# Application of 3D Flow SimulationTowards Blown Film Die Optimization

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**Abstract**

This paper demonstrates how a 3D Finite Element Method (FEM) flow simulation can be applied towards the analysis and optimization of a spiral mandrel type die for the production of blown (tubular) film. The paper also shows how a 3D FEM flow analysis can identify a die design flaw that would otherwise be difficult to solve.

**Introduction**

The potential advantages and benefits of the spiral mandrel distribution system have basically made it the standard design for dies used to produce blown or tubular film. Figure 1 is an image of a spiral mandrel die with the body and upper die lip cut away to show the spiral ma ndrel and inner die lip. The polymer melt normally enters the die from the bottom center and is distributed to the spirals via channels commonly referred to as ***ports***. The spiral channels are simply helical grooves cut into the mandrel that direct the polymer around the circumference of the die. A small gap is formed between the internal diameter of the body and the external diameter of the mandrel that allows the polymer to leak out of the spirals. The spiral channel depth normally reduces along the channel length forcing more and more polymer out into the annular gap and ultimately producing an annular flow in the axial direction. After the spiral distribution section, the material generally flows through a ***relaxation chamber*** and then through the ***die lips*** and exits the die.

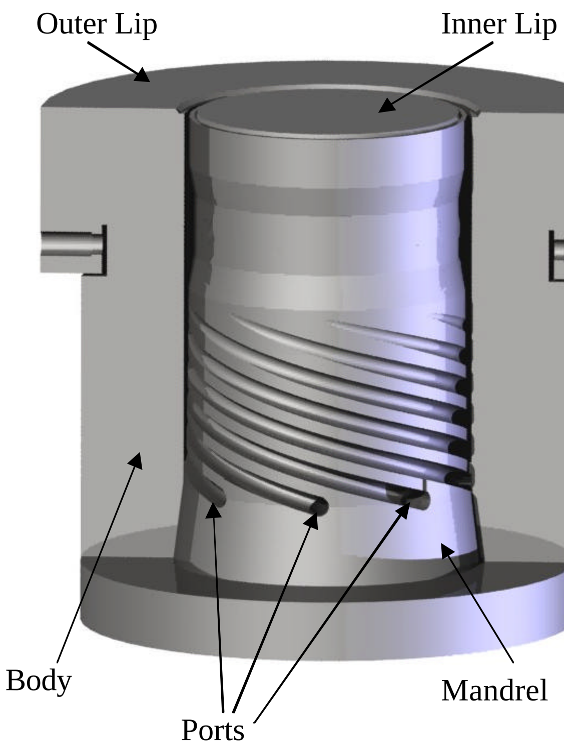


**Figure 1 A cut away view of a spiral mandrel die**

The main advantage of a spiral mandrel type die lies in the way it distributes the polymer. The gradual leakage of the polymer out of the spiral channel as it traverses around the circumference results in a layering effect. This layering of the material from the different ports provides some additional mixing or homogenization of the polymer giving more uniformity to the product. This helps smooth variations in color due to poor mixing and reduces variations caused by large temperature gradients in the polymer melt coming from the extruder. Of course the degree of layering depends on the specific design of the spiral distribution system and how well the leakage out of the spiral channel is controlled.

Despite the popularity of this type of die, it can suffer from some particular and even peculiar problems that can be very difficult to diagnose. For example, if the geometry of the spiral distribution system is not designed properly in relation to the polymer flow rate and polymer properties, the die may not distribute the polymer adequately resulting in poor performance and ultimately poor product quality. This will be one of the items that this paper will focus on. In an extreme case, the design can result in a ***back flow*** that essential creates a stagnation point in the flow field. The problem is that this stagnation point cannot be seen and the only indication is a visual defect that appears as a line in the product. With prolonged running, the stagnation may start to create a build-up of degraded material but this may be overlooked during the cleaning of the die.

## Flow Simulation

There has been a significant amount of work performed on developing computer simulations of this relatively complex flow field in an attempt to help spiral mandrel die designers avoid poor designs [1-6]. A detailed review and evaluation of several models was published in a dissertation by the Perdikoulias [7] and this work ultimate led to the development of several commercial simulation packages. The one thing that all these models had in common is that they used a "control volume" approach with many simplifying assumptions in order to achieve practical computational times with the computer hardware limits that were available at the time.

The first fully 3D Finite Element Method flow analysis of a spiral mandrel die is believed to have been performed in 1991 [8]. However, at that time, it was determined that the computing costs and time required made this type of analysis impractical for daily design work. Rather, the results of the 3D FEM simulation were used to validate and improve the control volume models so that they could be used with more confidence.

Over the past few years, the advances in computing power have made 3D FEM flow analysis a very viable and practical tool for analyzing and designing spiral mandrel dies and helping to better understand the complex flow phenomena that can occur in these types of flow fields. The simulations in this presentation were performed with the Compuplast®, Virtual Extrusion Laboratory™ 3D FEM module and Spiral Die Template that was developed to aid in the generation of efficient grids for the simulation.

## Flow Distribution Analysis

While 3D FEM flow analysis is a very power tool that gives precise and accurate details about the flow field, it is not always easy to make some conclusions about the results or the performance of the die. The following example will demonstrate this and suggest a method of analyzing and comparing the performance of spiral mandrel dies.

Figure 2 show some results of a 3D FEM flow analysis on a spiral mandrel distribution system. Due to the periodic nature of the distribution system, the calculation time is reduced by simulating only one section between ports. This assumes that all of the spiral channels are identical which is how these types of dies are normally manufactured.

