Thermal-oxidative Degradation of PGA, PLLA, and Random Binary PLLA-PGA Copolymers

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ABSTRACT

Dimerization process is essential for producing copolymers. The features of dimerization process like thermal-oxidative degradation should be well known to reach maximum efficiency and a superior reactor design. Also, the degradation mechanism of biodegradable polymers is important during sterilization processes. Thermal-oxidative degradation of PGA, PLLA, and their binary copolymers was investigated under isothermal heating as well as dynamic heating. All the samples were prepared by a polycondensation process and were characterized by TG, DTG, DSC, and HNMR analyses. Activation energy under dynamic heating was obtained by using Friedman plot. A new three stage mechanism, namely random, transition, and specific stages is proposed for dynamic heating degradation. Isothermal heating investigation is conducted under an inert atmosphere, and frequency factor and activation energy were achieved. It was found that the activation energy under isothermal heating is generally higher than that under dynamic heating. It was found that the rate of degradation increases significantly with an increase in temperature. The effects of pressure on the degradation rate were studied in different atmospheres with various oxygen partial pressures. Pressure effect was correlated by a second order polynomial in terms of total pressure. The obtained activation energies under isothermal heating were in good agreement with those reported by others. The complete kinetic scheme suitable for reactor design for the thermal-oxidative degradation of the samples was reported. Finally, the optimal operational conditions for the dimerization process were reported.

Keywords: Activation Energy, Dimerization, Frequency Factor, Reactor Design, Thermal-oxidative Degradation

INTRODUCTION

In the past three decades, biodegradable polymers such as polylactic acid (PLA), polyglycolic acid (PGA), and their binary copolymers have been in use for widespread applications [1,2]. The results of several histological studies on lactide, the dimer of PLLA, have verified that the human body can metabolize lactide into carbon dioxide and water without any undesirable response [3].

The majority of the commercially produced lactic acid (LA), the precursor of PLLA, is by the bacterial fermentation [4]. An extensively used method to prepare PLLA and PGA respectively from LA and glycolic acid (GA) was presented by Gilding and Reed [2]. More advanced methods for the

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pre paration of biodegradable polymers/copolymers can be found elsewhere [5]. Mohammadi-Rovshandeh and his co-workers synthesized and characterized novel biodegradable tri-block copolymers from L-lactide, glycolide, and polyethylene glycol/polypropylene glycol [6, 7]. Ajioka et al. reported a kind of one-step method, a direct solution condensation polymerization from LA and GA, to synthesize PLLA-PGA copolymers [8, 9]. Improved methods for synthesizing PLLA by direct dehydration polycondensation have been reported [10-12]. The process is much simpler than the ring-opening polymerization method demonstrated first by Carothers in 1932 [13]. Later on, there have been several attempts of condensation polymerization to gain more simplicity as one can find in reference [4] and references therein. The optimal synthetic conditions of PLLA and PLLA-PGA copolymers by means of melt copolycondensation directly from LA and/or GA with a feed molar ratio of 50/50 were presented [3, 14].

To meet different properties suitable for certain applications and specific requirements, random copolymers of PLLA-PGA can be made by binary combination of dimers with arbitrary weight/mole percentage of each one. It is crucial to determine characteristics of the polymer/copolymer for proper usage into vital environments after synthesizing. For example, nanoparticles of PLLA-PGA copolymers were used for encapsulating an efficient anti-cancer drug [15]. During sterilization, the poly mer/copolymer may unfavorably be decomposed due to an increase in temperature, so the thermal characteristics of polymer/copolymer should be known to hold it stable. Athanasiou et al. investigated sterilization, toxicity, biocompatibility, and clinical applications of PLIA-PGA copolymers [16]. On the other hand, it is useful to know the kinetics of thermal degradation to get a new sight of dimerization process and to design a proper reactor. Such dimer can produce high molecular weight polymer by the ring-opening polymerization method [16]. It was found that

the purification of PLLA before heating increases the thermal stability by removing molecules with low molar mass and residual amounts of catalyst [17,18]. The thermal degradation of PLLA under nitrogen atmosphere was investigated by Nalbandi and found to be a single stage type with activation energy of 21-23 kcal.mol^{-1} [19]. The oxidative-thermal degradation of PLLA was investigated and it was found that the presence of oxygen/air aggravates polymer degradation with activation energy of 22-28 kcal.mol^{-1} [20, 21]. Wachsen et al. applied an interesting degradation-recombination scheme to modeling the thermal degradation of PLLA [22]. It was presented that the kinetic degradation constant (frequency factor) varies in the range of 107 s^{-1} and the energy of activation changes in the range of 28.7 kcal.mol^{-1} for crude PLLA which contains residual tin catalyst [23]. The kinetic parameters of the thermal degradation of PLLA in a blend with polyethylene (PE) were reported, from which it can generally be realized that adding PE increases the stability of PLLA [24]. Gupta and Deshmukh studied the thermal degradation of PLLA in the presence of air and found that the polym uyjer undergoes a thermal-oxidative degradation [20,21]. The thermal degradation of PLLA, PGA, and PLLA-PGA copolymers in a physical blend with poly (ε-caprolactone) (PCL) was studied under an inert atmosphere [25]. Regrettably, none of the above studies have reported the frequency factor and activation energy in their kinetic scheme for PLLA-PGA copolymers. This proposition makes the kinetic scheme unusable to establish a good reactor design. Moreover, pressure effects on the kinetic scheme should be known for designing reactor. The effects of pressure on the reaction rate for PLLA and PLLA-co-PGA have not been investigated so far. Hence there is an urgent need for new studies in this field. The main goal of this work is to find all unknown features affecting the reaction rate and kinetic parameters. The thermal degradation of PGA in the presence of vapor and at different

pressures was investigated in the previous work, where it was concluded that the thermal degradation of pure PGA indeed conformed to a single-stage-type reaction at high temperatures [26].

There is only limited information on the mechanism of the thermal degradation of biodegradable polymers [25, 27-29]. It was reported that PGA is degraded by random chain scission through some changes in the degradation rate [30]. A new approach says that the mechanism of PGA thermal degradation changes from random chain scission to specific chain end scission when the temperature increases [25].

