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A Study of L-Lactide Ring-Opening Polymerization Kinetics

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Summary: The paper presents an experimental study of L-lactide polymerization in molten state using as initiator the Stannous Octoate. The experiments were performed in a Haake mixer. The operating temperatures were between 170 and 195 °C, the reaction time up to 60 min and monomer to initiator initial molecular ratio between 10^2 and $5 \cdot 10^3$. The conversion was determined by using ^{1}H NMR and the molecular weights distributions by SEC. A preliminary mathematical modeling study was also performed, based on experimental data and a previously published reaction scheme.

Keywords: bulk ring-opening polymerization; mathematical modeling; polylactide

Introduction

Polylactide is used mainly for medical applications, but in the last time it is accepted also to play a major role as a packaging material. Numerous studies indicate that the polylactides are sufficiently biocompatible, with a minority suggesting otherwise.[1–3] Polylactides have the best temperature and mechanical characteristics for production of plastics and fibers with the necessary set of properties. Ring opening of lactide can be carried out in melt or solution by cationic, anionic and coordination mechanisms, depending on the initiator utilized. The most active initiator for the L-lactide ring-opening polymerization is considered stannous octoate (bis 2-ethyl hexanoate- $SnOct_2$), which causes a low degree of racemization at high temperature. It has a low toxicity and is accepted by the US Food and Drug Administration.[4]

One of the first studies concerning L-lactide polymerization using stannous octoate as initiator was published in 1987 by Eenink.[5] The study reports data concerning the influence of process parameters on the polymer characteristics. The published works in the field of L-lactide polymerization were reviewed by Stridsberg et al.,[6] Drumright et al.,[7] Wu et al.[8] and Dechy-Cabaret et al.[9]

Many authors investigated the mechanism of L-lactide polymerization in presence of stannous octoate. The most important reaction mechanisms proposed are the cationic one proposed by Schwach et al.[10] and the coordination-insertion mechanism proposed by Kricheldorf et al.[11,12]

Schwach et al.[10] detected lactyl octoate- terminated short chains of polylactide and evidenced that hydroxyl impurities could act as chain transfer agents. The same experimental observation was reported by Zhang et al.[13,14]

Kricheldorf et al.[15] carried out the polymerization of L-lactide at 180 °C with $Sn(Oct)_2$ under various monomer to initiator ratios. They detected also significant amounts of octoate polymer end groups. The apparent degree of polymerization indicated that, on the average, only one octoate group per initiator was transformed into an end group. The highest monomer conversion was obtained at 180 °C, using a monomer to initiator ratio of 200, for a reaction time of 1 h. The mechanism of L-lactide polymerization initiated by stan-

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nous octoate in the presence of benzyl alcohol as co-initiator was studied by Kricheldorf et al.[11] and in presence of butyl alcohol respectively by Penczek et al.[16] and Kowalski et al.[17]

Hyon et al. studied the bulk lactide polymerization at 130 °C and reported the highest molecular weight for an initiator amount of 0.05% wt $SnOct_2$. They are also evidencing that at high temperatures, depolymerization reactions could also take place.[18]

Degee et al.[4] reported a significant intensification of the L-lactide polymerization process kinetics using triphenyl phosphine as co-initiator for a monomer-to-initiator molar ratio of 5000. Based on the study of Degee et al.[4] a reactive extrusion process study was published by Jacobsen et al.[19] A high monomer conversion (98%) for a mean residence time of 7 minutes and a temperature of 180 °C was reported in this study.

In spite of the practical importance of the L-lactide polymerization process there are a small number of kinetic studies published in the open literature, including comparisons of theoretical results with experimental data. The most recent ones are published by Witzke et al.[20] and Mehta et al.[21] In this work the bulk polymerization process of L-lactide initiated by stannous octoate is studied in a laboratory batch reactor. Based on the obtained experimental data, a preliminary mathematical modeling study was also performed by using a reaction scheme and kinetics published by Schwach et al.[10]

Experimental Part

The L-Lactide dimer was purchased from Boehringer Ingelheim and the Stannous Octoate (Sn bis-ethyl-2-hexanoate) initiator from Sigma Chemicals. The aim is to investigate the process characteristics in the commercial purity conditions of the lactide and initiator. Consequently, both the L-lactide dimmer and stannous octoate initiator were used as received, without any treatment. The polymerization reactions have been carried out in a Haake Rheocord internal mixer with a R600 chamber. The set-up allows the monitoring of the torque and the control with a good accuracy of the reaction temperature. The total mass of the sample is 50 grams. In order to better control the added initiator quantity it has been first dissolved in toluene and then injected into the reaction chamber.

