WhitePaper

MOULD LEVEL MEASUREMENT

Measuring the steel level in continuous casting

BERTHOLD

Introduction

Radiometric based mould level measurement is the dominating technology for measuring the steel level in continuous casting. This technology has been available for more than 50 years and now with more than six thousand systems deployed. In this article performance, statistical variation, influencing factors and source selection are discussed. Furthermore, the recently developed possibility of continuously measuring the thickness of the casting powder layer is discussed.

Process description

Continuous casting plants enable the improvement of the steel qualities produced and reduce the production costs quite considerably by saving on investments and personnel, as well as better utilisation of the material and thus a considerable reduction in operating costs. These advantages, as well as the improvement of the process in general, have led to the fact that today almost all steel qualities can be cast and therefore about 99% of the total steel production is done through continuous casting.

In principle, a continuous casting machine consists of one or more moulds, which serve as shaping and cooling elements. A mould consists of a copper tube or copper block with an open cross section corresponding to the dimensions of the steel format to be produced. The copper mould is placed in a water jacket through which cooling water flows. Before casting begins, the mould is closed at the bottom by a cold strand.

The steel is delivered in a ladle and drained into a tundish above the mould and then distributed to one or more moulds. This tundish is often fitted with a stopper rod or slide valve to control the flow of steel into the mould. The molten steel is distributed into up to about eight moulds arranged side by side. Within the 70 to 90 cm long mould, the steel cools down to such an extent that an outer solid shell is formed. The still red-hot steel strand leaves the mould at the bottom and is sprayed with pressurised water in the subsequent secondary cooling section. As a result, the inner zones also solidify after a short time.

To reduce the friction between the mould and the steel shell, the mould oscillates at a frequency of 60 to 360 strokes per minute with an amplitude of approximately 3 to 10 mm. The friction is also reduced by the induced flow of mould powder between the strand shell and the mould wall.

In the critical start-up phase of the casting process, the level in the mould above the cold strand rises rapidly and at the right moment the drives must be switched on, which first pulls the cold strand and then the red-hot steel downwards via a roller system. At the same time, the amount of steel flowing into the mould must be controlled in such a way that overflowing is prevented. The casting speed depends on the casting cross section and varies from 0.5 and up to more than 6 metres per minute.

Fig.1 Schematic figure of a continuous caster

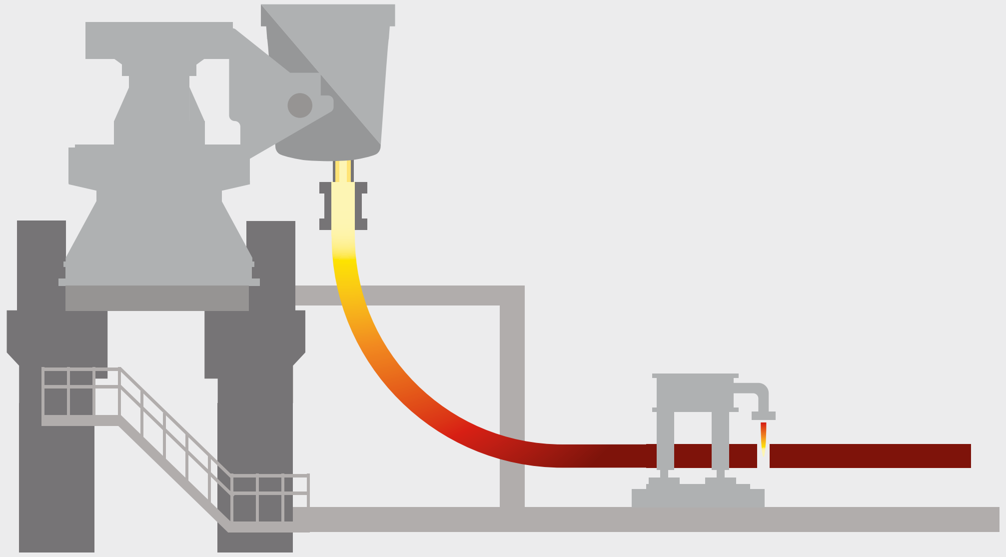


Figure 2 shows the principle the mould level measuring and the components of the continuous casting machine that can be influenced by the control system and the actuator.

Depending on the casting speed, the mould must be continuously supplied with enough liquid steel to keep the steel level in the mould constant. There is a metallurgical optimum for the correct mould level. If the level becomes too high, there is a risk that the mould will overflow or that sealing elements at the mould head will burn. If the steel level becomes too low, the cooling effect is insufficient, and the solidified outer shell of the strand gets so thin that it can break through below the mould and the still liquid core leaks out. Both an overflow and a breakthrough mean an operational disruption, which is associated with very high costs, due to the repairs and cleaning that means several hours of interruption of operation. A very important point, especially in the case of high-grade steels, is the metallurgical interrelationship with uniform cooling and the associated quality of crystallization and the microstructure created during solidification of the steel.

