

Characterizing the bulk viscosity of polypropylene melt

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Uniaxial compression experiments show that the bulk viscosity has a higher magnitude than shear viscosity and should therefore not be neglected during flow analysis of the injection-molding process.

Shear viscosity has a large influence on heat dissipation and molecular orientation during the filling and packing-holding stages of injection molding, and it is therefore an important factor to consider during flow analysis of the overall process. In turn, the heat dissipation and molecular orientation affect the quality of the final parts (in terms of their strength and level of shrinkage). In addition, although the affect of bulk viscosity on compressibility and wave absorption during fluid flow has been known for several decades,^{1,2} this parameter is now mainly ignored in flow simulations (in which the fluids are mostly considered to be incompressible or divergence-free). During the packing-holding stage of injection molding, however, the density of the melt can change by more than 10%,³ i.e., the melt is in fact compressible and not divergence-free. The bulk viscosity in flow simulations is thus likely to be an important factor, which should not be neglected.

In several previous studies, the attenuation of pressure waves has been used as a way to try and measure the bulk viscosity of fluids (e.g., methane and water).^{2,4} With this method, however, it is difficult to measure the bulk viscosity of polymer melts during the packing-holding stage of injection molding. A uniaxial compression experiment (see Figure 1) has therefore been developed⁵ to measure the bulk viscosity—and to obtain the pressure-volume-temperature (PVT) diagram—of several types of polymer melt. Although this method is closely related to the real melt flow during the packing-holding stage, the dependence of its bulk viscosity measurements on various packing-holding stage parameters (e.g., temperature, strain rate, and volumetric change) has never been investigated.

In our work, we used a similar uniaxial compression approach⁵ (the experimental setup is illustrated in Figure 1) to obtain the bulk viscosity and PVT diagram of the 1100NK polypropylene homopolymer.⁶ We have also developed a bulk viscosity matrix model—based on compression deformation, melt temperature, and compression speed—for simulating the injection molding packing-holding stage. These three parameters, which we also measured in our experiment, are mainly

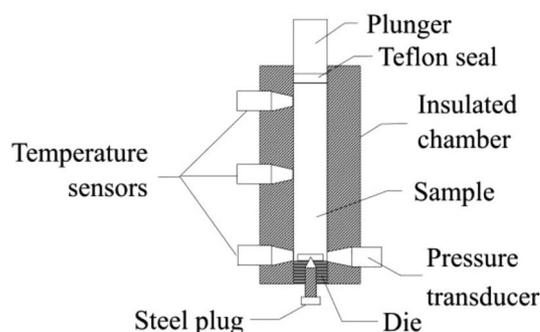


Figure 1. Schematic diagram of the experimental setup for uniaxial compression (Rosand RH7 capillary rheometer).⁶

associated with the bulk viscosity. Furthermore, we used the Kelvin-Voigt model⁵ (i.e., spring and dashpot in parallel) to determine the bulk viscosity of our material. For this calculation, we varied the compression deformation (0–10%), compression speed (0.5–70mm/minute), and melt temperature (190–210°C). We also used the same experimental setup to measure the shear viscosity of the polypropylene (following the ASTM D1238 standard procedure) to compare with our bulk viscosity results.

Our experimental results (see Figure 2) show that the bulk viscosity decayed exponentially with increasing strain rate (which was directly proportional to the compression speed). In addition, we found that this decay function was similar to that for the previously measured bulk viscosity of both high-density and low-density polyethylene.⁵ We can explain these results because the randomly coiled molecular chains become more oriented in one direction at higher compression speeds, thereby leading to more displacement of molecules. Since bulk viscosity can be considered as the resistance to the volumetric compression,² the increased compressional speed therefore also gives rise to a decrease in the bulk viscosity. In contrast, at the lower compression speed the randomly coiled molecular chains have more time to re-entangle (because of Van der Waals interaction forces), rather than point in one particular direction. There is thus a greater resistance to the movement of the molecules (as caused by the compression), and

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the bulk viscosity is increased.

