Foundry 4.0 – Shell Room Experience with SlurryTrack Inline Viscosity Monitoring and Control System

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Purpose

Last year we presented an overview of our Rheonics sensors, emphasizing the advantages and benefits to be had by automating casting slurry viscosity and density. At that time, we were a fairly new presence in the world of investment casting, and then (as now) on a steep learning curve. Today, we would like to share experience that some of our early adopters have gathered over the past couple of years, with the goal of making our and our customers' learning available in the interest of advancing automated slurry monitoring and control in the investment casting community as a whole.

We will start off with a review of the importance of viscosity and density control with a view toward shell room automation, answering questions like:

- Why are slurry viscosity and density important in shell building?
- An evaluation of traditional methods for controlling slurry viscosity and density
- Factors affecting a viscosity/density measuring device selection for slurry application

Viscosity and density: Importance in shell building

Viscosity is a measure of a fluid's resistance to flow. Viscosity of slurry has a profound effect on the quality of each layer deposited in building the shell. By influencing the rate at which slurry runs off a pattern that has dipped and removed from the drum, it determines the ultimate thickness of the layer. If the viscosity is too low, the slurry will run off too quickly and result in a thin, excessively fragile shell layer. If too thick, the layer will also be too thick, and may dry incompletely and unevenly.

Tighter control of slurry viscosity has been found to contribute to the ease and quality of shell building, as well as the quality of the finished cast goods.
Several literature and studies to investigate the effect of controllable shell building process variables on the shell properties cited viscosity as an important input variable.

Density is also an important parameter for characterizing slurry. Density is a measure of the total solids content of the slurry, and may not be directly related to viscosity. Over the past year, users have shown an increasing interest in density monitoring in addition to viscosity. The SRD offers density measurement and viscosity monitoring in one compact sensor.

Shell properties affected by viscosity and density of the slurry:

Layer & final thickness
Surface finish

Permeability
Strength
Edge coverage
Edge strength
Bending strength
Thermal characteristics

Requirements for a viscosity/density monitoring device from the casters' perspective

Whatever means are used to measure slurry viscosity, the caster should not need to be a measurement specialist. A good, reliable and unobtrusive measurement system provides a trusted tool, rather than an added burden to the caster's craft.

The traditional method of measuring slurry viscosity is the Zahn cup, a kind of efflux cup, that measures – or rather estimates – the viscosity of a slurry sample taken from the drum. The operator dips the cup in the slurry, closing the hole at the bottom of the cup with a finger. They then start a stopwatch, while simultaneously opening the hole. The stopwatch is stopped when the last drop leaves the cup. The number of seconds from full to empty depends on the viscosity.

A number of subjective factors limit the precision – the repeatability – and therefore the reliability of the measurement. These include:

- The operator's judgement of when the cup is empty – is it the last drop to leave the cup? Or when the stream of slurry breaks up into drops? Even though a particular operator's measurements may be repeatable, do different operators' measurements agree with one another?
- How clean is the cup? Repeatability of the measurements requires that the cup's volume has not been changed nor has the hole been narrowed by deposits of dried slurry. Repeatable and reliable measurements require a completely clean, undamaged cup, free of all deposits and residues.
- What is the temperature of the material in the cup? Viscosity is notoriously dependent on the temperature of the fluid, and can vary greatly with even small temperature variations. A reliable and repeatable measurement requires accurate measurement of the fluid's temperature, which is impossible with a typical Zahn cup.

In addition to these key factors, human nature also plays a role in slurry viscosity and density measurement. The measurements require interrupting the workflow to pull a sample from the drum. The measurement is messy and somewhat unpleasant. Operators may delay or even neglect cup measurements for this reason. And because other operations demand their attention, they may not clean the cup as thoroughly as is necessary for the next operator to make accurate measurements.

Despite its limitations, Zahn cup viscosity measurements have become a *de facto* viscosity measurement in investment casting, as in many other industries. Users often ask us if SlurryTrack viscosity measurements, expressed in centipoises or mPaS (millipascal seconds), can be converted to cup seconds in order to provide continuity with their current measurement methods.

The SlurryTrack software allows the user to build their own correlations between cup seconds and centipoise readings. As in nearly all applications that measure viscosity of non-Newtonian fluids, there is no universal conversion factor or formula for direct conversion. However, users report that for each formulation of a particular material, a workable conversion formula can be found. But because the conversion is dependent on the composition of the fluid, each user must perform their own correlation based on their own cup measurements.