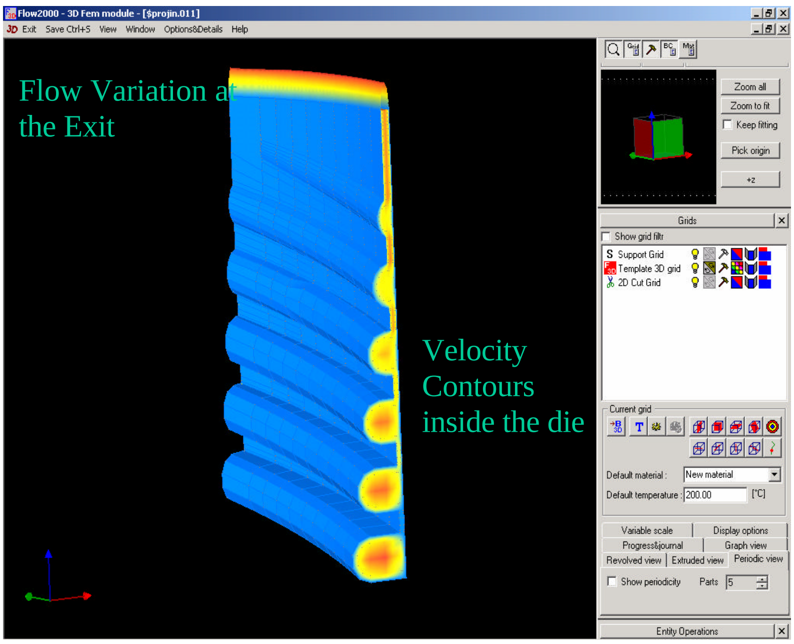


**Figure 2 Velocity contours in a spiral mandrel flow field**

The results shown in Figure 2 are the velocity contours on the visible surfaces of the flow field and the velocity profile at the exit. The red color indicates high velocity while the blue color indicates low velocity. Since the velocity at the wall is assumed to be zero, the surfaces that represent the walls of the flow channel have a blue color. The results also indicate that the velocity has a maximum value in the channel and in the center of the flow field at the exit of the spiral mandrel distribution system.

However, when trying to compare the performance among different die designs, the color contour plots such as these generally do not provide sufficient details to make good conclusions. In order to better quantify the performance of the die, a more precise analysis is required.

For example, the distribution performance of the die can be quantified by plotting the variation in the velocity around the circumference. This means we need to select and plot the maximum velocity at several locations around the circumference of the annular channel. Another way to analyze the results would be to integrate the velocity profile at a series of angular positions across the gap at the exit of the die. The integration of the velocity profile is a local volumetric flow rate per unit area which can be plotted against angular position to show the flow variation.

Figure 3 compares the Flow Distribution (variation) in 2 spiral mandrel dies designed to extrude the same product. The design details are proprietary but they are not required for the purposes of this paper. It is sufficient to say that Die 2 was developed to be an improvement over Die 1 in terms of lower system pressure (larger channels) with equally good distribution performance. However, it was found that Die 1 performed better than Die 2. The results of the flow distribution comparison in Figure 3 indicate that Die 1 does provide a marginally better flow distribution than Die 2 but it was not believed that this difference was significant or sufficient to explain the difference in performance that was observed. For this reason, an additional analysis technique was developed.

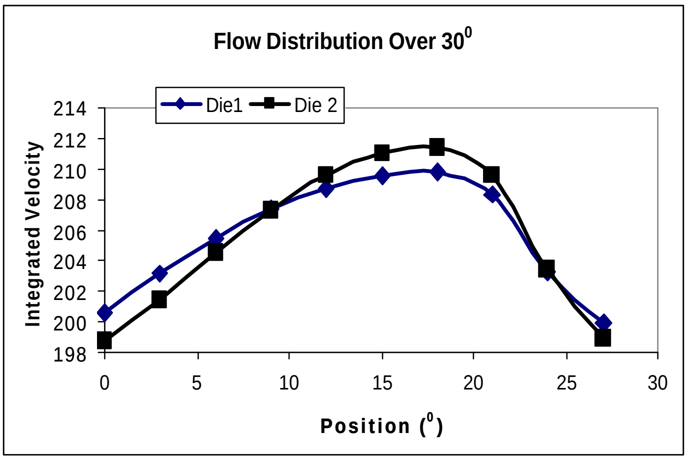


**Figure 3 Calculated flow variation in Dies 1 and 2:**

**Die1: +2.03% to –2.76%; Die2: +2.84% to –3.35%**

**Pathline Analysis**

One of the advantages of doing a fully 3D FEM flow analysis is that the velocity field can be calculated in sufficient detail to allow for the determination of the ***pathlines*** in the flow filed. The ***pathlines*** can be used to demonstrate how a particle placed at a certain position will travel through the flow field. Furthermore, particle paths can be calculated in both the forward (to see where are particle will go) and backward (to see where a particle came from) directions. Figure 4 shows some particle paths within the same flow field shown in Figure 2. In this case, the front wall has been made transparent so that the particle paths, which are defined by the blue points at the start of the spiral, can be observed.

