“Novel Extrusion Platforms for the Continuous Processing of Energetics”

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Abstract

The continuous processing of energetic materials requires extrusion machinery equipped with various types of safety features, thus are differentiated from machinery available to civilian industries. In this paper two novel extrusion platforms, first one involving a flexible manufacturing platform and the second designed to process nanoenergetics are described, to illustrate the procedures necessary to design extrusion platforms for energetics manufacture. Particular emphasis is given to the safety features of the new machinery, along with a detailed discussion of their flexibility and ease of use. The use of material-specific mathematical modeling in the design of the extrusion platforms is also elucidated as a first line of defense for safety and ease of use.

Continuous processing of energetics

While Ko-Kneaders and Rotofeeds have been successfully utilized for the continuous processing of energetic materials, largely, production of energetics in the United States has been confined to batch technology. Interest in continuous production has been increasing, but this interest has been limited to development over the past several years. As technology has improved in many areas, a renewed interest in continuous processing of energetic materials has gained momentum in the U.S. Some of the major advantages to be derived from continuous processing are: higher production capacities, while maintaining lower in process inventories; the economics of lower installation and operational costs; more uniform product quality, and lower personnel contact with hazardous materials. The twin screw processing system is capable of direct in line extrusion of a product into a final geometric form. This negates the requirement for additional separate stand alone ram extrusion systems for forming energetic products. Reducing the reliance on multiple pieces of hardware for additional process steps reduces the handling of the energetic material dramatically; thereby reducing the exposure of labor to large quantities of energetic materials and the overall risk of manual-handling related incidents.

Furthermore, continuous processing technologies are inherently safer than the batch processing methodologies because of the small amount of the energetic material found in the confines of the processor at any given time during the manufacture. This allows for processing of extremely viscous mixtures without the potential for overburdening the drive, which typifies batch mixing. The ability to easily mix and convey highly filled mixtures leads to the utility of this equipment for increasing solids loading in composite explosives and propellants.

Continuous processing technologies are also more amenable to the control of the properties of the propellant since the surface to volume ratio of the continuous processor is orders of magnitude higher than the typical batch processors used in conventional processing, thus making it easier to achieve relatively homogeneous temperatures and degree of distributive and dispersive mixing during manufacture. Furthermore, continuous processing technologies like the twin screw extrusion process have the added benefit of flexibility since the screw and barrel sections are generally modular and interchangeable, thus providing a myriad of geometries for processing of energetics, with each screw and barrel configuration representing a different processor.

However, the opportunities offered by the continuous processes like the twin screw extrusion process come at the price of necessitating extensive characterization and simulation tasks prior to the processing of the first pound of the propellant (1-30). Such characterization uses specialized techniques to characterize the rheological behavior, including the characterization of the viscoplasticity and the wall slip behavior of the energetic material, thermal properties, decomposition characteristics, the conditions under which the particles or the binder of the energetic suspension migrates or filters out, means to keep the air out, development of surface irregularities, analysis for the degree of mixedness of the ingredients as part of the characterization of the energetic formulation (1-30). This is especially necessary considering that unlike other industries, which also utilize continuous processors, trial-and-error procedures should not be used in the energetics industry. The wrong marriage of geometry, operating conditions and material properties will invariably result in an incident that is likely to generate significant losses.

Some of the preliminary characterization tasks which are necessary in the development of a continuous processing technology for the manufacture of energetic formulations include TGA and DSC analysis, the characterization of various material functions, including temperature and wall shear stress dependent shear viscosity, extrudate swell, flow instability and wall slip behavior of the energetic formulation, the simulation of the coupled flow and heat transfer occurring in the twin screw extruder, the design of the shaping geometry including the die, and validation experiments generally using thermal imaging and well-instrumented twin screw extruders. Such characterization and simulation tasks are essential to the safe processing of energetic materials, which can be accomplished without the use of precarious trial-and-error procedures.

Introduction to operation and Safety Features

Designing mixing equipment that answers the needs of today’s energetic material producers requires an in-depth understanding of the safety and performance problems facing this industry. Our long association with the industry has allowed us to design and produce mixer/extruders that recognize the safety concerns without compromising performance. Here two of these extruders will be used as examples for illustrating the integration of safety into design and manufacture of continuous processing machinery. These two extruders are interesting because the first one (ME7.5) is, to our knowledge, the smallest twin screw extruder in the world, designed specifically for the processing of nanoparticles and the second is the most flexible manufacturing platform for energetic materials processing with the ability to be converted into a single or twin screw, co-rotating or counter-rotating extruder. The intermesh between the two screws in the twin screw extruder mode can be altered to any degree of intermesh ranging from the tangential to the fully-intermeshing mode (Universal Mixer/Extruder) also. Furthermore, the barrel is splittable with a hydraulic mechanism and the sensor, feed, vacuum locations as well as the total length of the extruder can be altered to fit the processing task at hand.

Obviously, safety has been the prime consideration in the design of both the ME7.5 and the 40mmUniversal. Safety becomes even a greater concern with the necessity to process without organic solvents, using binders that are themselves energetic and with nanoparticles with their very high surface to volume ratios. The decomposition characteristics of some of the relatively new materials are also a cause for worry..

Development and Safety Issues

In general, the following summarizes how the extruders work and how the principal design of the geometries is made. Product ingredients enter the machine through various feed-ports. The product passes to the conveying screws, where it is carried from the drive end to the mixing section. A custom tailored agitator section (material specific and designed using mathematical modeling employing 3-D Finite Element Method) then alternates product mixing and thermal conditioning until the product is fully homogenized and reaches the desired temperature. The product then moves to the vent section for devolatilization. Next the mixture moves into the discharge section where pressure is developed to extrude the product through a die to develop a continuous geometric form.

These unique pieces of processing machinery, though based on twin screw polymer processing compounders, were specifically designed for use in the continuous manufacture of energetic materials. Therefore, they differ from polymer processing machinery commonly used in the marketplace today in a considerable number of ways. Aside from the ability to properly mix and extrude a variety of energetic materials, the prime consideration in design was, and is, safety. The energetics industry should not tolerate the use of trial-and-error procedures since as noted earlier any wrong marriage of the geometries, operating conditions and material properties will lead into an incident with possible significant loss of property. Thus, the ability to predict the coupled flow and heat transfer to occur in the extruder at the design stage introduces a significant advantage.

Mini twin screw extruder ME 7.5 for processing of nanoenergetics:

The ME7.5 (Figures 1, 2) was designed using mathematical modeling and was built initially for the distribution and coating of nanoparticles. The twin screws have a diameter of 7.5 mm (Figure 3), are co-rotating, fully intermeshing and self-wiping with an L/D of 15/1. Typical distributions of velocity, pressure, shear rate and temperature for the processing of an energetic thermoplastic-elastomer-based compound in the first mixing zone of the mini twin screw extruder (Figure 4) are shown in Figures 5-8, covering the distributions of shear rate, i.e., the second invariant of the rate of deformation tensor (Figure 5), the distributions of the second invariant of the stress tensor (Figures 6 and 7) and distributions of the component of the velocity vector in the main flow direction (z-direction) in Figure 8. The design thus relies right from the beginning on the knowledge of the detailed thermo-mechanical history that the target formulation is to be exposed during processing. The entire processing operating condition space can be probed to determine if there are precarious conditions under which the energetic formulation will develop stagnant “dead” zones, hot spots which will generate temperatures which are greater than the decomposition temperature of the energetic material, and pipe line flows which will give rise to the passage of the material through the extruder without intermixing with the rest of the ingredients.

The degree of fill in the extruder is also determined as a function of the possible operating conditions. This is especially crucial since for a given set of operating conditions the energetic material should not back-up into the feed hoppers or into the vacuum port. Thus, overall the mathematical modeling of the processing operation for a target formulation allows the design of the machine to be tailored and precarious geometries can be eliminated at the design stage. The ability of the extruder to process the given formulation is also fully assessed to recognize what the maximum and the minimum flow rates are to be and what the distributions of residence time, shear rate, pressure and temperature are to be in the twin screw extruder.

The ability to select the screw configuration on the basis of mathematical modeling of the process for a target formulation is again important, especially considering that most safety departments will not allow the utilization of segmented shafts and will insist on the use of solid screw agitators. Also for the 7.5 mm twin screw extruder shown in Figure 1 the screws are so small as to not permit the utilization of slip on elements and the entire screw needs to be machined in one piece (Figure 3). How would you design the screw configuration if you do not have the facilities to mathematically model the flow and heat transfer occurring in the extruder? Thus, the utilization of the simulation technologies allows the designing of the proper screw configuration right from the beginning, thus providing not only safety of knowing to what thermo-mechanical history that the energetic material is to be exposed but also savings in cost and schedules by eliminating the trial and error necessary otherwise for the screw design.

It is also important to recognize that the thermo-mechanical history that the energetic material will be exposed to in the extruder will also depend on the geometry of the die to be used. The flow and temperature history in the extruder is directly affected by the presence of the die since the extruder will generate enough pressure to overcome the pressure drop at the die. The pressurization rate and thus the degree of fill will be a function of the die used. Thus, the mathematical problem needs to be solved as a coupled flow and heat transfer problem covering both the extruder and the die. One of the die designs used for the mini is shown in Figure 9. This is a rectangular slit die designed to produce rectangular extrudates, which can then be used for the testing of the nanoenergetics grain. The FEM mesh for the die is shown in Figure 10 and typical results of pressure distribution and the z-velocity distribution over a cross section of the die are shown in Figures 11 and 12. Thus, the design of the die is an integral part of the design of the extruder for the processing of the energetics formulations.

40mm Universal Extrusion Platform (MU 40):

The Universal extrusion platform is a multi-flex platform which can be operated as a single screw extruder, fully intermeshing co-rotating twin screw extruder, fully intermeshing counter rotating twin screw extruder, tangential co-rotating twin screw extruder, or tangential counter rotating twin screw extruder (Figures 13 and 14). One of the configurations involves twin screws with a nominal diameter of 40mm and the length of the machine is variable in 5/1 L/D sections up to 40/1 L/D maximum. However, depending on the nature of the application the extruder can be custom designed for other sizes also. In Figures 15-30 the distributions of velocity, shear rate, pressure and temperature for a tangential counter-rotating twin screw extruder configuration for an energetic material are shown. The die used is again a slit die, which can generate rectangular extrudates. The ability to determine conditions which are precarious and their weeding out at the design stage is again emphasized by these results. These typical results pertaining to a mass flow rate of about 72 lb/hour of an energetic simulant composition suggest that the details of the thermo-mechanical can indeed be determined using simulation and conditions which are precarious can be recognized and the wrong marriages of geometry, operating conditions and the material to lead into safety concerns can be eliminated before the processing of the first pound of the energetic material.

The specific requirement for the power capability can also be determined using mathematical modeling of the process for the target formulation. Closely allied with specific horsepower requirement is residence time of mixture within the process zone, for while total power calculations rely on screw speed, torque and available motor power. Typically residence times 30 seconds to 20 minutes are observed, dramatically improving safety over batch mixing operations.

Dispersive mixing implies the breaking apart and scattering of agglomerated materials, whether they are binder molecules or solid particles. Distributive mixing implies the even apportioning of each phase and ingredient of the final product. In the twin screw mixer, studies have indicated that appropriate mixing normally occurs within fifteen percent of the available processing area, the remainder of which becomes available for forwarding, shearing, deaerating and consolidating the mixture.

The ability to devolatilize and/or deaerate an energetic formulation is of considerable importance due to the degenerative effects of such entrapments on mechanical properties and sensitivity. Comparative studies show that because of the low volume to surface area ratio and the rapid exposure of fresh mixture to the vacuum source, deareation and devolatilization of mixtures are more complete in this type of equipment than in batch type processors. This enhances the safety of the process, especially considering for example the possible adiabatic compression of the air to result in catastrophic losses.

Specific Safety Issues and Corresponding Design Features

Issue: Temperature control

One of the primary safety issues related to processing energetic materials is the requirement for precise control of the temperature of the energetic material. The most critical parameter for safely processing energetic materials is the ability to control the temperature of the product, both the apparent mass (or bulk temperature), as well as localized temperature due to shear energy, stress etc.

The twin screw mixer converts the mechanical energy of the rotating screws into heat through shear forces generated within carefully maintained clearances between the screws and between each screw and the barrel housing. The viscous energy dissipation is directly related to the deformation rate and the shear viscosity of the mixture (scales with the square of the deformation rate and directly proportional to the local shear viscosity). The shear viscosity of the mixture changes with increasing degree of mixedness of the ingredients of the formulation and the total specific energy input. As the shear viscosity of the energetic formulation being processed is also a strong function of temperature, it is essential to control temperature at various sections of the barrel. These sections include the feed zones, mixing zones, dearation zone, discharge zone, and, when used, the extrusion zone and die head assembly. The temperature of the energetic formulation should not be allowed to reach the decomposition temperature of the formulation. Since there is no way one can measure the formation of the hot spot in the extruder during the processing one needs to predict and eliminate conditions which lead to hot spot temperatures which reach the decomposition temperature of the formulation.

In addressing this issue, the optimum temperature control comes from the tailoring of the agitator for the specific process. This is done via mathematical modeling of the process and hardware utilizing three dimensional computer models generated specifically for this purpose. These models afford the capability to recognize and predict energy input, which is related to temperature rise, and provides for tailoring the screw geometry to keep that input within specific boundaries to ensure that the material is always processed within safe temperature parameters. Such computer models are also designed to predict pressure generation in the process and to predict the goodness of mix by following particle distribution through the entire length of the process.

In addition to optimizing the agitator profile for a specific process, these mixer designs incorporate the largest possible liquid media channels for the thermal conditioning of the process by providing the greatest possible surface area to volume ratio within the barrel envelope. Independent multiple zone controls and in process monitoring instrumentation is employed at strategic locations through out the length of the barrel and in the die. In addition to utilizing these sensors to monitor and control process temperature, they can be used for emergency equipment shut down and to trigger a high response rate deluge system for the equipment. IR and UV detectors can also be installed as part of the equipment system for triggering a deluge system.

Another important contributor to control of heat build up addressed by this design is the ability to control horsepower. A specially designed variable speed and torque control hydrostatic drive affords the flexibility to finitely control process energy input.

