DYNAMIC TORQUE OF A SINGLE SCREW EXTRUDER

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Abstract

The dynamic torque for a 63.5-mm extruder was measured with a Wheatstone strain-gage bridge attached to its single-stage screw between the drive and flow channel. Measurements were made of torque for three resins: (1) LDPE pellets, (2) PET pellets, and (3) PET powder. The results show that the dynamic torque of each resin is unique, and that it depends upon screw speed and on solids' conveying barrel-metal temperature.

Background

Strain gages [1] were used to measure extrusion torque for the study of solids' conveying. The strain gages were mounted to an isolated section of the barrel of a device, which simulates the solids' conveying section of a single-screw extruder. The barrel stresses provided the torque, and the torque was used to calculate average friction factors.

The dynamic load (amperage) of an extruder drive was recorded [2], and it was shown to correlate with pressure stability. Instability of low frequency (flow surging) was studied for HIPS. The surging was attributed to solids' conveying instability because the barrel temperature of the solids' conveying section was found to have a profound affect on the dynamic load.

The study here uses strain gages mounted directly to a screw to measure its dynamic torque. This arrangement provides a highly responsive signal of the dynamic torque for the complete screw without the contribution of the drive (torque losses due to drive inefficiencies and damping). Torque can be studied for high or low-frequency variation.

Experimental Apparatus

A 63.5-mm extruder screw was equipped with four strain gages as shown in Figure 1. The gages were mounted as a Wheatstone bridge to the screw in a recessed annulus between the drive and the beginning of the solids' conveying section. The strain measurement had inherent temperature, thrust, and bending compensation. The torsional strain of the screw was calibrated to represent torque up to almost 5500 N-m.

The electrical connections were made through a bore in the screw and then through a pipe at the drive end. A slip ring mechanism (four coin silver rings with two carbon brushes per ring) on the end of the pipe transmitted the signal from the turning screw to a bridge signal conditioner (Sensing Systems Corporation 1601C) to give analog output. The frequency response was flat to 100 Hz. The output data were digitally sampled every 0.04 second.

Variables

Three polymers were tested, LDPE pellets, PET pellets, and PET powder. Different screw speeds were used at different solids' conveying barrel-metal temperatures as shown in Table 1. The other barrel temperatures were kept constant as shown. In addition, average barrel-pressure profile and flow-rate were recorded.

Table 1

Barrel Temperature Profiles

Zone	LDPE, Pellets	PET, Pellets	PET, Powder
Nominal rpm	20, 40	15, 25	15, 25, 35
Zone 1	177 °C, 204 °C	243 °C, 260 °C	254 °C
Zone 2	204 °C	265 °C	265 °C
Zone 3	260 °C	277 °C	277 °C
Zone 4	260 °C	277 °C	277 °C
Zone 5	260 °C	277 °C	277 °C
Zone 6	260 °C	277 °C	277 °C
Product	264 °C – 274 °C	282 °C	282 °C

Results

Bimodal Frequency Distribution

Typically, the frequency distribution of the dynamic torque was bimodal. Therefore, the torque data are plotted as a function of time over a long time period and over a short time period. The length of the time period for each plot was chosen to capture typical variations in torque that occur. A sampling period of 5 minutes is used to illustrate low frequency results, and a sampling period of 10 seconds is used to illustrate the high frequency results. The length of time for the high frequency is chosen to be 10 seconds so that only a few screw revolutions will occur.

The period of time over which the data are studied depends upon the application of the results. Low frequencies would be most indicative of flow instability that would be evident in the product (e.g. cast sheet). High frequencies (with a period typically less than that of a revolution of the screw) would likely not be seen in the product because disturbances of high frequency are normally dampened in the delivery system [3]. However, the nature of the periodic torque at a high frequency is another parameter that might be used to characterize solids' conveying.

Observations of Long Period Oscillations

LDPE Pellets

Figure 2 shows the results for LDPE at two speeds (20 rpm and 40 rpm) and two temperatures of the solids' conveying zone (177 °C and 204 °C.) Figure 2 shows that the torque amplitude of the LDPE is very small and that the effect of screw speed on the dynamics of torque is slight. However, screw speed is shown to have a major effect on average torque. As would be expected, higher screw speed is associated with higher torque.

The torque data for the LDPE show that the solids' conveying barrel-metal temperature has a slight influence on the average torque. Barrel metal temperatures in the solids' conveying section of 204 °C have a slightly lower average torque than that of the barrel-metal temperatures of 177 °C. The effect is most pronounced at the speed of 40 rpm, but it is still slight. Low frequency variability of the torque is slight and has a long period. It could be the result of drifting machine conditions, such as barrel-metal temperature drift.

The stability of the LDPE torque of Figure 2 also indicates that the nature of the extruder machine does not contribute to the torque dynamics. Gearbox teeth chatter and screw misalignment are two example sources of torque variability that would be a result of the extruder mechanics. Based on these constant torque results for LDPE, it is assumed that torque variability for the other data is not caused by the machine.

Torque data for LDPE were also measured for individual changes in temperature of all of the other barrel zones, and the effect on dynamic torque was not measurable or plotted. However, the average torque slightly changed because of the change in motor power for different barrel heats.

PET Pellets

Data for PET pellets are shown by Figure 2 for two conditions of speed (15 rpm and 25 rpm) and two conditions for the first barrel-metal temperature (243 °C and 260 °C). The variations in torque that are shown are much more significant than those for LDPE. As can be seen, the variation in torque for the PET pellets is as high as about 100 N-m for the 25 rpm condition at the barrel-metal temperature of 243 °C. The period of oscillation is about 30 seconds. At the lower speed of 15 rpm, the variation in torque is less pronounced and the period slightly deceases.

The influence of the solids' conveying barrel-metal temperature is pronounced for the PET pellet torque amplitude of Figure 2. As the temperature is raised from 243 °C to 260 °C, the average torque and the amplitudes of the torque oscillations decrease, and the frequency of the oscillations increases. This occurred for both of the 15 rpm and 25 rpm test speeds.

