The behaviour of two-phase polymer flows in an accumulator

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Summary

An experimental setup was developed to study the phenomena occuring in an accumulator for use in a multilayer injection moulding technique. Special interest was taken in the effects of combining different materials in the accumulator. An attempt was made to simulate the experiments numerically, using the finite element technique. The use of more advanced material models might be necessary to give a good quantitative agreement between experiments and simulations.

Introduction

The use of a multilayer injection moulding technique is a very attractive method to realize layered structures within thin walled products. Although this technique as such is not new, its practical applications have been limited for a long time to sandwich constructions, where, via a sequential injection process, three layers in the product are realised. The inner layer typically consists of the same material as the outer layer, containing some foaming agent. Due to the natural limitations of the process, it can only be used for relatively thick walled products.
Only during the last years the application of this technique has been extended to thin walled products. By using an adapted method of injection it is possible to realise thin, excentric layers of rather uniform thickness over the complete product.
Still, the existing technology has some major limitations. First, the restriction to only two materials. Attractive material combinations which are used in e.g. casting or film-blowing are impossible without the use of an intermediate "glue" layer. This drawback is being overcome by the development of a three component injection moulding technique at our laboratory.
Secondly, the restriction to simple geometries is limiting the possible applications of this technique, whereas one of the big advantages of the injection moulding process is its versatility in the geometrical design. This problem can be overcome by the use of computer simulations to predict the exact flow of each particle into the mould. The great advantage of such a simulation is that it can be inverted to give the starting position of each particle depending on its final position. This way, even in complex geometries the configuration of the injected material can be defined.
However, using the (short) injection phase of the injection moulding process for building up this configuration is not always possible, since the time required is limited by the opening and closing times of the valves in the distribution device. Therefore an accumulator has to be used, in which some required configuration can be realized during the cooling time of the previous product, after which the contents of the accumulator can be injected into the mould in one stroke. In this study the behaviour of different types of polymer materials and combinations of materials in an experimental model of such an accumulator is investigated, and an attempt is made to predict this behaviour using a finite element model of the experiment.

1. The accumulator

The basic design of the accumulator consists of a piston in a cilinder, as shown in figure 1. During the filling stage of the accumulator, the fluid material entering the accumulator will drive out the piston, while the piston will drive out the accumulated material during the injection phase. A phenomenon which is typical for this type of flow can be observed near the piston. During the filling stage, the particles will decelerate as they approach the piston, aquiring a transverse velocity and spilling out towards the wall. This phenomenon is generally referred to as "fountain flow". During the emptying of the accumulator this process is reversed into a so-called "reverse fountain flow".

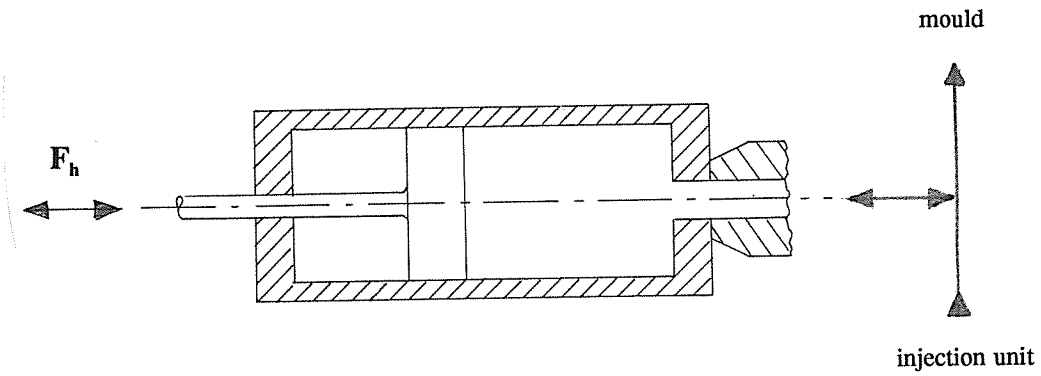


Figure 1) Schematic model of an accumulator

2. Setup of the experiments

An experimental setup has been developed to study the phenomena occurring in an accumulator as described above, such as the fountain flow. The model of the accumulator, as shown in figure 2, consists of a cylinder, heated by six heating elements, in which a plug (ϕ16 x 54 [mm]) consisting of different coloured slices of a polymer material is entered. It is also possible to use different materials in one plug.

When experiments are performed with two materials, the plug is devided in two equally-sized parts of the two materials which are used, as shown in figure 3. The naming convention A/B in

