Modelling the Investment Casting Process

Some preliminary results from the UK Research Programme

"Fundamentals of Investment Casting" (FOCAST)

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ABSTRACT

The research programme "Fundamentals of Investment Casting" (FOCAST) has been funded by the Engineering and Physical Sciences Research Council in Great Britain at the Net Shape Laboratory of the IRC in the University of Birmingham. This paper presents some initial results from the research in the areas modelling of wax injection, de-waxing and casting.

1. INTRODUCTION

Scrap occurs during the investment casting process due to, amongst other reasons, dimensional variations, mould cracking and poor cast metal quality. The dimensional variations are the result of the sum of variabilities encountered during the process, wax pattern injection, shelling, de-waxing, firing and casting. Mould cracking, according to Snow (1998) is mainly due to problems occurring during de-waxing. Cast metal quality is dependent on the initial quality of the metal, and can also be altered by the metal flow during the mould filling.

A research program is being run at the University of Birmingham sponsored by the UK Engineering and Physical Sciences Research Council (EPSRC) and a consortium of industrial companies, aimed at developing a better understanding of the physical phenomena leading to the appearance of defects. Within the project modelling is being investigated in order to understand and predict the defect appearance. The modelling research efforts are concentrated on three aspects of the investment casting process:

- Wax pattern injection. This stage can be result in overall dimensional problems in the cast part. The use of numerical modelling could allow the determination of the final pattern's dimension and the prediction of the appearance of surface defects such as weld lines.
- The de-waxing process. A better understanding of the shell cracking during de-waxing could give key information on assembly design leading to reduced shell cracking.
- Casting. Better control of the liquid metal flow to enable an increase in quality of the cast parts metal

These research activities should lead to the development of numerical tools, based on commercial simulation packages, to predict and avoid these defects. In order to develop these numerical tools, experimental work is first carried out to determine which kind of models can be used to describe the physical phenomena occurring combined with the measurement of thermo-physical parameters of these models. Simulation packages able to use these models are then used, and some numerical experiments are carried out to demonstrate the prediction capabilities of the new numerical tool.

In this paper, the prospective models and the physical data required for each of these three parts of the process are discussed. Some initial numerical results for the wax pattern injection and the casting are presented.

2. MODELLING OF WAX PATTERN INJECTION

The waxes used by the investment casting industry are complex blended materials. The rheological behaviour of this kind of material is temperature and shear-rate dependent. The waxes exhibit the behaviour of an elasto-visco-plastic material when in the solid state and in the *mushy zone*, and as a visco-plastic material in the liquid state. Waxes are compressible materials and exhibit both temperature and pressure dependent compressibility. Both the viscosity and compressibility are temperature dependent so a description of the wax flow should take into account the heat transfer in order to be reasonably accurate. The heat transfer is modelled using the first Fourier law. This enables the conduction and convection heat transfer to be considered. The thermo-physical parameters needed are the heat capacity and thermal conductivity of the wax, and the heat transfer coefficient between the wax and the mould. This last parameter is probably the most difficult to obtain and it is also pressure and coating/surface finish dependant. In order to predict the final dimensions of the injected pattern, the shrinkage should also be characterised. A model taking into account the different physical phenomena influencing the shrinkage - volumetric shrinkage, crystallinity, mould restraint - can be used. In summary the parameters to be determined in order to predict the flow and the solidification of the wax during the injection are:

- apparent viscosity of the wax, mainly in the mushy zone during processing,
- compressibility of the wax,
- heat capacity of the wax,
- thermal conductivity,
- heat transfer coefficient with the mould,
- shrinkage parameters.

Some mould characteristics are also required:

- heat capacity,
- thermal conductivity.

Few studies have been carried out on the determination of these parameters for the investment casting waxes, but S. Chakravorty (1999) has presented results of a study carried out at the UK National Physical Laboratory, Teddington UK, on five different waxes. This study shows that the general behaviour of all these waxes is the same, so that the same kind of model can be used for each of them. Nevertheless, the differences from one wax to another are such that the models' parameters have to be determined for each wax. In our research program, different waxes are investigated both filled and unfilled. The results presented here are based on a filled wax.

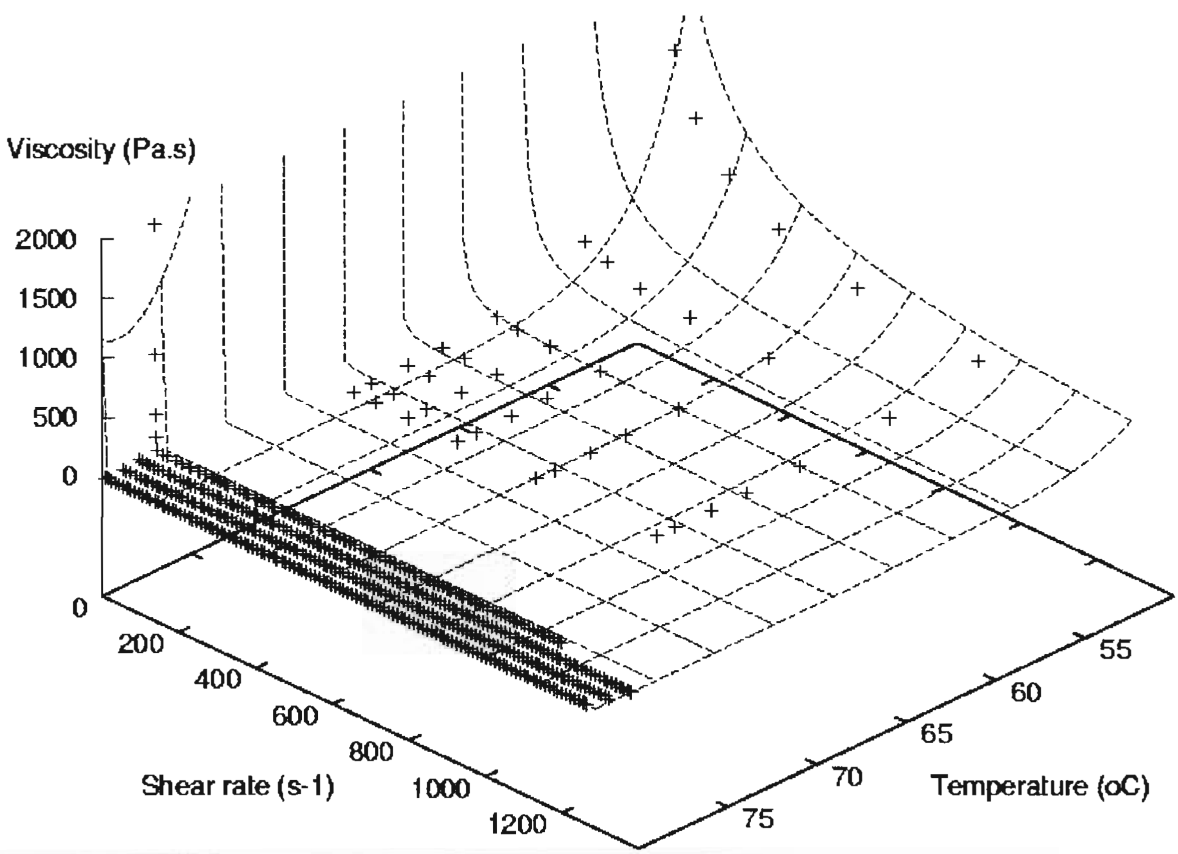

Figure1: Viscosity of the wax as function of temperature and shear rate. Comparison of experimental (+) and model (dashed lines) predicted values.

The apparent viscosity has been investigated using cone and plate rheometry for the high temperatures, and capillary rheometry for the low temperatures. The values obtained for both experiments are in good agreement. A Carreau model has then be used to describe the evolution of the apparent viscosity as a function of the temperature and the shear rate. Figure 1 shows the experimental values of the apparent viscosity as function of shear rate and temperature together with predicted values from the model.