PET Powder

Figure 3 shows the data for PET powder at the single barrel-metal temperature of 254 °C. The data are for three speeds, and the variation in torque is most pronounced of the three polymers tested. The low frequency oscillations appear to be a maximum at about 200 N-m amplitude at the lower screw speeds of 15 and 25 rpm. At the highest screw speed of 35 rpm, the torque amplitude is somewhat diminished, but still greater than that for pellets. The data for PET pellets of Figure 2 showed the reverse trend in that the variation in torque was smallest at the lowest screw speed.

Flow Rates

The mass flow-rate is a linear function of screw speed for each of the polymers. It was highest for the PET pellets, and lowest for the LDPE. The melt density of the LDPE (s.g. = 0.83) was significantly lower than that of the PET (s.g. = 1.17), which is the major reason for the lower mass flow of the LDPE. On a volume melt-flow basis, the flow rates were comparable. The average measured flow rates as a function of speed, N, are given in Table 2. In general, the flow rate was independent of barrel temperature, except for LDPE. The higher barrel zone temperature (204 °C) for LDPE had almost a 5% lower flow rate than that shown in Table 2.

Table 2

Mass Flow Rate, N = rpm

Resin	Flow, kg/hr
LDPE pellets (177 °C)	1.075 N
PET pellets	1.721 N
PET powder	1.562 N

Discussion of Long Period Oscillations

Solids' conveying and melting are the two readily accepted sources of extrusion instability that can be attributed to the polymer characteristics. Some other factors, such as feed resin uniformity, feed-hopper level cycling, barrel-zone temperature cycling, drive irregularity, or load fluctuation are also possible sources of oscillations, but they have been assumed to be negligible because of the steady LDPE results.

Melting Rate and Flow Rate

If the melting rate is too low for the polymer at the prevailing flow rate, then the unmelted material can not pass the constriction of the compression section of the screw. The flow rate will slow until sufficient melting has occurred or the solid bed breaks up and then pass through the metering section of the screw. This produces a "slow and go" flow situation and instability, especially when occurring with the break up of the solid bed. Flow instability is shown to coincide with motor load or torque oscillations [2].

Table 1 shows that the flow rate of LDPE is much less than those for PET, pellets or powder at the same extruder speed. In addition, the heat of fusion of all of the polymers is about the same at about 140 kJ/kg. Therefore, the energy needed to melt the LDPE polymer will be significantly less than for the PET polymers at the same speed. Melting will be much more easily accomplished for the LDPE than for the PET.

Barrel Metal Temperature and Melting Rate

The effect of the solids' conveying barrel-metal temperature (Figure 3) for LDPE will also provide greater melting rate when compared to PET pellets or powder. Note that the barrel metal is at a temperature (177 °C or 204 °C) that is higher than the melting point (125 °C) of the LDPE. The PET data have barrel-metal temperatures (243 °C to 260 °C) near the melting point (250 °C). Therefore, there is much greater potential for melting of the LDPE so that melting will be initiated much sooner. The result is a smaller solid plug entering the compression section, which will melt more quickly (less solid plug mass, larger surface area-to-mass ratio) and will more easily pass (smaller initial solid plug dimension) through the compression section. Therefore, barrel-metal temperature in solids' conveying is another factor that causes the LDPE to melt more readily than the PET.

Melting Rate, Frequency, and Amplitude

The data for PET pellets of Figure 3 show that the barrel temperature changes the amplitude and frequency of its torque. A higher barrel temperature lowers the amplitude of the torque and increases the frequency for both screw speeds. Again, melting rate is a likely cause in that a smaller solid-plug would be entering the compression section at the higher temperature. The smaller plug causes smaller amplitude and takes less time for melting to "catch up" with the rate, which increases the frequency.

Therefore, the LDPE has both lower flow rate and higher melting potential to make it melt much more efficiently than PET, which gives it the most consistent torque. In addition, the effect of barrel-metal temperature to change the dynamic torque of the PET pellets also indicates that melting is a major factor in the torque oscillations for it.

Barrel Pressure-Profiles and Solids' Conveying

The effect of solids' conveying on stability must be considered. The data for the flow rate for PET pellets showed that the flow rate was independent of barrel-metal temperature. The data for the barrel pressure-profile for the PET pellets of Figure 4 show that the pressures at the higher barrel-metal temperatures to be significantly lower. The conclusion is that the solids' conveying efficiency was not greatly affected by the barrel-metal temperature change for PET pellets because flow rate did not change. The barrel-metal temperature primarily improved the melting rate, which resulted in a smaller solid-plug and improved torque stability.

Figure 5 shows the data for the LDPE pressure profile to be similar to that for the PET pellets, except that the pressures are lower and the effect of barrel-metal temperature is much less pronounced. Both of these observations substantiate that the melting is more than sufficient for the LDPE. However, the flow rate at the higher barrel-metal temperature (204 °C) was about 5% less than that at the lower barrel-metal temperature (177 °C). The conclusion is that friction factors were affected by the barrel-metal temperature, but they did not produce torque oscillations of low frequency.

Screw Speed and Melting Rate

The effect of screw speed on the low frequency oscillations can also be tied to the melting rate. At lower speeds, the melting rate will be proportional to screw speed. As speed is increased, the melting rate will not increase at as great a rate. This has been shown [4] to be a result of the greater heat loss to the barrel at the higher speeds (peak melt-pool temperatures are higher). Therefore, the higher speeds would cause greater torque oscillations, and this is shown by Figure 2 for PET pellets. On the other hand, the melting rate for the LDPE was high enough that the speed did not appreciably affect the torque dynamics through a change in melting rate.

PET Powder

The low-frequency torque oscillations for PET powder in Figure 3 are the largest of those observed in this study, and the range of frequencies of the PET-powder torque appears to be the greatest. Also, the data of Figure 3 for PET powder exhibit little change in torque amplitude as speed is increased from 15 to 35 rpm.