Figure 4 shows how some particles travel out the far end of the channel but due to the periodic nature of the flow field a corresponding particle from the prior spiral will enter the flow field on inlet side making the path continuous. In this fashion, one can see how some particles will leave the spiral channel early while other particles travel further

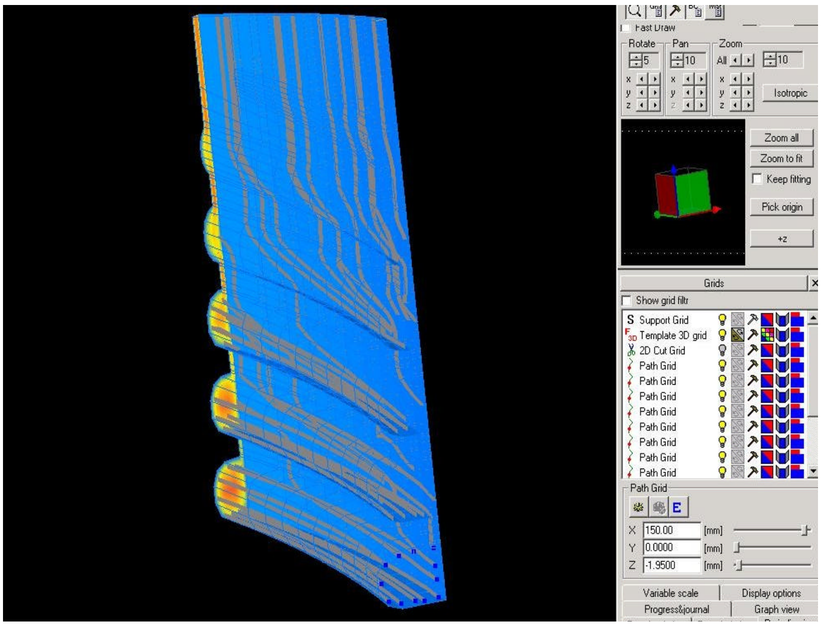


**Figure 4 Particle paths within the flow field**

down the channel before they exit and flow upwards. It can also be seen how the particles that exit their spiral channel are given a circumferential flow component as they flow over the subsequent spiral channels. Particle path analysis is a powerful technique that can help provide a very detailed understanding of the flow field and can be used as to quantify the performance of the die.

Figure 5 shows the placement of 12 "seed" particles at the inlet of the spiral channel. The particles have been placed around the circumference of the inlet at a small distance from the wall. Then, careful tracking of these particles to the die exit and connecting the exit points in the same sequence as the particles are defined would indicate how the material from any spiral channel inlet would be distributed at the exit. While this technique may not describe the distribution of all of the material from the inlet, it is believed that if the position from the wall is constant it can provide a good relative comparison between dies. This analysis technique was used to investigate the difference between Die 1 and Die 2.

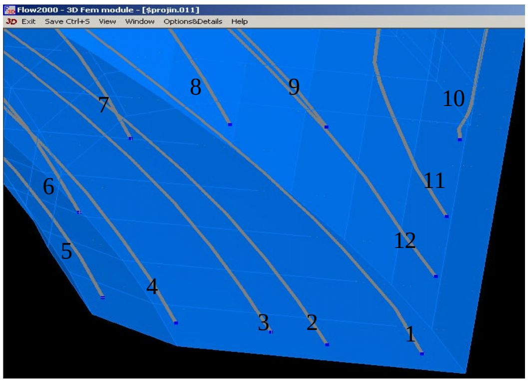


**Figure 5 Pathline seed positions at inlet**

Figures 6 and 7 both show the angle over which the majority of the material for each spiral was distributed in Die 1 and Die 2, respectively. It can be seen that Die 1 distributes the material over a larger circumference of the exit than Die 2; (83° versus 66°). What this means is that spiral distribution system design in Die 1 would have a better ability to smooth out any non-uniformity in the melt stream including any thermal variations.

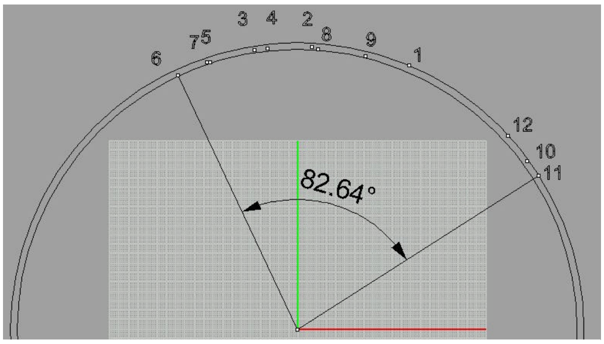


**Figure 6 Pathline positions at exit of Die 1**

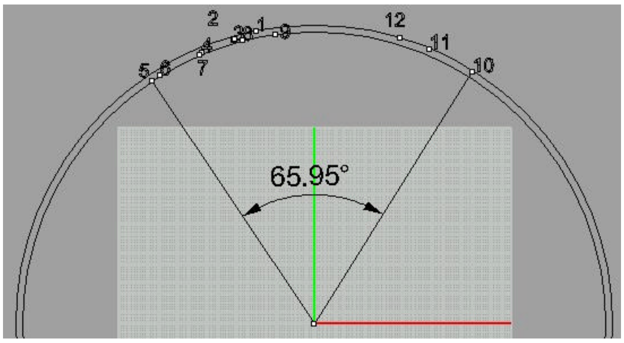


**Figure 7 Pathline positions at exit of Die 2**

The pathline analysis technique presented above was used to evaluate a new spiral mandrel die design that was developed to operate at a higher production rate and yet lower system pressure while still giving good quality film.

Figures 8 shows the angle over which the material from the inlet of the new die (Die 3) was distributed over the circumference at the exit. Comparison of Dies 1, 2 and 3 indicates that Die 3 would distribute the material from any spiral over the largest circumference. This would give the best homogenizing performance of the 3 die designs.