Laboratory measurements may be more accurate but come with their own problems. In addition to the messiness of drawing samples, they introduce a sizable delay between sampling and reporting of results. That means that any corrective action will be based on a *previous* condition of the slurry – typically hours, or even days ago – and not on its current condition. This makes using lab results for slurry consistency correction an uncertain and risky business.

On top of these factors, slurry is a “living” fluid – its condition is based not only on its composition and its temperature, but on its flow history. Slurry in the drum – the slurry that will ultimately coat the pattern – is in constant motion. Slurry that is drawn from the tank is stationary. It will flow differently through a hole in the Zahn cup, or around the rotor of a lab viscometer, differently from the way it flows in the drum. In the case of lab measurements, the solids in the sample may begin to settle, making the sample non-uniform.

An ideal viscosity and density monitoring system should be:

- Repeatable – measurements made today on the same slurry composition should match those made yesterday or tomorrow.
- Sensitive and precise – differences in slurry behavior that are relevant to its performance in shell building should be clearly and reproducibly registered by the monitoring system.
- Capable of measuring in the drum while patterns are being coated – in-drum measurement allows for taking immediate corrective action as slurry consistency drifts out of its specified limits. Sampling interrupts the workflow, while yielding imprecise measurements of questionable usefulness.
- Robust enough for in-drum measurements – Delicate, easily damaged sensors are unusable in the slurry drum. A suitable sensor must not only survive possible rough handling and abrasive slurries, but also thorough cleaning and removal of tenacious deposits of accidently dried-on slurry.
- Capable of taking continuous measurements, at a rate that is useful to the operator, or necessary for automated consistency control.
- Should not require calibration – its accuracy and repeatability should remain unchanged over years of operation.
- Should be compatible with factory and enterprise data systems and models – should have interface and data format that can be read by PC, PLC, or any other device used by the caster to collect and analyze process data, and to give control commands to process systems.
- And perhaps most important, should be “transparent” to the operator – it should not interfere with the operator’s workflow, but should alert them to any irregularities that develop in slurry consistency.

Rheonics SRV/SRD and **SlurryTrack technology** offer a simple and efficient bridge to bring slurry management up to the modern standards that prevail in today's highly automated shell rooms. It is based on small, very robust density and viscosity sensors, coupled with an advanced, industry 4.0-ready data analysis and control system.

Details of the system’s design and implementation have been discussed elsewhere, so only a brief summary is necessary here.

The system consists of a sensor and the SlurryTrack analysis and control system. The sensor is less than six inches long, and weighs about a half pound. Nevertheless, it can withstand the rigors of continuous operation in the most aggressive slurries, as well as cleaning procedures for removing dried-on residues, without ever requiring recalibration.

The sensor’s compact construction has proven a great advantage for in-drum installations. Operators usually make use of the protection cage and long insertion stem that are available with the system. The cage protects the sensing element from damage through accidental collision with the drum walls or other objects, while the stem facilitates rapid and easy removal of the sensor for periodic cleaning and storage if the drum is taken out of service for any reason. In addition, a quick-release mounting system is available to facilitate easy removal and repeatable placement in the drum, if the probe needs to be removed for cleaning, or for drum maintenance.

