Examination of the Performance of a High Speed Single Screw Extruder for Several Different Extrusion Applications

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Examination of the Performance of a High Speed Single Screw Extruder for Several Different Extrusion Applications

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Abstract

This study investigates the extrusion characteristics of a High Speed Single Screw Extruder, (HSSSE), to determine suitability for use in several different extrusion applications including Sheet, Fiber and Extrusion Coating. Three different material types were evaluated including a Polypropylene, PP, and High Impact Polystyrene, HIPS, for sheet extrusion, a PP fiber grade and Low Density Polyethylene, LDPE, extrusion coating grade. The extruder used for the study was a highly instrumented 63.5mm, (2.5 inch), 40:1 L/D extruder equipped with a 375KW, (500 HP) motor. Screw speeds up to 1200 rpm were evaluated.

The study demonstrated that a properly designed HSSSE could greatly improve the processing capability of a small diameter single screw extruder for a wide range of applications.

Introduction

One way of increasing the throughput capability of a single screw extruder is to simply increase the screw RPM. This is easier said then done. Depending on the extrusion process, certain extruder sizes have been chosen to meet the melt quality requirements of a given extrusion process. The typical limitations for a given process at high screw speed are poor melt quality caused by exceeding the melting capacity of the screw design and degradation caused by high melt temperature.

Use of a smaller diameter extruder of less than 90mm diameter, (3.5 inch), can offer several advantages to achieve a higher throughput at higher screw speed. One important advantage of a smaller diameter extruder is better heat transfer characteristics. The heat transfer area to volume output ratio of a smaller diameter machine offers a wider and more flexible processing window when compared to a larger extruder. The heat transfer area to volume ratio declines rapidly with increasing extruder size. See the Figure 1 below. A higher ratio for a smaller diameter extruder will lead to improved melting efficiency and better control of melt temperature.

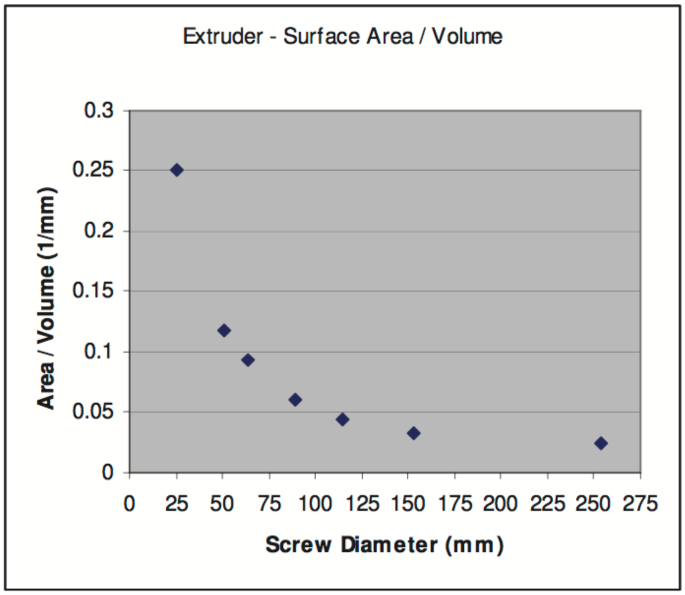

Figure 1. Extruder Surface to Volume ratio vs. Extruder Diameter

The torque requirement to rotate a Single Screw Extruder, (SSE), screw increases exponentially as the extruder diameter is increased for a given extrusion process. See Figure 2. A small diameter single screw extruder below 90mm diameter, (3.5 in), offers the advantage of a lower torque requirement. In this range, a Direct Drive extruder design can be implemented utilizing a Permanent Magnet Synchronous or A/C motor without the use of a gear reducer to further improve energy efficiency. [1]

