

ORIGINAL PAPER

# Moldability analysis of several types of polypropylenes using flow-length measurement

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#### ABSTRACT

The suitability of a polymer to be processed by injection molding is called moldability. The technicians in injection molding companies tend to estimate moldability by using a parameter named Melt Flow Index (MFI), which however can be often misleading since it represents the ability of a melt to flow in specific conditions, very different from the ones that the polymer encounters during injection molding. A much significant parameter is the so-called flow-length, which is the length reached by a polymer during injection molding in a thin cold cavity. In this work, three commercial grades of polypropylene were injection molded in a cold thin cavity and the flow-lengths were measured in function of injection pressure and temperature. The results obtained were correlated with the rheological parameters. The results demonstrate that the MFI is misleading as a technical parameter for the moldability of polypropylene. An empirical equation is proposed to describe the flow-length of polypropylene in function of injection **J (2023) 10: 159-167** 

Keywords: Polypropylene; injection molding; flow-length; melt-flow index.

#### INTRODUCTION

Injection molding is a plastic materials manufacturing process that is widely used on an industrial level to produce objects of various sizes and shapes, even complex ones, characterized by very high productivity [1]. During the injection molding, a molten polymer is forced into a thin cold cavity, normally with a high length/ thickness ratio. One of the main goals of the process is to completely fill the cavity, and the suitability of a polymer to achieve that goal is commonly called moldability.

Moldability depends on material viscosity and thermal diffusivity and is a critical factor determining the choice of a polymer for a given application. Historically, polypropylene has been one of the most used polymers for injection molding, and even recently, it has been widely used due to its excellent moldability [2-7].



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Technicians of injection molding companies tend to estimate the moldability of a polypropylene considering the so-called melt flow index (MFI). This index is defined as the mass of polymer, in grams, flowing in 10 minutes through a capillary of a specific diameter and length at a specific temperature and load. A lower MFI indicates a more viscous polymer, while a higher MFI indicates a more fluid polymer. The ASTM standard for determining the melt flow index of thermoplastic polymers is ASTM D1238 [8], which is widely used in the plastics industry as a quality control measure for polymer raw materials and finished products. According to this standard, the test conditions for determining the melt flow index of polypropylene are a temperature of 230°C a load of 2.16 kg and a capillary with a diameter of 2.095 mm and a length of at least 8 mm. Despite its wide use, the MFI is often a misleading characteristic since it completely neglects the solidification process. Indeed, during injection molding, the polymer gets in contact with a cold mold, and this causes the solidification which depends on the boundary conditions [9, 10] and, in case of polypropylene, also the evolution of complex morphologies which determine the final properties [11-15]. A much better index for moldability is the flow-length which can be measured for instance by mean of the so-called spiral flow test. The spiral flow test consists in measuring the length of the resin that flows along a very long cavity, under specific conditions of temperature and pressure [16-20]. ASTM D3123 [21] is a standard test method for evaluating the degree of spiral flow of a material by measuring the length of a spiral flow path in a standard test specimen under specific conditions of temperature, pressure and loading time. The standard applies to thermosetting resins but not to thermoplastics. This means that the researchers interested in estimating the moldability of polypropylene by measuring the flowlength can choose the channel thickness, the temperature of the melt and of the mold and the pressures. An

analysis of the phenomena which determine the final length can be found in the works by Richardson [22-24], which can be simplified in the following equation provided by Van Krevelen [25]:

$$L = CH\left(\frac{H^2}{\alpha}\right)^{\frac{n}{1+n}} \left(\frac{1}{K}\right)^{\frac{1}{1+n}} \left(P\right)^{\frac{1}{1+n}} \tag{1}$$

in which H is the thickness of the channel,  $\alpha$  the thermal diffusivity, K and n are the consistency and the flow index of the power law describing the viscosity of the material at high shear rates, P is the pressure at the injection point and C is a constant of order of magnitude 0.1. The flow-length L, although more complex than the MFI, is a much better index for moldability since it considers rheological and thermal properties of the material.

