Continuing the Conversation

Naturally Pressurized Fill System

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Abstract

David Poweleit approached me during the late summer of 2018 and asked if I would be interested in continuing the conversation surrounding Naturally Pressurized Gating and John Campbell’s work. After the animated 2016 T&O conference and the emergence of several papers pertaining to flow controlled gating at the 2017 T&O. He was concerned that the industry would lose momentum if we didn’t keep the dialogue going.

I have been involved with this system since 2011. Bob Puhakka and I collaborated to develop all of the tools and methods that he presented in 2016. Bob’s excellent computer and simulation abilities combined with my tooling design background gave us complimentary skillsets that allowed us to invent the Rapid-Prime Basin, Vortex Step Ingate (this evolved into various other ingate options discussed later) and shop floor best practices. By using simulation validation to finalize designs, we successfully poured defect free castings.

In 2012 we cofounded Cast Differently and worked with many foundries in North America and beyond. My paper is simply visuals developed by John, Bob and myself to explain the oxide phenomena. As well as my experiences and opinions on best practices, that I gained training foundries on how to implement this type of system.
Company Background

Highland Foundry is one of North America’s leading steel and stainless steel foundries. The Company was founded in 1970 and was a third generation company before it was acquired by Canerector in 2010.

The success of the company is based on four pillars. A team of highly technically skilled individuals, a management team dedicated to continuous improvement, a culture that embraces new methods and technology and a strong focus on the new generation of young professionals. This has allowed Highland to foster a reputation for providing world class, high quality castings in all industries they serve.
The facility is located in Surrey British Columbia, which is a suburb of the iconic Port Metro Vancouver. The port handles over 50% of all container shipments entering or exiting the country. This location allows us to be in close proximity to all major transportation routes. The Vancouver International Airport and multiple US border crossings fall within a 45km (28mi) radius of the foundry.

Highland is a “Job Shop” with 115 000sq.ft. of manufacturing space that is utilized to pour over 140 unique alloys. We are known for our focus on stainless steel castings of high complexity in both geometry and specification. The alloy families that we target are Austenitic, Super Austenitic, Martensitic, Precip. Hardening, Heat Resist, Tool Steels, Nickel Base, Carbon and Alloy steels and custom Alloys. But we really enjoy Duplex and Super Duplex. So much so that we have recently partnered with Sandvik and obtained exclusive license to develop SAF 2707HD, which is a new Hyper-Duplex Alloy.

Highland has a long list of certifications but some of the highlights are ISO 9001-2015, PED (both are Lloyds Registered) ABS, Norsok M650 rev 4 and qualified EMDC (ExxonMobil, Shell, BP and Statoil)
Subject Background

My experience with Naturally Pressurized Fill Systems began in 2011. I was about to start my second co-op term and my Canadian Gov’t research project was to develop a new technique of pouring tensile test bars. The scope was to take some of Mark Jolly’s early simulations that he had developed with John Campbell and apply them to a method that would minimize the potential for air entrainment and hopefully translate into better Mechanical properties.

As luck would have it there was a man by the name of Bob Puhakka that was working with a small stainless foundry in Ontario. Bob was in collaboration with John Campbell trying to develop a method of casting that also minimized air entrainment. I was placed at that facility and over the summer and ensuing few years we developed many new techniques, methods, tooling and actively pushed our research and education to further our understanding of what we were seeing on the shop floor.
After meeting at Alloy Casting Industries, and founding Cast Differently we un-relentlessly tried to make southern Ontario into the Silicon Valley of Castings. Ultimately (and not surprisingly) our relationship soured we parted ways after I had been his Plant and Operations Manager at Custom Aluminium Foundry. I was picked up by Highland Foundry shortly after and I continued my journey down the bi-film rabbit hole.

**Introduction**

2017 T&O

As some of us know explaining the Oxide and Bifilm phenomena takes longer than a 15 min session once a year in Chicago. When I asked David what it was that he wanted me to talk about specifically? Put briefly, he stated “Do something like Joe Plunger”.

