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A STUDY OF L-LACTIDE RING-OPENING POLYMERIZATION IN MOLTEN STATE

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S-a investigat procesul de polimerizare în masă a L-lactidei utilizând octanoatul de staniu drept inițiator, într-un malaxor de tip HAAKE Rheocord, la două rapoarte molare momomer/inițiator şi la temperatura de 185 °C. Deschiderea de ciclu a L-lactidei a fost confirmată prin analize FT-IR, conversiile monomerului au fost determinate atât prin ^{1}*H-NMR cât şi prin SEC, iar masele moleculare ale polimerului au fost determinate prin SEC. S-au obținut conversii ale monomerului de 80 – 90 % şi mase moleculare relativ mari ale polimerului.*

The L-lactide bulk polymerization process was investigated in a batch HAAKE Rheocord mixer using stannous octoate as initiator at two molar monomer to initiator ratios and a temperature of 185 °C. The ring-opening of L-lactide was confirmed by FT-IR, the monomer conversions were determined both by ^{1}*H-NMR and SEC, whereas the molecular weights were measured by SEC. Monomer conversions between 80 – 90 % and relatively high molecular weights were obtained.*

Keywords: L-lactide polymerization, FT-IR, 1H-NMR, SEC

1. Introduction

Within the last decades the polylactide materials are accepted to play a major role in the packaging industry due to their biodegradability. The published literature indicates also that polylactide products are sufficiently biocompatible, so that they can be used in different medical applications[1]. The monomers used in the polylactides (PLA) synthesis are the lactic acid or the L-lactide, a dimmer of lactic acid. The L-lactide polymerization could be carried out in melt or solution by cationic, anionic, coordination mechanism by different techniques [2] and depending on the initiator used. The most used ring-opening lactide polymerization initiator is stannous octoate (bis 2-ethyl hexanoate, $SnOct_2$), which

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causes a low degree of racemization at high temperature. It is accepted by the US Food and Drug Administration due to its low toxicity [3] . One of the first studies concerning L-lactide polymerization using stannous octoate as initiator was published in 1987 by Eenink [4]. 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 [5], Drumright et al [6], Wu et al [7] and Dechy-Cabaret et al [8].

Many authors investigated the mechanism of L-lactide polymerization in presence of stannous octoate. The most important published reaction mechanisms are the cationic one proposed by Schwach et al [9] and the coordination-insertion mechanism published by Kricheldorf et al [10, 11].

Schwach et al. [9] 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 [12, 13].

Kricheldorf et al [14] carried out the polymerization of L-lactide at 180°C with $Sn(Oct)_2$ under various monomer to initiator (M/I) ratios, detecting significant amounts of octoate as polymer ending groups. The apparent degree of polymerization indicated that, on the average, only one octoate group per initiator molecule was transformed into an ending group. The highest monomer conversion was obtained at 180°C, using an M/I ratio of 200, for a reaction time of 1 h. The mechanism of L-lactide polymerization initiated by stannous octoate in the presence of benzyl alcohol as co-initiator was studied by Kricheldorf et al [10] and in presence of butyl alcohol respectively by Penczek et al [15] and Kowalski et al [16].

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, depolymerization reactions could also take place, especially at high temperatures [17].

In spite of the practical importance of the L-lactide polymerization process, there are a small number of kinetic studies of L-lactide polymerization initiated by stannous octoate published in the open literature. One of the most important was published by Witzke et al [18].

The present work describes our experimental results concerning the L-lactide bulk polymerization initiated by stannous octoate, using commercial monomer without any additional purification. Analysis of the polymeric products by FTIR, ^{1}H-NMR and SEC shown that, in the described working conditions, the polymerization is almost complete (80 – 90% conversion) and leads to polymers with relatively high molecular weights.

Our objective was to compare the size-exclusion chromatography (SEC) and ^{1}H-NMR methods, in the measurement of the monomer concentration in the reaction mixture. There are several published studies using a similar technique to determine the monomer conversion in a L-lactide ring-opening polymerization process [19, 20], but no detailed comparisons with a higher accuracy method as ^{1}H-NMR were presented. In our work, we show that the SEC can be a reliable technique to determine the conversion for the L-lactide ring-opening polymerization process, as a more convenient alternative to ^{1}H-NMR method (more costly and time consuming). The results presented in this paper follows the kinetic study published before [21] for the same polymerization process.

