Investigation of Pressure Distribution during Flow Regulation with a Stopper and Associated Mould Level Stability in a Continuous Cast-ing Simulator based on Liquid Metal

Joakim Eck, Pavel E. Ramirez Lopez, Michel J. Cervantes

Stopper systems are widely used in the Continuous Casting (CC) process to control the steel flow from the tundish to the mould during casting of high-quality grades. The flow regulation region is subjected to severe under-pressures and generation of pressure fluctuations, especially around the narrowest gap and the tip of the stopper. This can lead to issues with air infiltration through the refractory materials, adverse flow regimes or even cavitation, which can lead to inclusions and level instabilities in the mould. Acquiring knowledge of such pressure distribution requires data from measurements which are difficult to conduct in the hostile high-temperature and corrosive environment of liquid steel in the plants.

In this work, the pressure distribution is investigated in a Continuous Casting Simulator (CCS) based on a eutectic Bismuth-Tin alloy (Bi 58%-Sn 42%) with a low melting point (137°C) equipped with a stainless-steel stopper rod. The pressure distribution is investigated through direct pressure measurements at two different points; a) Direct pressure measurement by sensor installed flush at the stopper-tip side and b) Indirect pressure measurements of back-pressure in the stopper argon line. The argon flow varied between 0 to 6 l/min, while casting speed varied between 0.6 to 1 m/min for a 1200 x 220 mm mould size.

Results show that considerable under-pressures take place in the flow regulation region, reaching levels as low as 6.6 and 80 mbar absolute pressure at the stopper tip side and argon line. There was a detectable difference in pressure between the direct pressure measurements and additional argon line measurements. Ultimately, it could be concluded that the argon line pressure measurements; often used as industrial standard for ensuring positive pressures in the casting system, generally overpredicts the pressure in the system. This could lead to inappropriate argon settings for a caster, generation of unwanted inclusions and mould level instabilities. It was additionally possible to acoustically detect the onset of cavitation in the liquid metal.

KEYWORDS: PRESSURE, OXIDATION, STOPPER ROD, SEN, LIQUID METAL

INTRODUCTION

Stopper flow control systems are widely used in continuous casting systems to control the flow of liquid steel from the tundish. Considerable under-pressures arise in these systems as the regulatory use of the stopper results in small flow areas in the SEN throat region where the flow is forced to accelerate resulting in reduced pressures, as describe through the Bernoulli equation. This can result in considerable pressure gradients between the liquid steel and ambient air which promotes air infiltration directly through the porous refractory material body or joints of the tundish/

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SEN which gives rise to issues related to oxidization such as formation of inclusions which in turn can result in issues related to clogging; where the inclusions attach and accumulate to the surface of the SEN and restrict the flow, and defects; where inclusions become entrapped in the solidifying steel leading to lower quality of the final product. One way to mitigate the low pressures in the system is through addition of argon via the stopper, but this can however have undesirable consequences in increased instability in the mould.
It is necessary to gain further understanding into the pressure behaviour in the stopper and SEN throat region of a continuous caster to ensure increased pressures in the system while minimizing the instabilities in the mould level. The conditions in the corrosive liquid steel held at temperatures above 1500 °C does however severely limit the number of measurements possible to conduct. Previous measurements have been conducted to measure e.g., velocity in liquid metal as reviewed by for example Eckert et al at HDRZ [1] and S Argyropoulos [2] which highlights some methods of measurement. However, the difficulty in making long term reliable measurements has led to the necessity to develop systems similar to that of the continuous caster for measurements, examples of such systems are full- or down-scaled water- and liquid metal models. One such liquid metal model is the Continuous Casting Simulator (CCS) developed at Swerim to simulate the continuous casting process using a eutectic bismuth-tin alloy with properties similar to that of liquid steel.
The focus of this paper is to investigate the pressure distribution in the stopper and SEN throat region in the CCS. Additional measurements of the mould surface level and velocity are conducted to identify how the flow regulation process affects the stability of the system. The goal is to gain further understanding into the effect of the flow regulation of continuous casting on the pressure in the system to identify sources of risk to ultimately find ways to further improve the process- and quality of casting.