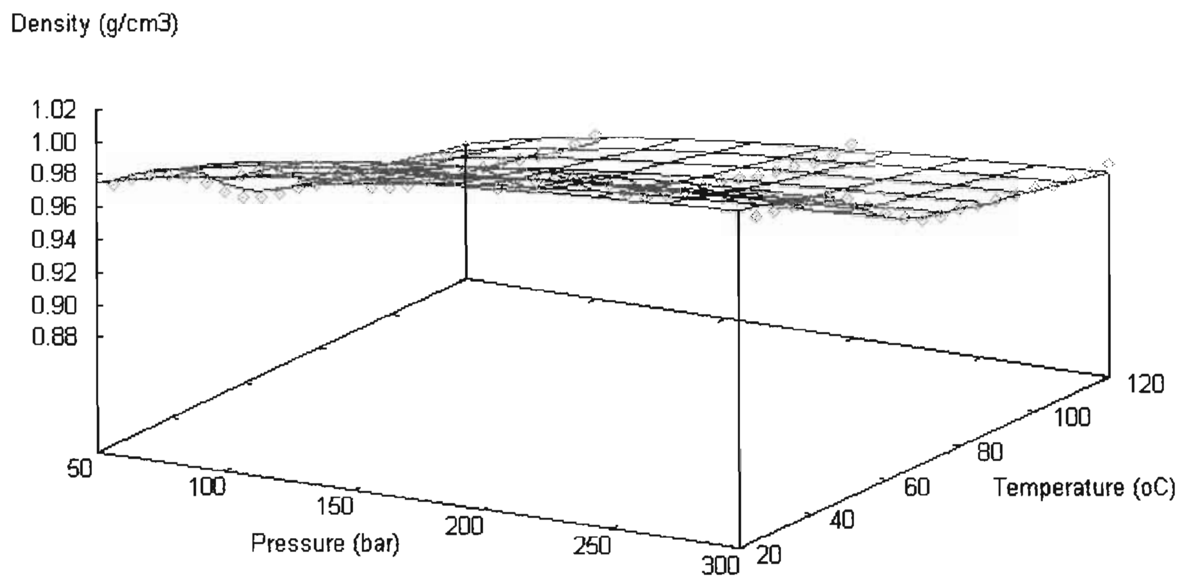

Figure 2: Evolution of the density as function of temperature and pressure. Comparison of experimental (points) and predicted values from the model (dashed lines).

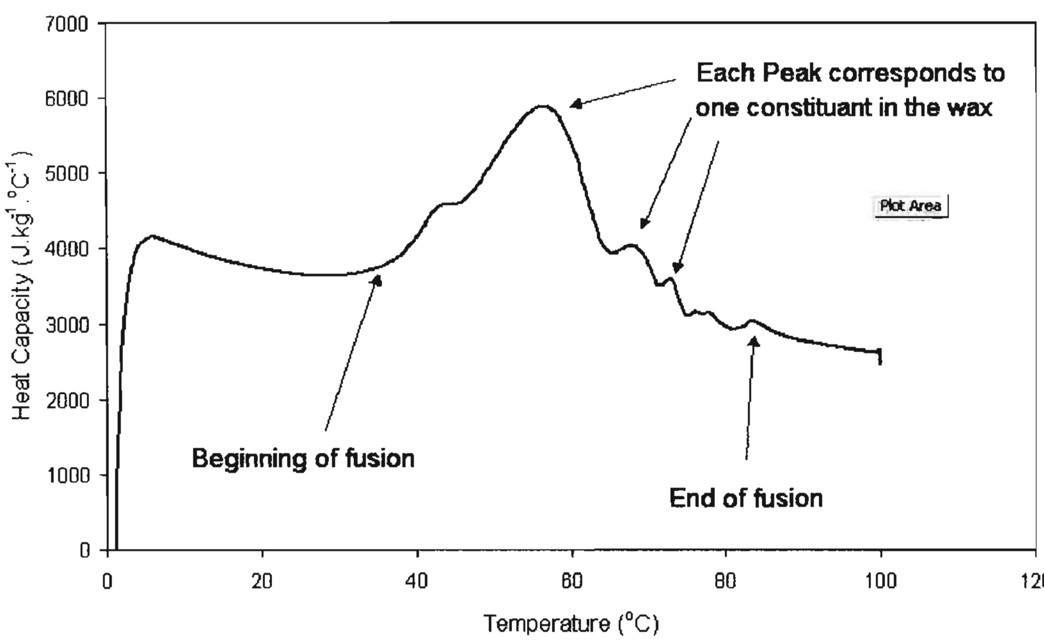

Figure 3: Differential Scanning Calorimeter results showing evolution of the heat capacity as a function of temperature, for a heating rate of 10°C/min

Density measurements are currently being made. The results for the specified waxes are not yet available, but data from the Chakravorty study allows us to test our modelling. Figure 2 shows the experimental data together with the predicted values from the model for an XLPS filled pattern wax.

The heat capacity has been measured using Differential Scanning Calorimetry (DSC) experiments for both waxes. Some other experiments have to been carried out in order to establish the influence of the heating and cooling rates on the heat capacity. Figure 3 shows the measured evolution of the heat capacity as function of temperature, for a heating rate of 10°C/min.

The thermal conductivity for the waxes has not yet been measured. A constant value in the range determined by Chakravorty in his study has then been used. A value dependant on the temperature and the pressure can be used if it is needed.

The shrinkage parameters have not yet been measured. As only qualitative data have been found in the literature (A. Sabau, 2000, K. Padmanabham et al., 1998, V.F. Okhuysen et al.1998) the shrinkage model has not yet been used in our numerical simulations.

Moulds made partially in aluminium and partially in Perspex have been used in order to be able to visualise the wax flow front during the experimental work. This was very important to allow the validation of the prediction of the numerical tool. Numerical simulations of mould filling have been carried out using two commercial software packages, Flow-3D (Flow 3D) and MoldFlow (Moldflow). Flow-3D was mainly used to validate the model as it is a more *open* code. Flow-3D enables any kind of fluid model to be included to describe the rheology of the wax. It also allows the modeling of a composite mould. For the test parts, which will be used in the project to determine how accurate the models prediction are, we have also used MoldFlow which allows only one material in the mould, but has some interesting features and fast computing capabilities. These fast computing capabilities are mainly due to simplification, so the quality of the results has yet to be validated.

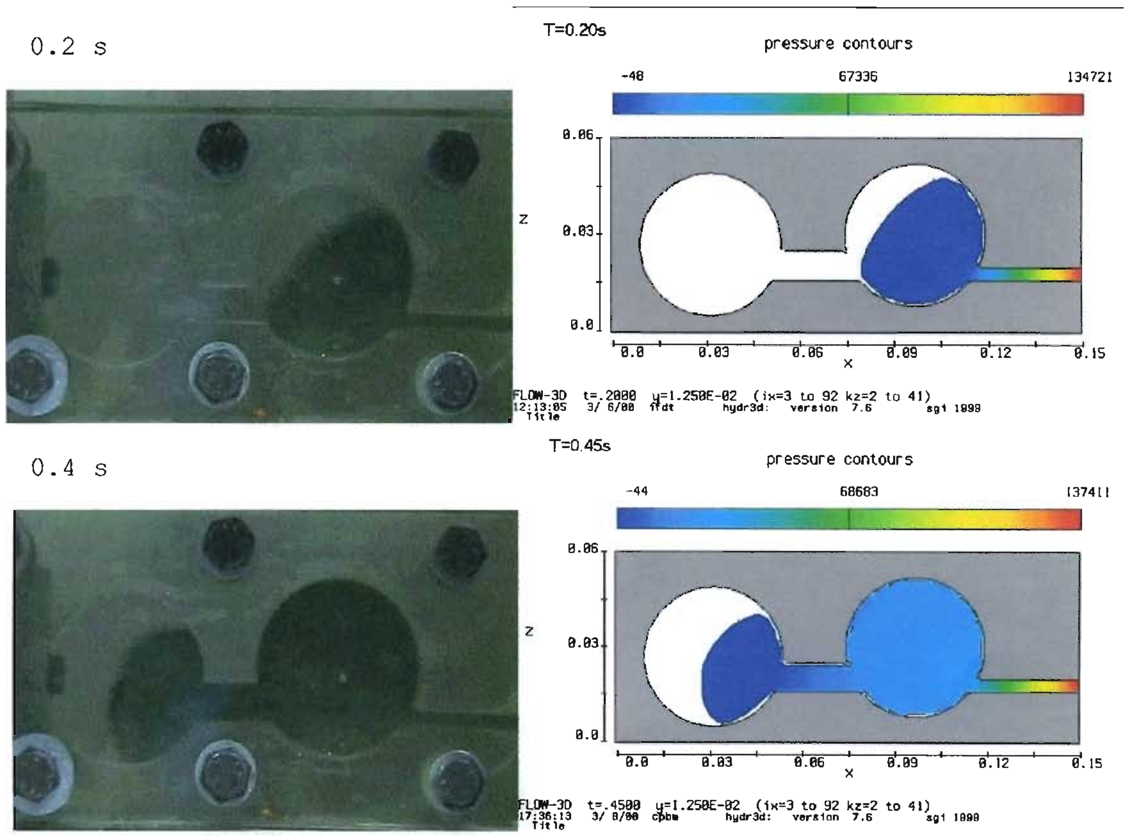

Figure 4: Comparison of the experimental and predicted filling front for injection of wax

Figure 4 shows a comparison between experimental and numerical results. A pattern which consists in a two-disc shape has been produced using a Perspex die, in order to be able to film the mould filling. The injection has been simulated, and the obtained filling fronts compared. The results show a good agreement between the simulation and the experiment.

