COATING DIE FLOW CHANNEL DESIGN FOR OPTIMIZED DISTRIBUTION

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Abstract

An improved design for the flow passage of slot or extrusion coating dies has been developed. The design creates a flow passage that has a uniform shear rate inside the die. A die with this type of flow passage will spread any and all materials uniformly regardless of the shape of the viscosity curve and also results in a uniform residence time inside the die which allows for reduced changeover time and material waste.

Introduction

Many technologies have been developed to assist in the process of applying coatings to webs of materials. One of the most common techniques involves the use of a die. By definition a die is a shaping tool. In coating a web a die is used to spread a stream of material and shape it into a uniform thickness over a desired width. Dies can be used to shape any material that can be made to flow. These include liquids, emulsions, hot melts, and polymers. Beyond coating, dies are also used to create webs of materials. Various names have become associated with a variety of dies typically tied to the material that is processed through the die. For fluids they are commonly called slot coating dies, or just slot dies. Dies that are used to shape molten polymers are typically called extrusion coating dies as an extruder is used to melt and pump the material to the die. If the die is used to make a film or sheet it is typically called an extrusion die. Other dies are called hot melt dies.

Figure 1. Coating Die with "T" style manifold

Conventional Technology

No matter the name or specific purpose all these types of dies have the common goal to take a stream of material and spread it out evenly over a desired width on a continuous basis. A die is most useful in forming materials that are difficult to flow and shape with simpler techniques. The die performs this task by directing the material through a specially designed flow passage that forces the material to flow in the desired fashion. The flow passage through a typical die is composed of several sections normally called the entrance, manifold, and land. In addition to those sections some dies may also include a preland and secondary manifold section. The shape of each of these particular sections is developed and installed in such a way as to spread the material evenly across the exit width of the die.

The entrance section is the connection point to the upstream device that supplies the material to the die. It directs the material to the manifold. The manifold is the primary channel for forcing the material toward the outside ends of the die. The manifold can have various shapes but is most often round, tear-drop, or a variation of the two shapes. It can be designed to direct the flow parallel to the die exit slot or be angled toward the exit slot. The former is typically called a "T" style manifold while the latter is

Figure 2. Extrusion Die - Coathanger style manifold

often called a Coat hanger manifold as shown in Figures 1 and 2. The principal purpose of the manifold is to spread the material outward. The preland is a region immediately downstream of the manifold. It consists of a tighter gap section of the die which is used in conjunction with the manifold to help direct the material outward from the center. The secondary manifold is a lower pressure region used to join the preland with the land. The land is the final section of the flow channel. Its purpose is to establish the material into the desired uniform thickness leaving the die.

Die design has evolved over the years to enable a die to be used to spread an extremely wide range of materials to most any width and thickness desired. A successful die design typically must take into account the flow properties of the material that is being processed. This is because materials do not all flow the same. An entire discipline has been developed to help understand the flow of materials and is called Rheology. The principle values used to design a die are the viscosity of the material and the rate of flow needed by the application.

Flow Properties

Viscosity is defined as the measure of a fluid's internal resistance to flow or also a measure of fluid friction. In scientific terms it is the ratio of Shear Stress divided by Shear Rate. The typical units of measure used are Poise, Centipoise, or Pascal-Seconds. The Shear Stress is a measure of the relative force that is applied to a quantity of fluid or material. The typical unit of measure is Dynes per square centimeter. The Shear Rate is the relative motion between adjacent layers of a moving liquid. It is calculated by taking the relative velocity of the material and dividing it by the length. It has the units Sec^{-1} or reciprocal seconds.

Fluids can be characterized as either Newtonian or Non-Newtonian depending upon how the viscosity is affected by changes in the shear rate applied to the fluid. Newtonian fluids are not affected by shear rate. The most common example is water. Non-Newtonian fluids are those that exhibit changing viscosity with changing shear rate. Most emulsions and molten polymers are greatly affected by the shear rate they are exposed to. Most commonly the viscosity decreases with increasing shear rates although a few isolated materials thicken under increasing shear. Most materials that must be processed through a die exhibit shear thinning behavior. It is important to note that there is also a wide variation in the specific ways that materials change in viscosity over ranges of shear and the magnitude of the viscosity itself also varies widely between materials and material blends. See Figure 3 for a log/log plot of the viscosity of nine different molten polymers over a range of shear rates as measured by a capillary rheometer. Understanding the science of material flow is very important in achieving a successful die design.