The amount of liquid steel leaving the tundish outlet in a unit of time is not constant, as the cross-section of the ceramic outlet can change due to wear or the build-up of slag or alumina. In addition, the steel flow is influenced by the fluctuating ferrostatic pressure due to changes in the steel level in the tundish. As a result, the level in the mould would change unless the steel feed was controlled either by an adjustable flow or the strand discharge speed.

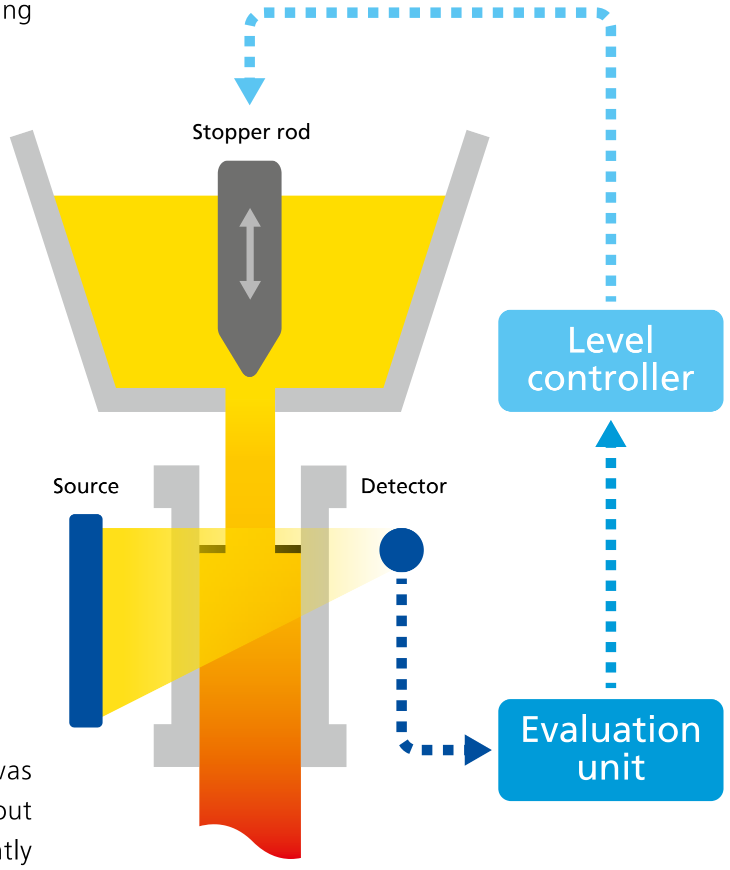
On-line measurement of the steel in the mould is therefore a prerequisite for the control of the actuator to achieve a reliable operation of the level control. Particularly high demands are placed on the control system, especially if it should also manage the casting start automatically.

Before automation of the critical steel level was possible, the necessary sequences were carried out manually by a worker who had to look constantly into the mould and observe the steel level. He then had to either influence the shell withdrawal speed via a potentiometer or control the flow rate from the tundish by means of a long lever with a plug. This work required the highest level of concentration, so that the workers had to take short turns.

The teaming of a single ladle takes about 40 to 60 minutes, depending on the size of the ladle. It is common practice to carry out sequential casting in which several ladles are cast in immediate succession without changing the tundish. In this way, the casting process can be extended to many hours. This avoids losses at the beginning and end of the strand and reduces the cost of renewing the lining in the tundish and by eliminating set-up times.

Of the many proposed and tested mould level measuring methods, today two technologies dominate the application namely radiometric- and electromagnetic technologies. More than six thousand strands worldwide are equipped and rely on radiometry for mould level measurement and this is the most frequently used technology for the application.

Fig.2 Principle of mould level measurement and mould level control



Radiometric mould level measurement

A radiometric based mould level system consists of three main parts:

- A radioactive source
- A scintillation counter (Detector)
- An evaluation unit

The source emits gamma radiation that hits the detector that transforms the gamma radiation first to light and then to electrical pulses. The detector outputs the pulses to the evaluation unit that in turn converts the information into a mould level value, using the recorded, stored, and active calibration curve.
The standard calibration curve for a radiometric mould level system is usually a calibration curve retrieved reading the 0 % (empty mould) and the 100 % (mould filled with a fitting steel block) and then interpolating a straight line in between the two end points (see Figure 4). For even higher precision modern systems allow for non-linear calibration curves with up to 21 different points that can be automatically recorded by the means of an automated calibration rig.
Radiometric mould level systems are immensely robust and can endure the harsh environment and conditions found in the metal industry. Both the source and the detector normally reside inside the mould and are well protected against e.g. overfilling of the mould. Modern sensors handle continuously operational temperature of up to 70 °C and can if necessary be supplied with water jackets for cooling with mould water.
Each single electrical pulse is sent from the detector to the evaluation unit as an EMC resistant amplified voltage pulse. Modern systems also use duplex communications between detector and evaluation unit over a standard industrial communication interface that even further ensures system robustness and redundancy.
The gamma source and the detector are arranged on the mould construction in such a way that the desired measuring range is achieved. Based on theoretical considerations and experience measuring ranges of between 100 and 200 mm are enough to compensate for possible disturbance variables and to allow for automatic start of cast. The length of the rod source used can be adapted to the mould geometry to achieve the required measuring range. By reducing the thickness of the copper, water, and steel layers in the path of the radiation as much as possible, it is possible to keep the required source activity low and thus minimize the effort for radiation protection.
Depending on the casting format and the mould construction, different arrangements of sources and detectors can be realised.