2. Experimental

a. Materials

The L-lactide monomer (L-LA) purchased from Boehringer Ingelheim and the stannous octoate initiator from Sigma Chemicals were used as received. The toluene used as solvent for the initiator product was rectified at atmospheric pressure. The purity of stannous octoate was 95 %, the main impurities of the mixture, as reported in the literature, being water (0.5 wt-%) and octanoic acid (4.5 wt-%) [19, 22, 23].

b. Experimental set-up and polymerization method

The polymerization reactions have been carried out in a Haake Rheocord internal mixer with a R600 chamber, its scheme being presented in Fig. 1. The set-up allows the monitoring the torque and the control with good accuracy of the reaction temperature.

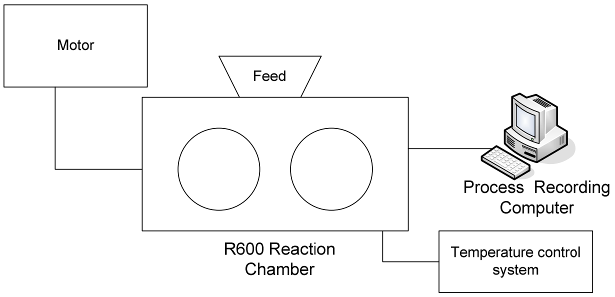

Fig. 1. *HAAKE Rheocord Mixer simplified schema*

The reaction chamber is electrically heated, the resistances being incorporated in three steel plates allowing the complete closing of the reaction chamber and also the temperature regulation. The cooling (if necessary) is performed with current of air at room temperature. The maximum temperature allowed by the apparatus is 400 °C. The device is also provided with two compatible Roller Rotors, having an external diameter of 19.05 mm. The free volume of the reaction chamber is 69 cm^3. The maximum speed of the rotors is about 250 min^{-1}.

Polymerization experiments were carried out at two molar M/I ratios (4500 and 2250 respectively) and a maximum reaction time of 36 min. The polymerization temperature was in all cases 185°C. Samples were taken for comparative analysis during each experiment at different reaction times. The total mass of the monomer used for an experiment was approximately 50 grams. In order to better control the dosage, the added initiator quantity has been firstly dissolved in anhydrous toluene. As an example, for the experiment corresponding to the minimum quantity of initiator (M/I = 4500 moles/mol), a quantity of 0.0313 g of stannous octoate was mixed with 50 g L-lactide. In this aim, a solution of 1 ml stannous octoate in 40 ml anhydrous toluene was prepared and then, 1 ml of the obtained solution was mixed with the specified L-lactide quantity in a flask. The mixture was fed into the reaction chamber, previously heated at reaction temperature. In order to take composition samples, the set-up screws were stopped about 5 seconds for each sample. The samples were immediately cooled in a current of cold air and then added into hermetically closed small plastic bags and stored at the refrigerator to stop the reaction. Before performing all analysis, the polymeric samples were dried 24 hours at 133 Pa and 40°C.

c. Characterization of the reaction product

The samples were characterized in solid state by FT-IR spectroscopy, using a Bruker VERTEX 70 instrument, equipped with a Harrick MVP2 diamond ATR device. The ^{1}H-NMR analyses were performed in deuterated chloroform at 25°C, using a Bruker 250 spectrometer.

The SEC measurements have been performed at 30°C using chloroform as solvent and a L-lactide solution of 5 mg/mL, on a Waters 510 apparatus, with a Polymer Laboratory PLGel 5 μm Mixed-C column. The detector was a Waters 410 differential refractometer, and the scaling has been made using polystyrene standards provided by PolymerLab. A flow rate of 1 mL/min (total time of 12 minutes) was used for each analysis.

2. Results and discussions

The main objective of this study is to qualitatively prove the extent of the polymerization reaction by FT-IR and ^{1}H–NMR analysis and further to see if the SEC analysis method could be a more convenient alternative.

