Modelling of gas-assisted injection moulding

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Modelling of gas-assisted injection moulding

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Summary

This report deals with the simulation of gas-assisted injection moulding. First, the main aspects of this technique will be discussed, such as the practical applications and the physics of a gas flow in a channel filled with a viscous fluid. Second, the effect of the gas flow on the resulting gas channel, i.e. the amount of material left on the mould wall, will be looked at, after a model of the gas front has been implemented in the simulation program VIP (Polymer Processing & Product Properties Prediction Program). Third, the filling of a rectangular configuration with two different materials, which have a viscosity ratio of 1000, will be simulated in the original program VIP. Both simulation experiments differ in the way which is looked at the interface, because in the first experiment will be looked in the length-height plane, while in the second will be looked in the length-width plane (according to Saffman and Taylor [11]). These results are of great importance for the simulation of gas-assisted injection moulding, because from a comparison with experimental results, it can be determined if the gas front model used is correct.
Notation

\( b \) : width \hspace{1cm} [ \text{m} ]
\( h \) : thickness \hspace{1cm} [ \text{m} ]
\( l \) : length \hspace{1cm} [ \text{m} ]
\( m = 1 - \lambda \) : fraction of the fluid left on the wall \hspace{1cm} [ - ]
\( \mathbf{n} \) : outward normal to the surface
\( v, u \) : velocities \hspace{1cm} [ \text{m/s} ]
\( x, y, z \) : coordinates
\( V, U \) : volume flux \hspace{1cm} [ \text{m}^3/\text{s} ]
\( \Gamma \) : surface tension \hspace{1cm} [ \text{Pa.m} ]
\( \epsilon \) : relative thickness of the polymer left on the mould wall \hspace{1cm} [ - ]
\( \eta \) : viscosity \hspace{1cm} [ \text{Pa.s} ]
\( \lambda = 1 - m \) : width of the gas core relative to channel width \hspace{1cm} [ - ]
\( \rho \) : density \hspace{1cm} [ \text{kg/m}^3 ]
\( \text{Ca} = \eta u/\Gamma \) : capillary number \hspace{1cm} [ - ]
Chapter 1  Introduction

Gas-assisted injection moulding is a process in which the molten plastic is injected in the mould followed by a pressurized gas, which takes care of the filling to be completed. This technique can be divided into three stages (figure 1). In the first stage, the polymer melt is injected in the mould, until it is filled to a certain percentage, the melt contacting the cold walls by which a solidified skin shall arise. In the second stage, the gas is injected under a constant pressure or a controlled volume flux, penetrating in the direction of the least flow resistance while driving the melt further into the cavity, until the mould is filled completely. In the last stage, further gas penetration may occur due to the shrinkage of the polymer.

Fig.1  A tube in three filling stages

The biggest advantage of gas-assisted injection moulding is, that hollow structures with improved surface quality can be produced at lower moulding pressures than required in standard injection moulding, because the pressure in the core of the product, where the gas ends up, is more uniform in the packing stage. Also the thermal stresses in the surface of the product will be reduced and, as a result of this, the product will be less inclined to warp.

In the plastic industry, two main gas-assisted injection techniques are commonly used; nozzle gas injection, in which the gas is injected through the resin injection nozzle, and mould gas injection, in which the gas is injected through a separate needle into the mould at a certain point. This last technique can be used to inject the gas at more then one point at a time. The dynamics of the gas penetration in both techniques are the same. Examples of products made with this technique are automobile mirrors, steering wheels, garden-furniture and key-boards. In order to apply gas-assisted injection moulding successfully, these products have to meet some design criteria that are characteristic for the process. The mayor one is, that they have to contain thick parts to lead the gas flow. Because it is very expensive to design a product by trail and error, programs are developed, which can predict these end properties.

Nowadays, it is possible to simulate the (multi-component) moulding process and derive properties of the final product. Between multi-component injection moulding and gas-assisted injection moulding does exist a great resemblance, but also some differences. The main difference is that in the former the difference in viscosity is at most a factor 10, while in the latter it is approximately a factor $10^7$. However, if simulations of gas-assisted injection
moulding are done with a difference in viscosity of a factor $10^3$, the Reynolds number will be too high and can give some problems in the numerical approximation. This is why the simulations are done with an artificial factor $10^3$. The equations used in multi-component injection moulding, as mentioned in Zoetelief [7], are also used to describe gas-assisted injection moulding. Consequently, it is possible to use the implementation of multi-component injection moulding in VIP to simulate gas-assisted injection moulding.