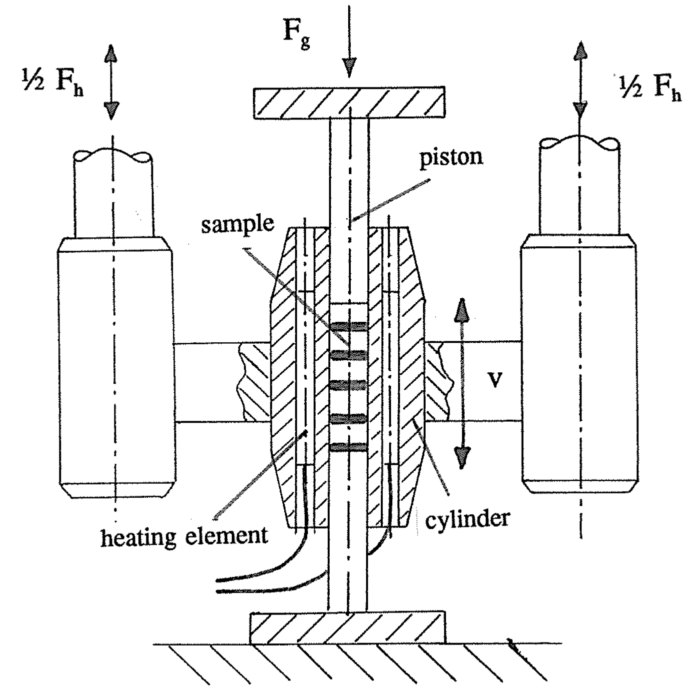


Figure 2) Experimental setup

figure 3, where A indicates the material at the bottom and B the material at the top, will be used to indicate the materials in the experiments in the further paragraphs. Two pistons are placed in the cilinder on both sides of the plug. The top piston is loaded with a weight F_g to prevent slip at the surface and the creation of shrinkage cavities during cooling. The bottom piston is fixed, while the cylinder can be moved up- and downwards by hydraulic pressure, resulting in a force F_h. It is clear that when the material has been heated above T_m and the cylinder is moving downwards, a fountain flow will occur at the top piston, while a reverse fountain flow will occur at the bottom piston.

Previous experiments (E.Vos et al) have given an indication of the effect of both temperature and velocity, these will not be investigated in further detail in this study. The materials which are used are Polystyrene (PS 678E, Dow), ABS (Ronfalin FX50, DSM) and Polyethylene (PE 2101 TN 47, DSM). These materials have been tested in all possible combinations of two materials at different cylinder displacements.

A/B

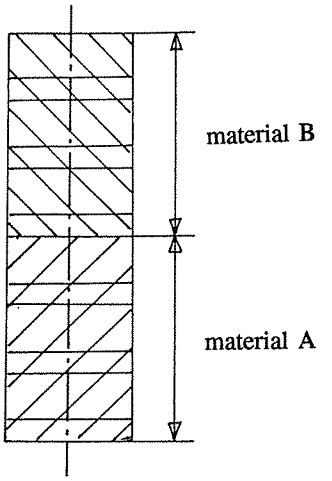


Figure 3) Plug configuration with two materials A and B

3. Numerical simulations

The experiments as described in the previous paragraph are also simulated using the finite element method. The model which is used uses a Galerkin approach to calculate the velocity field. The flow is assumed to be viscous, two-dimensional, incompressible, steady and isothermal. The continuity and Navier-Stokes equations read

$$\nabla \cdot \underline{u} = 0,$$

$$-\eta \Delta \underline{u} + \rho (\underline{u} \cdot \nabla) \underline{u} = \rho \underline{f}.$$

Note that time effects are not considered because of the steady-state assumption.

The flow behaviour of the different materials is described with the following constitutive equations:

* **PS: Cross**

$$A=e^{\left(\frac{-A_1(T-T_0)}{A_2+T-T_0}\right)},$$

$$\eta=\frac{AB_1}{1+\left(\frac{\dot{\gamma}}{B_2}\right)^{1-n_1}}.$$

* **ABS: Herschel-Bulkey/Cross**

$$A=e^{\left(\frac{-A_1(T-T_0)}{A_2+T-T_0}\right)},$$

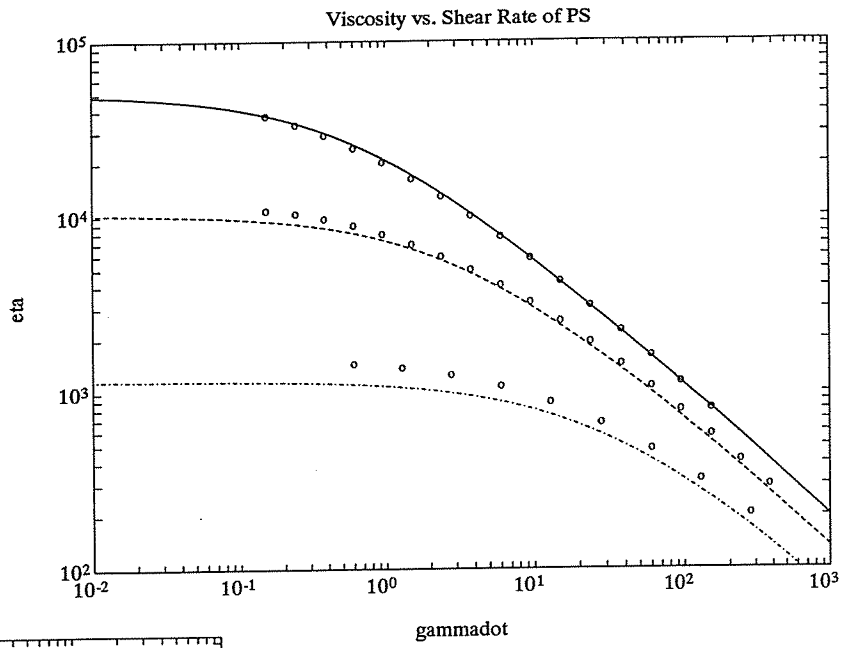
$$\eta=\frac{B_1A}{(A\dot{\gamma})^{1-n_1}}+\frac{B_2A}{1+\frac{(B_2A)^{1-n_2}}{B_3}}.$$