EXPERIMENTAL SETUP

Continuous Casting Simulator (CCS)

The CCS located at Swerim, Luleå, which was used during the experiments in this paper uses of the Eutectic Bismuth(52 wt%)-Tin(48 wt%) (EBT) liquid metal alloy circulating in a closed-loop system consisting of tundish-SEN-mould. Fig. 1 below visualizes a conceptual sketch of the CCS with the different subsections highlighted.

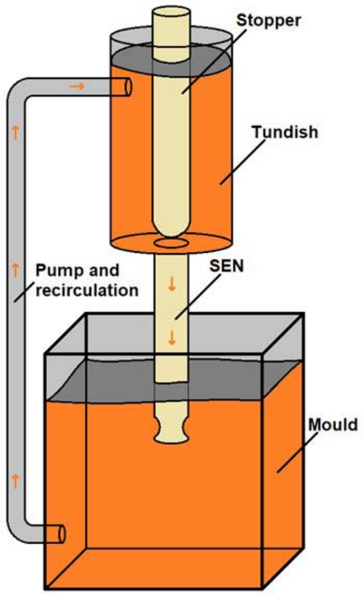

Fig.1 - The Continuous Casting Simulator design with the different subsections highlighted.

The mould is full-scale according to industrial continuous casters to as accurately as possible replicate the flow conditions experienced in the steel industry, with the slab dimensions of 1200x220 [mm]. The different parts of the entire system are manufactured out of steel, including the stopper and SEN used in the trials. The liquid metal is pumped from the bottom of the mould to the tundish to allow for the closed loop.

The main differences affecting the flow between the CCS and real casters is firstly that in the CCS the slag layer is represented by a silicone oil and secondly that no solidification of the liquid metal occurs as the EBT alloy is kept isothermally at 160˚C, well above its melting temperature of 135˚C. The alloy was specifically selected to allow for temperatures considerably lower than that of liquid steel which makes for a more hospitable environment for sensors allowing for a wider range of measurements. The EBT alloy's main flow affecting material properties are similar to those of liquid steel, with the exception of the melting temperature, as can be seen in Tab 1.

Tab.1 - The material properties of Eutectic Bismuth-Tin alloy and liquid steel.

Material property	EBT, 150℃ [3,4]	Steel, 1600℃ [3,5,6]
Density [kg/m³]	8580	7800
Kinematic viscosity [m²/s]	$1.25 \cdot 10^{-6}$	$0.9 \cdot 10^{-6}$
Dynamic viscosity [mPa·s]	10.7	6.3
Electrical conductivity [S/m]	$1.0 \cdot 10^{6}$	$0.7 \cdot 10^{6}$
Thermal conductivity [W/m·K]	19	30
Specific heat capacity [kJ/kg·K]	0.17	0.5

The five flow affecting parameters which were varied during the trials, as well as the range in which they are changeable, are shown in Tab 2.

Tab.2 - Dimension of the mould and the operational range for the different parameters of the CCS.

Parameter	Value
Casting speed, $\boldsymbol{u_{cst}}$	0.7 – 1 [m/min] (0.66 – 2.2 [ton/min])
Argon flow rate, $\boldsymbol{q_{arg}}$	<12 [N·lt/min]
Stopper position, $\boldsymbol{h_{stp}}$	0.01 – 0.017 [m]
Tundish level, $\boldsymbol{h_{tun}}$	0.7 – 1.0 [m]
Immersion depth, $\boldsymbol{h_{im}}$	95 to 115 [mm]

Pressure sensors operational principle and placement

A WIKA S-10 piezoresistive pressure sensor (PRPS) is installed to measure back-pressure in the argon line. The sensor is made for general industrial applications which limits its maximum operational temperature limit thus restricting it to purely indirect measurements. Piezoresistive pressure sensors detect pressure by measuring the resistivity of a piezoresistive element attached to a membrane which undergoes deformation due to a pressure gradient across its surfaces, see top right part of Fig 2.