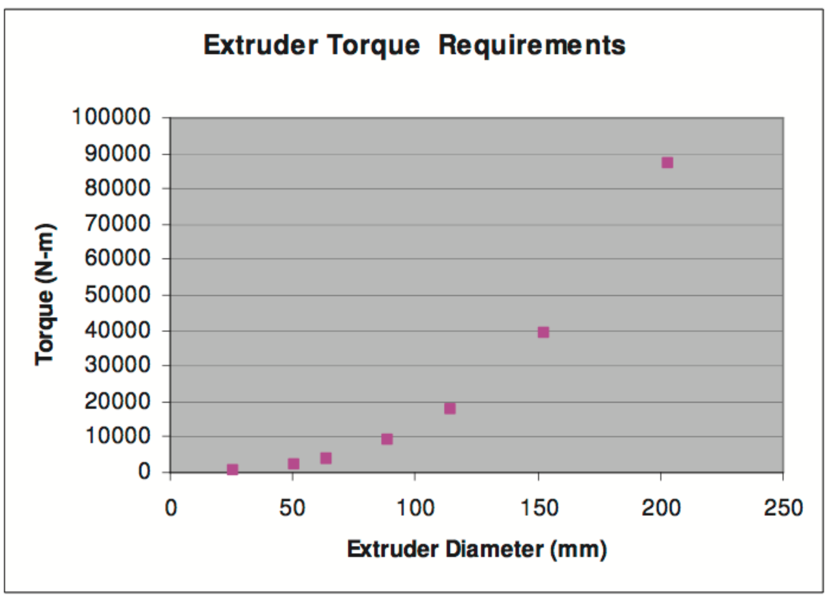

Figure 2. Torque requirements for Single Screw Extruders

Using a smaller diameter extruder to provide the same output of a much larger extruder also has the practical benefit of requiring less material to construct the extruder. This improves the economics of the design and results in a smaller footprint for a given output.

A HSSSE application is characterized by a screw circumferential speed of greater than 1 m/sec. This translates to a screw speed of greater than 300 RPM for a 63.5mm extruder. Most extrusion applications today utilize screw speeds much lower than this with the exception of extrusion coating. The screw speed range examined in this study was in the range of 400 to 1200 RPM. This corresponds to a circumferential screw speed of 1.3 m/s to 4 m/s.

In the 1990’s, high-speed extrusion was successfully demonstrated for compounding applications using a corotating twin-screw extruder. Most co-rotating twin-screw extruders are constructed from a flexible design platform consisting of segmented barrels and screws. It can easily be manipulated to optimize the processing section of the extruder. A typical maximum screw speed in the range of 600 RPM was commonly used in the mid – 1990’s, the new technology demonstrated a 1200 RPM capability. The co-rotating twin screw is operated in a starve feed mode so feed rate is independent of screw speed. This creates a flexible operating window for the process. The authors demonstrated that the high-speed process could dramatically improve throughput and maintain material properties even with higher processing temperature. [2]

Unlike Twin Screw Extruders, SSEs are constructed from a one-piece barrel and a one-piece screw. The extruder is typically flood fed so the throughput of the extruder is dependent on screw speed. This greatly narrows the operating window of this process. It is also much more difficult to optimize, compared to the corotating twin screw, because of the one-piece construction of the barrel and screw. HPM Corporation conducted studies in 1997 on a high-speed extruder using a two-stage triple wave single screw design. The paper focused on processing various materials for a compounding application. The paper concluded that an appropriate screw design would be very critical in achieving acceptable performance. [3]

The University of Paderborn recently published work on processing a range of LDPEs for a high temperature extrusion coating application using a HSSSE. The highspeed process exhibited problems with air entrapment and poor melt quality above 400 RPM and was not able to achieve the desired melt temperature range. The study demonstrated the importance of screw design in HSSSE applications. They also proposed the possibly of using a longer extruder L/D to increase both dissipative energy and residence time. [4]

This study investigates the extrusion characteristics of a HSSSE to determine suitability for use in several different extrusion applications including Sheet, Fiber and Extrusion Coating. Three different material types were evaluated included a PP and HIPS for sheet extrusion, a PP fiber grade and LDPE extrusion coating grade.