Apart from thermal degradation, hydrolytic/oxidative and in-vitro degradations can separately or simultaneously take place in the presence of relevant active agents like oxygen and vapor. In case of hydrolytic or in-vitro degradation, the rate of degradation is much lower than that of thermal and oxidative degradations [31-36]. Mixed degradation, e.g. thermal-hydrolytic or thermal-oxidative, has seldom been studied and only one report on the thermal-oxidative-hydrolytic degradation of PGA is available [26]; thus, it is of great importance to investigate mixed degradation in which the dimerization process is prevalently designed to be conducted under air atmosphere. The main objectives of our work are studying thermal-oxidative-hydrolytic degradation of crude samples and acquiring a reliable kinetic scheme suitable for reactor design. To our knowledge, no similar study has been accomplished so far. In this paper, the effects of temperature, polymer loading and water/oxygen partial pressure on the degradation rate are investigated. The frequency factor and activation energy of each crude sample are reported as well.

EXPERIMENTAL PROCEDURE

Raw Material

Glycolic acid (70% aqueous solution with a density of 1.26 gr/cm³), L-Lactic acid (90% aqueous solution with a density of 1.21 gr/cm³) and antimony (III)

oxide (Sb_2O_3) as the catalyst were purchased from the Merck Company, Germany. A tiny amount of D-Lactic acid or D-L-Lactic acid (below 1%) was within L-Lactic acid, so PLA and its copolymers thorough this work are in the form of PLLA with high optical purity.

Synthesis Method

Condensation polymerization method was used to prepare all the samples due to simplicity and economical features. This method obtains samples with relatively low molecular weight. The preparation trend was more or less according to that of Gilding et al. [2], albeit with some innovations.

PGA

PGA preparation method can be found elsewhere [26]. The method is summarized in Table 1. The used setup for the preparation of samples is illustrated in Figure 1.

PLLA

At the beginning, 0.34 gr of antimony (III) oxide was added to 0.3 L L-lactic acid when mixing into a batch reactor equipped with an electrical mixer (40-60 rpm). The temperature of the homogenous solution was kept at 150°C for 2 hrs under a nitrogen atmosphere. In this stage, the un-bonded (extrinsic) water is vaporized. Then, the temperature was set on 175°C for 5 hrs in the presence of nitrogen (stage No. 2). The amount of water separated from the L-LA was frequently measured. The water is condensed into a double pipe heat exchanger linked to the top of the reactor (see Figure 1). The solution obtained from the previous stage is subjected to the temperature of 190°C for 90 min (stage No. 3). The end point of this stage is when the 90 percent of the total amount of theoretical water is extracted from the solution. In the second and third stages, a lot of bonded (intrinsic) water is chemically separated; nevertheless, there is still a little bit of water in the solution.
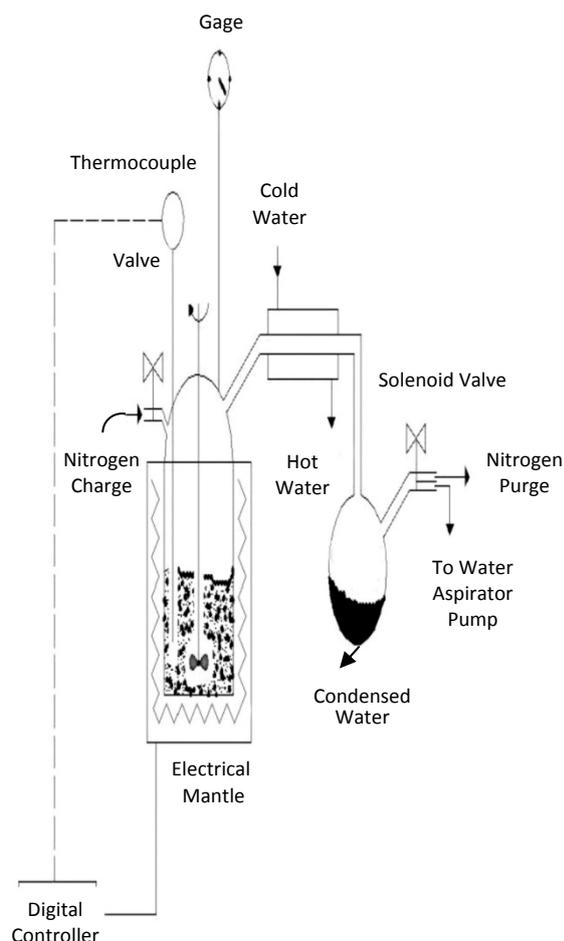
Figure 1: The setup used for polymer/copolymer preparation.

the temperature decreased to room temperature, afterwards. According to our experience, this method compared to other condensation polymerization styles obtains a good PLLA sample with relatively higher molecular weight and mechanical resistance.

Copolymers

Aqueous solutions of L-LA and GA with feeds ratios of 25/75, 50/50 and 75/25 (weight percent) were used to generate different PGA-PLLA copolymers, namely 25PGA-75PLLA, 50PGA-50PLLA and 75PGA-25PLLA. The method of synthesis resembles the one introduced in section 2.2.2 and can briefly be found in Table 1.

Material Balance

Table 2 shows the results of material balance for the preparation of crude samples. This is helpful to evaluate the yield of polymerization/copolymerization. The amount of water separated during preparation process determines progress and degree of completeness of polycondensation. The yield of dehydration is defined as:

$$\text{Yield} = (1 - \frac{\left| W_{\text{total}} - W_{\text{sep}} \right|}{W_{\text{total}}}) \times 100 \qquad (1)$$

In the fourth stage, the temperature of the system decreased to 50°C and the nitrogen flow stopped while the vacuum pump (or water aspirator) was immediately allowed working to extract the rest of bonded water. This stage remained for 16 hrs and

where W_{total} and W_{sep} are the weight of theoretical water and separated water respectively.

Table 1: Polymer/copolymer preparation method used in this study.

Polymer/ Copolymer	Stage No.							
	1		2		3		4 (vacuum)	
	t (min)	T (°C)	t (min)	T (°C)	t (min)	T (°C)	t (min)	T (°C)
PGA [26]	240	120	120	180	240	140	960	50
PLLA	60	150	300	175	90	190	720	150
25PGA-75PLLA	30	120	60	150	330	180	540	170
50PGA-50PLLA	60	120	300	180	30	190	540	170
75PGA-25PLLA	130	130	170	180	60	190	720	170

Table 2: Yield of dehydration for crude samples.