VIP does make use of a labelling technique to perform particle tracking. Therefore all material particles are treated in the same way, although they represent different materials. By doing so, the simulation of gas-assisted injection moulding in VIP will come up with two main problems:

1. The way the gas front proceeds in the polymer melt.
2. The thickness of the material left on the wall after the gas front has passed.

In a gas channel with a laminar gas flow, a parabolic velocity field will arise. If this parabolic velocity field is used to model the velocity field at the gas front, the width of the gas channel will decrease as the gas penetrates the melt, while in practice the width of the gas channel is uniform. Thus it is to be concluded that the velocity field at the gas front is not parabolic.

So, the main goal of this work is to modify the simulation of gas-assisted injection moulding in such a way that a constant gas core width is predicted. For this purpose the following tasks have been formulated:

1. Simulate the filling of a rectangular product, with two materials, which have a viscosity ratio of order 1000. The interest is focused on the gas core width.
2. Consider the physics at the gas front and develop a new gas front model that has to be implemented in the program VIP.
3. Check whether the new gas front model has any influence on the thickness of the gas channel and compare the results with results in the literature.
2.1 introduction

For the simulation of gas-assisted injection moulding, it is necessary that the physics of the gas penetrating in the melt are known. The gas flow in the core has a parabolic velocity profile, while the velocity profile at the gas front is not known and has to be studied. Several experiments have been done in order to understand these physics (Reinelt and Saffman [4], Taylor [2], Poslinski and Stokes [5]) and finding the shape of the gas front (Saffman and Taylor [1], Cox [3]), as will be discussed in the next paragraph.

2.2 literature overview

Saffman and Taylor [1] studied the penetration of a fluid into a Hele-Shaw cell, which does exist of two closely spaced parallel sheets of glass, containing a more viscous fluid. Because it had been shown that the unstable accelerating interface between two fluids of different viscosity develops in such a way, that long fingers of the less viscous fluid penetrate into the more viscous one, they took a channel, narrow enough to allow only one finger within the channel width. After studying the penetration of the finger in the length-width plane, they proposed a correlation between the velocity of penetration of the finger and the description of the front shape of it (equation 1).

\[ v = \lambda u \]

\[ x = \frac{1 - \lambda}{\pi} \ln\left( \frac{1}{2} \left( 1 + \cos \left( \frac{\pi y}{\lambda} \right) \right) \right) \]

Where \( v \) is the velocity of the fluid at infinity in front of the finger, \( u \) the velocity of the finger, \( \lambda \) the width of the gas core relative to channel width, \( x \) and \( y \) are coordinates relative to the nose of the finger in the length and width direction respectively, as shown in figure 2.

![Fig.2 Finger moving into a channel](image)
Taylor [2] measured the fraction of fluid m, which was left on the wall after the core of the fluid was driven out by air and which is given by equation 2.

\[ m = \frac{u - u_m}{u} \quad (2) \]

where \( u \) is the velocity of the bubble and \( u_m \) the mean velocity of the fluid ahead of it. When he measured this as a function of \( \text{Ca} \), he found that with \( \text{Ca} \) increasing towards 2.0, \( m \) reaches a limiting value just above 0.56 [-].

Also, Cox [3] considered this problem, and found that the fraction \( m \) reaches an asymptotic value of 0.60 [-], when \( \text{Ca} \) is increased. In his calculations he assumed that the fluid is incompressible and that just like the gravity forces, the inertia terms in the equations of motion are negligible. The negligible gravity force implies that the bubble is axisymmetric. The experimental results he obtained were in good agreement with the equation he derived. Also, the profile of the gas front travelling through the viscous fluid was measured and an exponential curve was fitted. Although the agreement between the fitted and the measured curve is very close, at the nose of the profile they do not match.

The steady-state shape of a finger penetrating into a region filled with a viscous fluid was examined numerically by Reinelt and Saffman [4]. They solved the Stokes equation for low Reynolds number flow, assuming the shape of the finger and dropping the normal stress boundary condition, which is the boundary condition of the pressure jump at the interface. Their numerical results were in good agreement with the results of Taylor [1]. For the axisymmetric case, they found an asymptotic value for the fraction \( m \) of 0.55 [-] at high \( \text{Ca} \) numbers.