The compositional characteristics for reaction mixture as well as the sampling times are presented in Table 1, for two molar M/I ratios. All samples were first analyzed in solid state by FT-IR method. The obtained FT-IR spectra corresponding to the representative samples for both considered M/I ratios, are presented in Fig.s 2 and 3, comparatively with the L-lactide monomer spectra. From these fig.s, it can be observed that the diminution of the ring specific vibration (650 and 935 cm^{-1}) is proportionate with the L-lactide polymerization time, until the complete disappearance. These bands were selected according to [24], but the the 935 cm^{-1} monomer specific band is reported also by other literature studies [3, 25, 26].

Table 1

Reaction mixture compositions and sampling times

Sample name	Monomer to initiator molar ratio M/I	Time [min]
KD11	4500	2
KD12	4500	6
KD13	4500	12
KD14	4500	22
KD15	4500	36
KD51	2250	2
KD52	2250	6
KD53	2250	12
KD54	2250	22
KD55	2250	36

This behavior evidences the starting of the ring-opening polymerization in the first 2 minutes and almost total consumption of the monomer after 36 minutes.

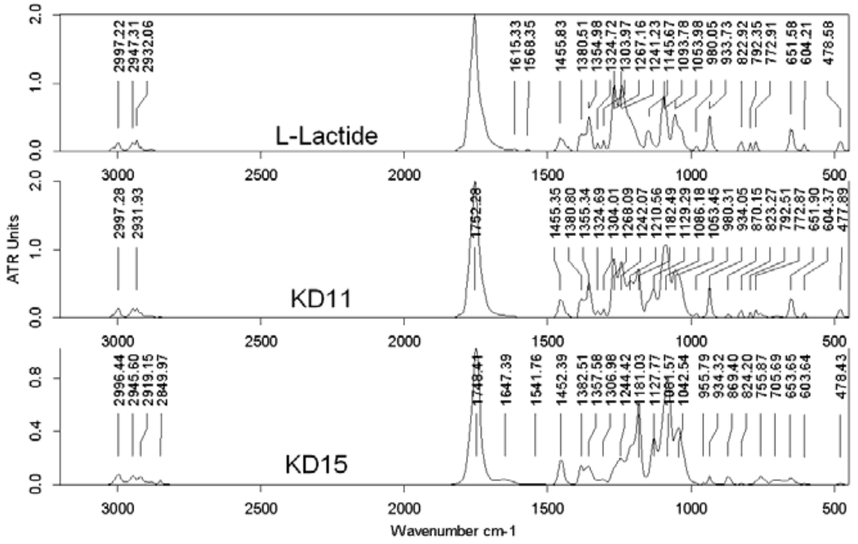

Fig. 2. FT-IR spectra for some experiments with M/I= 4500

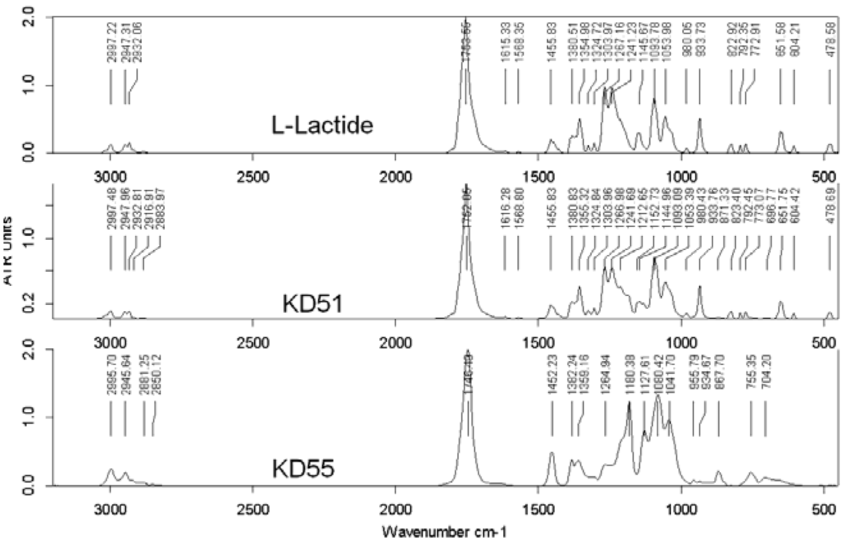

Fig. 3. FT-IR spectra for some experiments with M/I= 2250

The quantitative determination of the monomer concentration was performed by ^{1}H-NMR spectroscopy from integration between methine quartets of monomer ($\delta CH_{L\text{-}LA}$=5.01 ppm) and of the polylactide (PL-LA) polymer ($\delta CH_{PL\text{-}LA}$=5.14 ppm) [27]. Irrespective of the molar M/I ratio the conversion is increasing up to values higher than 80-90%.

