An automatic ladle level measurement system for monitoring ladle fill rate during tapping

A. Rödfalk*, J.P. Nilsson*, N. Brogden*, P. Bloemer*, A. Lyons*, and O.J. Østensen†

**AGELLIS Group AB, Lund, Sweden*
†Elkem Thamshavn, Orkanger, Norway

Reliable and accurate metal transfer information during silicon tapping from an EAF is invaluable for decision-making and process optimization, while obtaining such information safely is a necessity.

Elkem Thamshavn Norway, a producer of metallurgical-grade silicon, identified inherent safety problems with gauging fill levels in ladles using dip bars while molten metal was continuously pouring from a rotating EAF. Operator safety was a paramount concern, and an alternative automatic method of controlling the tapped fill level needed to be found.

It was also considered that further benefits could be achieved such as monitoring the tapping flow from the EAF in order to identify any clogging, as well as the potential to use the live feed from such a system to assist decision-making regarding work around the tap-hole area.

Agellis Group AB, Sweden, a company with over 30 years of experience in gauging molten metal levels in the metals industry, was able to design a solution for Elkem Thamshavn that would provide the required real-time process data while enhancing operator safety.

This paper shows how the Agellis AB EMLI-L system was successfully installed at Elkem Thamshavn's EAF continuous tapping area, how ladle fill levels were constantly monitored, and how full ladles were replaced by empty ones without the need for operators to be in the tapping area to take level readings. The results were used to compare the accuracy and reliability of Elkem Thamshavn's current measuring methods with that of the EMLI-L system. The paper also covers how problems such as how to connect, run, and protect cables in and around the EAF tapping area, as well as connector and cabling survivability during the three day refractory pre-bake period, were solved.

Finally, the paper discusses the potential production improvements, maintenance requirements, and data integration attainable through the installation of the system, as well as the major safety improvements that have been achieved.

Keywords: Silicon metal, ladle level, EAF tapping, process optimization, dip bars, electromagnetic measurement, operator safety.

Introduction

Elkem Thamshavn (Figure 1) produces metallurgical-grade silicon, the main product used as a raw material in the production of silicones and as an alloying element in aluminium. Filtration of dust in the exhaust gases from their smelting furnaces also recovers Microsilica®.

Figure 1. Elkem Thamshavn, Norway

Silicon tapping method

Elkem Thamshavn operates an EAF melting process that involves rotating the vessel while tapping into ladles. The production of silicon is a continuous process. Silicon is constantly tapped from the EAF into a ladle. Each ladle can accommodate approximately 4 t of silicon, and the filling time for a ladle is usually between 90 and 120 minutes.

An empty ladle is placed on a rail-borne ladle car that is pulled into the tapping position by a small truck (Figure 2). At the same time a full ladle is removed from the same tapping position. The tapping position varies over time around a 180 degree arc.

There is also a rail-borne tapping platform that can be moved into possible tapping positions. There is an office quite close to the EAF where the operators are located when not directly engaged in ladle operations or any other task on the tapping floor.

Figure 2. Empty ladle on car

Ladle level measurement

In order to monitor the progress of the tapping operation, the level of silicon in each ladle needs to be regularly measured. This measurement is performed manually by operators who use dip bars to measure the distance between the top of the ladle and the liquid silicon surface.

Due to the continuous nature of the tapping process, this manual measurement is performed mostly while molten silicon is being poured into the ladle from the rotating EAF (Figure 3). Elkem Thamshavn identified inherent safety problems with this method of gauging the fill levels in the ladles. Operator safety was a paramount concern, and therefore an alternative, automatic method of monitoring the ladle fill level was sought.

Figure 3. Switching ladles during tapping

Other potential benefits of a continuous automated measurement system, such as tracking the rate of tapping flow, were also considered. This type of information could then be used to optimize the tapping logistics and to manage tap-hole blockages more efficiently. Additionally, information from a continuously measuring system could be used to improve tapping area operations and to assist decision-making regarding work around the tap-hole area.

Agellis automatic level measurements

Agellis Group AB of Sweden has decades of experience in the design, construction, and supply of molten metal measurement systems for both the ferrous and nonferrous metal industries.

Since molten silicon has similar conductive properties to molten metals, Agellis was able to offer Elkem Thamshavn a solution for real-time ladle level measurement based on Agellis' proven ElectroMagnetic Level Indicator for Tundishes (EMLI-T).

The ladle-adapted version of this system (EMLI-L) was designed to measure metal levels when filling ladles. By the placement of sensor loops behind the refractory against the inside of the ladle shell and using electromagnetic field propagation, the system is capable of detecting the presence and measuring the level of molten silicon (and other highly conductive materials) as the ladle is filled.