Polymer/ copolymer	W_{total}(gr)	W_{sep}(gr)	Yield (%)
PGA [26]	586.90	584	99.04
PLLA	101.64	99	97.40
25PGA-75PLLA	140.17	138	98.45
50PGA-50PLLA	171.44	168	97.99
75PGA-25PLLA	173.76	171	98.42

Characterization and Thermal Analysis

To characterize the prepared samples, we applied TGA, DTG, NMR, and DSC tests before the isothermal experiments get started. All the samples were not purified in all the tests, except for the HNMR test. All the copolymers were random type, as the HNMR test shows in Figure 4. The GPC tests for the evaluation of polymer/copolymer molecular weight were expensive and not applicable to PGA and to the copolymers containing up to 20 %wt. PGA because they become partially solved only in hexaflouroisopropanol. This solvent is very expensive and infrequent.

TG and DTG Measurements

A thermogravimetry analyzer (TGA Q50 V6.3) performed the dynamic heating degradation under an inert atmosphere of nitrogen (60 ml/min). The reference substance was platinum and the experiments were commenced from ambient temperature to 600°C. The sample weights were selected in the range of 25-35 mgr. The RAMP method (constant heating rate) was used for analyzing when the balance and sample gases were the same as argon at a flow rate of 40.0 ml/min and 60.0 ml/min respectively. From Figure 2 (TG and DTG plots obtained at a heating rate of 20°C/min), the global decomposition peaks for crude PGA, PLLA, 25PGA-75PLLA, 50PGA-50PLLA, and 75PGA-25PLLA are observed at 316.40, 373.09, 362.89, 369.56, and 369.8°C respectively.
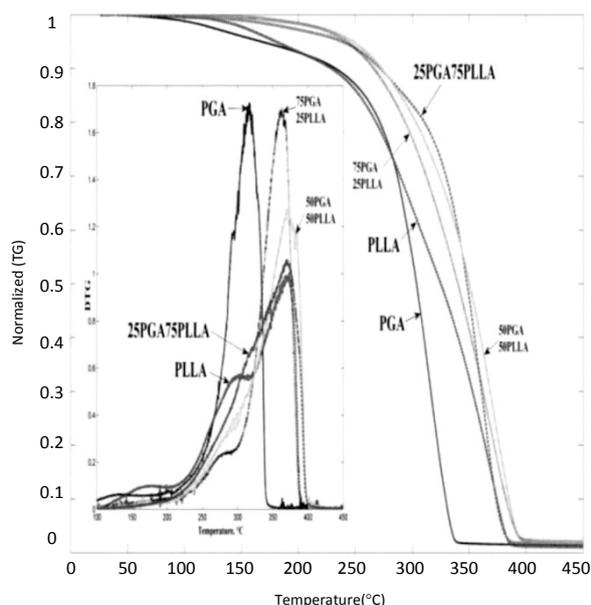

Figure 2: Normalized TG and original DTG plots for the crude samples.

Two paradoxically local maximum points are also observed for PLLA and 25PGA-75PLLA at 307 and 286°C. This treatment is, perhaps, due to impurities and various molecular weight chains. However, the obtained values for the first (local) decomposition peak temperature are in good agreement with those reported earlier [25]. The polymer/copolymer weight loss values are approximately 70%, 88%, 73%, 72%, and 78% respectively for PGA, PLLA, 25PGA-75PLLA, 50PGA-50PLLA, and 75PGA-25PLLA at the global decomposition peak. The weight loss values are 40% and 13% for PLLA and 25PGA-75PLLA at the first local peak respectively. Total polymer weight loss values at the end of degradation are determined as 99.57, 99.04, 98.53, 98.29, and 98.10% correspondingly taken place at 600, 600, 500, 500, and 500°C respectively for PGA, PLLA, 25PGA-75PLLA, 50PGA-50PLLA, and 75PGA-25PLLA. Indeed, Figure 2 shows that PLLA is more stable than PGA against thermal decomposition.

DSC Measurements

For better characterization, the glass transition and melting point of our samples were determined by RAMP method using DSC Q100 V9.0 analyzer. Between 1.5-3 mg of the crude samples was held in

sealed aluminum crucibles when the heating rate was 20°C /min at an argon flow rate of 50 ml/min. The range from -90.14 to 397.24°C was the choice of beginning and ending temperatures respectively. Figure 3 reveals that glass temperatures (T_g) for 75PGA25PLLA and 50PGA50PLLA are 41.93 and 35.40°C respectively. The considerable crystallinity of PGA makes a dramatic endotherm in the DSC curve, showing that the melting point of crude PGA is 209.12°C. Surprisingly, there are three endotherms for PLLA: the first at 117.01°C (T_c), the second around 167°C, and the third at 187.1°C (the melting point).
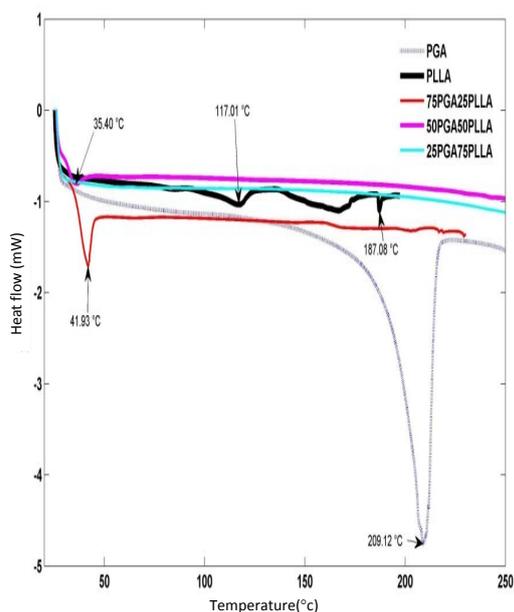

Figure 3: DSC analysis of the crude samples.

The first endotherm for PLLA is related to the temperature of crystallinity, as reported elsewhere [37]. As one can see in Figure 3, PLLA and 25PGA75PLLA do not have any glass temperature. The crystallinity of the synthesized samples can be extracted from the DSC analysis. The degree of crystallinity is in direct proportion to the area under the DSC curve. As clear, PLLA is partially crystalline, while PGA is fully crystalline. 75PGA25PLLA is relatively crystalline, whereas 50PGA50PLLA and 25PGA75PLLA are nearly amorphous. The degree of crystallinity and melting point of PLLA decrease with

decreasing optical purity. The obtained PLLA has up to 99 percent L-unit; therefore the degree of crystallinity is between 45-70% [37]. The degree of crystallinity of PLLA in this work is calculated by mathematical relation and found to be 54.81%. PLLA's with optical purity less than 87.5 percent are amorphous. The crystallinity of 50PGA50PLLA and 25PGA75PLLA are 8.85 and 7.93 percent respectively.