Continuing Reinelt and Saffman's work, Poslinski and Stokes [5] tried to develop a model for the dynamics of the gas-melt system and the formation of the fluid layer during gas-assisted injection moulding, based on results they obtained from their experiments. They concluded that at low penetration rates, more liquid is displaced downstream of the gas front, resulting in a thinner fluid layer with an axial thickness gradient. At higher penetration rates, the thickness distribution becomes uniform, and \( m \) approaches 0.56 [-] as with Newtonian fluids, which means that \( m \) does not depend on the velocity of penetration at high penetration rates. Good agreement for this model with the experiments is obtained when the blowout time approaches 1 s., and the velocity of the gas front is of order 0.1 m/s.

Another approach was followed by Johannaber and Konejung [8]. They divided the dynamics at the gas front into two basic phenomena: a plug flow in which a plug of polymer melt, as wide as the width of the gas channel, is shoved forward by the gas (figure 3), and an extensional flow in which the gas forces a volume of polymer to be pushed aside to the tube wall (figure 4). They concluded that the penetration of the gas front in a polymer ought to be a combination of these two situations, and \( m \) depends on the ratio of the strain and shear viscosity. However, it is to be doubted that extensional flow does play a role in gas-assisted injection moulding.

In order to solve the equations, which describe the dynamics at the gas front, in all these studies assumptions have been made like:

- using incompressible fluids.
- assuming a 'sharp' interface between both fluids.
- assuming a pressure drop across the interface.
- neglecting gravitational effects.
- neglecting the inertia terms in the equation of motion.
Some assumptions have been made without good arguments like Saffman and Taylor [1], who made assumptions about the shape of the finger, which they could not justify. The biggest problem however is that in most articles, the capillary number is assumed to be low, indicating that surface tension is dominating, while in gas-assisted injection moulding $Ca = 1000$. Also, the velocity of the particles at the interface, which has a connection with the processes at the interface during filling, was never mentioned. It is clear that if this velocity is known, the modelling of gas-assisted injection moulding would make great progress.
Chapter 3  Simulation of gas-assisted injection moulding in VIP

§ 3.1  introduction

A model of the gas front is implemented in the program VIP. For that purpose, in § 3.2 a possible model for the gas front is developed and implemented, and the problems, which occurred with implementation are discussed in § 3.3. In § 3.4, the results of the simulation in VIP, with and without the model, will be shown and compared with the results of a similar simulation with the program SEPRAN (§ 3.5 and § 3.6). The SEPRAN-results are obtained by simulating multi-component injection moulding of two materials, which have a difference in viscosity of 1100 [6]. Finally, conclusions will be drawn in § 3.7.

§ 3.2  derivation of the gas front model

At the derivation, the first problem that occurs is the velocity field of the gas front, which is not known and depends on the dimensions of the cavity, the height of the gas core and the gas volume flux at the entry. Because of the parabolic velocity profile the width of the gas core decreases as it penetrates the polymer melt, in contrast with practice, where the gas core width is uniform. The intention is to implement a model that changes the velocity profile around the gas front in such a way, that the height of the gas core stays the same. A first order approximation of the velocity field around the gas front is chosen so these new velocity profiles in the nodal points of the mesh are uniform in the thickness-direction with a value that is the mean velocity across the cavity. However at the nodal points the gas front passed, it is not correct to modify the velocity profile over the entire thickness, because the velocity of the residual polymer at the mould walls tends to zero (figure 5).

![Fig.5  velocity profile across cavity height](image)

In these points, the velocity will be modified only in the gas. In illustration of the modification of the velocity profiles around the gas front, the consequences for the nodal points are shown in figure 6 and 7, in which z denotes the thickness-direction, y the length-direction and x the width-direction of the cavity.
§ 3.3 implementation of the gas front model in V1p

In the part of the program V1p, in which the viscosity is calculated, some statements have to be implemented, which derive the new viscosity between the injection positions in the thickness-direction after a certain time, when the switch point from polymer to gas has been reached. In this modification use is made of the ratio of viscosity between both materials, like $\text{viscos} = \frac{\text{viscos}}{1000}$
The number of switch points during the filling process, the switch points itself and the injection positions in the thickness direction, between which the viscosity has to be modified are in a data file, which can be read by the main program in the input stage. The modification of the velocity profiles in the nodal points around the gas front, is based on the time labels, with which can be seen, whether or not the material in this point is gas. For every time step, a loop over all nodal points is done to detect the nodal points near the gas front. A nodal point is said to be near the gas front, if it is in the gas core and has at least one neighbour point in the melt region. All neighbour points in the melt region are also designated as gas front points. In illustration of this, the flow diagram of this modification is shown in figure 8.