An Optrand AutoPSI fibre-optical pressure sensor (FOPS) was installed flush in the stopper tip at the throat of the nozzle, i.e., at the circumference where the cross-sectional area of the liquid metal flow is at its lowest and the pressure in the system therefor is expected to reach a minimum. This sensor is designed to measure pressure inside spark plugs in the engine of cars, which allows it to survive in elevated temperature and high-pressure environments. [7] The fibre-optical pressure registers pressure by measuring the intensity of the light reflected from a membrane which deforms from the pressure gradient across its surface, see bottom right part of Fig 2. The placement of the two pressure sensors in the upper part of the CCS is visualized in the left part of Fig 2 and 3. The specifications of the two pressure sensors follows in Tab 3.

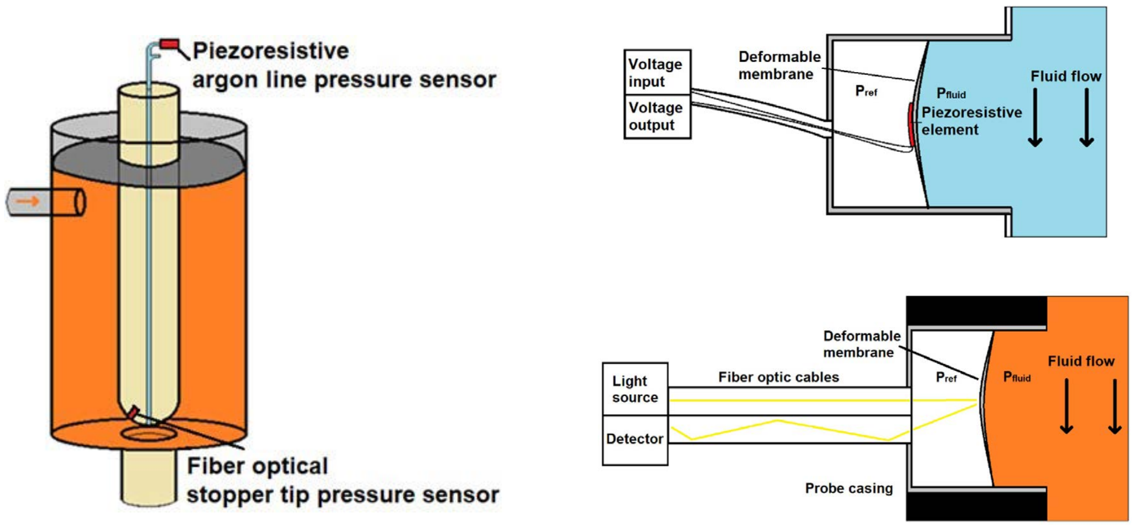

Fig.2 - The installation positions of the argon line- and stopper tip pressure sensors in the CCS.

Fig.3 - installation position of the FOPS (hole to the right) seen relative to the argon injection hole (to the left).

Tab.3 - operational range and conditions of the WIKA S-10 and Optrand AutoPSI pressure sensors [7, 8].

Parameter	Value	
Pressure sensor type:	WIKA S-10	Optrand AutoPSI
Sampling frequency:	10 Hz	
Max. optimal temperature:	<125°C	<350°C
Absolute pressure range:	0-2.5 bar	0-7 bar
Installation position:	Indirectly in argon line	Flush on side of stopper tip

Surface measurement operational principle and placement

A CHRocodile M4 chromatic confocal distance sensor was utilized to measure the surface during the trials. The sensor splits white light into different wavelengths with varying distances to their respective focal points and uses the reflection of the respective wavelengths of light to determine the distance to the liquid metal surface. A sketch of the basic operational principle is displayed in Fig 4.