Issue: Control of product pressure

Pressure control is another area of special interest, both because it varies directly with temperature and because many materials require pumping through a die assembly under large consolidation forces. Also, pressure increase in regions such as the feed zone or near shaft seals indicates undesirable conditions. Closely related to the critical characteristic of process temperature control is the requirement to keep the product within desired pressure limits, especially in the extruder portion of the unit. Pressure control is required to eliminate the possibility of inter-granular shear and to preclude seal leakage due to loading created by product upsets (i.e. die blockage, feeder or pump failures etc.).

In addressing this safety issue, these mixers feature computerized optimization of the discharge screws that ensure design extrusion pressures are met with a minimum 50% safety margin on degree of backfill of the screws. During processing pressure transducers monitor internal barrel pressure at critical points and will trigger shut down of the unit if preset safety limits are exceeded. As with the temperature sensors, the pressure sensor can be used to trigger a deluge system.

Issue: Electrical Discharge

The potential of ignition due to electrical discharge is another area of concern when processing potentially hazardous material such as energetics due to the electrical sensitivity of many of the formulations. In addressing this potential safety issue, the design of these systems is such that all electrical components in the mixer area are either fully explosion proof to Class I group D and Class II groups EF&G standards or are intrinsically safe as per the National Electric Code. By definition from the NEC, intrinsically-safe equipment and wiring shall not be capable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of flammable or combustible atmospheric mixture in its most easily-ignitable concentration.

In the design of the two extrusion platforms we have used hydrostatic drive systems, which puts the primary electrical power source outside of the mixing area in a non-hazardous environment. The torque pick up device on the drive motor needs to be intrinsically safe, as are all the temperature and pressure transducers on the mixer proper. In our designs the hydrostatic power unit utilizes a special polyolesther synthetic fire retardant fluid that is classified as non-hazardous. The drive is designed to be unidirectional to prevent the inadvertent start up of the machine in the reverse direction.

Thermal conditioning for the hardware is accommodated via liquid media circulated through cooling channels in the barrels. The media conditioning systems are remotely located from the process in a non-hazardous area.

Additionally, the ME7.5 machine is small enough that the entire machine and the ancillary components supporting the process can be placed in a hood to optimize safety. A typical processing rate for this unit is around 50 to 100 grams per hour.The equipment is supplied with grounding lugs to dissipate static electric charge before it can build up on the machinery

Issue: Metal-to-metal contact

Frictional ignition of the product due to dynamic metal contact is a concern for the processing of energetic materials. Experience has shown that the hydrodynamic film of the product will support the screws off of the barrel surface in most applications. However, under certain conditions, the film can break down and metal contact can occur (especially for formulations which lack elasticity as manifested by a relatively low first normal stress difference upon rheological characterization). When this happens, it is desirable to have the barrels and screws manufactured from materials that prevent adhesive wear which generates frictional heat. The screws and barrels of these units are manufactured from a through-hardened stainless alloy that is specifically designed to resist wear and corrosion. They are then treated to a specially developed proprietary process of ferritic nitro carburizing that changes the surface of the metal for several thousands of an inch in depth, imparting a greater hardness to the metal at the surface and reducing its coefficient of friction. This reduces the possibility of any metal-to-metal pick up and greatly reduces the energy generation from any contact of the screws to the barrel bores.

Screw speed is a concern because of the possibility of reaching tip speeds exceeding the friction sensitivity of energetic oxidizers. Additionally, at a given torque and throughput rate, the localized heat transfer capacities of energetic binders and plasticizers may be process self limiting factors. Because reliable prediction of such hazard levels is difficult, it is generally assumed best to operate at the lowest possible screw speed necessary to achieve the mixing and consolidation of phases required by mechanical property constraints. However, maintaining the shear required to maximize binder-filler interaction at any screw speed occurs when the mixture is processed at maximum torque. Consequently in our designs we have chosen a hydrostatic drive unit as the optimal drive for meeting these requirements. Numerous mathematical models that have been run as well as tests generated over a wide variety of screw speeds and torques indicate control of agitator configuration also compensates for changes in screw speed through effects upon energy input and/or residence time.

The thrust bearing and seal assembly for the ME7.5 machine is manufactured from a special carbon fiber reinforced electrically conductive polymer and precludes any metal contact with the agitator shafts at the drive end of the machine. The agitators are supported at the drive end by sealed anti-friction bearings, which are located outside of the seal area. The 40mm Universal has thrust bearings mounted in the gearbox, remote from the barrel assembly and are separated from the process material by seals and a considerable air gap. The agitators are supported on the drive end by anti-friction bearings mounted in the gearbox.

Issue: Maintenance

Another safety consideration is maintainability and good housekeeping characteristics of the processing machinery for energetics manufacture. In addressing the particular use for any equipment, it is obvious that cleanliness is an essential part of the safety consideration. In addition safe maintainability has to be considered a high priority as it is evident that personnel will be required to clean and disassemble the unit after shutdown from live material runs, or if a system fault occurs.

Addressing this issue, the following design features were incorporated into our designs. In the fully-intermeshing mode, the agitators in the mixing and extrusion area are fully conjugal; that is, an arc on one agitator fully describes the surface of the mating agitator through a 360-degree revolution. Hence, the agitators completely wipe each other and the barrel bores within the clearances prescribed. From a process standpoint, this assures that the surfaces are completely regenerated of product, but possibly as important, it means that the machine is internally self cleaning, and will purge itself of product when run after the purge feeders are shut off. There should be no stagnation areas in the machine, orifice plugs and other devices sometimes used in polymer processing to restrict flow are avoided in the design of extruders for energetics manufacture to ensure that no voids or pockets are present which could entrap material in the unit.

The mini extruder designed for the processing of nanoenergetics, ME7.5, features a horizontally split barrel and die assembly, which is held together by quick release clamps. The barrel and die assembly also separate vertically for ease of cleaning. The barrel separates from the drive assembly via the same quick release clamps. The agitators can be removed from the machine by the use of a novel release mechanism that does not require the use of tools. The drive sleeve which holds the agitator shafts in the machine is slid back after it is released outside of the process area via a spring loaded detent system. When this sleeve is moved, it releases the agitator shafts from the radial and thrust bearing assembly and they can then be removed from the machine. This process can be accomplished without the need for special tools in the product area.

The 40mm Universal features barrel sections that are both horizontally and vertically split. The barrel can be separated at the horizontal split line and the entire upper barrel section opened via the hydraulic power unit for ease of cleaning and maintenance. This also allows for easy access to change out and re-configure the agitator assemblies. The barrel sections are electrolysis nickel-plated on the exterior surfaces to aid in cleaning and to prevent corrosion of the components.

Additionally, the ability to access the equipment via the split barrels on both designs affords the operators to perform dead stops. This is a process that allows for important observations and data gathering when the machinery is stopped and disassembled during steady state operation. Typically, when running inert formulations, this allows the operator to peer into the process zone in search of otherwise difficult to determine information, such as stagnation, metal-to-metal contact points, leakage paths, and percent fill of various portions of the process zones. This information has been used during development to verify data predetermined from the 3D computer models.

To eliminate cracks and crevices, the ME7.5 agitators are a monolithic design. They are precision tooled from solid bar stock, thereby yielding better torsional and bending strengths versus segmented designs for these small diameters. The solid agitators are designed and custom built for each application via computer modeling.

While slip on elements are highly suited for testing a wide variety of formulations, the equipment designed to process a given energetic mixture need not offer such flexibility, because once process parameters are established for a steady state operation, no adjustments should be necessary. Furthermore a fixed agitator configuration may be used for mixtures requiring different treatments through control of such variables as temperature, screw speed, torque and residence time. This conclusion is based, not only on mathematical modeling, but also on data gathered by observation when dead stops are performed during operation.

Issue: Process control and Data Acquisition

Acquisition of process data and control of the process as well as safety parameters are critical features of this design. Both extrusion platforms are operated via a state-of-the art open architecture PC Laptop based system that includes full instrumentation to monitor and control zone temperatures and screw speed, monitor product temperatures, process pressures and screw torque. The software allows remote operation of the unit as well as remote data collection; either wireless or via the Internet. All of the safety features are programmed with automatic shut down for over temperature, over pressure or over torque of the system. Mechanical safety back up for over torque in the form of a quick response, high flow relief valve is an integral part of the hydrostatic drive system on both units.

Additional Features

In addition to the major safety features described, other design features for these machines that contribute to safer operation and also optimize some of the processing versatility of the equipment are:

- Ample mechanical safety margins in design.
- Infinitely variable speed control throughout the designed operating range.
- Overtorque shutdown protection.
- Integral and complete hydraulic system for the barrel top opening on the 40mm Universal.
- Integral and complete hydrostatic drive system.
- Designed for full vacuum as well as internal pressure.
- Injection ports in the barrel for the introduction of liquid additives.
- Multiple feed ports for solids addition.
- Corrosion resistant enhancement for the agitators and barrels.
- Complete data acquisition and control system.

Also, there are several pieces of ancillary equipment that have been designed to compliment this equipment in applications where explosion proof or intrinsic safety are a requirement.

Summary:

In closing, one of the prime design considerations for the development of extrusion technologies for processing of energetic formulations is safety. All the features mentioned in this presentation lend themselves to the safe application and operation of extrusion equipment for these types of applications. However, as indicated the geometry and the operating conditions need to be selected for a given energetic formulation, the initial characterization of which is essential for the mathematical modeling of the process to understand the thermo-mechanical history that the energetic material will be exposed to during the processing stage.

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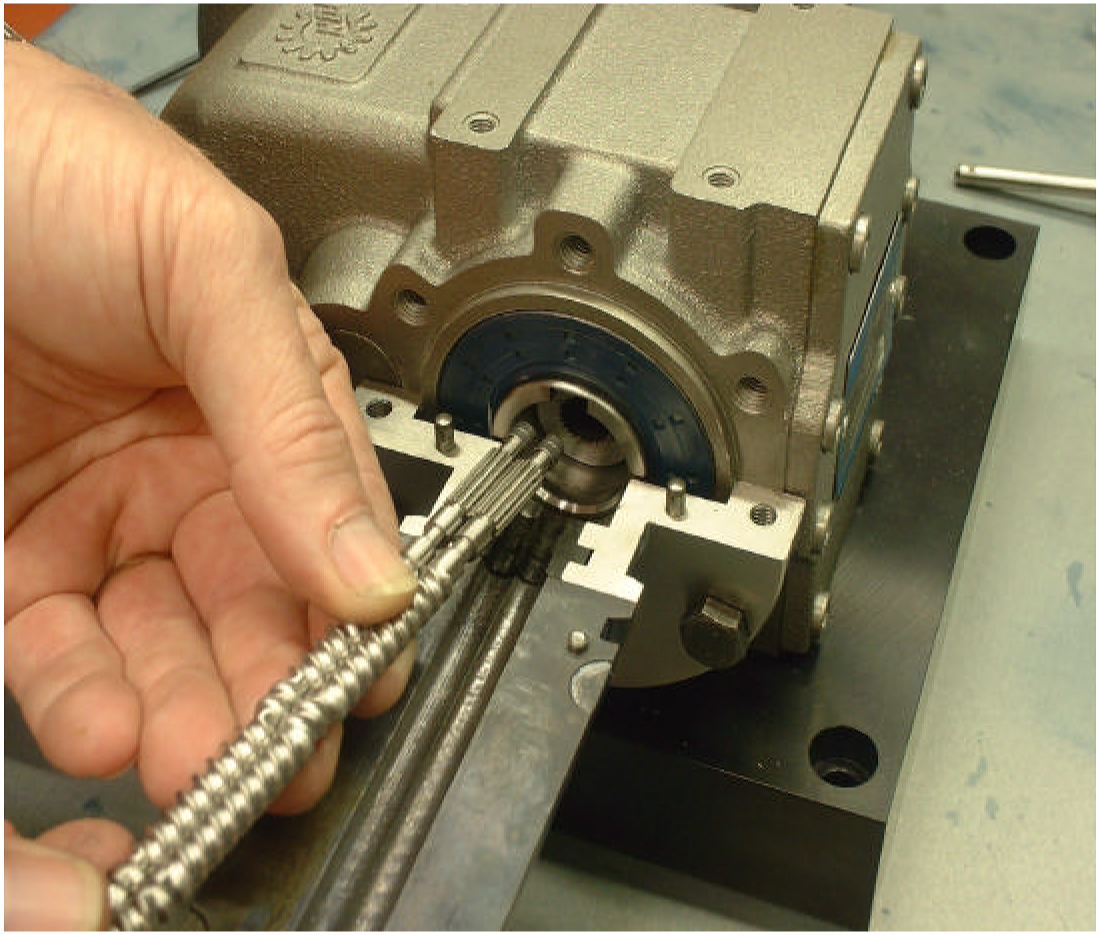
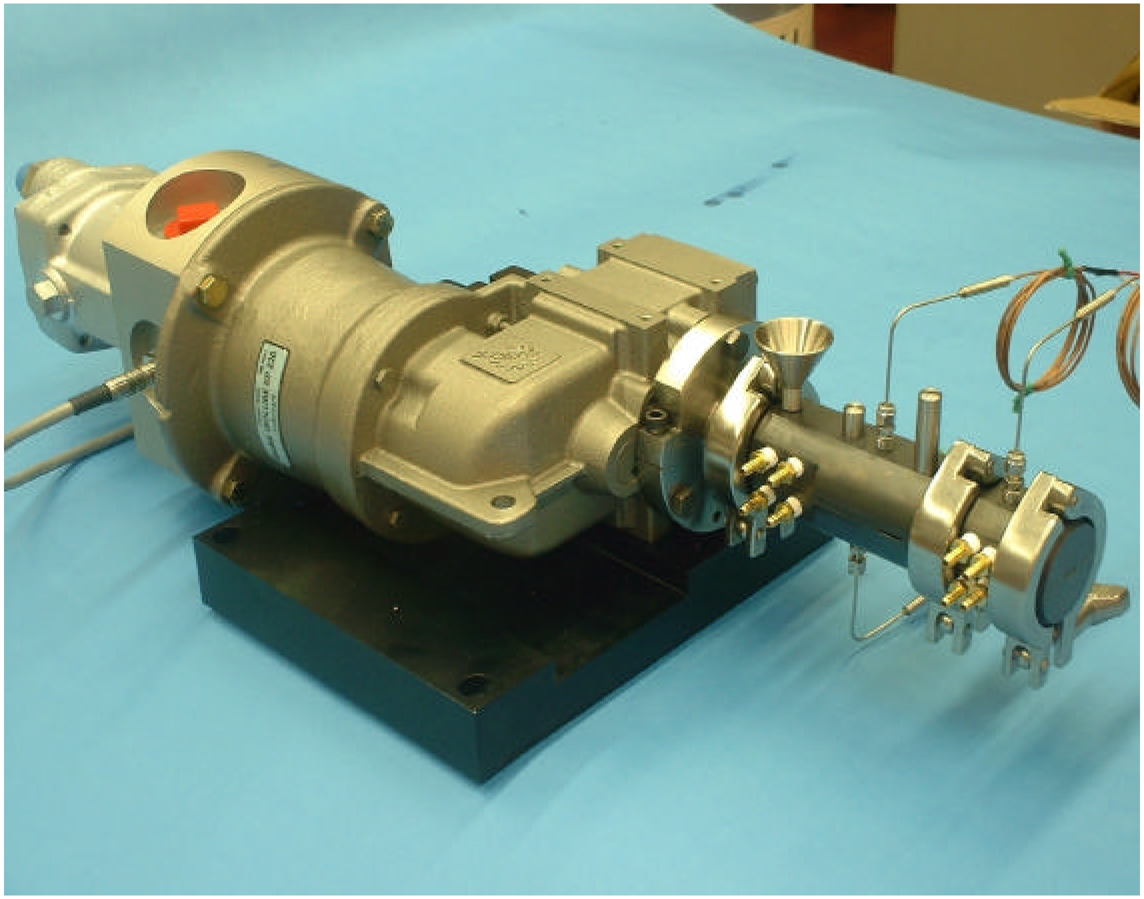
List of figures:



