Modelling Filters in Light Alloy Casting Processes (or "What Really Happens When Aluminium Flows Through a Filter")

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ABSTRACT

A number of different types of so-called "filters" are used in the metalcasting industries with the aim of imparting some cleaning effect and flow control on the liquid metal as it passes through them. The filters range from simple planar meshes through extruded channels to reticulated foam structures and they are manufactured from a range of materials going from metals to glass or ceramics. It is most common that software packages used in the industry model the filters by a simple pressure drop associated with some area fraction and permeability parameters.

Recent experimental work at the IRC in Birmingham (Cox et al., 2000) has shown that filters of the same type can behave very differently depending upon the casting process in which they are employed. Modelling filter geometries for a range of different casting processes has indicated that the flow of metal and heat losses through the filters are rather complex and should be considered when using filters in the casting processes. This paper will present a number of cases of different types of filters modelled and different processes and indicate some of the sensitivities of the processes to boundary conditions imposed by the process.

INTRODUCTION

Filters are commonly used in the foundry industry. The real action of the filters on the liquid metal is not really understood. Some filters are claimed to have a chemical action on the liquid metal or to be able to clean the metal by stopping the impurities or oxides that will result in inclusions in the cast part. However, some recent experiments carried out at the University of Birmingham in investment casting and results available on sand casting (Backman at al., 1999) have shown that the action of filters may be different in these two processes. As the main difference between these two processes is the mould temperature, the hypothesis of a partial solidification of the metal in the filter occurring in the sand casting process during the "priming" stage of the filling has been advanced, whereas there is no or less solidification in investment casting. In order to verify this hypothesis, and to reach a better understanding of how filters work, a numerical investigation of the flow and heat transfer in filters in both sand and investment casting has started at the University of Birmingham, in the framework of the FOCAST project. The FOCAST[1] project is an EPSRC project aimed to increase the understanding of the investment casting process.

Another issue is the way the simulation packages predict the influence of the filters on the metal flow. The filters are most of the time modelled as porous obstacles characterised by a pressure drop calculated from porosity and some surface ratios such as open porosity or proprietary coefficients. For example, for an extruded ceramic filter, with an open porosity of 0 in the directions normal to the extrusion direction (direction of the flow of the liquid in the filter as well) and an open porosity equal to $1-\frac{S_c}{S_f}$ in the direction of extrusion, where S_c is the surface occupied by the ceramic in a section normal to the extrusion direction and S_f is the total surface of the filter in the same section, the flow loss coefficient can be calculated from the permeability of the filter using the formula given in equation 1, where K is the flow loss, P is the permeability of the filter, m is the viscosity of the liquid metal, r his density and V_F the volumetric fraction of fluid which is equal to the open porosity in the direction ofd extrusion of the filter. The permeability can be estimated from equation 2 (Scott et al., 1986), where d is the hydraulic diameter of the canal through which the liquid is flowing, V_F is the volumetric fraction of fluid, b and l are dimensionless parameters determined from the geometry of the porous media.

[1] For more details http:\\irc.bham.ac.uk\epsrc\focast

$$K = \frac{\rho P}{\mu V_F}$$ Equation 1

$$P = \frac{d^2}{b}(V_F)^{\lambda}$$ Equation 2

This paper will present the preliminary results of this numerical investigation. First, the different models that have been used are presented, followed by the results obtained. A discussion of these results and their perspectives conclude the paper.

MODELS

Three kinds of geometry of filters have been considered. Figure 1 shows the straight extruded filter (a), the shifted extruded filter (b) and the foam filter (c). Due to the complexity of the geometry of the foam filters, the resulting numerical model is huge in term of cells required to represent it. Therefore, very few results will be presented here for the foam filter. The shifted extruded filter does not exist in practice but is an intermediate model between the extruded and the foam filter, as it increases the tortuosity of the path that the liquid metal has to follow and keep the same volume or mass of ceramic material. It is still far from a foam filter as its thermal mass is very large compared to a foam filter. Three designs of filter print have been tried as well. Figure 2 shows them with the straight extruded ceramic filter.

Flow of liquid aluminium A356 [about 7% silicon and 0.6% magnesium] has been studied in sand and investment casting for the straight and shifted extruded filter. The thermo-physical data used for the aluminium alloy have been provided by the National Physical Laboratory (NPL, 2000). The liquid aluminium has been modelled as a Newtonian fluid. For the mushy zone, a variation of the viscosity as function of temperature described by equation 3 has been used.

$$\eta = K \exp\left(B f^s\right)$$ Equation 3

where η is the viscosity of the metal, K is the viscosity of the fully liquid metal, B is the sensistivity of the viscosity to the solid fraction, and f^s is the volumetric solid fraction.

For the filters, the heat capacity has been measured by Differential Scanning Calorimetry. The density has been measured. The heat conductivity has been estimated from the work of Hayashi et al. (Hayashi et al., 1998).