I had been in the audience during the 2017 conference and I can admit that it was somewhat bittersweet. Excitingly there were people on stage presenting examples of our work and talking about their experiences with Naturally Pressurized Gating.

Inversely it brought back the painful memories of Cast Differently’ s failure and all of the resistance that I had faced in years past.

While selfishly I was jealous that there were people on stage using terminology, analogies and examples that I had developed to assist in explaining the complicated world of Oxide film management. I had a perceived and unfounded ownership over the material being presented.

However upon reflection after the conference I came to the realization that what I had witnessed was in short, what I had been working to accomplish my entire casting career. Having people look at their fill systems critically, and see if maybe there is a better way. Tweaking others concepts to work for their own process.
Humorously it dawned on me that this is the embodiment of the SFSA. We get together as a collective group, meld our ideas, then leave for our respective companies as better Metallurgists, Scientists, Owners and Foundry men/women.

**Campbell’s Work**

I would be doing a disservice to the collective attendees reading this if I didn’t first give a brief explanation of Campbell’s theories. Although my directive is to continue the conversation, we need to first cover the basics.

Dr. John Campbell is Professor Emeritus at the University of Birmingham. He has published 150 papers, 20 patents, acquired 2 masters and two doctorates over his distinguished career. The most recognized being his work with Cosworth and counter gravity casting. This breakthrough in casting technology came after some lessons he learned casting Tin Bismuth heat exchanger cores at Ford Motor Company. Cosworth heard about the success he had, and asked him to help them with their race engine block division. Prior to his involvement 50% of all castings poured, failed on the test stand. You can imagine this was very expensive, and John’s fresh approach eliminated the failures and set the stage for how ALL engine blocks are cast today.

Although I missed the 2016 T&O. I have been present many times for the presentation that got everyone thinking that there might be something new to investigate in regards air entrainment and the effect it has on casting quality. I will preface my paper by admitting that I am one of the converted. My introduction to casting literature was “Concise Castings” by John Campbell and the principles discussed within it have stuck with me through my career.
What is an Oxide?

An oxide is formed on any alloy and is the interface between the molten metal and the atmosphere that surrounds it. In our case, on this planet it is largely oxygen. As scientists and engineers we know that oxygen and metals have a tumultuous relationship. This can easily be demonstrated if one were to witness welding without an inert shielding gas. Placing uncoated carbon steel out in the weather or simply looking at a century old copper roof and its greenish film.

To now relate this unavoidable interaction to casting technology. Any metal regardless of its state, liquid, mushy or solid, if exposed to the environment, it must have an oxide layer on its surface.

The oxide will grow one atom thickness at a time, and will continue to do so for as long as the conditions allow for it. Truthfully for eternity as we have yet to find a naturally occurring deposit of Super Duplex, Austenitic Stainless or Carbon Steel.

We manufacture these materials under extreme conditions and upon creation; they immediately start to revert back to their base state. Rusting and oxidizing away to nothing.
Intuitively it would be unreasonable to assume that there is a delay before the newly created alloy starts to form an oxide. Within the furnace the melting process introduces of an immense amount of energy. We have created the ideal environment for these alloys to readily react with the atmosphere.

The best method to visualize this oxide is John’s method of using a piece of paper. The paper is the oxide and due to the buoyancy differential with steels it floats on the surface.

Considering it grows from the surface of the melt. The surface that is adjacent to the melt is atomically bonded and can be described as relatively sticky. The opposing surface that is exposed to the atmosphere however is completely dry. By definition oxides are ceramics and completely chemically inert. They are also extremely stable at temperature with Alumina Al2O3 for example having a melting point in excess of 2000°C (3632°F).

How are Oxides Generated?

If a surface oxide is left intact and does not rupture, or become entrained on itself. It does not have the potential to degrade casting properties or quality. However if through turbulence the two dry surfaces come into contact, there is no bonding that can occur. Effectively the folded oxides become micro porosities that can serve as crack initiation / propagation points. Or present themselves in other undesirable ways.
If they are generated in high enough concentrations they have the ability to agglomerate together forming macro inclusions. John is often quoted saying “It looks like shrink, but it probably isn’t”.