A test shape, which is component-like, has been designed for investigating real geometries during injection and de-waxing. The design chosen was a cylinder and the details are given in figure 5. Figure 6 shows the filling time predicted by Moldflow for the cylindrical part using different injection points. The injection points are shown using a white cone. Fig 6a shows the predicted filling using an injection point in the 4mm thick cylinder part. The filling result obtained is a mis-run, and the mould is not fully filled in the thinner part of the cylinder. Fig 6b shows the predicted filling using an injection point in the 2mm thick cylinder part, the thinner one. The filling result obtained shows that the pattern is filled completely but there is a high probability weld-lines in the darker area. Fig 6c and 6d show the predicted filling obtained using an injection point situated on the back of the cylinder, in the thickest part (see fig 6d). This last injection point is, according to the simulation's results, the best one for this part.

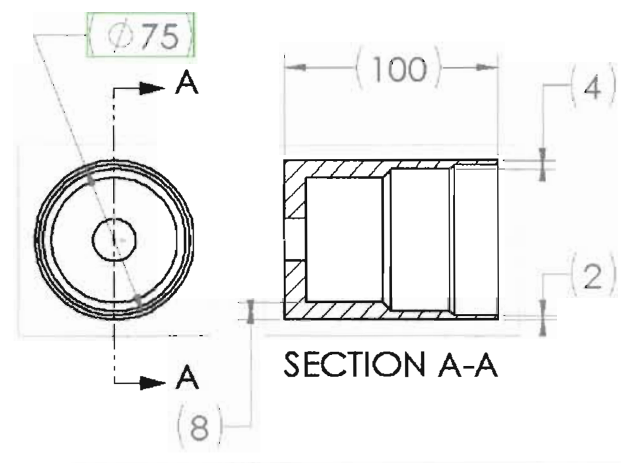

Figure 5: Design of the cylinder test part (dimensions in mm.)

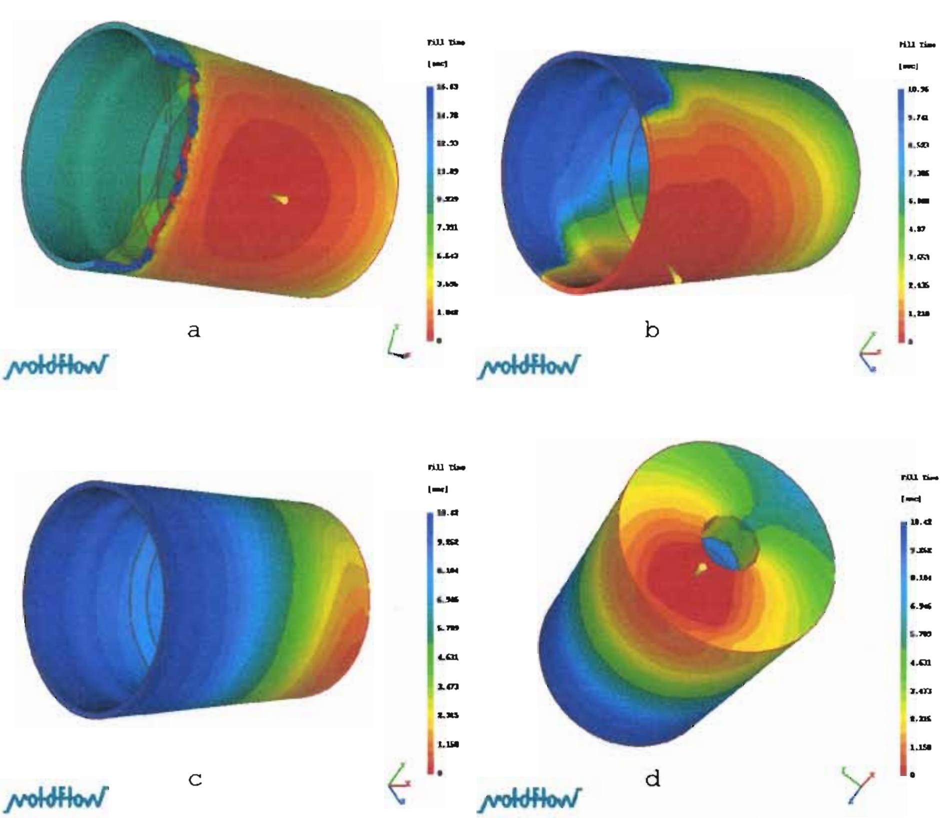

Figure 6: Filling times of the cylindrical test part. Three different injection points (1: a, 2: b, 3: c and d).

The simulations on the two-circle part have shown that the filling front and filling time are dependent on the wax injection pressure and temperature. Nevertheless, experimental results have shown that the control of these parameters on the used injection machine is often not very accurate.

3. MODELLING OF DE-WAXING PROCESS

The de-waxing process consists of the removal of the wax pattern, runner and sprue from the green shell. This is usually done using an autoclave, in which steam at high pressure (8 to 10 bars) and temperature (approximately 180°C) is introduced. The steam transfers heat to the wax through the shell, the wax then melts and flows out of the shell. The principle of the de-waxing process is very simple, but the physical phenomena that occur are less simple. The steam penetrates the shell, which is a porous, thus changing its heat capacity and thermal conductivity; the wax expands on heating prior to melting and this expansion is constrained by the shell. This may lead to shell cracking which is the main problem that occurs during de-waxing.

The aim of the modelling of de-waxing process is to predict the shell cracking. The phenomena to model are:

- wax expansion,
- wax flow,
- heat transfers through the steam, the shell and the wax,
- shell mechanical behaviour,
- steam condensation/vaporisation,
- condensed steam penetration in the shell.

In order to do that, several models are required:

- shell mechanical behaviour,
- steam penetration in the shell,
- heat transfer in the system,
- phase change for the wax,
- phase change for the steam/water,
- wax rheology.

Experimental work is now being carried out to characterise these phenomena, in order to be able to choose the appropriate models in each case and to determine the material parameters and boundary conditions.

4. MODELLING OF THE CASTING PROCESS

The main problem in the casting process is the filling of the mould. The investment casting process aims to be net-shape and it enables the production of complex geometry part with thin sections. The main problem addressed at the moment concerns the control of the metal flow during the filling. This research project is using two approaches to further the understand understanding of the filling process namely macro-modelling of the flow in the running system and modelling of the flow within the filter.

MODELLING OF FLOW THROUGH A FILTER

In traditional sand casting, ceramic filters are often used to control the metal flow. The main effect of the ceramic filters is to reduce the velocity of the flow, which increases the metal quality by reducing the level of surface turbulence in the liquid metal, and therefore its oxidation. It has been shown that the use of ceramic filters leads also to a slight increase of the part filling time. However a study carried out at the IRC (Cox et al. 2000) has shown that for the investment casting process, the use of ceramic filter does not affect the filling time. As a result of this, a research program to give a better understanding of how filters affect the metal flow has been launched. One explanation for the difference between filters in sand casting and in investment casting is that during the filling in sand casting partial solidification of the metal occurs in the filter thus reducing the flow rate. In investment casting the mould/shell and filter are heated thus less or no solidification occurs and the flow rate is not, or less, affected. In order to verify this assumption, the study of the metal flow and heat transfer in and around the filter has been proposed.

In an initial study an extruded ceramic filter in sand casting was modeled. Usually investment casting foundries use ceramic foam filters, but the geometry of this kind of filter is far more complex with a resulting higher demand for RAM and CPU time on the computer. A next best scenario consisted of creating a "shifted extruded filter". This was achieved by creating the filter from four layers each shifted horizontally with respect to the others. This was to increase the tortuosity of the metal path through the filter, in order to be more representative of the foam filter. Work continues on the production of full CAD model to represent a foam filter.