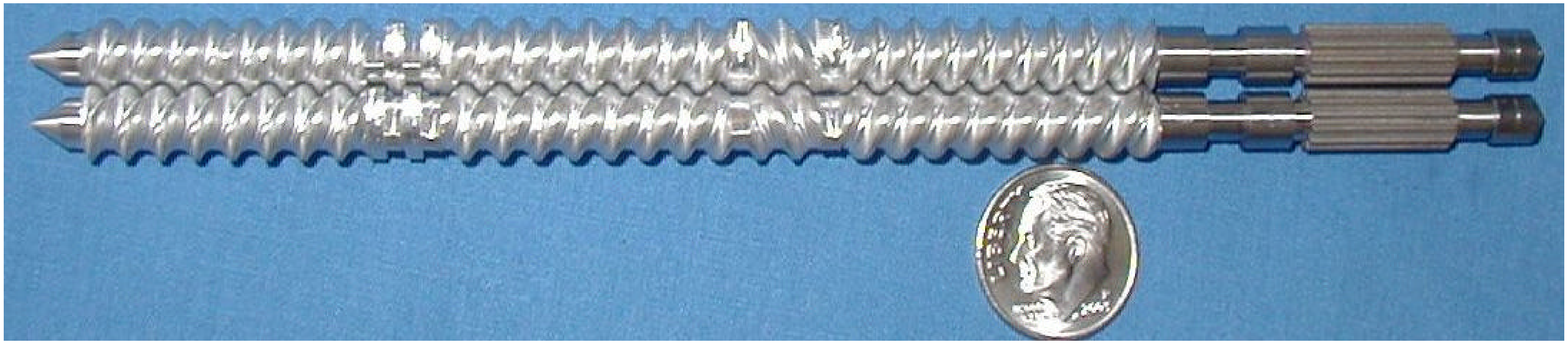
Mini extruder of MPR specifically designed for processing of nanoenergetics

Figure 1



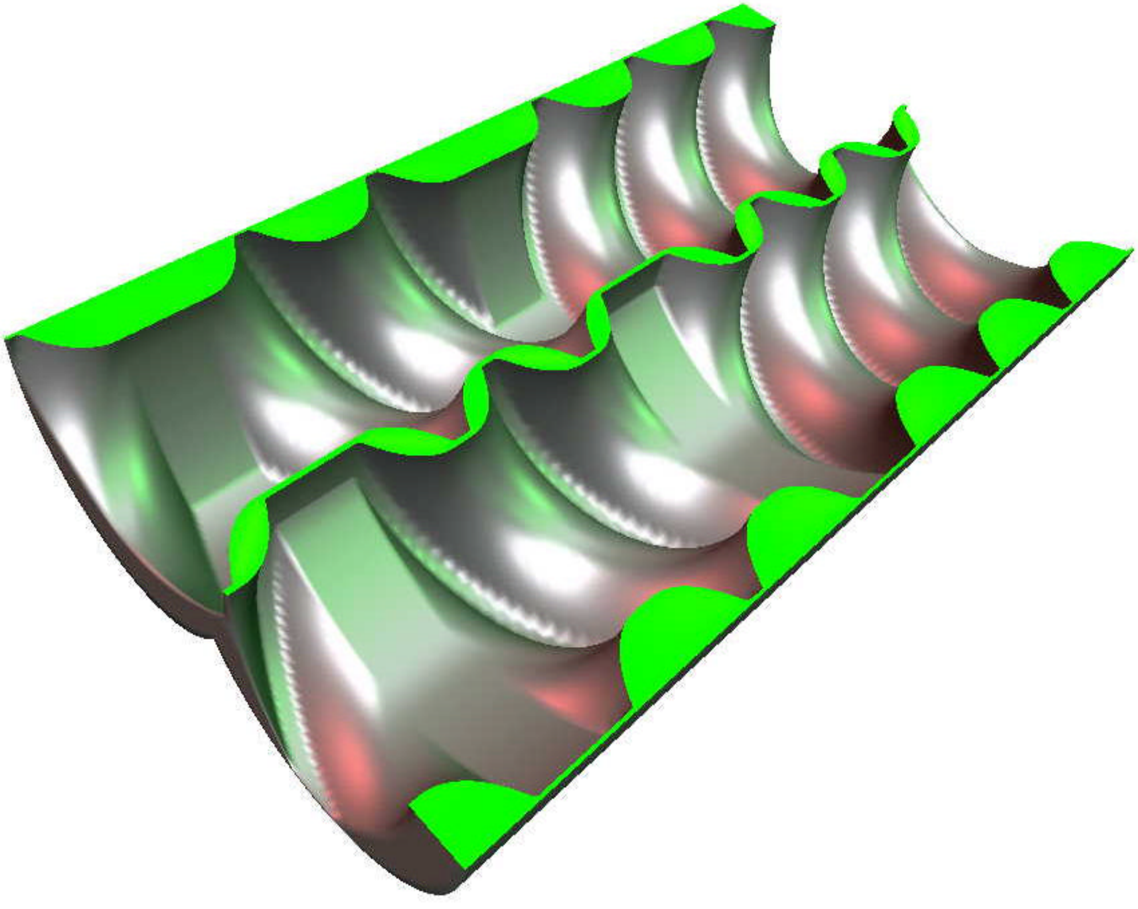
Mini extruder of MPR specifically designed for processing of nanoenergetics

Figure 2



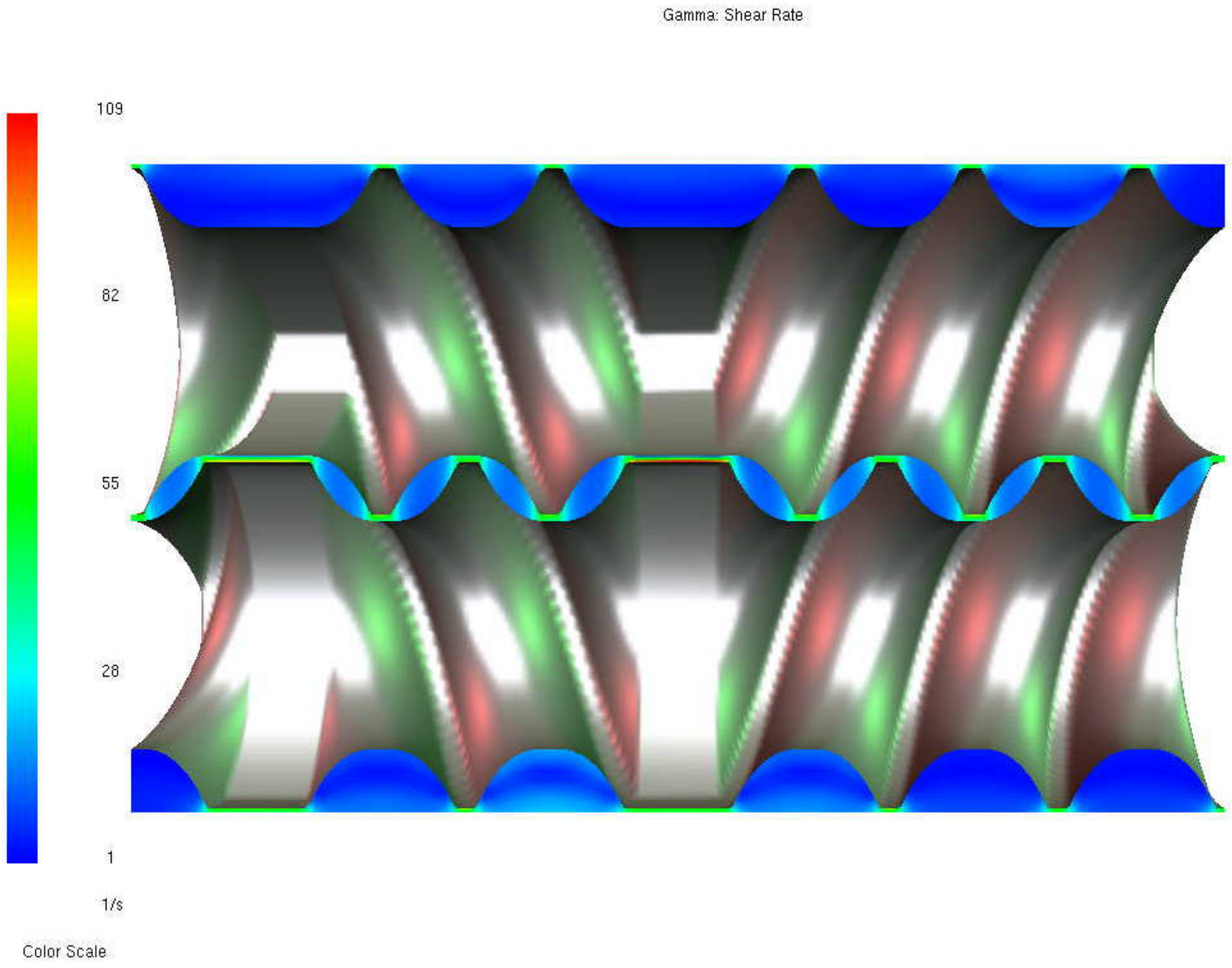
Screws of the mini extruder of MPR specifically designed for processing of nanoenergetics

Figure 3



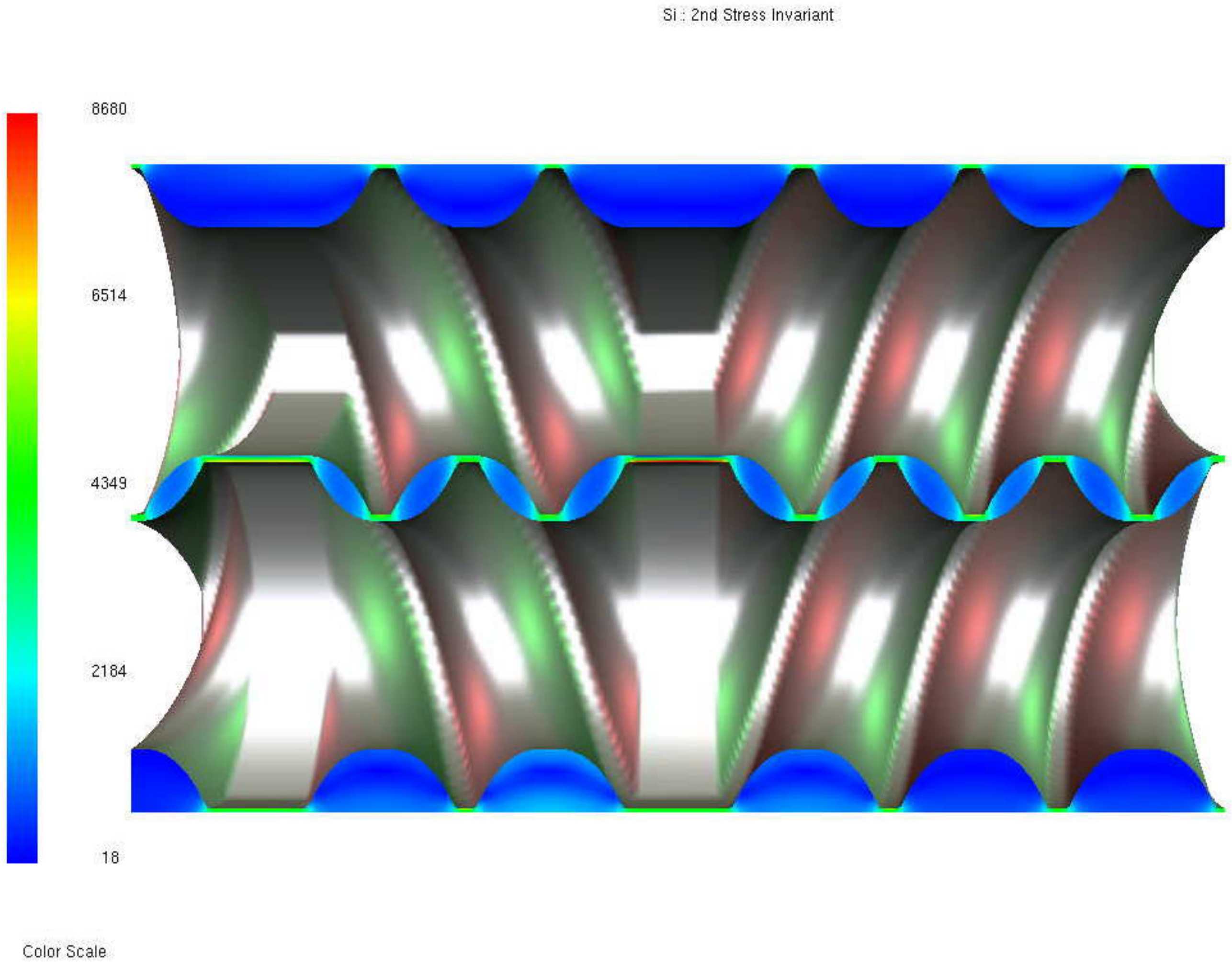
Mini Extruder First Section Flow Channel Cutaway