The pressures in the solids' conveying region for powder were about 1/3 those for PET pellets as shown in Figure 4. This coincides with the lower flow rate for the powder (91% of pellets), and indicates that the solids' conveying driving forces are significantly lower for the powder as compared to those for the pellets. The low initial pressures of Figure 4 for the PET powder, especially at 15.7 rpm, indicate that the solids' flow is not ample, which makes the rest of the screw "starved" for resin. The lower forces will also reduce the melting rate. Again, a "slow and go" condition exists, where the flow in the rest of the screw is intermittent to accommodate the less than adequate supply from the solids' conveying section. Therefore, one source for instability for PET powder is inadequate solids' conveying.

Solids' Breakup Length from Torque Period

The periods of the long oscillations from Figures 2 and 3 can be used to model the approximate lengths of solid polymer that break up at the end of melting. The flow rate (Table 1) is divided by the compacted feed resin density (LDPE, 1015 kg/cu-m or PET, 1140 kg/cu-m), and solids' channel cross-sectional area (0.0016 sq-m from data of Figure 1) to calculate the solids' axial-velocity. Assuming that this velocity prevails for all of the unmelted resin, then the product of the period of the oscillation and the velocity approximate the axial length of solid that breaks up. Table 3 summarizes the results of this calculation.

Table 3

Length for Solids' Breakup from Torque Period

	T	Speed	Per., Min.	Per., Max.	Len., Min.	Len., Max.
	^{o}C	rpm	Sec.	Sec.	D	D
LDPE, pel.	177	40	9	18	1.0	2.1
PET, pel.	243	15	39	42	2.4	2.6
PET, pel.	243	25	27	33	2.8	3.5
PET, pel.	260	15	18	24	1.1	1.5
PET, pel.	260	25	15	21	1.5	2.1
PET, pow.	254	15	36	115	2.0	6.4
PET, pow.	254	25	30	100	2.8	9.3
PET, pow.	254	35	15	85	2.0	11.1

Table 3 clearly shows that the PET powder resin to have a very delayed melting and random melting performance as compared to PET pellets or LDPE pellets. The lengths for breakup of solids of pellets are shown to be 1.0 D to 3.5 D. However, the range for the PET powder is between 2.0 D and 11.1 D. Since the pumping section of the screw is 12 D, some solids for the PET powder were occasionally nearly exiting the extruder. The table also clearly shows the effect of the higher temperature (260 ^{o}C vs 243 ^{o}C) on decreasing the solids' length for the PET pellets (1.1 D to 2.1 D vs 2.4 D to 3.5 D).

Observations of Short Period Oscillations

Figures 6 – 8 show the same data as for Figures 2 and 3, except that the time period is reduced to 10 seconds. Also, the y-axis for the LDPE in Figure 6 is expanded and has a suppressed origin to magnify its variability.

LDPE Pellets

Figure 6 shows the high-frequency torque oscillations for LDPE pellets to be independent of speed and temperature. Both the frequency and amplitude of the highest frequency oscillations do not vary appreciably.

PET Pellets

The data for PET pellets in Figure 7 show that a small high-frequency torque exists. Also, for the higher speed condition, a lower frequency (about 0.5 cycles/s) component appears. The effect of temperature is minimal.

PET Powder

The data for PET powder in Figure 8 have the same general nature as for pellets of Figure 7, but the amplitude of the low frequency (about 0.5 cycles/s) torque is greater. The wave shape is less consistent than those for LDPE and PET pellets.

Discussion of Short Period Oscillations

The high-frequency oscillations are likely a result of solids' conveying and frictional effects. The thermal inertia involved with melting makes its contribution to high frequency torque unlikely, but solids' conveying depends on the nature of the resin solid-to-metal friction. This can have a rapid "slip-stick" nature to its character. Therefore, the data for high-frequency oscillations are assumed to be an indication of the solids' conveying nature of each polymer.

The PET powder was observed to have the greatest variation in torque at high frequency (Figure 8). The variation was random as compared to PET pellets (Figure 7) and LDPE (Figure 6). Data for low-frequency torque were also most random, which reinforces the assertion that the solids' conveying is key to the instability of the PET powder. The torque for the PET pellets does not have the amplitude of the PET powder, but the frequency appears to be similar. The frequency appears to be a function of the polymer and not a function of the resin form, pellets or powder. This is more evident from observation of LDPE pellets, which has a high-frequency torque as compared to either PET. Therefore, it may be possible to distinguish polymer solids' conveying characteristics based on the dynamic torque of solids' conveying. A laboratory solids' conveying machine with dynamic-torque measurement capability would provide such information.

The observation that the temperature or speed had little effect on the high frequency torque for LDPE indicates that its friction factors are stable. Amplitude and especially frequency of the torque are consistent for the two different speeds and temperatures of Figure 6. The steady torque performance of the LDPE of Figure 2 confirms this.

Finally, it should be noted that polyethylene extrusion is commonly done with a single extruder and no melt pump. PET extrusion, on the other hand, requires a melt pump or metering extruder after a plasticating extruder to assure steady flow. This is consistent with the dynamic torque measurements of the two polymers made here.

Conclusions

1. Dynamic torque has a bimodal frequency distribution.
2. Dynamic torque, frequency, and amplitude, greatly depend on the resin.
3. LDPE had much more constant torque than did PET pellets or powder. Torque variability at low frequency is apparently a result of the melting rate not matching the rate of the screw, which results in solids' break up.
4. The high-frequency torque was independent of speed and temperature, but dependent on polymer. It is apparently a result of solids' conveying friction.