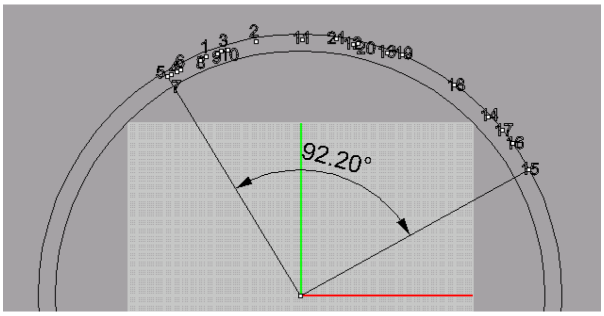


**Figure 8 Pathline positions at exit of Die 3**

Figure 9 compares the predicted Flow Distribution at the exit of Dies 1 2 and 3. It can be seen that the predicted variation for all the dies is comparable with Die 2 and Die 3 being almost identical. Under production trials it was found that Die 3 did indeed produce film of better quality than Die 2, and at least as similar quality, to Die 1. this would imply that the improvement is due to the ability of Die 3 to spread the material over a lager part of the circumference.

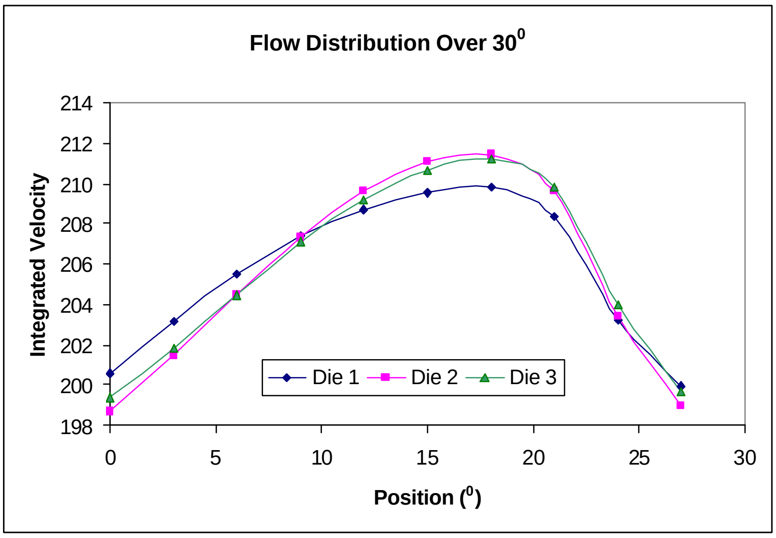


**Figure 9 Calculated flow variation in Dies 1, 2 and 3:**

**Die 1: +2.03% /–2.76%, Die 2: +2.84%/ –3.35% ,Die 3: +2.67% /-3.08%**

### Backflow Phenomenon

The pathline analysis was also used to identify a problem in another spiral mandrel die that resulted in a visual defect in the film. The defect was observed as a set of pronounced machine direction lines that equaled in number to the number of spirals in the die. This indicated that the problem was related to the spirals but it was not known as to what characteristic of the spirals resulted in the defect. A 3D FEM flow analysis was performed on the die in an effort to determine the reason for the problem.

Figure 10 show the pressure contours in the spiral mandrel system and the velocity at the exit (top) of the spiral distribution system. From these results one can conclude that no part of the spiral channel is consuming any excessive pressure drop and that the material distribution, judging from the uniformity of the velocity profile at the exit appears to be acceptable. However, these two criteria alone do not guarantee that the die will have acceptable performance since the product from this die did exhibit the line defects described above.

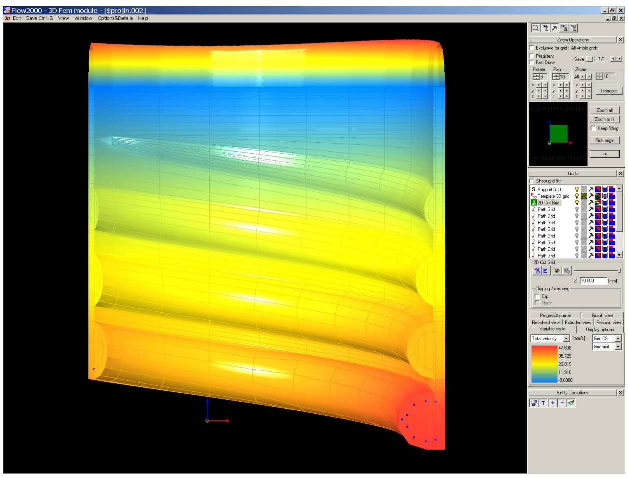

**Figure 10 Pressure Contour and Exit Velocity of a Spiral Section from a 3D FEM analysis**

Figure 11 shows some particle paths that were calculated from the 3D FEM flow simulation. The figure shows the path the particles would take from various points near the inner surface at the entrance of the spiral channel. In this case, 2 of the 3 periodic sections of the die are shown to better demonstrate the pathlines. The interesting result is that several of the pathlines suggest that some material leaks out of the spiral channel almost immediately and then travels back in the opposite direction of the preceding channel for a short distance before it leaks out and begins to flow in the axial direction of the die. This results in kind of weld line and a stagnation region where the pathlines from the two channels meet. In a properly designed die, all of the pathlines should travel in the same direction as the spiral channel for some distance and then axially as the material leaves the channel and approaches the exit of the spiral distribution system as shown in figure 4. They should never travel in the opposite direction. This "backflow phenomenon" occurs when too much material leaks out of the channel prior to the first overlap which is a result of a poorly designed spiral distribution system. While this may be intuitively obvious for a design, it is something that cannot be easily observed on the equipment and clearly demonstrates the advantage that flow simulation offers to the design of complex flow fields such as those that occur in spiral mandrel dies.