* **PE: Carreau-Yasuda**

$$A=e^{\left(\frac{A_2}{A_1}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right)},$$

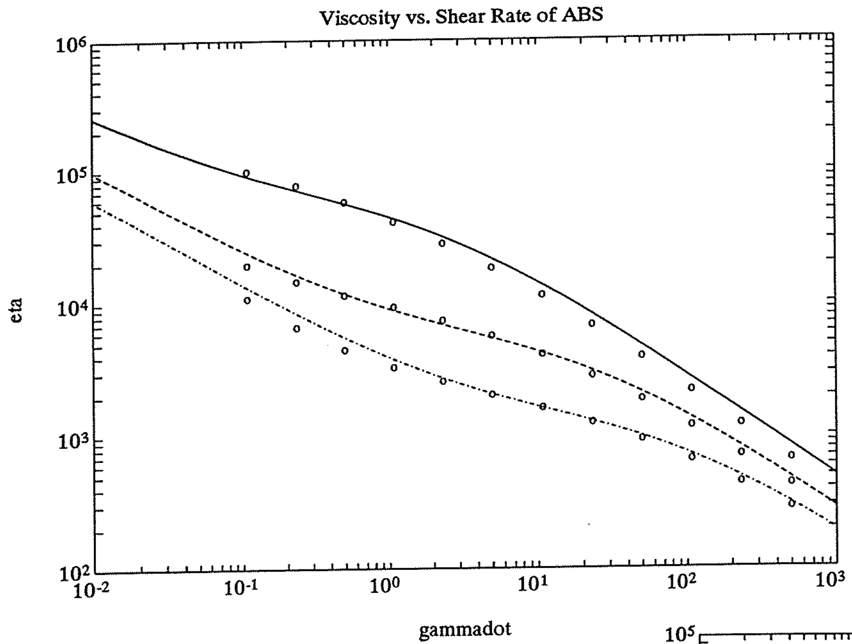
$$\eta=B_1A(1+(B_2\dot{\gamma})^a)^{\frac{n_1-1}{a}}.$$

The parameters in these models are chosen as to fit the flow curves derived from dynamic rheometric measurements. The fitted values of the parameters can be found in table 1, the resulting fits are shown in figure 4.



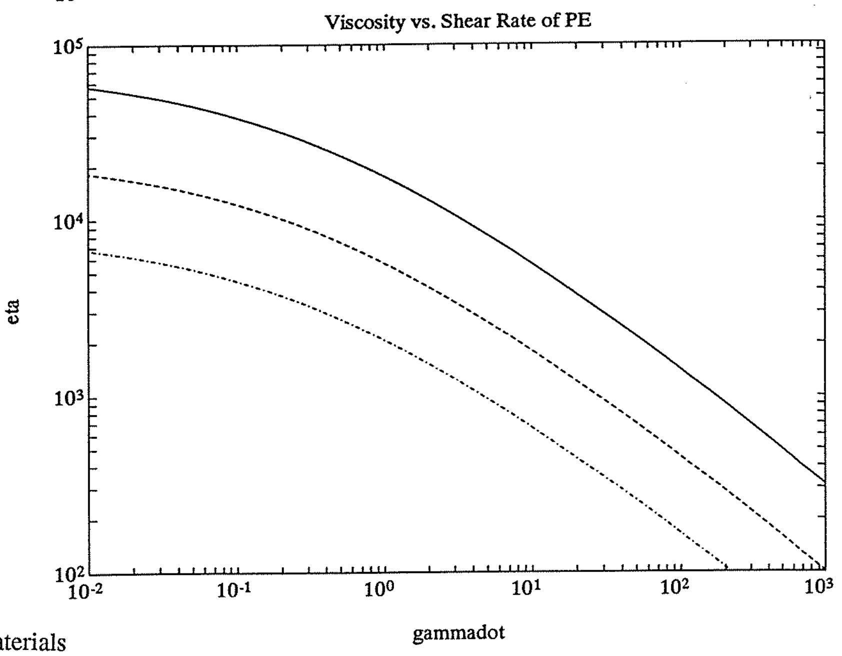
PS:

-	:	170 [°C]
--	:	190 [°C]
-.	:	230 [°C]
o	:	measured data



ABS:

-	:	170 [°C]
--	:	200 [°C]
-.	:	230 [°C]
o	:	measured data



PE:

-	:	170 [°C]
--	:	200 [°C]
-.	:	230 [°C]

Figure 4) Viscosity models for the used materials

Table 1) Parameter values

	PS	ABS	PE
A_1	25.7418	7.039	8.314
A_2	61.0555	119.7	$66 \cdot 10^3$
T_0	373	473	463
B_1	$4.763044 \cdot 10^{10}$	$4.3 \cdot 10^3$	$3.4585 \cdot 10^4$
B_2	$3.08 \cdot 10^4$	$5.2 \cdot 10^3$	3.039
B_3	-	$1.174937 \cdot 10^5$	-
n_1	0.252	0.1	0.32107
n_2	-	0.2	-
a	-	-	0.45836

