing fused-cast behind the fiber board. Only the signal processing changes for the different configurations. The scanning system is configured for the furnace wall so that it will fit around the structural and other components. The system used for the research and development of the sensor itself is shown in Figure 1(b). The system was built to allow for testing on the different sides of the test furnace and at other locations.



(a) (b)

Figure 1. (a) Concept of the furnace tomographic imaging system. (b)Scanning system used for development of the sensor.

To have a fundamental understanding of the materials at high temperatures, we measured the RF propagation loss at high temperatures. The RF properties of the materials change as temperature increases. The probe must be designed for these properties. These properties were measured in-house at PaneraTech, Inc. using a small kiln to heat the different bricks and measure the RF properties at high temperatures. Using this data, the probe antenna was modeled using a computational electromagnetic code and designed to achieve the desired performance. Prototype sensors where subsequently built and the feasibility of these was shown and is detailed in the next section.

GLASS PENETRATION MEASUREMENT STUDIES

To demonstrate the feasibility of the furnace tomography sensor, we tested the system on a developmental furnace at Libbey, Inc. in Toledo, OH. The furnace had four sidewalls consisting of AZS. On one sidewall, a bonded AZS, super-duty firebrick block and fiber board were placed against the AZS. The bonded AZS and super-duty block had pre-cut channels to allow glass to flow from a hole drilled in the fused-cast AZS to the outer layers. These bricks where surrounded by the same type of brick, but without channels. The test furnace at Libbey is shown in Figure 2. A drawing of the channels cut into the layers are also shown. A vertical and horizontal channel guide the molten glass into the horizontal groove cut into the super-duty brick. Mortar was used to seal these blocks to make sure the glass was contained in this small area. The installation of the bricks against the fused-cast AZS are also shown in Figure 3.

We performed the tomographic mapping over the area with these cut-outs in addition to the surrounding wall that does not contain glass penetration. This area is shown in Figure 4. A thermal image of the outside of the wall is also shown. There is no indication of glass penetration in this image: the outer surface of the panel is relatively uniform in temperature. The internal furnace temperature was held at 2500 ^{o}F during these tests.

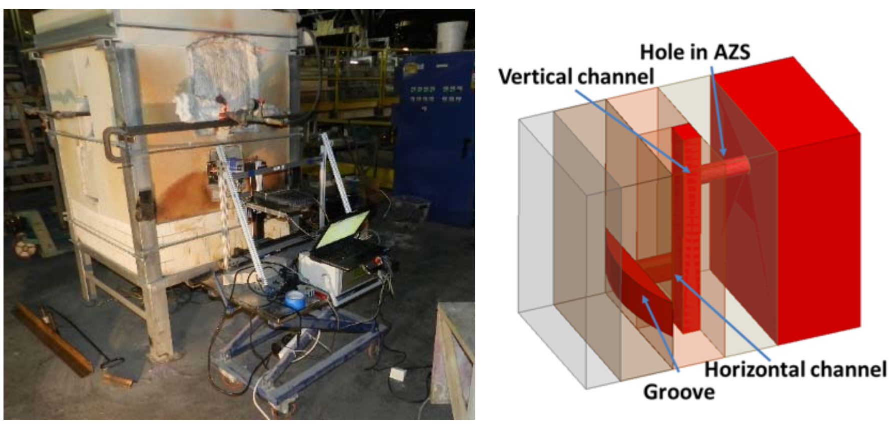


Figure 2. Libbey Test Furnace and diagram of the channels created inside the insulation wall to create glass penetration.