Fig.3 Main parts of a radiometric system

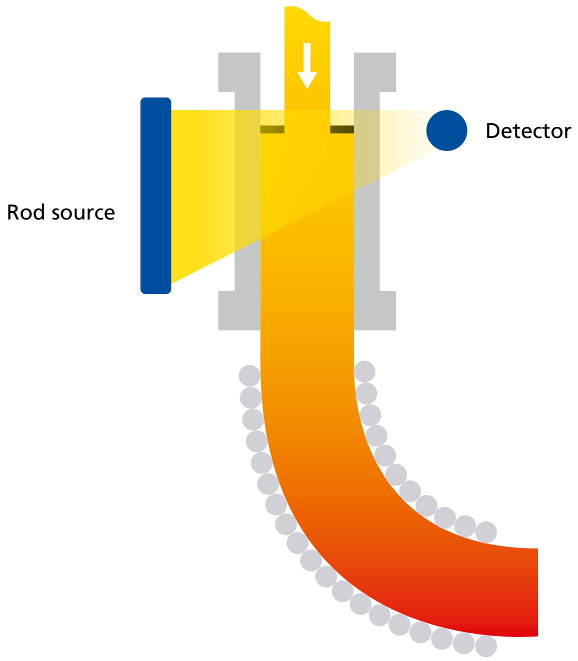


Fig.4 Calibration curve for a radiometric system

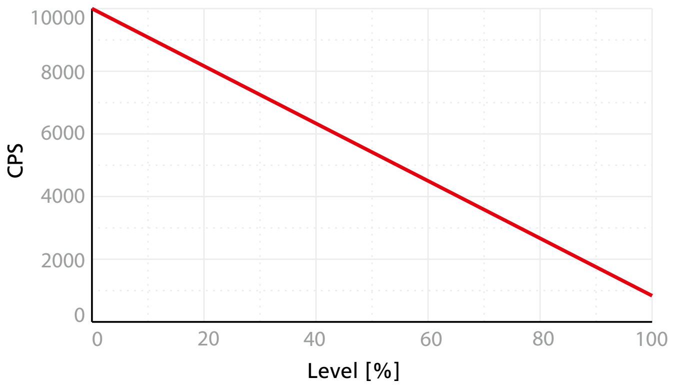
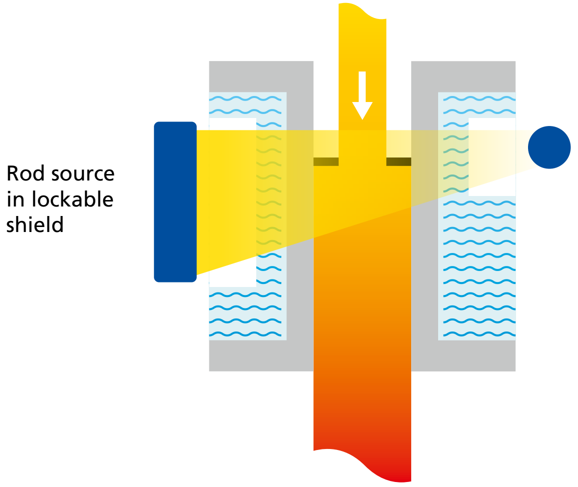
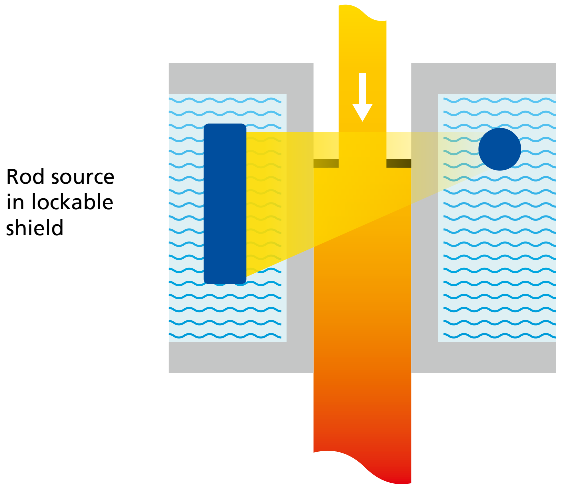