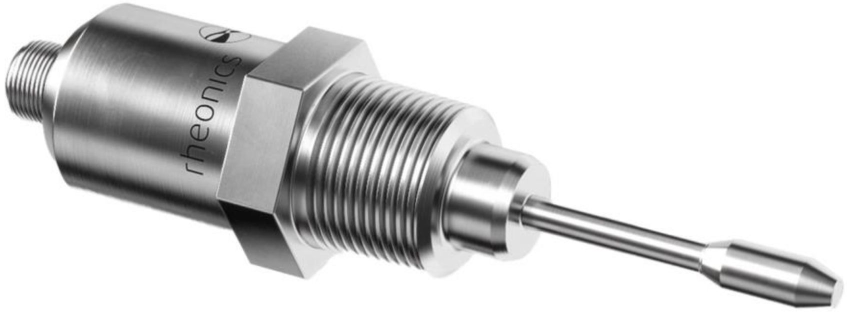

Figure 1: Rheonics SRV viscosity sensor

Figure 2: Rheonics SRD viscosity and density sensor

Moving on to the analysis and control unit, SlurryTrack electronics is delivered in a stainless steel cabinet with DIN-rail mounted components and an industrial PC with touch-screen control. In addition to providing an intuitive operator interface for data collection and control settings, the SlurryTrack cabinet has connections for a wide variety of interfaces, including Modbus, Ethernet, 4-20mA channels, HART, USB, and Bluetooth. This allows SlurryTrack to work and play well with enterprise data systems, making it particularly useful for correlating measured slurry consistency with shell and casting quality measures, over long time periods. The rich data collection and analysis opportunities it offers allow detection of potential problems before they have a significant impact on shell and casting quality and yield.

Now we move on to how to give viscosity and density monitoring a place in the shell room, in general, and some strategies for implementing it in practice. This will take us into points such as:

- Setting up a viscosity and density monitoring system, including installation
- Strategies for monitoring viscosity, starting with simple graphing of viscosity and density data, all the way toward setting up slurry profiles, alarms, and preparing the way for full process automation
- Implementing automatic control of slurry properties
- Dealing with the tough realities of the shell room - cleaning and maintenance of viscosity and density sensors in an abrasive and adherent world
- The possibilities of process optimization presented by automatic monitoring and control.
- Future music - the role of a learning community for taking shell room automation from a buzzword to an everyday reality.

Setting up viscosity and density monitoring

The hardware store: making room for the viscosity/density sensor in the slurry tank

Installing a viscosity and density measuring system in the slurry drum requires a bit of planning. Some considerations are:

- Planning phase:
    - Do you need viscosity and density measurements, or is viscosity sufficient?
    - Will you be monitoring more than one drum in the same shell room?
- Where will you install it on the drum?
- Where will you locate the monitoring and control cabinet?
- How will you connect the system to your enterprise data network?

Before you order a system, you will need to decide if you need both density and viscosity measurement, or if viscosity alone will do. Although viscosity and density are both important for slurry drum monitoring, some users find that viscosity is sufficient for their needs. Viscosity monitoring alone has several advantages, the most important being that Rheonics' SRV sensor can detect buildup of deposits on its sensing element and can alert the operator that cleaning is necessary. Density sensors generally cannot distinguish between deposits on the sensor and increases in measured density, since both load the sensor with additional mass. So for highly deposit-prone, sticky slurries, the SRV, which measures only viscosity, may be a better choice. Before deciding on a sensor, it makes sense to ask yourself what you will use the measurements for. If the measured values are intended to trigger either a manual or automatic correction of the slurry, will density or viscosity be the deciding factor? This can help guide your initial sensor selection.

How many sensors will you be operating in each shell room? If the answer is more than one, it will pay to consider getting a system with multistation monitoring that can service and monitor several slurry drums at once. Rheonics provides SlurryTrack systems with up to 12 stations, so that only one cabinet is necessary to monitor up to 12 stations simultaneously. A single industrial PC services all of the sensors, and produces operator-selected display and, when installed, control modes for each station.

Setting up the sensor in the slurry drum

Users report that it is both best practice and most convenient to install the sensor near the inner wall of the slurry drum. There are two reasons for this. First, it is advantageous to have as large a flow velocity across the sensor as is possible. Since slurry is a shear rate-sensitive fluid – its apparent viscosity varies strongly with how strongly it is being sheared – having a higher flow rate has been found to give the most stable and reproducible readings.

Therefore, we now give narrower guidelines for sensor installation. Because the sensors may be installed in any position, we previously left it up to the user to figure out how best to install it. But we found that users asked for more guidance, or else made mounting decisions that were less than optimal for the particular situation. Therefore, we currently make recommendations for things like minimal distance of the probe from the tank wall, immersion depth, and in the case of the SRD, the orientation of the sensor with respect to the flow direction of the slurry in the tank.

Users have also pointed out that the slurry density and viscosity values vary with depth of the probe in the tank. Since the slurry level drops as shells are built, there is no "perfect" position for the probe. However, the variation of readings with depth is much smaller than the repeatability errors of cup measurements, and lies within the tolerance limit of most slurries. It is therefore recommended to place the probe at a depth that will ensure that is always completely immersed in slurry, no matter what the operating level of slurry in the tank.