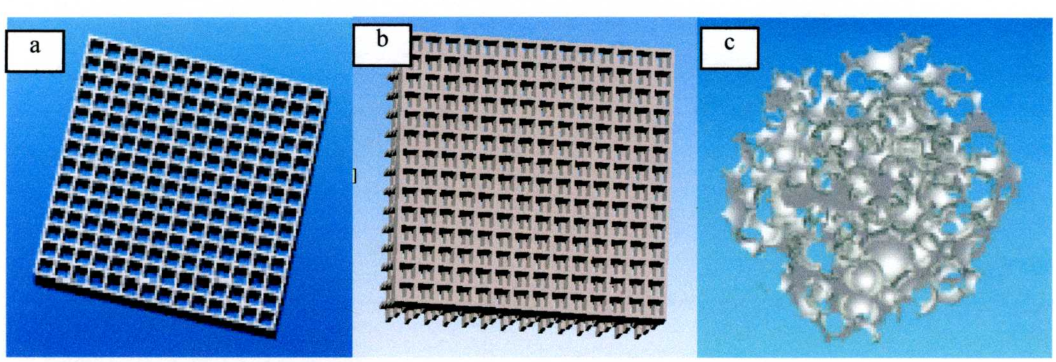

Figure 1: Three kinds of filters, extruded ceramic filter (a), shifted extruded ceramic filter (b)

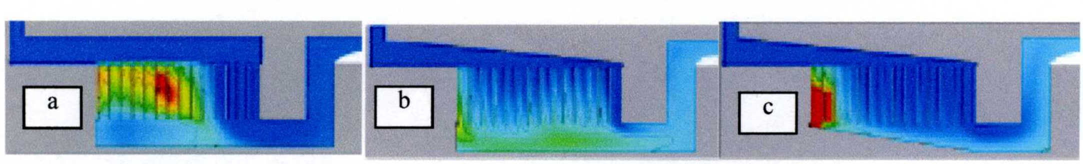

Figure 2: Three designs of filter print, non tapered (a), top tapered (b) and top and bottom tapered (c).

The heat transfer coefficient between the liquid metal and the filters has been estimated as a value of 20000 $Wm^{-2}K^{-1}$. The heat transfer coefficient between the liquid metal and the sand has been estimated as a value of 600 $Wm^{-2}K^{-1}$ (Woodbury et al., 2000). The heat transfer coefficient between the liquid metal and the ceramic shell has been estimated as a value of 10000 $Wm^{-2}K^{-1}$ (Stemmler et al., 2000).

SIMULATION RESULTS

Simulation has been carried out using the three designs of filter print in sand casting. For the investment casting, only the non-tapered running system has been used. The simulations have been carried out using Flow-3D[2] .

MODELLING THE GEOMETRY OF THE EXTRUDED FILTER VERSUS USING A POROUS OBSTACLE.

Flow-3D is the package used for the simulation presented in this paper. One way to model a filter is to use a porous obstacle and define the parameters discussed in the introduction. This has been done for an extruded ceramic filter. In the same time, a simulation in which the filter is described as a obstacle by its geometry has been carried out. Figure 3 shows a comparison at a given time between the predictions of the two models. The prediction of the filling is in fact not very different with the two models, even if it can be seen on this pictures that the porous obstacle is less filled than the filter defined by its geometry. But there is a huge difference on the prediction of solidification, has shown on the figure. In the case of the porous obstacle, figure 3 left, the area where the maximum solidification occurs is at the bottom left of the filter, and there is only less than 10% solid. In the case of the filter defined by its geometry, the amount of the maximum solidification is in the centre of the filter, and the amount of solidified liquid is about 50%.

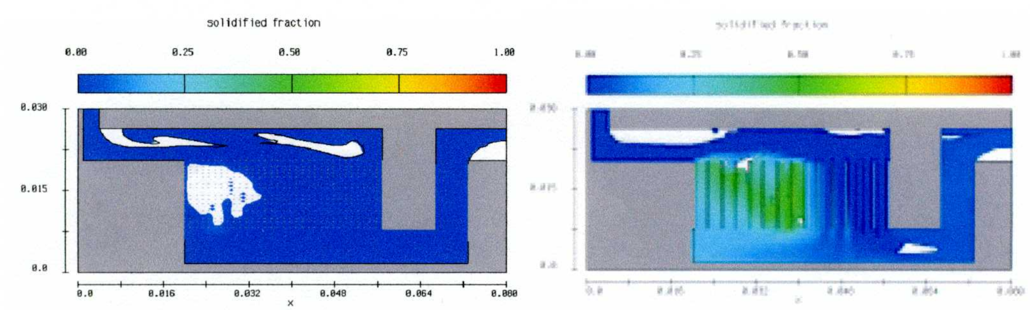

Figure 3: Comparison of the filling and solidification predicted for an extruded ceramic filter modelled as a porous medium (left) and with its own geometry (right)

COMPARISON OF THE STRAIGHT AND SHIFTED EXTRUDED FILTERS.

In order to look at the influence of the geometry of the filter, comparisons have been made in the case of sand casting, with a non-tapered filter print.