Figure 4



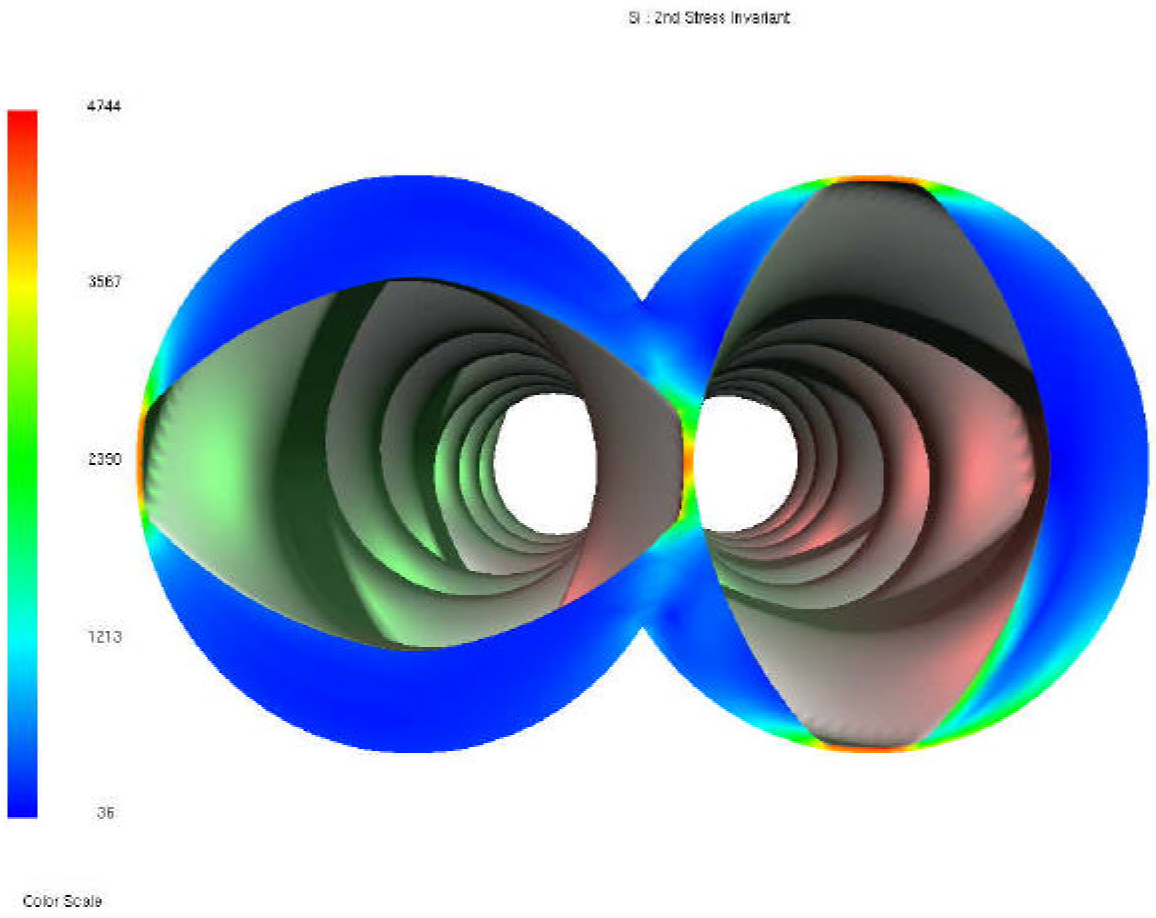
Mini Extruder First Section, 0.05 lb/hr, 105°C, shear rate distribution

Figure 5



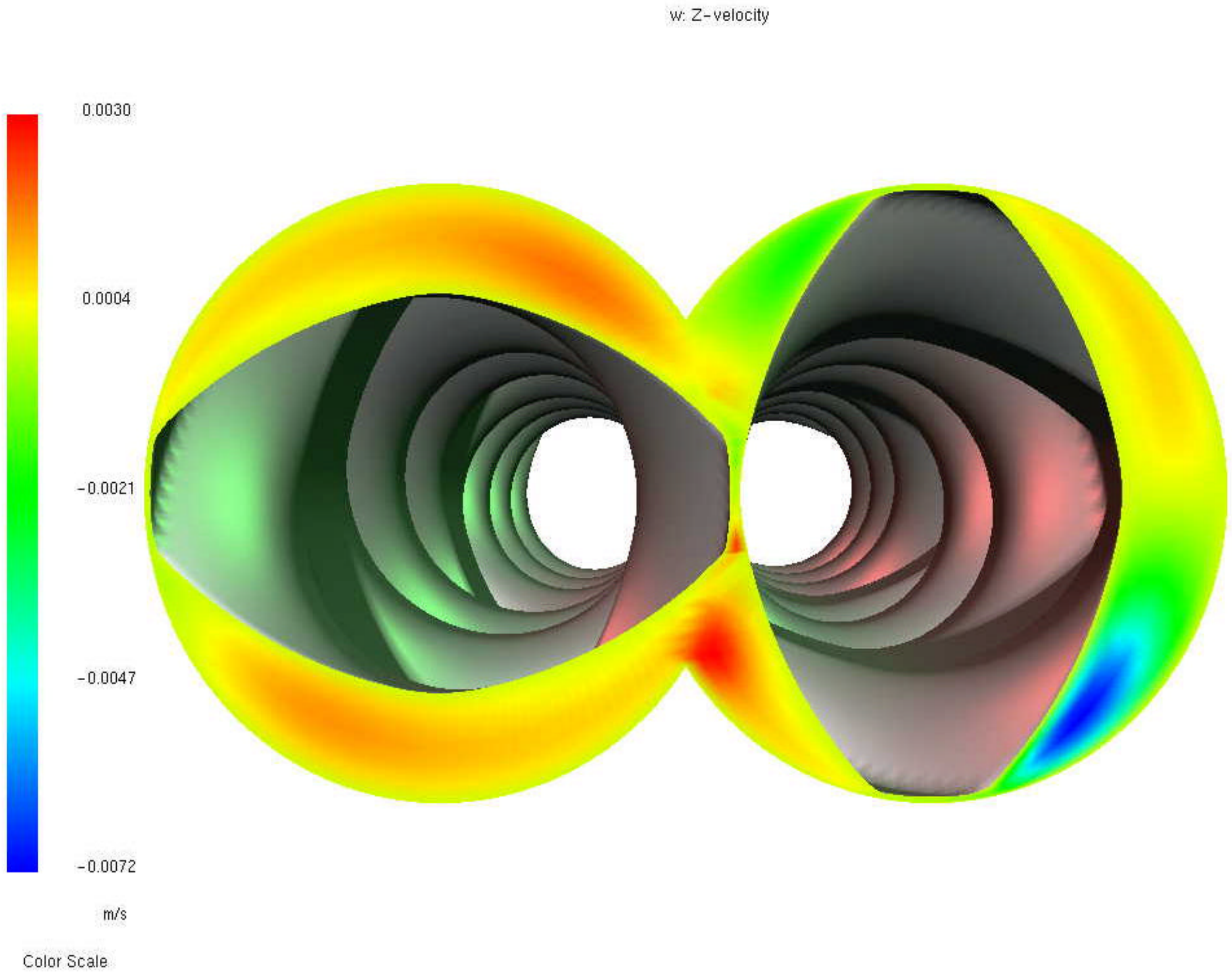
Mini Extruder First Section, 0.05 lb/hr, 105°C, second stress invariant

Figure 6



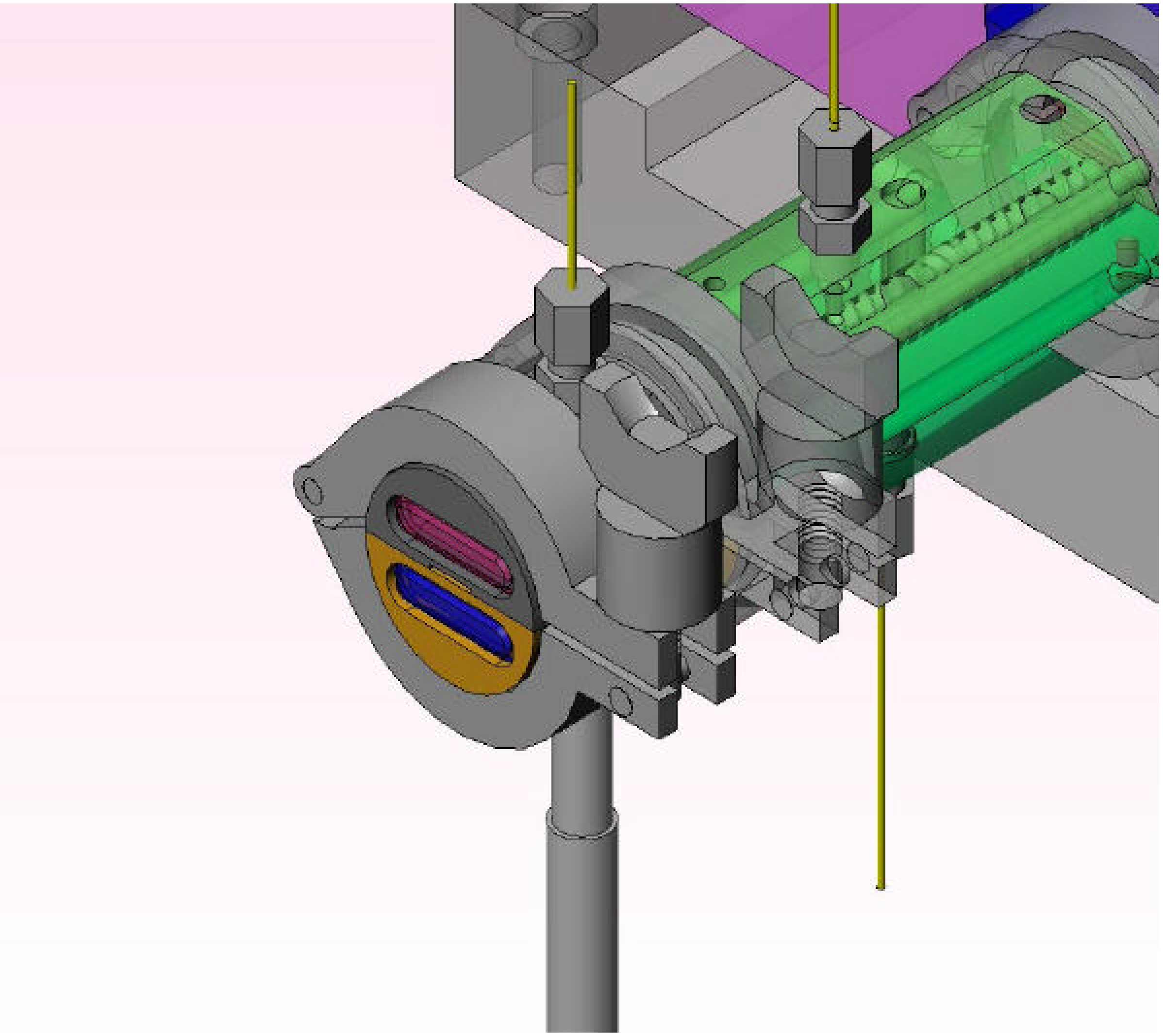
Mini Extruder First Section, 0.05 lb/hr, 105°C, second stress invariant

Figure 7



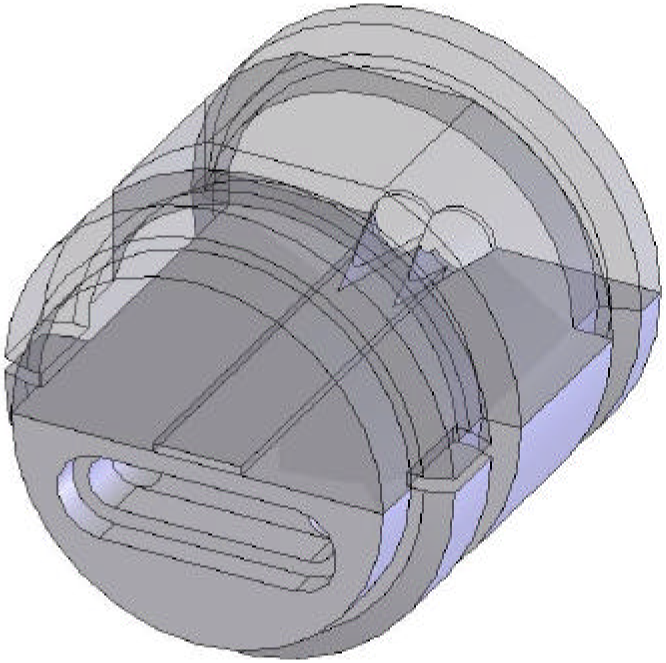
Mini Extruder First Section, 0.05 lb/hr, 105°C, z-velocity

Figure 8



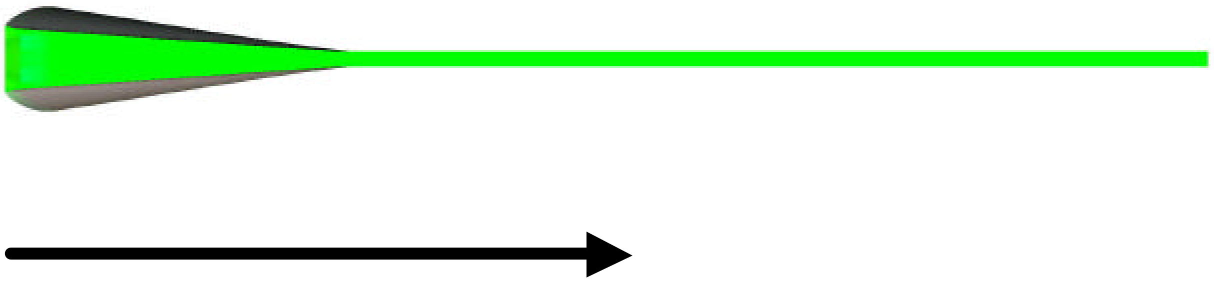
Slit die design of the mini twin screw extruder