Fig.5 External arrangement with reduced water jacket



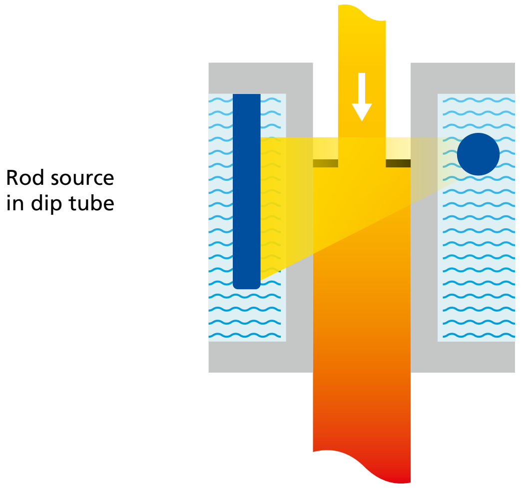
In the external arrangement, the source is installed in a shield, which is attached to the mould outside the water jacket. To reduce the attenuation of the radiation, the water jacket and the water layer is largely reduced.
Depending on the available space, the detector can be arranged either outside the mould or inside the water jacket. This arrangement is preferred for tubular moulds for billet casting formats.

Fig.6 Internal arrangement



The internal arrangement of sources with shield requires the installation of these components in the water jacket or the support frame of the mould. The detector then is arranged horizontally inside the water jacket by means of a protective tube.
This type of installation makes it possible to achieve sufficient reductions in the wall thickness of the copper plates and the steel plates of the support frame, as well as a reduction in the distance between source and detector, as required for bloom and slab formats.
Installation of shielding material is necessary if the source shall be installed in the water jacket or in the supporting frame of the mould without own shield. This arrangement is necessary where space is particularly limited.

Fig.7 Internal arrangement with dip tube



The installation and removal of the source is carried out with the aid of a special shield which has auxiliary equipment and can be placed on the mould above the source installation point. The source can then be inserted from the shield into the protective tube in the mould via an extension rod, so that unprotected handling of the unshielded source is not necessary. This arrangement requires particularly low source activity and has the advantage that no major modification measures are required, even for retrofitting.

Statistical variation

Ionising radiation is generated by decays of radioactive materials. These processes do not take place periodic evenly but follow a statistical distributed regularity. That means that even at constant mould level, the output signal undergoes statistic fluctuations. These fluctuations are of a physical manner and not real level fluctuations. The statistical standard deviation (σ) depends on registered impulse rate (N) from the detector and the effective time constant (τ) in the evaluation unit for the signal processing. The relative standard deviation can be expressed using the following formula:

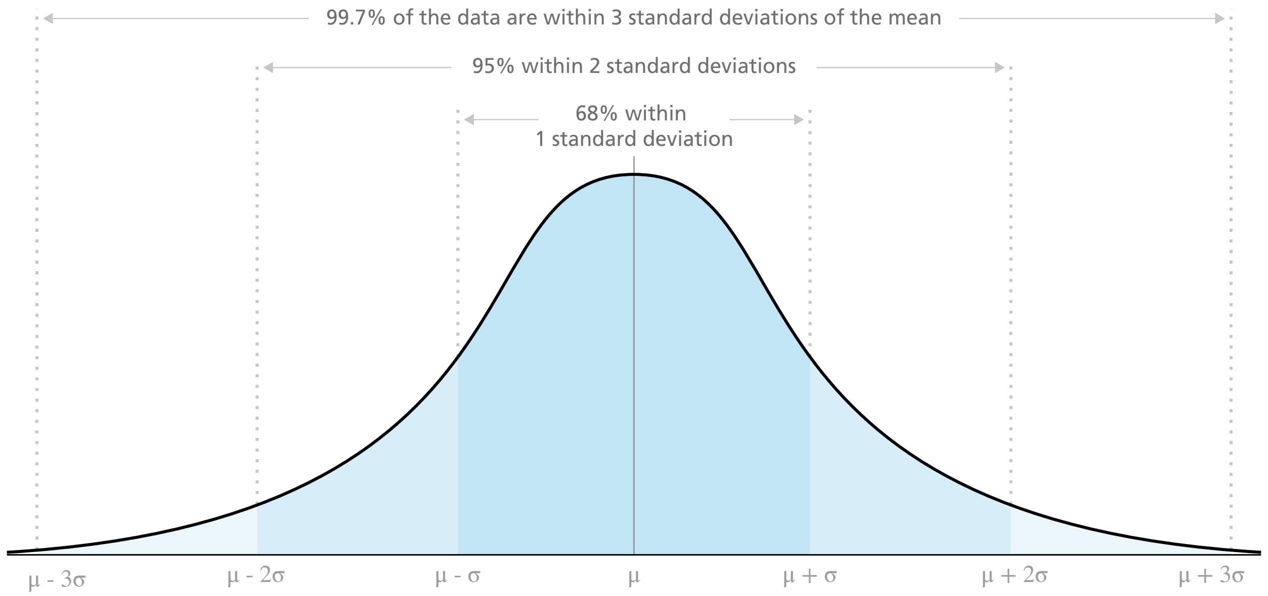
$$\frac{\sigma_N}{N} = \frac{1}{\sqrt{2*N*\tau}}$$