Sodium Chloride crystal agglomerating under micro gravity.
The other oxide generator is due to excessive velocity. This is simply due to the physics of the world we live in. If the velocity increases beyond that of the natural surface tension of a given alloy, the surface meniscus ruptures exposing an exponential amount of “new” surface to the atmosphere (oxygen) and in turn, forming more and more oxides.

Cascading Metal Simulation – ruptured meniscus exposes more surface area.

The Eureka moment for John came when a Live Video Xray camera was placed perpendicular to the sprue and runner of an aluminium casting within the casting lab at University of Birmingham. The images are dramatic as any person that has been tasked with addressing casting defects can attest. It was assumed that the entrainment being observed must be a contributing factor to the defects that he was trying to mitigate.

Live video radiography, University of Birmingham casting laboratory.
How BAD is it?

It was theorized and calculated by Raymond Monroe 30 years ago that the populations of oxides can easily reach the thousands and even millions for an average casting. Obviously the amount of oxide varies with volume of metal poured but in his research he found that for $1\text{ft}^3$ of metal poured there could $1\text{in}^3$ of oxide generated. This was followed up by Christoph Beckermann and the graph shows the amount of air that would be required for this statement to be true.

![Graph](image)

Figure 2: Variation of inclusion volume fraction with relative entrained air volume for carbon/low-alloy steel [2].

In my opinion the nonferrous industry has had a better handle on oxide control than us steel founders. Not that it was necessarily a conscious decision to eliminate oxides. But it happened out of necessity as the difficulty of these alloys steered the direction of the best practices as they evolved over the decades.

I feel this was largely due to the buoyancy of the oxides and how they dealt with them. The brass and bronze foundries struggle with drossy material and in aluminium you have to be extremely careful as the oxides have near identical buoyancy to that of the alloy. Once entrained, they are extremely difficult to extract.
It is almost standard practice to use a tapered sprue with aluminium and bronze and I see them more widely adopted in those markets, than I have seen in the steel industry.

**Do Oxides even exist?**

I have found evidence that they do.

Like most changes, they are met with resistance. I have experienced apprehension about Campbell’s theories everywhere I have gone. The 2017 T&O was the very first time I had witnessed it being discussed with an open mind.
Highland was no different when I started. I decided the easiest way to get the “buy in” was to test what we were seeing. The number one complaint was Cope side inclusions.

Thankfully shortly after starting at Highland I was asked to give a paper on Modern Casting Techniques at the University of British Columbia (UBC). That paper turned into my co-authoring a paper on Water Cooled Chill Effectiveness with a young PhD student working on her thesis. After the successful defence of her paper - she owed me a favour.

I had a decent level of confidence that the cope side defects being observed were none other than re-oxidation inclusions that were coming from the furnace to ladle transfer and subsequent pouring through a conventional gating system. I knew I could shift the tide of acceptance if I was able to obtain a sample of the inclusion and have it analysed.

We received an order for a casting that consistently had issues on the cope side of the flanges. We poured the casting and during shakeout I carefully removed the cope and excavated the sand around the top of the flange. I extracted a piece of the inclusion and gave it to my new PhD friend at UBC. Luckily for me she was working in the SEM lab and she analysed my sample and performed EDX on it.
As we look at the results of each point there are three elements that kept occurring in the highest concentrations. Si, Zr and O.
Since we use Silica and Zirconium for the molding material and mold coatings using Alumina and Zirconium, you can infer that their presence is expected. However, the one that should not be there is Oxygen. My in-house trial was able to replicate what the SFSA found in 1987.

But how do we get rid of them?

Of Campbell’s 10 rules, number one is start with Clean Metal. Ensure that your melt department is actually following that. I occasionally witness melting trying to save the company money by limiting the use of slag trap or wanting to use extra re-melt, or pouring every last drop of metal into the casting cavity.