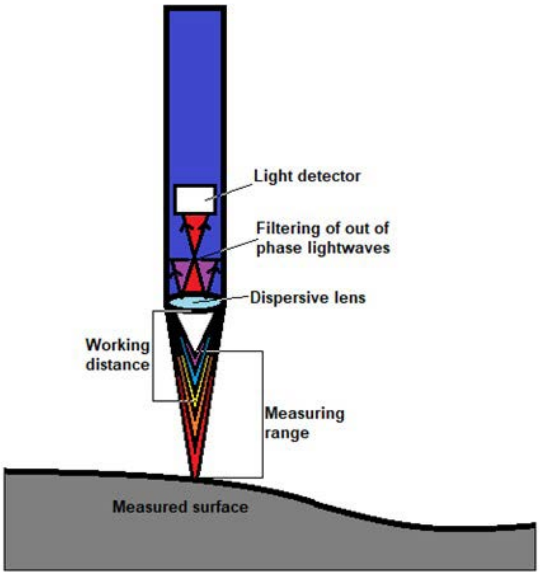

Fig.4 - Operational principle of a chromatic confocal distance sensor.

Additionally, a triangulation blue line laser was used to measure the surface fluctuation across the surface over a line. This sensor measures the distance by projecting a line laser on the liquid metal surface and triangulating the position of the reflected light, as seen in Fig 5. Both sensors were installed above the mould at their respective working distance specified in Tab 4.

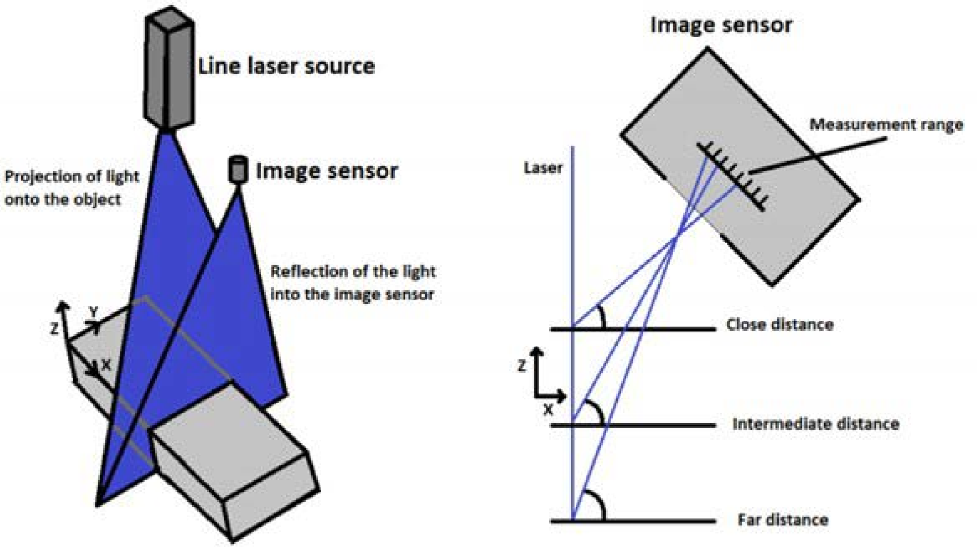

Fig.5 - Operational principle of blue line laser.

Tab.4 -Operational range of surface measurement sensors.

Parameter	Value	
Surface measurement sensor:	CHRocodile M4	Blue line laser
Working distance:	76.5 mm	240 mm
Installed distance from SEN:	270 mm	340 mm
Measurement width:	0-point	100 mm-line

Permanent magnetic velocity probe operational principle and placement

Velocity measurements were conducted with permanent magnetic probes (Vives) to measure the surface velocities in the mould. The probes determine the velocity using the hall effect, i.e., the voltage build-up across the conductor (in this case, the liquid metal) exposed to the probes magnetic field. Four sensors were installed to measure 1 cm underneath the surface of the mould whereas reliable results were only retrieved from one installed 5 cm away from the SEN.

Experimental trial conditions

Pressure- and velocity measurements were continuously conducted with periodic surface level measurements conducted over one-minute periods for the different casting conditions under the trials. The casting conditions were alternated so that for each casting speed the argon injection rate was varied. The range over which the values of these parameters were varied is as follows:

- The casting speed took the value of 0.6, 0.7, 0.8, 0.9 or 1 [m/min], this corresponds to a mass throughput of 1.36, 1.59, 1.81, 2.04 or 2.27 [tons/min], respectively.
- The argon flow rate was alternated for each casting speed between 0, 1, 2, 3, 4 and 6, [N·lt/min] respectively.

