Authors' Reply to Discussion of "Simulation of Fluid and Inclusions Dynamics during Filtration Operations of Ductile Iron Melts Using Foam Filters"

R.D. MORALES, O. DÁVILA-MALDONADO,
A. ADAMS, L. OLIVEIRA, and B. ALQUIST

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The authors appreciate the opportunity given by Professor Campbell to discuss his views regarding the contents of our article.[1] We will discuss each issue raised in his document in order as follows.

(1) Existence of films. Solubility of oxygen in aluminum at a homologous temperature of 1.2 is about 0.001 mass pct.[2] The very small solubility of oxygen in aluminum explains the immediate formation of alumina films as soon as liquid aluminum makes contact with any source of oxygen. From a chemical reaction engineering standpoint, the reaction between aluminum and oxygen is considered as instantaneous. Therefore, during pouring operations of aluminum alloys, the formation of those bi-films is probable; however, claiming that they are more important than inclusions in the conventional concept that a metallurgist knows is audacious. Recently,[3] an experimental work related with filtration of aluminum alloys using foam filters has been published. There the authors in their Figures 7 through 9 present inclusion-trapping mechanisms that are very similar to our Figures 1(a) through (d). Even, in this work, their authors report that filtration efficiency, measured by Coulter counters, reaches a minimum for inclusion sizes close to 30 μm. In addition, a metallographic analysis of spent filters, much like we did in our experimental work, shows that the density of inclusions decreases exponentially between the filter inlet and the filter outlet. These are remarkable agreements with our theoretical analysis; indeed, in our Figure 17(a), we present also that a minimum at 30 μm and our calculated global filtration coefficients presented in Figure 18 show minimum efficiencies around those inclusion sizes. In our Figure 13, obtained through completely theoretical considerations, we obtained the same exponential decay of inclusion density from the filter inlet to the filter outlet. Such an agreement is even more interesting, since in the case of inclusions in aluminum alloys, flotation mechanisms are substituted by sedimentation mechanisms, as usually their density is larger than liquid aluminum alloys. Those authors did not identify the presence of bi-films and instead they found numerous occurrences of oxide films smaller than 25 μm, which were subjected to the same trapping mechanisms of adhesion and sedimentation. In our work, we did not find bi-films, and the reason is related to various thermodynamic and kinetic aspects. Solubility of oxygen at the same homologous temperatures is 0.27 mass pct,[2] which is considerably larger than the solubility in aluminum. Iron under oxygen saturations instead of forming bi-film forms a massive slag. Moreover, in iron castings, the simultaneous presence of carbon and silicon enhances the thermodynamic activity of carbon.[4] Therefore, carbon in iron melts under the presence of air or oxygen will react instantaneously with oxygen to form CO_g.[5] To form inclusions rich in silicon and manganese, a heavy melt reoxidation is necessary, and even under those conditions, there will be precipitation of massive slag particles. Finally, from a practical point of view, we must not overlook the fact that in foundries there are, unfortunately, all sorts of possibilities to enhance melt dirtiness such as hard slags, slag carryover, sand entrainment, *etc*., well before the melt goes through the filter. All of these particles are classified as exogenous inclusions, which, definitively, are not related with the concept of bi-films at least in the sense that Professor Campbell defines them[6] but are, certainly, candidates to be trapped by a foam filter.

(2) If those bi-films exist in aluminum alloys, very surely their mechanical strength should be very small and then certainly their integrity will be fractured and divided when they are strained during their passage through the foam filter. After the filter, they will become into numerous small inclusions that will be entrained by the flow field, as we made clear in our article for small 2-μm inclusions. Indeed, flotation or sedimentation forces are various orders of magnitude smaller than drag forces for small inclusions; we certainly agree that would be the case. However, instead of having bi-films in iron melts, we have inclusions, in the sense defined by international standards,[7] and exogenous inclusions coming from previous metal handling operations such as flows through launders and troughs and sand entrainment. It is worth emphasizing here that no filter makes the flow laminar downstream; rather, it provides different flow patterns in the casting piece due to different shear straining mechanisms of the fluid when this is stressed by the filter's walls.