For context on how critical you can be. In the aluminium industry I developed a procedure where after rotary degas and subsequent TiBor additions. We would use a filter and VERY gently skim the entire surface of the melt, removing as many of the surface oxides as possible prior to pouring.
LADLE SPOUT

I have had good success modifying the spout of the ladle to concentrate the stream of metal. I have converted most of the Ladles at Highland from the widely used V spout to a smooth round transition. The rational being that a cylinder of falling metal has less exposed surface area, than that of two flat surfaces that sheer past each other that you get with a V Spout. This greatly reduces how much of the surface comes into contact with the air, in relation to the volume being poured.
BASIN

The easiest thing I have found to change *today* is your pouring basin. As presented in the paper by Beckermann and Majidi at the 2016 T&O and others during the 2017 conference. There is a compelling case for the Offset Step Basin. The geometry is ideal to greatly minimize the amount of air entrainment prior to entering the fill system.

There are many iterations of this but the one that I prefer is the *Rapid Prime - Offset Basin*. I will admit that I have creators bias, but it works very well.

Calculate

\[ bV = \sqrt{2g \cdot bh} \]

Rapid Prime Offset Basin
The geometry incorporates the traditional weir and sharp corner geometry to help with the shearing effect that takes place when the velocity vectors falling in the Z direction are redirected horizontally.

![Velocity within Basin](image)

I have found you need to size the basin appropriately for your fill system. \( Q = V \times A \)

I ensure that the basin holds at least 3 seconds of metal to address any fill rate variations introduced by the ladle operator. The metal height maintained within the basin during pouring is also very important as the velocity leaving the basin is critical to preventing entrainment within the sprue.

The area over top of the sprue is much less than that of where the stream of metal enters from the basin. When the metal rises over the weir it is forced into a smaller area reducing the time required priming the top of the sprue without changing the volumetric flowrate leaving the ladle.

The overall height of the basin is also important and is dependent on that of the alloy being poured. The buoyancy of the oxide determines the height required. We want to float the oxide out of the metal and have it agglomerate on the top of the metal contained within the basin. We achieve this by arresting the velocity of the falling metal prior to entering the top of the sprue.
We know there is an oxide created from the lip of the ladle to the basin. We make the basin depth such that the oxide floats prior to being sucked down the sprue.

Last year someone used my jumping off a dock analogy and it is very accurate way to describe how it works. "If you wear a life jacket and jump off a dock into 4ft of water you will hit the bottom. If you were to instead jump into 20ft of water you would NOT hit the bottom. Since the buoyancy floats you back to the surface" The top of the sprue is the “bottom” in this analogy.

Joe Plunger and I were in the same group last year for the Workshop, and anyone that witnessed Group 3’s pour saw that our setup had a significant amount of bubbles within our basin. It was so extreme that we actually had to slag it off during the pour so that bubbles did not go down the sprue at the end of the pour, tarnishing its otherwise great performance.
Simulation showing Velocities within basin and fill system
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**SPRUE**

For a very long time metal casters have understood that velocity is a problem. This was addressed by expanded runner logic that increased the cross sectional area from the base of the sprue to the runner and finally the ingates. However from the live video RT of the runner Campbell used, we can see that the increased area definitely reduces the velocity but it dramatically increases air entrainment before the ingate.

After witnessing this Campbell designed a sprue that had the same cross sectional area and matched the profile that an unrestrained falling fluid would form.

The math is straight forward and the only thing that needs to be determined in your shop is the *Friction Correction Factor* as the conditions in every foundry are unique due to sand GFN, binder system, coatings and alloys poured.