Figure 4 illustrates the placement of the transmitter and receiver coils in a typical ladle.

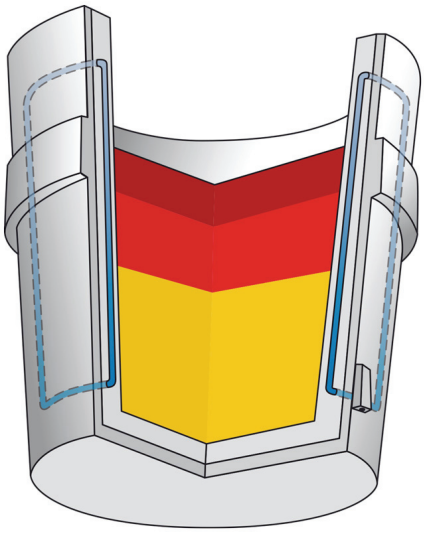


Figure 4. Sensor installation

By leveraging their existing metal level measurement technology in this way, Agellis was able to quickly supply a trial measurement package tailored to the silicon tapping environment at Elkem Thamshavn. This package was then installed and used to perform the trial described in this paper.

Trial circumstances

The EMLI-L trial was initiated by Elkem Thamshavn as one component of a larger smelter safety and performance enhancing project. The system was installed as part of a student thesis project and therefore not initially integrated into the regular operating budget of the smelter, since it was deemed a temporary test to evaluate potential safety benefits to the tapping procedures. Furthermore, only two ladles were initially equipped with the required sensor coils. Later in the project a further two ladles were equipped, bringing the total number of measureable ladles to four at the height of operative testing.

From Agellis' perspective the trial served as a proof-of-concept for the EMLI-L system and an opportunity to further enhance and improve the ladle level measurement platform.

Trial objectives

Elkem Thamshavn decided to conduct the trial of the Agellis EMLI-L system over a six-month period. The aim was to see if the system was capable of providing accurate, real-time liquid silicon level measurements in ladles during silicon tapping from the EAF.

The first priority for Elkem Thamshavn was to avoid exposing workers to the hostile and dangerous environment around the EAF. This would be partly achieved by automatic level measurement, which was intended to replace future manual dip pin measurements.

The second priority for the trial was to be able to monitor the filling rate and thus predict when the ladle in use was going to be full.

In order for the system to be of benefit, a number of site-specific challenges would have to be resolved.

Validation of safety benefits

In order to improve the safety of operators, the installed system would have to reduce the time spent by the operators in the immediate area around the mobile tapping position. Additionally, the system must be readily accessible to operators and not cause confusion or otherwise adversely affect the tapping operations.

Validation of level measurement capability

Since automated ladle level measurements were the key to removing operators from the tapping area, the system must be able to provide clear, consistent, and reliable level measurements to the operators. Operators would also have to feel comfortable relying on the system in order to properly schedule access to the tapping area and thereby eliminate unnecessary exposure.

Validation of fill rate monitoring capability

Since the level measurements were performed continuously in real time, the possibility of monitoring ladle fill rate was to be validated. By monitoring the rate of level change in the ladle it should be possible to predict fill completion time and also to quickly detect blockages in the tapping stream from the EAF. This information could then be used to optimize tapping operations and to plan the tapping logistics more efficiently.

Solving site-specific challenges

Since every installation is unique, site-specific challenges were expected and it was important to validate that these issues could be managed during the trial to ensure reliable operation of the EMLI-L system in the long term. Specifically, the following issues were foreseen:

- Temperature exposure of coils and contacts (exposure to pre-heating oven)
- Electromagnetic interference from the EAF itself
- Cabling to the mobile ladle cars
- Safe connection and disconnection of cables to the ladle cars.

Trial equipment

The system supplied by Agellis consisted of the following initial equipment:

- 1 × control unit (CU)
- 1 × management unit (MU)
- 2 × preamplifier units (PU)
- 1 × switch box (SB)
- 2 × flexible ladle connector cables
- 2 × ladle sensor sets
- 2 × ladle connectors
- 2 × preamplifier connectors
- 1 × system installation cable set.

Aside from the above list, the trial package was later expanded to support a total of four ladles. The level analysis software and operator user interface were also enhanced stepwise during the trial period.

Control unit

The control unit (CU) performs all sensor data analysis and outputs real-time silicon level measurements to the management unit (MU). The CU also generates the transmitter signal to the sensors. In a normal installation, the CU is connected directly to the plant PLC.

