A Review of Fluid Flows in Liquid Metal Processing and Casting Operations

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Fluid flows have proved to be an integral part of many metallurgical processing operations. Metal, slag, and gas flows invariably affect the viability, effectiveness, and efficiency, of our reactor vessels. The performance characteristics of our blast furnaces and steelmaking vessels, such as BOF’s, OBM’s, ladles, tundishes, and the moulds of continuous casting machines, are all strongly influenced by such flows. Similarly, liquid metal quality and cast micro-structures, are also bound up with the way fluids have flowed and interacted. In all these aspects, the rapid evolution in our techniques and abilities to mathematically and physically model single and multi-phase flows and their attendant heat and mass transfer processes, have contributed significantly to our understanding, and ability, to control and improve these metallurgical processing operations, and to develop new and better processes. The evolution and application of computational fluid dynamics (CFD) over the past four decades has been particularly impressive. The author’s many fine Japanese graduate students have made very valuable contributions to this new field of research for Process Metallurgists, as well as to the founding and scientific support of the McGill Metals Processing Centre, MMPC, following their return to Japan.

KEY WORDS: fluid flow; computational fluid dynamics; water models; blast furnace; steelmaking vessels; ladles; tundishes; moulds; continuous casting; strip casting; horizontal single belt casting; inclusions; liquid metal quality; LiMCA; ESZ-pas; ab-initio heat flux predictions.

1. Introduction

It is indeed a very great honor to be invited by the Board of Directors of the Iron and Steel Institute of Japan, to accept honorary membership, on the occasion of the 94th General Assembly of ISIJ. On being invited to present a review lecture on any topic of my choice, I did so with great pleasure, and decided to make a personal review of the relevance of fluid flows in metallurgical processing operations. As an undergraduate at Imperial College in the early 1960’s, this subject received no attention. The emphasis in our syllabus was primarily physical metallurgy, and teaching staff were more concerned about the relationship between the microstructure of metals and alloys and heat treatments, phase transformations and their resulting effects on physical properties (tensile strength, elongation, drawability, toughness, fatigue properties, etc.). With the problems of welded ships spontaneously cracking apart in arctic waters, and the world’s first commercial jet liners (De Havilland’s Comets) dropping out of the skies in the early 1950’s, such an emphasis was probably understandable! Nonetheless, the Royal School of Mines of Imperial College still retained a strong extractive metallurgy component to its curriculum at that time, centred on thermodynamics and high temperature physical metallurgy, and lead by Professor F. D. Richardson.

As a reasonably inquisitive undergraduate, I would often wonder during our extractive and hydrometallurgy lectures as to why reactions in the Open Hearth Steelmaking Process were so slow compared to those in Bessemer’s Steelmaking Vessels, why was the Iron Blast Furnace round, but the Imperial Zinc Smelting Blast Furnaces rectangular? Why was the Pierce-Smith Copper Converter a horizontal cylindrical vessel fitted with many tuyeres blowing in air, rather than vertical, like Bessemer’s (bottom air blown) Steelmaking Furnace? Also, what happened to Bessemer’s other big steelmaking idea, which proposed twin roll casting for the production of steel strip? Why instead were massive ingots cast, then hot rolled, then cold rolled, instead of sheet steel being cast directly from the liquid state between a set of rotating drums? Professor Richardson no doubt shared similar thoughts, since he was successful in obtaining further research funds from the Nuffield Research Foundation, so as to form the John Percy Process Metallurgy Group, of which I was one of three young founding trainees (R. Carr, R. Guthrie, M. Moore)!

With the wisdom of hindsight, many of the answers to my questions involve fluid mechanics together with associated flows of heat and mass transfer, while others still seem to make little sense, and are probably rooted in the traditions of a specific industry. Nonetheless, it almost a truism that metallurgical extraction processes, both pyro-metallur-
gical and hydro-metallurgical, all involve fluid flows, in one way or another, in association with heat and mass exchanges between gaseous, liquid and solid phases.

Today, fluid flows still abound for the material scientists, but I suspect few appreciate it, unless their educational background includes a little Process Metallurgy, or its equivalent. Consider the production of advanced materials involving the chemical vapor deposition (CVD) of turbine blade super-alloys with nickel based deposits of alumina, or the transport of SiF₄ gas and special additives onto the insides of glass tubes so as to create fibre-optic cables, or the wetting and coating of plastic compact discs with molten aluminum, or the role of natural convection in the production of single crystals of silicon from a melt, etc., etc.

2. The Theory of Fluid Flows

What exactly do we know about fluid mechanics? Stripped to its essence, a fluid is defined as a substance that cannot sustain shear stresses without moving. For instance, a stable, motionless pool of liquid steel can be contained within an adiabatic ladle, but if there are any heat losses to the walls, thermal density differences between cooler steel at the sidewalls will lead to gradients in density and therefore weight. These spatial differences in gravitational forces, in turn, will generate re-circulatory natural convective flows. Similarly, once a tap-hole or slide-gate nozzle is opened, the large static pressure on the liquid is no longer counterbalanced by the equal and opposite resistance of the closed nozzle, and a pressure gradient is established, causing the liquid to accelerate out of the vessel as an inertially-driven flow. Thus the fundamental equations describing the flow of fluid within such flow systems are those requiring continuity of mass and conservation of momentum, the latter deriving from Newton’s Second Law of motion:

\[ \sum F = ma \]

Here, \( \sum F \), the vector sum of the forces acting on a fluid element of mass, \( m \), can include the forces of gravity, pressure, shearing, electromagnetic and inertia. The sum of these forces acting on a fluid element is equal to the product of the mass of a fluid element and its vector acceleration.