References

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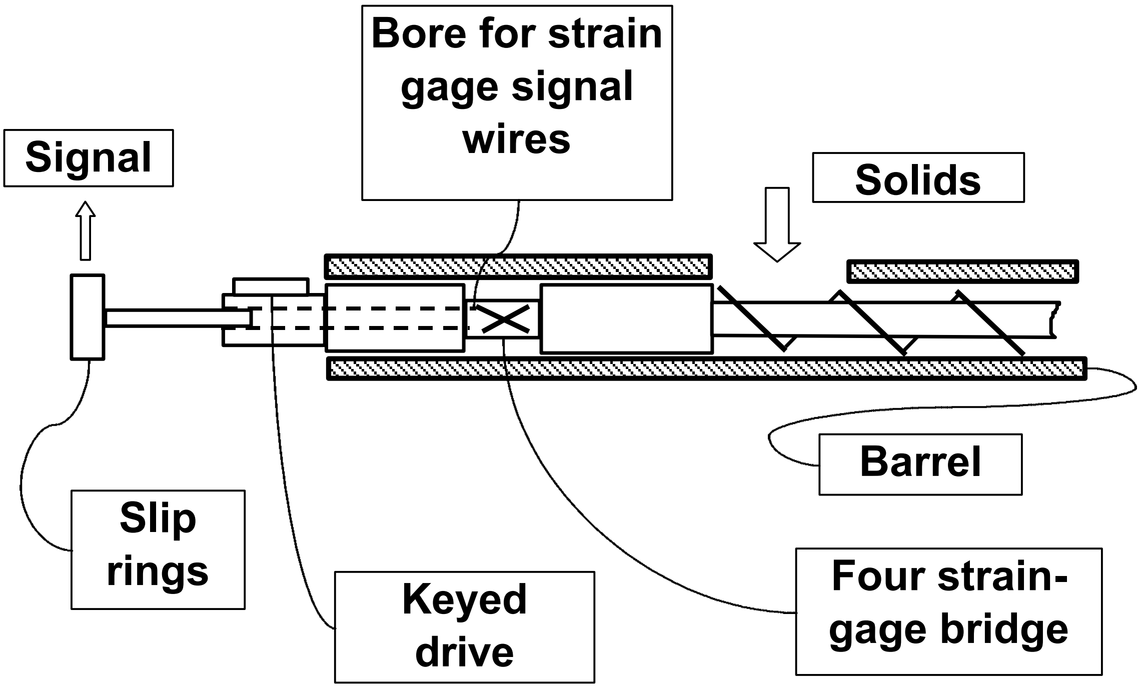

Screw: 8D-5D-12D
63.5 mm barrel bore
57.1 mm lead
6.35 mm flight width
63.4 mm flight diameter
40.6 mm solids diameter
57.4 mm pumping diameter
11.4 mm feed channel depth
3.0 mm pumping channel depth
3.67 compression ratio

Figure 1.Schematic of strain gage set-up for dynamic torque measurements.

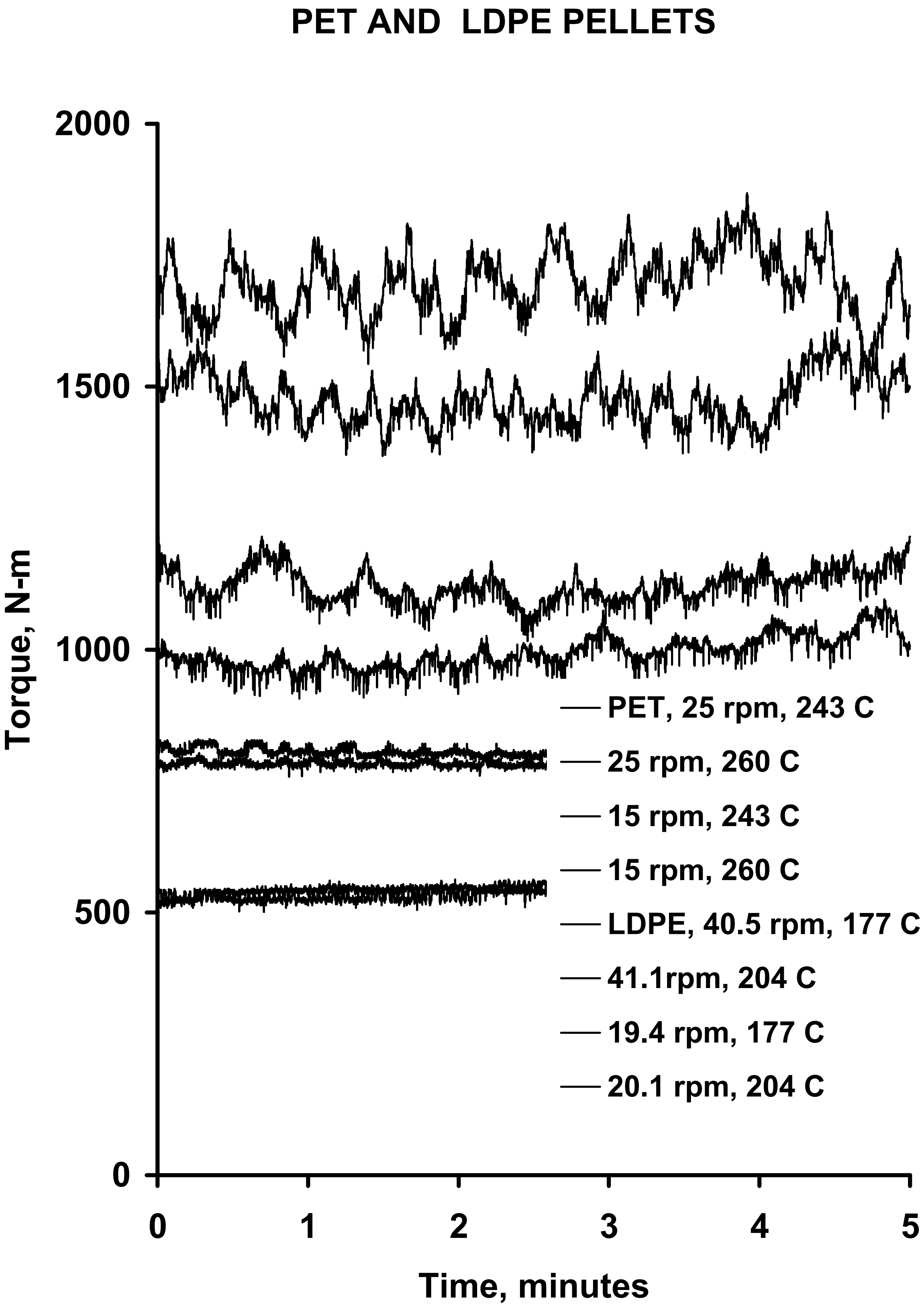

Figure 2. Torque at low frequency for PET pellets and LDPE pellets.