Simulations on the filters have been carried out with the Flow-3D simulation package, using for the LM25 (A356). The following conditions were used in the model:

- liquid metal considered as a Newtonian fluid,
- viscosity increase in the mushy zone,
- RNG turbulence model,
- heat transfer through the liquid metal, the filter and the sand,
- heat exchange between the liquid metal and the filter, the liquid metal and the sand (interface heat transfer coefficient)

The data for the LM25 have been provided by NPL (NPL). The heat capacity for the filter has been measured at the IRC from a commercial filter. The thermal conductivity has been calculated from (Hayashi 1998). The sand data are from the MAGMAsoft materials database.

The results show that in both cases of extruded and shifted filter some solidification occurs within the filter. Figures 7, 8 and 9 show comparisons of the metal flow and solidification state between these two models during the beginning of the mould filling. Fig. 7 shows that the back filling in the runner before the filter is faster in the shifted filter indicating there is more resistance to flow through the filter. It also shows that the liquid metal takes more time to flow through the filter. This is due to the higher tortuosity of the filter. There is then a resultant lower velocity of the liquid metal after the filter. Figs. 8 and 9 indicate that more solidification occurs after the filter in the shifted filter's case. Fig 10 shows that the amount of solidified metal after the filter decreases with time.

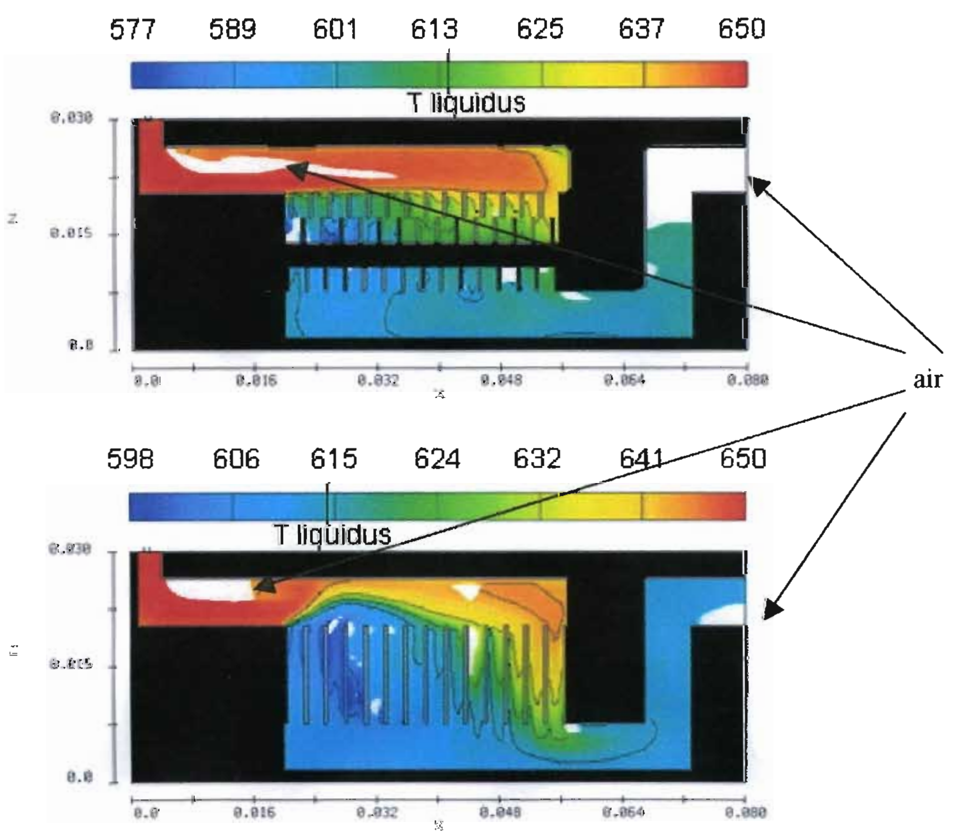

Figure 7: Comparison of the filling and the solidification in an extruded (bottom) and a shifted extruded (top) filter (temperatures in °C)

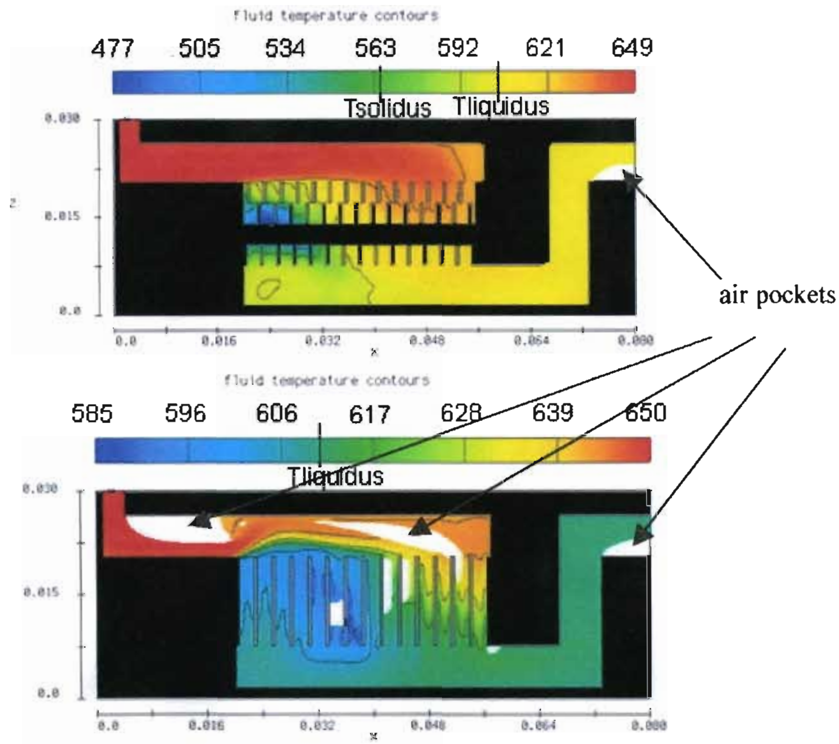

Figure 8: Comparison of the solidified fraction of aluminium alloy in the running system after 0.225 s. (extruded - bottom shifted extruded - top, temperatures in °C)

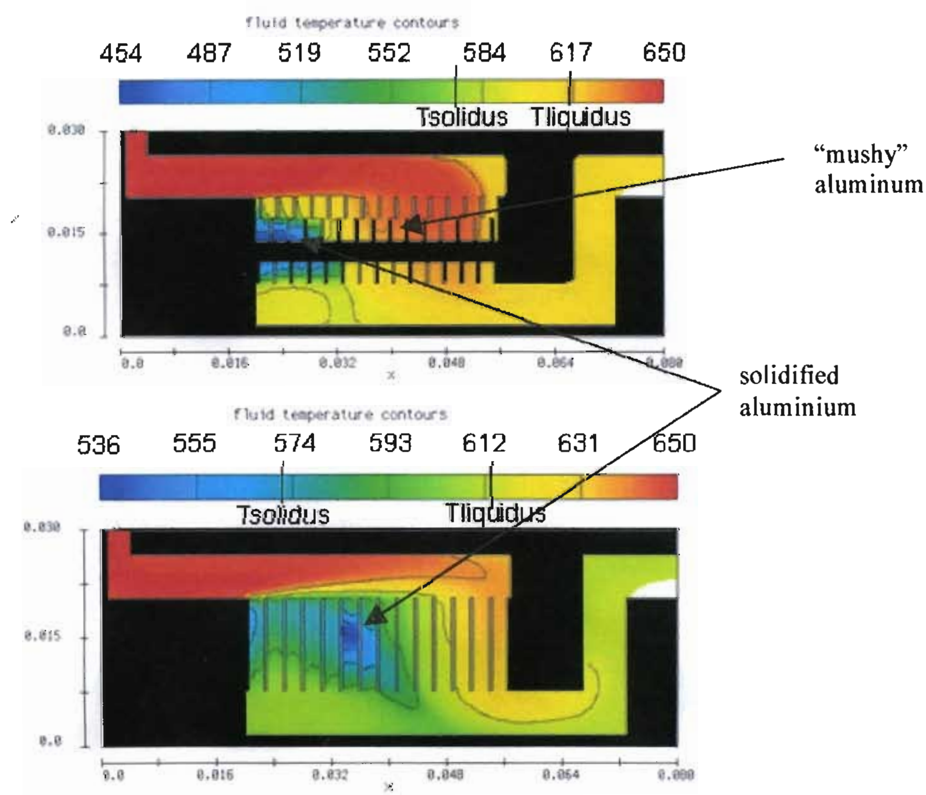

Figure 9: Comparison of the solidified fraction of aluminium alloy in the running system after 0.3 s. (extruded - bottom shifted extruded - top, temperatures in °C)