Newton’s Second Law of motion is hopefully known to all of us from our schooldays. In our physics courses, we were able to predict missile ballistics, rocket trajectories, and the like, and we were advised to ignore frictional effects! If we now imagine an infinite number of minute fluid masses (elements), but these are now in contact with one another, as well as in relative motion to each other, then we must include these frictional effects. These are the shearing and normal stresses generated at the surface boundaries of these imaginary fluid elements.

For metallurgists involved with mattes, molten metals, liquid slags and gases, Newton again comes to the rescue with his Law of Viscosity. This law, in its simplest form, states that a liquid, in parallel flow to a flat plate (boundary) will experience an x-directed tangential shearing stress, \( \tau_{xy} \). This shear stress is set up between two fluid layers (containing imaginary cuboids), in the presence of a shearing velocity gradient in the y-direction, according to:

\[ \tau_{xy} = -\mu \frac{dU}{dy} \]

In three dimensional flows, there can be a total of nine components of shear and normal stresses, \( \tau_{xx}, \tau_{yy}, \tau_{zz}, \tau_{xy}, \tau_{yz}, \tau_{xz}, \tau_{zx}, \tau_{zy}, \tau_{yz} \) that need to be considered. When all these considerations are taken into account, and generalized, so as to allow for rotational (vs. irrotational) flows, the combination of Newton’s laws of viscosity and motion, plus continuity, leads to the famous Navier–Stokes (N-S) equation for flows within an incompressible, Newtonian fluid. In vectorial form, the N-S equation can be summarized as follows:

\[ \frac{\partial}{\partial t} (\rho \mathbf{V}) + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla P - \nabla \cdot \mathbf{\tau} + \rho g \]

for a co-ordinate system, in which the “observer” to the flow, is stationary (Eulerian framework). This partial differential equation shows that the changes in values of the convective momentum terms (on the left hand side of the equation) as fluid passes through a fixed, infinitesimal volume element (e.g. an imaginary cuboid) within the flow field, is balanced by changes in pressure, together with shearing stresses at the surfaces of the micro-volume element, plus the forces of gravity. In the case of liquid metal flows taking place within an induced or imposed magnetic field, there is an additional electromagnetic force term, \( F_e \) that will act on the volume element. The integration of this highly non-linear partial differential equation had not been possible using analytical methods, apart from special cases, such as creeping flows when the convective terms can be ignored, or when the viscous forces can be ignored (i.e. potential or inviscid flows). While many useful analytical solutions were obtained for converging flows, or for accelerating flows around submerged objects (i.e. potential flows based on the Euler Equation), in the early 20th century, it was not possible to solve flow separation problems analytically. This required the introduction of empirical drag coefficients, and the like, to macroscopic versions of the momentum and energy equations, in order to account for pressure drops and drag forces associated with the many recirculatory and separated flow systems we encounter in nature.

It took the advent of the modern computer in the 1960’s to allow us to model such typical real life flows. By discretising the N-S and continuity equations, and imagining many imaginary cuboids (volume elements), we were able to obtain particular solutions to practical problems. Nonetheless, for the past forty years, we have lacked computers of sufficient power to resolve turbulent flow problems directly, since the imaginary volume elements needed to capture turbulent micro-flows, (also governed by the N-S equation), have been just too small, and too numerous, to match the capabilities of our best computers, even today. I well remember the ATLAS computer at the University of London, which took up a whole room, but was incapable of much output, back in 1966, before the development of transistors. As we all now know, miniaturisation allowed for the development of desk top computers that now take up far less space, consume far less energy, and provide far greater performance, than the old ticker-tape ATLAS computer.
Similarly, software has become so much more user-friendly, and powerful, since my early days as a graduate student, in 1965. In parallel with these advances, Computational Fluid Dynamics (CFD) began to evolve, growing ever more important, in concert with our computing capabilities.

Since the post World War II pioneering works of Dr. C. Hirt at the Los Alamos Laboratories in the 1950's, and those of Professor D. B. Spalding and his colleagues in Mechanical Engineering at Imperial College, in the mid to late 1960's, increasingly efficient numerical methods have been developed to compute flow fields in systems of practical interest. By 1979, Salcudean and Guthrie were able to report on a previously declared impossibility, to compute three dimensional flows in ladles!, with helpful advice from Dr. Hirt. Another early example of these personal efforts involved predicting the flow of liquid steel through a tundish into the oscillating mould of a slab caster. To accomplish these flow predictions, imaginary volume elements into which fluid enters and leaves, the specific flow environment of interest, were set up, as illustrated in **Fig. 1**, this time with the assistance of CRAY Research.

For the past fourty years, these imaginary volume elements were made as small as possible, say a cubic centimetre, or a cubic millimeter, depending on the power and speed of the computer available. The whole array of micro-flows into, and out of, each of these elements were solved, so as to satisfy the boundary conditions applying to the flow domain (e.g. vessel geometry, flow input, entry velocity, number of exit flows, etc.), together with continuity and momentum.