NMR Measurements
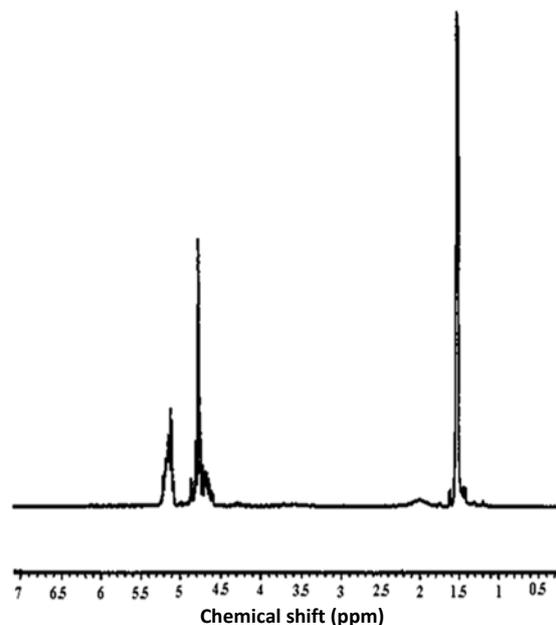
Figure 4: 1HNMR test for 25PGA75PLLA.

To find the structural details of copolymers (random or block), HNMR test was used for purified copolymers. Crude copolymers were purified by recrystallization in ethyl acetate (4 stages) to remove inferior peaks. As shown in Figure 4, the signals of 1HNMR spectra for 25PGA75PLLA split to distinct peaks due to the random distribution of monomers in the backbone structure. This treatment occurs for random copolymers.

Kinetic Scheme

Dynamic Heating

To search for the degradation mechanism of dynamic heating, the so-called Friedman plot shall be prepared from for example the data in Figure 2, where the variation of ln *(dα/dt)* against inverse

temperature is depicted up to the decomposition peak temperature. Conversion, α, is defined by:

$$\alpha = 1 - \frac{m_A}{m_{A,0}} \qquad (2)$$

All kinetic schemes assume that the isothermal rate of degradation is a linear function of a temperature-dependent rate constant, k, and a temperature-independent function of the mass concentration, m, in the below form:

$$-\frac{dm_A}{dt} = k_{th} f(m_A) \qquad (3)$$

The general kinetic scheme may be made upon the reversible reaction defined as follows:

$$A \underset{k_2}{\overset{k_1}{\rightleftarrows}} \text{Volatile + Dimer product + Solid residue}$$
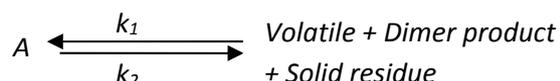
The reaction is assumed to be irreversible, so k_1 becomes zero and k_2 changes to degradation rate constant. The temperature dependency of degradation rate constant under an inert medium can be expressed by an Arrhenius equation:

$$k_{th} = k_0 \exp(-E_a / RT) \qquad (4)$$

where k_0, frequency factor, is temperature independent. The combination of Equation 3 and Equation 4 gives:

$$-\frac{dm_A}{dt} = f(m_A) k_0 \exp(-E_a / RT) \qquad (5)$$

Biodegradable polymers are recognized to be degraded according to universal first order reaction rather than higher orders [29, 38,39].

$$f(m_A) = m_A^{\ n} \qquad n = 1 \qquad (6)$$

Several empirical kinetic schemes were developed based on the fitting operation on the degradation data, but not based on well-known theories. As a

merit, the first order reaction is the most used kinetic scheme, which has rigorous theoretical and experimental basics. For this reason, the first decomposition reaction is used in this work.

If the sample temperature is changed by a constant heating rate, $\beta = dT/dt$, the variation in the polymer weight can be analyzed as a function of temperature [39].

$$-\frac{dm_A}{m_A} = \frac{k_0}{\beta} \exp(-\frac{E_a}{RT}) dT \qquad (7)$$

Friedman method is probably the most derivative technique for calculating activation energy [40-42]. This kinetic scheme would be valid to evaluate activation energy only under an inert atmosphere. Thus, an active atmosphere shall be investigated in the isothermal heating tests on the foundation of different kinetic schemes (See section 2.5.2.).

Isothermal Heating

The thermal-oxidative degradation of samples is investigated in isothermal heating because controlling oxygen/water partial pressure is simpler than dynamic heating. Once more, the relevant kinetic scheme may be made based on a first order reaction just as dynamic heating (Equation 3). The major difference is the definition of degradation rate constant so that it agrees with pressure variation and oxygen partial pressure. As previously reported [26], a kinetic model of Kelen, capable of inserting pressure effect into unimolecular decomposition rate, is used to estimate the degradation rate constant [43]. Kelen's basic approach to pseudo-unimolecular degradation rate constant is expressed in the following form:

$$k = k_{th}(T) F_c F_p \qquad (8)$$

where, k_{th} is the true thermal degradation rate constant, which is evaluated under an inert atmosphere and it is only temperature dependent as Equation 4 dictates. The correction factors of F_c and F_p in Equation 8 depend on the polymer

loading and total pressure. They are temperature-independent. The factor of F_p would compensate for the oxidative-hydrolytic contributions to the pseudo-unimolecular degradation rate constant. Commonly, functionality of F_p is determined based on the empirical correlations due to simplicity. Substituting Equation 6 into Equation 5 and making integration results in:

$$-\ln \frac{m_A}{m_{A,0}} = kt \tag{9}$$

The time variation of mass fraction retained during isothermal stage (Equation 9) can be simplified [25]:

$$\frac{m_A}{m_{A,0}} = 1 - kt \tag{10}$$

where

$$\alpha = kt \tag{11}$$

Equation 10 is just a deterministic approach toward Equation 9 (a truncated expansion for the exponential term); however, it gives reliable results for a wide range of degradation for a short period of time. Isothermal heating is investigated at different pressures associated with different oxygen/water partial pressures using Equation 10. The setup is founded to handle the planned air/water partial pressures [26].