Management unit

The MU acts as the user interface for the operators and allows direct access to the CU for purposes of parameter adjustment and signal logging. However, in a normal installation, the MU is not essential for system operation since the CU is designed to operate the system independently.

Switch box and preamplifier units

In this type of measurement scenario, the raw sensor signal is very weak. Therefore the signal received from each ladle requires amplification before analysis can be performed. A preamplifier unit (PU) is therefore used to perform initial filtering and amplification of the received signal. However, since Elkem Thamshavn employs flying ladle changes during tapping, it was deemed necessary to use a second PU to allow rapid switching of the measurement from one ladle to another. The switching between connected ladle PUs is performed by the switch box (SB), which is connected to both PUs and selects which transmitter/receiver line is to be connected to the CU at any one time. This would allow for two ladles to be connected and thereby avoid requiring an operator to switch connector cables during the actual ladle change operation.

Sensors, connectors, and connector cables

Sensor coils were fitted inside the ladles during relining. Since the tapping ladles were to be continually exchanged, it would be necessary to connect and disconnect the ladles from the PUs. Additionally, the ladles would be exposed to oven baking temperatures of up to 650° C. Therefore, each sensor-equipped ladle was fitted with an Agellis designed and manufactured, heavy-duty, high-temperature industrial connector, and a matching connector was fitted beside each of the two PUs. Custom-length industrial cables were then used to connect the ladle to be measured to one of the

available PUs. In this way, the ladle tapping system could be serviced by continually disconnecting full ladles and connecting empty ones to the measurement system.

System installation cable set

The various components in the EMLI-L system were connected using standard Agellis cabling, with the final connections performed on site during the trial commissioning.

Trial installation

The equipment was divided into two main groups.

- Sensor coils and ladle contacts
- Main system cabinets and cabling.

Ladle sensor installation

The ladles in use are quite small and have an outer diameter of about 2 m and a height of about 1.7 m. All ladles are equipped with spouts located about 100 mm below the top of the ladle.

Elkem Thamshavn requested a safety freeboard of 350 mm to avoid over-filling which, taking into account the location of the spout, gives a maximum level of 450 mm from the top of the ladle.

Sensors, sensor protection, and heavy-duty connectors were installed in both the ladles initially used in this trial.

Please see Figure 5 below for an illustrates of a sensor-equipped ladle.

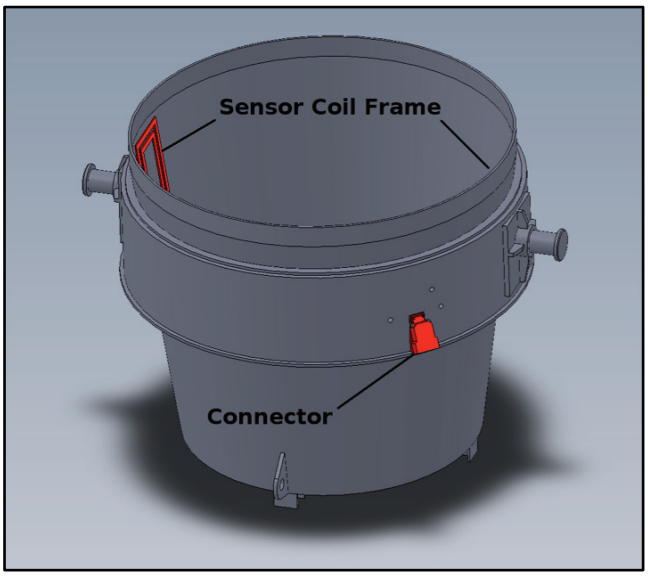


Figure 5. Ladle with sensor and connector

Sensor mounting

The transmitter and receiver sensors were mounted on opposite sides of the internal ladle walls in open steel frames.

Both sensor coils were routed internally around the ladle to a common exit hole. The coil leads were then attached to the externally mounted ladle connector. The ladles were then re-lined and oven dried.

Thermal considerations for ladle contacts

When a ladle has been relined it is put in an oven for drying. The drying process takes about 3 days, during which the entire ladle (including connector) reaches a maximum temperature of about 650°C.

As a consequence of this type of high thermal load, Agellis chose to use their own proven high-temperature industrial contacts initially designed for the demanding EMLI-T system. The only necessary modification to these contacts was to not apply the usual outer surface paint.

Main cabinets and cabling

The Agellis equipment was installed by Elkem Thamshavn with the assistance of Agellis engineers as shown in Figure 6.