The SRV and SRD are available with a tank mount adaptor, that encloses the sensitive part of the probe in a strong stainless steel cage, and provides a ¾ NPT pipe as a mounting stem that enables submerging the sensor to the proper depth in the slurry drum. The immersion depth should be sufficient that the sensor is never above the fluid surface during the course of operation, and it should be high enough in the drum so that it doesn't contact the bottom.

A quick-release mounting system is available that facilitates easy removal of the probe from the drum when cleaning is necessary, when slurry is being replaced, or when other maintenance is being performed on the tank. In all cases, there must be means for washing down the probe when it is removed from the slurry. If slurry is allowed to dry on the probe, it may form a hard, tenacious coating that is difficult to remove, possibly calling for chemical removal. Mechanical removal of long-dried slurry on the probe risks damaging its sensing element. There should always be a bucket of clean water available near the drum in which to immerse the sensor, in case it needs to be removed, as a short-term alternative to a washdown. The arrangement of the sensor in a slurry tank is shown schematically in Fig. 3.

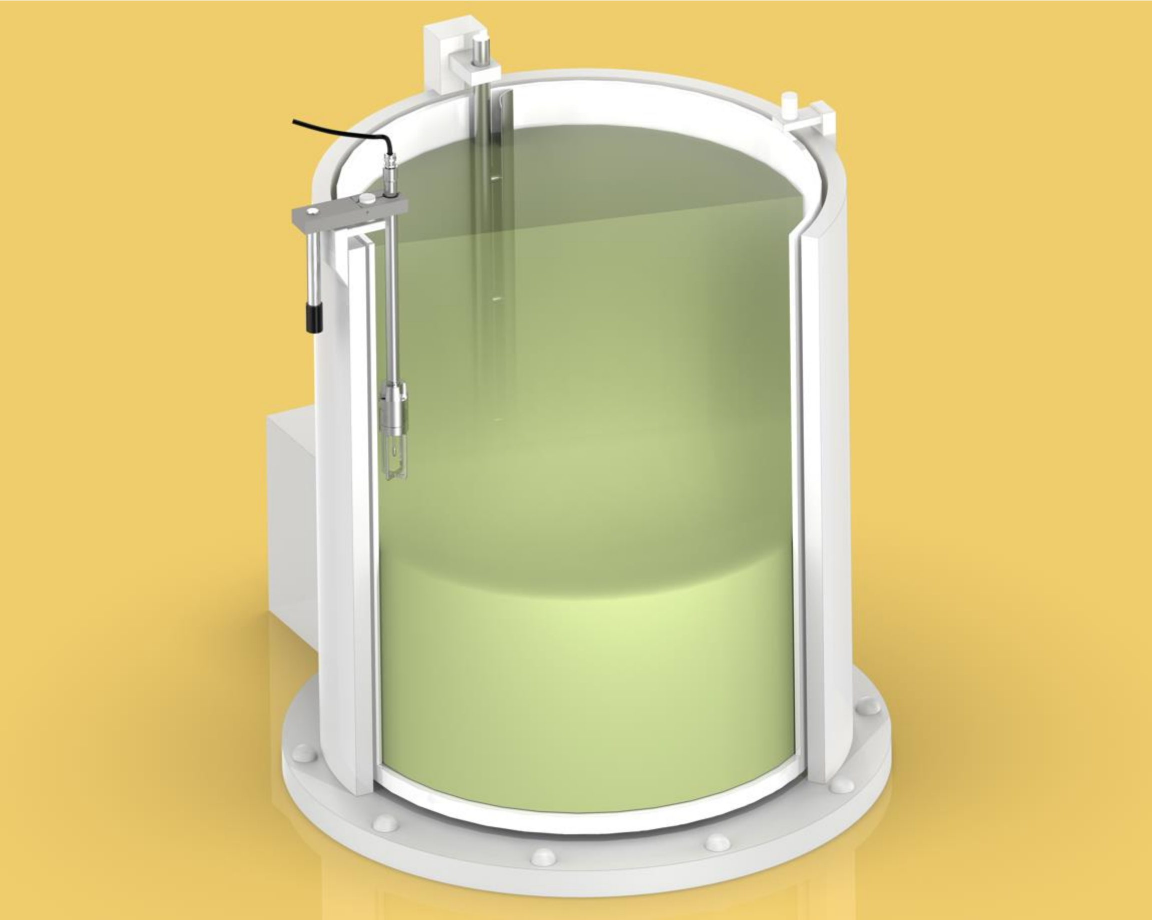

Figure 3: Rheonics SRV/SRD in slurry tank, showing tank mount

Monitoring: **Connect and go!**

Once the probe is installed in the tank, it is connected to the SlurryTrack cabinet by means of a sensor cable. In the event that the cabinet needs to be installed outside the shell room, cable lengths of up to 500 meters can be used without affecting the measurements.
Then turn it on and it’s ready to go! The instruction manual will show the operator how to get a first display of the viscosity – and in the case of the SRD – the density of the slurry.