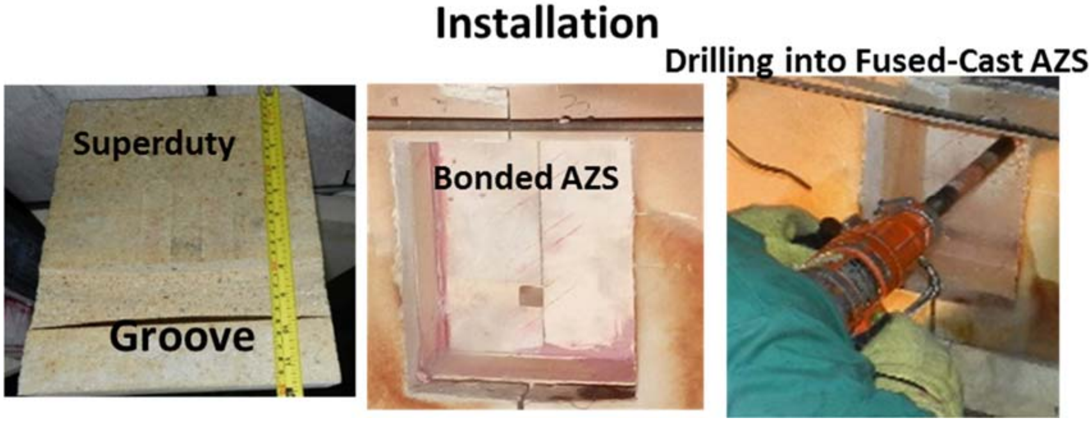


Figure 3. Photographs of the cut-outs into the super duty and bonded AZS bricks and drilling the fused-cast AZS.

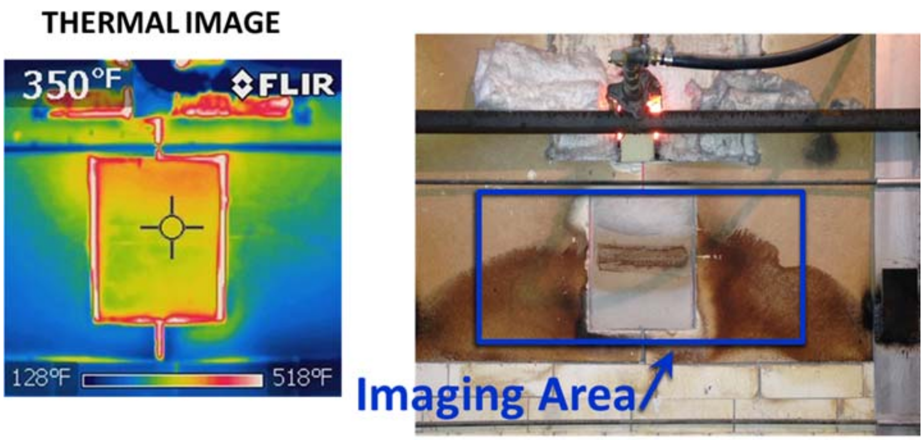


Figure 4. Thermal image of the area with glass penetration and the furnace tomographic system imaging area on the test furnace.

After signal processing, the tomographic images are formed of the internal wall structure. Due to the different material properties of the bricks, we expect a signal to be measured that correspond to the interface between each brick. Any glass penetration into this layer will alter this signal, and depending on the material properties of the blocks, the signal may increase or decrease in power. These effects are readily identified in the imaging results in Figure 5. We show horizontal vs. depth slices in the tomographic imagining results. The first slice is a cut through the vertical center of the blocks. We observe signals at each interface along the horizontal scan, except in the center of the scan at the fused-cast/bonded AZS interface near 9 inch depth. This lack of signal indicates that glass penetration has occurred at this layer. The second slice is cut through the groove in the super-duty block. The shape and location of groove is very well defined in the imaging in this slice. This indicates that we can easily map glass that has eroded into joints and into the blocks, not only at just the brick interfaces.