\[\text{for every node } i \leq i < n\]

\[\text{time-label node > switch-time?} \quad \text{no}\]

\[\text{yes} \quad \text{What are the neighbour-nodes?}\]

\[\text{How many neighbours have time-label < switch-time?} \quad \text{none}\]

\[\text{one or more} \quad \text{current node is near gas front}\]

\[\text{modify velocity profile of this node}\]

\[\text{modify velocity profile of those neighbours with time-label < switch-time}\]

\[i = i + 1 \quad \text{yes}\]

\[i < n? \quad \text{no}\]

\[\text{continue}\]

**Fig. 8** flow diagram of the modification of the velocity profiles

---

### 3.4 numerical testing results

In order to get to know, if the implementation of the model has any influence on the numerical results, simulations have been performed with and without the modified gas front velocities. The filling of a rectangular configuration *without* the velocity modification has been simulated for two different cases:

- length x width x thickness = 0.1 x 0.02 x 0.0005 m. (m1) and length x width x thickness = 0.2 x 0.02 x 0.0005 m. (m2) respectively.
- The viscosity of the fluid is modelled as a Newtonian fluid and a Power Law fluid respectively.
- In the thickness 21 and 41 grid points are used respectively.
- The switch from polymer melt to gas takes place at a filling percentage of 40% in both cases.

The results of these simulations (figure 9) show, that the width of the gas channel decreases continually as the gas penetrates the polymer melt. Consequently the width approaches zero.
if the configuration is long enough.

\[ m \text{ as a function of the y-position} \]

\[ \text{without implementation of the model} \]

Also three simulations have been executed with the modified velocity, which have different configuration lengths: \( m_1 \), length = 0.1 m.; \( m_2 \), length = 0.2 m.; \( m_3 \), length = 0.3 m. Because in the simulation with Newtonian fluids without the model, breakthrough of the gas occurs it is preferred to continue the testing in comparison with the situation without breakthrough of the gas. So, in all cases the viscosity is modelled like a Power Law and the difference in zero-viscosity equals 1000. To eliminate breakthrough for sure, the switch point is set at a filling percentage of 50%. From the results (figure 10) it is clear that as the gas penetrates the polymer, the width of the gas channel decreases, but at a certain point the width does not decrease any further.

It is to be concluded, that the implementation of the model surely has influence on the width of the gas channel and as a result of that, the width of the gas channel becomes uniform.
**m as a function of y-position**

*with implementation of the model*

<table>
<thead>
<tr>
<th>Legend</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>m1 [%]</td>
<td></td>
</tr>
<tr>
<td>m2 [%]</td>
<td></td>
</tr>
<tr>
<td>m3 [%]</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10  testing results with implementation of the model

§ 3.5  simulating data for gas-assisted injection moulding

The SEPRAN-simulation does make use of the next data:
- thickness of the channel = 0.038 m.
- length of the channel = 0.4 m.
- density of the fluids = 1000 kg/m³
- viscosity of the polymer melt = 11 Pa.s
- viscosity of the gas = 10⁻² Pa.s
- velocity profile at the entry:
  \[ v = 0.09d_0*(1.0d_0-(y/0.019)^2) \]
- both materials are modelled like Newtonian fluids

A similar simulation is performed in VIp for comparison, using the same input data. Although the width of the channel has no influence, because at the boundary of the mesh a slip condition exists, it has to be given in in the VIp simulation and is chosen 25% of the length.
§ 3.6 results

§ 3.6.1 VIP-results

For a filling percentage of 100%, simulated with the program VIP, a plot of the velocities in the length-thickness plane is shown in figure 11, in which the thickness of the gas core can be seen, because the velocity in the polymer approaches zero in comparison with that in the gas.

Newtonian 41 gridpoints \( \eta \text{eta}1/\eta \text{eta}2=1100 \) \( \text{deltat}=5d-2 \) penalty=1d12

![Figure 11: Velocity as a function of the place in the length-height plane](image)

From this plot \( \epsilon \) and \( \lambda \) can be calculated for different length-coordinates (table 1). This table shows that \( \epsilon \) varies between 0.375 [-] and 0.900 [-] and stabilizes on approximately 0.85 [-] (the value of 0.900 [-] is calculated in the nose of the bubble profile). These values do not match with the asymptotic value of \( m = 0.56 \) for a circular tube found by Taylor, which means a relative thickness of the polymer left on the mould wall of \( \epsilon = 0.337 \) [-].
Table 1 numerical values calculated from figure 11