In a next step, the installer hooks up whatever interfaces are needed to connect the SlurryTrack to an enterprise data network. The installation and operating manual supplies all the necessary information, backed up by a competent support team that includes interfacing and networking specialists.

What to expect from monitoring software

Looking at a display of the raw data as it comes from the sensor may be confusing. Slurry is not a uniform, homogeneous fluid. Bits of solidified material may be carried along with the material circulating in the drum. All of this adds “noise” to the raw measurement data. But closer inspection of even the raw data shows that there is a baseline value to which the measurements repeatedly return. And the duration and time of the noise glitches are usually much faster than any actual changes in the bulk slurry. Therefore, filtering functions are available that enable the operator to filter out the noise and display only the trend of density and/or viscosity. And it is this filtered measurement value that allows the system to control the slurry properties without, for instance, adding water every time the viscosity meaurement twitches “up”.

Processes that change the viscosity and density of slurry include temperature changes, evaporation, and removal of material from the drum. These are all relatively slow processes, so low data rates are preferable to fast-responding sensing. We don't want alarms going off every time the slurry is agitated by insertion of a pattern in the drum, but we do want to follow slow changes in the slurry properties to avoid shell defects and rejected cast parts.

Control

Automatic viscosity control is the gold ring that we'd all like to grab. Automatic viscosity control using conventional "grab and measure" monitoring with the Zahn cup is not possible, and laboratory instruments too fragile and fussy for shell room, in-drum service. True automatic slurry consistency control needs a stable, robust sensor that will not change its properties despite exposure to the abrasive,, rough-and-tumble world inside the slurry drum.

The Rheonics SRV and SRD offer the stability needed for reliable automatic slurry viscosity and density control. Backed up by the Rheonics SlurryTrack predictive tracking control system, the tools are finally available to enable automatic slurry monitoring AND control.

In developing the SlurryTrack predictive tracking control system, user feedback has been an essential part of the process. We have learned that slurry increases in viscosity very slowly. Therefore, any control system must take that into account. If the system is being used to control the slurry consistency by dilution, it is important to *never* add so much diluent that viscosity drops below the minimum allowable value. Correction of overdiluted slurry may require reformulation of the entire tank contents.

Preventing over dilution requires a “conservative” controller that does not trigger dilutions on occasional spikes in the sensor readings, but makes use of stored historical data to judge whether and when dilution is called for. And when dilution occurs, it is in small portions, smaller that is usually used for manual correction of tank viscosity. That way, the system can measure the response of the tank to these small additions, and keep the slurry viscosity in a very narrow range, rather than the jumps experienced when large quantities of diluent are added because the latest cup readings show excessive viscosity.

The technology is still taking baby steps. In the last few years we have heard encouraging reports from adopters of our system, leading us to believe that full shell room automation is within reach. But we are all on a learning project, and this will be the subject of the last part of this presentation.

Fig. 4 shows how the SlurryTrack can be connected to provide viscosity or density control using a valve to dose diluents or other additives.