Determine Sprue Velocity:

\[ V = \sqrt{2gh} \]

Target a desired Volumetric Flowrate for Area 1

\[ A^2 \frac{b}{r} = \frac{R \cdot k}{V \cdot e} \]
Calculate the Volumetric Flowrate of the Fill System

\[ Q = V \cdot A \]

Using knowns; Calculate for Area 2

\[ A_2 = \frac{Q}{bV} \]

I witnessed a few presentations last year that had randomly tapered sprues. I do agree that any form of taper is arguably better than a straight sprue, but I challenge designers to take the time to try and calculate it. As this is the last opportunity to eliminate entrainment from the falling melt.

Comparison between random and calculated tapered sprues
RUNNER

One question that went unanswered last year was;

Why is the Sprue Rectangular? and the Runner so thin with this system?

For the Sprue there are two reasons. First it is for the ease of manufacture. To have a round tapered sprue you need to have a Lathe with a bed long enough to turn one continuous taper. This is a little challenging but also wastes a lot of material. By using a rectangular sprue you can keep one surface flat on the mill table and then machine the taper on the remaining three sides in one simple setup. The boxes can also be segmented and the handling of the tooling is far easier.

The second reason ties into why the runner is so thin. The height of the runner is dictated by the sessile drop height of the alloy. If you put a given alloy on an un-wetted substrate it will sit at a specific height and is held in check by its own surface tension. (If you start measuring the height of spilled metal on your foundry floor you will notice that certain alloys are always the same height).

\[
Ro \text{ (steel) } = .412''
\]

\[
\text{Velocity } = \sqrt{2gRo}
\]

\[
= \sqrt{(2)(386 \text{ in/s}^2)(.412)}
\]

Velocity (max) = 17.8 inches/ second

maximum critical meniscus velocity = 17.8 in/s
By using the naturally occurring surface tension we can help eliminate the potential for air entrainment along the top of the runner, if we make the height the same as the alloy would take - unrestrained.

We want to “hug” the uncompressible fluid metal with a straight jacket of sand.

The sessile is where the universally accepted approx. max ingate velocity of 20in/s comes from.

Keep in mind when splitting the runner for multiple ingates. You need to do it symmetrically to achieve a balanced system. If the runner areas do not match, or are at different angles, you are opening up the potential for entrainment.

**VELOCITY CAPTURE**

We can see that prior to the ingate we have a very nice system in respect to air entrainment. But once we enter the mold - all hell breaks loose.

Through trial and many errors we were able to develop some solutions to the velocity capture component of the system.
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VOXTERX STEP INGATE

What we know is that if we kill the horizontal velocity vector by converting it into a tangential motion like the Vortex, then redirecting it vertically. We can gain the assistance of gravity to further slow the metal. Finally a geometry change forces the metal to change shape, shedding more inertia and arriving at an acceptable ingate velocity.

**Priming Issue** - The Vortex has always had a small priming issue where the first metal that falls down the sprue ultimately finds its way into the casting. When I was at CAF we would pour very large beautiful aluminium castings but on occasion they would exhibit small randomly distributed defects. The casting quality was exceptional but not perfect. Since we were striving for perfection, subsequent designs addressed this.

Priming Issue – Pre Solidified metal observed on rising fluid front. (Blue specks in slot gate)
TOP GATE

Another option is using a Top Gate setup like Joe Plunger showed last year with great success. The surge cylinder at the end of the runner captures the leading metal front (addressing the priming issue of the Vortex) and the damaged metal is stored away. The surge cylinder also completely eliminates the rolling back wave that has historically been the big reason to avoid runner extensions.

A Trident gate is extremely effective especially with nonferrous alloys. I would recommend this as the current best practice for this system.
Conclusion

For the Naturally Pressurized Fill System to work as intended you must adopt the entire design. By incorporating bits and pieces, the improvements will be lost in the noise generated by the rest of your existing system. To be successful you need to be starting with a Foundry that has its process in control. As any poor sand, melting, and coating technologies can easily obliterate the positive results. Regardless of which ingate design you choose, by staying true to the principles and always filling from the bottom of your casting, and preventing the melt from being able to fall unrestrained generating. You can start to have greater confidence and predict the casting quality from your office instead of at shakeout or blasting.