Some additional remarks should be made concerning the models that were used. First, the Herschel-Bulkey/Cross model for ABS does not give satisfactory results if the parameters are used which follow by fitting the model to the rheometric measurements which were performed. Therefore, the parameter n_1 has been varied as to give a better fit to the experiments. This gives a lower value for n_1, effectively giving a more "Bingham"-like behaviour. Secondly, the heating and cooling stages which take place before and after the displacement of the cylinder were not modelled. Because the material is heated it will expand, causing the upper piston to move and thereby inducing an extra flow even without cylinder displacement. This effect is complicated by the fact that the material is heated (and cooled) from the outside, yielding a non-uniform temperature distribution during these stages of the experiment. This effect has been approximated by adding the total effect of both the heating and cooling stages (which can be found by performing an experiment with zero displacement) as an additional displacement prior to the numerical simulation of the experiment. A polynomal approximation was used to fit the zero material displacement of the simulation to the experimental results. Of course this is not exactly what happens, since part of the additional displacement takes place after the displacement of the cylinder, but at this point it is not possible to determine which part of the additional deformation takes place during the heating and which during the cooling stage of the experiment. Since the cooling is done at a much slower rate, and thus with lower temperature gradients within the sample, it is presumed that most of the additional deformation occurs during the heating of the sample. The experimental and numerical displacement field due to the temperature effects are shown for PS in figure 5. The effect for PE and ABS is comparable, both qualitatively as quantitatively, therefore the same numerical approximation of the displacement filed was used.

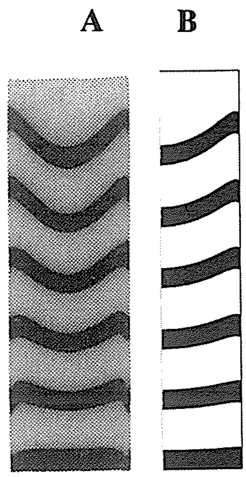


Figure 5) Deformation induced by heating and cooling, experimental (A) and numerical (B)

4. Results

The results of the experiments themselves and of the numerical simulations of the experiments can be found in figure 6a-i. All experiments and simulations are performed for cylinder displacements of {10,20,30,40} [mm]. The axial speed of the cylinder is 1.2 [mms^{-1}], the temperature at which the experiments were performed is 200 [°C]. The material and cylinder are cooled slowly to minimise the forming of shrinkage cavities and additional flow during the cooling stage. Because of the heating equipment used, it is not possible to extend the time used to heat the material. After heating the sample to 200 [°C] it is kept at this temperature for 15 [min], to assure a uniform temperature distribution within the sample. Next we will try to give a phenomenological description of all experiments and some possible explanations for certain observations.

6a) PS - At 10 [mm] cylinder displacement, the experiment shows some characteristics of a plug flow, which disappear at higher displacements. This might be caused by the displacements induced during the heating/cooling stages. The numerical simulations show a more or less parabolic flow for all displacements, which is in good qualitative agreement with the experiments. The total deformation however is slightly exaggerated.

6b) PS/ABS - Compared to the flow of plain PS, the material near the bottom piston is more displaced in axial direction, in both experiments and numerical simulations. This might be caused by the higher viscosity of

ABS, at least at lower shear rates, which forces the PS to flow more inwards in the plug. Another effect which is seen is the forming of a "tip" at the PS/ABS boundary at a displacement of 20 [mm]. This might be caused by a yield stress in the ABS, but is not found in the numerical simulations. Again, a larger total deformation for the numerical simulations is found, allthough the PS/ABS boundary has a smaller deformation in the numerical simulations.

6c) **PS/PE** - Here the same effect as with the PS/ABS flow is found, i.e. a larger deformation of the material near the bottom piston. Again this might be explained by the higher viscosity of the top material, in this case PE. The numerical simulations give a good description of the deformation of the PS/PE boundary, even quantitatively, but the deformation within the PS domain are exaggerated.

6d) **ABS** - It can be seen that the simulations give a relatively good qualitative description of the experiment at small deformations, but give a much lower total deformation for all cylinder displacements. This might be caused by the exagerrated yield stress, implemented in the model to get a qualitative agreement with the "plug-flow" phenomenon found in the experiments. One other interesting point is the decrease of this phenomenon at higher deformations. This is not in agreement with earlier experiments with ABS (E.Vos et al).

6e) **ABS/PS** - Here the same effect as with the PS/ABS flow in figure 6b is found, i.e. the PS is deformed stronger than with plain PS, while the ABS is less deformed. Again, this is probably caused by the higher viscosity of the ABS. In the simulations only small differences in the ABS flow near the ABS/PS boundary, compared to plain ABS flow are found. The high deformation rate of the PS, especially near the ABS/PS boundary might be caused by the plug flow of ABS, which leads to the occurence of a flow behaviour resembling the reverse fountain flow near the ABS/PS boundary. This effect can also be found in the simulations.

