The contributors have attempted to discuss modern trends in polymer flame retardancy. They have also tried to reflect the interest that exists in the creation of new forms of ecologically friendly flame retardants for polymers. This interest will give rise to a solution of many practical and political problems in the future. The chapter contains modern ideas and studies focused attention on five trends in polymer flame retardancy: intumescent systems, low-melting glasses systems, polymer nanocomposites, organic char forms, silicon inorganic systems and preceramic additives.

1. Introduction

Our environment has mostly polymeric nature and all polymers burn whether natural or synthetic. The use of polymer flame retardants has an important role in saving lives. There are four main families of flame-retardant chemicals: Inorganic flame retardants including aluminum trioxide, magnesium hydroxide, ammonium polyphosphate and red phosphorus. This group represents about 50% by volume of the global flame retardant production [1].

Halogenated flame retardants, primarily based on chlorine and bromine. The brominated flame retardants are included in this group. This group represents about 25% by volume of the global production [1].

Organophosphorus flame retardants are primarily phosphate esters and represent about
20% by volume of the global production [1]. Organophosphorus flame retardants may contain bromine or chloride.

Nitrogen-based organic flame retardants are used for a limited number of polymers. The flame retardant chemicals' industry has historically been driven by regulations and standards. The normal fire-, smoke-, and toxicity-related standards have been joined by environmental standards caused by the alleged environmental impact of halogens and the alleged toxicity of antimony. Although suitable replacements have not been found for these materials in all cases, the environmental concern has served to depress their growth levels from what it would otherwise have been and/or channel the growth into alternative chemical products. In connection with the amendment of the Ordinance on Dangerous Substances, the federal government of Germany passed a new Ordinance on the ban and restriction of certain chemicals, compounds and products (Chemikalien-Verbots-Verordnung) which became effective on 1-st November 1993 (BGBI I, 1720) and has been amended the first time on 6th July 1994 (BGBL I, 1493). The ordinance has replaced the following Ordinances:

1. An ordinance on the Ban of PCB and PCT of 1989
2. An ordinance on the Ban of Pentachlorophenol of 1989
3. First Ordinance on Chloroaliphates of 1991
4. An ordinance on "Dioxins" and "Furans"

In addition to Tetra- up to Hexachlorodibenzo-p-dioxins/furans with Chlorine atoms at position 2,3, 7, 8 (8 substances transferred from the Ordinance on Dangerous Substances, App. V, 3), the amendment of 6-th July 1994 extends the number of congeners of this type by some additional Penta- up to Octachlorodibenzo-p-dioxins/furans. Now the total number of restricted chlorinated PCDD/PCDF-Congeners amounts to 17 substances. The threshold concentrations for these chemicals in substances preparations and products were decreased considerably, depending on theirs toxic potentials. However, plant treatment agents, intermediates, and a few more products were excluded from this regulation. For the first time, 2, 3, 7, 8 - brominated dioxins and furans are restricted now as well; 8 PBDC/PBCF-.

Congeners were added to the list of the regulation. This was the result of an approximation process to the scientific progress concerning the appearance, environmental fate, toxicity and analytical methodology of these substances.

In December 1992, the European Commission granted Germany an exception under Article 100 (A) (4) of the treaty from EU-legislation issued in 1991 restricting the marketing and use of substances and preparations containing PCP and its compounds (Council Directive 91/173 EEC amending for the ninth time Directive 76/769/EEC). This consent was necessary because the German legislation imposed, differing from the EU-directive, wider restrictions and lower concentrations limits of PCP. After an action of France against the consent, in May 1994 the European Court of Justice annulled the decision by the Commission on the grounds that no adequate reasons had been given for it and thereby Article 190 of the treaty had been violated. In September 1994, the Commission pronounced a new decision and confirmed the German legislation again.
The Commission verifies now the possibility to propose a total ban of PCP for the EU. In this connection one can expect in a near future some new unexpected steps in this direction. It doesn’t necessarily mean the total ban of halogenated flame retardants in the next 5 - 10 years. But it actually means a complete reconsideration in a direction of polymers’ flame retardancy development. It is obviously, the new efforts will be directed on the ecologically-friendly flame retardant systems. This review is devoted to some new directions in this area.

The main flame retardant systems for polymers currently in use are based on halogenated, phosphorous, nitrogen, and inorganic compounds (Figure 1). All of these flame retardant systems basically inhibit or even suppress the combustion process by chemical or physical action in the gas or condensed phase. To be effective, the flame retardants must decompose near the decomposition temperature of the polymer in order to do the appropriate chemistry as the polymer decomposes, yet be stable at processing temperatures.