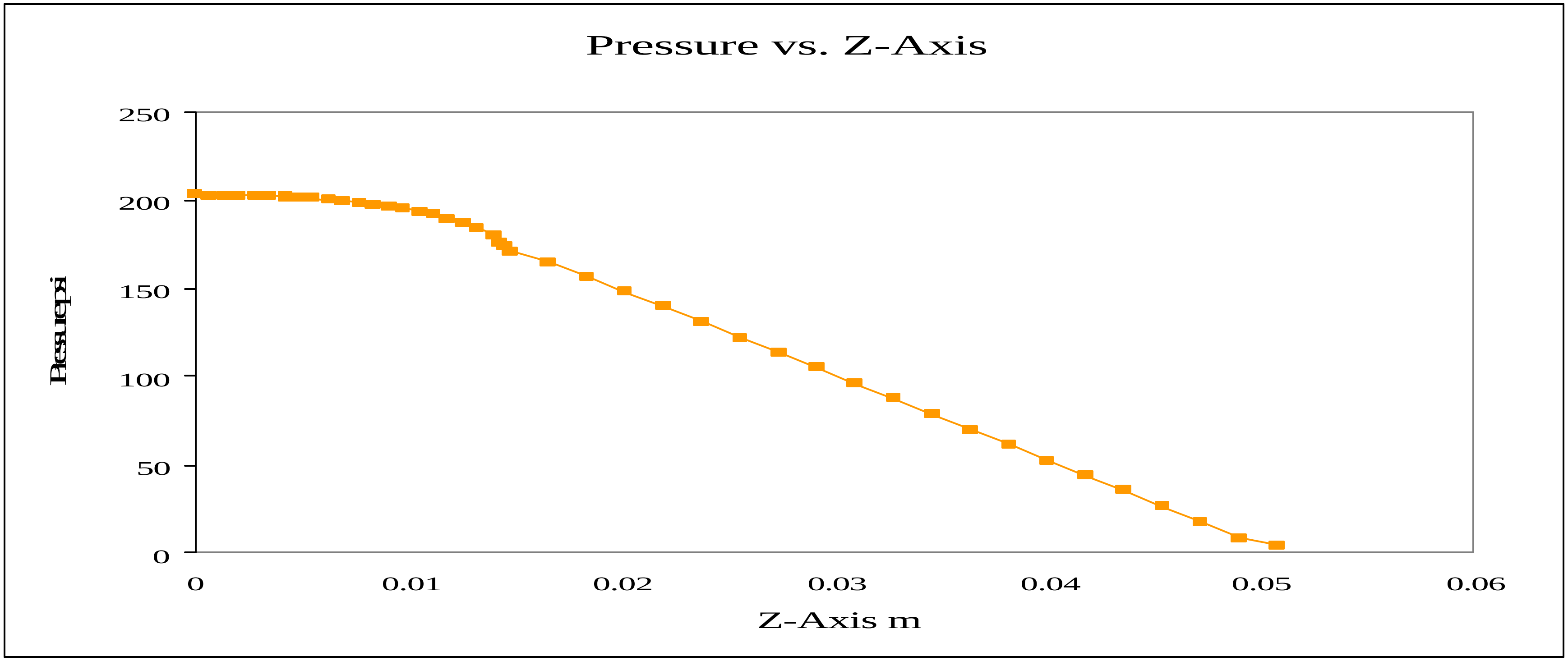
Figure 9



Mini Extruder Die Flow Channel

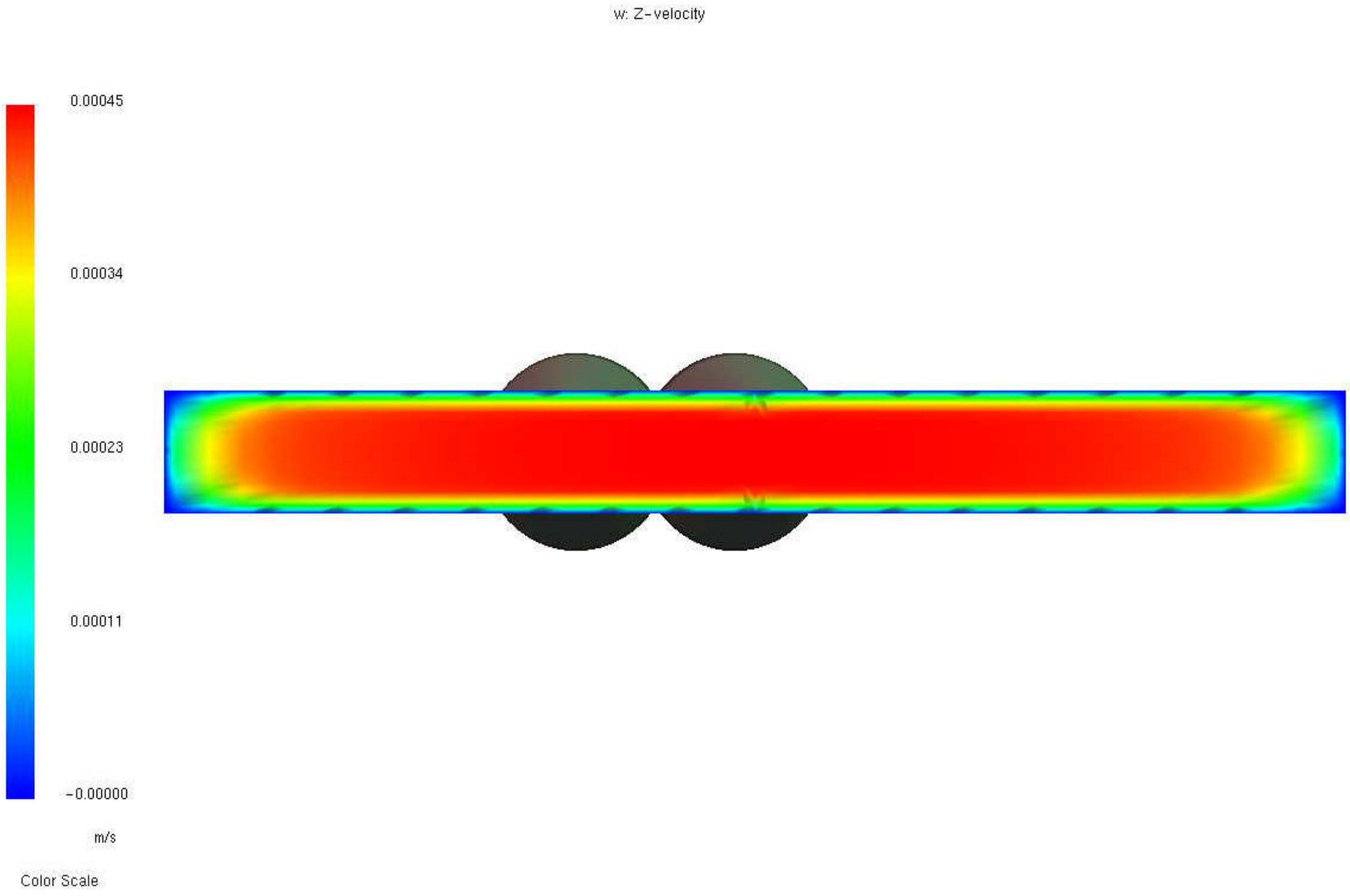
Figure 10





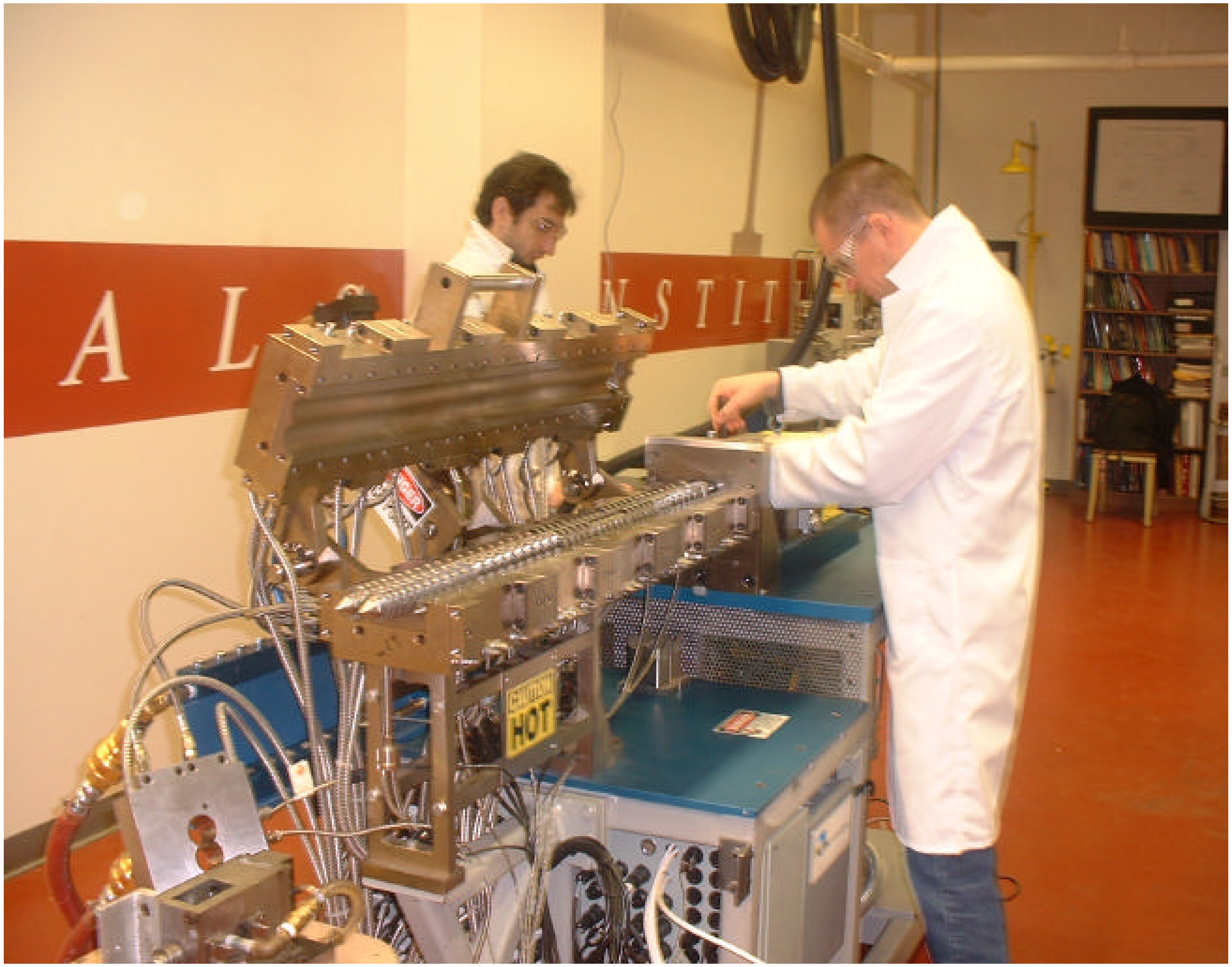
Mini Extruder Die, 0.05 lb/hr, 200 psi,105°C

Figure 11



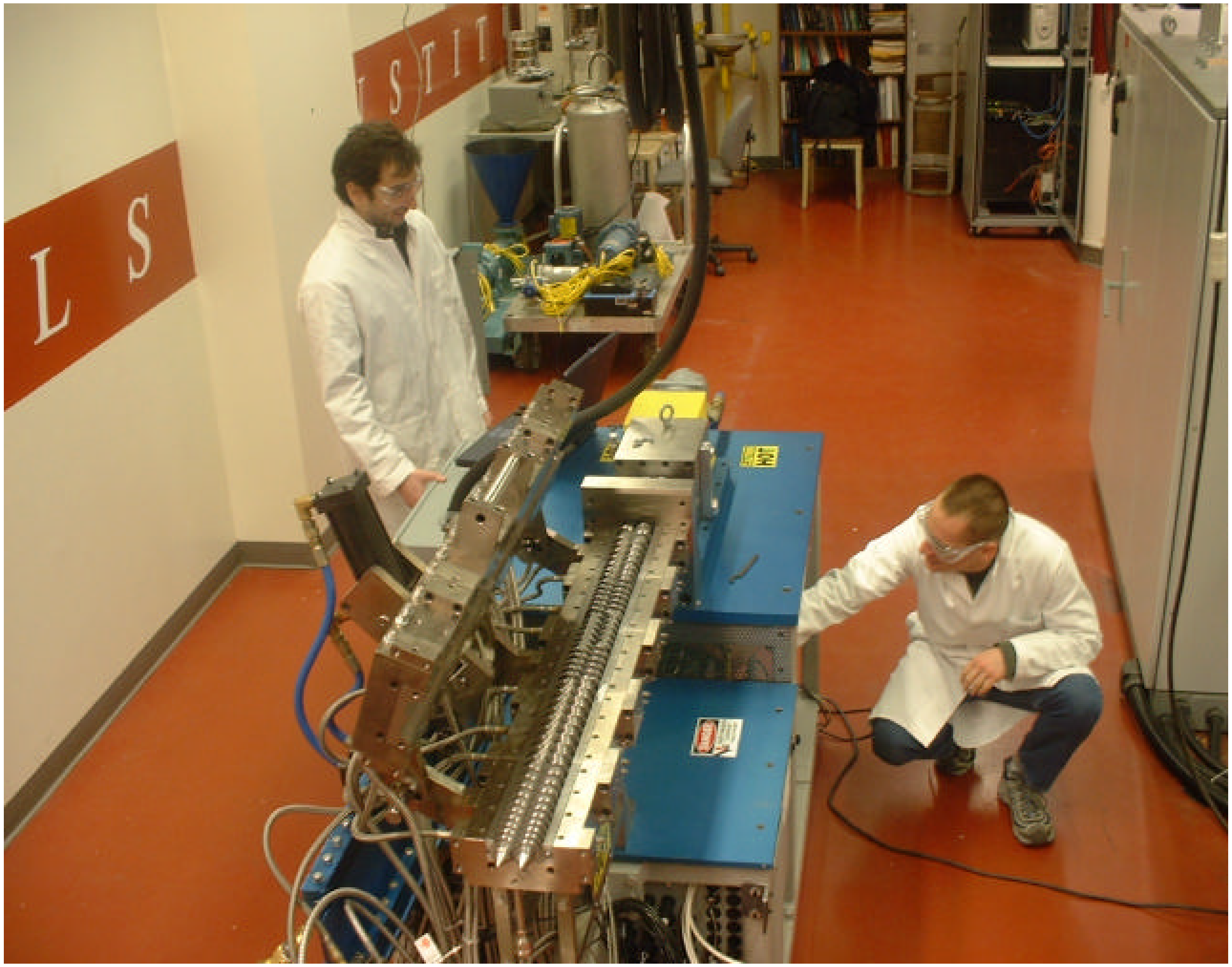
Mini Extruder Die, 0.05 lb/hr, 200 psi,105°C, z-velocity distribution