RESULTS AND DISCUSSION

To estimate activation energy under dynamic heating, Friedman data points were prepared. Some of the doubtful data points were rejected. The conditions for dynamic heating can be found in section 2.4.1. The fitting process was accomplished by MATLAB 7.5.2007b Curve Fitting Toolbox. The linear least square optimization method of Trust-Region with a confidence level of 95% was applied. Variation of *ln(dα/dt)* versus *1000/T* is the Friedman plot, which is constructed from ascending portion

of DTG curve until the main decomposition peak is appeared. The results indicate a change in the activation energy for PGA, PLLA, 25PGA-75PLLA, and 50PGA-50PLLA likely due to the change in the degradation mechanism from random chain scission at low temperatures to specific chain scission at high temperatures. For 75PGA-25PLLA any change in the slope is not noticeable. Lower activation energy for 25PGA-75PLLA is related to weight losses below 3%, whereas higher activation energy is obtained from the weight losses from 3% to 80%. Oddly enough, a transition zone during changing mechanism is evident for PGA and PLLA, while for copolymers two zones of random and specific scissions become merged. Thus as concluded in DSC section, the property of crystallinity can directly affect activation energy because crystalline structures need an extra energy to be activated. At low temperatures, PGA is degraded by ester interchange leading to the formation of larger olefinic chains with the liberation of smaller amount of glycolide (dimer) and methyl glycolate due to the decarboxylation of chain ends [44]. Conversely, at high temperatures, PGA is degraded by the decarboxylation of chain ends with glycolide and methyl glycolate as the main products [44]. Similar observations for PLLA were also reported [17]. Sivalingam et al. claimed that this procedure occurs for all aliphatic polyesters, while an obvious contradiction is here for 75PGA25PLLA, which does not show any changes in the activation energy and degradation mechanism [25].

The statistical parameters of fitting and the obtained activation energy are listed in Table 3, which shows a considerable decrease in the activation energy of the crude samples in comparison with that of the pure samples [25]. Fitted curves 1, 2, and 3 correspond to random, transition, and specific degradation mechanisms respectively. This mechanism (3 stages) is reported in the present work for the first time.

Table 3: Activation energy of dynamic heating for the crude samples.

Sample	Random E_a (kcal/mol)	Transition Ea (kcal/mol)	Specific E_a (kcal/mol)	R-squared of Fit 1	R-squared of Fit 2	R-squared of Fit 3	RMSE of Fit 1	RMSE of Fit 2	RMSE of Fit 3
PGA	7.27	21.40	13.72	0.956	0.992	0.962	0.0864	0.0627	0.0218
PLLA	5.04	13.30-17.58	9.85	0.922	0.988-0.943	0.993	0.0817	0.1593-0.0515	0.0133
25PGA75PLLA	5.47	14.51	27.38	0.822	0.980	0.998	0.1998	0.0619	0.0196
50PGA50PLLA	-	13.44	15.48	-	0.995	0.990	-	0.0223	0.0591
75PGA25PLLA	-	6.97	14.80	-	0.995	0.994	-	0.0108	0.0547

So far, the results are insufficient so as to complete kinetic scheme because frequency factor is still unknown. Besides, the effects of pressure and polymer loading on the kinetic parameters shall be investigated in an isothermal mode. Hence the kinetic scheme is improper for reactor design as the main goals of the present study. To study the effect of total pressure on the retained weight of samples, several experiments were carried out at different total pressures (absolute pressure) as well as initial oxygen/water partial pressures. The results are depicted in Figure 5 for PLLA, 25PGA-75PLLA, 50PGA-50PLLA, and 75PGA-25PLLA; similar results for PGA can be found elsewhere [26].
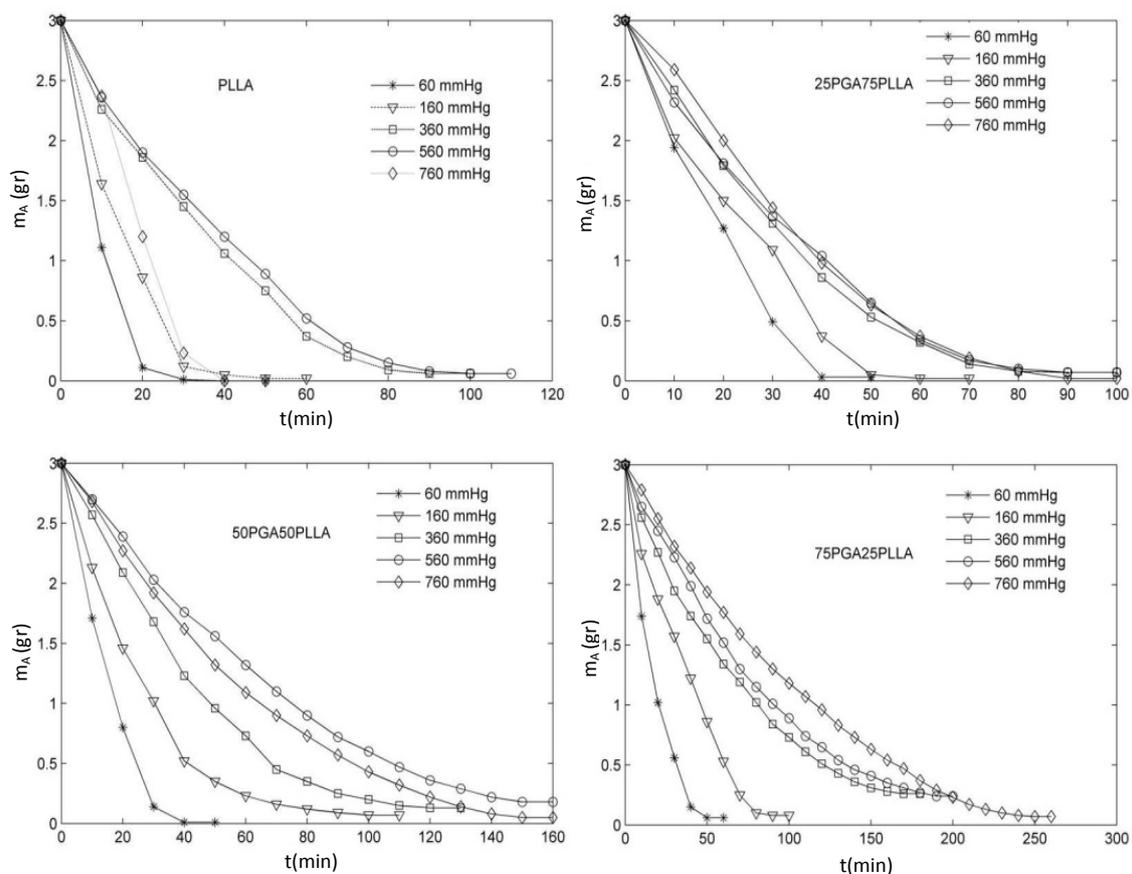

Figure 5: Variation of retained weight of samples with time at various total pressures; the temperature and polymer/copolymer loading are 260°C and 3 gr.