RESULTS

Pressure

During the trials there were some initial issues receiving a signal from the FOPS, this was later resolved around 10:30. The lowest absolute pressures registered averaged over one set of casting conditions was 80 mbar (8 000 Pa) for the PRPS at and 6.6 mbar (660 Pa) for the FOPS at the casting speed of 1 m/min with no argon injection. At the moments of lowest pressure it was possible to hear the occurrence of cavitation (i.e., formation- and collapse of cavities in the system due to the vaporization and condensation of the constituents of the liquid metal) through sounds which can most easily be described as similar to the popping of popcorn.

The complete resulting pressure from measurements across the entire trial day is shown in Fig 6. It can be seen throughout the period of measurements with both sensors operational that there is an offset of approximately 200 mbar between the PRPS and the FOPS.

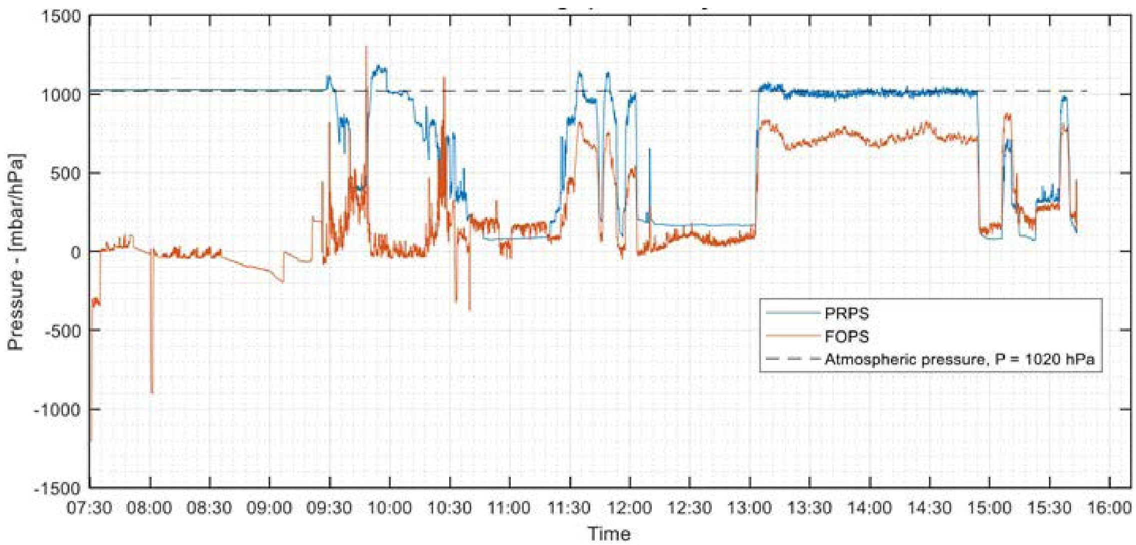

Fig.6 - Pressure measurement from trial day for piezoresistive- and fibre-optical pressure sensors (PRPS and FOPS, respectively).

A regression analysis was conducted on the pressure results on account to six different parameters to determine the dependability of the pressure fluctuations to the different parameters. The regression parameters were the argon injection rate, $\boldsymbol{q}_{Ar}$, the casting speed, $\boldsymbol{u}$, the stopper position, $\boldsymbol{h}_{st}$, the tundish height, $\boldsymbol{h}_{tun}$, the immersion depth, $\boldsymbol{h}_{im}$, and finally a composite parameter defined as the product of argon injection rate and immersion depth, $\boldsymbol{q}_{Ar}\cdot\boldsymbol{h}_{im}$. The last composite parameter was determined to be used as it was found to have the highest coefficient of determination (i.e., R^2-value which is the proportion that the variation in the depended variable is due to this parameter whereas 1 is complete correlation and 0 is no correlation) out of the products of the different individual parameters. The resulting adjusted R^2-values for the different parameters are shown in Tab 5 whereas the colour is green or red with increasing- or decreasing degree of correlation, respectively. For more details into R2-values see for instance [9].