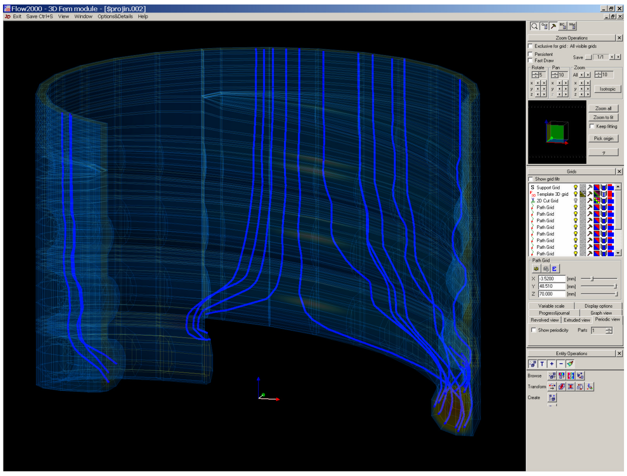

**Figure 11 Particle Paths from 3D FEM analysis**

**Concluding Remarks**

The ongoing advances in computer development and relatively lower cost of computational power have made fully 3D FEM flow analysis a viable tool for simulating the performance of complex flow fields such as those found in spiral mandrel dies. Once the flow field can be accurately simulated, then design criteria can be developed to help evaluate and compare die designs in an effort to optimize the performance. A technique was presented for analyzing the homogenizing ability of a spiral mandrel die through the use of pathline analysis. This analysis was used to evaluate and compare the performance of 3 dies and the results had good qualitative agreement with the observations that were made on the actual equipment. It was also demonstrated how the pathline analysis helped to explain the appearance of a visual defect on a film product. It was shown that the defect resulted from the material leaking early out of the spiral channel and flowing "backward" down the preceding spiral channel resulting in a weld line and stagnation point.

**References**


1. Proctor, B., "Flow analysis in extrusion dies", SPE Journal, 28, 34-41 (1972)
2. Wortburg, J and Schmitz, K.P., Design and optimization of a spiral mandrel die" Kunstoffe, 72, 198-205 (1982)
3. Vlcek, J., Kral, V and Kouba, K., "The calculation of the form of a spiral mandrel", Plast. Rubber Proc. App., 4, 309-315 (1984)
4. Vergnes, B. and Agassant, J.F., "Die flow computations: A method to solve industrial problems in polymer processing" Advances in Polymer Processing, 6, 441-445 (1986)
5. Rauwendaal, C., "Flow distribution is spiral mandrel dies", SPE ANTEC, 917-923 (1986)
6. Vlcek, J., Perdikoulias, J. and Vlachopoulos, J., "Determination of output uniformity from spiral mandrel dies", Intern. Polym. Proc., 2, 174-181 (1988)
7. Perdikoulias, J., "Polymer flow through spiral mandrel dies: Analysis and Design", Master's Thesis, McMaster University, Hamilton, ON Canada (1988)
8. Coyle, D.J. and Perdikoulias, J. "Flow Simulation and visualization in spiral mandrel dies", SPE ANTEC, 2445-2447, (1991)
9. Virtual Extrusion Laboratory™, Ver. 6.0, Compuplast International Inc, USA, Canada, Czech Republic

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# Application of 3D FEM Flow Simulation Towards Blown Film Die Optimization

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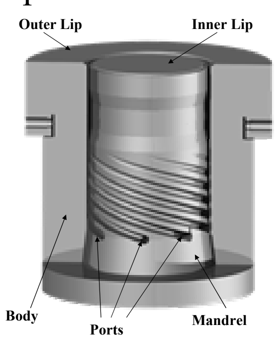
Presented by:
**John Perdikoulias**
Title
**Vice President**

## The Objective

- To determine the reason for an observed difference in performance between two existing dies (Die 1 appears to perform better than Die 2)
- To evaluate a new die design (Die 3) to ensure that the performance is better than both the previous dies.

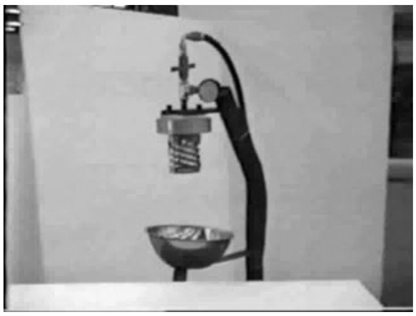
Simulations Performed with the Compuplast Extrusion Simulation Software

## Spiral Mandrel Die

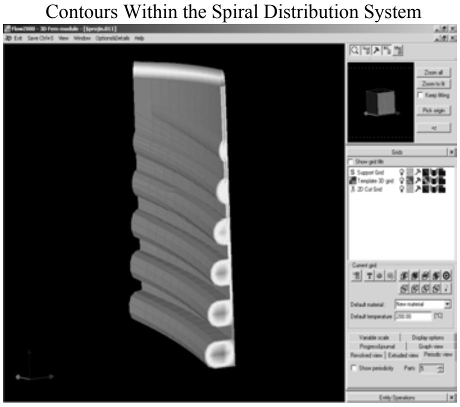



**A cut away view of a spiral mandrel die**

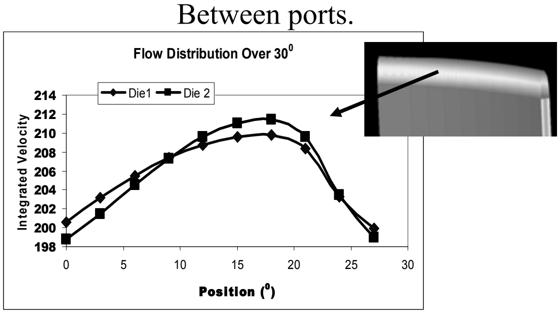
# Spiral Flow Visualization



3D FEM Results Showing A Typical Velocity Contours Within the Spiral Distribution System



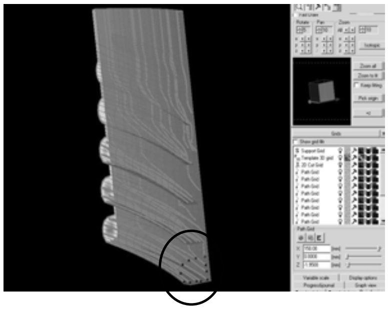
Comparison of Flow Distribution Between ports.