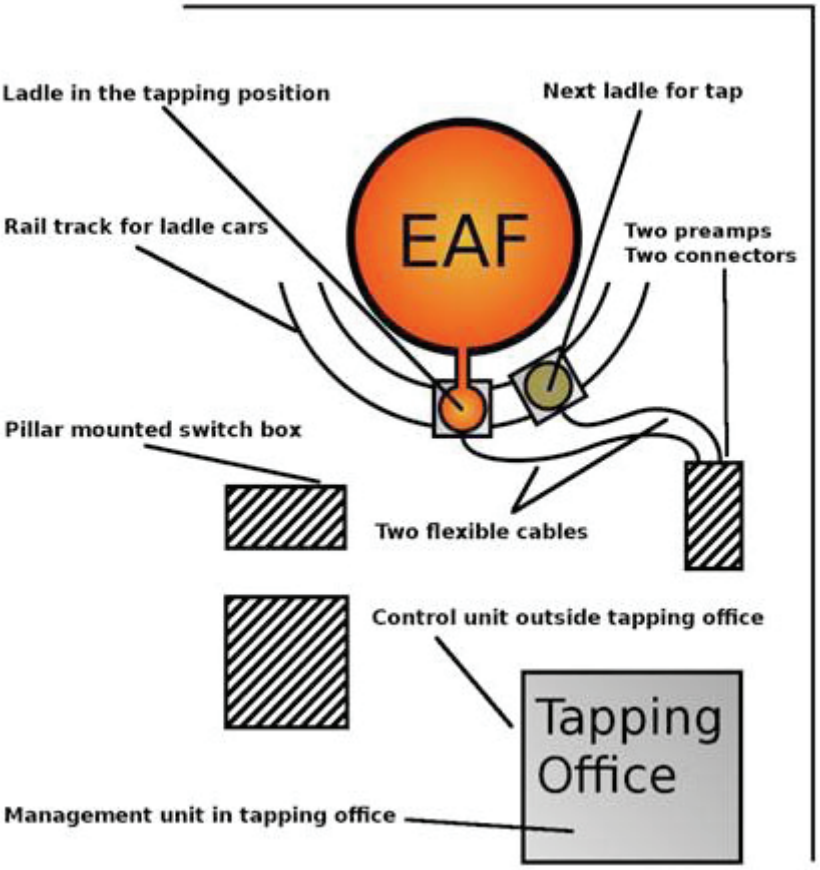


Figure 6. Trial installation overview

Elkem Thamshavn practices flying ladle changes. It is therefore necessary that the next ladle is prepared and calibrated before tapping to the current ladle is completed. This means that both the ladle currently receiving silicon and the next ladle in line must be connected at the same time. Selection of which ladle to engage was to be performed via a manual handle on the switch box.

The longest possible distance from the wall-mounted PU connector to a ladle in a tapping position was about 35 m. Therefore the flex cable between the ladle and the wall connector needed to have a total length of about 35 m. In order to avoid risk to operators, the ladle connector could not be disconnected during the flying ladle change. Instead, each flex cable was equipped with a male-female connector pair about 5 m from the ladle. The disconnection could then be performed at a safer 5 m distance from the hot ladle before the full ladle was moved out of the tapping position.

Since the ladle-end cable section will be dragged with the ladle that is moved after filling it was decided that the connectors used for connecting the two flex cable sections should not be too large or heavy.

See Figure 7 for an illustration of the divided flex cable design.

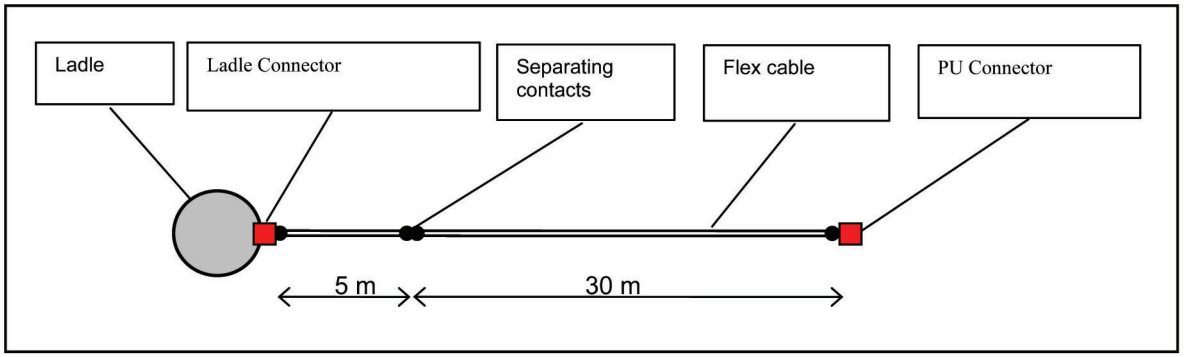


Figure 7. Cable connection overview

Trial commissioning

The commissioning comprised the following stages:

- Final cabinet connections and system power-up
- Cold testing
- Hot testing.