The composition of reaction mixture was determined by ^{1}H RMN method and the polymer molecular weights distribution by SEC measurement. The ^{1}H RMN analyses have been carried out on a Brucker 250 model, at the Fédération des Polyméristes Lyonnais. The samples were dissolved in deuterated chloroform.

The SEC measurements have been performed at room temperature using chloroform as solvent, on a Waters 510 apparatus, with two Polymer Laboratory PLGel 5 μm Mixed-C columns. The detector was a Waters 410 differential refractometer, and the scaling has been made using polystyrene.

Results

The experiments were carried out at different temperatures and initial L-lactide to initiator molar ratios. The main results are presented in Figure 1 to 7.

In spite of the relatively large scatter of experimental points, the diagrams permit to draw several conclusions regarding the lactide polymerization process. A first conclusion is that the bulk polymerization process can be conducted at reactions times of the same order of magnitude as the residence times of the melts in twin-screw extruders. This permits to use these apparatus as polymerization reactors, taking the benefits of the reactive extrusion technique advantages.

Figure 1 and 4 present the time dependence of monomer conversion at different temperatures and monomer to initiator ratios. As expected, the temperature has

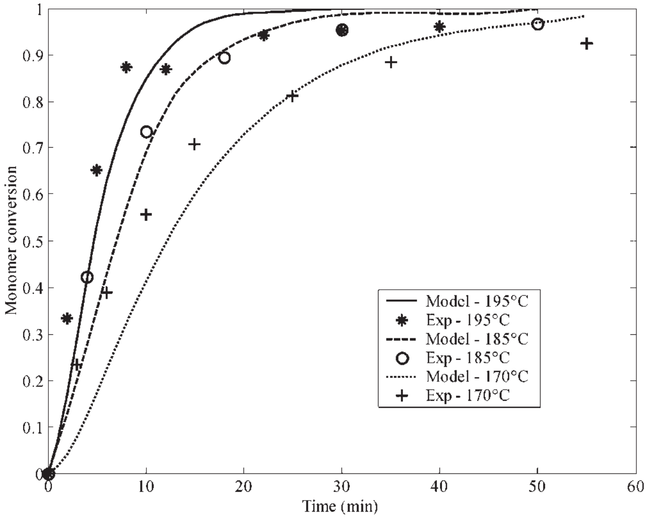

Figure 1.
Time dependence of L-lactide conversion, M/I = 2250.

a strong effect on the monomer conversion. At a temperature of 195 °C a monomer conversion level about 90% is achieved in a reaction time around 10 min. The two diagrams are also evidencing the influence of molecular to initiator ratio on the monomer conversion. As seen, the decrease of this ratio (increase of initiator concentration) is determining an increase of the monomer conversion.

Figure 2,3,5 and 6 show the time evolutions of polymer average molecular weights in different working conditions. The polymer molecular weight is increasing faster on the first interval of reaction time, due to the relatively high propagation rates induced by the higher concentration level of monomer in the mixture. As the monomer concentration decreases, the propagation rate is diminishing and the molecular

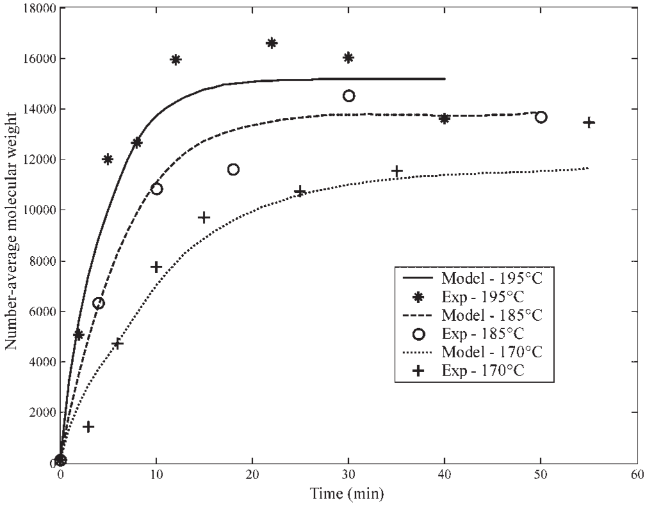

Figure 2.
Time dependence of the number average molecular weight, M/I = 2250.