Flow Variation of Die1: +2.03% to –2.76%
Flow Variation of Die2: +2.84% to –3.35%

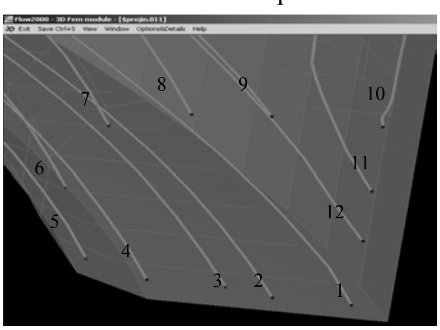
# Particle Path Analysis: Die 1

A number of particles were inserted at one of the spiral channel inlet to define a enclosed area. The objective was to observe how the polymer from that area was distributed at the outlet.



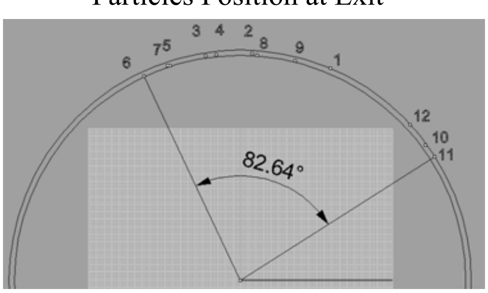
# Die 1

## Particle Position at Spiral Start

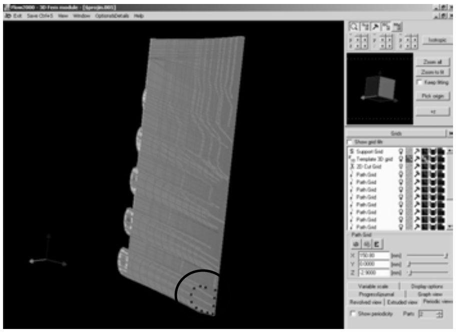



# Die 1

## Particles Position at Exit

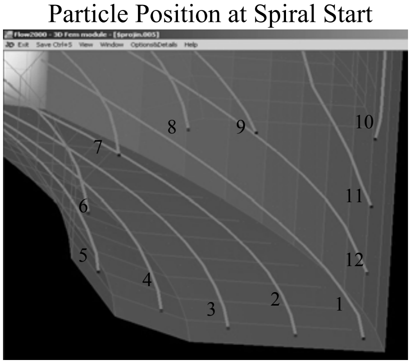


## Particle Path Analysis: Die 2



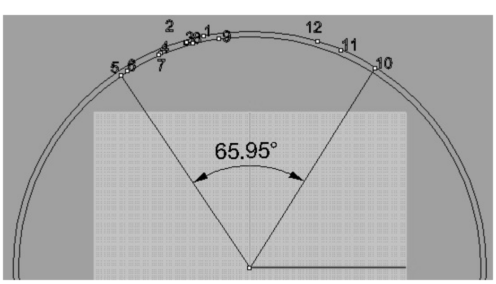
## Die 2

Particle Position at Spiral Start

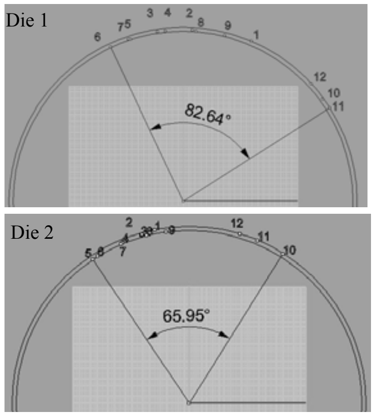



## Die 2

Particles Position at Exit



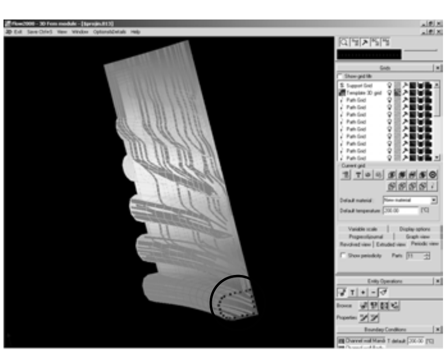
Die 1 appears to distribute the polymer from each inlet over a larger circumference of the die exit. This provides better mixing of any thermal variation that enters the spiral channel at the inlet.




## Remarks

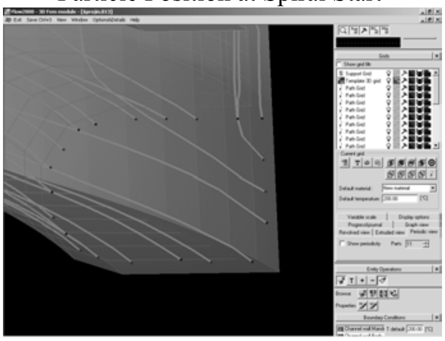
- The simulation predicts what is believed to be an insignificant difference in flow variation at the exit of each die.
- Also the simulation indicates that Die 1 distributed the polymer from each spiral inlet over a wider circumference of the die exit.
- This also gives a better homogenizing effect to smooth out any thermal variation that may enter the spiral channel at the inlet.
- This result can explain why Die 1 appears to perform better than Die 2.