We also find that the influence of melt temperature on the bulk viscosity of the propylene was similar to that of strain rate, i.e., we measured lower bulk viscosity values at higher temperatures (see Figure 2). The increase in melt temperature initiates the expansion of the molecular structure and thereby enlarges the free interstitial space that the molecules can occupy during the compression. The molecules can therefore be displaced more easily and the resistance to the

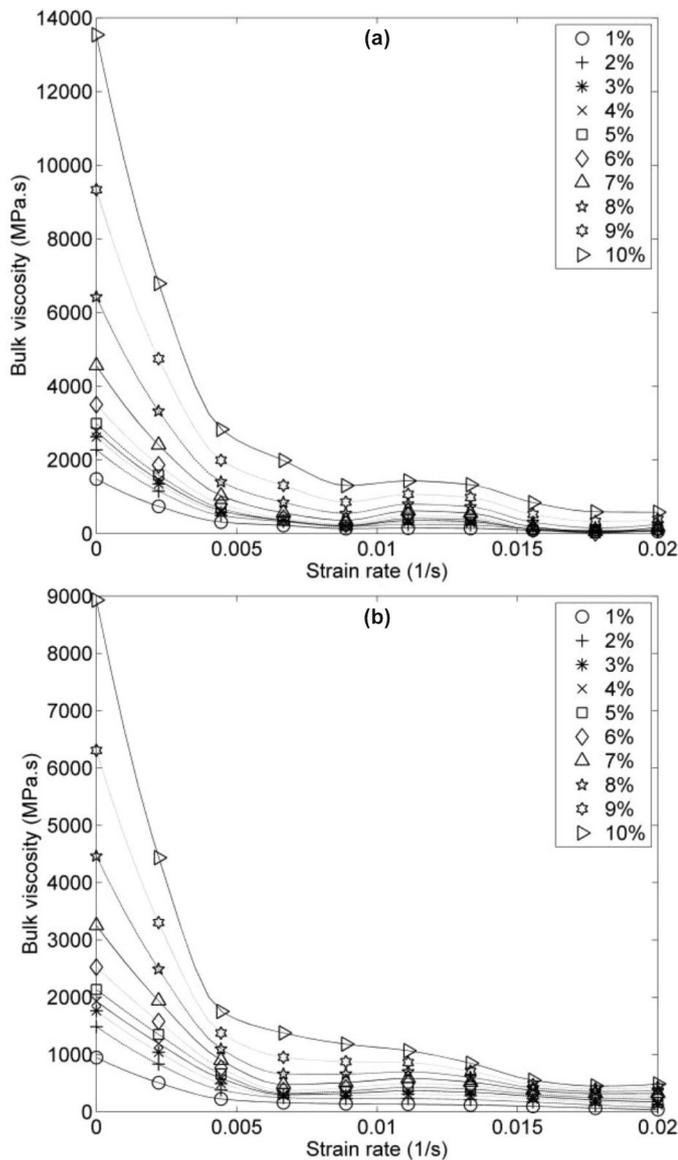


Figure 2. Experimentally measured bulk viscosity of polypropylene, as a function of strain rate, for different levels of compression deformation (1–10%) at a melt temperature of (a) 190°C and (b) 205°C.⁶