For a standard deviation of 1σ the approximate rule is that approx. 68% of all measured values fall within the range of the deviation +/- σ around the expected value. The 2σ-value about 95.5 % of all measuring values are counted as a typical statistical error and the "maximum" statistical fluctuation corresponds to the 3σ-value with 99.7 % of all measuring values. In a measuring process, it is quite common to calculate using the 3σ- value for statistical errors. From the expression for the statistical error, it is evident that influencing the size of the fluctuation is possible only through change in the impulse rate or in the time constant. An increase of the impulse rate with the given geometry can be achieved by increasing the source activity or the detector sensitivity. The limits of the source activity are given from the maximum allowed dose rates outside the mould cover and the amount of room available and the therefore, possible size of the lead or tungsten shield.

An increase in the time constant is only possible on a limited basis for control technical reasons. Normal measuring ranges span from 100 mm up to approximately 200 mm. Since the casting speed can be about 100 mm per second for small casting cross sections, the full measuring range is passed in 1 to 2 seconds during start-up. This must be considered when selecting the time constant which can then be between 0.2 and 0.5 seconds during start of cast for fast casters.

Modern electronics makes it possible to considerably decrease the statistical error of the mould level signal by using dynamic filters. In realising this, one assumes that in normal undisturbed casting process, the possible mould level fluctuations are much smaller as during casting and other irregular changes are not to be expected. Under these circumstances, operation can be continued with a considerably shorter time constant.

Fig.8 Density function of normal distribution



Time constant and system response time

To cope with statistical variation, modern radiometric systems use advanced filtering for smoothing the raw signal with retained adequate system response time. Implementing a RC-Filter with settable time constant brings several benefits compared to e.g. using a moving average filter. Major benefit for the RC-Filter, compared to a moving average filter with same standard deviation, is that the RC-filter reacts quicker. Figure 9 shows how a RC-Filter (green line) and a moving average filter (orange line), proving the same standard deviations, react to a step change in the ideal signal (blue line).

During normal casting conditions the actual level changes are in a +/- 1 % range and the RC-Filter implementation provides a fast reacting measurement system. The figure below shows the time delay for an RC-Filter. For an RC-Filter, 63 % of the level change is conveyed to the output signal in one time constant or almost 50 % in half a time constant. In the case using a time constant of 1 s, filling the mold from 0 % to 100% instantly, keep it at 100 %, would then yield an output response of:

- 50% after 0.5 s
- 63% after 1 s
- 86.5% after 2 s
- 95% after 3 s
- 100% after 5 s

Fig.9 Comparison between RC-filter (green) and moving average (orange) filter response to a step change (blue)

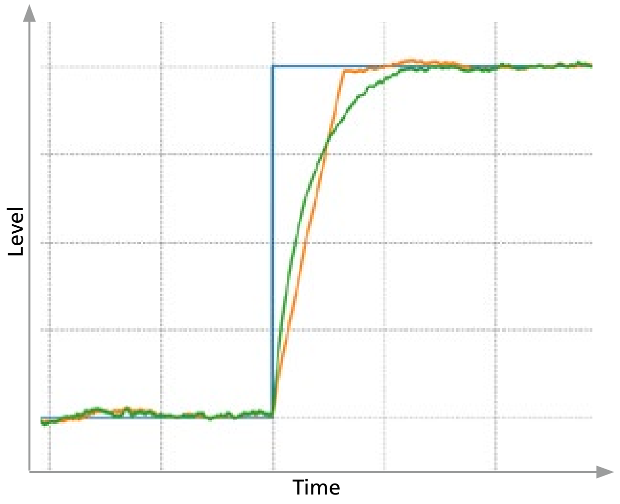
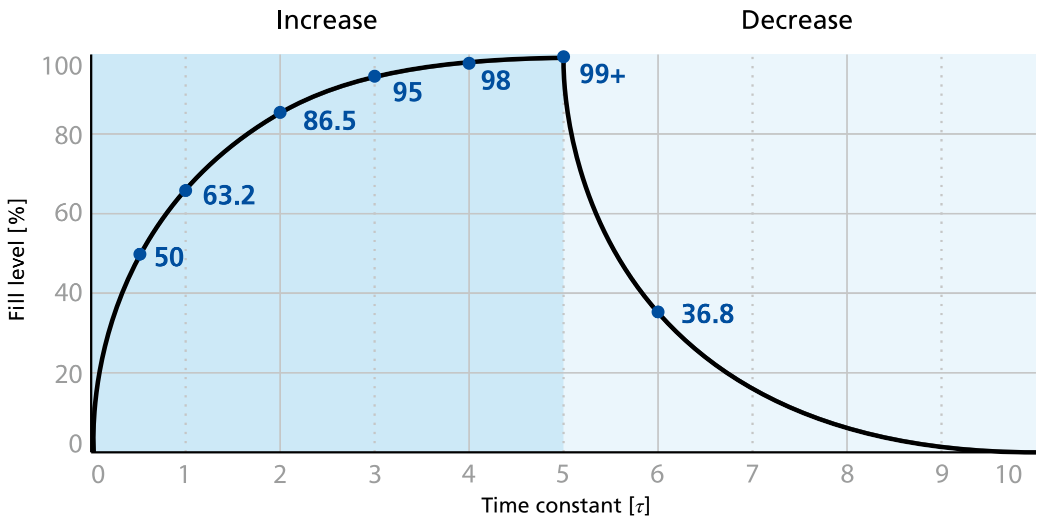