We expect the samples weight loss to be more observable at lower pressures (relative vacuum states) because of the Le Chatelier' principle. Relative vacuum state causes a decrease in the normal boiling point of the samples in favor of an increase in the rate of degradation. On the other hand, the presence of oxygen in the system (higher pressures) can increase the rate of degradation by oxidizing chain ends.

These two agents (low pressure against oxygen atmosphere) act oppositely in a way that for a relatively short while the first agent (vacuum) and for a long while the second agent (oxygen) are dominant, as it is clear from Figure 5. In a long period of time, the polymer chains become more fractured, and oxygen can consequently attack more carbon end atoms. Figure 5 shows that with an increase in the percentage of PLLA through copolymers, the second agent (oxidation) overcomes the first agent. Thus PGA is more resistance to oxidation than PLLA at any given time. Since the water aspirator pump was working at room temperature so as to induce a vacuum state, the minimum available pressure is identical to the water vapor pressure at 25°C, i.e. 23.78 mmHg [45]. Therefore, the total pressures of 60, 160, 360, 560, and 760 mmHg correspond respectively to 0.3963, 0.1486, 0.0661, 0.0425, and 0.0313 as water mole fractions and 0.127, 0.179, 0.196, 0.201, and 0.203 as oxygen mole fractions. All the mole fractions were calculated with the help of the science of phase equilibrium assuming that the partial pressure of volatile is negligible [46]. Equation 10 offers to make a linear fit plot on the data of $m_A/m_{A,\,0}$ versus time for obtaining degradation rate constant at different pressures. The slope of each linear plot gives us the relevant degradation rate constant. Table 4 summarizes the results of all the experiments. From this table, it is evident that the degradation rate at a pressure of 760 mmHg is surpassed by the one at 560 mmHg due to a greater oxygen mole fraction as demonstrated beforehand.

Table 4: Results of isothermal experiments.

Parameter in question	Test description	y_{water}	$y_{nitrogen}$	y_{oxygen}	P_{total} (mmHg)	L (gr)	T (°C)	$k \times 10^3$ (1/min)	Adjusted R-squared	RMSE
Temperature	PLLA+ air+ water	0.023	0.772	0.205	760	10	180	0.178	0.998	0.011
							200	0.440	0.996	0.017
							220	1.335	0.993	0.020
							240	4.465	0.997	0.016
							260	13.205	0.996	0.021
							280	17.360	0.992	0.029
	25PGA75PLLA+ air + water	0.023	0.772	0.205	760	10	220	0.679	0.996	0.016
							240	2.722	0.998	0.009
							260	8.602	0.996	0.017
							280	14.862	0.992	0.030
	50PGA50PLLA+ air + water	0.023	0.772	0.205	760	10	220	0.541	0.999	0.021
							240	1.516	0.999	0.005
							260	6.897	0.991	0.017
							280	12.760	0.994	0.021

Parameter in question	Test description	y_{water}	$y_{nitrogen}$	y_{oxygen}	P_{total} (mmHg)	L (gr)	T (°C)	$k \times 10^3$ (1/min)	Adjusted R-squared	RMSE
	75PGA25PLLA+ air + water	0.023	0.772	0.205	760	10	220	0.218	0.994	0.021
							240	1.012	0.999	0.005
							260	3.255	0.994	0.016
							280	10.601	0.987	0.026
Pressure	PLLA+ air+ water	0.291	0.560	0.149	60	3	260	48.170	0.939	0.121
		0.109	0.704	0.187	160			35.677	0.952	0.079
		0.049	0.752	0.199	360			13.941	0.979	0.044
		0.031	0.766	0.203	560			13.193	0.981	0.039
		0.023	0.772	0.205	760			31.600	0.981	0.056
	25PGA75PLLA+ air + water	0.291	0.560	0.149	60	3	260	27.331	0.986	0.042
		0.109	0.704	0.187	160			20.632	0.970	0.057
		0.049	0.752	0.199	360			16.680	0.987	0.037
		0.031	0.766	0.203	560			15.270	0.979	0.042
		0.023	0.772	0.205	760			16.428	0.993	0.026
	50PGA50PLLA+ air + water	0.291	0.560	0.149	60	3	260	36.672	0.980	0.052
		0.109	0.704	0.187	160			22.030	0.969	0.051
		0.049	0.752	0.199	360			14.773	0.999	0.006
		0.031	0.766	0.203	560			9.464	0.991	0.019
		0.023	0.772	0.205	760			11.362	0.996	0.012
	75PGA25PLLA+ air + water	0.291	0.560	0.149	60	3	260	26.810	0.928	0.095
		0.109	0.704	0.187	160			12.946	0.975	0.045
		0.049	0.752	0.199	360			8.964	0.974	0.032
		0.031	0.766	0.203	560			7.678	0.994	0.016
		0.023	0.772	0.205	760			6.544	0.995	0.013
Loading	PLLA+ air+ water	0.023	0.772	0.205	760	3	280	40.330	1.000	0.000
						5		35.801	0.986	0.042
						7.5		22.797	0.992	0.025
						10		17.360	0.992	0.029
						12		16.789	0.991	0.030
	25PGA75PLLA+ air + water	0.023	0.772	0.205	760	3	280	31.301	0.997	0.021
						5		24.883	0.993	0.033

Parameter in question	Test description	y_{water}	$y_{nitrogen}$	y_{oxygen}	P_{total} (mmHg)	L (gr)	T (°C)	k×10³ (1/min)	Adjusted R-squared	RMSE
						7.5		19.844	0.989	0.033
						10		14.862	0.992	0.030
						12		14.980	0.995	0.023
	50PGA50PLLA+ air + water	0.023	0.772	0.205	760	3	280	27.073	0.995	0.024
						5		19. 802	0.993	0.026
						7.5		15.763	0.987	0.028
						10		12.760	0.994	0.021
						12		11.572	0.993	0.021
	75PGA25PLLA+ air + water	0.023	0.772	0.205	760	3	280	18.634	0.990	0.029
						5		13.517	0.991	0.025
						7.5		12.345	0.991	0.022
						10		10.601	0.987	0.026
						12		9.726	0.987	0.024
Nitrogen atmosphere (flow rate of 377 cm³/min)	PLLA+ nitrogen	0	1	0	-	3	250	31.273	0.975	0.030
							270	56.536	0.986	0.022
	25PGA75PLLA+ nitrogen	0	1	0	-	3	250	9.683	0.980	0.035
							270	13.176	0.989	0.027
	50PGA50PLLA+ nitrogen	0	1	0	-	3	250	9.127	0.995	0.016
							270	14.699	0.985	0.029
	75PGA25PLLA+ nitrogen	0	1	0	-	3	250	3.342	0.988	0.015
							270	11.831	0.996	0.014