## Die 3 (New Design)



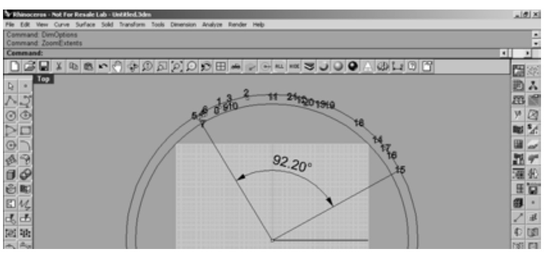
## Die 3

Particle Position at Spiral Start



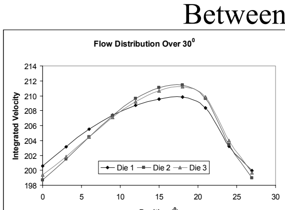
## Die 3

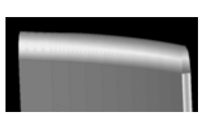
Particles Position at Exit




The spreading effect of the proposed Die3 is higher than the two dies previously mentioned.

## Comparison of Flow Distribution Between ports.



Flow Variation of Die 1: +2.03% to –2.76%
Flow Variation of Die 2: +2.84% to –3.35%
Flow Variation of Die 3: +2.67% to -3.08%

The flow variation of Die 3 is slightly higher than Die1 and lower than Die 2 but this difference is believed to be insignificant.

## Additional Remarks

- Die 3 is predicted to have similar flow variation but better spreading performance than both previous dies.
- The particle path analysis is another good criteria that can be used to determine how the material from each spiral distributes over the circumference of the die.
- If done with sufficient accuracy, the particle path analysis can be used to determine the layering of the material form each spiral more precisely.

## The "Back-Flow" Problem in Spiral Mandel Dies

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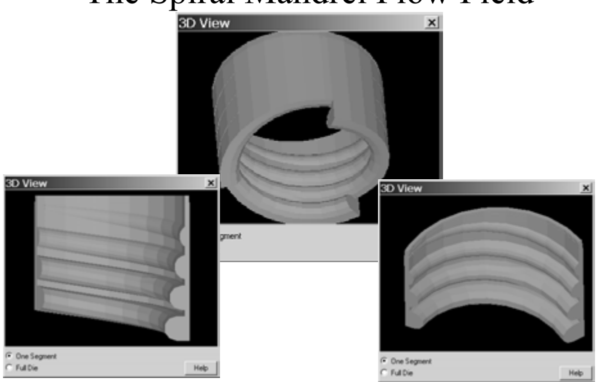
## Potential Problem

- With some Spiral Mandrel type dies, a flow defect is sometimes observed that appears like a weld line in the product.
- It may also be observed in the product as a very localized thin section that repeats around the circumference of the die as many times as there are spirals.

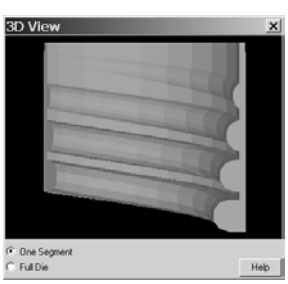
## Why Does It Happen And How Can It Be Avoided?

- The important criteria for the analysis of the problem is to evaluate how the material leaks out of the spiral channel.
- An example will be used to demonstrate the phenomenon

## The Spiral Mandrel Flow Field




## The Spiral Flow Field Geometry

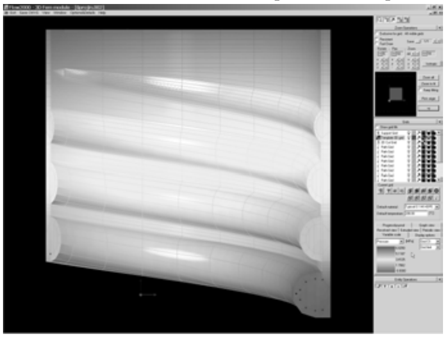



- 100 mm Diameter
- 3 Spirals
- 4 overlaps
- 60 mm Run Out
- 12 mm Channel
- 10 mm Initial Depth
- 2.5 mm Gap

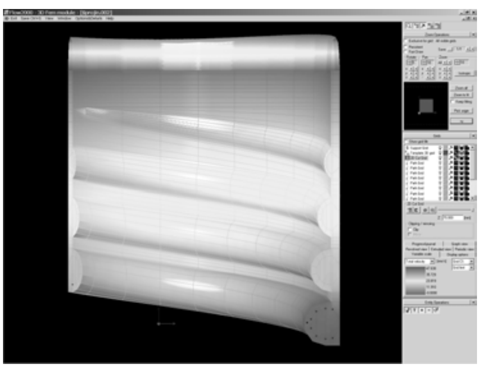
HDPE, 75 Kg/Hr at $210^{o}C$

# 3D FEM - Pressure Drop

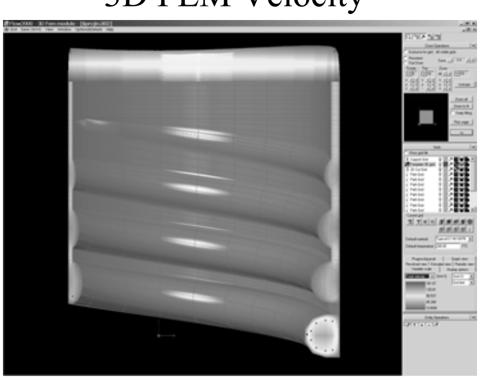
**FLOW 2000™** 3D FEM Die & Spiral Die Template