Figure 4 shows the beginning of the filling for both straight and shifted extruded ceramic filters. Figure 4a and 4b show that the beginning of the filling is very similar with the two filters until the liquid metal start to enter the filter. Figure 4c and 4d show that in the case of the straight filter, the metal goes through it faster. They also show that the back filling of the runner above the filter is faster with the shifted filter. The filling of the filter is faster as well with the shifted filter. Figure 4e and 4f show that the position of the lowest temperature is affected as well by the flow of the metal in the filter. In these two figures, the red or dark color in the runner area corresponds to a temperature of about 650°C and the blue or dark color in the filter area corresponds to a temperature of about 570°C. With the straight filter, there is more re-circulation of liquid metal in the filter, and in fact, the lowest temperature area is in the middle of the filter, whereas with the shifted filter it is on the left side of the filter. In both cases, the lowest temperature is in the area where the velocity of the liquid metal is the lowest. For comparison, the exit temperature at 0.2 s. are about 611°C for the straight filter and 600°C for the shifted filter.

Figure 5 shows a comparison of filling time for the two kinds of filter. The volume of metal plotted corresponds to the volume

[2] http:\\www.flow3d.com

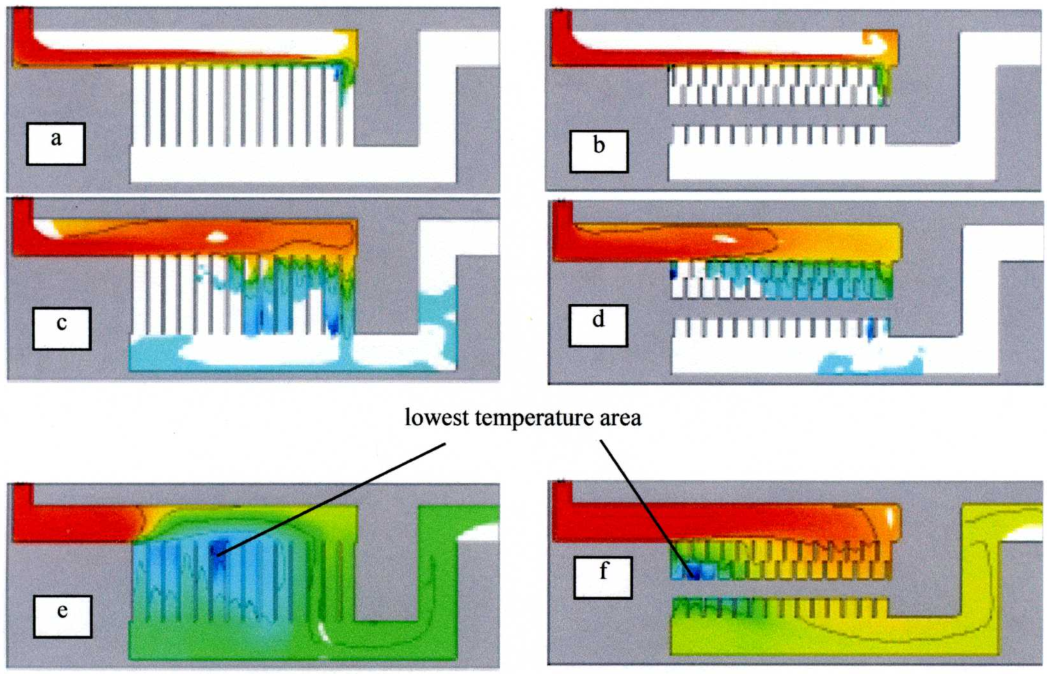

Figure 4: Comparison of the filling with straight and extruded filter (coloured by temperature). a and b: 0.03s; c and d: 0.07 s; e and f: 0.2 s.

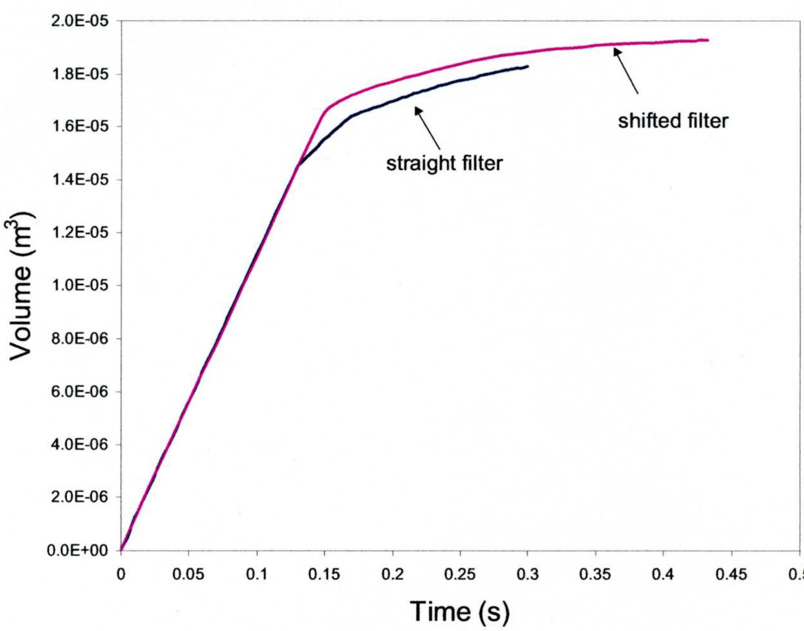

Figure 5: Comparison of the filling time for the straight and shifted extruded filters.

in the frame that is plotted in figure 4. The volume available for the liquid in the frame for the two types of filter are the same. Figure 5 shows that in the case of the shifted filter, after 0.13s, the volume increases faster than with the straight filter. After 0.15s, the evolution of the volume seems to be very similar, with an offset. The difference is explained by the back filling of the runner above the filter that is faster in the case of the shifted filter, as its permeability is lower due to the higher tortuosity of the metal path.