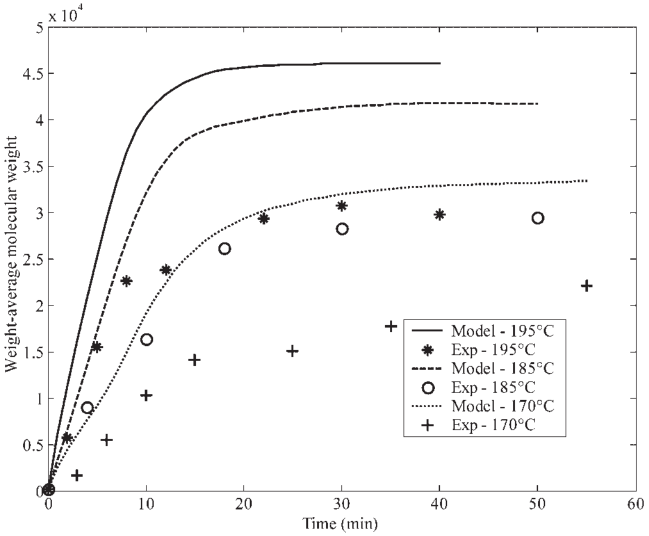

Figure 3.
Time dependence of weight average molecular weight, M/I = 2250.

weights tend to stabilize, the curves becoming almost flat. Moreover, at high working temperatures (over 180 °C), the molecular weights present a decreasing trend on the last time interval, due to the process reversibility. From Figure 2, 3, 5 and 6 there can be also evidenced the temperature and monomer to initiator ratio influences on the average molecular weights of the polymer at different reaction times. Two observations can be drawn in this respect from the diagrams in Figure 2, 3, 5 and 6. The first one concerns the dependence of the number-average molecular weight

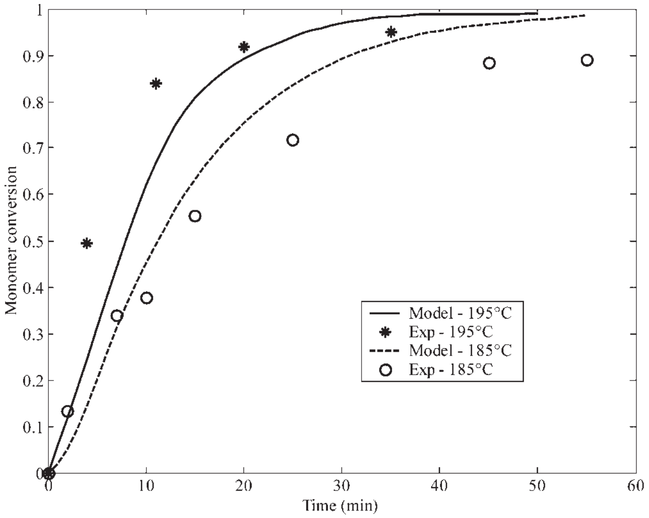

Figure 4.
Time dependence of L-lactide conversion, M/I = 4500.

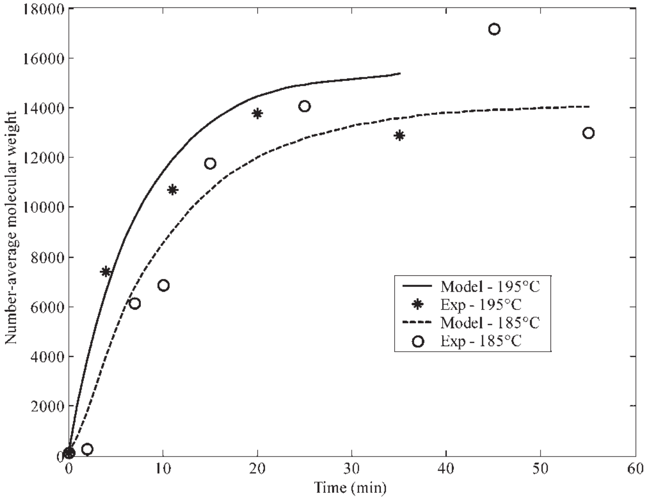

Figure 5.
Time dependence of number average molecular weight, M/I = 4500.