Since these volume elements were small, but large in comparison to the scales of turbulence (e.g. 0.1 mm), and associated time scales (e.g. 1 ms), it was/is customary to write a time averaged form of the N-S equation, the so-called turbulent N-S, or Reynolds equation, and to solve time averaged flows, and velocity flow fields, according to:

\[
\frac{∂}{∂t}(\rho V) + [V \cdot (\rho V V)] = - \nabla P - [V \cdot \tau^{(i)}] + [V \cdot \tau^{(e)}] + \rho g
\]

Because of this restriction, the discipline has needed to develop models of turbulence appropriate to the types of flows involved. Over the last forty years, considerable efforts have been expended in such endeavors, and significant advances have been made. To make matters much easier, a good number of software packages for solving Computational Fluid Dynamics (CFD) problems are now commercially available. These packages allow engineers to predict flows in well set systems with some accuracy. Similarly, by solving these sets of highly non-linear Partial Differential Equations (PDE's) in parallel, using banks of computers, it has also become possible to solve ever more numerous, and ever finer, sets of finite volume elements. The next logical step in these developments, are *ab-initio* CFD predictions. These allow such fine grids, and such small time steps, that microscopic turbulence can be simulated directly, without the need for macroscopic models of turbulence. As a good example, I would like to draw attention to complex CFD predictions being carried out by Dr. Kouji Takatani and fellow researchers in his research laboratory at SMI, using some 240 computers, all working on parts of the numerical solutions, in parallel with one another, allowing for extremely fine grids.

Even under these best of circumstances, there will still remain many instances of uncertainty in predicting just what happens in complex two phase flow problems such as slag droplet entrainment into liquid steels, or three phase flows such as bottom bubbling, foaming, iron droplet-laden, slags in BOF's. CFD predictions of such phenomena are likely to be wrong, in the absence of supporting experimental data and observations. For such situations, physical modeling plus plant measurements, wherever possible, in conjunction with CFD, remains the preferred, and essential, tool for research.

In the next section of this address, I would like to choose a few examples from the rich variety of fluid flow phenomena that are a part of typical iron and steelmaking operations, so as to show how well, or not, we can model them, and how these flows can be beneficial, or not, to an operation. Let us start with one of Metallurgy's most magnificent reactor systems, the Iron Blast Furnace.

### 3. The Iron Blast Furnace

The iron blast furnace is a counter-current exchanger of heat and mass, in which a descending burden of iron ore (hematite) slowly descends in the form of a packed bed, from a height of some 25 m, down to a horizontal line of some 30–40 tuyeres, set radially, where the final conversion of now molten iron oxides to carbon saturated molten iron, takes place. As we all now know, based on the dissections of "flash frozen" Japanese blast furnaces, the successive layers of ore and coke retain their coherence during the descent, and this is vital for the successful counter-flow of hot ascending gases (CO, CO, N₂, H₂O, H₂) through the coke slits in the softening cohesive zone. If these windows, or slits, for the passage of gases up into the descending burden are compromised through excessive breakdown of coke say, the back pressure will build up and the furnace productivity will drop. Again, thanks to thirty years of research, we now know the importance of sizing, and avoiding fines. Thus, for minimising pressure drops up a vertical packed bed, it is important that the ore be uniformly sized, and that fines which will block the interstices between the iron oxide lumps, sinter, or pellets, be minimized as far as possible. This requires correct firing of the green sinter or pellets to ensure cohesive silicate bonds. As a result of these improvements, fluid flow through the burden has been dramat-
ically improved, smelting rates increased, and blast furnace efficiencies increased by a factor of about two since forty years ago. Concurrent with these flow improvements, the reducibility of the burden’s iron ore has been improved through the use of sinter or pellets, instead of lumps of ore.

As we ended the twentieth century, DOFASCO had switched to 100% pellet burdens from lumps of ore, and the next question to tackle was how much bunker C oil (high sulphur) could be used as a replacement for expensive coke. That was my task as a young professor working in their steelworks.7) I lost a lot of weight, and much sweat, injecting oil into the tuyeres of their #3 blast furnace. That furnace is shown in Fig. 2, blowing its snort valve in the evening air. More recently, Pulverized Coal Injection (PCI) into the raceways of a blast furnace, has become globally popular. In both cases, the purpose is to replace expensive metallurgical coke in the burden, with inexpensive units of alternative carbon sources. Today, the champion amounts still remain something of a burning issue for debate. 

Today’s maximum rates of 290 kg/t PCI will bring the theoretical coke requirements down to 210–260 kg/t of hot metal. Again, fluid mechanics, combustion, and the penetration of un-combusted coal particles into the packed bed of coke surrounding the raceways on gas flows, are all involved. Many other fluid flow phenomena can occur within a blast furnace, some of which are definitely harmful. Local flooding, burden fluidization and/or short circuiting, are to be avoided at all costs.

The blast furnace is essentially a countercurrent plug flow reactor that has proved its worth and versatility over the last two hundred years. Its predicted demise is still not evident in terms of a competing process, although blast-furnace-like reactors such as COREX and FINEX that avoid the coke-making step, represent logical extensions to this technology.

Comprehensive mathematical models of blast furnaces have been constructed that allow for the flows of gases, solids, and liquids, together with gas compositions, degree of ore reduction, pressure and temperature fields, and the location, shape and extent of cohesive zone, fines injection, etc., all to be predicted. An excellent example comes from the work of Professor Yagi’s research group at Tohoku University. His senior member, Dr. Hiroshi Nogami, spent a year at McGill in 2000 AD, setting up equipment to physically model PCI injection.

The CFD analyses are based on a finite difference code. This discretised model can track the motion of gases, solids, and liquids, through the array of volume elements shown in Fig. 3. The predictions are illustrated in Fig. 3 ((a), (b), (c), (d), respectively), for gas, solids, liquid, and powder flows. The code makes use of the N-S equation plus continuity, using an artificially high viscosity to treat the movement of the solid burden. Coupling of the solids with the kinetics of chemical reactions via the solution loss reaction for coke dissolution, and reduction of iron oxides to wustite, gives the volume fraction of coke and ore entering each volume element. Clearly, some serious accounting is needed to couple all the flows correctly. Figure 3(d) shows the base case for the flows of gas, fines (from PCI), solids, and liquid phases.8) More recently, as computer powers continue to climb, the Discrete Element Method is an promising alternative approach to solving these types of flow systems, given that the individual particles of coke and ore do start life as discrete particles as they descend down the shaft of a blast furnace (i.e. a continuum approach to solid granular flows in blast furnaces is questionable).