Another interesting parameter to investigate is the volume of solidified metal in our system. Figure 6 shows the comparison of the volume of solidified liquid, normalised by the total volume of metal. It appears that in the case of the shifted filter the

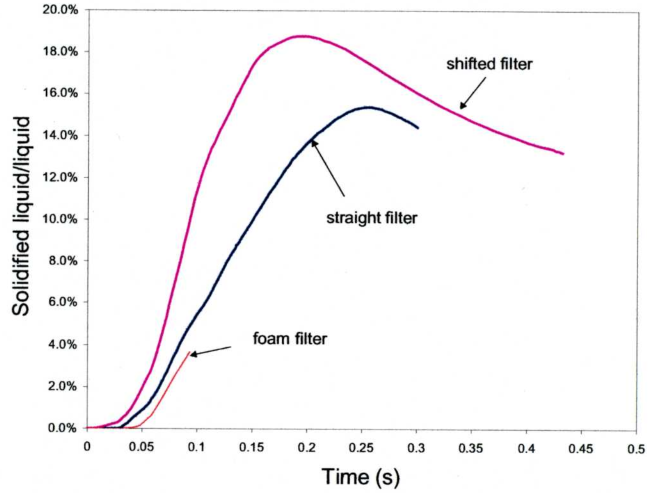

Figure 6: Comparison of the amount of solidified metal with straight and shifted extruded filters, and foam filters.

amount of solidified metal is higher than in the case of the straight filter, at a given time in the priming. This can be explained by the higher tortuosity of the metal path that implies a lower velocity of the liquid metal through the filter, and therefore larger heat loss for the metal. The results available with the foam filter when this paper was written are also shown in figure 6. It shows that the amount of solidification predicted with the foam filter is lower at the beginning of the filling. This can be explained by the lower thermal mass of this filter compared to the extruded ceramic filters.

COMPARISON OF THE SAND AND INVESTMENT CASTING

In order to look at the influence of the process condition, comparisons have been made in the case of a straight extruded filter, with a non-tapered filter print.

Figure 7 shows the comparison of the amount of solidified liquid, normalised by the volume of metal in the system. It is then obvious that the amount of solidified metal is lower in investment casting, where the mould and the filter are heated at 350°C before casting, whereas in sand casting they are at room temperature. This lower amount of solidified metal will result in a larger area of the filter through which the metal can flow, and therefore a faster filling of the part.

COMPARISON OF THE USE OF STRAIGHT AND SHIFTED FILTERS IN INVESTMENT CASTING

It has been shown that the use of a shifted filter, which increases the tortuosity of the metal path, leads to an increase of the percentage of solidified metal in the case of sand casting. It has also been shown that the pre-heating of the mould and the filter lead to a drastic decrease of the solidified volume in the system. Therefore, it is interesting to look at the effect of the use of a shifted filter compared to a straight one in the case of the investment casting process. Figure 8 shows such a comparison. The effect of the geometry of the filter is still apparent, but the amount of solidified metal is much lower.

EFFECT OF THE RUNNING SYSTEM

Much experimental work has been carried out at the University of Birmingham in the Castings Research Group under the guidance of John Campbell. Using real-time x-ray benefits have been shown when filters are placed so that the major flow direction is at right angles to the direction of flow of the liquid metal. This is contrary to typical practice within many foundries where the largest cross section of the filter is placed transversely across the metal stream. The following modeling and experimental work demonstrate the problems associated with such positions in the initial stages of filling.

The experimental work carried out at the university of Birmingham by the Casting Research Group is mainly based on foam filters. Figure 9 presents an example of this work where the same running system was used without filter, with an extruded