(Mn) and weight-average molecular weight (Mw) on temperature and monomer to initiator (M/I) ratio. On the working domain Mn and Mw increase with the M/I ratio (consequence of diminution of the polymer centers concentration in reaction mixture) and with temperature. The temperature dependence can be explained by a stronger effect of this variable on the propagation step than on the termination reactions. The second observation concerns the process reversibility. As already mentioned, several previous studies evidenced a weak reversibility of L-lactide polymerization.[18,20] This particularity could explain the fact that the conversion curves tend to

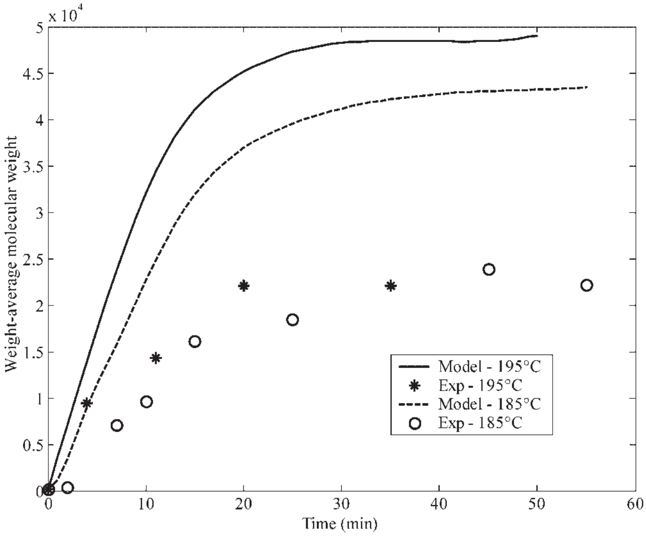

Figure 6.
Time dependence of weight average molecular weight, M/I = 4500.

Table 1.
Calculated kinetic parameters values.

Parameter	$\overline{k_i}$, $l \cdot mol^{-1}\ min^{-1}$	$\overline{k_p}$, $l \cdot mol^{-1}\ min^{-1}$	$\overline{k_{tm}}$, $l \cdot mol^{-1}\ min^{-1}$	$\overline{k_{ts}}$, $l \cdot mol^{-1}\ min^{-1}$
Values	4.509e-4	2.118e-3	1.505e-3	2.241
Parameter	E_i, $J \cdot mol^{-1}$	E_p, $J \cdot mol^{-1}$	E_{tm}, $J \cdot mol^{-1}$	E_{ts}, $J \cdot mol^{-1}$
Values	37956	79813	39290	39562

plateau out on the last time interval and the time dependence of Mn at high temperatures present an evolution with a weak maximum.

The Kinetic Model of the Polymerization Process

The first step in the kinetic analysis was to determine the order of monomer consumption rate. Since the time dependence of $-\log(\frac{[M]}{[M]_0})$ is approximately linear, it turns out that the monomer consumption rate is first order in respect with the monomer, at least during the first period of the reaction (Figure 7). The same results was also reported by Eenink[5] for the L-lactide polymerization system using stannous octoate as initiator.

To develop a kinetic model for the polymerization process, we considered the reaction mechanism proposed by Kowalski et al.[17] This mechanism is assuming that the polymerization of L-lactide/stannous octoate system proceeds by simple monomer insertion described in Figure 8. In addition to Kowalski scheme, we considered that termination reactions occur by chain transfers to monomer as well as with the impurities present in the reaction mixture.

In order to develop the kinetic model based on the mechanism presented above, four reactions were considered: initiation, propagation, chain transfer with monomer and chain transfer with the impurities present in the reaction mixture. In the following paragraphs, the impurities present in the reaction mixture will be formally called ''solvent'' and the corresponding kinetic constant named ''chain transfer with solvent'' constant. All the reactions are considered irreversible. In a simplified

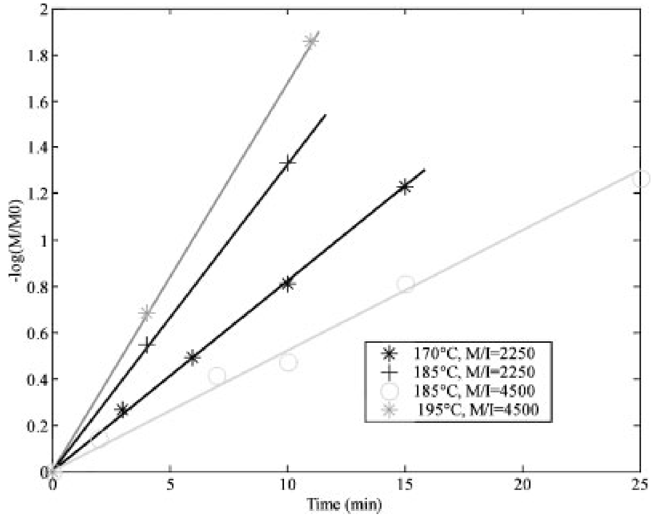

Figure 7.
$-\log\left(\frac{[M]}{[M]_0}\right)$ vs. time.