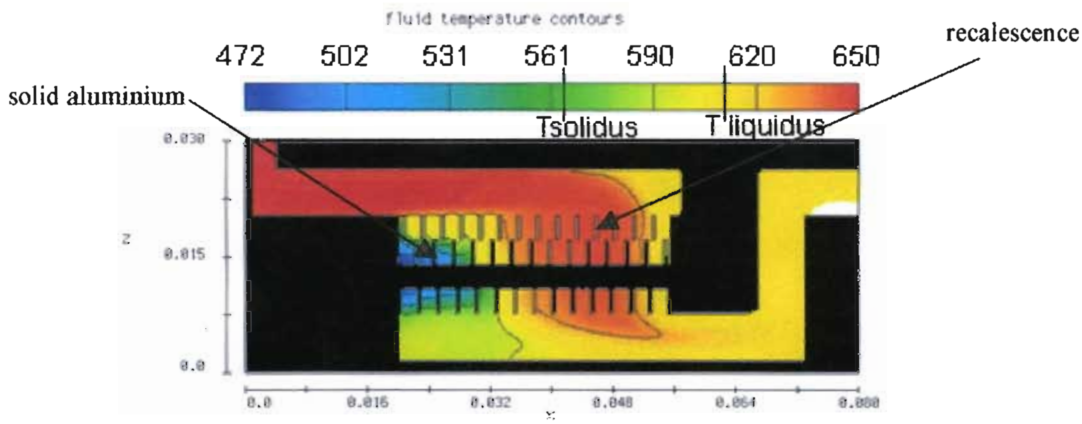

Figure 10: Solidified aluminium alloy in the running system after 0.43 s. for the shifted extruded filter (temperatures in °C)

These simulation results show that in the case of sand casting, the use of a filter decreases the velocity of the metal, and that the use of filters with high tortuosity factor enhances this decrease. These simulations also show that a partial solidification occurs in and after the filter, and that this metal will re-melt after a while. This re-melting is due to the increase of temperature in the runners and in the filter, due to the heat exchange with the liquid metal going through them.

RUNNING SYSTEM MODELLING

Work on macro-modelling of the running system has concentrated on the development of three types of running system which can them be correlated with the measured mechanical properties of the final castings. These running systems can be described as follows:

1. Top gated
2. Bottom gated uncontrolled fill
3. Bottom gated controlled fill

The top gated system (1) consisted of a pouring cup placed onto a top runner bar of 25 X 25 mm square section from which were suspended 6 bend test casting pieces as depicted in Figure 11a. The Uncontrolled bottom gated system consisted of a conical pouring cup tapered downsprue going into a runner bar with a section 25 X 25 mm square. This was then connected to a cross runner from which ingates were connected to the bend test bars. There were no filters in the system. The second system is shown in Figure 11b The third system consisted of a rectangular pouring basin with a weir connected to a downsprue which was connected to a runner bar 5 mm deep and 50 mm wide. This ran over the top a filter to a bubble trap. From the bottom of the filter the runner continued to a dross trap (or pressure reducer). A cross runner of 25 X 25 mm square cross section was connected to the top of the first runner to which the test bars were connected. (Figure 11c).

A CAD model was create for each running system and the filling simulated using Flow-3D CFD software. The alloy chosen was a steel alloy CLA11 (3%CrMo). All the castings were made under controlled conditions at one of the partner foundries. To date the results of the bend tests have not been completed but will be the subject of further papers. Some castings were poured at the University and analysed during filling using the real time x-ray facility.

Casting modelling clearly shows the different natures of the filling with the various running systems. The top pour system fills in a highly turbulent manner with a large amount of metal stream break-up and splashing. The effect of top pouring on mechanical properties has been reported by Nyahumwa et al.(1998) and it is expected that similar results will be found in the investment casting process.

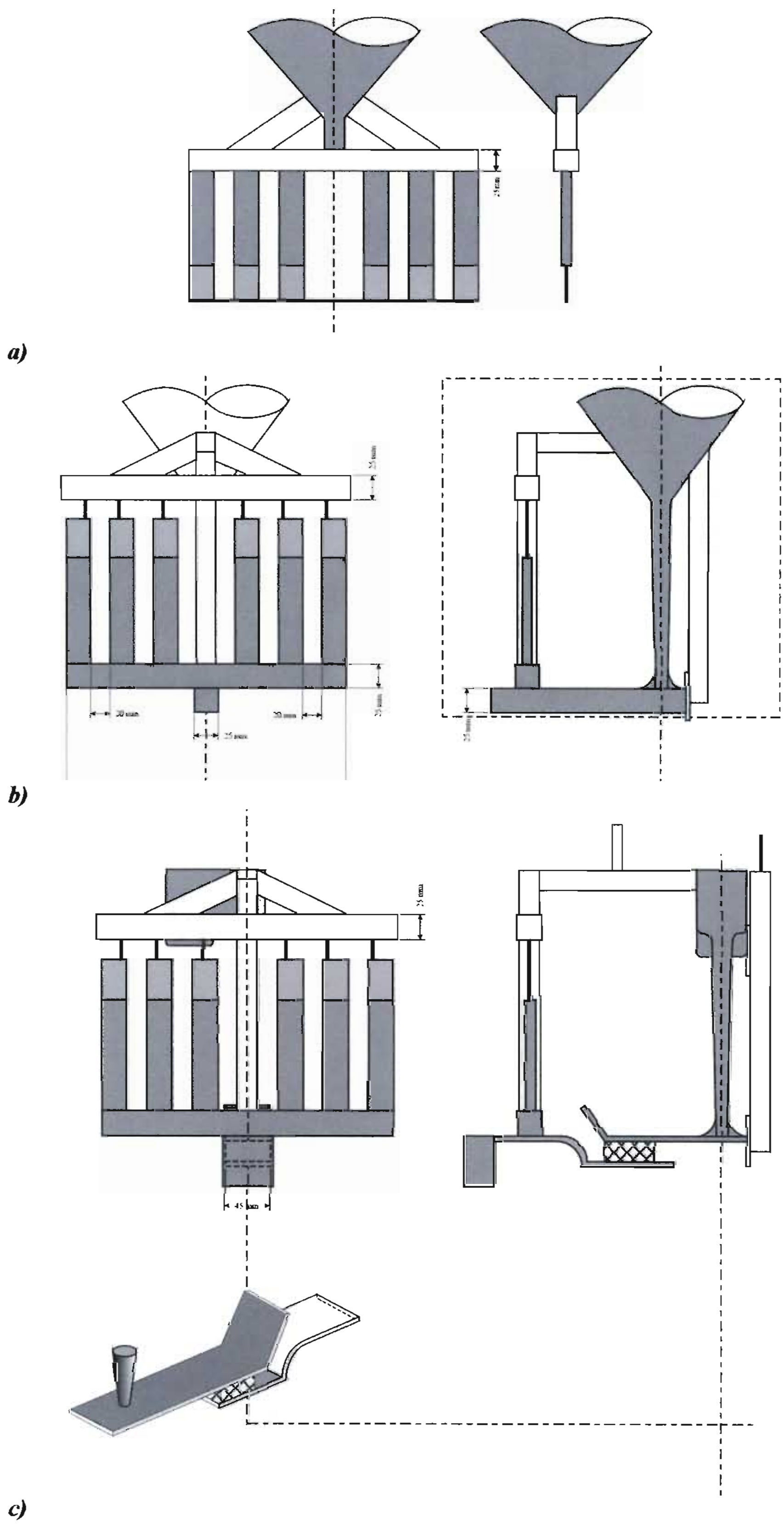

Figure 11: Schematics of the three running systems adopted by the study a) top gated system, b) bottom gated uncontrolled system, c) bottom gated controlled fill

Figure 14 shows some snapshots of the second running system. The downsprue back-fills well initially within 1 second but as the metal progresses to other parts of the system problems appear. Firstly there is some jetting in the up-runner at the end of the bottom runner. A rolling back-wave then develops in the bottom runner bar thus giving the opportunity for oxide surface entrainment (Campbell 1993). Looking at the cross runner, turbulence and jetting is observed and is shown in Figures 14 d-f. Figure 15 shows these phenomena captured in the real-time x-ray pictures.