In Fig. 4 are presented comparatively the ^{1}H-NMR spectra for the representative polymerization samples, for both molecular M/I ratios. It could be observed the diminution of the signal characteristic for monomer (right quartet) as well as the rise of the intensity for the polymer characteristic signal (left quartet), the variation being proportional with the reaction time. These aspects proves once more the almost complete monomer consumption during the two batch experiments.

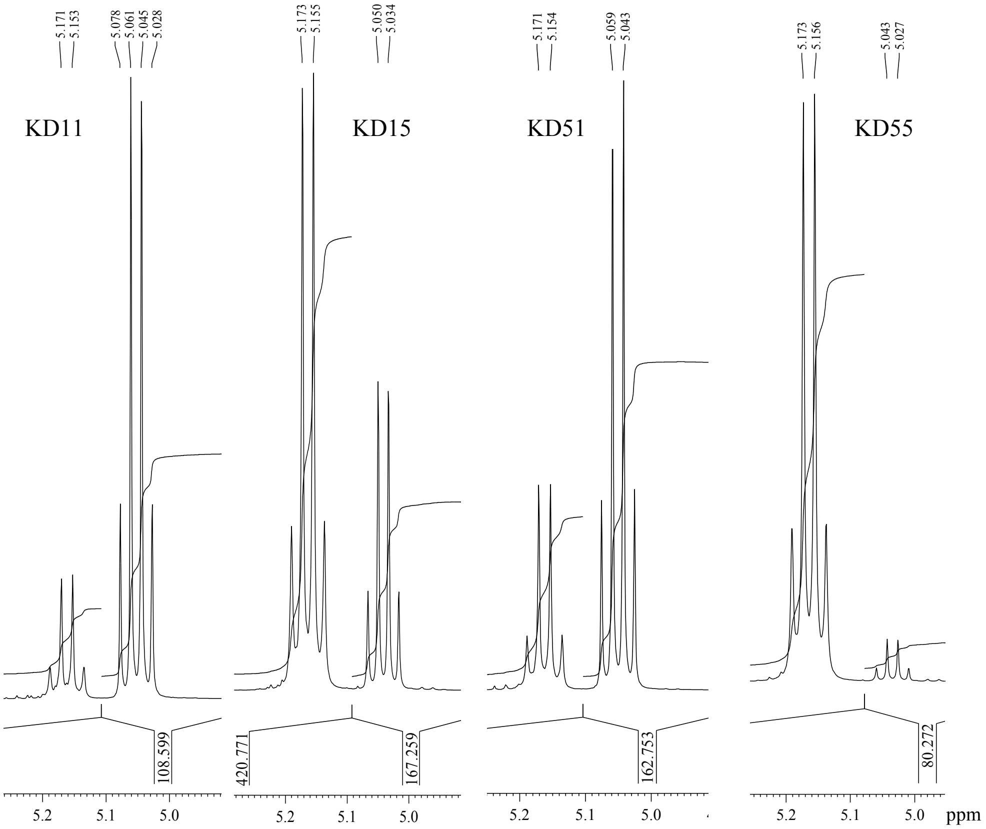

Fig. 4. ^{1}H-NMR spectra for M/I= 4500 series (KD11 and KD15) and M/I= 2250 series (KD51 and KD55)

The monomer conversions determined by ^{1}H-NMR for all experiments are presented in Fig. 5. The conclusion that can be drawn from Fig. 5 is that a constant reaction temperature grants monomer conversion increasing with the initiator concentration (decrease of M/I ratio). The explanation is the presence in the reaction system of a higher density of polymerization centers.

All samples were characterized also by size exclusion chromatography (SEC). This method, usually used for determinations of molecular weights and molecular weights distributions, allows the determination of the monomer conversion in this case, by using the peak area for polymer (Ap) and the corresponding area for monomer (Am).