# 3D FEM - Exit Velocity

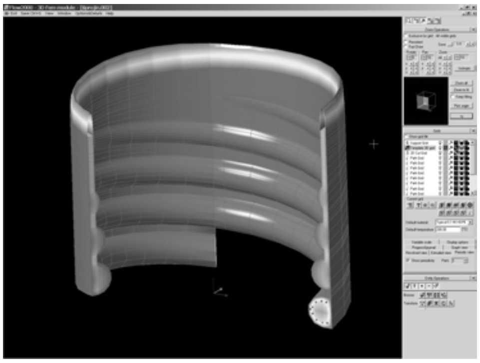


# 3D FEM Velocity

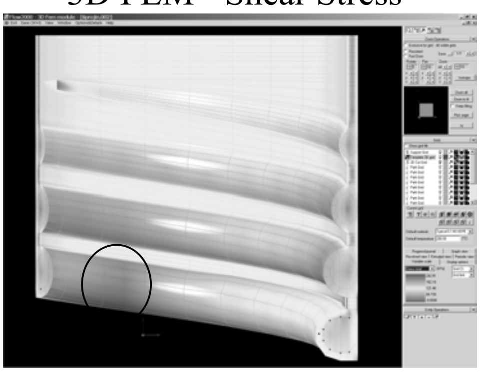


# 3D FEM Velocity

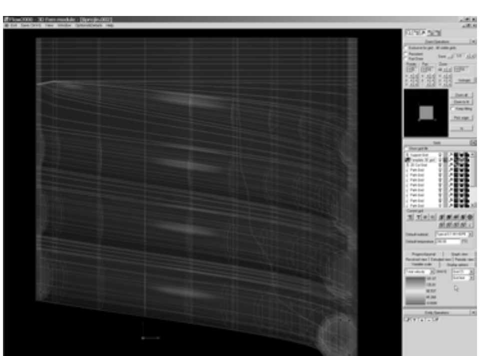
(2 of 3 sections)



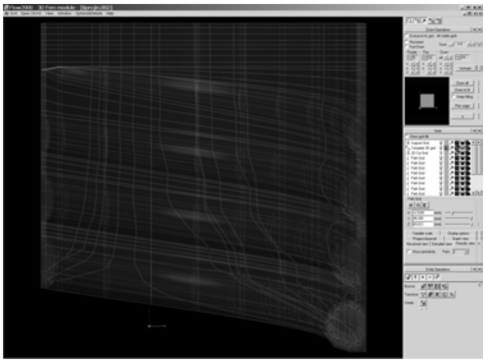
# 3D FEM - Shear Stress



# 3D FEM - Particle Path

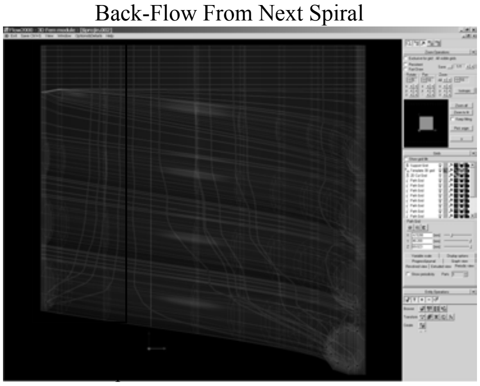


# 3D FEM - Particle Paths



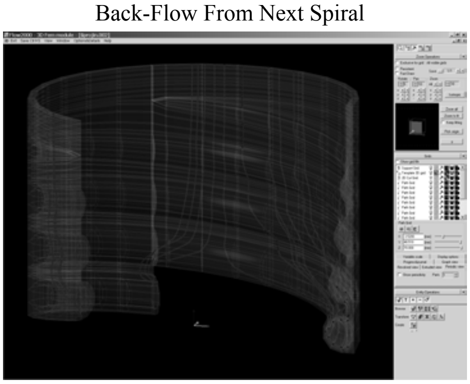
# 3D FEM - Particle Paths

Back-Flow From Next Spiral



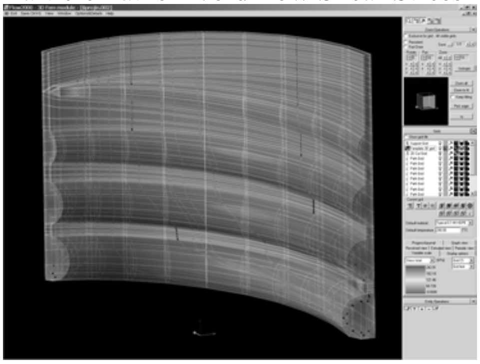
# 3D FEM - Particle Paths

Back-Flow From Next Spiral

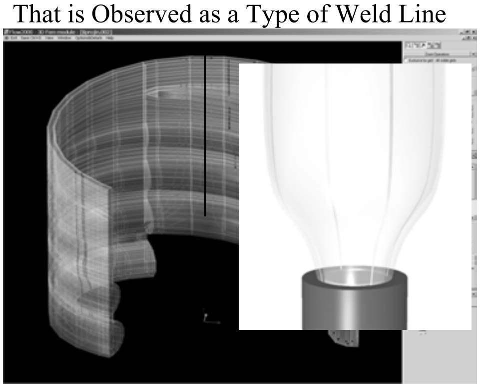


## 3D FEM Analysis

Particle Paths Avoid Low Shear Stress



The Back-Flow Essentially Forms a Defect That is Observed as a Type of Weld Line



## Concluding Remarks

- Even though the die design, pressure drop and final flow distribution appear to be acceptable, this **does not** mean that the die will perform well.
- 3D FEM analysis with particle tracking can help to explain and visualize complex flow phenomenon

# Thank You

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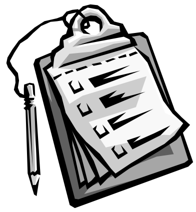

***Please remember to turn in your evaluation sheet...***