The extruder used for the study was a highly instrumented 63.5mm, (2.5 inch), 40:1 L/D extruder equipped with a 375KW, (500 HP) motor. The screw speed range examined in the study was from 400 to 1200 RPM. This corresponds to a circumferential screw speed of 1.3 m/s to 4 m/s.

Experimental

The study examined four different materials. See Table 1. The materials included an extrusion grade of PP and HIPS suitable for a sheet thermoforming application, an Extrusion Coating grade of LDPE and a PP fiber grade.

Grade	Type	MI ASTM D1238	Density g/cc	Application
Total 825E	HIPS	3	1.04	Sheet
Total 4481WZ	PP Co poly	4	0.905	Sheet
Exxon 3854	PP Homo Poly	24	0.9	Fiber
Dow 722	LDPE	8	0.918	Ext. Coating

Table 1. Resin Specifications

Experiments were conducted on a highly instrumented 63.5mm 40:1 L/D Davis-Standard extruder equipped with seven electrically heated/air cooled barrel zones. See figure 3. A Thermatic® Temperature Control system was used to control the barrel temperatures and measure the heat flux in each zone of the extruder. Eight pressure transducers were located along the axial length of the barrel at approximately 5 L/D increments, to measure the axial pressure generation along the screw. A pressure transducer and exposed junction melt thermocouple were located in the discharge adapter of the extruder in order to evaluate the output and thermal process stability of the melt. A valved adapter and a 762cm, (30 in), wide coathanger sheet die with a 1.27 mm, (0.050 in) die gap was utilized for all of the trials. A 4 L/D Static mixer was installed between the valved adapter and the die for the sheet extrusion evaluations.

Figure 3. – 63.5mm 40:1 L/D, Instrumented extruder

The study investigated three experimental screw designs. A two-stage moderate to high intensity screw design was used for processing the sheet grade PP and HIPS. A lower intensity two-stage screw was used to test the Fiber grade PP. The Extrusion coating grade LDPE was tested on a single stage very high intensity mixing screw design.

The data recorded at each operating condition included the extruder output, melt temperature measured with an exposed junction thermocouple in the melt stream at the entrance to the die, motor power consumption, and pressure at the discharge of the extruder. The pressure readings were recorded with a data acquisition system at a rate of 50 Hz. The processing stability was evaluated for each material by monitoring pressure variation and melt temperature variation vs. time at the discharge of the extruder. The melt quality of the extrudate was inspected visually as it exited the 762 mm wide extrusion die. The screw speeds examined ranged from 400 to 1200 RPM for each of the materials. The operating conditions and extrusion data for each of the tests is summarized in Table 3.

Discussion of Results

The object of this paper is to investigate the extrusion characteristics of a HSSSE and determine the suitability for use in several different extrusion applications including Sheet, Fiber and Extrusion Coating. The suitability of the HSSSE for each application was judged by comparing the performance against a pre-defined set of parameters that are commonly used in industry for each application. The process parameters examined included, feeding consistency vs. screw speed or linearity of specific output, (kg/hr-rpm), vs. screw speed, acceptable melt temperature range and required process stability. The process stability was evaluated by monitoring pressure variation, as an indication of output consistency, and melt temperature variation in time, as an indication of thermal homogeneity. Melt quality was inspected visually for defects exiting the die. The desired process parameters for each application are listed in the table below.

Grade	Type	MI ASTM D1238	Density g/cc	Application
Total 825E	HIPS	3	1.04	Sheet
Total 4481WZ	PP Co poly	4	0.905	Sheet
Exxon 3854	PP Homo Poly	24	0.9	Fiber
Dow 722	LDPE	8	0.918	Ext. Coating

Table 2. Acceptable Process Parameters

The output rate, melt temperature and power consumption are plotted vs. screw speed for each of the materials tested in Figures 4, 5, and 6, respectfully. The graphical presentation of the data will be used in the discussion of results below.