6f) **ABS/PE** - Characteristic for this experiment is the dominance of the PE flow, which yields a more parabolic flow profile for ABS, even at lower deformations. This might be caused by a higher viscosity of the PE, possibly because of viscoelastic effects, as well as the higher deformation of the ABS compared to the experiment with only ABS. The simulation shows a flow which is still more or less dominated by the ABS, comparable to the results seen with the ABS/PS flow. This could be a consequence of the absence of viscoelastic effects in the models which were used.

6g) **PE** - Here a deformation pattern is found which is comparable to that of PS, allthough the total deformations are generally smaller. Again, this is probably caused by the absence of viscoelastic effects in the models. The simulations also show smaller deformations compared to PS, but are still too large compared with the experiments.

6h) PE/PS - Here the simulations give a relatively good description for the deformation of the PE/PS boundary at higher deformations. The lower deformation of the PE compared to the experiment with plain PE, probably caused by the lower viscosity of PS, can be found experimentally and numerically. The "tip" forming of PS due to high deformation rates near the center of the plug and the PE/PS boundary is not found in the simulations.

6i) PE/ABS - Compared to the flow of plain PE, we see that the experiment yields slightly smaller deformations for the PE, whereas the simulations show an opposite effect. As stated previously this might be a result of not taking viscoelastic effects into account in the models of the materials.

Displacement 10 20 30 40 [mm]

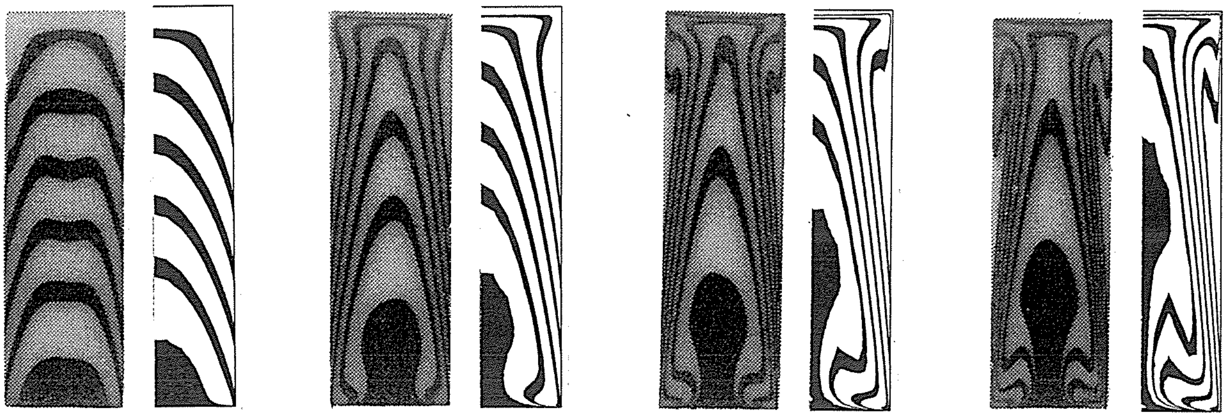


Figure 6a) Deformation of PS

Displacement 10 20 30 40 [mm]

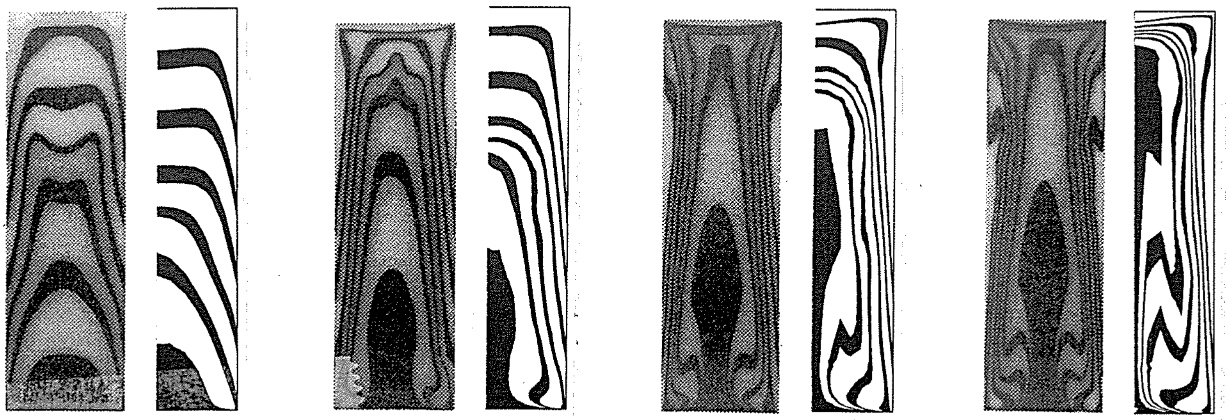


Figure 6b) Deformation of PS/ABS

Displacement 10 20 30 40 [mm]