Figure 12

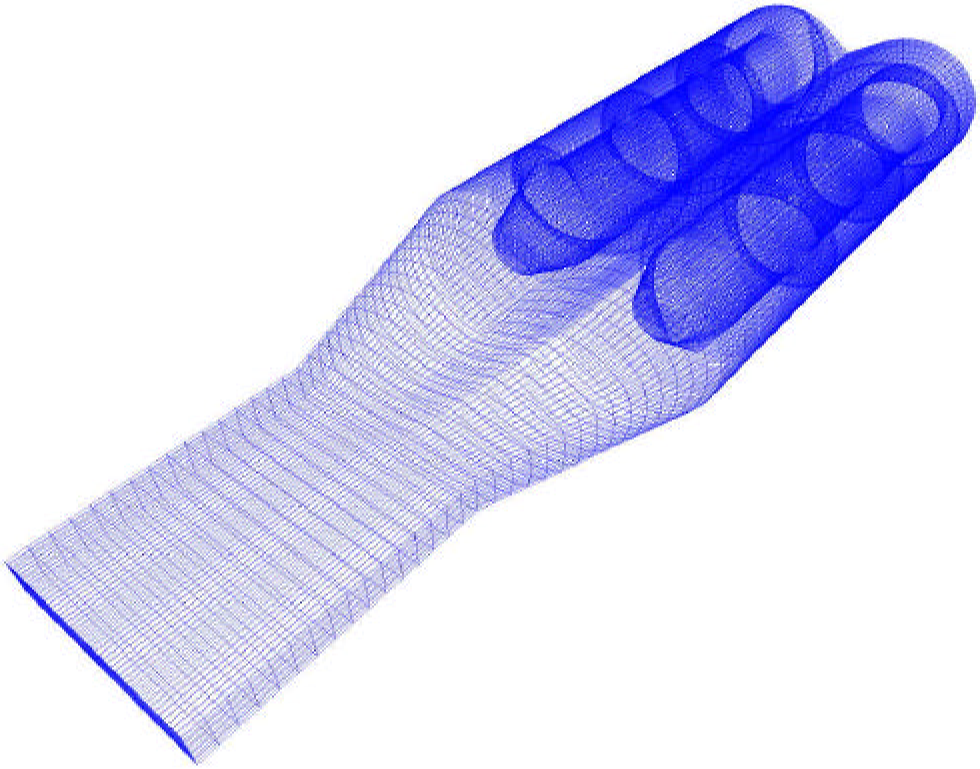


MPR Universal extrusion platform on the counter-rotating mode

Figure 13

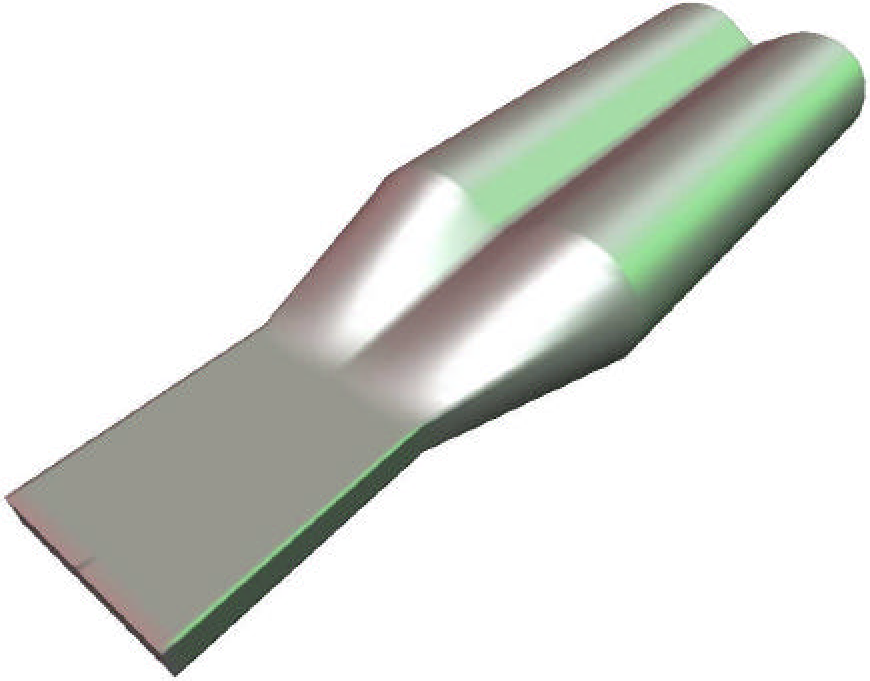


MPR Universal extrusion platform on the counter-rotating mode



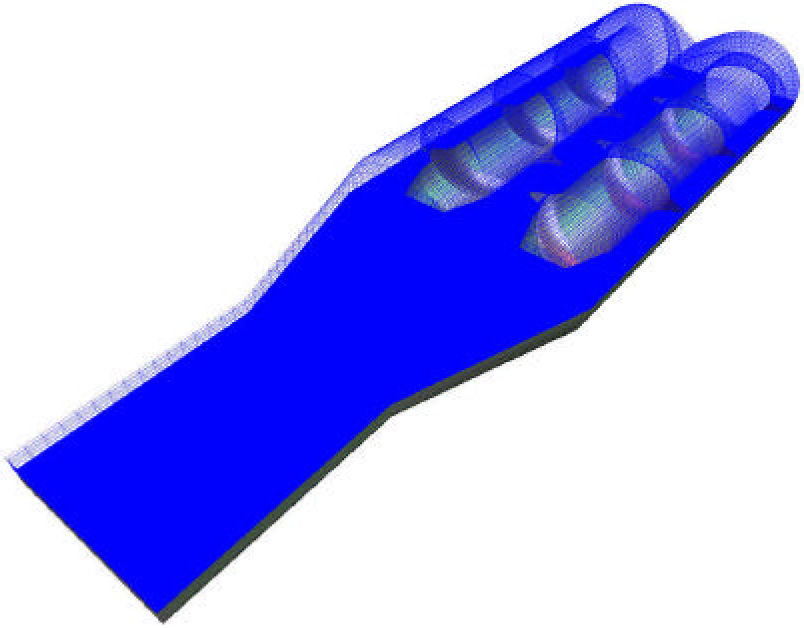
Flow Channel FEM Mesh- Universal tangential counter-rotating configuration

Figure 15



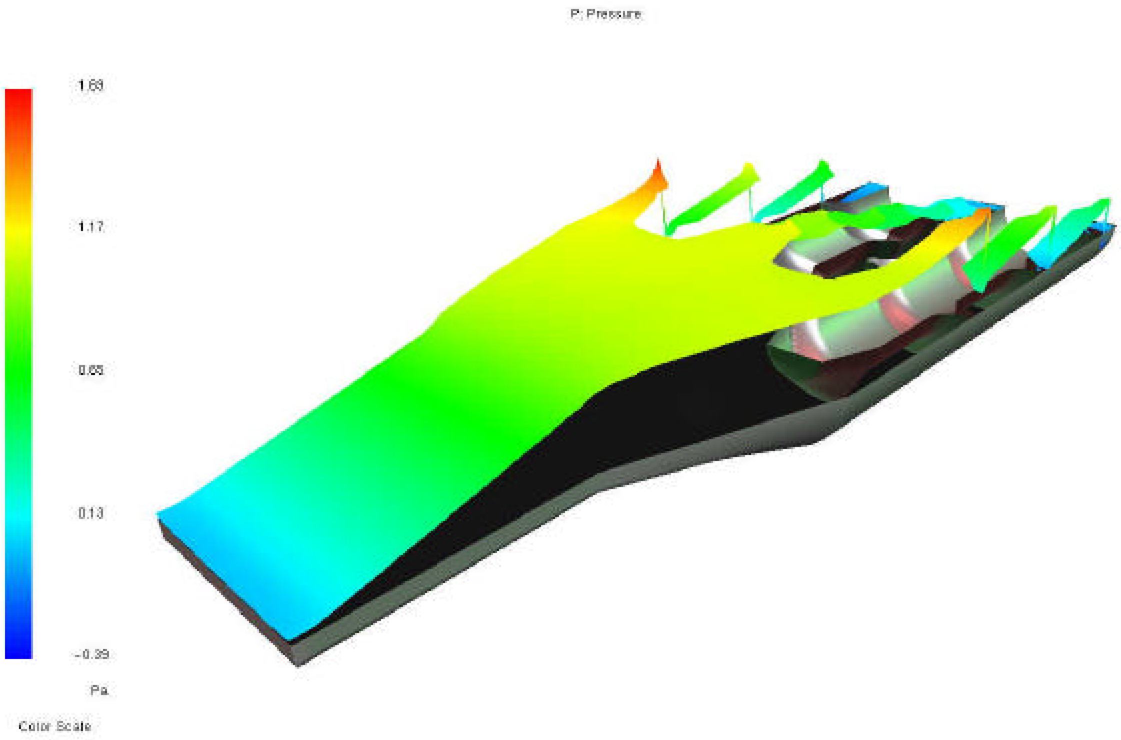
Flow Channel Solid Model- Universal tangential counter-rotating configuration

Figure 16



Flow Channel Cutaway- Universal tangential counter-rotating configuration

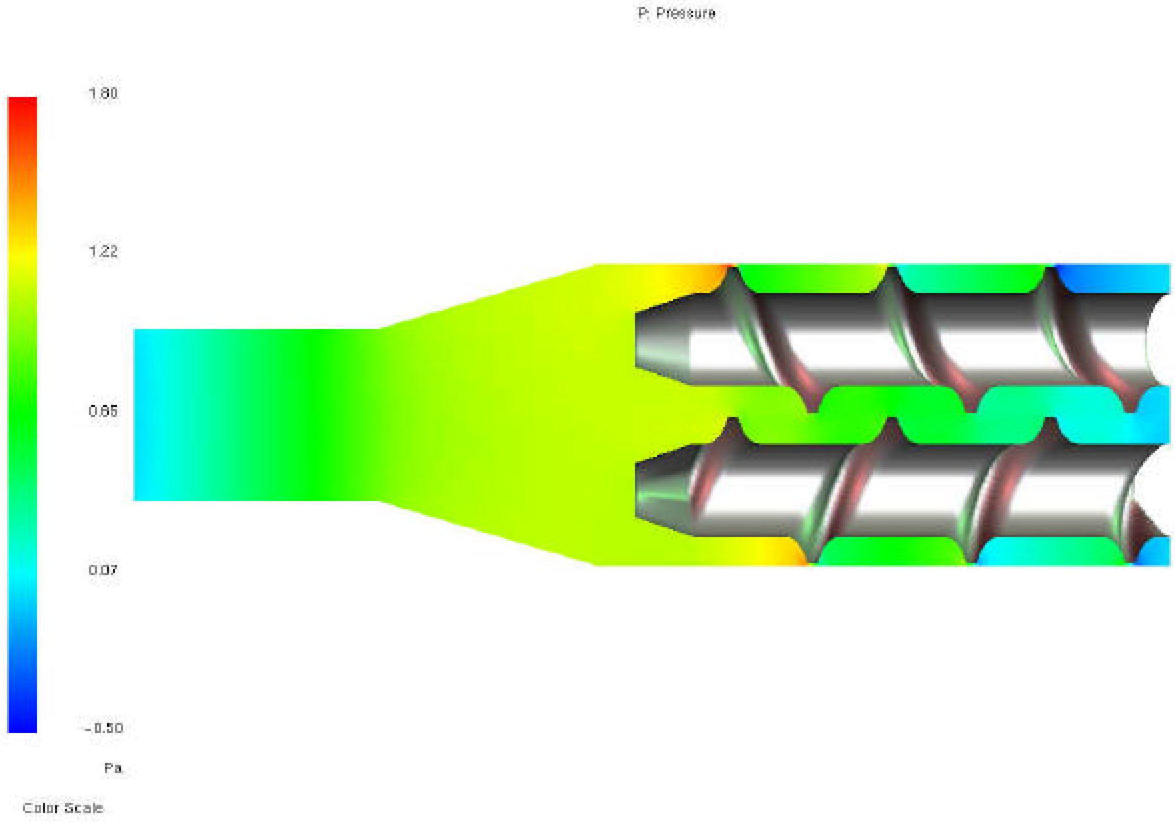
Figure 17



M

Pressure distribution in the Universal extruder (tangential mode) and its slit die configuration:
100 RPM at 180°C in, 72.3 lb/hr, peak pressure = 271 psi