Final connections and power-up

Inspections of the installed equipment and validation of final cable connections took half a day. The system was powered up and the CU was configured for initial testing.

Cold testing

During cold testing of the system using empty ladles, a preliminary analysis of the frequency spectrum near to the EAF was performed using the CU. This frequency scan indicated strong electromagnetic interference from the EAF in the lower frequencies. The CU operating frequency was therefore increased to 1 kHz in order to avoid the bulk of this interference. The system was tuned to optimize the pre-amplification and transmitter energy levels before continuing with the hot testing.

Hot testing

Once the system was correctly configured for the local measurement environment, testing continued on ladles being filled with molten silicon. Initial results were very positive, but not perfect. Apart from the constant low-frequency EAF disturbance, the sensor coils were saturated during work on the tap-hole using high-power electrodes. This disturbance was spread across the entire measureable frequency spectrum, as shown below in Figure 8. Fortunately, this type of interference occurred only when the tap hole became blocked and needed to be re-opened.

Figure 8 clearly shows the SNR benefit of increasing the measurement frequency to avoid the constant EAF-generated interference. However, the wideband interference produced when re-opening the tap-hole completely swamps the relatively low-amplitude 1 kHz operating signal.

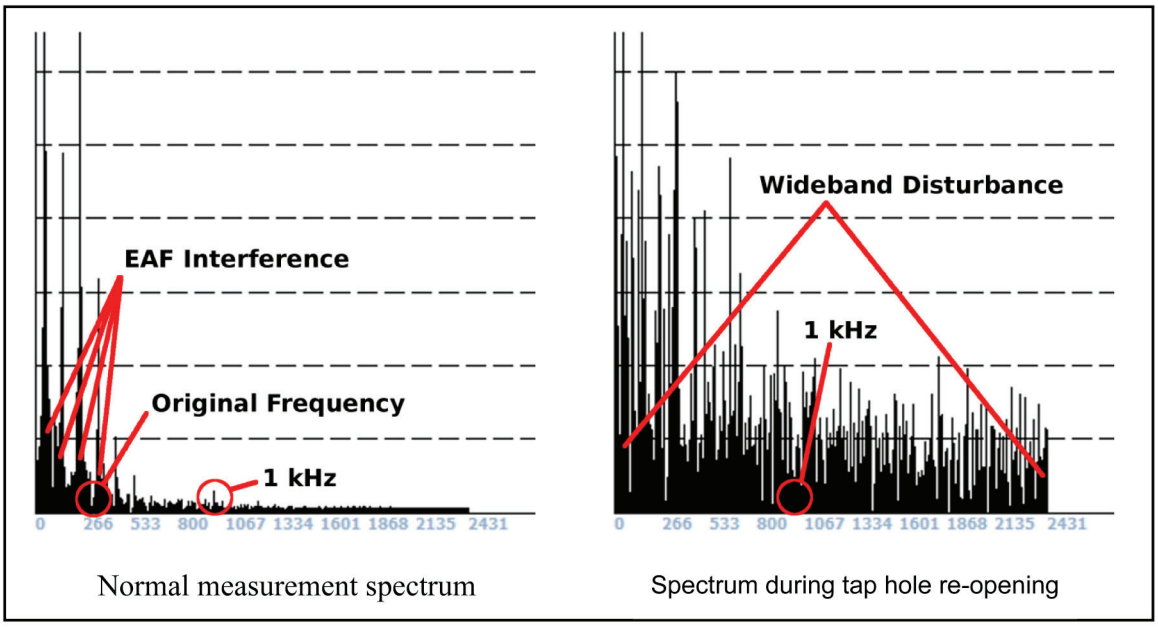


Figure 8. Effect of tap hole widening procedure on interface

It was therefore necessary to enhance the analytical software to handle this scenario safely. A VPN connection to the system was installed in order to enable remote support by Agellis during the trial.

Trial measurements

Measurements proceeded over the trial period, resulting in very interesting tapping process data which was logged on the MU for later review. Improvements to the analysis software were made based on these observations and used to improve the measurement capabilities.