<table>
<thead>
<tr>
<th>l [m]</th>
<th>ε [-]</th>
<th>λ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.375</td>
<td>0.625</td>
</tr>
<tr>
<td>0.05</td>
<td>0.500</td>
<td>0.500</td>
</tr>
<tr>
<td>0.10</td>
<td>0.650</td>
<td>0.350</td>
</tr>
<tr>
<td>0.15</td>
<td>0.750</td>
<td>0.250</td>
</tr>
<tr>
<td>0.20</td>
<td>0.800</td>
<td>0.200</td>
</tr>
<tr>
<td>0.25</td>
<td>0.850</td>
<td>0.150</td>
</tr>
<tr>
<td>0.30</td>
<td>0.850</td>
<td>0.150</td>
</tr>
<tr>
<td>0.35</td>
<td>0.900</td>
<td>0.100</td>
</tr>
<tr>
<td>0.40</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

§ 3.6.2 SEPRAN-results

The SEPRAN-results show the filling of the channel in two stages of the filling process (figure 12), from which can be calculated that $\varepsilon = 0.40$ [-] and consequently $\lambda = 0.60$ [-]. These values are in closer agreement with the values found by Taylor [2] than the VIP-results.

Fig. 12 filling process in two stages
§ 3.6.3 comparison of these results

From the results it is clear that the amount of fluid m left on the wall, calculated using SEPRAN, is more in accordance with experimental observations than those calculated using VIP. That in the program VIP, for the filling of the channel, use is made of a volume flux boundary condition at the entry of the channel, instead of a prescribed pressure, could have a small influence on the results, but it could never totally be responsible for the big deviation between the results using VIP and SEPRAN. A cause for the big deviation could be that in the VIP-simulation, the thickness of the channel is 38% of the width and 9.5% of the length of it. Consequently, one can hardly maintain that this is a thin product and the pressure is constant in the thickness-direction, as assumed in the program VIP, which does make use of the 2.5D approach. Another possibility could be, that the model used does not describe the dynamics of the gas front in a proper way. The last cause could be due to discretization errors, caused by the mesh of the grid points in the thickness-direction.

§ 3.7 conclusions

It is clear, that the successful part of the model is that the width of the gas channel penetrating the polymer does decrease until a certain value and continues to be constant at this value. In contrary with this, the amount of fluid left on the wall, when the gas front has passed, is much too large and consequently the model is unsuccessful in this.
Chapter 4  Penetration of a gas in a polymer melt according to Saffman and
Taylor

§ 4.1 introduction

While in chapter 2 the literature on gas penetration has been discussed, in this chapter the
experiments of Saffman and Taylor are looked at (§ 4.2). After closely looking at the
influence of the mesh and the phenomena at the entry of the mesh on the simulation results,
an attempt is made to simulate these experiments (§ 4.3). At the end, the results will be
shown and conclusions will be drawn.

§ 4.2 experiments of Saffman and Taylor

The penetration of a fluid into a Hele-Shaw cell containing a more viscous fluid is studied
by Saffman and Taylor [1], who did their experiments with the use of a rectangular cavity
with dimensions: \( b \times l \times h = 0.0254 \times 0.91 \times 0.0008 \) m. These experiments differ from those
discussed in chapter 3, since Saffman and Taylor studied gas penetration in the length-width
plane, while in chapter 3 the length-height plane is considered (figure 13).

![Diagram](image)

\textit{Saffman and Taylor}

A combination of oil and water was used for the filling and the viscosity ratio of the fluids is
450. They concluded that, as the speed of penetration increases, \( m \) rapidly increases towards
0.5 [-] and remains close to this value over a large range of speeds.
§ 4.3 simulation of the Saffman and Taylor experiments

§ 4.3.1 influence of the number of elements

In order to test the influence of the number of elements in the width-direction of the mesh, a simulation has been executed in which the number of elements in the width-direction is four, focusing on the width of the gas channel. However, in VIp it is not possible to look at the difference in viscosity in the midplane of the entire mesh. Another possibility to look at the width of the gas channel is to show the volume fluxes in this midplane, because in the gas the volume fluxes and velocities are much higher than in the polymer (figure 5). For \( t = 1.826 \) s, the volume fluxes in the midplane are shown (figure 14).

\[
\text{Volume flux} \quad \text{time} = 1.826E+00 \ [s]
\]

Fig.14 test simulation in behalf of the influence of the number of elements in the width-direction

It is clear that the interface in the length-direction is parallel to the element division. This could be a coincidence, because according to the experiments, \( m \) has to be approximately 0.50 \([-\]\), but the result could also find its origin in the number of elements in the width-direction equal to four. In order to check this, a simulation has been executed, in which a different mesh is used (figure 15).

\[
\text{Volume flux} \quad \text{time} = 2.286E+00 \ [s]
\]

Fig.15 test simulation in behalf of the influence of the number of elements in the width-direction with nonsquare elements
From this figure it is concluded, that the interface is parallel to the element division and it is necessary to use a number of elements in the width-direction, such that there are no element boundaries at 0.25 and 0.75*width.