Figure 10 shows that a RC-Filter reacts quickly to changes, but it takes about 5 time constants to get the full effect of a change. This means that a RC-Filter is very well suited for small fast changes such as the conditions found for mould level during casting. For the startup of a caster, modern systems allow the use of shorter time constants in the startup phase, where the system response time is more important than the precision.

The system update time is of course also a vital parameter, where a modern mold level system provides a newly calculated output value about every 5 ms allowing for the RC-Filter to work at its optimum.

Fig.10 RC-Filter time delay



Optimizing the performance

As explained above in this document the relative statistical standard deviation can theoretically be described as:

$$\frac{\sigma_N}{N} = \frac{1}{\sqrt{2 * N * \tau}}$$

This conveys that both an extended time constant (τ) and increased source activity or impulse rate (N) improve the precision of the measurement.
Including the total measuring range (L_t), the casting set point (L_{sp}), and using the empty mould count rate (N_{empty}), yields the following formula for the system standard deviation at casting set point in millimeters.

$$\sigma_L = L_t \sqrt{\frac{1 - \frac{L_{sp}}{L_t}}{N_{empty} * 2 * \tau}}$$

Applying this expression, for quite some normal conditions, for a small cross section caster

N_{empty} = 10 000 counts per second
τ = 0.8 s
L_{sp} = 112.5 mm (75 % of the total measuring range, L_t)
L_t = 150 mm

conveys the statistical deviations listed in the table below.

Standard deviation	Deviation in mm
1σ	0.6
2σ	1.2
3σ	1.8

Under the conditions given, a mould level precision of +/- 1.2 mm or better for 95% of the time and within +/- 1.8 mm for 99.7% of the time should be expected.

Conducting the same calculation for twice the source activity (N_{empty} = 20 000), yields the following corresponding result.

Standard deviation	Deviation in mm
1σ	0.4
2σ	0.8
3σ	1.3

This example clearly shows that the source activity/sensor sensitivity plays a significant role for the achievable measurement precision. The same expression can be rearranged and used to elucidate the minimum acceptable N_{empty} for the conditions and a required statistical deviation (σ_L).

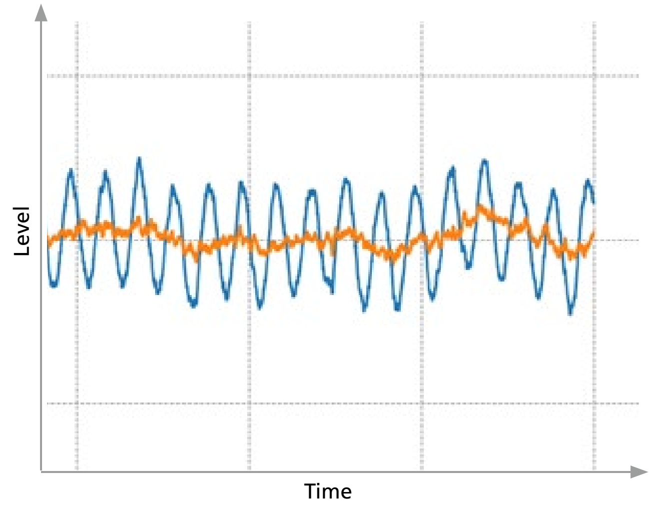
The golden rules for precision for radiometric mold level measurement can be summarized as:

- A higher empty count rate (N_{empty}) improves the precision in the whole measuring range.
- Extended time constant (τ) gives smoother level signal, but slower response time.
- Higher set point (L_{sp}) for casting level improves the precision of the measurement.

Influences

Mould oscillation
As previously described, the mould oscillates during casting. The source and the detector, which are often mounted directly in the mould, follow this movement, which means a relative change with respect to the casting level. In principle, this oscillation is transmitted to the output signal of the level measuring system. For most casting formats this influence is averaged out to such an extent that the disturbance becomes practically negligible.
For formats with a stroke frequency below about 180 strokes per minute, the mould oscillation signal, could influence the mould level signal negatively. However, in modern systems this influence can be dynamically filtered out using digital Infinite Impulse Response (IIR) filtering with almost no significant impact in signal quality or response time.