Among many tests done to investigate polymer/copolymer loading effect, we found that initial sample loading does not have any effect on the degradation rate constant as long as loading is higher than 10 gr. For loading below 10 gr, however, a difference in the degradation rate is observed likely due to the carbonization of the samples. It is discovered that at any given time, the rate of the carbonization of PLLA is higher than that of PGA. An extra methyl branch into the PLLA structure presumably increases the amount of carbonization. Loading (up to 10 gr) is an inert factor; thus the parameter of F_c in Equation 8 takes a unit value. Our conclusion for polymer loading effect is thoroughly consistent with that in Refs. [26, 47].

Several experiments were established at various temperatures at 760 mmHg. Sample loading for all the experiments in this section was 10 gr. The results are tabulated in Table 4, where it is clear that the degradation rate raises with an increase in temperature. Characteristic curves to evaluate the degradation rate constant for the samples at different temperatures are shown in Figure 6.

Statistical analyses such as adjusted *R*-squared and RMSE for all the fitted plots are reported in Table 4. The quantity of RMSE is a criterion for fitness quality and is defined as:

$$RMSE = \frac{\sqrt{\sum_{1}^{n}(A_{exp} - A_{fitting})^2}}{n} \qquad (12)$$

In fact, our basic measure of how closely a model fits some data is the Root Mean Squared Error (RMSE), which measures the average mismatch between each data point and the model (here is linear). The reported degradation rates in Table 4 were all obtained from Equation 10, which describes how this parameter varies with time.

We repeated the experiments with an adjusted *R*-squared lower than 0.90 to gain high accuracy.
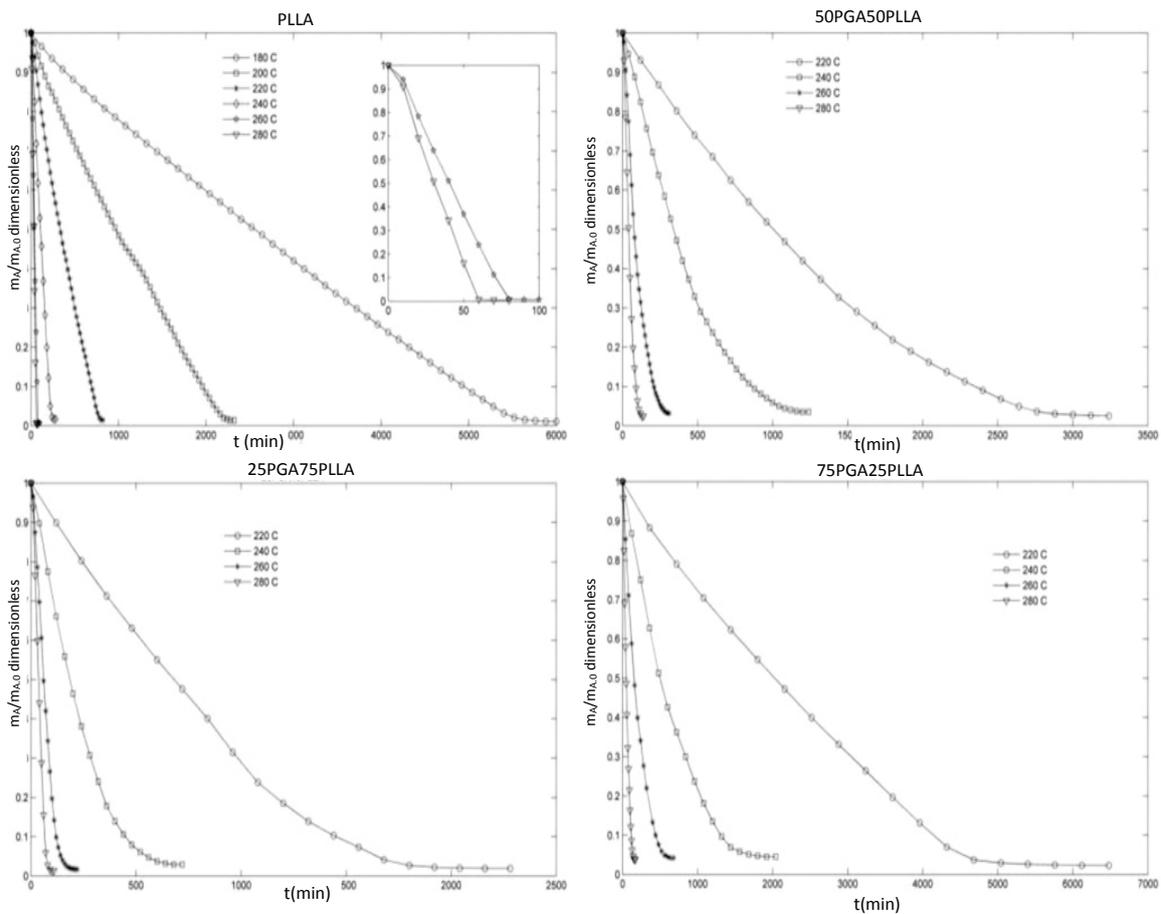

Figure 6: Variation of mass fraction retained with time at different temperatures at atmosphere pressure.

The true thermal degradation constant has to be acquired under an inert atmosphere and in the absence of oxygen and vapor. Before studying pressure dependency of degradation rate constant under thermal-oxidative-hydrolytic mode, this quantity must be specified. For all the samples, it is investigated at two temperatures as one can see the results in Table 4. Information is also available on true degradation constant of pure PGA [26].

Activation energy and frequency factor in different atmospheres were found considering Arrhenius plot. The results are incorporated into Table 5. Normal values (true values under an inert atmosphere) of activation energy and frequency factor are shaded in Table 5. It was found that activation energy in an oxygen/vapor atmosphere is higher than that in an inert atmosphere due to oxidative-hydrolytic-thermal degradation. In general,

the activation energy obtained under isothermal heating is higher than the one obtained under dynamic heating. However, the obtained activation energies are in good agreement with those reported in literature, especially in Refs.[19-21, 25].

Table 5: Activation energy and frequency factor obtained in different atmospheres.