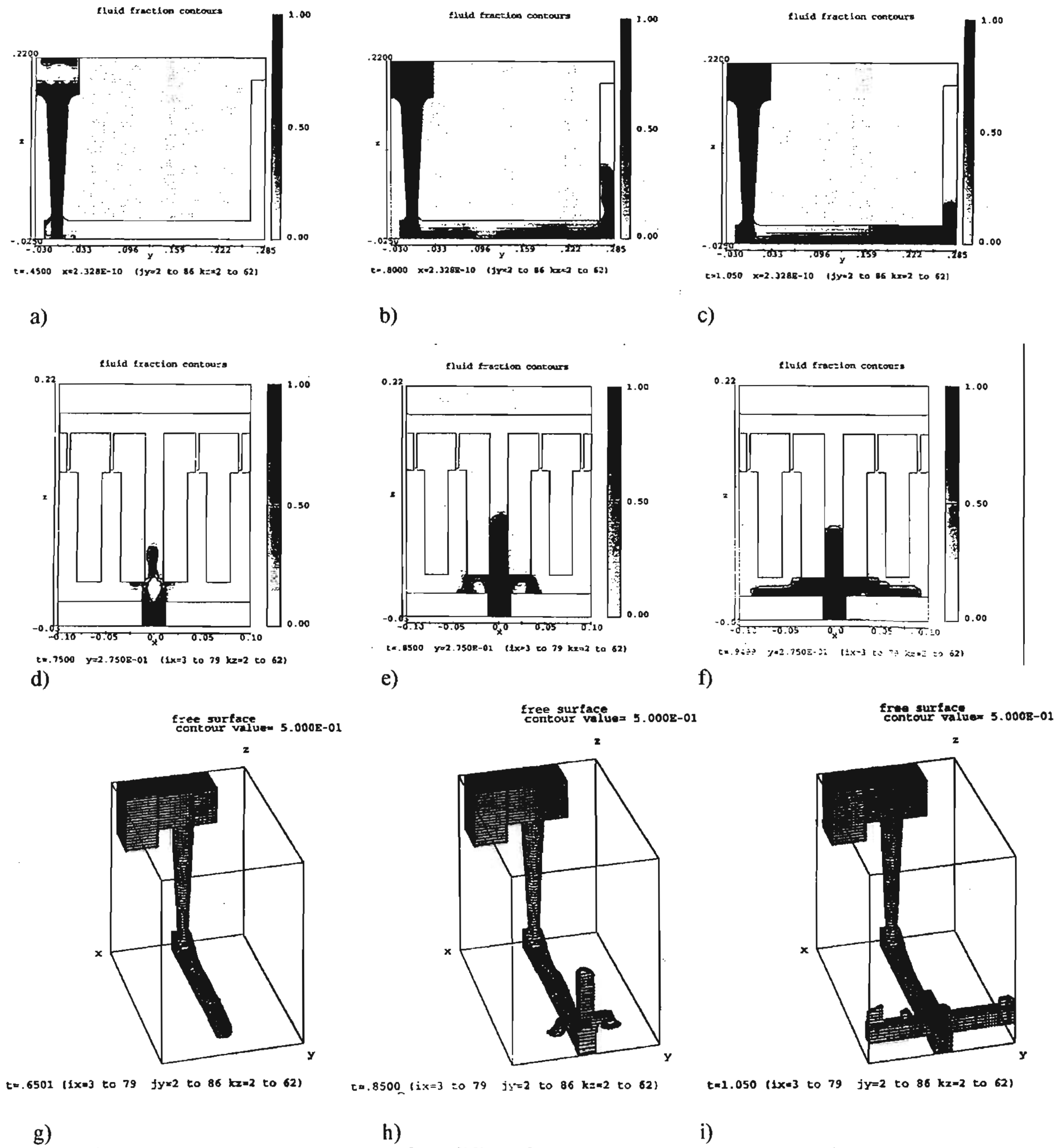

Figure 14: Computer simulation snapshots of the filling of the bottom-gated uncontrolled filling system a) shows the back-filling of the downsprue, b and c show the development of the rolling back-wave, d-f show jetting and the development of turbulence in the cross runner and g-to h are 3D isometric view of the same events.

Figures 12 shows 4 snapshots of the filling of the test bars. In the first shot the start of a rolling back-wave on the top runner can be seen and this develops further as the filling progresses. The random splashing in the test bars them selves can be seen in the later shots. The two central bars are the last to fill and this can also be seen in the real-time x-ray stills shown in Figure 13.

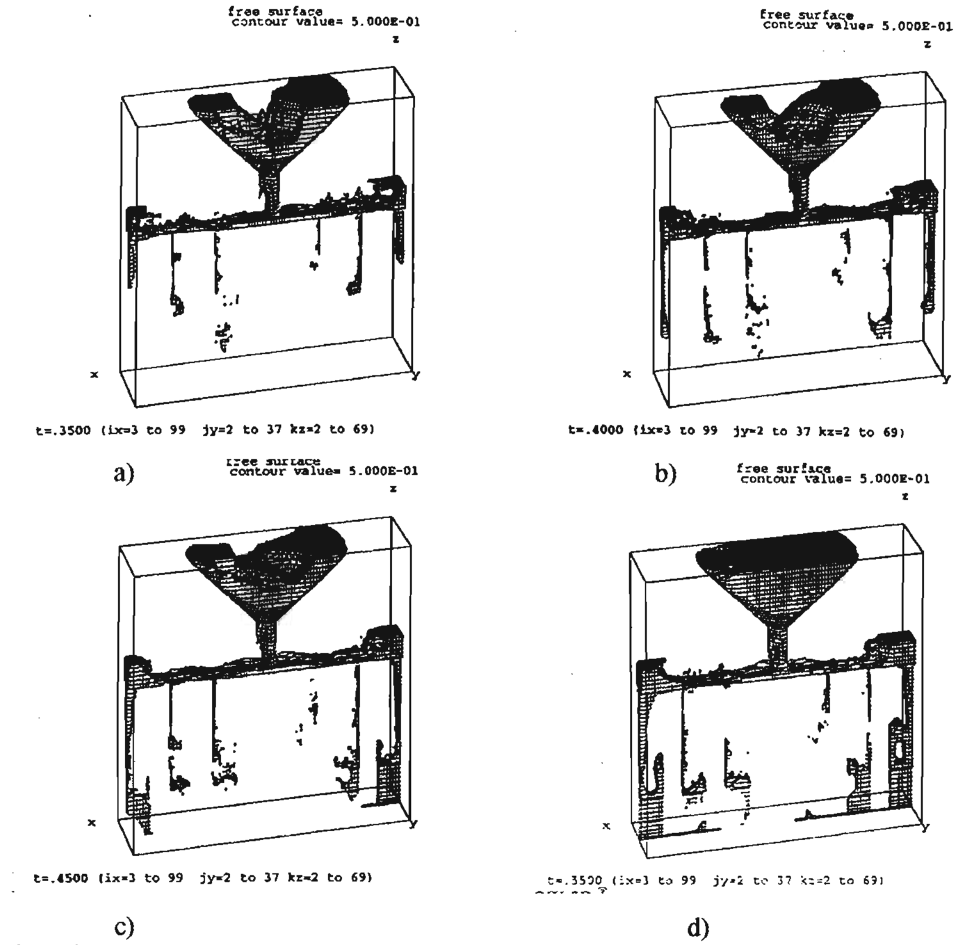

Figure 12 Snapshots from the simulation of the filling of the top gated running system showing the turbulent nature of the liquid metal. 12c shows the development of the back-wave in the top runner and 12d shows the uneven filling pattern and splashing.

a) ***b)*** ***c)***

Figure 13: Real-time x-ray video stills of the top gated running system showing the turbulent nature of the liquid metal filling a) and b show splashing, jetting and the random behaviour of the falling metal stream. c) shows an entrapped bubble in the far right test casting.