The output rate vs. screw speed for each of the materials is shown below in figure 4.

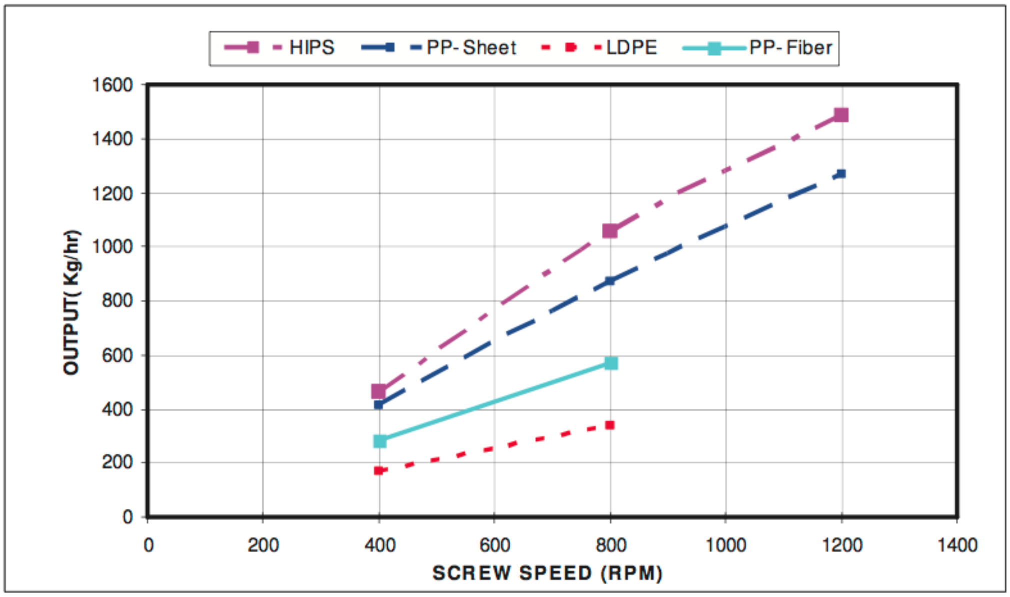

Figure 4. Output rate vs. Screw Speed

The melt temperature vs. screw speed for each of the materials tested is shown below in Figures 5.