All these advanced models are of significant help in understanding complex processes, and running various scenarios for predicting likely effects in making physical and chemical changes in burden materials.

4. Steelmaking

Flows in steelmaking vessels play a critical role in the productivity levels that can be achieved. When Henry Bessemer invented his surprising pneumatic steelmaking process in 1856 (English patent 356, February 12th, U.S. patent, November 11th), it represented an early fore-runner of today’s OBM [K-BOP, Q-BOP] steelmaking vessels. In both cases, carbon saturated iron is intimately contacted with an oxidising gas, through the submerged jetting of high velocity gases. The principal limitation of the Bessemer process was the high nitrogen content in the steel resulting from its absorption into the melt from the air blast during refining. While its steelmaking kinetics were attractive, so much so that US steel production rose from 910 t in 1810 to 45 000 t in 1871, thanks to the presence of seven Bessemer plants, the Siemens Open Hearth Process, even with its much lower kinetics, was gaining ground on account of its flexibility in scrap/hot metal charging ratios, the low nitrogen contents of its refined steel, and the monopolistic business cartel set up by Bessemer.

Figure 4 shows the changes in processes that have been used to produce steel in the United States over the years. The kinetically superior Bessemer Furnace gave way to the much slower, but easier controllable Open Hearth Furnaces. These processes, in turn, were ousted by the Basic Oxygen Furnaces, that are now giving way, in scrap rich North America, to very large Electric Arc Furnaces. In terms of fluid mechanics, it is my view that luck was on the side of both the Bessemer and Siemens-Martens steelmaking processes.

In terms of fluid flows, let us recall the great concern that
was generated among BOF steelmakers when the OBM, or Q-BOP, process, was first introduced to steelmakers in the late 1970s. This new process was developed by MaxHutte, in collaboration with Dr. Guy Savard and Dr. Robert Lee, of Canadian Liquid Air (Air-Liquide) Montreal, Canada. They had invented a new tuyere that could inject pure oxygen into steel without dissolving away the refractories around the steel entry nozzles. This was accomplished by shrouding the oxygen jet with a physically protective hydrocarbon gas. It also transpired that the endothermic cracking of hydrocarbon gases created a protective "mushroom" of solid steel. Their invention held the promise of a new life for the Bessemer Process. The injection of pure oxygen into molten pig iron resolved the nitrogen problem, that had helped lead to the demise of Bessemer's Process, while the Savard/Lee shrouded tuyere solved the problem of catastrophic attack of the refractories surrounding the tuyeres by FeO slag formation, when blasting regular jets of pure oxygen into Bessemer vessels.

Unfortunately for Savard and Lee, their 1958 invention (U.S. patent 2,855,293, October 7th) had come just a little too late to pre-empt the BOF process. Thus, in 1954, Dofasco had acquired the Canadian license from Linz-Donowitz for the LD, or BOF process, and became the first company in North America, and the second in the world, to adopt this new top blown oxygen converter process. Since the kinetics of this process were so superior to those for the Open Hearth, and liquid oxygen was available at competitive prices from the gas industry, the BOF system rapidly became a dominant force in North America, as witnessed by Fig. 4, reproduced from Figure 35 of A. B. Wilder's review of Bessemer steelmaking, which shows the flow incorrectly descending from the impact point of the oxygen jet, rather than moving up towards it.

From a fluid dynamics perspective, there was always the nagging problem that blasting supersonic jets of oxygen onto a bath of liquid iron, as per a BOF, rather than into a bath of liquid iron, as per an OBM/Q-BOP could not be the best way to energetically couple the slag and metal phases. This, together with the fact that the linear decrease in carbon with blowing time tails off at about 0.1 mass% carbon with top-blowing, suggests that the transport of dissolved carbon from within the steel bath towards the fire-point becomes rate limiting. Indeed, when refining times of 14 min for the new Q-BOP process using the Savard-Lee shrouded tuyere (vs. 20 min for the BOF), and turnaround carbons of 0.04% vs. 0.07%, were announced by US steel, BOF operators acknowledged that more stirring was needed if they were to compete on the basis of productivity.

Figure 6(a) shows the results of some AISI sponsored mixing time studies that were carried out using 1/5 and 1/20th scale water models of BOF's at McGill by Oymo and Guthrie, together with corresponding confirmatory CFD studies of multi-submerged-bubbler arrays by Mr. Nobuhiro Kurokawa, of SMI, during his one-year stay at McGill doing CFD modeling (Fig. 6(b)).

Our mixing time results showed that 1) only 5% or so of the kinetic energy of a top blown jet is transferred into bath stirring energy for conditions applying to BOF practices, whereas essentially all the incoming kinetic, pressure and
potential energy of the submerged jets in bottom blown practices are used for stirring, and 2) for best mixing conditions, the plugs or nozzles set in the bottom of BOF vessels should be arranged asymmetrically, at about one third radius, so as to be on the outer lips of the cavities created by the top blown oxygen jets.

With these modifications, refining times, and turndown carbon levels obtained by Q-BOP furnaces, could be almost matched by passing only 5% of the gas through the bottom bubblers. Clearly, fluid mechanics was a very important part of metallurgy from a process efficiency point of view. Similarly, good fluid mechanics can translate into millions of dollars profits, whereas bad fluid mechanics will translate into equivalent losses. For BOF steelmakers, these bottom bubblers allowed them to survive the arrival of Q-BOP technology, and to almost match the improved metallurgical performance of such vessels.