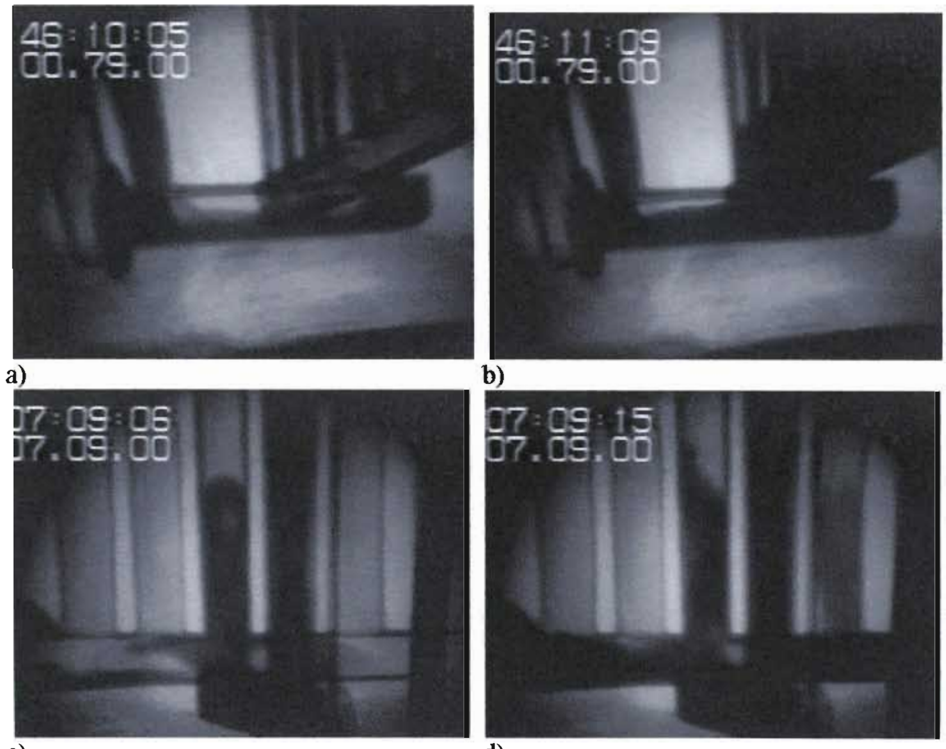

Figure 15: Real-time x-ray video stills of the bottom-gated uncontrolled filling system. a and b show the incomplete filling and development of the rolling back-wave in the bottom runner (cf. 14 b and c). c shows the jetting up the central up runner and jetting along the cross runner as in 14 e and h and 15 d shows the development of the rolling back-wave in the cross runner as seen in 14 f.

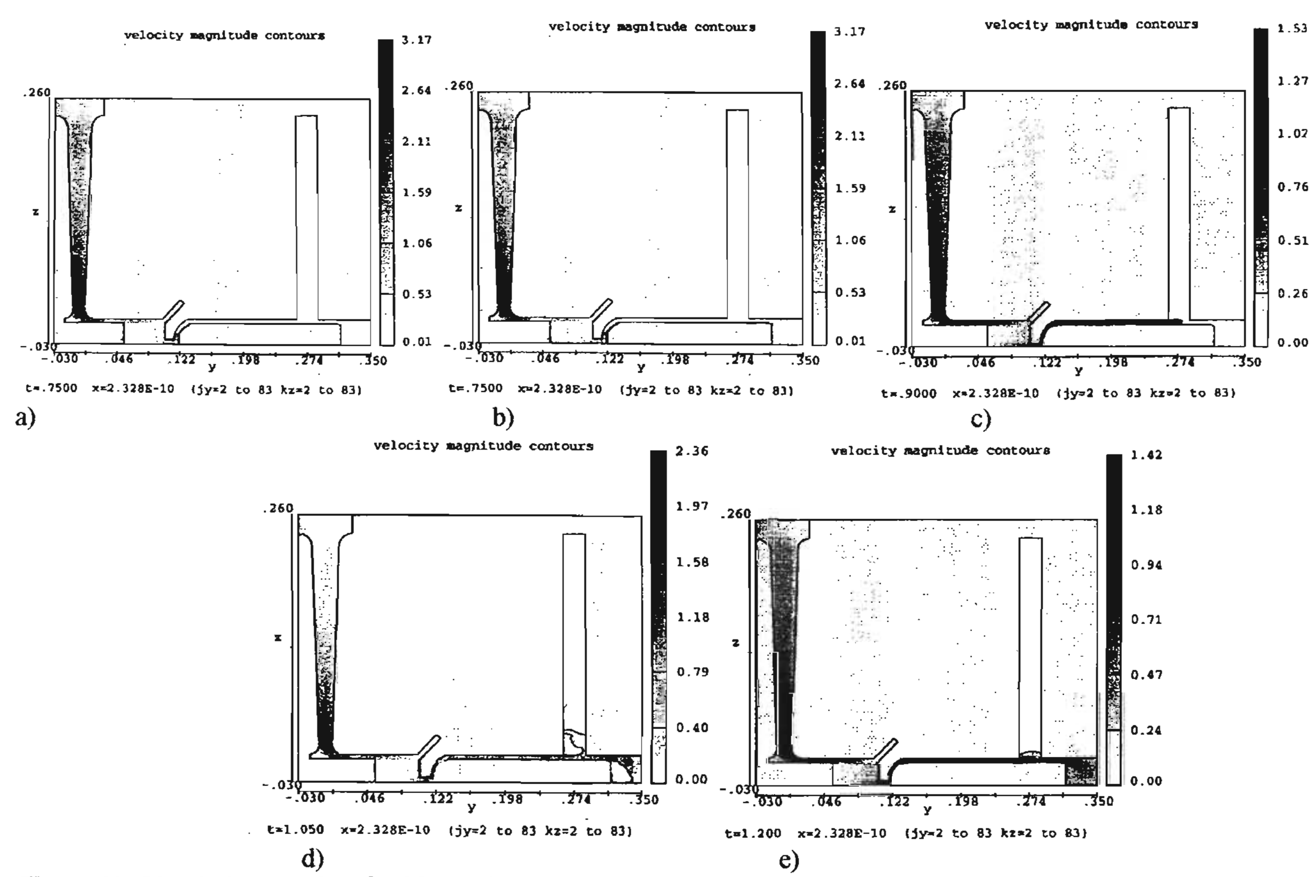

Figure 16: Simulation results of a 2D section through the centre line of the of the third running system showing the filling of the downsprue at 0.75 s (a), progression through the filter (b,c) , the effect of the dross trap (d) and the small amount of jetting into the cross runner(d) and finally the start of quiescent fill in the casting cavity (e).

Figures 16 and 17 are the simulation results achieved in the third running system. Again the downsprue back-fills quickly and appears full by 0.75s. There is then some splitting of the stream as it progresses along the horizontal runner until it arrives at the bubble trap. Flow after the filter appears to be controls although a little jetting into the up-runner is observed as the metal enters the dross trap (pressure reducer) at the end of the runner. As the metal fills the cross runner there does appear to be some evidence of a back wave (Figure 17h) but it may just be undulations on the surface. Flow after this point appears to be extremely quiescent and the test bars fill evenly (Figure17i). The real-time x-ray pictures confirm the simulation results (Figure 18).

The third running system shows a more quiescent filling in both the simulation and real-time x-ray results. However there are some regions and times at which there appears to be some turbulence and surface folding. It remains to be seen how much damage this may have done to the liquid metal. This demonstrates the lack of a quality index or measure for running systems which relates the damage a running system may have inflicted on the liquid metal as it fills the casting cavity. An investigation on such a quality index is currently underway at Birmingham.

5. CONCLUSIONS

This paper presents the preliminary results of an on going study on the modelling of the investment casting process. It shows that modelling of the different steps of the investment casting could lead to a better understanding of the origin of the defects. It also shows the capability of defect prediction of some of these models.

Modelling of the injection of waxes has shown that if the correct rheological mode is chosen for the fluid behaviour of the waxes then the liquid filling pattern observed in reality can be simulated with computer codes. Use of a plastics injection code gives information on the effect of different ingate positions on the quality of the filling.

Modelling of liquid metal flow through a ceramic filter has shown that some solidification and recalescence occurs during the passage off liquid metal through a filter and that the level of solidification is increased with increased tortuosity experienced by the liquid metal.

The research work carried out on running systems demonstrates that thin running systems of the types now being recommended and applied by the sand foundry sector can be manufactured and used in the investment casting industry. The simulations results indicate that these running systems give a quiescent fill but to date there are no mechanical property data to support this conclusion.

The work planned to be carried out on the de-waxing process should lead to a better understanding of the cracking formation and propagation of cracks in the shell during the de-waxing process.

6. WORK IN PROGRESS

In order to better understand the behaviour of waxes during processing a series of experiments is being run to characterise fully their microstructure, physical and mechanical properties. A model wax system has been developed in order to lend some understanding to the individual contribution of the components from which the waxes are the manufactured.

Much work is being carried out on recording both visual, process and thermophysical data during the injection of wax patterns. This includes measurements of dimensional changes and the relationships with processing parameters.

Development of a digital representation (i.e. CAD model) of a ceramic foam filter is being developed and a simulation of the liquid metal flow the filter will be made.