(3) The authors agree with Professor Campbell in the sense that any flow disturbance is a potential source of damage for the iron-casting quality, but we

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R.D. MORALES, Professor, and O. DÁVILA-MALDONADO, Graduate Student, is with the Department of Metallurgy and Materials Engineering, Instituto Politecnico Nacional, Mexico C.T. CP 07338, Mexico. Contact e-mail: rmorales@ipn.mx A. ADAMS, Senior Engineer, is with FOSECO Metallurgical, Inc., Cleveland, OH 44142. L. OLIVEIRA, Simulation Engineer, is with FOSECO Industrial e Comercial Ltda., Sao Paulo 0557000, Brazil. B. ALQUIST is with FOSECO Morval, Inc., Guelph, Ontario N1H 1C Canada.

disagree, on the grounds of the precedent discussion, that it will induce the so called bi-films. Sano and Matshusita[8] reacted Fe-Si droplets with gases levitated in a magnetic field, and they found a decrease of silicon oxidation rate with time and oxygen potential. The reason was the formation of a film rigid enough to support the strain stresses originated by the velocity field of the droplet stirred by the effects of the electromagnetic field. Silicon oxidation decayed because oxygen had to diffuse through that film, slowing the kinetics of oxidation. Nevertheless, that film is not the one defined according to Professor Campbell′s concept, and its stiffness and strength lead us to better call it a slag layer made of iron and silicon oxides rather than a film or a bi-film. If carbon is present together with silicon in those experiments, then oxygen will react first with the former element and once leaving the droplet scarce from carbon it will react with silicon as research indicates.[5,9,10] There is no doubt: any benefit that a filter may bring about can easily be lost downstream with a bad feeding design for the melt. Certainly, what our Figures 15(a) through (c) and 16(b) indicate are potential sources of melt oxidation for this specific filter print, which would lead to the formation of CO blowholes or, eventually, to the precipitation of slag.

(4) This point raised by Professor Campbell is in complete disagreement with the experimental results provided by References [1] and [3] and, of course, with our theoretical analysis. Therefore, no further commentaries are necessary in this regard.

(5) It is common that in foundry literature and in commercial CFD codes applied to this field of technology, surface turbulence is discussed. Actually, surface turbulence is a consequence of bulk turbulence or, simply, flow turbulence. Although the authors do not have elements to debate this point, in regard to the effects of the well on turbulence, and therefore assume that Professor Campbell′s view is correct, the presence of a filter definitively modifies flow turbulence downstream. Because turbulence is not local in space and has a history by which a filter dissipates energy. The dissipation of turbulent kinetic energy has a very important influence on the flow downstream to an extent that can minimize or mask the influence of a well at the sprue bottom. There are filters that do not dissipate turbulent kinetic energy at all, and there are others that have an enormous influence on the dissipation rate of turbulent kinetic energy;[11] the foam filter is among the later ones. Dynamics of microflows through pores and channels found in filters deserve more research effort, and they represent the key, among other fluid flow factors, to delivering melts with controlled turbulence into the casting.

For inclusions as small as 0.05 μm, as Professor Campbell points out, we can say that there is a fundamental and basic problem with simulating their behavior in castings the way we did: the boundary layer thickness developed on the surface of such particles is larger than their sizes. Therefore, the approach of solving the classical Navier–Stokes and Lagrange equations does not work anymore. Instead, the probabilistic Lavengin equation is a better method.[12] However, the authors' awareness of this fact is expressed clearly in our article and is underlined as one of our limitations in the analysis. Finally, the authors do not debate with Professor Campbell′s view in the sense that our work lacks application savor and leaves that final opinion to the rest of our readers. However, the authors feel very fortunate to discover that the experimental results of Reference 3 for aluminum are in excellent agreement with what we found in iron melts.

The authors quite agree with Professor Campbell in the sense that still further research is necessary and it was a refreshing experience working in the foundry field. Most of the defects in castings come from lack of turbulence control, and this makes the foundry area a fertile one for those who like fluid flow fundamentals.

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