Fig.11 Signal without (blue) and with mould oscillation compensation (red) for a caster with a low mould oscillation frequency



Casting powder
When radiometry was initially deployed for mold level measurement, open casting with oil as lubrication was standard operation procedure. The thin oil layer on top of the molten steel in the mould did not influence the mould level signal at all. With the introduction of closed casting practice, using casting powder layers of several centimeters, the powder layer became an influencing factor. This is especially true when using Cs-137 as source, due to its lower specific energy.
Apart from the source material used, the cross section format also influence of the casting powder. Large cross section formats have a relatively higher influence from the casting powder due to the longer beam pathway in the powder and hence a larger attenuation than for smaller formats. For larger formats one strives to reduce the length of the beam pathway during the design phase and therefore corners of the mould are used instead of the cross section.
Recent development has turned the casting powder sensitivity for radiometry into a benefit, enabling for continuous measuring of the steel and the powder layer thickness simultaneously. Combinations of different other technologies have been used to also provide the powder layer information, but all so far with poor results. Here radiometry offers an important benefit, by allowing for two level measurements using a single, well proven robust technology.

Electromagnetic fields
Since the introduction of radiometric mould level, photomultiplier tubes (PMT) have almost extensively been used in detectors. Since PMT technology is based on flying electrons, PMTs are sensitive towards interference from strong electromagnetic fields. Such fields divert the trajectory of the flying electrons causing incorrect amplification. This sensitivity was for long no issue, while strong electromagnetic fields were not present in the moulds. With the introduction of electromagnetic stirrers (EMS) and electromagnetic breaks (EMBr), to improve quality of the steel produced, radiometric mould level detectors then had to be shielded using special designed detector housings.
Quite recent development in the semiconductor industry has brought Silicon based photomultipliers (SiPM), which are virtually immune towards influence from electromagnetism. At least one supplier offers SiPM-based detectors for radiometric mold level measurement. The use of EMBr or EMS calls for the use of SiPM based detectors to guarantee no negative interference.

Radioactive source

Relevant source materials

There are virtually two different elements, with their specific isotopes, used for radiometric mold level measurement being Cs-137 and Co-60. For multiple reasons Co-60 is the most adequate source material for a mould level application and in the table below, several relevant parameters are listed for the two options.

As seen for the specific energy Cs-137 has about half of the energy compared to Co-60, which means that only a minor part of the radiation from Cs-137 will reach the actual detector on the other side of the mold. To compensate for this lower specific energy of the Cs-137, the actual amount of radiometric material must be significantly increased, up to five times, in order to provide the desired measurement precision. Using Co-60 as the source material will allow for the use of a lower source activity.

Also due to the specific energy, casting powder will have a significantly larger influence on the mould level signal, when using Cs-137 than for Co-60 as source material.

In a Cs-137 source the Cs-137 material is embedded in ceramic point and therefore a typical Cs-137 rod source constitutes of such multiple points sources. In a Co-60 rod source, the Co-60 is a continuous metal wire helix wounded around a carrier rod.

This continuous helix approach allows for the design of a linear response curve, which in turn allows for a simple two-point calibration procedure.

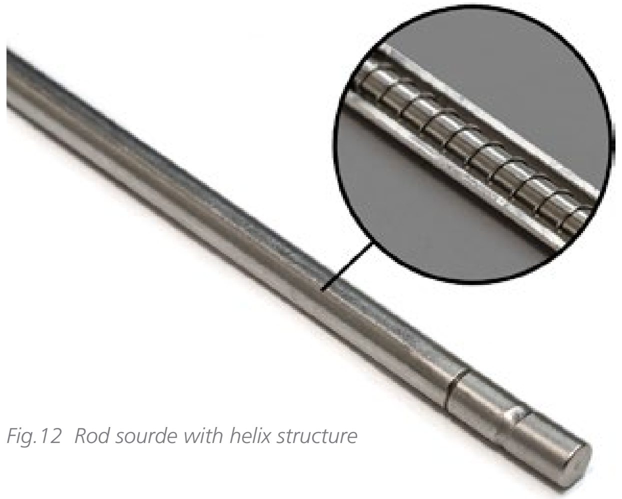


Fig.12 Rod sourde with helix structure

When considering the half-life values of the two considered materials, at the first glance Cs-137 might appear to be economically beneficial, but due to its much higher cost this is seldom the case. Furthermore, the national legislation recommended working lifetimes for radioactive sources, are normally in the range of 10-15 years.