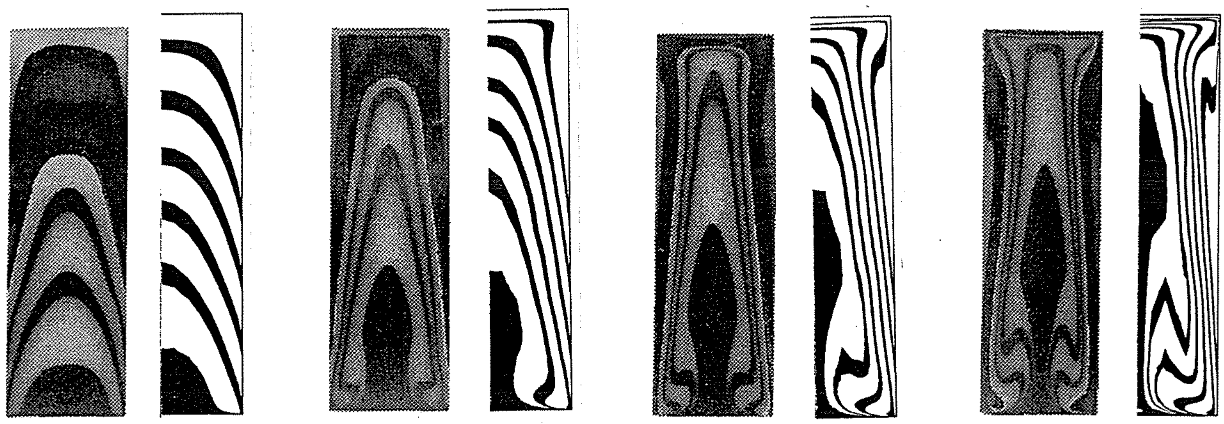


Figure 6c) Deformation of PS/PE

Displacement 10 20 30 40 [mm]

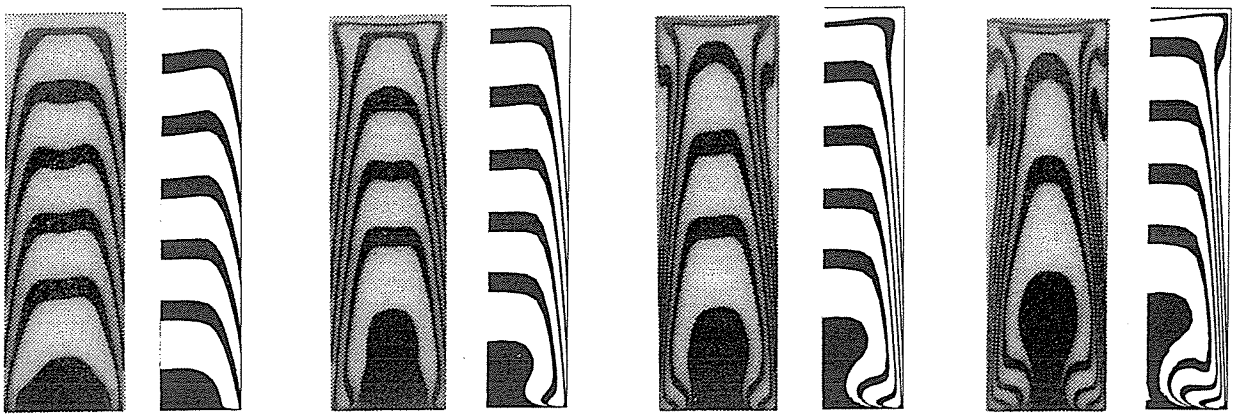


Figure 6d) Deformation of ABS

Displacement 10 20 30 40 [mm]

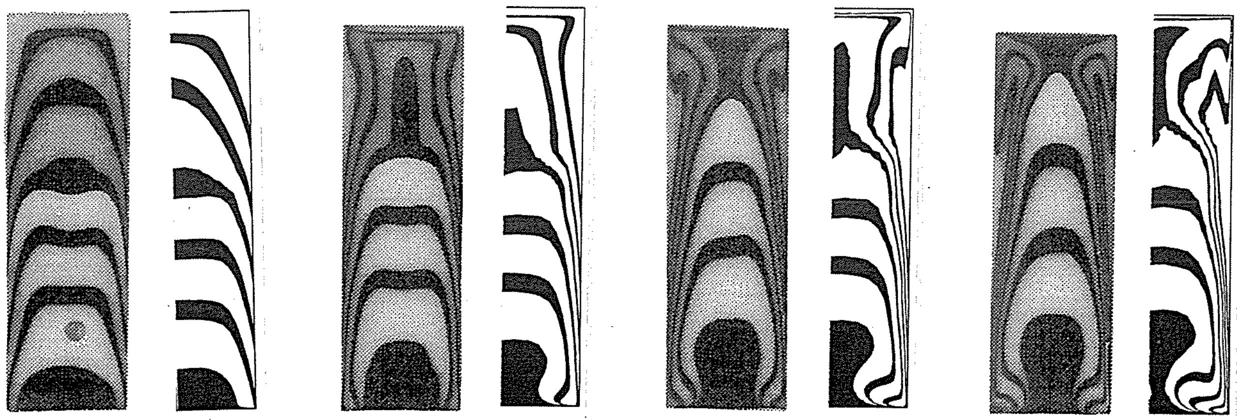


Figure 6e) Deformation of ABS/PS

Displacement 10 20 30 40 [mm]