Conventional flame retardants, such as halogenated, phosphorous or metallic additives have a number of negative attributes. An ecological issue of its application demands the search of new polymer flame retardant systems. Among the new trends of flame retardancy it can be noticed the use of intumescent systems, polymer nanocomposites, preceramic additives, low-melting glasses, different types of char-formers and polymer morphology modification [1]. However, it should be assumed the close interactions between the different flame retardant types in order to achieve a synergistic behavior. The block scheme of polymer flame retardant systems is given on Figure 1.
2. Organic Char Former

The study of new polymer flame retardants has been directed at finding ways to increase the tendency of plastics to char when they are burned [2, 3]. There is a strong correlation between char yield and fire resistance. This follows because char is formed at the expense of combustible gases and because the presence of a char inhibits further flame spread by acting as a thermal barrier around the unburned material. The tendency of a polymer to char can be increased with chemical additives and by altering its molecular structure. It has been studied polymeric additives (polyvinyl alcohol systems) which promote the formation of char [4-6]. These polymeric additives usually produce a highly conjugated system - aromatic structures which char during thermal degradation and/or transform into cross-linking agents at high temperatures.

Decomposition of PVA goes in two stages. The first stage, which begins at 200°C, mainly involves dehydration accompanied by formation of volatile products. The residues are predominantly polymers with conjugated unsaturated structures. In the second stage, polyene residues are further degraded at 450°C to yield carbon and hydrocarbons. The mechanism involved in thermal decomposition PVA has been deduced by Tsuchya and Sumi [7]. At 245°C water is split off the polymer chain, and a residue with conjugated polyene structure results:

\[
\left( -\text{CH} - \text{CH}_2 \right)_n - \text{CH} - \text{CH}_2 \rightarrow \left( -\text{CH} = \text{CH}_2 \right)_n - \text{CH} - \text{CH}_2 + \text{H}_2\text{O}
\]

| OH | OH | OH |

Scission of several carbon-carbon bonds leads to the formation of carbonyl ends. For example, aldehyde ends arise from the reaction: In the second-stage pyrolysis of PVA, the volatile products consist mainly of hydrocarbons, i.e.

\[
-\text{CH} - \text{CH}_2 - \left( -\text{CH} = \text{CH}_2 \right)_n - \text{CH} - \text{CH}_2 \rightarrow -\text{CH} - \text{CH}_2 - \left( -\text{CH} = \text{CH}_2 \right)_n - \text{CH} + \text{H}_2\text{C} - \text{CH} -
\]

| OH | OH | OH | O | OH |

In the second-stage pyrolysis of PVA, the volatile products consist mainly of hydrocarbons, i.e. \( n \)-alkanes, \( n \)-alkenes and aromatic hydrocarbons (Table 1) [7]. Thermal degradation of PVA in the presence of oxygen can be adequately described by a two-stage decomposition scheme, with one modification. Oxidation of the unsaturated polymeric residue from dehydration reaction introduces ketone groups into the polymer chain. These groups then promote the dehydration of neighboring vinyl alcohol units producing a conjugated unsaturated ketone structure [8]. The first-stage degradation products of PVA pyrolyzed in air are fairly similar to those obtained in vacuum pyrolysis. In the range 260°C-280°C, the second-order-reaction expression satisfactorily accounts for the degradation of 80% hydrolyzed PVA up to a total weight loss of 40%. The activation energy of decomposition appears to be consistent with the value of 53.6 kcal/mol, which is obtained from the thermal degradation of PVA [8].
Changes in the IR spectra of PVA subjected to heat treatment have been reported [8]. After heating at 180°C in air, bands appeared at 1630 cm⁻¹ (C=C stretching in isolated double bonds), 1650 cm⁻¹ (C=C stretching in conjugated dienes and trienes), and 1590 cm⁻¹ (C=C stretching in polyenes). The intensity of carbonyl stretching frequency at 1750 - 1720 cm⁻¹ increased, although the rate of increase of intensity was less than that of the polyene band at low temperatures. Above 180°C, although dehydration was the predominant reaction at first, the rate of oxidation increased after an initial induction period. The identification of a low concentration of benzene among the volatile products of PVA has been taken to indicate the onset of a crosslinking reaction proceeding by a Diels-Alder addition mechanism [8]. Clearly, benzenoid structures are ultimately formed in the solid residue, and the IR spectrum of the residue also indicated the development of aromatic structures [8].