Fig.13 Continuous rod source vs. source with multiple points

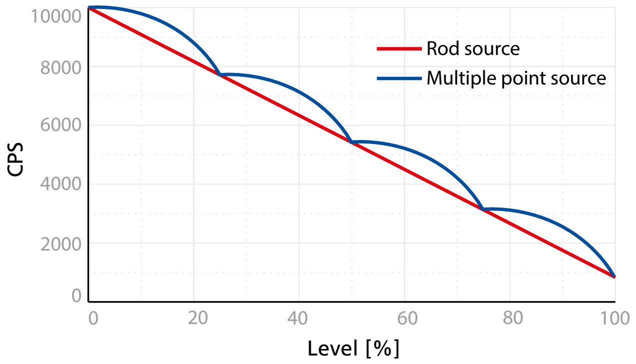


Fig.14 Relevant Cs-137 and Co-60 parameters

	Cs-137	Co-60
Specific gamma energy	660 keV	1173/1332 keV
Source activity	Higher (up to 5 times)	Lower
Casting powder influence	High	Low
Physical from	Ceramics point sources	Metal wire
Rod style	Multiple points	Continuous
Pricing	High	Most economic
Calibration	Always non-linear	Linear
Half lifetime	30,18 years	5,27 years
Legislation lifetime	National legislation	National legislation
Designed lifetime	10 (-15) years	10 (-15) years

Activity optimized source

In former times a linear system response curve was almost a prerequisite for a well working measurement system. With modern electronics almost any shape of a monotonous response curve can easily be handled. This fact has enabled a source design called Activity Optimized Source (AOS) which allow for one of the following two features:

- Improved precision at unchanged source activity
- Smaller source activity at unchanged precision

Both these features are based on having evaluation electronics that handles at least a three-point response curve and normally the 50% level is then designed as the mid-point.

Improved precision at unchanged source activity:
This is achieved by changing the activity distribution from the lower part of the source to the upper parts. The lower part of the source is only usable during start of cast and then the precision requirement is not so high. The upper part of the source is utilized all the time during normal casting and hence increasing the activity in this region improves casting precision. The overall source activity then stays constant.

Smaller source activity at unchanged precision:
By a simply reduction of the precision in the lower part of the mould (below 50%) the precision in the control region of the mould can be kept constant, while reducing the source activity. This is helpful when using small shields or low radiation permits.

Fig.14 Improved precision at unchanged source activity

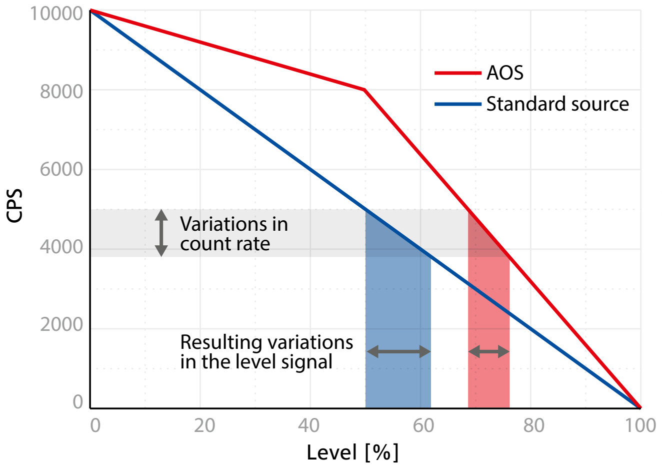
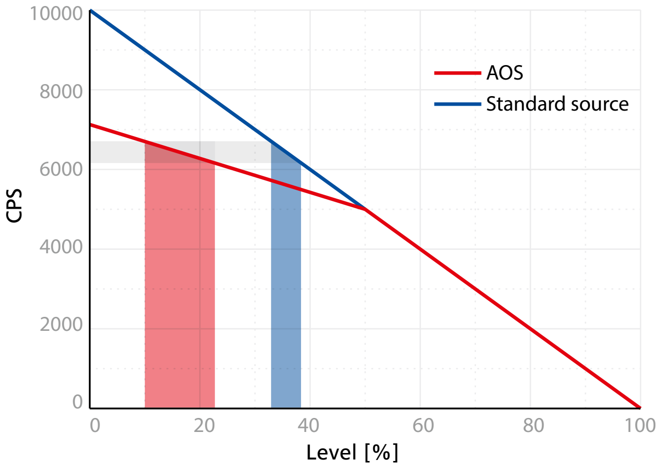


Fig.15 Smaller source activity at unchanged precision



Summary

Radiometry is the most frequent used technology for mould level measurement for continuous casting of steel for good reasons and it has been around for more than 50 years. This technology can be applied for almost any mould formats, environmental conditions, and offers an unparalleled robustness.

State of the art equipment includes advanced filtering for suppression of mould oscillation as well as for the statistical variations and delivers a true response time of about 5 ms. Leading suppliers offers radiometric detectors based on SiPM-technology that are fully EMC immune and can coexist with EMBr or EMS without special preparations or considerations.

Co-60 is the preferable source material for radiometric mould level measurement and offers considerable benefits compared to the more expensive and lower performing Cs-137.

Recent development has introduced radiometric detectors that can simultaneously measure the steel and the powder level during continuous casting. With this unprecedented ability, radiometry will for the foreseeable future, stay as the default choice for the application and constitute a future proof investment.

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