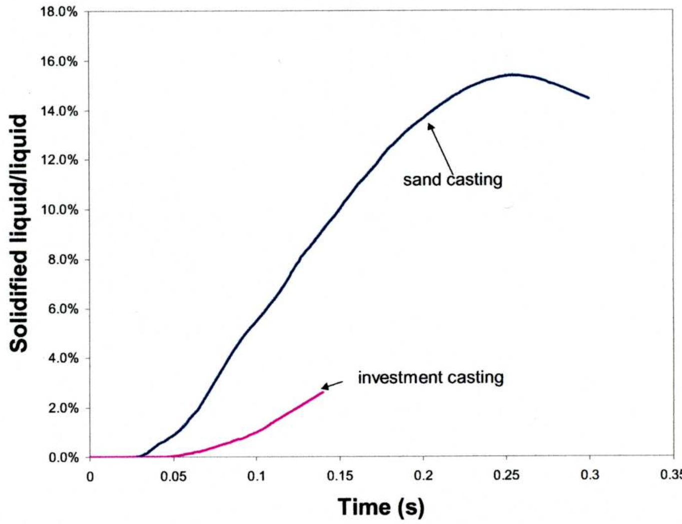

Figure 7: Percentage of solidified metal in sand and investment casting

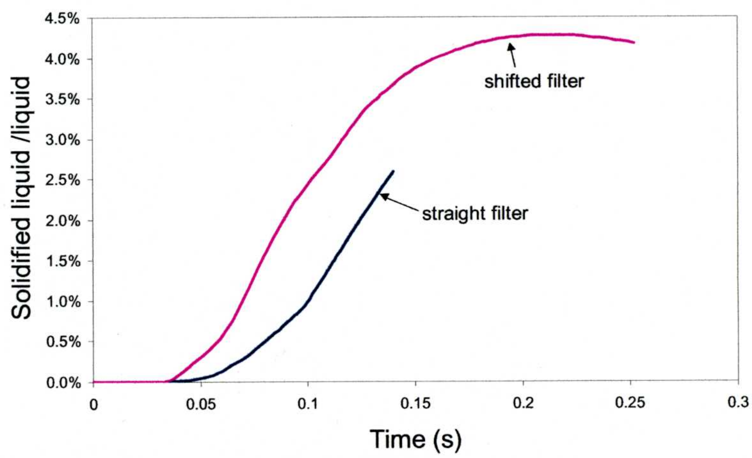

Figure 8: Comparison of the percentage solidified in investment casting for a straight and a shifted ceramic filter.

ceramic filter and a ceramic foam filter. It appears then that in the case where the filter print is empty, the metal is just going down under the action of gravity (figure 9 left). In the case of the extruded ceramic filter, as the metal is flowing in the direction of the filter, the metal stream is just going through the filter (figure 9 center). In the case of the foam filter, a large quantity of metal is stopped by the filter, which seems to be gradually filled and a large amount of liquid start to fill the cavity above the filter (figure 9 right).

The simulation work has mainly been carried out on the extruded filters because of their simpler geometry compared to foam filters. The time penalty for simulation of a foam filter is enormous. For example, without parallel processing, 1s. filling for an extruded filter is 3-4 days CPU time and 0.1 s. filling for a foam filter is 8 months!

Figure 11 shows a comparison of the influence of the orientation of the filter on metal flow. The first orientation is a position that is often recommended by the filter producers. The third one is the one that has been used in this paper and the one that should give the best results according to the experiments carried out by the Casting Research Group of the University of Birmingham. Looking at the filling, all the design appear poor, as features such as jetting, splashing and re-circulation occurs. In fact the last design allows a faster filling of the filter and filter print, in about 0.2s (cf. figure 4e). After that time the filter will not create any disruption in the metal flow, whereas with the other design it seems that the filter print will only be filled when the filling of the part will create enough resistance to the flow.

Looking at the filling of the non-tapered filter print, it appears that when the liquid metal stream reaches the end of the runner

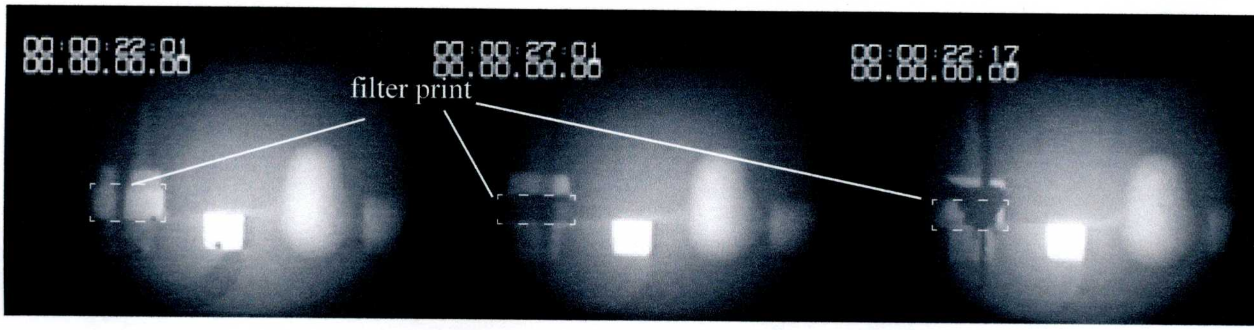

Figure 9: X-ray of a same running system without filter (left), with an extruded ceramic filter (center) and a foam filter (right) (Jolly, 1998).