In this work, an analysis of the moldability of three commercial grades of polypropylene is conducted by measuring the flow-lengths reached during injection molding tests. The results are interpreted in terms of the rheological properties of the polymers and put into evidence the fact that the MFI can be misleading as a moldability index.

### **EXPERIMENTAL**

#### Materials

Three commercial grades of polypropylene are used in this work. The commercial names are provided in Table 1, together with the basic properties found in the technical datasheet. In the following, the materials will be introduced as grade A, B or C according to the codes mentioned in Table 1. It can be noticed that the MFI of the grade B is higher with respect to the other two grades.

#### **Rheological measurements**

A TA Instruments CSL 100 controlled-stress rheome-

**Table 1**. Summary of the main properties of the polypropylene grades adopted in this work, as reported on the technical datasheet. The materials are referred to by the letters reported in the "Code" column.

Grade	Code	Filler	Density	Melt flow index	Flexural modulus	Heat deflection temperature
Hostacom CR1171 G1	A	Talc 12%	0.990 g/cm <sup>3</sup>	12 g/10 min	1800 MPa	54°C
Hostacom ERC 198N G14008	В	Talc 20%	1.06 g/cm <sup>3</sup>	15 g/10 min	1800 MPa	57°C
Unipetrol Mosten MA712	С	-	0.910 g/cm <sup>3</sup>	12 g/10 min	1550 MPa	58°C

ter was adopted to carry out rheological measurements in dynamic mode. The following parameters were set: stress = 500 Pa, frequency range = 100 - 0.1 rad/s, and gap = 1mm.

The tests were repeated, for each material, at three different temperatures: 170°C, 200°C and 230°C. For each test, the software provides the complex viscosity  $\eta^*$ , which according to the Cox-Merz rule, known to be valid for polypropylene [26], can be assumed to be equal to the shear viscosity at a shear rate, in s<sup>-1</sup>, equal to the frequency, in rad/s.

#### Injection molding and measurements of flow length

The press used for injection molding is a HAAKE MiniJet press powered by alternating current and equipped with a compressed air connection to guarantee the desired pressures in the injection phase. The cavity adopted is a slab having the following dimensions: thickness 0.5 mm, width 3 mm, and length 50 mm.

Taking into account the nature of the materials, their melting point and the suggested temperatures to be used in the industrial process, the injection molding tests were performed at three different injection temperatures, in particular 200°C, 230°C and 260°C, and a mold temperature of 25°C.

The test was repeated with four different pressure values at the injection point: 100 bar, 200 bar, 400 bar and 800 bar.

The pressure was held for 10 seconds, which was enough to allow the complete solidification of the polymer inside the cavity and thus to reach maximum flow length.

By combining the temperature and pressure conditions, a total of twelve different tests were performed for each material. Each test was then repeated a total of five times, in order to verify the reproducibility of the experiment, and, therefore, the test was carried out correctly. Each individual sample was measured using a digital caliper.

#### **RESULTS AND DISCUSSION**

The rheological measurements are reported in Figure 1. All the viscosities show the typical behavior of ther-

moplastic polymers, with a negative slope, in the loglog plot, which decreases on increasing the frequency (or the shear rate). The viscosity decreases on increasing the temperature. It can be noticed that, in the range of variables analyzed, the grade B (Figure 1b), which is the material having the largest MFI, presents viscosity values larger than the other two materials. This is



**Figure 1**. Measurements of complex viscosity in function of frequency and temperature for the three materials adopted in this work. Codes are provided in Table 1.



consistent with the fact that MFI refers to one specific point on the rheological curve, taken at a shear rate which is normally high and depends on the viscosity of the material itself [27, 28]. The grade B presents the lowest values of viscosity.