However, the story is probably not quite so straightforward as might appear. Dr. Shigenori Tanaka, of NSC, carried out physical simulation experiments of top and bottom blowing furnaces, during his doctoral studies at McGill. He showed that bottom bubbling into a water/paraffin system creates an inverse emulsion that would correspond to the entrainment of slag droplets into liquid steel. This is illustrated in Fig. 7(a), where one sees the entrainment of paraffin droplets into water, and being generated by simulated bottom blowing practices. Figure 7(b) shows that with simulated top blowing only, no such inverse emulsions are generated. Figure 7(c) provides confirmation that this phenomenon also operates in BOF steelmaking; the photograph shows spherical droplets of frozen slag found in sublance samples of steel taken from a melt. These tests were arranged by Dr. S. Tanaka, following his return to Japan, by taking a sub-lance sample, during combined blowing operations at one of NSC’s steelplants. This teaches us that enhanced mixing of the steel bath to bring carbon more rapidly to the firepoint is probably less important than the decarburization achieved by creating extra surface areas for slag/metal contact for the carbon–oxygen reaction. i.e. oxidising slag droplets in the steel, and carbon containing steel droplets ejected into the slag, are primarily responsible for governing reaction rates in BOF furnaces. Certainly more research work is needed in this area before we can quantify the relative importance of the various reaction sites that lead to the decarburization of hot metal in BOF reactors and other similar pyrometallurgical processes such as HIS-MELT, DIOS, etc. Dr. H. Nakajima studied, and demonstrated similar phenomena, for gas stirred ladles with slag layers on top.

As a postscript, slag chemistry and slag splashing can be used to improve refractory lifetimes of BOF’s very significantly. As such, the use of bottom stirring is now less popular globally, given that porous plugs have a finite lifetime. Similarly, the lower turndown carbon levels possible with bottom stirring is not so critical these days, given that most integrated steel-plants now have vacuum degasser units, for removal of hydrogen, oxygen, and nitrogen. For this, higher turndown carbon levels are needed to removal dissolved oxygen on a one carbon atom, to one oxygen atom, basis. However, to illustrate the many variants available towards making steel, Japanese steel-plants where a de-Phos BOF is followed by a de-C BOF, bottom bubblers are still used. For instance, I was informed by Dr. H. Nakajima, that the SMI...
Wakayama plant can now achieve 8–9 min de-C refining times.

5. Ladle Metallurgy

Let us now move on to ladle metallurgy, and see how fluid mechanics can have a critical effect on the efficiency of these processing operations. The stirring of ladles by the use of submerged porous plugs remains commonplace. However, in the 1960's, a ladle of steel was typically let to "rest" after the teeming operation, in order to allow the inclusions of silica or alumina generated by the additions of ferro-silicon or aluminum, to float out. We still do the equivalent in the reverberatory gas fired holding furnaces in the aluminum industry, and melt quality does improve nicely with holding time, as inclusions either float out, or settle. With the advent of continuous casting, it was found that steelmaking teeming ladles needed to be stirred in order to maintain thermal homogeneity, metal superheat being a critical aspect of casting. An unanticipated result, however, were the major improvements in steel quality, in terms of the lower levels of inclusions that resulted, as recorded by a drop in total residual oxygen in the solidified steel.

One of the more critical aspects of ladle metallurgy is the addition of ferro-alloys, deoxidants and de-sulphurisers to the steel, in critically controlled amounts. Fluid mechanic simulations of the ways these additions should be made have provided a fertile area for research and development. Based on numerical modeling of an aluminum sphere melting in liquid steel, we were able to predict, and then experimentally confirm, that a frozen shell of steel would form around the aluminum steel, and would only melt back, once the molten aluminum had reached the melting point of steel. This early discovery turns out to be universally applicable. Techniques include bulk alloy additions during ladle filling. Addition trajectories, followed by release of their molten contents and dispersion into liquid steel, mark the end points of their traced paths.

Thanks to all these flow simulations, we now know how best to add additions into steel, in order to intermix them efficiently and rapidly. Techniques include bulk alloy additions via the "boot method", by bullet shooting, wire feeding, the CAS technique, etc. The bullet shooting technique was practised by SMI at their Wakayama plant. It was my first opportunity to work directly with Japanese steel workers, back in 1979. Thanks to the help of Dr. Masaaki Tanaka, and Dr. Ken Katogi, we were able to show how their aluminum bullets, measuring some 24 mm diameter, and 400 mm long, and fired into a filling ladle of steel at 60 m/s, could be easily modified with thin localized strips of insulation, so as to melt sub-surface, at lower steel superheat temperatures. Later, we went on to apply this knowledge to the wire feeding of aluminum, which is essentially a continuous bullet shooting process! Wire feeders are now used extensively throughout the industry. Clearly, an understanding of the fluid mechanics and associated heat and mass transfer allows for some very significant improvements to the technologies associated with the control of steel chemistry.

6. Tundish Metallurgy

It is now well known that the way liquid steel flows into and through a tundish, can play a major part on steel quality. Many papers have been written, and many computations performed, which show how inclusions can be floated out of the steel into the overlying film of slag, using appropriate flow control techniques. The placement of dams and weirs can be very helpful for intermediate sized inclusions, but are of no help in the removal of small inclusions, since

\[
\text{Stokes Velocity (mm/s)} \\
\text{Inclusion Diameter (μm)} \\
\text{Stokes Velocity (mm/s)} \\
\text{Inclusion Diameter (μm)}
\]

\[
\text{Residual Ratio}
\]

Fig. 8. (a) Complicated trajectories followed by spheres of aluminum (O SG~0.4) and ferromanganese (● SG~0.8) dropped into a ladle being filled with an angled steel jet; (b) alloy additions during ladle filling, in which the steel jet enters vertically.