§ 4.3.2 phenomena at the gas-entry

If gas-assisted injection moulding of a rectangular configuration is simulated, the problem arises, that there is a slip condition at the boundary of the mesh. Consequently, if the cavity is partly filled and the switch to gas injection is made, the polymer is shoved forward by the gas and no channel shall arise. This can be solved by using an injection area, which is not as wide as the width of the cavity, or by modelling a runner. The second option is chosen, because a disadvantage of the first is that the width of the gas channel is possibly influenced by the width of the injection area. The result is shown in figure 16.

\[
\begin{align*}
\text{Volume flux} & \quad \text{time} = 1.586E+00 \quad [s] \\
\text{LEVELS} & \\
1 & 1.199E-09 \\
2 & 4.879E-02 \\
3 & 9.758E-02 \\
4 & 1.464E-01 \\
5 & 1.952E-01 \\
6 & 2.439E-01 \\
7 & 2.927E-01 \\
8 & 3.415E-01 \\
9 & 3.903E-01 \\
10 & 4.391E-01 \\
11 & 4.879E-01
\end{align*}
\]

Fig.16 test simulation in behalf of the phenomena at the gas-entry

From this it is clear that a simulation with six elements in the width-direction and a runner at the entry gives satisfying results and that m is between 0.50 [-] and 0.67 [-].

§ 4.3.3 final simulation-configuration

In this paragraph, a summary is given of the final simulation configuration.

- The dimensions of the rectangular configuration are length x width x thickness $= 0.3000 \times 0.0254 \times 0.0008$ m.
- The viscosity of the oil Saffman and Taylor used (Talpa) is 4.5 Poise. The viscosity of water is 1.0 Poise. Consequently the difference in viscosity [ Pa.s ] equals 450.
- The fluids are modelled like Newtonian fluids.
- The midplane of the rectangular configuration is modelled with the use of 60 x 6 elements.
- In thickness, 21 grid points are used.
- The filling time equals 6 seconds.
- The switch point from oil to water is at 3 seconds.
§ 4.4 numerical results

After the simulation has been executed, plots of the volume flux during filling are produced. In figure 17 these are shown for two stages of the filling process.

![Volume flux](image1)

**Fig. 17** volume fluxes in the midplane of the configuration

From this figure it is impossible to read the width of the gas channel.

§ 4.5 conclusions

The results of the simulation of this experiment are illegible so it is impossible to conclude, whether or not these results do agree with the experiments performed by Saffman and Taylor. However, the testing result with the runner and six elements in the width-direction, shown in figure 16, does show interesting results like \( m \), which varies between 0.50 [-] and 0.67 [-]. This result approximates the value of \( m = 0.50 [-] \) Saffman and Taylor found, so probably the results of this simulation are approximating those of the experiments, but to know this for sure the results of the simulation have to be made legible.
Chapter 5  Conclusions and recommendations

The implementation of a new model of the gas front is partly successful: the width of the gas channel penetrating in the polymer melt does decrease until a certain value and continues to be constant at this value. In contrary with this, the amount of fluid left on the wall, when the gas front has passed, is much too large and consequently the model is unsuccessful in this.

As a continuation on this report some recommendations for future research can be given:

- In the program V1p, the grid points are moved until the interface between the solidified polymer and the polymer melt, is modelled by the grid plane (figure 18), in which the main parameter is the glass temperature. This can also be done for the interface between the polymer melt and the injected gas. A parameter in this could be the time labels.

- The simulation of gas-assisted injection moulding, now is implemented in the program V1p, which makes use of the 2.5D approach. Maybe it is better to develop a model of the gas front in 3D and then try to modify it, so it can be implemented in the program V1p.

- The results of the simulation of the experiments of Saffman and Taylor have to be made legible, so one could see, wether or not the results do agree with the experimental results. Maybe this can be done by modifying the program V1p, so the viscosity can be shown in the midplane of the configuration.

Fig.18  spatial discretization perpendicular to the midplane
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