The length of the samples measured after injection



**Figure 2**. Measures of sample lengths after injection molding tests as a function of injection pressure and melt temperature. The mold temperature was kept at 25°C. The error bars are not reported but are within +/- 1.5mm for all the tests.

molding, namely the flow-lengths, are reported in Figure 2. For each material, higher pressures and lower temperatures induce larger flow lengths. Consistently with the rheological measurements, for each temperature and pressure, grade C reaches the largest lengths, being less viscous. Grade B appears to have the worst molding, despite having the largest MFI. This confirms that MFI can be misleading for injection molding.

The rheological measurements reported in Figure 1 were described by the so-called Cross-WLF equation [10]:

$$\eta = \frac{\eta_0 \alpha_T}{1 + \left(\frac{\eta_0 \alpha_T \dot{\gamma}}{\tau_0}\right)^{(1-n)}}$$
(2)

$$\alpha_T = exp\left[\frac{-c_1(T-T_r)}{c_2 + (T-T_r)}\right]$$
(3)

in which,  $\eta$  is the viscosity (equal to the complex viscosity if one assumes the validity of the Cox-Merz equation)  $\eta_0$ ,  $\tau_0$ , n,  $c_1$  and  $c_2$  are constants,  $\dot{\gamma}$  is the shear rate (equal to the frequency);  $\alpha_T$  is the thermal shift factor and  $T_r$  is a reference temperature at which the shift factor is equal to 1.

At large shear rates, Eq. 2 simplifies into the rheological power-law equation:

$$\eta = K\dot{\gamma}^{n-1} \tag{4}$$

in which, the flow index is equal to the parameter n of the Cross equation and the consistency is:

$$K = \left(\eta_0 \alpha_T\right)^n \tau_0^{1-n} \tag{5}$$

From Eq. 5 it is possible to define a thermal shift factor for the power-law expression, which is equal to:

$$\alpha_{T,PL} = \alpha_T^{\ n} \tag{6}$$

The parameters adopted to describe the data, as reported in Figure 3, are given in Table 2.

For each grade, a mastercurve of the flow lengths versus pressure was obtained according to the following equation:

$$L_{g}(T,P) = \frac{1}{k_{T,g}(T)} L_{g}(T_{r},P)$$
(7)

in which, the subscript "g" stands for the grade chosen (A, B or C),  $k_T$  is a parameter to be determined for each material and temperature, and  $T_r$  is a reference temperature (chosen here as 200°C). The results of this procedure are reported in Figure 4. It can be noticed that a mastercurve could indeed be obtained. Assuming the validity of Eq. 1 and considering Eq. 5, for each material a relationship should hold between



**Figure 3**. Description of the rheological data by means of the Cross-WLF equations (Eqs 2 and 3).



**Figure 4**. Mastercurves of the flow-lengths for each grade at the reference temperature of 200°C.

 $k_{T}$  and the parameters of the rheological power-law expression, and in particular:

$$k_T = \alpha_{T,PL}^{1/(n+1)}$$
(8)

Considering that for all the materials (see Table 2) n is in the range 0.29-0.41, the value of the exponent 1/(n+1) should be close to 0.75.

In Figure 5, the values of  $k_T$  are reported versus the values of  $\alpha_{T,PL}$  for all the materials and all the temperatures. It can be noticed that a power-law indeed holds between the two parameters, but the exponent is much higher than expected (1.9 instead of 0.75), indicating that the flow-lengths are more sensitive to temperatures than expected. This result suggests that some other parameters depending on temperature, not considered in Eq. 1, should be accounted for. Probably, also the mold temperature, which in this work was set to 25°C, could play a role [20]. In particular, it is possible that the average temperature of the melt flowing in the cavity is lower than the injection temperature. This effect is not considered in this work.

Still following the relationship suggested in Eq. 1, a power-law should hold between the flow-lengths and

Table 2. Parameters of the Cross-WLF equations.