Fig. 9. Relationship between the residual ratios of inclusions in steel outflow to the mould versus their Stokes velocities. CFD predictions for a full-scale water model of the Lake Erie slab casting tundish of Stelco (now US Steel).
their float-out velocities are so slow. Computational results\(^{17,18}\) for the Stelco Lake Erie tundish are shown in Fig. 9, where separation ratios are seen to be enhanced by FCD devices for inclusions with rising velocities between 1 and 4 mm/s.

Larger inclusions with higher Stokes rising velocities were predicted to float out of the Lake Erie tundish, whether or not flow control devices (FCD) were present. Alternative techniques to remove very small inclusions may be the use of bubble swarms.

7. Gas Shrouded Flows

Recent work at McGill by Kinnor Chattopadhy, using the FLUENT code, has been focusing on modeling the flows generated within a steelmaking tundish when argon-shielded ladle shrouds are used.

Computations of the dispersion of argon bubbles, together with their residence times, as a function of gas flowrates, and bubble sizes, have been made, for comparison with experiments. If the bubbles are relatively large, say 6 mm diameter, then a reverse flow is generated close to the entry point of the ladle shroud into the tundish, and a gas plume is generated, as seen in Fig. 10. At higher gas shrouding flowrates, corresponding to 10% of entry steel flows, the flow reversal around the entering steel jet causes the layer of protecting slag to be peeled back, exposing steel around the ladle shroud to air, with the attendant dangers of steel re-oxidation, as in Fig. 10(d).

However, computations demonstrate that if one reduces bubble sizes from some 6 mm down to 0.25 mm diameter, then such micro-bubbles have low rising velocities, and become dispersed throughout the tundish. Such bubbles could be very effective in removing the smaller inclusions from a real steelmaking tundish. The phenomenon has recently been demonstrated physically, using the full scale model of the 4 strand 12 t delta-type tundish shown in Fig. 11.

Certainly, one of the advantages of CFD predictions of tundish flows versus physical models is the ease in which one can test various scenarios, and to incorporate many complicating factors. For example, during a ladle change, the fresh steel entering the tundish is generally hotter by 5–10°C than steel in the tundish. In such cases, the new steel will tend to “float” over the colder (more dense) existing steel. Alternatively, cooler entering flows of steel will sink towards the exit nozzles (SEN’s), causing short circuits of inclusion-laden steel to these exit nozzles.

On the other hand, in order to simulate real tundish prac-

![Fig. 10. Bubble tracks at (a) 2%, (b) 4%, (c) 6%, (d) 10% of gas/water entry flowrates, and corresponding near surface velocity fields predicted from the numerical model under transient conditions.](image-url)
...text continues here...
Here we see that the acceleration and consequent motion of the particle as it enters the ESZ is affected by: 1) the fluid drag force for steady translation of a submerged body, 2) by an added mass effect during relative acceleration, 3) by the inertial forces of the fluid itself while it accelerates into the ESZ, 4) by the particle’s history force, 5) by gravity forces, and finally, 6) by an electromagnetic force, \( \mathbf{F}_e \). This body force is known as the Lorentz magnetic force and is defined by the equation \( \mathbf{F}_e = \mathbf{J} \times \mathbf{B} \), where \( \mathbf{J} \) is the current density vector, and \( \mathbf{B} \), the magnetic flux vector.

The drag force on a submerged object is well known. Less appreciated is the added mass force which takes into account the fact that any accelerating or decelerating spherical body must also accelerate half its volume of surrounding liquid that it displaces. In the case of LiMCA, acceleration forces \( \sim 200 \text{ g} \) make this factor very significant given that an inclusion accelerates from an exterior low velocity \( \sim 10 \text{ cm/s} \), to a velocity in the order of 4 m/s at the vena contracta of the ESZ, over a distance of \( \sim 500 \text{ m} \), or less.

The Basset history force also needs consideration, and is needed to take into account the development of the boundary layer (vorticity) around the accelerating inclusion. The force is expressed in terms of the time integral of the particle acceleration at \( t \) weighted by \( (t - \tau)^{1/2} \) where \( (t - \tau) \) is the elapsed time since that past acceleration. The history
term proved to be relatively minor in this instance.

The electromagnetic forces generated within the liquid metal are the result of a self induced magnetic field generated by the heavy electrical currents passing through the ESZ (e.g. 60 A). These are needed for obtaining measurable voltage pulses during the passage of inclusions, given the high electrical conductivity of liquid metals in comparison with ionic liquids. The extremely high current densities, $j$, within the ESZ ($\sim 10^9$ A/m$^2$) create a strong radial magnetic force field $F_e$. This force field then produces a strong outwards radial force on an inclusion, $F_{ep}$, proportional to the product of $F_e$ and the volume of the non-conducting particle:

$$F_{ep} = -\frac{3}{4} V_p F_e = -\frac{3}{8} V_p \mu_m I^2 r$$

Figure 18 shows computed self inductive magnetic force fields generated in variously shaped ESZ’s. The first ESZ was originally used for monitoring inclusions in molten magnesium, in which a BN orifice could be readily machined, the second shows the parabolic ESZ used for aluminum melts, while the last shows the preferred ESZ for steel melts. Since computed force fields for steel melts cause insulating inclusions to migrate towards the sidewalls, with which they can collide, attach, roll along, and/or detach from, the sidewalls of the ESZ, impacts can produce spurious signals. By limiting the length of the particle deflection zone to 1 mm, and residence times to about 2–3 ms, passthrough fractions of inclusions are significantly enhanced, and “noise” minimised.