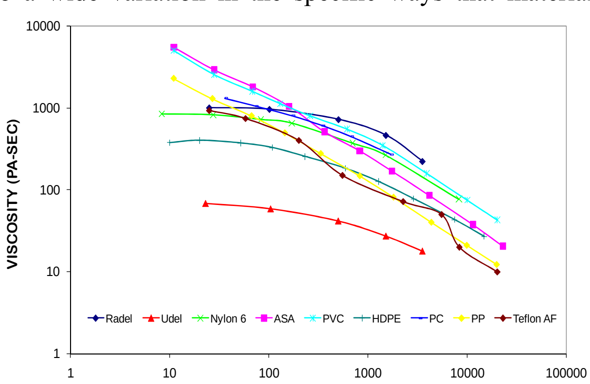

Figure 3. Viscosity versus Shear Rate - Polymers

Design of Die Flow Channels

The principle flow variables that must be considered in designing a die are:

- Rheology properties of the particular material
- Process Temperature
- Flow Rate
- Shear Rate
- Geometry of the flow channel

The first three variables are situational inputs. They define the target for design. The last two are design variables. The flow channel design determines the shear rate at a given flow rate making those variables interdependent on each other. For most dies of conventional design the shear rate inside the die varies from point to point. By knowing how a particular material flows over a range of shear rates it is possible to design a die to achieve a uniform exit velocity at the die lips for a particular situation. This is normally accomplished by shaping the manifold, preland, secondary manifold, and land in such a way as to balance the resistance to flow (also called the pressure drop) between the entrance to the manifold and the die exit slot. Many dies incorporate an adjustment feature in the final land gap area to be used to compensate for various unknown factors and changes in material flow properties over time. A consequence of most die designs is that material that exits from the die at the center is inside the die for a much shorter period of time than the material that exits from the regions at the ends of the die. This is because most die channel designs balance the resistance to flow and not the overall flow itself. Another consequence of conventional die designs is that a particular die can only be optimized for the flow of materials that have substantially the same or very similar flow characteristics.

Design for Constant Shear

In the early 1980s a die design analysis was undertaken at the University of Massachusetts to determine if it might be possible to create a flow channel design that is less dependent on actual flow characteristics of a particular material to be processed through the die. The research, conducted by Winter & Fritz, led to a successful die design methodology that achieved a universal flow channel design [1]. The design for the flow channel was based on two principle techniques. The first one is in a change in the manifold design from the more standard round or tear drop to a slit cross sectional shape. This is to match the flow that occurs in the preland and land areas. The second technique is to design the channel in such a way as to have a constant uniform shear rate in the entire manifold and preland sections of the die. By doing this the channel design becomes insensitive to the particular flow characteristics of a material. See Figure 4 for the die design equations that were developed by Winter & Fritz. Subsequent process studies verified that the design did indeed yield the desired results.

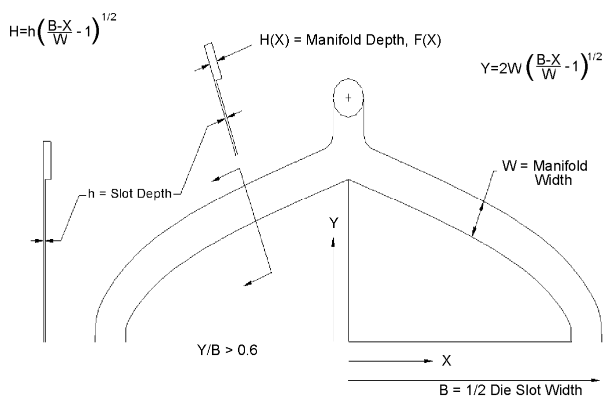

Figure 4. Constant Shear Manifold Design Equations

Although the design was successful in concept it was not adopted into widespread use. This is due to the relatively large wetted area that is a consequence of the design. It is comparable in size to other designs only at narrow widths typically less than about 18”. The front to back depth of the preland is a direct function of the exit slot width. Increasing the width causes the depth to increase in direct proportion. As the wetted area grows larger it becomes difficult and cost prohibitive to design a die that will resist the internal forces that occur and maintain the desired flow channel design.

New Version of Constant Shear Design

Recently a review of this earlier research was undertaken by Professor Mohamed Elgindi with the assistance of Professor Robert Langer of the University of Wisconsin–Eau Claire. Their goal was to determine if there was a technique for achieving distribution under constant shear while overcoming the depth penalty of the existing method. Using advanced mathematical techniques they succeeded in creating a new model. The new model has a manifold that expands in width as it extends toward the ends of the die while maintaining the condition of constant shear rate. This change reduces the front to back length of the preland as compared to the earlier design. This development allows for the design of dies of wider widths without the excessive increase in wetted area. See Table 1 and Figure 5 for a comparison of dies from 12” to 30” in width. The preland length is reduced from 35% to 38% depending upon the specific case. All designs have the manifold width divided by the manifold depth ≥10 which is desired for optimum results.