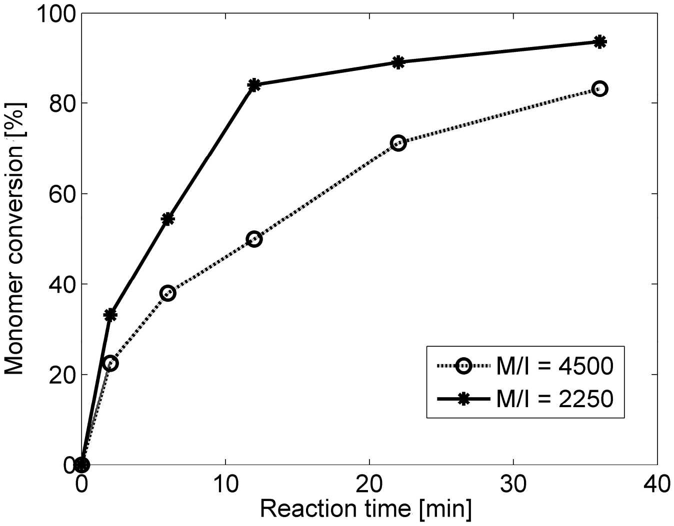

Fig. 5. The monomer conversion evolutions evaluated from ^{1}H-NMR

The relation used to calculate the monomer conversion (C) is:

$$C = \frac{A_p}{A_m + A_p} \cdot 100 \qquad (0)$$

In Table 2 there are presented comparatively the values for monomer conversion obtained by ^{1}H-NMR and SEC for all the reaction samples.

Table 2

Conversion values estimated by *^{1}H-NMR and SEC*

Sample name	Conversion(%) ^{1}H-NMR	Conversion(%) SEC
KD11	22	23
KD12	38	32
KD13	50	48
KD14	71	70
KD15	83	82
KD51	33	33
KD52	54	62
KD53	84	80
KD54	89	87
KD55	94	92

A good agreement can be observed among the monomer conversion values calculated by the two methods for all polymeric samples. In both cases the conversion has a rising evolution to values over 80 – 90 %. The SEC analysis as well as the ^{1}H-NMR indicate a higher monomer conversion in the experiment with a higher initiator concentration (M/I = 2250). These results are proving that the SEC technique could be a reliable method to determine not only the molecular weights of the polymers but also the monomer conversion providing the specific elution volume for the monomer is known.

The molecular weights of the polymers were also determined by SEC analysis. Fig.s 6 and 7 show comparatively the SEC characterization for the 2 min (KD11 and KD51) and 36 min (KD15 and KD55) samples, for both M/I ratios.