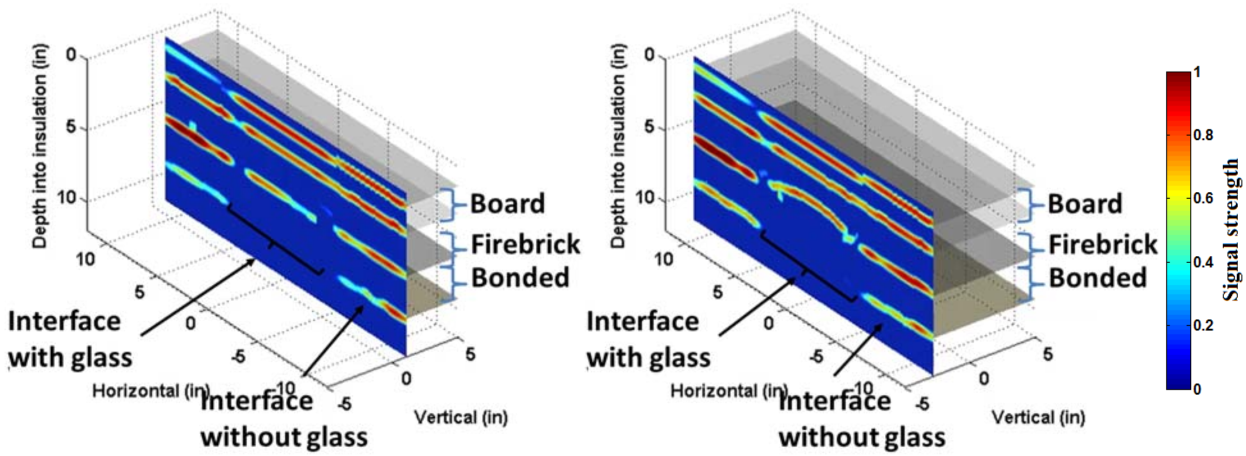


Figure 5. Tomographic imaging results at two different vertical levels inside the blocks.

Given these known signatures from the glass penetration at each depth, it is then possible to automatically identify any glass penetration into the layers. We developed an automatic detection algorithm and applied this to the collected data on the test furnace. The results are shown in Figure 6 below. This glass identification is shown at the fused-cast/bonded AZS interface. As we see, glass is only identified in the 10" wide panel. No glass is found in the surrounding areas at that interface. It is also found inside the groove in the super-duty block as well. Once these areas have been identified, they can be marked, reported and visually displayed.

The test furnace was shut-down and after cooling, the sidewall was opened to confirm glass penetration into the channels and interfaces. Figure 7 are photographs showing that the glass penetrated to the super-duty groove. It was also found that glass had filled the interface between the bonded AZS and fused-cast AZS. As noted above, the presence of the glass at this interface was determined due to the change in the signal received at this interface. These results prove the feasibility of the sensor technology for glass penetration detection.

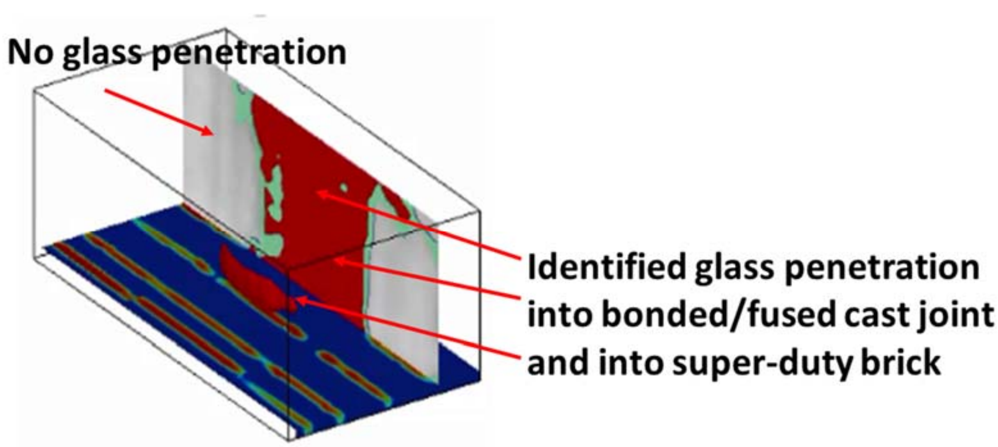


Figure 6. Glass identification at the fused cast/bonded AZS interface joint and into the groove in the super-duty firebrick.

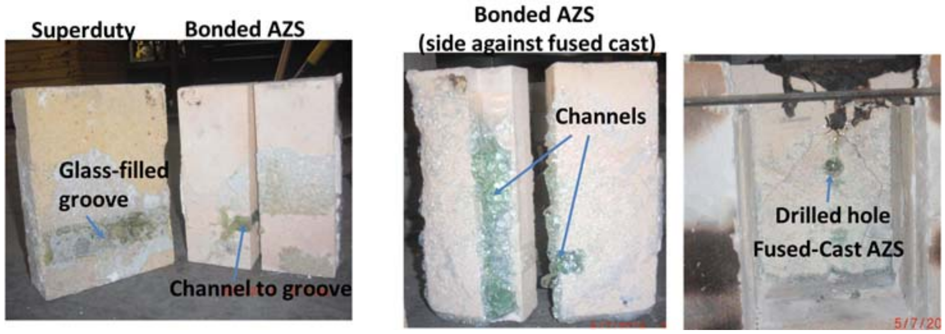


Figure 7. Glass penetration into channels after furnace shutdown.