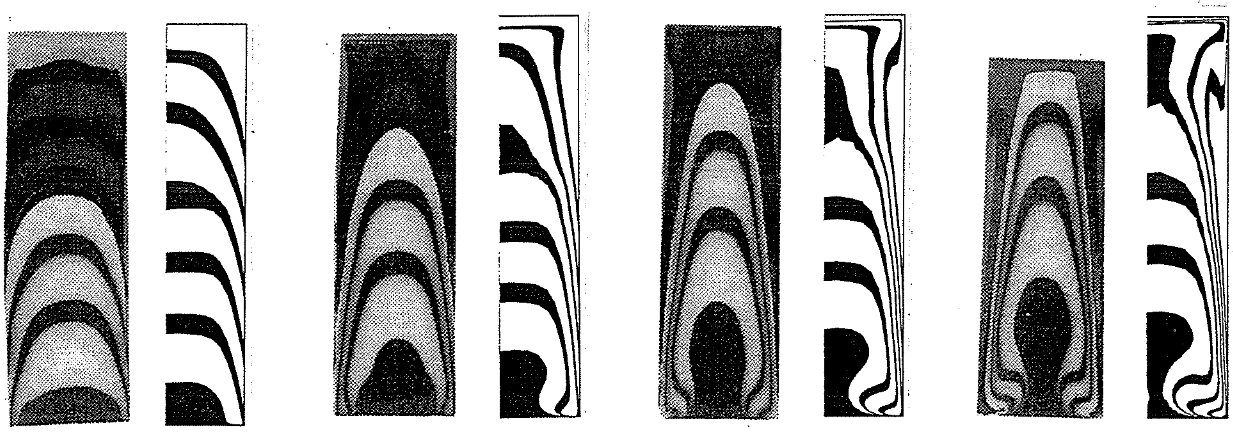


Figure 6f) Deformation of ABS/PE

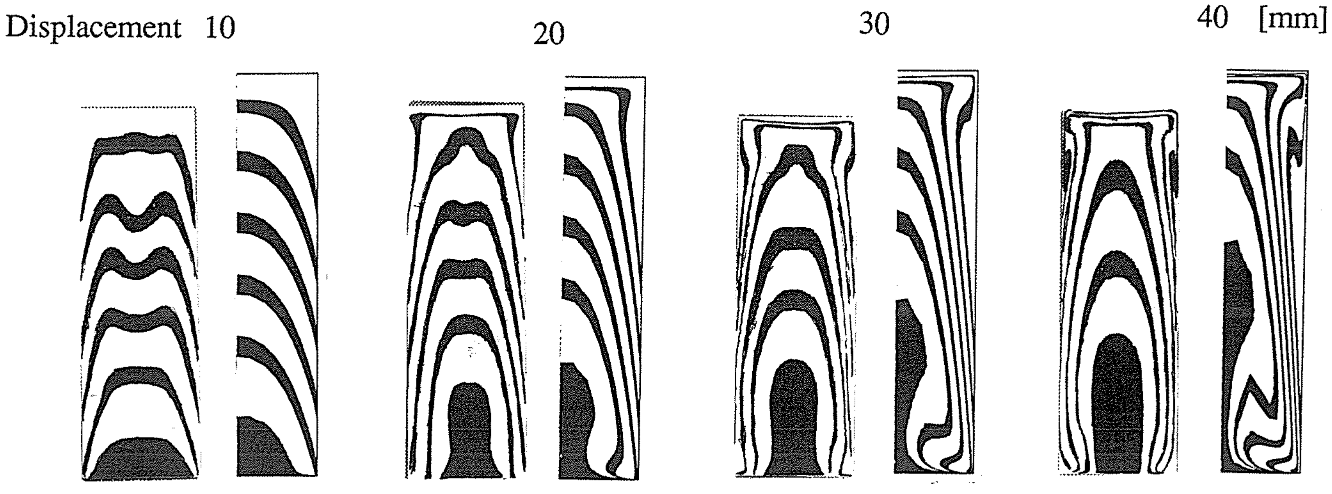


Figure 6g) Deformation of PE

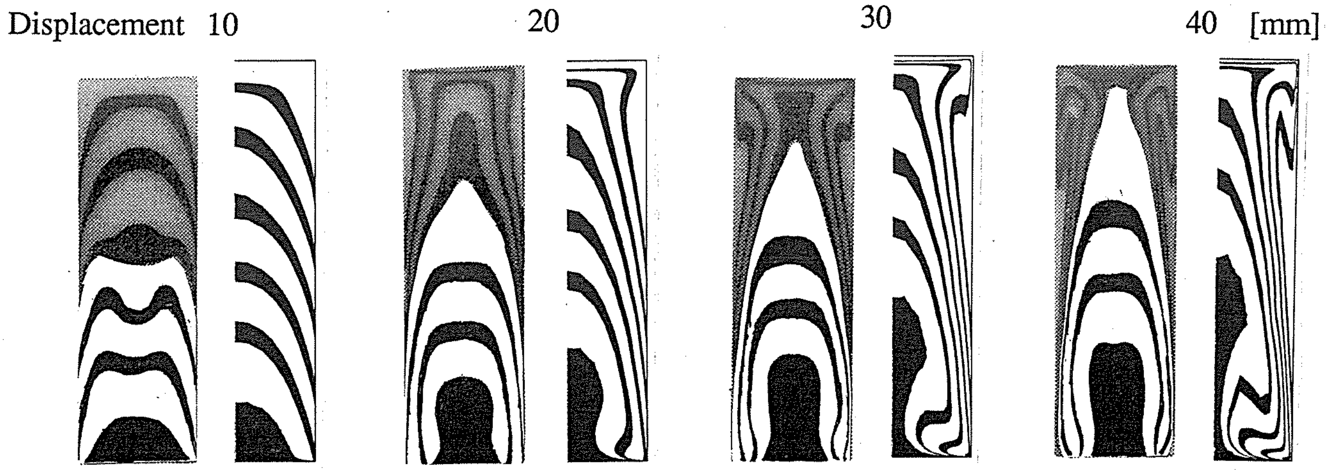


Figure 6h) Deformation of PE/PS

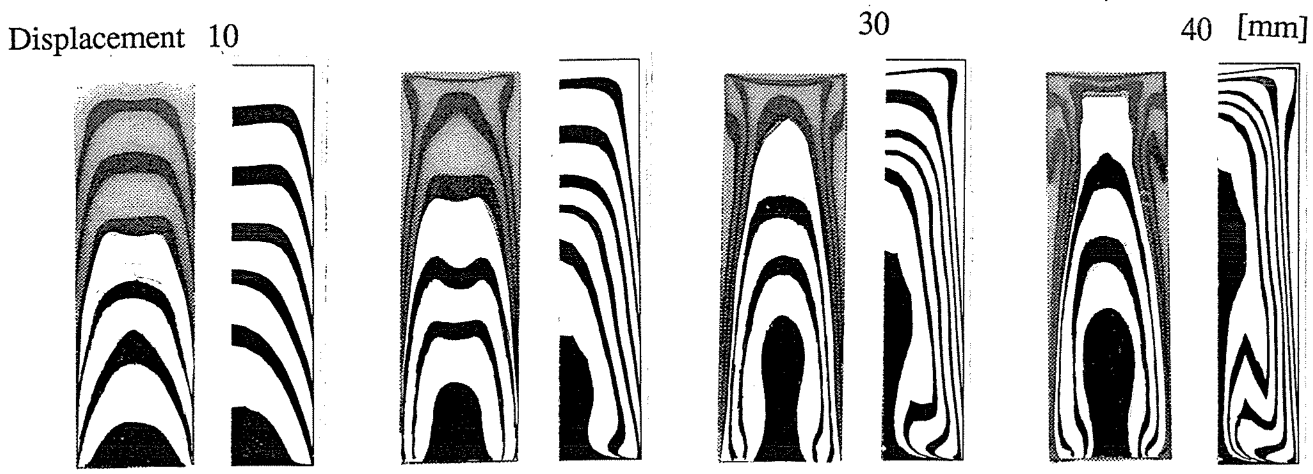


Figure 6i) Deformation of PE/ABS

5. Conclusions and Recommendations

With the use of model experiments and finite element simulations several phenomena occuring in a two-phase polymer flow have been studied. The simulations which were performed give qualitatively good results, but show more or less severe quantitative differences from the experiments. This indicates that the model which was used for the finite element calculations does not suffice. Before any further conclusions can be drawn, it is necessary to understand the phenomena occuring for only one material should be understood and its numerical simulations brought into agreement with the experiments.

Possible defects of the model might be:

* The parameters of the viscosity models of the materials which were used. The parameters were derived from dynamic rheometric measurements, which might not be a valid approach for this type of flow. It might be possible to use another way to characterize the materials which gives better results.

* The viscosity models themselves. As stated before the viscosity models which were used give good fits for the different materials, but they do not take transient or viscoelastic effects into account. Expansion of the finite element computations to include this type of material behaviour might improve the results. Of course more extensive characterization of the materials will be necessary.