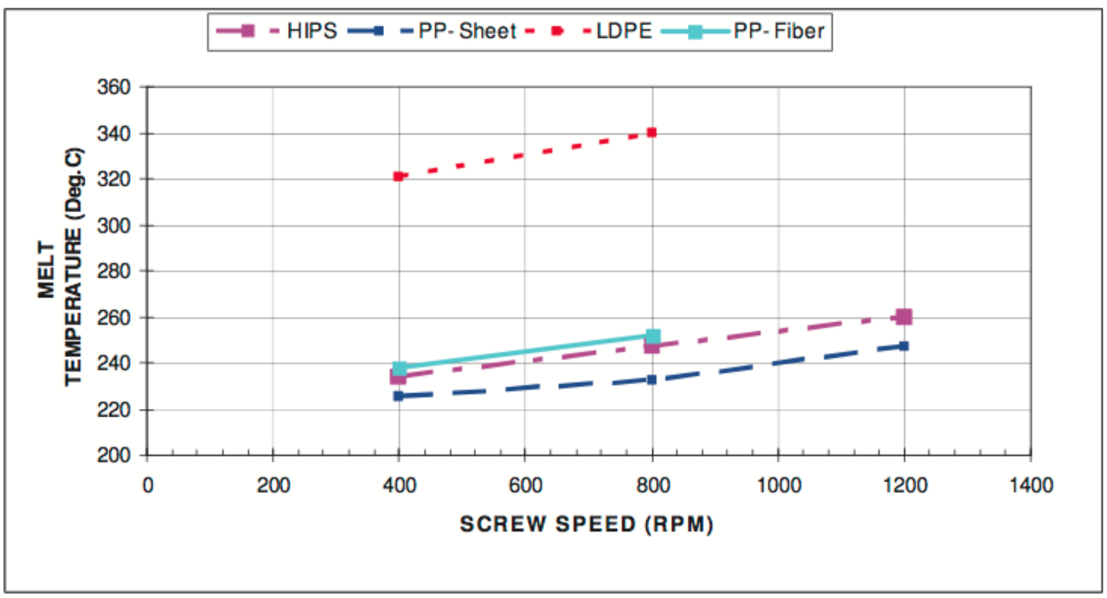

Figure 5. Melt Temperature vs. Screw speed

The motor power consumption vs. screw speed for each of the materials tested is shown below in Figure 6.

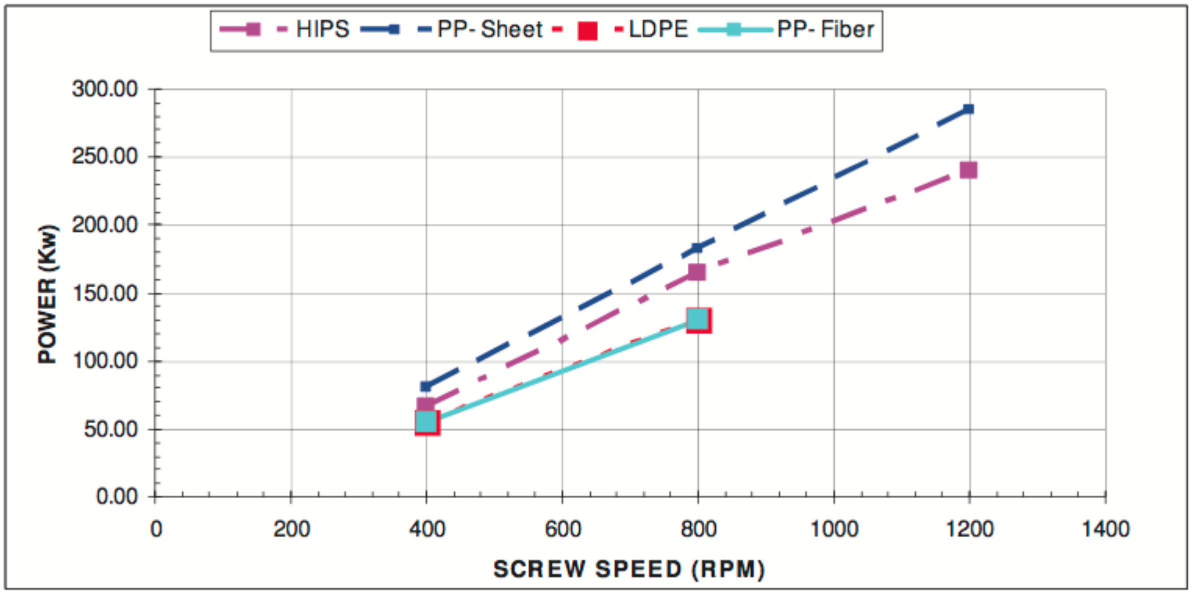

Figure 6. Drive Power vs. Screw Speed

The Specific output kg/hr- rpm vs. screw speed for each of the materials is shown in Figure 7. This figure examines the linearity or feeding consistency of the through put vs. screw speed and can help identify the point at which process limitations due to solids conveying or melting capacity occur.