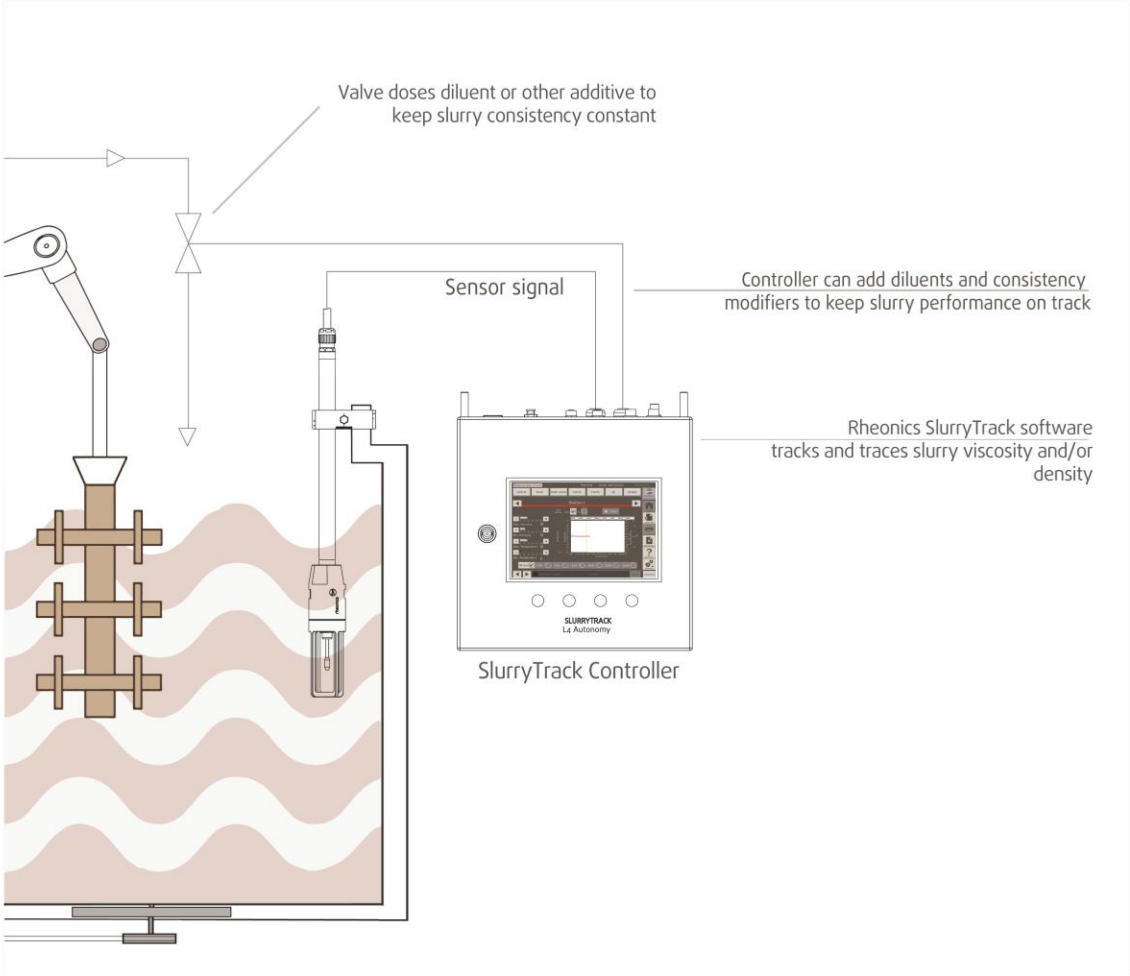

Figure 4: SlurryTrack system for controlling slurry consistency

Clean sensors in a challenging environment

The purpose of shell-building slurries is to adhere to and form a uniform coating on wax patterns, a difficult surface for *anything* to stick to. But a wax pattern only needs to survive one trip through the slurry tank - it eventually goes to pattern heaven when it makes room for the molten metal that is the point of the whole operation. A viscosity and density sensor generally has a surface more conducive to slurry adhesion than the wax of the pattern, and therein lies one of the biggest challenges to in-drum viscosity monitoring.

Detecting deposits on the sensor probe, and removing these deposits in an in-line process, has been one of the biggest challenges of implementing in-drum slurry monitoring. There are two main tasks to facing this challenge, which we will discuss individually:

1. Detecting and removing deposits
2. Detecting effects of abrasion on the long-term survival and accuracy of the sensor.

Deposits on our sensors has been an important and recurring concern. Many of the sensors we produce are used in coating processes, from printing to painting to battery electrode coating, and of course, shell building. Coating materials must be adherent – it is a central part of their function. We tried to build a sensor that never needed cleaning, but the non-stick coatings we tried did not perform well and were insufficiently durable. Therefore our focus changed to making the sensors easy to clean. Their inherently rugged construction and hermetic sealing makes them very resistant to damage by mechanical cleaning methods such as high-pressure washing or simple wiping with a rag. In addition, we have listened to operator feedback and have helped them devise standard operating procedures that become an integral part of their process.