Tab.5 -Operational range of surface measurement sensors.

Parameter	$R^2_{adj,PRPS}$	$R^2_{adj,FOPS}$
q_{Ar} [N·l/min]	0.347	0.256
u [m/min]	0.001	0.117
h_{tun} [mm]	0.129	0.236
h_{st} [mm]	-0.036	-0.016
h_{im} [mm]	0.123	-0.034
$q_{Ar}·h_{im}$ [N·l·mm/min]	0.561	0.545

It is possible to distinguish that the argon injection-immersion depth composite parameter has the highest coefficient of determination for both pressure measurements. Similarly, the argon injection rate has a relatively high coefficient of determination for both measurements with somewhat higher correlation for the argon line measurements whereas the tundish level also is seen to result in a dependency for both measurements but with a higher dependency for the stopper tip sensor. The difference is mainly seen in that the argon line measurement depends on the tundish level has a correlation with the immersion depth but not the casting speed whereas the stopper tip pressure has the opposite relation. Notable is that the regression analysis indicates that neither pressure measurement is dependent on the stopper position.

Surface measurements

It was overall difficult to conduct surface level measurements at higher argon injection rates as the argon gas interacted with the silicone oil to form a foamy layer which deflected the light away from the sensors. The blue line laser was seen to be more sensitive to the oil layer even without argon injection. Results from the point surface measurements at lower argon injection rates is presented for 0.7 and 1 m/min casting speed, respectively, in Fig 7.

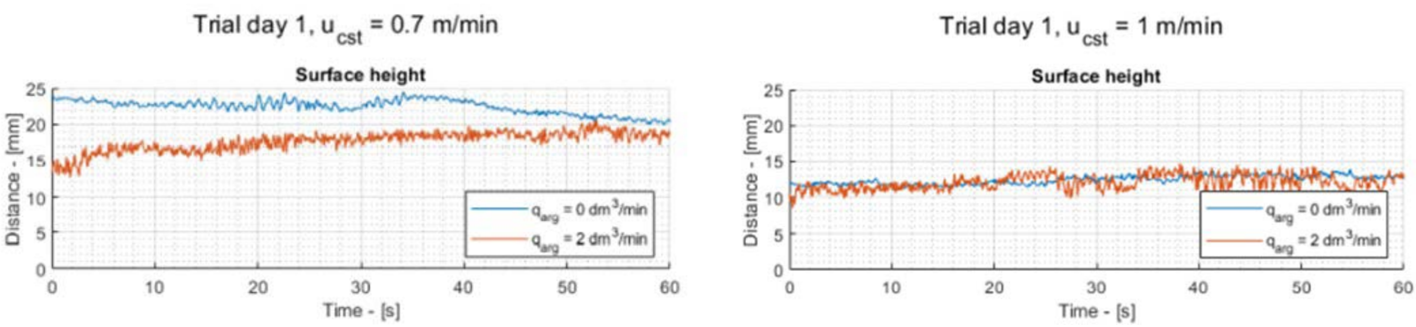

Fig.7 - Surface level measurement with the chromatic confocal point light sensor.

Overall, the high frequent surface fluctuations increase slightly with an increase in argon injection rate while the low frequent fluctuations remain on a similar level. A measurement surface from the blue line laser sensor during the trial conditions of 0.7 m/min casting speed and 2 Nl/min argon injection is shown in Fig 8.