Parameter	Unit	Grade A	Grade B	Grade C
η	Pa.s	6560	16729	1372
<b>C</b> <sub>1</sub>	-	120.1	2.471	7.892
C <sub>2</sub>	-	6705	125.3	367.7
τ	Ра	19948	15430	31472
n	-	0.31	0.41	0.29
T <sub>r</sub>	°C	200	200	200



**Figure 5**. Relationship between the coefficient describing the temperature dependence of flow length and the rheological thermal shift.

the pressure at constant temperature. The exponent should be 1/(n+1), namely about 0.75. The analysis is reported in Figure 6: the exponent of obtained relationship is much lower (0.36 rather than 0.75). In this case, the difference could be ascribed to the effect of pressure on viscosity, which is not considered in Eq. 1, but can significantly change the flow-behavior of polypropylene [29] especially at high pressures.

A further normalization can be attempted on the results reported in Figure 4, by choosing a coefficient such to make all the results to collapse on a single plot reporting the final length versus pressure:

$$L_{g}(T,P) = \frac{1}{k_{T,g}} \frac{1}{k_{r,g}} L_{C}(T_{r},P)$$
(9)

in which, the subscript stands for the grade chosen (A, B or C) and  $L_{c}(P)$  represents the length reached by sample C. The results are presented in Figure 7.



**Figure 6**. Power-law dependence of the flow lengths and the pressure. m is the exponent of the power-law function that best fits the data (reported as continuous black lines).



**Figure 7**. Results of Eq. 8, by which all the results of flow length collapse on the measurements taken for sample C at 200°C.

The values obtained are  $k_{r,A} = 0.77$  for sample A and  $k_{r,B} = 0.66$  for sample B (obviously,  $k_{r,C} = 1$  for sample C). According to Eq. 1, a relationship should hold between  $k_r$  and the parameters of the rheological power-law expression, and in particular:

$$k_{r,g} = \frac{K_C^{1/(n_c+1)}}{K_g^{1/(n_g+1)}} \cong \left(\frac{K_C}{K_g}\right)^{1/(n+1)}$$
(10)

in which, again the subscript identifies the grade (g=A, B or C) and it is considered that the values of n are very close for all the grades, so a single value can be used.

The relationship between  $k_{r,g}$  and  $(K_c/K_g)$  is reported in Figure 8: the exponent is 1.84, which is much higher than expected, but consistent with the one reported in Figure 5.

From the analysis reported above, for different grades of polypropylene, the following empirical ex-



Figure 8. Relationship between the two parameters reported in Eq. 10.

pression can be suggested for the description of the final length reached in a cold mold:

$$L = D \left(\frac{1}{K}\right)^{1.85} P^{0.37}$$
(11)

Where D is a constant determined by the thickness of the channel and by the mold temperature.

The results of the description are reported in Figure





# 9, in which D= $7.2 \times 10^7$ (L in mm, K in Pa.s<sup>n</sup>, P in bar) is considered.

Equation 11 states that the flow-length heavily depends on the rheology of the polymer.

#### CONCLUSIONS

In this work, an analysis of moldability of three commercial grades of polypropylene was conducted by considering the flow lengths reached in a thin cavity during injection molding tests. The analysis of the results allowed to obtain a correlation with the rheology of the materials, measured by a rotational rheometer. The results demonstrate that the melt flow index (MFI), which is commonly used as a measure of moldability, can be misleading: the material with the highest MFI does not necessarily have the longest flow-length. An equation based on literature indications was used to describe the effects of rheometric parameters and pressure on the final flow-length. It was found that the flow-lengths are more affected by temperatures than expected, likely due to the fact that the proposed equation neglects the effect of mold temperature on the average polymer temperature. Vice-versa, the effect of pressure was found to be less significant than expected, likely due to the fact that pressure-induced viscosity increase is not considered in the model but it can be significant.

An equation was thus proposed to describe the flow lengths reached by three different commercial grades of polypropylene injection molded in a cold cavity changing the injection temperature and the pressure. The equation requires just the knowledge of the rheology of the material in terms of the two parameters of the power-law equation.

The proposed equation can be used for polypropylene injection molded in a thin cavity at room temperature within a wide range of injection temperatures and pressures.

#### **CONFLICTS OF INTEREST**

The authors declare that they have no conflicts of interest.



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