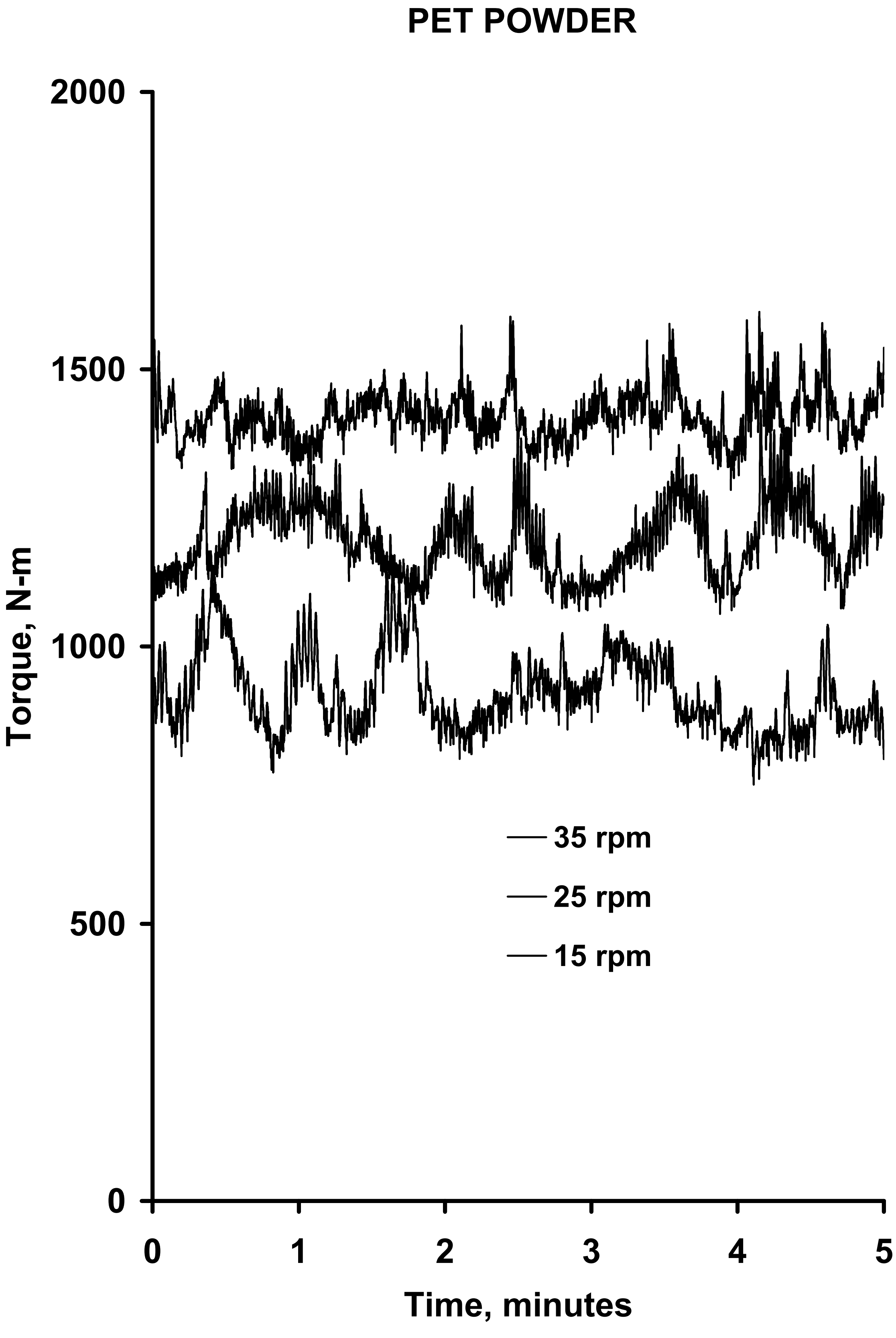

Figure 3. Torque at low frequency for PET powder at barrel metal temperature of 254 °C.