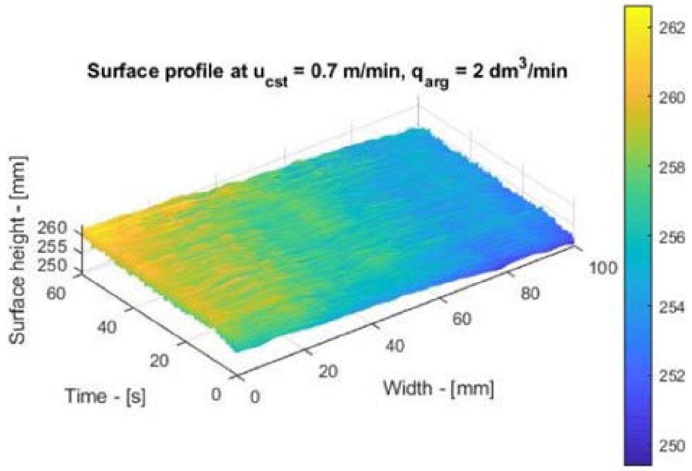

Fig.8 - Surface level measurement with the blue line laser sensor.

It is possible to distinguish higher frequent wave fluctuations at different times (i.e., as y-value increase) in the surface plot as well as a gradual level increase until the end of the measurement.

Velocity measurements

Four sensors were installed in the mould for measurements whereas one of the sensors resulted in consistent measurements over longer time periods. The reason behind the inconsistent measurements of the three other probes is believed to be due to the silicone oil forming an insulating layer on the electrodes of the probes as they are dipped through the mould surface. The resulting velocity measurements from the reliable velocity measurement in the near SEN region of the mould is presented in Fig 9.

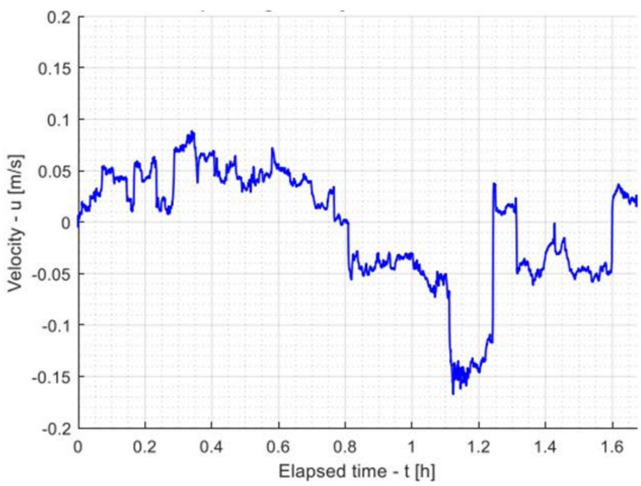

Fig.9 - Velocity measurement from near SEN region.

The velocity overall fluctuates quite a bit in both magnitude and direction. Initially the velocity is in the positive direction (towards the SEN) but then the velocity direction reverses, and the magnitude increases for a time until it reverses again.

DISCUSSION

The absolute pressures which were detected in the system were considerably low and very close to absolute vacuum. At these pressures there is a high likeliness of air infiltration into the system and possibly even that different constituents of the liquid metal may start to vaporize resulting in cavitation. It is however worth considering that the CCS system uses stainless steel which results in a very tightly sealed system which likely results in lower pressures than those which can be realised in the ceramic refractory materials used in actual continuous casters. The actual casters would likely be less susceptible to reach as low pressures as due to air infiltration occurring more readily already at higher absolute pressures there.

The pressure difference between the two different ways of measuring pressure can be seen to be considerable. In the industry it is generally the indirect argon line measurements that are used to ensure that the pressure in the system is positive as it is not possible with direct pressure measurements due to the hostile conditions of liquid steel. The difference which is seen to be in the region of 200 mbar means that the operational regions previously thought safe due to a measured positive pressure in the stopper can result in negative pressures in the SEN throat region. This in turn risks leading to air infiltration through the refractory body and joints which ultimately results in oxidation and an increase of inclusions in the system with clogging or poor material quality as possible consequences. The existence of the offset between the measurements at these two regions can be explained by that the liquid metal flow reaches it maximum velocity, and thus by Bernoulli principle its lowest pressure, at the cross section with minimal flow area which corresponds to the FOPS point of measurement at the side of the stopper tip. The velocity then decreases, and the pressure thus recovers, as the flow proceeds to the tip of the stopper where the argon line pressure is indirectly measured by the PRPS. It is also likely that additional minor pressure losses and possibly leakage take place in the argon line between tip and the point of measurement, the effect of these are however likely negligible.