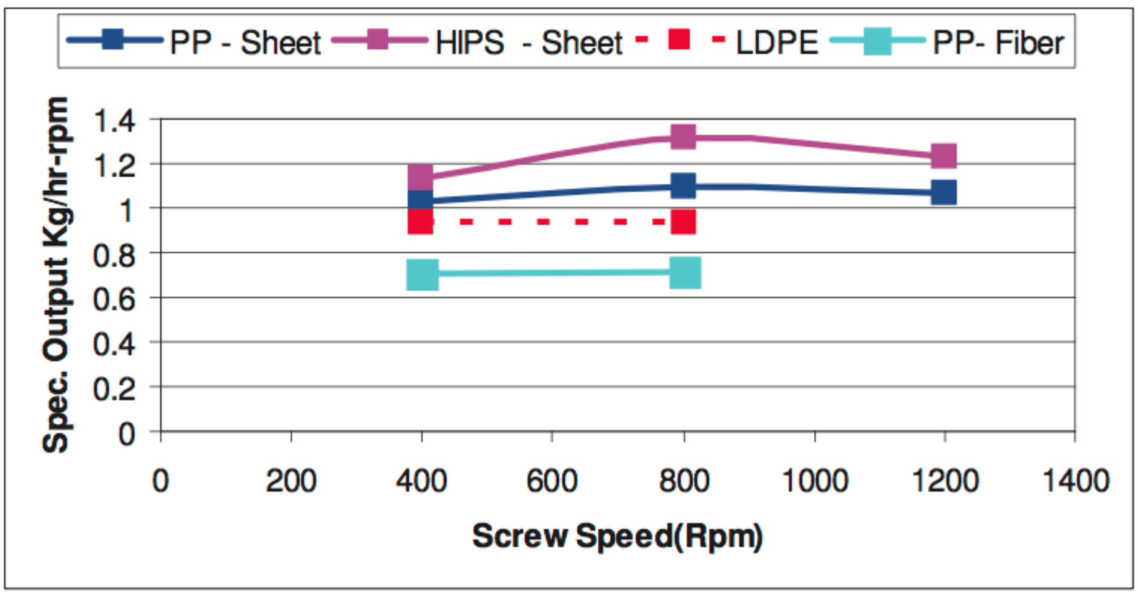

Figure 7. Specific output vs. Screw Speed

The experimental data for each of the materials tested will be compared below to the process requirements shown in Table 2.

<u>PP Sheet Extrusion</u>
The output vs. screw speed for the PP sheet extrusion grade material is shown in Figure 4. This figure shows that the rate increased linearly with screw speed. Figure 7 shows the specific output rate, kg/hr-rpm, defined as the output rate divided by the screw RPM. This figure shows a slight increase at 800 RPM however, at 400 and 1200 RPM the value was constant. The relatively constant specific output throughout the processing range, indicates that solids conveying zone of the screw was operating efficiently. The variation in specific output of less that 1.8 % over the desired processing range is well below the required feed rate consistency criteria.

The melt temperature vs. screw speed is shown in Figure 5. The melt temperature increased with increasing rpm, but remained in an acceptable range when compared to the processing criteria listed in Table 2. The melt temperature increased from 225 Deg C, at 400RPM, to a maximum of 247 Deg C at 1200 RPM.

The thermal process stability remained in the desired range up to the 800 RPM operating condition. At the 1200 RPM operating condition, the melt temperature fluctuations in time increased to 2.2 Deg C.

The variations in pressure at the extruder exit, P-BP, were in the range of +/- 2% target set in the processing criteria. Most sheet extrusion systems have extruders equipped with melt pumps to handle this level of pressure variation.

Visual inspection of the melt curtain at the 400 and 800 RPM conditions showed excellent melt quality. The visual melt quality of the extrudate declined at the 1200 RPM condition. A melt disturbance was observed in the sheet exiting the die.

Overall, the performance of the HSSSE for processing a sheet grade of PP was acceptable up to a screw speed of 800 RPM. To ensure consistent output and reduce the thermal gradient in the melt stream exiting the extruder, a melt pump and static mixer are recommended for this application.

HIPS Sheet extrusion grade

The output vs. screw speed for the HIPS sheet extrusion grade material is shown in Figure 4. The specific rate, shown in Figure 7, was lowest at 400 RPM and reached a maximum at 800 RPM. The peak specific output at 800 RPM was 10% above and the 400 RPM condition was 10% below the average specific output. These conditions exceeded the upper limit defined in Table 2.