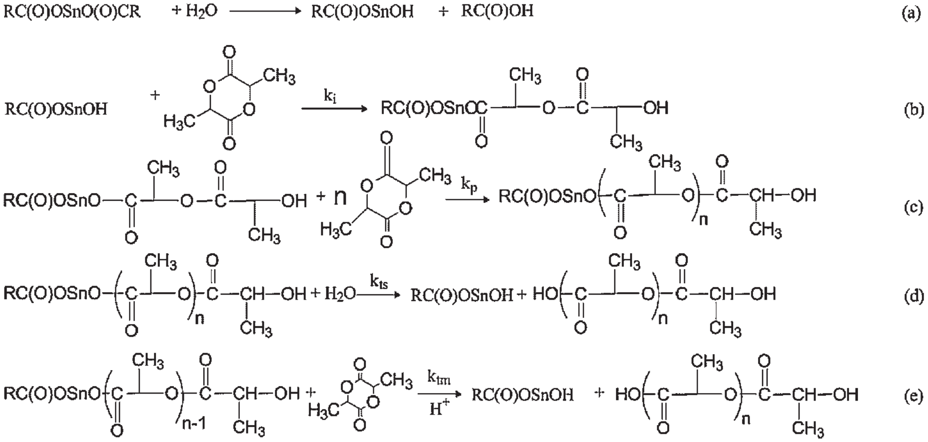

Figure 8.
Mechanism of polymerization of dilactide in the presence of stannous octoate.

way, the elementary reactions (a) - (e) presented in Figure 8 are written as:

$$I + M \xrightarrow{k_i} R_1 \tag{1}$$

$$R_i + M \xrightarrow{k_p} R_{i+1} \tag{2}$$

$$R_i + M \xrightarrow{k_{tm}} R_1 + P_j \tag{3}$$

$$R_i + S \xrightarrow{k_{ts}} R_1 + P_j \tag{4}$$

where I – initiator, M –monomer, R_j – active polymer chain, P_j – dead polymer chain

In addition, the following hypotheses are considered:

- The density of the reaction mixture is considered constant in respect with time;
- Each initiator molecule initiates a polymer chain;
- Termination occurs by transfer to monomer and solvent and is irreversible;
- Concentrations of the reactants may depend upon time but are independent of spatial position within the reaction vessel (no gel effect appears in the reaction mixture);
- Rate constants are chain length independent.

In accord with the hypothesis presented above, the mathematical model for the ring-opening polymerization process in a batch reactor is represented by the equation (5)–(13). The structure of this model is based on a scheme published by Scwach et al.,[10] adapted by adding the termination reaction by chain transfer to impurities present in the reaction mixture.

$$\frac{dI}{dt} = -k_i IM \tag{5}$$

$$\frac{dM}{dt} = -k_i IM - k_p M\lambda_0 - k_{tm} M\lambda_0 \tag{6}$$

$$\frac{d\lambda_0}{dt} = k_i IM \tag{7}$$

$$\begin{aligned}\frac{d\lambda_1}{dt} = {} & k_i IM + k_p M\lambda_0 \\ & + k_{tm} M(\lambda_0 - \lambda_1) \\ & + k_{ts} S(\lambda_0 - \lambda_1)\end{aligned} \tag{8}$$

$$\begin{aligned}\frac{d\lambda_2}{dt} = {} & k_i IM + 2k_p M\lambda_1 + k_p M\lambda_0 \\ & + k_{tm} M(\lambda_0 - \lambda_2) \\ & + k_{ts} S(\lambda_0 - \lambda_2)\end{aligned} \tag{9}$$

$$\frac{d\mu_0}{dt} = k_{tm} M\lambda_0 + k_{ts} S\lambda_0 \tag{10}$$

$$\frac{d\mu_1}{dt} = k_{tm} M\lambda_1 + k_{ts} S\lambda_1 \tag{11}$$

$$\frac{d\mu_2}{dt} = k_{tm} M\lambda_2 + k_{ts} S\lambda_2 \tag{12}$$

$$\frac{dS}{dt} = k_{ts} S\lambda_0 \tag{13}$$

$$t = 0, \quad I = I_0, \quad M = M_0, \quad S = S_0,$$
$$\lambda_i = 0, \quad \mu_i = 0, \quad i = 0..2$$