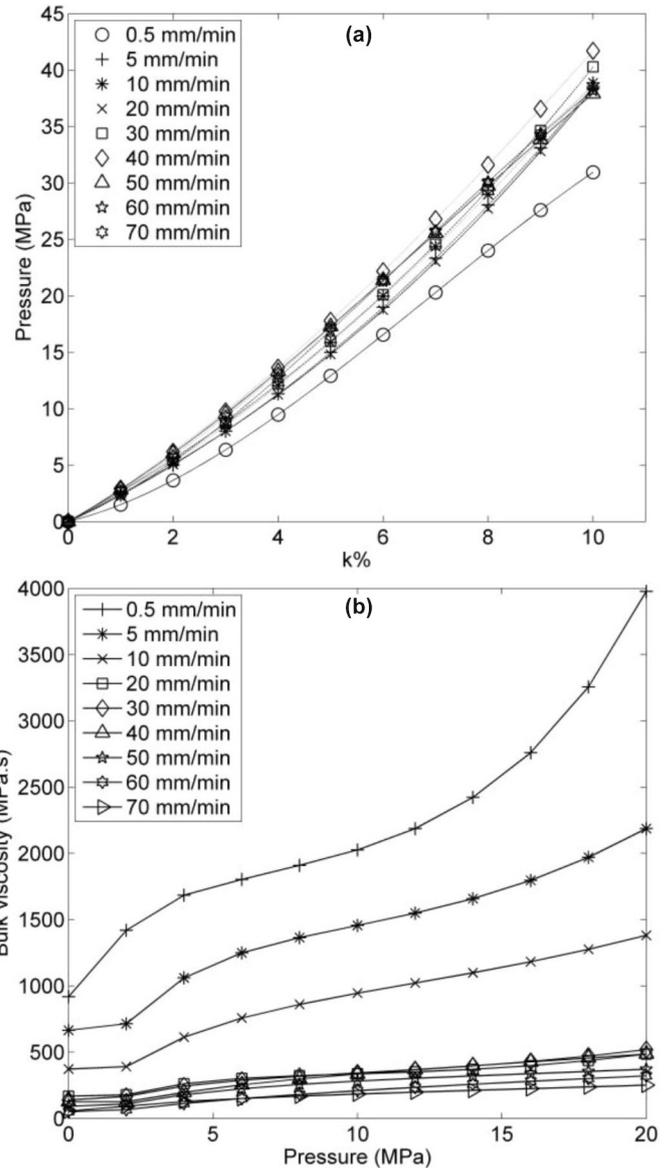


Figure 3. Polypropylene melt pressure measured as a function of compression deformation ($k\%$) for different compression speeds (0.5–70mm/min). (b) Bulk viscosity of the melt as a function of pressure (for different compression speeds) at a melt temperature of 205°C.⁶

volumetric change is reduced. Our results indicate, however, that the bulk viscosity increased with an increased level of compression deformation (see Figure 2). This is because the high compression deformation reduces the interstitial space between the molecules and has the opposite effect of the increased melt temperature. Lastly, we observe

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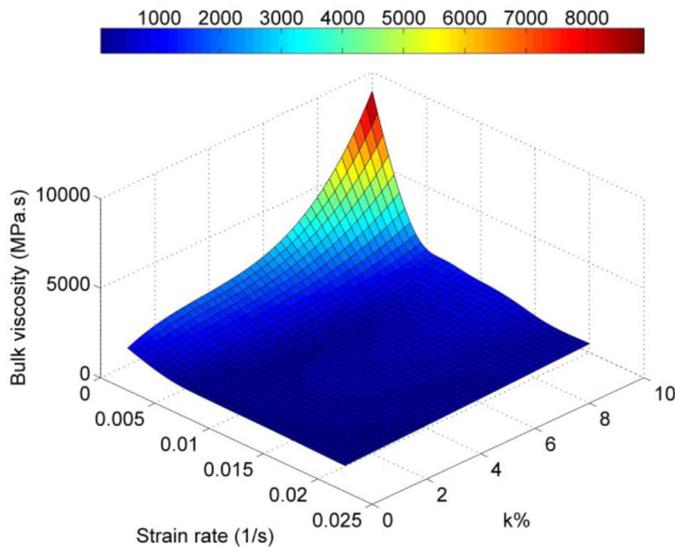


Figure 4. Determined bulk viscosity matrix model for polypropylene, as a function of strain rate and compression deformation at a melt temperature of 205°C.

from our experiments that the melt pressure increased proportionally with the compression deformation—see Figure 3(a)—and the increased melt pressure therefore caused a similar trend to the compression deformation on bulk viscosity: see Figure 3(b).

On the basis of our measured compression deformation, strain rate, and melt temperature-viscosity dependence, we developed an empirical bulk-viscosity model for the simulation of an injection molding packing-holding stage. In particular, we used this matrix model to define the relationship of the bulk viscosity with the various parameters of interest (see Figure 4). By linearly interpolating the matrix data, we can thus obtain the bulk viscosity within the range of experimental parameters. Furthermore, because the bulk viscosity decays exponentially with strain rate, we can determine the bulk viscosity when it lies outside the range of our matrix model by extrapolating from the exponential function.

In summary, we have used a uniaxial compression method to investigate the bulk viscosity of polypropylene. At the macroscopic scale, we find that the bulk viscosity is dependent on compressional deformation, strain rate, and melt temperature. Specifically, the bulk viscosity increases with increased compression deformation, but decreases with increased strain rate and melt temperature. We can interpret these results at the microscopic scale and determine that the bulk viscosity relates the ability of the molecules to occupy free interstitial spaces. Our results also show that the magnitude of the bulk viscosity is significantly (about 10^5 times) greater than the shear viscosity of the same material. We therefore believe that it is important to pay more

attention to the bulk viscosity of melts when simulating the packing-holding stage of injection-molding processes (i.e., because it can act as a substantial additional cause of heat dissipation). In the next stage of our research we will use numerical simulations to study the effects of bulk viscosity on melt flow during the packing-holding stage of injection molding.

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