Typical measurement of ladle level using EMLI-L

The ladle tap in figure 9 illustrates the filling of an empty ladle. Due to the inherent signal transfer function, the raw sensor signal inverts early in the filling process. This signal behaviour is mostly managed by the analysis software, but still results in a signal jump as the system switches to higher level measurements.

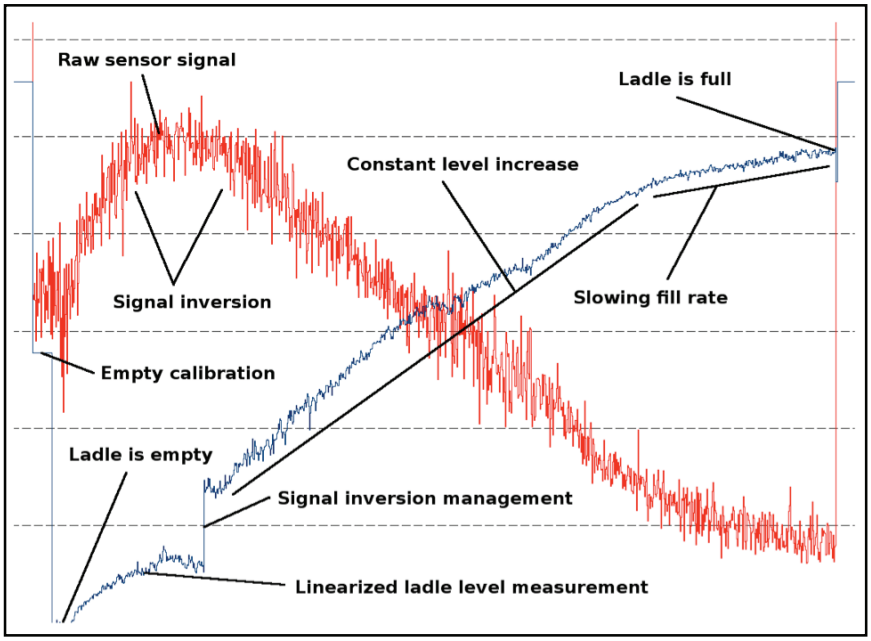


Figure 9. Typical undisturbed ladle filling operation

However, this inversion does not adversely affect the measurement at the more interesting higher levels. In fact, the specific behaviour of the inversion was used in later versions of the software to improve calibration of the measurements for differences in individual ladles with regard to the signal transfer function.

In Figure 9, the relationship between the raw signal and the linearized ladle silicon level can be seen. In this specific example, most of the fill is made with a relatively constant flow from the EAF. During the final part of the tap, a decrease in fill rate can be discerned. This is caused by a reduction in the EAF flow rate, which is very difficult for operators to evaluate visually due to the intense stream glare.

Since the flow rate determines the final fill time of each ladle, better knowledge of the filling process can be used to improve coordination of tapping operations. Furthermore, by monitoring the fill level remotely, operators do not need to approach the ladle during filling to determine the remaining fill time, until absolutely necessary.

Measurement with heavy interference

As can be seen in Figure 10, the re-opening of the EAF tap-hole using a high-power electrode blocks measurement during the re-opening operation, but does not otherwise affect measurement of the ladle fill level.

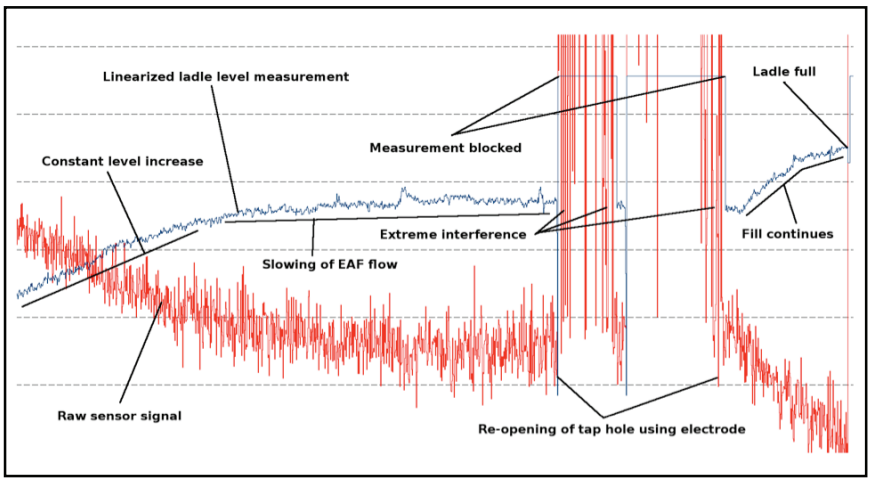


Figure 10. Disturbed ladle filling operation

This example shows how a normal filling operation is greatly delayed due to a gradual slowing of EAF flow. By monitoring the EMLI-L measurements, operators should be able to significantly reduce this type of delay by quickly noticing the flow reduction and beginning re-opening procedures much earlier in the process.