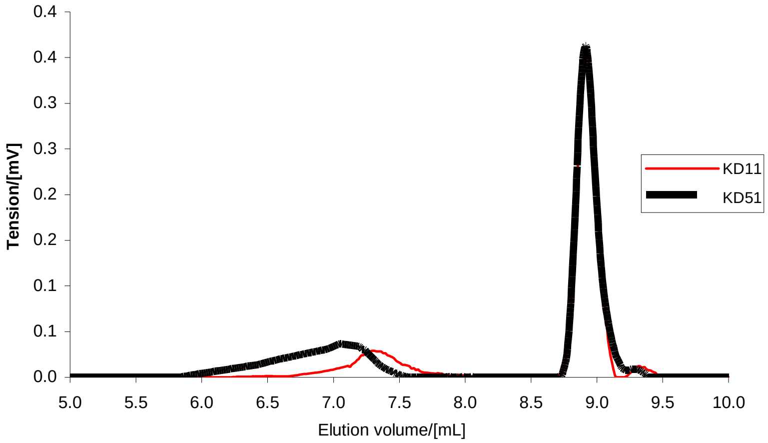

Fig. 6. SEC diagrams for KD11 and KD51 – 2 minutes polymerization time

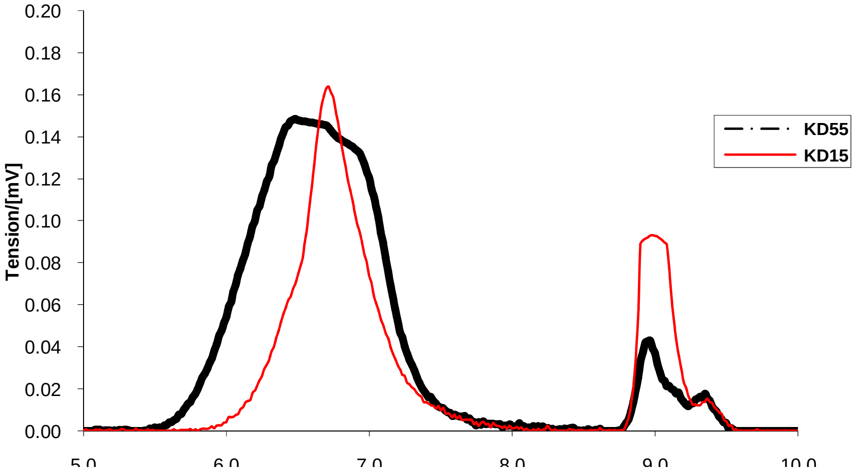

Fig. 7. SEC diagrams for KD15 and KD55 – 36 minutes polymerization time

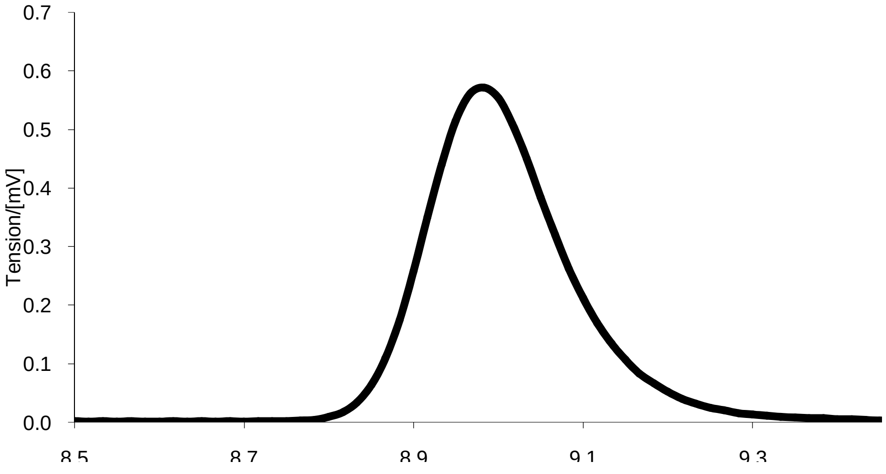

Fig. 8. SEC diagram for L-lactide dimer

It is well known from the SEC technique theory that the small molecular weight polymers exit from the chromatographic column at high elution volumes. The right peaks in the Fig.s 6 and 7 that exit at an elution volume of approximately 9 mL, corresponds to smaller molecular weights compounds from the reaction mixture, probably in this case the un-reacted L-lactide. To confirm the hypothesis that the elution volume for the monomer is about 9 mL (depending on the calibration of the chromatographic columns), its sample was examined by SEC and the chromatogram is presented in Fig. 8. A high area for monomer peak at the beginning of the polymerization process proves a small monomer conversion after 2 minutes (Fig. 6). To the end of the polymerization process (after 36 minutes), the peak area for the polymer is increasing, proving an almost complete polymerization (Fig. 7). Also a shift of the KD51 and KD55 diagrams to smaller elution volumes shows higher molecular weights at M/I = 2250 than at M/I = 4500 (Fig.s 6 and 7). For KD15 sample we obtained a number-average molecular weight of 17000 kg/kmole and for KD55, a number-average molecular weight of 21700 kg/kmole. In all cases the polydispersion index (ratio between weight and number-average molecular weight) is close to 2.

3. Conclusions

The polymeric materials obtained by molten state polymerization of L-lactide using stannous octoate as initiator were characterized by SEC, ^{1}H-NMR and FTIR techniques. The FT-IR analysis proved the opening of the L-lactide cycle until the complete consumption of the monomer. We also evidenced a practical possibility to calculate the monomer conversion from SEC chromatograms in the case of L-lactide ring-opening polymerization. This technique turns up to be a reliable technique, and the results are close to those obtained by the ^{1}H-NMR analysis.

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