* Temperature effects. As shown in this study, the heating and cooling of the material which is necessary before and after the actual experiment disturbes the results severely, especially for small deformations. One approach could be to minimize the effect of heating and cooling in the experiments, another could be to include the heating and cooling stages in the finite element simulation. Another approach for the computations will be necessary, since the expansion of the material causes the plug to vary in size, which makes it impossible to use a fixed mesh for the simulations, at least for the heating and cooling stages.

* Boundary problems. Apart from the problems occuring at the singularity in the boundary conditions between the wall and the pistons, which were already studied by E. Vos et al, a new boundary is introduced if two materials are used, i.e. between these two materials. Especially when fountain-type flows occur near this boundary, e.g. in the ABS/PS experiments, a mesh refinement in this region could be necessary to give accurate results, although this might not be so straightforward since this boundary is deformed during the experiment.

References

H. Meijer et al, 'Polymeerverwerking en Reologie, Deel 1: Basis', Coursebook no. 4713, Eindhoven University of Technology, 1992.

H. Meijer et al, 'Polymeerverwerking en Reologie, Deel 2: Toepassingen', Coursebook no. 4714, Eindhoven University of Technology, 1992.

E. Vos et al, 'Multilayer Injection Moulding', Int.Pol.Proc. Volume 6, Issue 1, pg. 42-50, 1991.