Additionally, the regression analysis shows that the indirect way to measure pressure is largely independent on the casting speed in the CCS. This means that it is unable to accurately determine the minimum pressure in the system as it is insensitive to the flow which takes place as the regulation region of the stopper where the pressure reaches a minimum. More surprising is that the regression analysis indicates that the measurement from both pressure sensors is completely independent on the stopper position. Logically the stopper position should have a large effect on the direct pressure measurement as the pressure in this zone changes considerably as the stopper further increases or decrease the flow area.

It was overall difficult to conduct measurements with both surface level sensors and velocity probes due to the interaction with the silicone oil and argon. It was however possible to see from the point level measurements that an increase in argon injection resulted in an increased high frequent level fluctuation whilst the low frequent behaviour remained similar. This is logical as the argon bubbles in the flow must escape through the surface of the mould. When there is no argon injection there should thus be just the larger scale liquid metal flow affecting the surface fluctuation in the system.

Further development will be needed to ensure the reliable measurement of velocity measurements and multiple points in the mould either by developing more robust probes or adjusting the dipping procedures of the sensors to ensure that no insulating layer is formed at the tip of the sensor. The velocity measurements that were conducted showed that the surface velocities in the CCS show no sign of reaching a steady state, the high- and low frequent velocity variations result in considerable variation in both the velocities magnitude and direction.

CONCLUSION

It was possible to reliably conduct both direct- and indirect pressure measurements in the liquid metal based CCS. The pressure measurements showed that considerable under-pressures took place with absolute pressures reaching as low as 6.6 mbar in the flow regulation region which results in considerable risk of air infiltration into the system. At these pressure levels it was possible to acoustically detect the occurrence of cavitation.

The difference in measured pressure between the direct pressure measurements at the side of stopper tip and the indirect pressure measurements in the argon line were in the region of 200 mbar. Indirect pressure measurements are the industrial standard for monitoring- and ensuring positive pressures in the system and which then likely means that the industry overall overestimates the pressure experienced in the caster. Regression analysis additionally indicates that indirect pressure measurements mainly is independent of the casting speed and stopper position.

Surface measurements were difficult to conduct due to the formation of a foamy layer of argon in the silicone oil. The measurements which were conducted showed a trend towards less stable mould level due to increased high frequency fluctuations in the mould at increased argon injection rates.

Velocity measurements were similarly difficult to conduct, successful measurements showed that the surface velocities in the near SEN region of the mould vary considerable in both magnitude and direction under stationary conditions.

REFERENCES

[1] Eckert S, Cramer A, Gerbeth G. Velocity measurement Techniques for Liquid metal flows. Magnetohydrodynamics – Historical Evolution and Trends, 275-294. 2007

[2] Argyropoulos S. Measuring velocity in high-temperature liquid metals: a review. Scandinavian Journal of Metallurgy, 273-28. 2001:30

[3] Ramirez Lopez P, Björkvall J. Liquid Metal Research. PPT Presentation. Swerea MEFOS. 2014.

[4] American Elements. Bismuth Tin Alloy. American Elements data sheet. Retrieved from https://www.americanelements.com/bismuth-tin-alloy (2020-08-10)

[5] Sutherland. Density of Steel. Hyper Textbook. Retrieved from: https://hypertextbook.com/facts/2004/KarenSutherland.shtml (2020-08-10)

[6] Engineering ToolBox. Thermal Conductivity of Metals, Metallic Elements and Alloys. https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html (2020-08-10)

[7] Optrand. Standard Sensor Packages. Optrand product sheet. Retrieved from: http://www.optrand.com/ (2020-08-10)

[8] WIKA. High-quality pressure transmitter For general industrial applications Model S-10. WIKA data sheet. Retrieved from: https://en.wika.com/upload/DS_PE8101_en_co_1392.pdf (2020-08-10)

[9] Eck J. Development of systematic measurement in liquid metal. Master thesis. 2019.