Figure 10 also shows how the EMLI-L system automatically detects the electrode interference and switches of level measurement output in order to notify operators that no reliable level measurements are available. Once the interference ends, the system automatically continues with reliable level measurement until the ladle is filled.

Validation of measurement accuracy

The ladle level measurements could be validated by cross-checking against manual dip bar readings.

This proved that during the initial set-up the system could satisfactorily measure the true fill level in the ladle during tapping conditions with power on in the EAF. The system was then left with the operators to use and gauge the system's reliability and accuracy over the coming months.

Some outstanding issues were then completed remotely based on the following comparative measurements:

- Trimming of linearization tables to increase accuracy
- Adjustment of temperature compensation of the received signals
- Adjustment to the automatic calibration functions to handle the noisy electromagnetic environment.

Agellis remained in contact with Elkem Thamshavn operators as the system was being run during production throughout the trial period. Agellis engineers also later returned to the plant during the trial to assist with improving the practical operation of the system and to address operator's requests on the user interface accessibility.

Additional challenges

During the trial some further challenges were discovered that required adjustments to be made to the system and to the operating procedures:

- Tap-hole re-opening interference
- Cable connection to moving ladles
- Gas stirring in the ladles.

Tap-hole re-opening interference

During the tapping process, the flow rate of the stream of molten silicon can be reduced by solidification in the tap-hole itself. When this is detected, an electrode is applied to the tap-hole in order to heat up the solidification and increase the flow rate.

As mentioned previously, this operation generates interference over a large frequency band, including the 1 kHz operating frequency. Since the level in the ladle is implicitly rather stable during a blockage of this type, this break in measurement is not a problem. However, it is very important that the system does not provide faulty measurements during the re-opening.

Therefore, the system was given the capability to detect this specific type of interference and to enter a safe mode of operation until the interference ceased. Whenever broad-spectrum interference is detected, the system shows a hazard icon on the MU and signals that the output is no longer valid.

In this way, the operators can be sure that the system can be relied upon when measuring under normal circumstances.

Cable connection to moving ladles

One of the major challenges was to find a safe and practical cable routing for the twin cables connecting the PUs with the ladles. These 30 m long cables could be damaged if run over by the ladle cars or other heavy machinery. Elkem Thamshavn worked hard on this issue and tested several different strategies to improve the practical connection and disconnection operations during tapping.

This was the single largest challenge to solve in order to ensure smooth and reliable operation of the system. A satisfactory solution was found using a combination of a cable drum and a strong yet flexible hydraulic hose to protect the ladle connection cable

Gas stirring in the ladles

It was found that the gas stirring in the ladles during tapping adversely affected the precision of the measurements. Since the EMLI-L system measures the top level of silicon in the ladle at any given time, the precision was reduced to ±25 mm when this kind of stirring affected the physical level in the ladle. However, this was found not to interfere with the primary function of the system of determining fill rate and completion time.

Operator user interface

While most automation installations tend to tie system output directly to the plant PLC, the trial nature of the EMLI-L system required a readily accessible user interface in the tapping office. In order for operators to more easily interpret the level output, a graphical application was customized and supplied for the MU located in the tapping office. This application was adapted and optimized during the trial based on requests from Elkem Thamshavn operators.

The screenshot in Figure 11 shows the display on the MU when the level in the ladle being filled was at 372 mm. With the large numerical level display and the colour-coded graphics, operators could monitor the fill status from a distance without having to constantly sit in front of the MU terminal.