The melt temperature vs. screw speed is shown in Figure 5. The melt temperature increased with increasing RPM. The upper limit of the melt temperature was reached at the 800 RPM operating condition. The melt temperature increased from 234 Deg C, at 400RPM, to 247 Deg C at 800 RPM. This exceeded the maximum temperature limit by 2 Deg C.

The thermal process stability remained in the desired range. The melt temperature fluctuations in time remained below 0.5 Deg C over the entire processing range. This indicates good thermal homogeneity.

The variation in pressure at the exit of the extruder, PBP, remained in an acceptable range for all of the operating conditions.

Visual inspection of the melt curtain at the 400, 800 and 1200 RPM conditions showed excellent melt quality.

Overall, the performance of the HSSSE for processing the sheet grade of HIPS was acceptable up to a screw speed of 800 RPM. The maximum melt temperature was exceeded above this screw speed. To ensure consistent output and reduce the thermal gradient in the melt stream exiting the extruder, a melt pump and static mixer is recommended. A lower intensity screw design is required to control the melt temperature above 800 RPM. Further optimization of the barrel temperature in the solids conveying zone could help to reduce the variation in specific output at the different screw speeds.

LDPE Extrusion Coating grade

The output vs. screw speed for the LDPE extrusion coating grade material is shown in Figure 4. This figure shows that the output rate increased linearly with screw speed. The specific rate shown in Figure 7 remains constant between 400 and 800 RPM. The constant specific output indicates that solids conveying remained efficient over this processing range. The specific output increased slightly between 400 and 800 RPM but remained within the desired processing range criteria.

The melt temperature vs. screw speed is shown in Figure 5. The melt temperature increased with increasing rpm and exceeded the target specifications between 400 and 800 RPM. The 1200 RPM condition was not tested due to the high melt temperature. The elevated melt temperature indicates that the screw design is imparting excessive mechanical energy into the material. A lower intensity screw design is required in order process this material above 400 RPM.

The thermal process stability of this design was excellent. The melt temperature fluctuations in time were less than 0.5 Deg C at both screw speeds. This is a good indication that the intensity of the screw design can be decrease to control the melt temperature.

The variations in pressure at the exit of the extruder, PBP, were negligible and were under +/- 1 bar for both operating conditions.

Visual inspection of the melt curtain at the 400 and 800 RPM conditions showed excellent melt quality.

Based on the results of the trial, a lower intensity screw design is required in order to operate above the 400 RPM operating condition and reduce the melt temperature to within an acceptable range.

<ins>PP – Fiber grade</ins>
A short test was conducted under high-speed conditions to examine the extrusion performance of a fiber grade PP on the moderate intensity two-stage screw design. The output vs. screw speed for the PP Fiber extrusion grade material is shown in Figure 4. This figure shows that the rate increased linearly with screw speed. The specific output rate, kg/hr-rpm, remained constant over the screw speed range from 400 – 800 RPM. This is well within the processing range required. See Figure 7.

The melt temperature vs. screw speed is shown in Figure 5. The melt temperature increased with increasing RPM. The upper limit of the melt temperature was reached at the 800 RPM operating condition. The melt temperature increased from 238 Deg C, at 400 RPM, to a maximum of 252 Deg C at 800 RPM.

The thermal process stability remained in the desired range. The melt temperature fluctuations in time remained below 1.1 Deg C over the entire processing range. This indicates good thermal homogeneity.

The variations in pressure at the exit of the extruder, PBP, were in the range of +/- 2% target set in the processing criteria for both operating conditions. Most fiber extrusion systems have extruders equipped with melt pumps to handle this level of pressure variation. Visual inspection of the melt curtain at the 400 and 800 RPM conditions showed excellent melt quality.

Overall, the performance of the HSSSE for processing a fiber grade PP was acceptable up to a screw speed of 800 RPM. The melt temperature exceeded the target limits at 800 RPM. The two stage screw design used for this short test imparted excessive mechanical energy into the material causing the melt temperature to exceed the maximum allowable temperature at 800 RPM. An optimized single stage screw design with a lower level of intensity is required for this process.