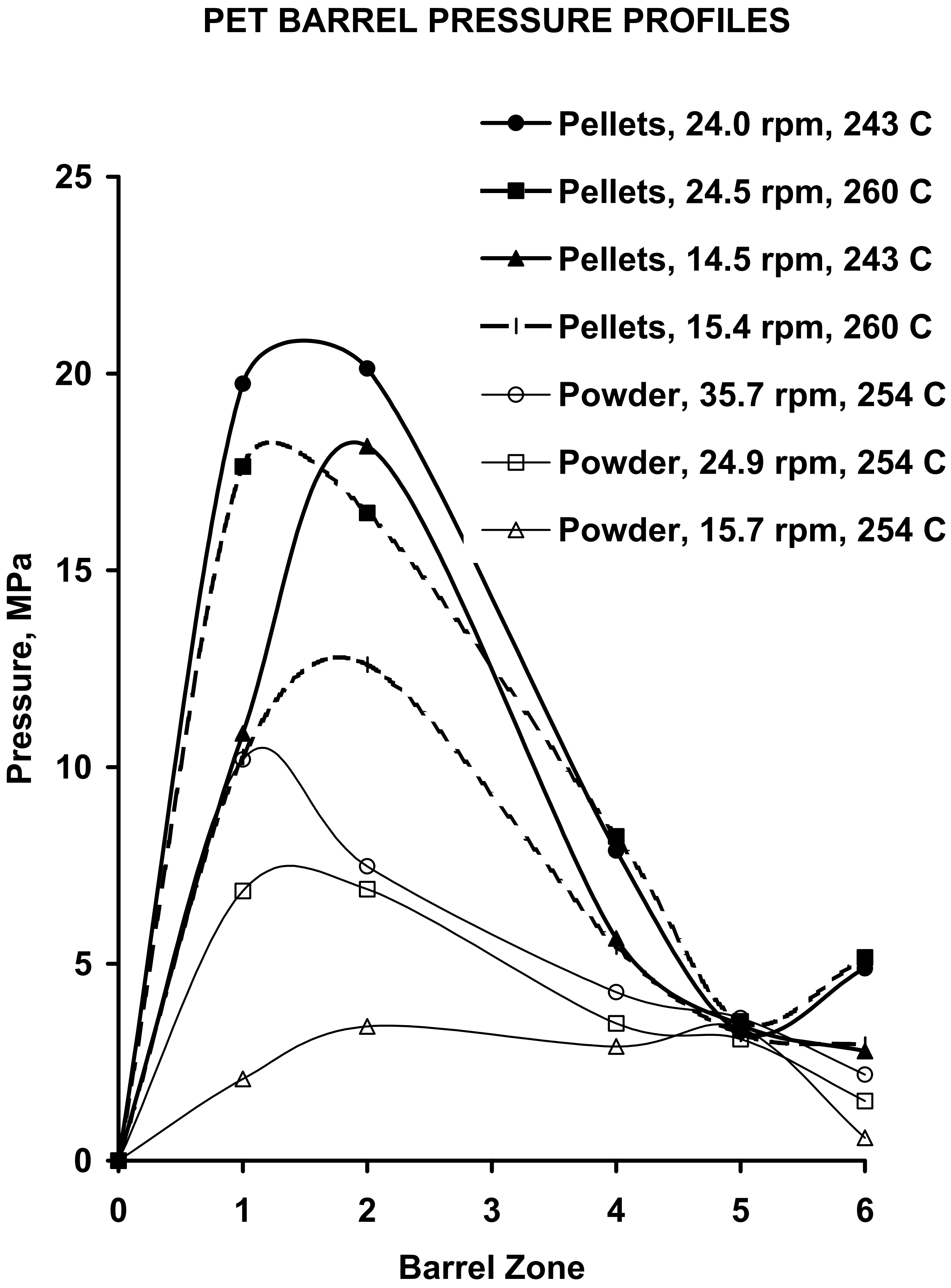

Figure 4. Barrel zone average pressures for PET.

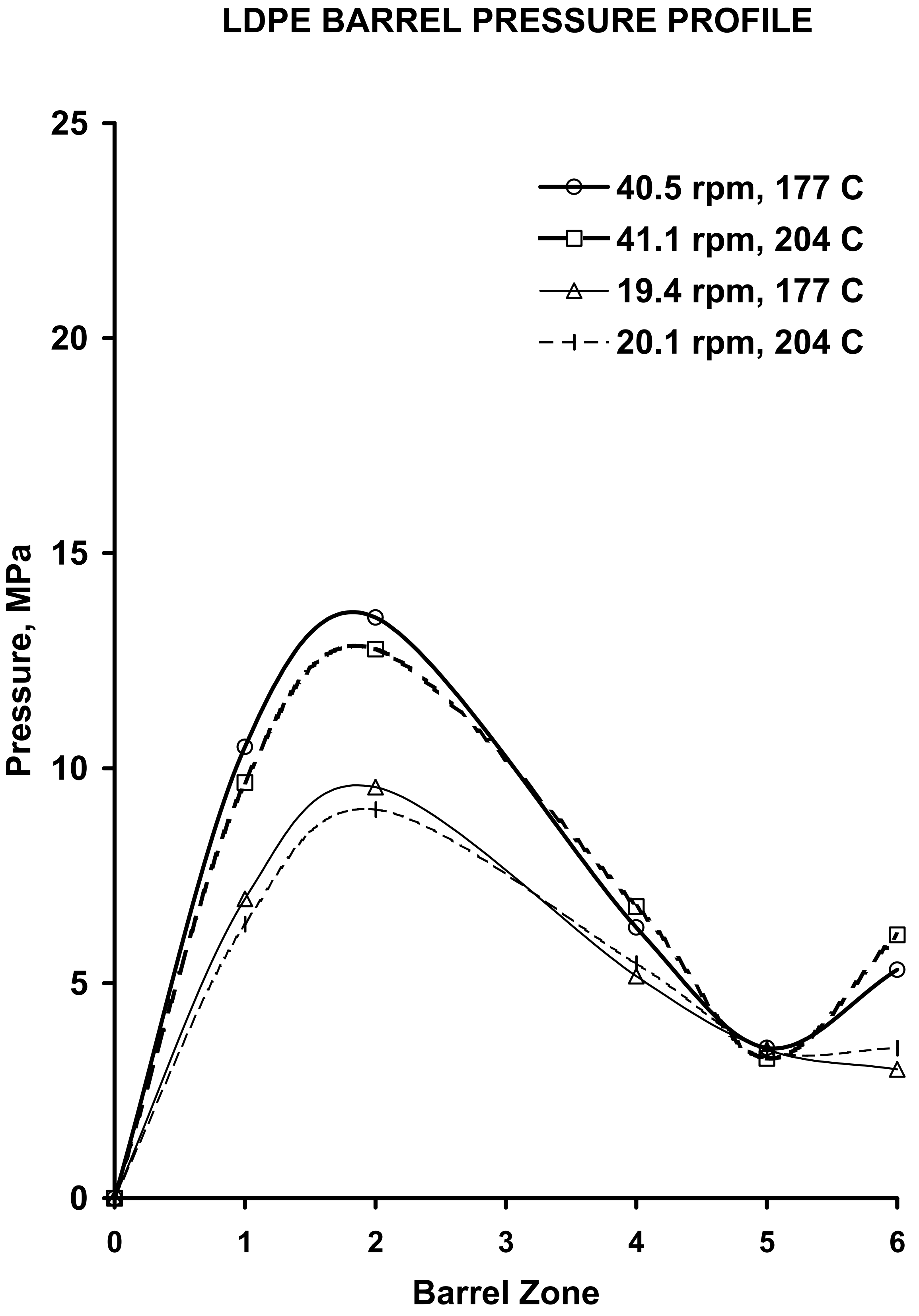

Figure 5. Barrel zone average pressures for LDPE.