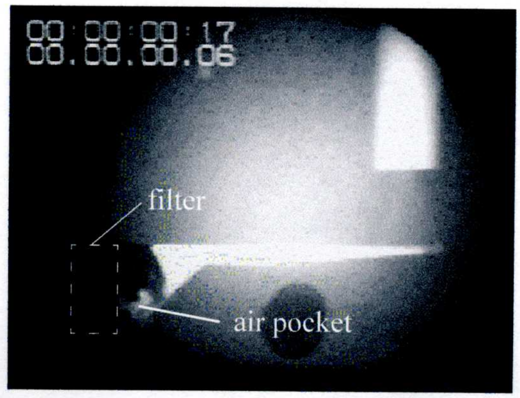

Figure 10: Experimental X-ray showing the metal flowing out of the filter in a non quiescent way, and falling down in the filter print

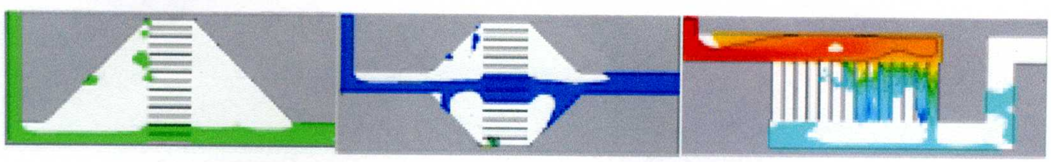

Figure 11: Comparison of different orientation/design of the filter print

above the filter, the pressure builds up at this point. The liquid metal then goes straight through the filter. It take a while for the runner above the filter to totally back-fill, and then the pressure stay higher at its end. This results in a flow of the liquid metal preferentially at the end of the filter. In order to avoid that, a tapered runner above the filter has been tested. The aim of such a runner is to reduce the back-filling time and to try to have a more constant pressure in the runner, in order to use a bigger section of the filter.

Figure 12, 13 and 14 show a comparison of the filling with the three designs of filter print. Figure 12 shows the flow with the non-tapered running system. Figure 13 shows the results with the top-tapered running system. The comparison of pictures 12a and 13a shows immediately the effect of the tapered runner on the flow. Using the straight runner, it is only at the end of the runner that liquid metal starts to go through the filter, whereas with the tapered runner, as soon as the metal stream touches the top wall of the runner, liquid metal starts to go through the filter. A comparison of pictures 12b and 13b shows that with the top tapered runner a larger length of the filter is used for the flow compared to the straight runner.

Comparison of pictures 12c and 13d shows again that the tapered runner use a larger length of the filter for the flow of the metal. This is shown by the lower values of the solid fraction in the first channels of the filter, which show that more liquid metal is going through these channels. Picture 13c shows that during the filling of the filter, there is some re-circulation of the liquid metal. This leads to a higher value of the solid fraction in the first (left) channels of the filters, due to the cooler metal going again through the filter. In order to avoid that, a tapered runner above the filter has been tried, to force the liquid metal towards the right after exiting the filter.

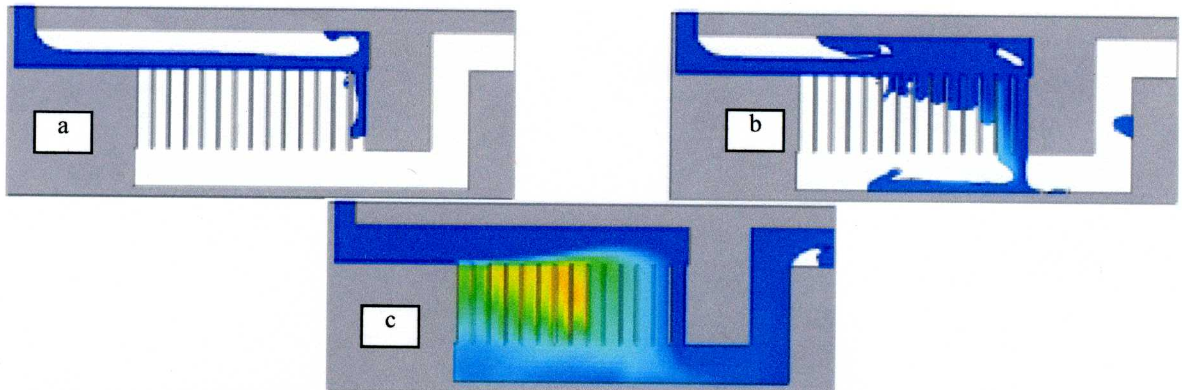

Figure 12: Volumetric solid fraction for the non tapered filter print at 0.03s (a)., 0.07s.(b) and 0.2s (c).