Conclusion

The study demonstrated that a properly designed HSSSE could greatly improve the processing capability of a small diameter single screw extruder for a wide range of applications.

The direct drive 63.5 mm, (2.5 in), HSSSE successfully processed the PP sheet grade within the defined processing limits up to a throughput rate of 1000 kg/hr. This is approximately 9 times larger that the output of a conventionally designed extruder used today. The HIPS sheet grade was processed within the design parameters up to 1100 kg/hr. With further screw design optimization to improve melting and mixing capability higher output rates are achievable. The LDPE extrusion coating screw processed the material up to a screw speed of 400 RPM.

Further optimization by decreasing the intensity of the screw design will widen the operating window.

Further optimization of the screw designs for each application will help to increase overall performance. Future work will focus on understanding solids conveying, melting and mixing within the HSSSE under high-speed extrusion conditions.

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KeyWords: High Speed Single Screw Extrusion, High output rate, sheet, fiber, extrusion coating

MATERIAL		HIPS	HIPS	HIPS	PP -Co	PP -Co	PP -Co	LDPE- EC	LDPE -EC	PP- Fiber	PP-Fiber
RPM		400	800	1200	400	800	1200	400	800	400	800
Kg/hr		461	1055	1486	413	873	1266	167	340	283	573
KW		67.0	165.0	230.0	80.0	183.0	285.0	53.0	130.0	76.0	178.0
Kg/Hr/Kw		6.9	6.4	6.5	5.2	4.8	4.4	3.2	2.6	3.7	3.2
Kg/Hr/Rpm		1.15	1.32	1.24	1.03	1.09	1.06	0.42	0.43	0.71	0.72
P- BP	Bar	94.00	116.00	105.00	91.38	124.14	130.76	39.17	41.03	21.17	31.24
P-HD	Bar	49	59	56	40	56	58	NA	NA	NA	NA
P-HD (var)	Bar	2	2	4	3	4	3	1	1	1	1
VAR.BP (%)	Bar	2.55%	2.07%	3.90%	3.32%	3.33%	2.11%	1.76%	3.36%	NA	NA
MELT TEMP	Deg C	234	247	260	225	232	247	321	339	238	252
VAR Deg C		0.5	0.5	0.5	0.0	1.1	2.2	0.3	0.3	0.6	1.1
		Set point	Set point	Set point	Set point	Set point	Set point	Set point	Set point	Set point	Set point
Z-1 TEMP	Deg C	232	232	232	232	232	232	260	260	204	204
Z-2 TEMP	Deg C	232	232	232	232	232	232	288	288	204	204
Z-3 TEMP	Deg C	232	232	232	232	232	232	302	302	204	204
Z-4 TEMP	Deg C	232	232	232	232	232	232	316	316	204	204
Z-5 TEMP	Deg C	232	232	232	232	232	232	316	316	204	204
Z-6 TEMP	Deg C	232	232	232	232	232	232	316	316	204	204
Z-7 TEMP	Deg C	232	232	232	232	232	232	316	316	204	204
D-1 TEMP	Deg C	232	232	232	232	232	232	316	316	232	232
D-2 TEMP	Deg C	232	232	232	232	232	232	316	316	232	232
D-3 TEMP	Deg C	232	232	232	232	232	232	316	316	232	232
D-4 TEMP	Deg C	232	232	232	232	232	232	316	316	232	232
D-5 TEMP	Deg C	232	232	232	232	232	232	316	316	232	232
D-6 TEMP	Deg C	232	232	232	232	232	232				
D-7 TEMP	Deg C	232	232	232	232	232	232				
D-8 TEMP	Deg C	232	232	232	232	232	232				

Table 3. Operating Conditions P-BP pressure reading at the tip of the screw P-HD pressure reading at the inlet to the die

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