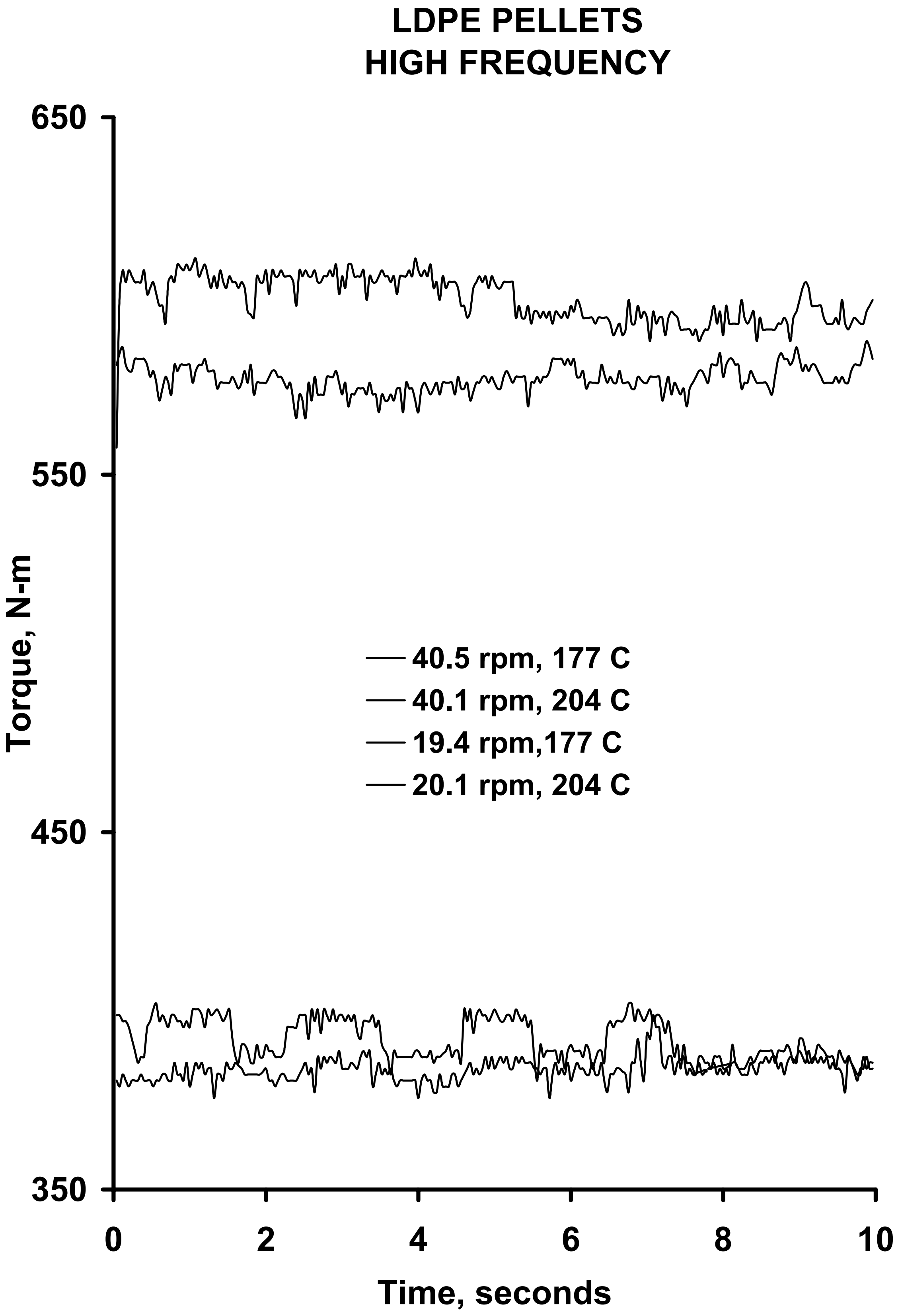

Figure 6. High frequency torque for LDPE pellets.