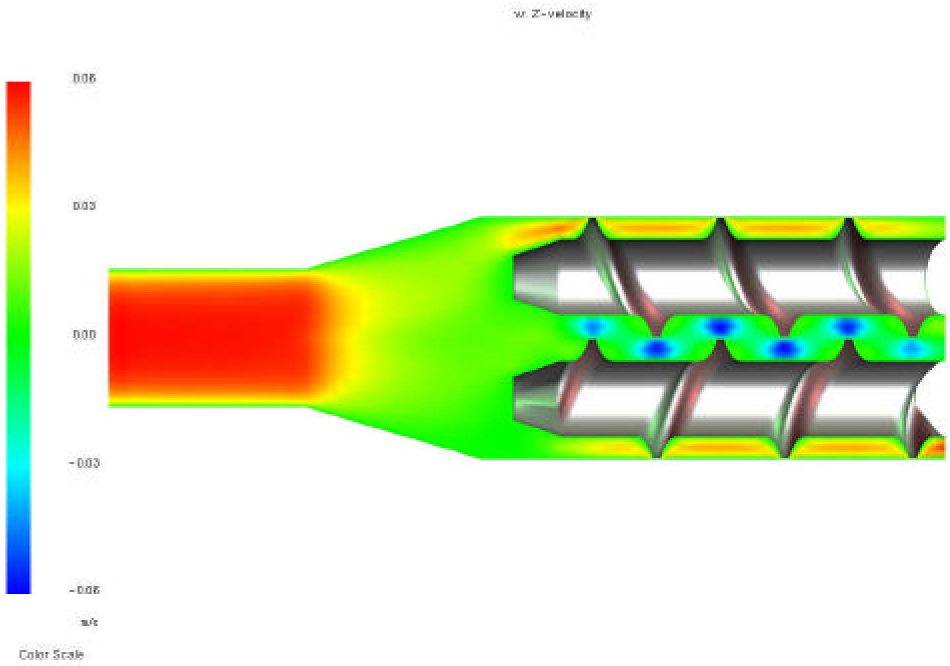
Figure 18



M

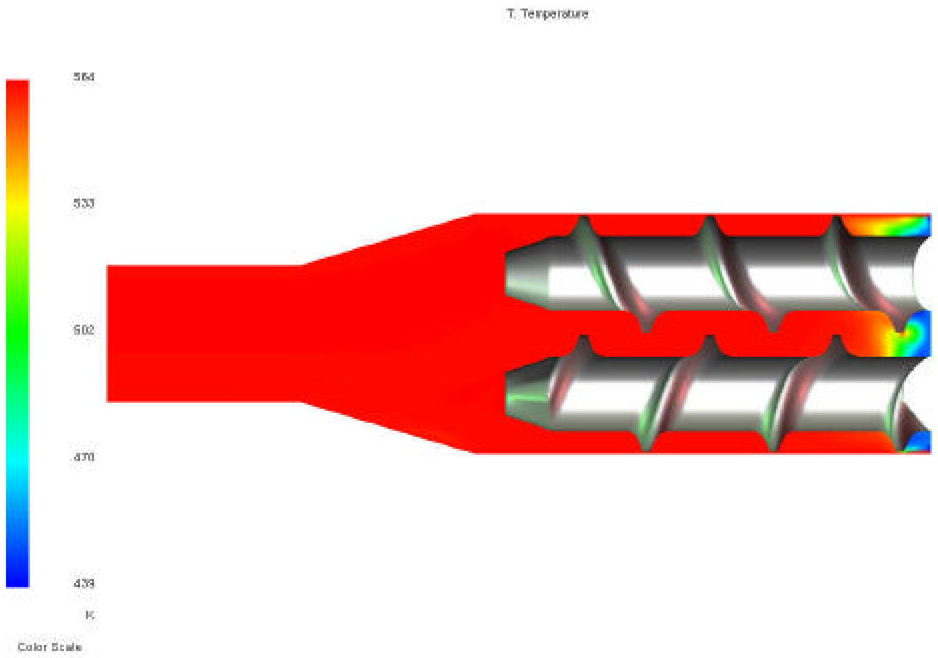
Pressure distribution in the Universal extruder (tangential mode) and its slit die configuration: 100 RPM at 180°C in, 72.3 lb/hr

Figure 19



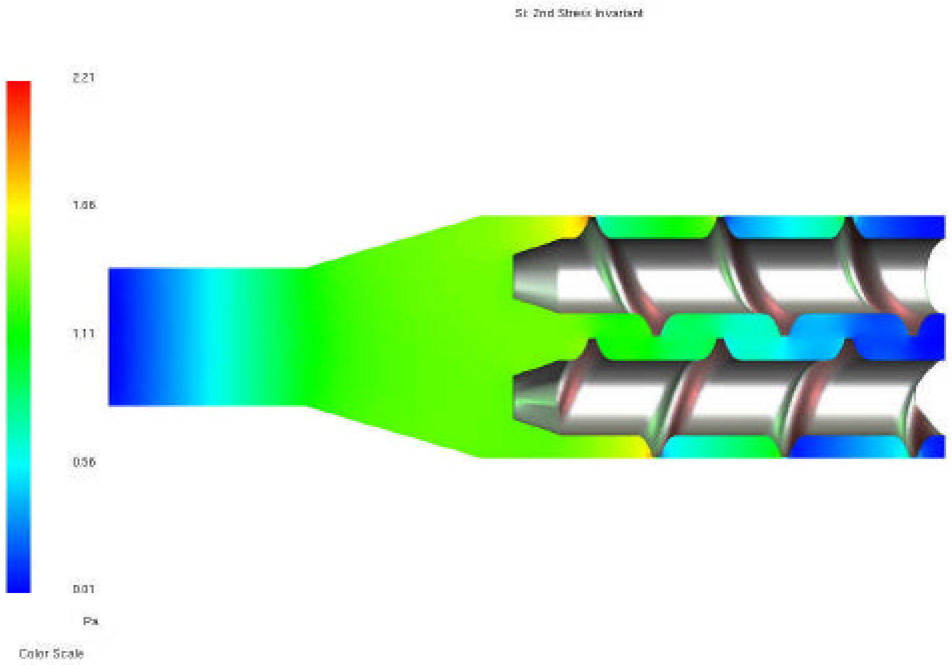
Z-velocity distribution in the Universal extruder (tangential mode) and its slit die configuration:
100 RPM at 180°C in, m=10,000 Pa-s^n, n=0.5, 72.3 lb/hr

Figure 20



Temperature distribution in the Universal extruder (tangential mode)
and its slit die configuration:
100 RPM at 180°C in, m=10,000 Pa-s^n, n=0.5, 72.3 lb/hr

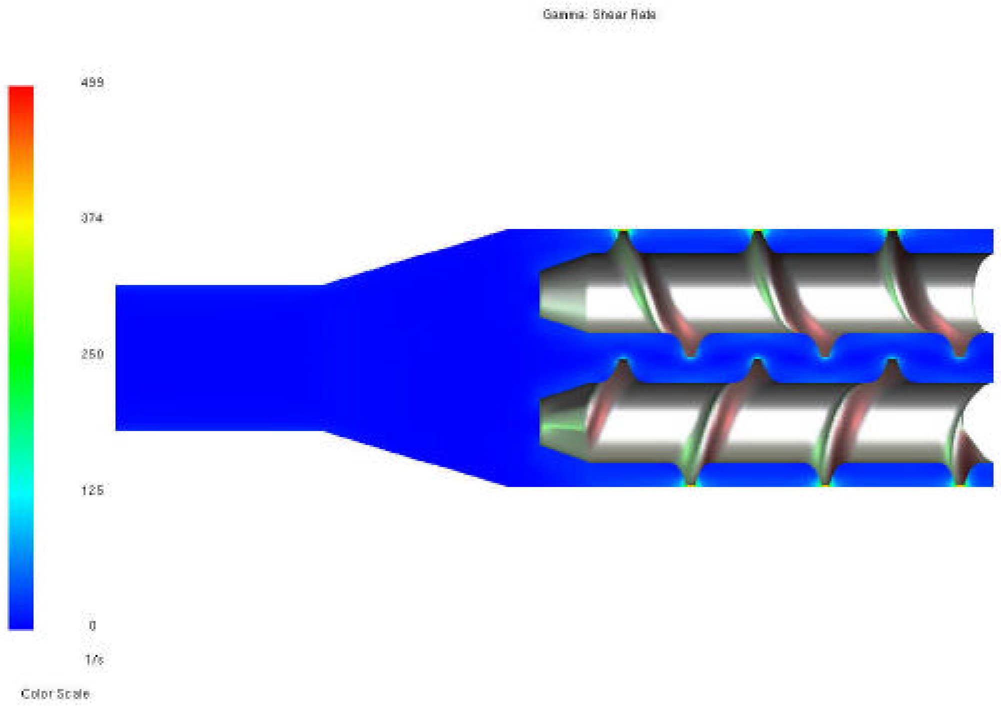
Figure 21



M

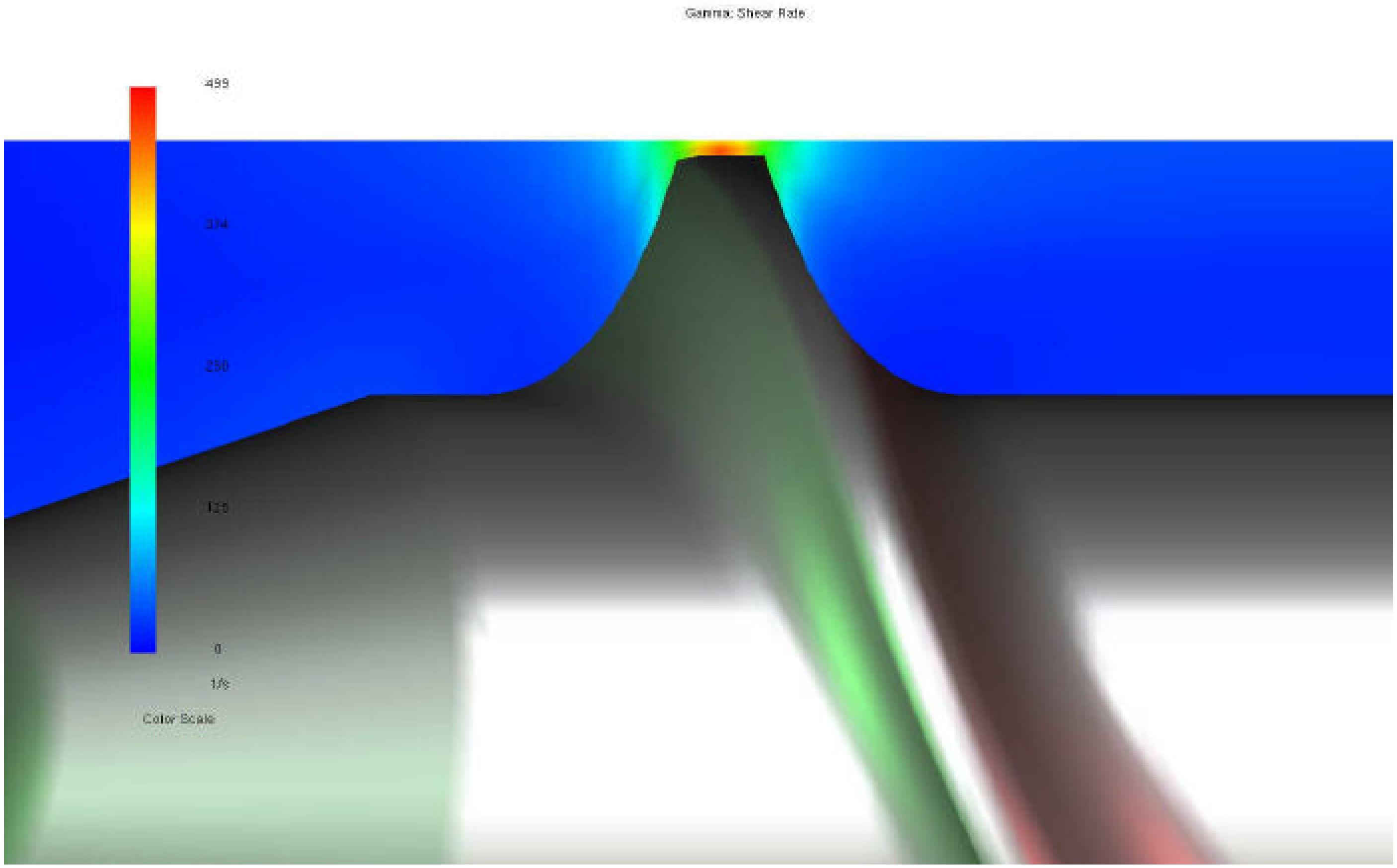
Stress invariant distribution in the Universal extruder (tangential mode)
and its slit die configuration:
100 RPM at 180°C in, m=10,000 Pa-s^n, n=0.5, 72.3 lb/hr

Figure 22



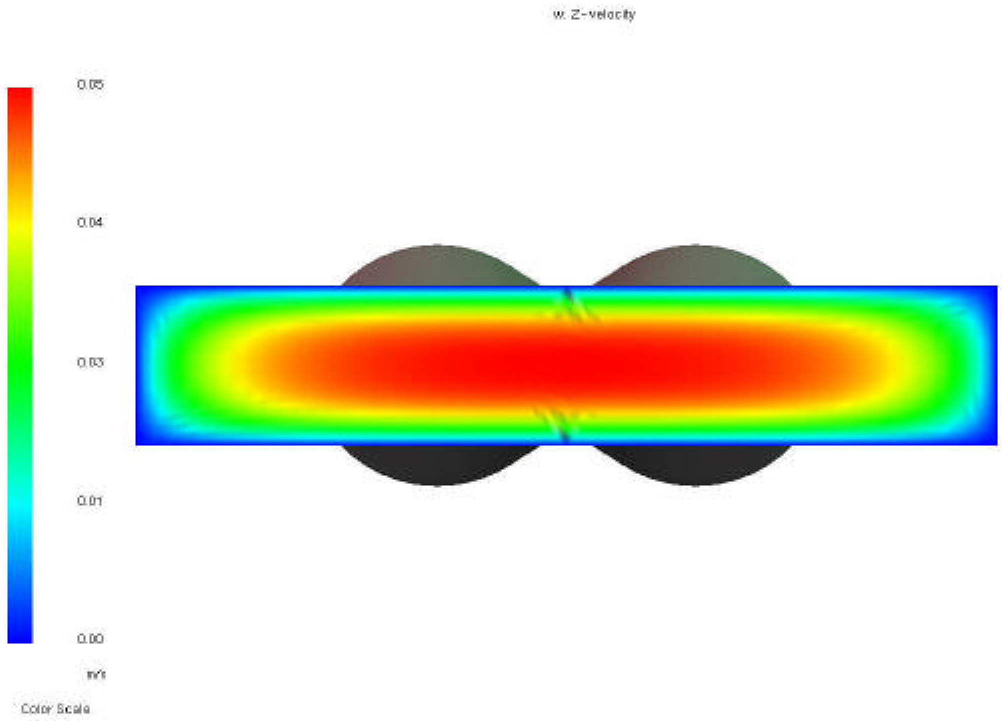
Shear rate distribution in the Universal extruder (tangential mode)
and its slit die configuration:
100 RPM at 180°C in, m=10,000 Pa-s^n, n=0.5, 72.3 lb/hr