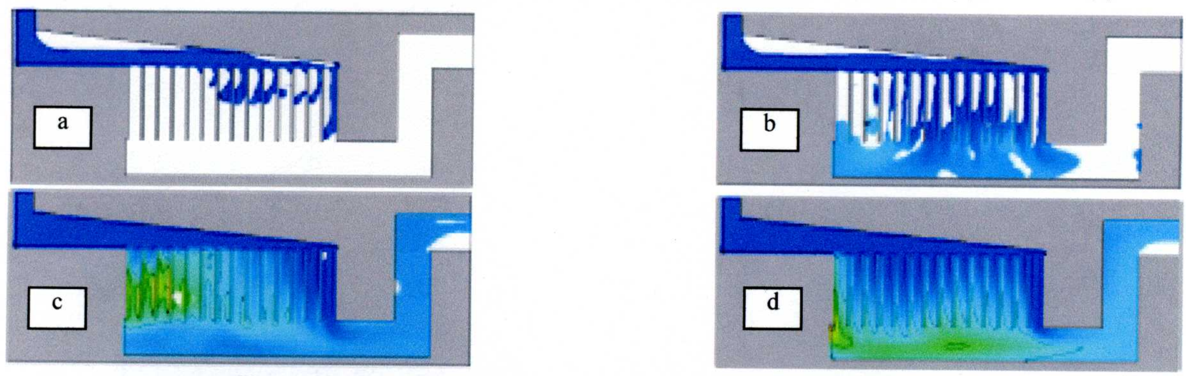

Figure 13: Volumetric solid fraction for the top tapered filter print at 0.03s (a), 0.07s.(b), 0.12s (c) and 0.2s (d).

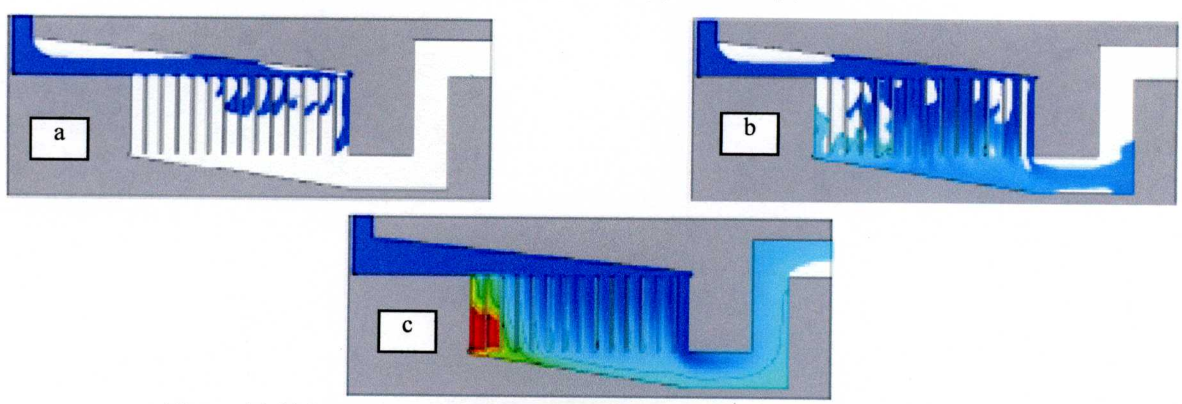

Figure 14: Volumetric solid fraction for the top and bottom tapered filter print at 0.03s (a), 0.07s.(b), and 0.2s (c).

The simulation results figure 14 show that in fact there is still some re-circulation of the metal, but less, and that results in obstructing the two first row of channels of the filter with fully solidified metal (picture 14c).

Figure 15 shows a comparison of the proportion of solidified liquid in the system for the three types of running systems. It appears that the tapered running systems generate more solid, but for a shorter time.

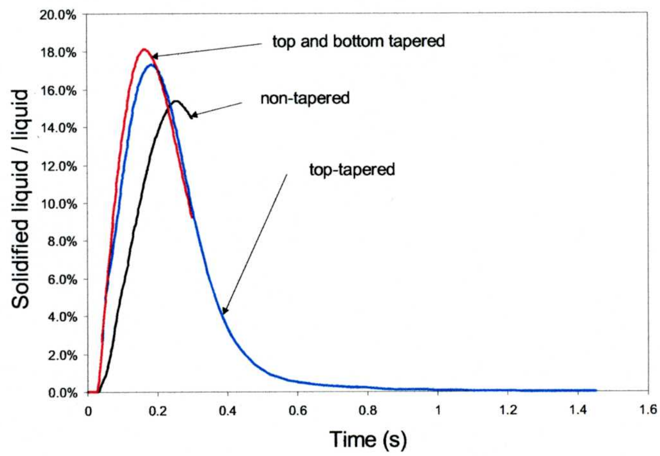

Figure 15: Comparison of the amount of solidified metal in the three kind of running systems.

SENSITIVITY STUDY

In these simulations, several parameters used where guessed, so a sensitivity study on the results has been started and is still running at the moment this paper is written. The parameters studied were:

1. Heat transfer coefficient between the liquid metal and the filter
2. Heat capacity of the filters

A356 is a well characterised alloy. Data including viscosity and heat capacity are well determined. This may not be the case for other alloys.

Simulations were carried out in the case of the sand casting, with straight extruded filter, and the first kind of running system. The parameter used were:

1. Heat transfer:

- 1,000 $Wm^{-2}K^{-1}$
- 10,000 $Wm^{-2}K^{-1}$
- *20,000* $Wm^{-2}K^{-1}$

2. heat capacity of the filter ($\rho.C_p$)

- 3.78×10^7 $J.m^{-3}K^{-1}$
- *3.78×10^6 $J.m^{-3}K^{-1}$*
- 3.78×10^5 $J.m^{-3}K^{-1}$

The values in italics are the values that have been used in all the simulations previously presented.