Table 1. Constant Shear Manifold Design Comparison

	CASE #1		CASE #2	
DESIGN INPUTS	OLD	NEW	OLD	NEW
DIE SLOT WIDTH	12	12	18	18
PRELAND GAP	0.075	0.075	0.075	0.075
MANIFOLD WIDTH - CENTER	1.5	1.5	1.75	1.75
MANIFOLD WIDTH - ENDS	1.5	3	1.75	3.5
DESIGN OUTPUTS				
PRELAND LENGTH	4.62	2.87	7.12	4.39
REDUCTION IN LENGTH - INCHES	1.75		2.73	
REDUCTION IN LENGTH - %	38%		38%	

	CASE #3		CASE #4	
DESIGN INPUTS	OLD	NEW	OLD	NEW
DIE SLOT WIDTH	24	24	30	30
PRELAND GAP	0.09	0.09	0.1	0.1
MANIFOLD WIDTH - CENTER	2.13	2.13	2.13	2.13
MANIFOLD WIDTH - ENDS	2.13	4.25	2.13	4.25
DESIGN OUTPUTS				
PRELAND LENGTH	9.17	5.85	11.18	7.27
REDUCTION IN LENGTH - INCHES	3.32		3.91	
REDUCTION IN LENGTH - %	36%		35%	

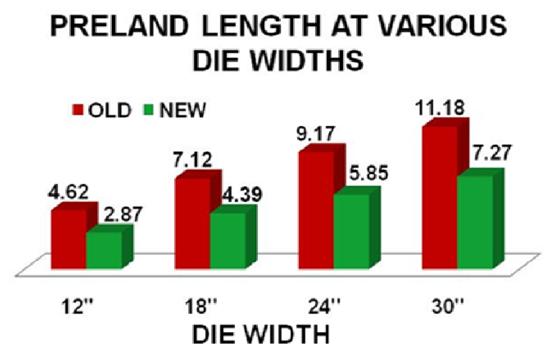

Figure 5. Comparison of Designs

Operational Results

A number of dies have been manufactured incorporating the design originally developed by Winter & Fritz. Most of those are narrow in width. Reports from users indicate they are extremely useful and able to be used on a wide variety of applications. Since development of the new version is very recent only a few dies have been manufactured but the results are very similar. The new technology is especially suited to applications that involve:

- Frequent color changes
- Time sensitive materials
- A wide variety of different materials to be processed

As an example a 19” wide version has been put into production for processing PVC compounds. In that application color changeover time of the new design is typically 75% less than the previously used coat hanger design. Another 24" wide version is able to process a wide variety of different materials successfully. Figure 6 shows a depiction of the flow profile inside a die with a constant shear manifold and how it compares to a die with a coat hanger manifold.

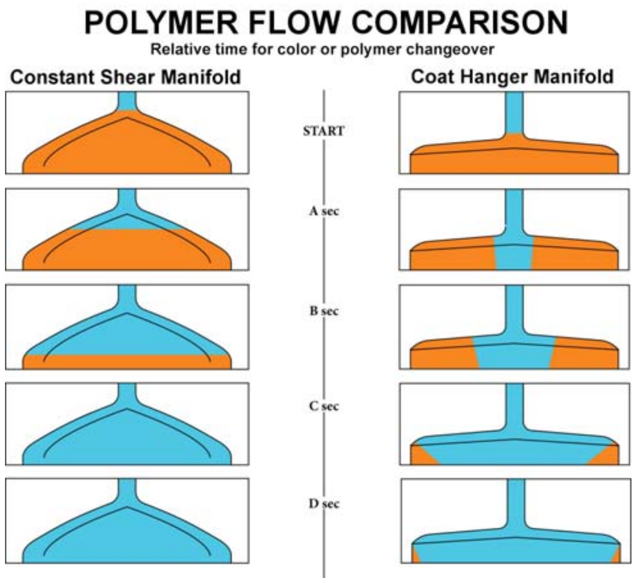

Figure 6. Color Change Time Comparison

Additional Benefits

Using a slit style manifold instead of a conventional round or tear drop style has another benefit. The design is much shallower and allows for a more compact design in multi-manifold applications as shown by the three layer die in Figure 7. The design has also been used in wider widths by placing multiple manifolds in parallel flow side by side using a flow splitting feed passage as shown in Figure 8.

Figure 7. Eight Inch Wide Triple Manifold Design

Figure 8. Parallel Flow for 40" Width

Conclusions

An improved design for the flow passage of slot or extrusion coating dies is possible by designing in such a way that the shear rate is constant inside the die. This feature yields many benefits as compared to conventional designs including reduced changeover time from product to product, the ability to balance the flow of virtually any material in the same die and a uniform material residence time inside the die. In addition, the die offers benefits in multi-manifold situations and can be used in much wider applications by installing multiple designs in parallel.

Acknowledgement

The author wishes to acknowledge the assistance of Professor Mohamed Elgindi and Professor Robert Langer of the University of Wisconsin – Eau Claire for their work in developing the new improved design.

References

1. H.H. Winter, H.G. Fritz, Polymer Engineering and Science, **26**, 8 (1986)