Detecting and removing deposits

The SRV viscosity sensor has a self-checking feature built into the SlurryTrack system. The SRV is based on a resonator that is immersed in the slurry. When the surface of the resonator is clean, its resonance frequency tracks in a predictable way with its viscosity reading. If this relationship changes, it can be detected by the SlurryTrack, and can trigger an alert to the operator that it needs to be cleaned.

Cleaning a sensor that has a buildup of wet slurry is usually just a matter of swishing it in a bucket of clean water, or washing it down with a hose. The more frequently this cleaning cycle is performed, the lower the risk that a strongly adherent deposit will form that needs stronger measures for its removal. To our great surprise, some operators have succeeded in removing hard, tenacious deposits from sensors that have accidently been left to dry while coated with slurry. We feared that the sensors were beyond rescuing, but the users found that even these deposits could be removed without changing the sensors' calibration!

In the event of a strongly adherent deposit that won't come off in a bucket of water, washdown with a high-pressure hose may be sufficient. If for some reason slurry has dried on the probe and cannot be removed by washing it, chemical removal may be necessary. The probe is made entirely of 316L stainless steel and is hermetically sealed, so that it will not be affected by chemicals generally used to remove these deposits from other equipment.

In general, prevention is the best cure. Periodic and frequent washing of the probe is usually sufficient to prevent deposits from forming. Users have reported creative solutions to this task, including using a robot arm to periodically remove the sense and swirl it around in clean water. But any approach to periodic, intermittent cleaning will reward operators with more consistent slurry data, without having to compensate for data drift caused by deposits.

Difficulty of detection of deposition on SRD

All of these measures for coping with deposits are doubly beneficial when used with the SRD density and viscosity sensor. Since the sensor measures density by a decrease in its resonance frequency as increased fluid density loads the sensor with additional mass, it cannot distinguish deposit buildup from increase in density. Therefore, it is essential to clean the SRD at short intervals, and to ensure the cleaning method is sufficient to maintain its density accuracy.

Developing and adopting cleaning methods and strategies is an ongoing learning process to produce the best possible slurry consistency despite the quirks of different slurry compositions. Users tell us that different slurries have very different adhesion properties on the sensor. Some are sticky and require frequent cleaning; others are less adherent, and cleaning intervals of hours, days or even weeks are sufficient to keep getting meaningful and useful data from the system.

Process optimization: benefits of enterprise data collection

Continuous monitoring allows long-term correlation of slurry properties with data on shell integrity and cast parts yield. This is only possible when the monitoring system is more stable than the shell building process itself – the more stable the system, the smaller the changes it can detect in slurry consistency. If the variation of the sensors' response is larger than the changes in slurry consistency, you wind up monitoring the sensor rather than the slurry, which is kind of beside the point.

Long-term measurements of slurry consistency trends and their correlation with overall process efficiency and yield is only possible with automatic monitoring and logging systems, such as the SlurryTrack and its associated sensors. We foresee a time when this and similar systems will enable optimization not only of slurry stability, but also slurry formulations, since it will then be possible to "tweak" and maintain slurry composition with much finer granularity than is possible with Zahn cups or with periodic grab-and-lab slurry tests. And this brings us to the final part of this presentation -- the role of community in the future of shell room automation.

Future prospects

The purpose of organizations like ICI is not only to provide a forum for meeting and greeting our fellow investment casting people - it also functions as an essential vehicle for community learning. ICI actualizes the potential in the investment casting community as a place to share experience that raises the general standard of the industry, from theory through daily practice. The better we do as a community, the better the chances for success of its individual members.

It is in that spirit that we came here this year, knowing that what we consider a great technology can only succeed if it works to ease the job of running a casting operation, and improving the value of the industry’s products and processes in the world marketplace.

We believe in the potential of our systems to improve both the efficiency and quality of investment casting, but we need your help in making that potential an everyday reality. We'd like to thank all of you who have patiently worked with us getting these systems running in real, productive shell-building operations, and who have generously shared their experience and data with us so we can together develop solutions that really work for everyday production. What we hope we offer in return is to free the shell room artisans to focus on building the best shells possible, by relieving them of the complexities of slurry measurements and stabilization.

Acknowledgments

We would like to thank users of the SlurryTrack for very useful feedback on their experience with the sensors and system. Particular thanks to Mark Christensen from PCC Structurals for feedback on this presentation, and for helping us understand some of the basic issues affecting performance of these systems from an operator’s perspective.