INTEGRATED SELF-MONITORING SMART FURNACE TECHNOLOGY

PaneraTech has already developed technology for probing exposed AZS refractory lining thickness. This has been implemented in a hand-held solution and an installed, in-situ solution. These sensors work in contact with the exposed AZS wall. The hand-held version allows the user to walk around the furnace and probe as many spots as possible. The in-situ version is installed on the furnace itself to continuously and automatically monitor refractory thickness. Two in-situ probes have already been installed at Libbey’s Toledo, OH plant on an operational furnace. The control box installed near the furnace is shown in Figure 8. The probes are only in contact with the wall during a measurement (which can be less than a second) and automatically retract when not performing measurements. Any number of in-situ probes can be installed in hard-to-reach areas such as throat and in areas where constant monitoring is required. These can be used to monitor critical locations such as the furnace throat and electrode blocks. Currently, these probes can measure the thickness of the AZS lining up to 5 inches. Work is underway to further increase the measurable range of these probes.

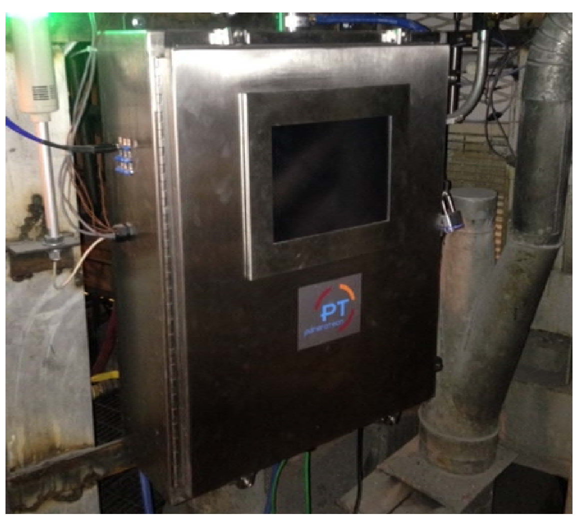


Figure 8. Control box for in-situ probes installed at Libbey, Toledo, OH.

These in-situ AZS thickness sensors, with the hand-held sensor, can be integrated together with the furnace tomography sensor system to create a self-monitoring smart furnace technology to avoid costly leaks and optimize furnace campaign. All furnace health and status data can be combined to generate reports and send alerts. The operators and maintenance staff will thus have awareness of the health of the furnace and be able to observe trends over time as well. This awareness will result in safer and longer furnace operation of furnaces through preventive and proactive maintenance.

CONCLUSIONS AND FUTURE WORK

We have proven the feasibility of the furnace tomography system on the Libbey test furnace. Using the small furnace at 2500 ^{o}F internal temperature, we were able to map and automatically identify glass penetration at the bonded AZS/fused-cast AZS interface and into the super-duty block as well. Further refinement of the sensor hardware and image processing is underway using a new test furnace at Libbey in Toledo, OH. This new furnace has several different walls that emulate several different kinds of glass penetration scenarios observed in actual glass furnaces. Additionally, this test furnace will enable further development of the system to measure and image the glass interface behind the insulation layers and AZS lining. Further steps include installation of the low-profile scanning system and demonstration on an operational furnace at Libbey, Inc. We will also further develop the signal processing to allow for imaging through extruded metal gratings that are used on some furnaces in addition to mapping behind structural beams located against the sidewalls.

Given the compact and flexible nature of this system, the full sidewall area of a furnace can be monitored allowing for glass penetration and refractory lining weak spots to be detected and monitored over time. Integrating this system with PaneraTech's other furnace monitoring solutions, a self-monitoring smart furnace can be realized.