Figure 23



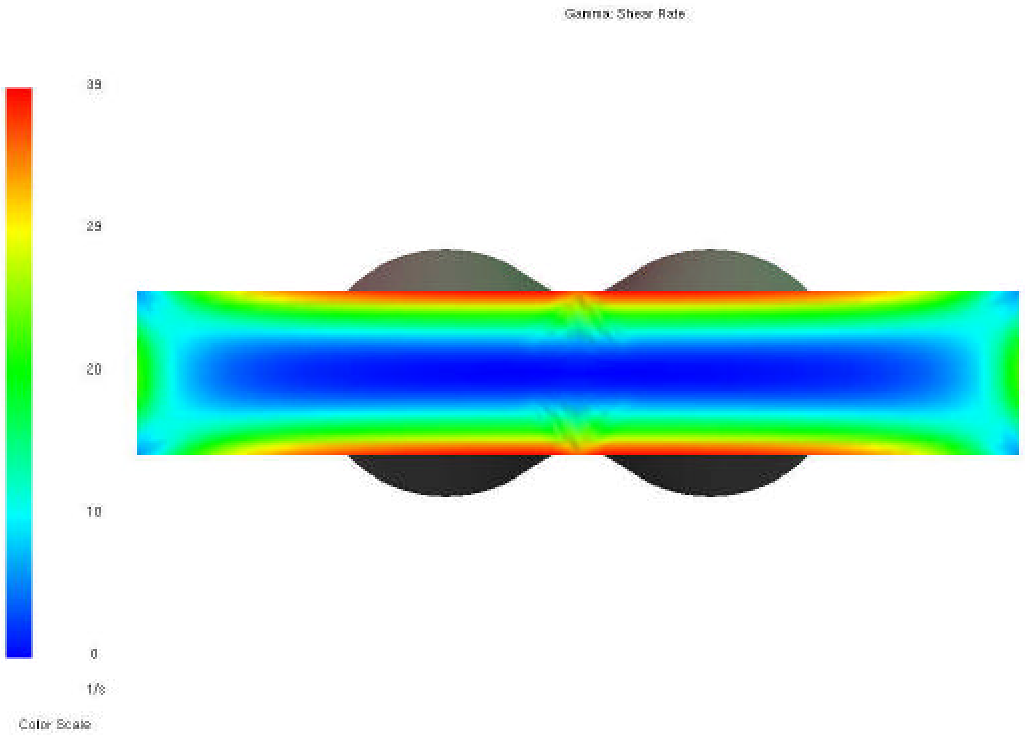
Shear rate distribution at the flight barrel interface:
100 RPM at 180°C in, 72.3 lb/hr, peak pressure = 271 psi

Figure 24



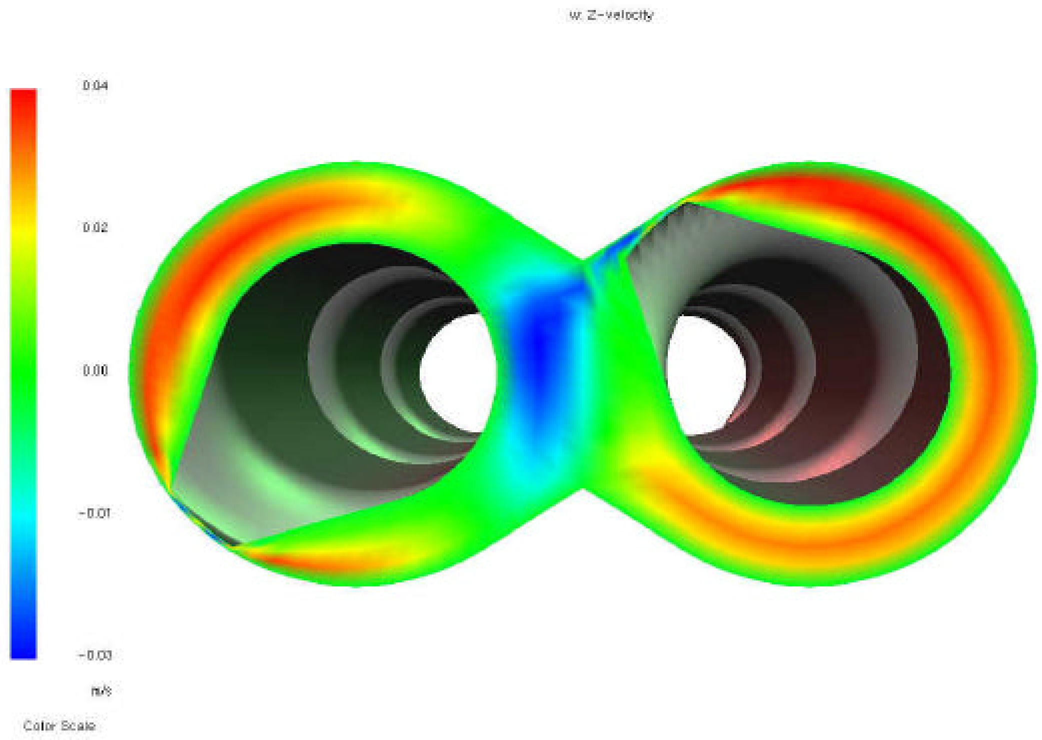
Z-velocity distribution at the die:
100 RPM at 180°C in, 72.3 lb/hr

Figure 25



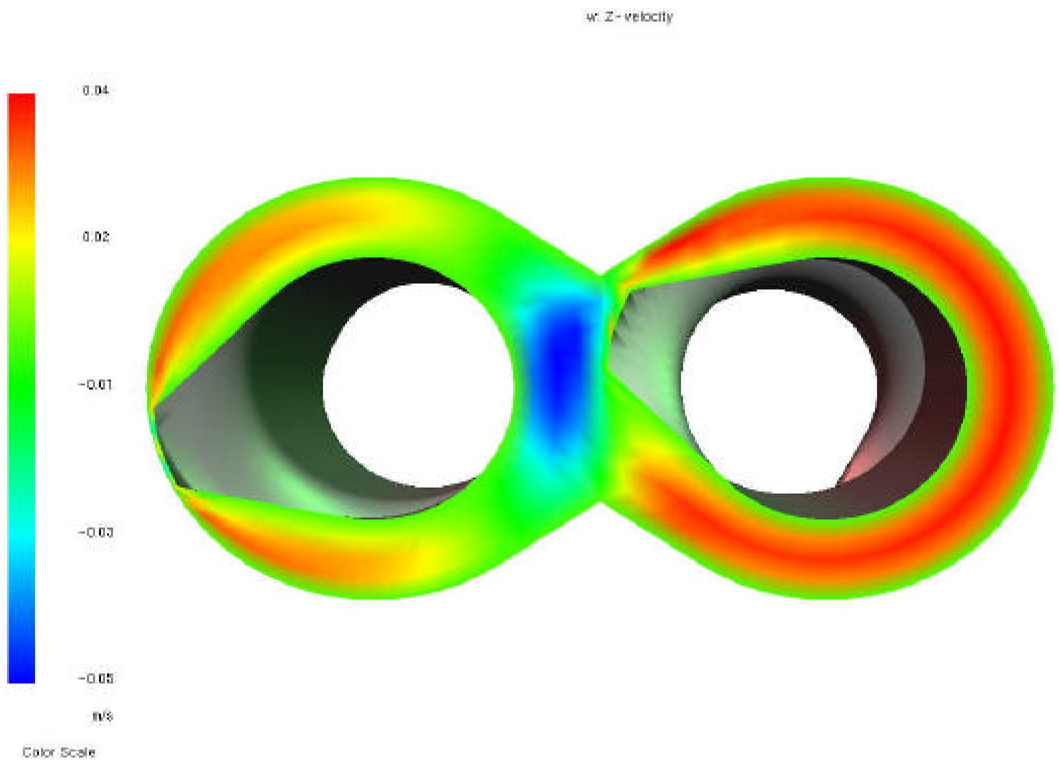
Shear rate distribution at the die:
100 RPM at 180°C in, 72.3 lb/hr

Figure 26



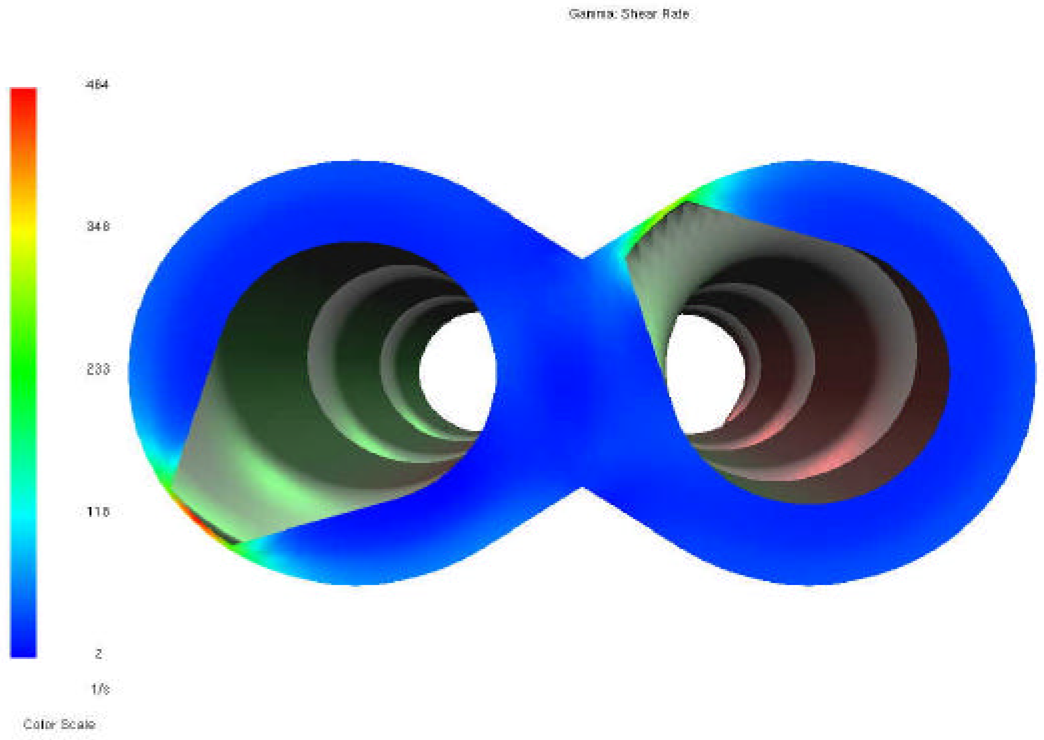
Z-velocity distribution in the screw channel:
100 RPM at 180°C in, 72.3 lb/hr

Figure 27



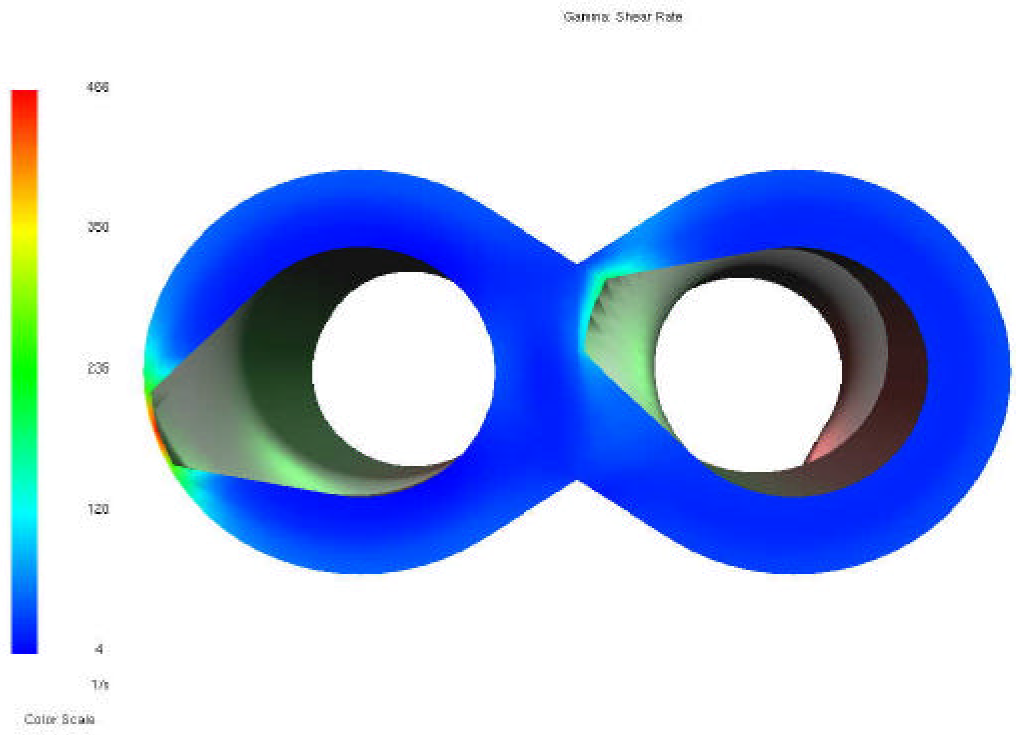
Z-velocity distribution in the screw channel:
100 RPM at 180°C in, 72.3 lb/hr, peak pressure = 271 psi

Figure 28



Shear rate distribution in the screw channel:
100 RPM at 180°C in, 72.3 lb/hr

Figure 29



Shear rate distribution in the screw channel:
100 RPM at 180°C in, 72.3 lb/hr,

Figure 30