where: I – initiator concentration; M-monomer concentration; S- solvent concentration;
λ_i – the moments of active polymers concentrations distributions (i = 0..2);
μ_i – the moments of dead polymers concentrations distributions (i = 0..2);
k_i – the initiation kinetic constant; k_p – the propagation kinetic constant;
k_{tm} – the chain transfer to monomer kinetic constant;
k_{ts} – the chain transfer to solvent kinetic constant;

To determine the impurities concentration, S_0, we considered that it consist mainly in the water present in the lactide monomer. Its concentration was measured by drying experiments and was evaluated to be about 0.07 % wt.

The polymer and monomer mixture density was calculated from the relation published by Witzke et al.[20]

When actual measurements of conversion, number-average and weight-average molecular weights are available for different experimental conditions, the problem becomes one of estimating the unknown parameters appearing in the differential equations based on multiresponse data.[22] The four kinetic constants, k_i, k_p, k_{tm}, k_{ts}, were expressed in terms of two additional parameters through an Arrhenius relationship:

$$k_j = A_j \cdot \exp\left(-\frac{E_j}{RT}\right) \tag{14}$$

It is well known that A_j and E_j in equation (14) are highly correlated, and hence it is advised to reparameter the equation around the mean temperature of the experimental runs, T_0, in order to reduce the degree of correlation. Finally the rate constants are formulated as follows:

$$k_j = \overline{k}_j\, exp\left(-\frac{E_j}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right); \qquad \overline{k}_j = A_j \exp\left(-\frac{E_j}{RT_0}\right) \tag{15}$$

T_0 was taken as arithmetic mean of the experimental temperatures used in the polymerization process. A nonlinear estimation procedure was developed and used to evaluate the kinetic constants ($\overline{k}_j$ and E_j for the initiation, propagation and the two chain transfer reactions). It was considered that there is no correlation among the three measurements (monomer conversion, number-average and weight-average molecular weights). The model error function considered in the parameter estimation method has the form:

$$J = \sum_{i=1}^{N} e_i^T W e_i; \quad e_i = y_{\exp,i} - y_{c,i} \tag{16}$$

In relation (16), $y_{\exp,i}$and $y_{c,i}$ represent the measured and calculated values of the monomer conversion, number-average molecular weight and weight-average molecular weight respectively; W is a weighting diagonal matrix having the elements $w_{11} = 3$ for the monomer conversion, $w_{22} = 2 \cdot 10^{-3}$ for number-average molecular weight and $w_{33} = 10^{-4}$ for weight-average molecular weight. The parameter estimation calculus was performed using the MATLAB "lsqcurvefit" procedure coupled with ode15s integrating function.

The numerical results are presented in Table 1. The calculated values of activation energy for the propagation step is close to those reported by other authors (80 kJ/mole reported by Eenink,[5] 70.9 kJ/mole by Witzke et al.[20] and 86.2 kJ/mole by Ryner et al.[23]).

The calculated values of monomer conversion and polymer molecular weights are presented in Figure 1 to 6 comparatively with experimental points. As seen, a satisfactory adequacy of calculated values to experimental data is obtained for the monomer conversion and the number-average molecular weight. For the moment we could not adequately describe by the presented polymerization model, the time evolutions of all the three process variables (monomer conversion, Mn and Mw). Further modeling studies are envisaged by considering the dependence of polymerization rate constants in respect with the chain length of monomer conversion, and the reversibility of the reaction, at least at the highest temperature. The latter explanation could be responsible for the lower experimental Mw values.

Conclusion

This work presents the results of a preliminary experimental and theoretical study of the bulk L-lactide polymerization process initiated by stannous octoate. The study evidenced the feasibility to realize high monomer conversions for reaction times that can be achieved in twin-screws extruders. It was also tested the adequacy of a mathematical model published in literature. The model describes satisfactorily the time evolutions of the monomer conversion and the number-average molecular weight only. A weaker quality of the fitting to the experimental data was obtained for the weight-average molecular weight (or polydispersity index of the polymer). Further studies are envisaged to improve the mathematical model structure in order to better describe all the polymer characteristics.

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