Figures 16 and 17 show the influence of the two parameters studied on the prediction of solidification. As should be expected, decreasing the heat transfer coefficient reduces the percentage of solidified metal at a given time. The interesting point is that with a heat transfer of about 1,000 $Wm^{-2}K^{-1}$ there is nearly no solidification even after 0.12s. Looking at the influence of the heat capacity of the filter, it would appear that increasing the heat capacity increases the amount of solidified liquid at a given time. That should have been expected as well, as with a higher heat capacity, the filter will take more heat from the liquid metal to increase its temperature. Therefore it appears that the amount of solidified liquid is controlled by the heat flux between the liquid metal and the filter, which is controlled by the heat transfer coefficient and limits the amount of heat that can pass from the liquid metal to the filter, and the heat capacity of the filter, which limits the amount of heat that the filter can receive. Another factor that will have a great influence and that has not been studied here is the flow rate of the liquid metal through the filter. The lower the flow rate, the longer the metal will be in the filter and therefore the more solidification will occur.

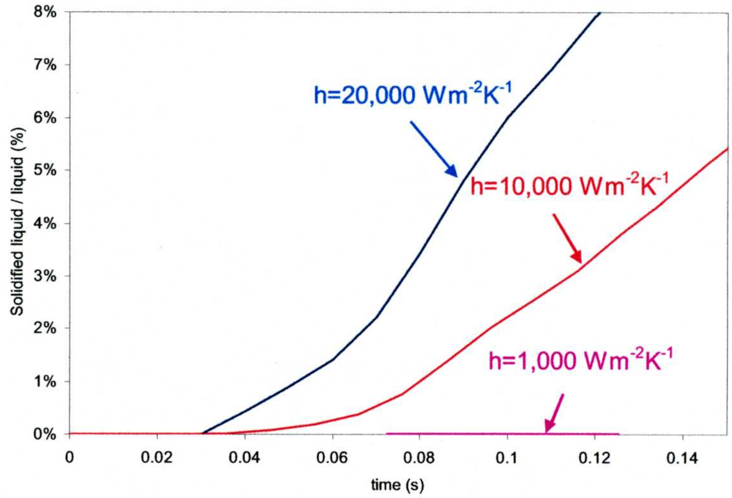

Figure 16: Comparison of the normalised solid volume with the three heat transfer coefficient

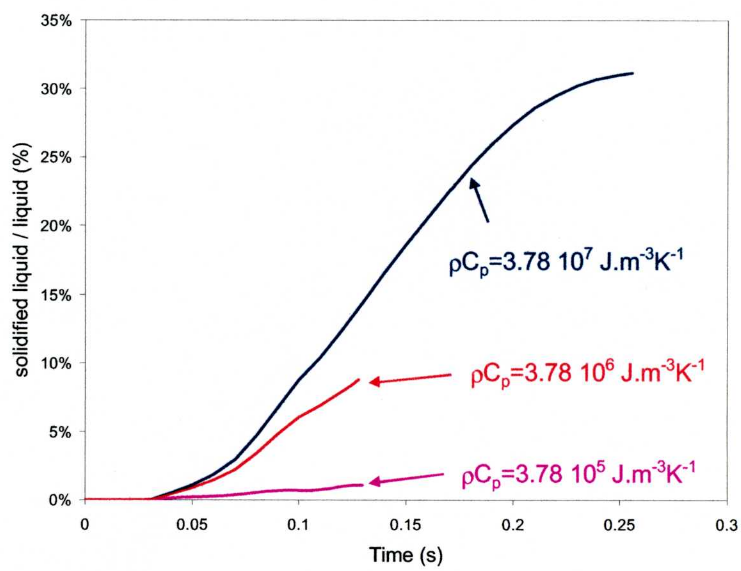

Figure 17: Comparison of the normalised solid volume with the three heat capacities

CONCLUSION

These simulations have shown that the ceramic filters have an influence on the flow and the solidification of the liquid metal in the running system:

a reduction of the permeability of the filter, equivalent to an increase of the tortuosity of the metal path, leads to a lower velocity of the liquid metal in the filter, and therefore to a higher loss of heat for the first metal going through the filter;

heating the mould and the filter, using the investment casting process for example, reduces the heat loss in the filter and therefore reduce the amount of solidified metal in the running system and in the filter;

tapering the runner above the filter results in using more of the filter and then reduce the re-circulation and the time where there are solidified metal in the running system and in the filter.

This work is not yet finished as the authors are planning to study the effect of using higher temperature melts such as steel, and some experiment in order to validate the numerical models presented here. These first results show that the action of the filters in the running system may be more complicated than a "simple" filtration unit. Nevertheless, the use of ceramic foam filter may not lead to a such amount of solidification in the running system, as the thermal mass of these filters is a lot lower than the one of the extruded ceramic filters. The simulation work is on-going for the ceramic foam filter. As the complex geometry has resulted in extremely long calculation times this work will just give us some idea of the nature of the flow and amount of solidification in the worst case and will not be a complete study of this kind of filter.

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