Another very interesting phenomenon, that proved crucial to the success of the original Limca probes, were the effects of applying very heavy currents. Figure 18 shows predictions for how electrical currents affect the way liquid steel passes through the 500 µm diameter fluted orifices. As seen, at lower currents of 20 A, high velocities are...
recorded in the straight section. As the current increases, a back pressure generated by the EMF force field slows the flow of steel through the ESZ. At amperages of 300 A, flow reversals are generated close to the axis of the entry region, making it difficult to fill the tube with a steel sample. This is illustrated in the reverse flows seen in Fig. 19 for fluted orifices in steel.

Our computations and experiments also reveal that the ESZ technique can make a distinction between different types of inclusions, based in their relative densities. In the future, we hope to demonstrate that liquid inclusions can be distinguished from solid inclusions for steel melts (i.e., calcium aluminates micro-droplets versus alumina inclusions).

In summary therefore, one sees how the physical characteristics of an apparently simple hole set in a sensing tube for monitoring melt quality, must actually be fashioned in such a way as to optimize the flow of inclusions into, and out of, the ESZ, so that their collisions with the sidewall are largely avoided.

As with many inventions, there were elements of luck to the development of satisfactory probes for steel, and improvements continue. In our case, most flows have proved very friendly, and bad flows have been circumvented, thanks to the knowledge provided by these CFD model simulations.

9. Moving Mould Technologies for Strip and Thin Slab Casting

(a) Twin Roll/Drum Casting

As a final topic to illustrate important fluid flows in metallurgy, I would like to return to Bessemer’s 1857 patent on the twin roll caster. One of the (many) challenges of the Bessemer system is to optimise the way liquid steel flows into the sump of the caster, and freezes against the rapidly rotating rolls. Any slight differences in the superheat of the metal flowing across the width of the caster can lead to the freezing of shells being thicker or thinner. Similarly, reverse flows or jetting flows can partially re-melt the freezing shells, which ideally, should come together perfectly at the roll nip, or kissing point.

Dr. Hideki Murakami, of NSC, carried out his doctoral studies at McGill, graduating in 1993, modeling turbulent flow, heat transfer and solidification in a twin roll caster. Figure 20 show show liquid steel should not be presented to the rolls. It shows the predicted fluid flow field generated in a 0.6m roll diameter pilot caster in Canada, using a conventional submerged entry nozzle of the bifurcated type used for slab casters. The corresponding solidification profiles are shown in Fig. 20(b), where it is seen that the centre of the forming shell is thicker halfway down the sump, than at the sides. The reason is a loss of superheat in the convective flow of liquid moving out to the side dams and re-circulating back across the roll surfaces. In order to avoid these three dimensional effects on shell uniformity, various slot nozzles were investigated mathematically, together with an extended nozzle directing the flow of liquid radially to the surfaces of the rolls, as first proposed by Herbertson and Guthrie back in 1987. These computations showed that surface turbulence, meniscus temperatures, shell uniformity and shell thickness, are all optimized by such radial flow arrangements.

(b) Single Belt Casting

Near net shape casting, which is a green technology in today’s ecologically sensitive climate, with steel production rates in excess of 2MT/year, are not a good fit for the productive capacities of realistic Twin Roll Casters. An alternative solution is the Horizontal Single Belt Caster (HSBC) for matching the production capacities of integrated steel plants. The fluid mechanics aspect is how to iso-kinetically feed liquid steel onto such a single belt caster.

Professor Klaus Schwerdtfeger and his research team have also been advocating such an approach, for the past twenty years, and it would appear that the day is finally dawning for the first commercial unit to be built for Salzgitter. Figure 21 illustrates the McGill Metals Processing Centre pilot scale Horizontal Single Belt Caster (HSBC), similar to the two DSC (Direct Steel Casting) pilot casters at Clausthal University, now being directed by Prof. Carl Heinz Spitzer.

(c) Ab-initio Calculations of Initial Solidification

Both TRC and HSBC (or DSC), involve the contacting of liquid steel with a chilling substrate. Since the first few moments of contact determine the quality of the strip’s bottom surfaces, it represents a critical aspect for any near-net shape, moving mould, machines. CFD models are needed to explore these critical first moments of solidification.

Given the scenario shown in Fig. 22, and the situation of idealized iso-kinetic plug flow of liquid steel on a water-
cooled moving belt, we can use a Lagrangian frame of reference to predict, from first principles, the instantaneous heat fluxes into the belt, and to predict heat fluxes and temperature gradients during the first moments of solidification for a low carbon steel. The results of these computations are shown in Fig. 23, where one sees that the fraction of liquid within the cells adjacent to the steel belt drop to about 65% after just 3 ms. By 10 ms, the steel in contact with the peaks on the belt surfaces are forming frozen lenses, which connect, as a freezing front moves up into the liquid steel above.