Test description	E (kcal/mol)	k_0 (1/min)	Adjusted R-squared	RMSE
PLLA+ nitrogen	16.707225	301341.6651	-	-
25PGA75PLLA+ nitrogen	8.6913318	41.58751492	-	-
50PGA50PLLA+ nitrogen	13.446213	3809.297241	-	-
75PGA25PLLA+ nitrogen	35.66856	2.71551×10^{12}	-	-
PLLA+ air+ water	24.481422	106536691	0.984	0.2345
25PGA75PLLA+ air + water	28.342206	2900067936	0.967	0.2483
50PGA50PLLA+ air + water	29.845608	9177310272	0.9727	0.2371
75PGA25PLLA+ air + water	34.772874	6.05306×10^{11}	0.9976	0.08072

The results summarized in Tables 4 and 5 are still incomplete without a correlation for F_p to be used for successful reactor design. The effect of pressure on the degradation rate constant (F_p) was investigated. When the normal frequency factor (k_0 or k_{th}) and F_c are given, F_p can be calculated by Equation 8. Table 6 includes the values of F_p acquired under different pressures. As demonstrated, F_p has a higher order of magnitude in the vacuum states. It first drops with pressure growth and then gradually rises since oxygen aggravates the degradation rate (Figure 7).

Table 6: True thermal degradation constant and F_p.

Test description	T (°C)	$k_{th}\times10^3$ (1/min)	P (mmHg)	F_p (dimensionless)
PLLA+ air+ water	260	42.304514	60	1.138649176
			160	0.8433379
			360	0.329539302
			560	0.311857973
			760	0.746965206
25PGA75PLLA+ air + water	260	11.326795	60	2.412950883
			160	1.821521445
			360	1.472614274
			560	1.348130694
			760	1.450366145
50PGA50PLLA+ air + water	260	11.633658	60	3.152232943
			160	1.893643427
			360	1.269849947
			560	0.813501652
			760	0.976648961
75PGA25PLLA+ air + water	260	6.3673	60	4.210575911
			160	2.033200886
			360	1.40781807
			560	1.205848633
			760	1.027751166

To design a reactor for conducting dimerization process, it is optimal to work away from the minimum point of F_p in every plot (Figure 7) because the rate of dimerization is the lowest there. The more the degradation rate is, the more desirable the dimer product is generated. In reactor engineering, it is important to maximize the rate of dimerization by setting operating conditions on the maximum value of F_p. The best option may be working under relative vacuum to avoid carbonization and oxidation and to have a greater degradation rate and consequently a higher dimerization rate. The functionality of F_p was found by fitting operation on the curves of F_p versus pressure, as can be seen in Table 7. It was found that a second order polynomial with respect to the pressure (mmHg) is capable of correlating the data very well.

In this stage, the kinetic scheme is ready for a comprehensive reactor design, in which the maximum rate of dimerization gives almost a pure dimer product. In our next work, we will centralize the reactor design for the dimerization process
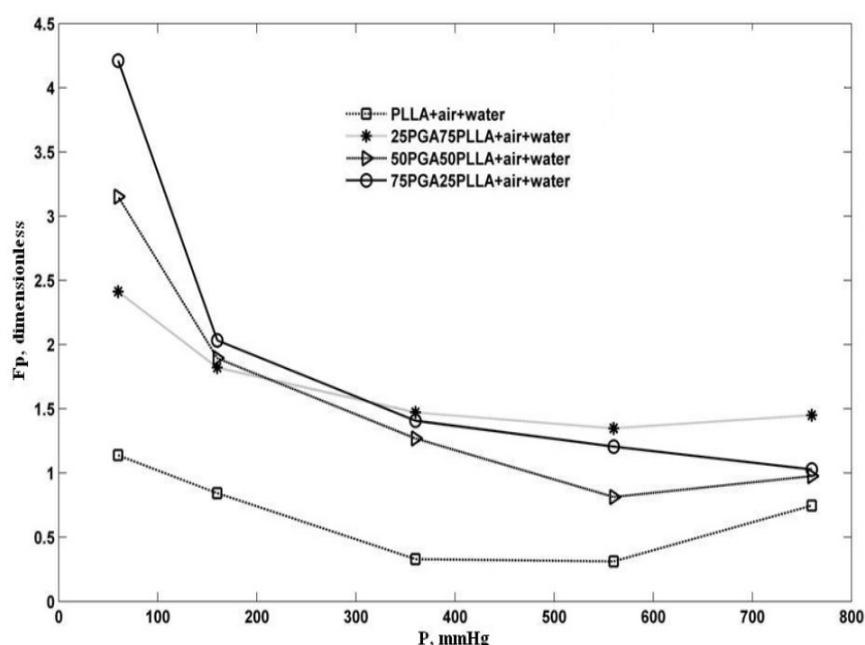

Figure 7: Variation of F_p versus total pressure.

Table 7: The correlations for F_p.

Sample	Correlation	Adjusted R-squared	RMSE
PLLA	$5.35050e-6P^2 - 0.0050P + 1.4536$	0.9817	0.0479
25PGA-75PLLA	$4.2679e-6P^2 - 0.0047P + 2.5962$	0.9265	0.1183
50PGA-50PLLA	$8.1082e-6P^2 - 0.0094P + 3.5035$	0.9191	0.2701
75PGA-25PLLA	$1.0824e-6P^2 - 0.0125P + 4.4546$	0.8726	0.6578

CONCLUSIONS

In this paper, the thermal-oxidative degradation of PLLA, PGA, and PLLA-PGA copolymers was studied at different water/oxygen partial pressures. The samples prepared by a new polycondensation method were characterized by TG, DTG, DSC, and HNMR analyses. Dynamic heating analysis showed that there may generally be three stages of degradation with different mechanisms as well as activation energies: random stage, transition stage, and specific stage. The obtained activation energies by dynamic treatment were in the expected range. Normal activation energy, frequency factor, and true degradation constant were evaluated in a nitrogen atmosphere and found to be in excellent agreement with those previously reported. It was found that the sample loading is inert, providing that the sample charge is up to 10 gr. It was found that the rate of degradation increases with a rise in temperature. It was also found that the presence of oxygen intensifies the rate of thermal degradation. Activation energies obtained in an oxygen atmosphere were higher than those obtained in an inert atmosphere. A second order polynomial in terms of total pressure was proposed to take pressure effect on the degradation rate constant into account. The complete kinetic scheme and optimal operational conditions were rendered for reactor engineering.

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