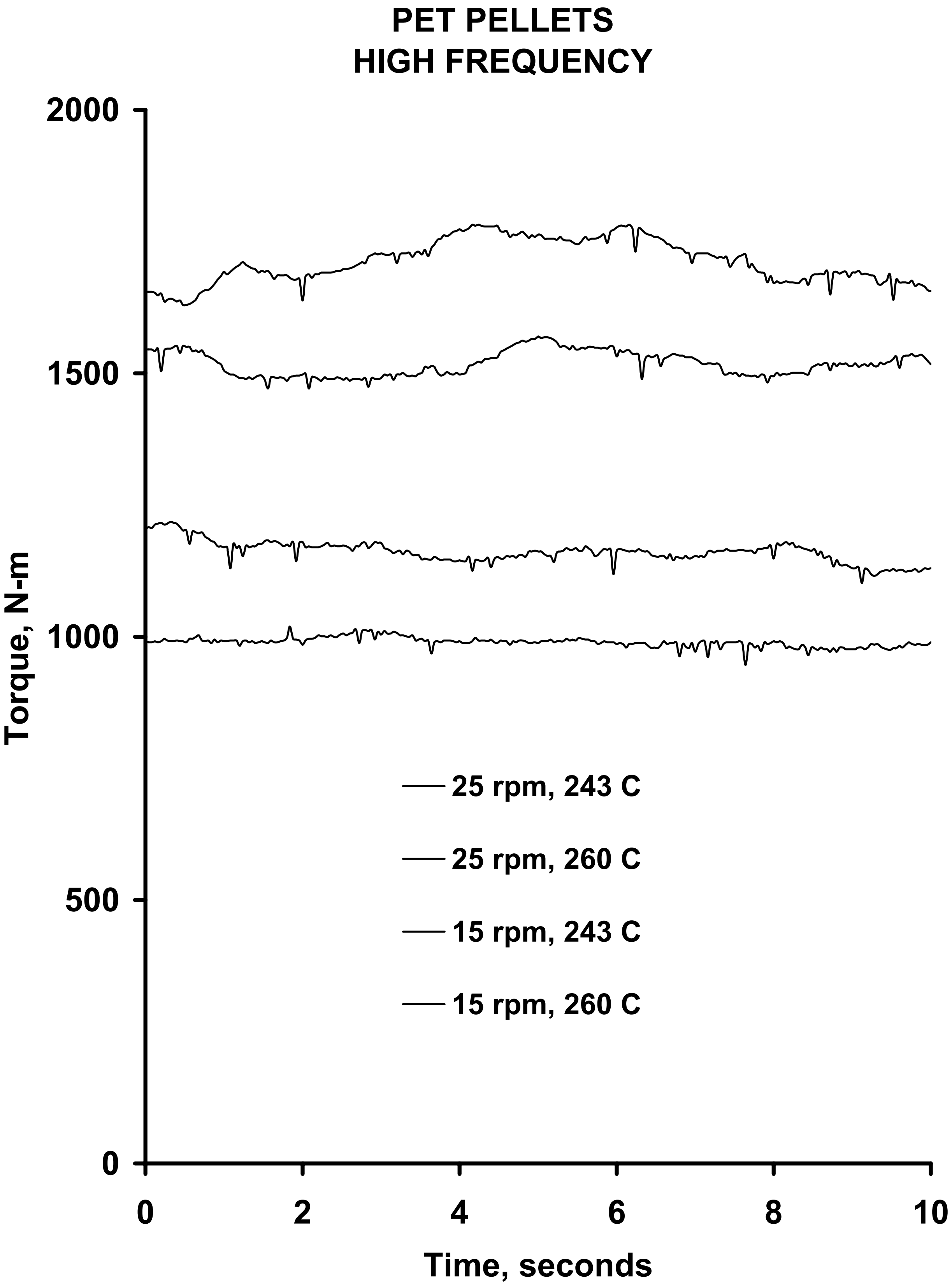

Figure 7. High frequency torque for PET pellets.

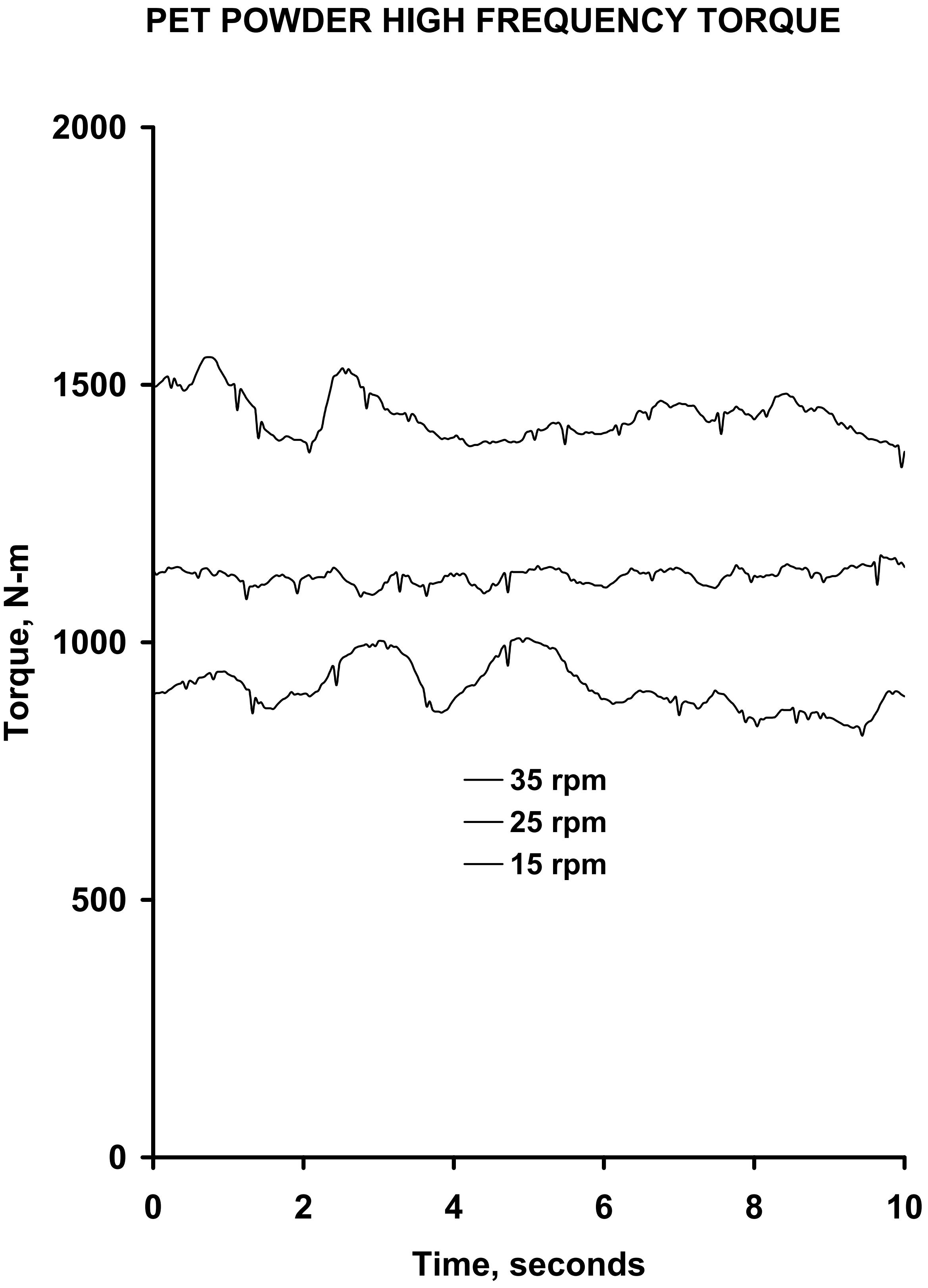

Figure 8. High frequency torque for PET powder at barrel metal temperature of 254 °C.