By 20 ms, the bottom surface of the strip is fully solidified, and bottom surface quality is already determined. The diagram to the right shows that the 1.5 mm steel strip will have solidified after 230 ms.35)

One of the problems with such rapid solidification is meniscus control. While parting agents such as graphite or oils can improve bottom surface quality greatly, this is at the expense of significantly reduced heat fluxes. To explore other possibilities, macro-textured surfaces were machined and tested. These substrates, illustrated in Fig. 24, were used to determine if bottom surface quality could be maintained at high velocities, at the same time as high heat flux conditions. It turns out that this is possible, to some extent, using patterns (d) or (e). Again, by comparing actual heat flux data, with those predicted, as illustrated in Fig. 26, for experiments involving the casting of AA6111 aluminum alloy strips, we see that one can actually predict heat fluxes from first principles, provided the substrate surface geometry is well defined. This points the way to ridding ourselves of the many empirical heat flux correlations, so prevalent in the literature, and being able to replace these with far more satisfactory ab initio heat transfer computations for solidifying systems.35,36)

Note the exponential decays in heat fluxes from the first moment of contact, followed by sudden drops in heat fluxes, after 140 ms for pattern (d), and 200 ms for pattern (e). This corresponds to the strip in contact with the copper substrate, shrinking and thereby separating from the ridges in the substrate, forming highly insulating gas gaps.

10. Concluding Remarks

The role of fluid mechanics in metallurgy has been sketched out by way of a number of general and personal examples. We have seen that the performance characteris-
tics of blast furnaces, steelmaking vessels, ladles, tundishes, and the moulds of continuous casting machines, are all strongly influenced by such flows of fluids.

As we have seen, the question of liquid metal quality, and cast microstructures, are also bound up with the way fluids have flowed and interacted. Perhaps without many of us acknowledging its pivotal role in many metallurgical processes, we all know intuitively that fluid flows are relevant to many processing operations, and they can be either friendly, or hostile.

These days, with the ever increasing power and capabilities of computer hardware, together with the development of CFD commercial software, it becomes increasingly possible to model many complex flows, and to find optimal solutions. Furthermore, practitioners no longer have to write their own codes! As such, the subject no longer remains in the exclusive domain of experts, but has become increasingly accessible to all would-be modelers. Nonetheless, in my experience, fluid flows often do not behave as one might anticipate. Similarly, to let students loose on these increasingly powerful, and increasingly user-friendly codes, is a dangerous undertaking. A good understanding and familiarity of the numerical methods and techniques must still remain an essential ingredient to their training. Finally, physical models, and actual plant experiments, will likely always be needed for quantifying our models of any radically new processes.

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Nomenclature

\[ a : \ \text{Particle radius (m)} \]
\[ \mathbf{a} : \ \text{Acceleration vector (m/s}^2)\text{)} \] or (N/kg)
\[ \mathbf{B} : \ \text{Magnetic flux density vector (weber/m}^2)\text{)} \]
\[ C_D : \ \text{Drag coefficient for submerged body in steady translation} \]
\[ D : \ \text{Diameter of ESZ orifice at vena contracta (m)} \]
\[ \frac{D}{Dt} : \ \text{Time derivative following a fluid element (s}^{-1}) \]
\[ \mathbf{F}_c : \ \text{Electromagnetic, or Lorentz, force per unit volume (N/m}^3) \]
\[ \mathbf{F}_{ep} : \ \text{Electromagnetic force on particle/inclusion (N)} \]
\[ g : \ \text{Gravitational acceleration vector (N/kg, or m/s}^2) \]
\[ I : \ \text{Electrical current (A)} \]
\[ J : \ \text{Electrical current density (A/m}^2) \]
\[ m : \ \text{Mass (kg)} \]
\[ P : \ \text{Pressure in fluid at a given location (N/m}^2) \]
\[ t : \ \text{Time (s)} \]
\[ \mathbf{U} : \ \text{Velocity (scalar) (m/s)} \]
\[ \mathbf{U}_p : \ \text{Velocity vector of particle (inclusion) (m/s)} \]
\[ \mathbf{U}_v : \ \text{Velocity vector in fluid (m/s)} \]
\[ \mathbf{U}_x : \ \text{x component of velocity vector for a Cartesian coordinate system (m/s)} \]
\[ \mathbf{V} : \ \text{Velocity vector (m/s)} \]
\[ \mathbf{V}_p : \ \text{Volume of particle/inclusion (m}^3) \]
\[ x, y, z : \ \text{Location of particle, or element of fluid, referred to a rectangular co-ordinate system.} \]

Greek
\[ \mathbf{\nabla} : \ \text{Kronecker delta} \]
\[ \partial : \ \text{Partial derivative} \]
\[ \sigma_e : \ \text{Electrical conductivity of fluid (} \Omega^{-1} \text{m}^{-1}) \]
\[ \sigma_{ep} : \ \text{Electrical conductivity of particle (} \Omega^{-1} \text{m}^{-1}) \]
\[ \mu : \ \text{Viscosity (kg m}^{-1} \text{s}^{-1}) \]
\[ \mu_m : \ \text{Magnetic permeability of molten metal (Henries/m)} \]
\[ \mu_o : \ \text{Magnetic permeability of free space=}4\pi \times 10^{-7} \text{(Henries/m)} \]
\[ \chi : \ \frac{5 \sigma_{ep}}{2 \sigma_{ep} + \sigma_e} \]
\[ \rho : \ \text{Density (kg/m}^3) \]
\[ \tau_{xy} : \ \text{x-directed shear stress generated by a shearing velocity gradient in the y direction (N/m}^2) \]
\[ \tau : \ \text{Time, where (t–} \tau\text{) is the time elapsed since the past acceleration of particle(s)} \]

Superscripts
\[ l : \ \text{Laminar} \]
\[ t : \ \text{Turbulent} \]

Subscripts
\[ p : \ \text{Particle} \]
\[ f : \ \text{Fluid} \]
\[ \text{std} : \ \text{Standard (drag coefficient)} \]
\[ e : \ \text{Electromagnetic} \]

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