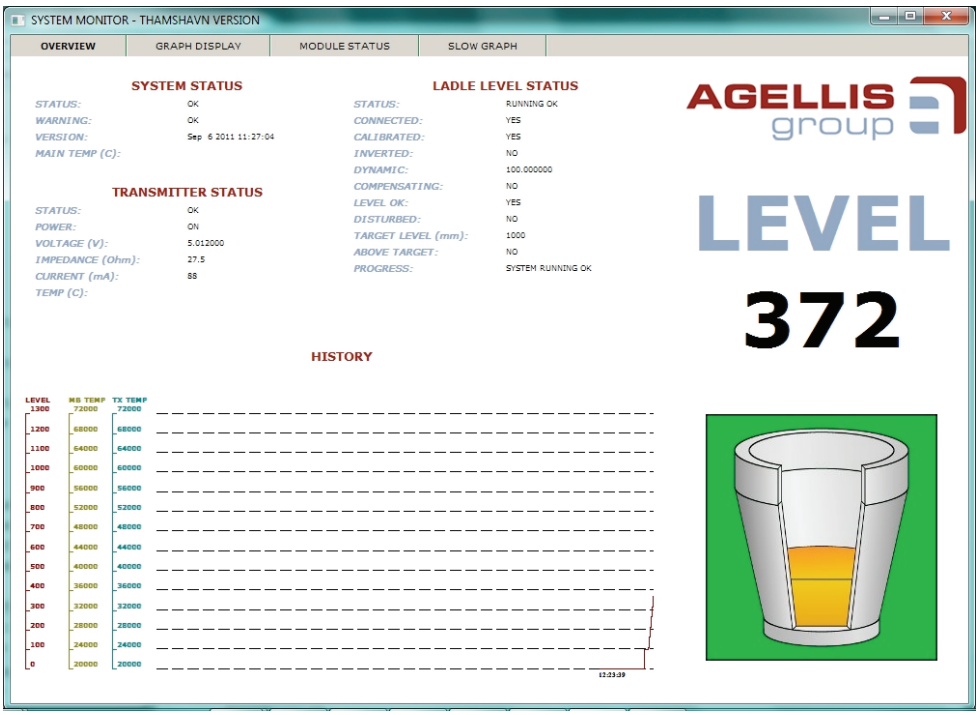
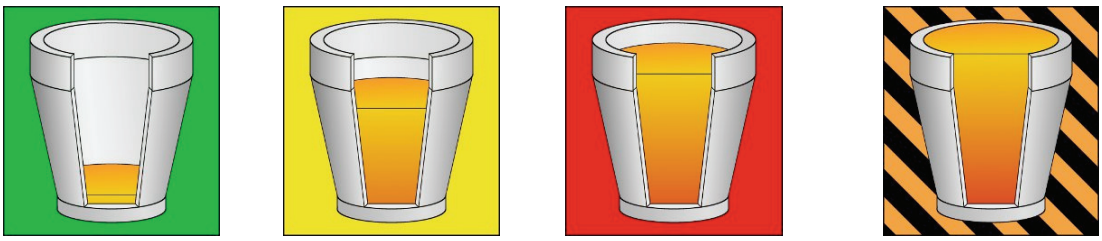


Figure 11. Customised system monitor application

The interface also supported system status monitoring on separate tabs and long-term logging graphs displaying general tapping trends over time. The colour codes are shown in Figure 12.



Green
Normal Fill

Yellow
Nearing Full

Red
Ladle is Full

Hazard
Overflow or Unknown

Figure 12. User interface graphical colour coding

Conclusions

In running this successful trial at Elkem Thamshavn, Agellis Group AB has proved that:

- Accurate and reliable automatic measurement of fill levels in ladles is indeed both possible and practical under plant conditions
- Measurements can be performed utilizing existing technology during tapping with furnace power on and with no disruption or change to the existing melting production processes
- This type of measurement system can be easily installed in ladles and the surrounding tapping area and its output linked to the plant PLCs
- The only issue that required further development was the trial flex cable connection/disconnection procedure and the vulnerability of trailing cables to physical damage. This issue was solved by adding a strong hydraulic hose as physical protection over the cables
- The EMLI-L system has an immediate impact on plant safety improvement, offers assistance to tapping operators, and provides invaluable data about the tapping process.

Acknowledgements

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References

Agellis Group AB. 2011. EMLI Tundish Real Metal Level Measurement - System Overview.
Doc. no: ***COM/DES/002253/REV B****. AGELLIS ADMS archive.*

AGELLIS Group AB. 2011. Case Study - EMLI T System - Höganäs Halmstadverken, Sweden.
Doc. no: ***COM/DES/001277/REV B****. AGELLIS ADMS archive.*

Rödfalk, A. 2010. Thamshavn pre-engineering report.
Doc. no: ***8131/REP/002064/REV A****. AGELLIS ADMS archive.*

Brogden N. 2011. Elkem Thamshavn log Analysis.
Doc. no: ***8131/REP/002329/REV B*** *AGELLIS ADMS archive.*

The Author

Anthony R. A. Lyons, *Sales & Marketing*, AGELLIS Group AB

35 years' experience marketing process measurement and control instrumentation to the world metals industry. Also experienced in the power, atomic energy, and offshore oil/gas exploration sectors.