Mechanical property data of the materials which have been cast using the different running systems is being collected. An analysis will then be carried out on the data using Weibull statistics.

7. ACKNOWLEDGEMENTS

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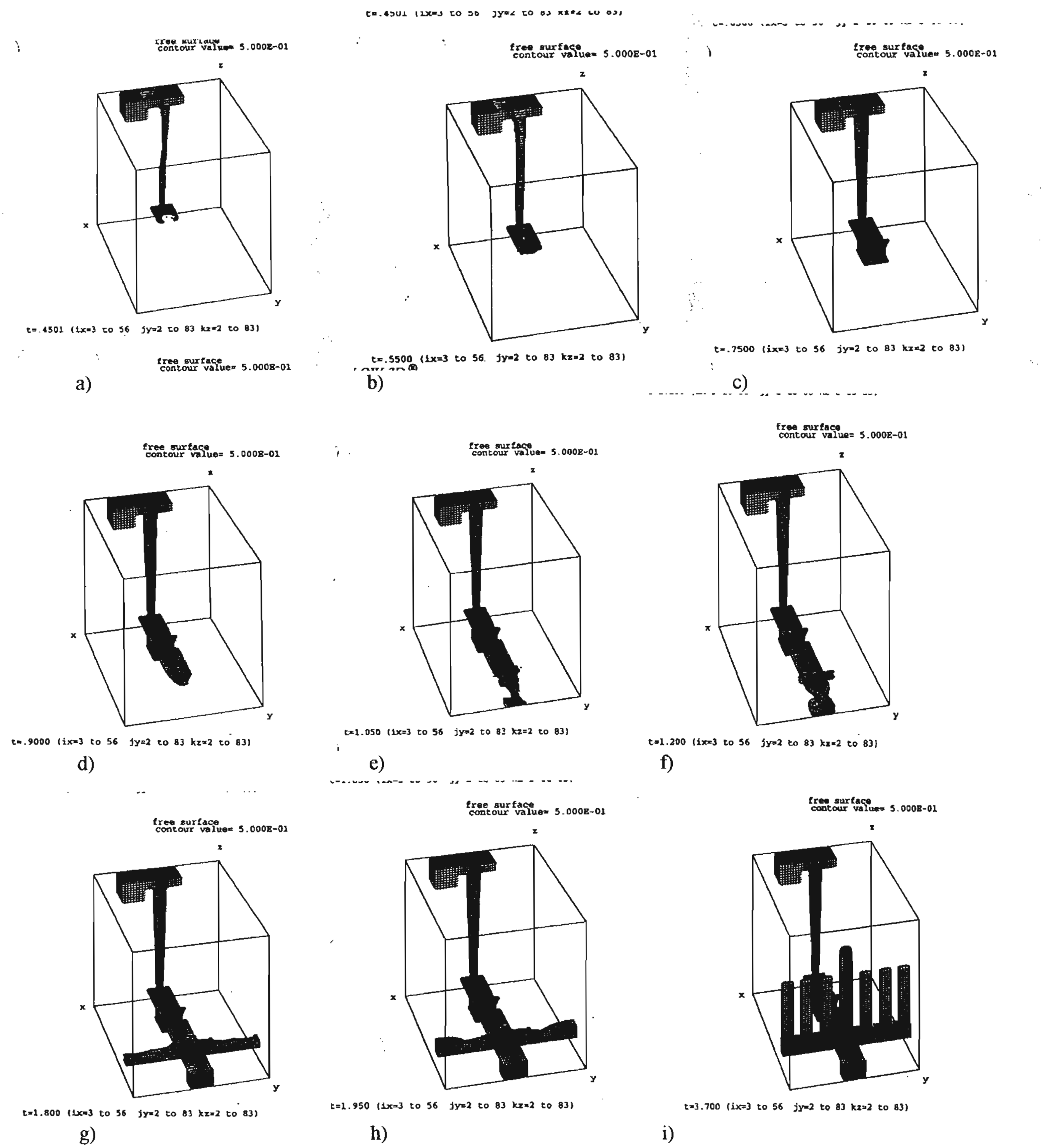

Figure 17: 3D views of the simulation results for the third running system showing the filling of the downsprue at 0.75 s, the splitting of the metal stream(a,b), progression through the filter (c) , the effect of the dross trap (e,f) and the small amount of jetting into the cross runner(g). 17i shows the even filling of the test bar castings.

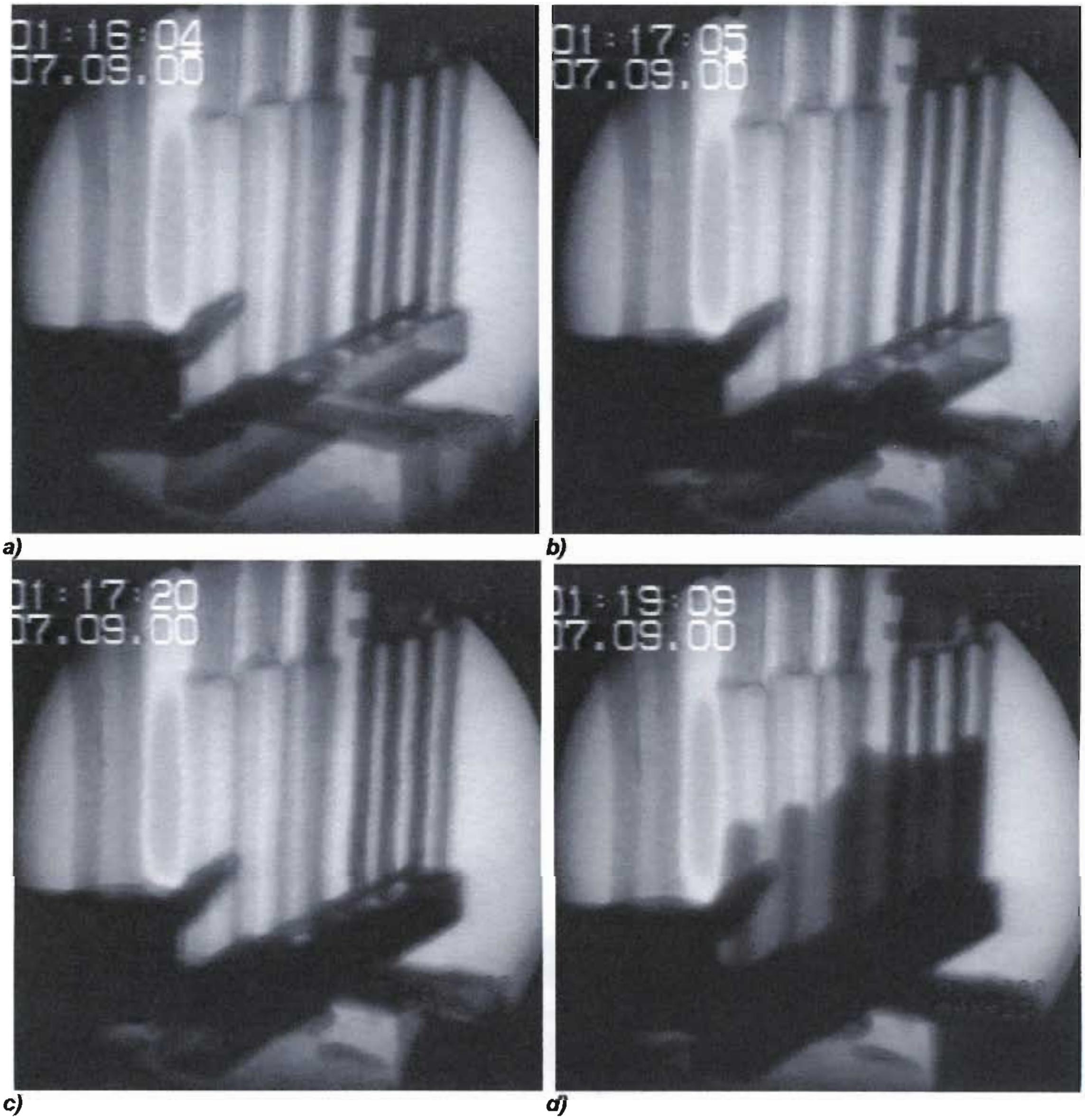

Figure 18: Real-time x-ray results for the third running system. a shows the full filling of the bottom runner. b shows the liquid metal entering the "dross" trap or pressure reducer (16 d, 17 e). c shows the metal filling the cross runner and possibly the start of a small undulation on the top surface (cf. 17 h) . d shows the even filling of the test bar castings (cf. 17 i).

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