<table>
<thead>
<tr>
<th>Products</th>
<th>Weight % of original polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>33.4</td>
</tr>
<tr>
<td>CO</td>
<td>0.12</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.18</td>
</tr>
<tr>
<td>Hydrocarbons (C₁ - C₂)</td>
<td>0.01</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>1.17</td>
</tr>
<tr>
<td>Acetone</td>
<td>0.38</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.29</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.06</td>
</tr>
<tr>
<td>Crotonaldehyde</td>
<td>0.76</td>
</tr>
<tr>
<td>3-pentene-2-one</td>
<td>0.19</td>
</tr>
<tr>
<td>3,5-heptadiene-2-one</td>
<td>0.099</td>
</tr>
<tr>
<td>2,4-hexadiene-1-al</td>
<td>0.55</td>
</tr>
<tr>
<td>Benzaldehyde</td>
<td>0.022</td>
</tr>
<tr>
<td>Acetophenone</td>
<td>0.021</td>
</tr>
<tr>
<td>2,4,6-octatriene-1-al</td>
<td>0.11</td>
</tr>
<tr>
<td>3,5,7-nonatriene-2-one</td>
<td>0.02</td>
</tr>
<tr>
<td>Unidentified</td>
<td>0.082</td>
</tr>
</tbody>
</table>

Table 1. Thermal decomposition products (240°C, 4 h.) [7].

Acid-catalyzed dehydration promotes the formation of conjugated sequences of double bonds (a) and Diels-Alder addition of conjugated and isolated double bonds in different chains may result in intermolecular crosslinking producing structures which form graphite or carbonization (b).
In contrast to PVA, it was found [9-11] that when nylon-6,6 was subjected to temperatures above 300°C in an inert atmosphere it completely decomposed. The wide range of degradation products, which included several simple hydrocarbons, cyclopentanone, water, CO, CO₂ and NH₃, suggested that the degradation mechanism must have been highly complex. Further research has led to a generally accepted degradation mechanism for aliphatic polyamides [12]:
Hydrolysis of the amide bond usually occurred below the decomposition temperature;

2. Homolytic cleavage of C-C, C-N, C-H bonds generally began at the decomposition temperature and occurred simultaneously with hydrolysis;

3. Cyclization and homolytic cleavage of products from both of the above reactions occurred;

4. Secondary reactions produced CO, NH₃, nitriles, hydrocarbons, and carbon chars.

An idea of introducing poly(vinyl alcohol) into nylon-6,6 composition was based on the possibility of high-temperature acid-catalyzed dehydration. This reaction can be provided by the acid products of nylon 6,6 degradation hydrolysis which would promote the formation of intermolecular crosslinking and char. Such a system we have called "synergetic carbonization", because the char yield and flame suppression parameters of the polymer blend of poly (vinyl alcohol) and nylon 6,6 are significantly better than that of pure poly(vinyl alcohol) and nylon-6,6 polymers.

It is well-known that nylons have poor compatibility with other polymers because of their strong hydrogen bonding characteristics. The compatibility of nylon-6 with poly(vinyl-acetate) (PVAc) and poly(vinyl alcohol) (PVA) has been studied [13]. Compatibility was judged from the melting temperature depression. The results indicate that nylon-6/polyvinyl alcohol blends are partially compatible. "Compatibility" in this work does not mean thermodynamic miscibility but rather ease of mixing blends to achieve small size domains. To improve the flame resistant properties of the poly(vinyl alcohol) - nylon-6,6 system the substitution of pure poly(vinyl alcohol) by poly(vinyl alcohol) oxidized by potassium permanganate (PVA-ox) has been offered. This approach was based on the fire behavior of the (PVA-ox) itself. It was shown experimentally using a cone calorimeter that there was a dramatic decrease of the rate of heat release and significant increase in ignition time for the oxidized PVA in comparison with the original PVA. The literature on the oxidation of macromolecules by alkaline permanganate presents little information about these redox-systems. One set of workers [14, 15] investigated the oxidation of PVA as a polymer containing secondary alcoholic groups by KMnO₄ in alkaline solution. It was reported that the oxidation of PVA by permanganate in alkaline solutions occurs through formation of two intermediate complexes (1) and/or (2) [16]:

\[ \begin{align*}
\text{O} & \quad \text{O} \\
\parallel & \quad \parallel \\
\left[ \text{C-(CH}_2\text{)}_y \quad \text{C-N} = \text{CH}_2 \text{)}_y - \text{NH}_2 \right] & \xrightarrow{\text{H}_2\text{O}} \left[ \text{C-(CH}_2\text{)}_y \quad \text{C-OH} + \text{NH}_2 \text{ (CH}_2\text{)}_y - \text{NH}_2 \right] \\
\downarrow & \quad \downarrow \\
\text{O} & \quad \text{O} \\
\parallel & \quad \parallel \\
\left[ \text{C-(CH}_2\text{)}_y \quad + \text{C} + \text{NH} \right. & \xrightarrow{\text{a}} \left. \text{-NH} = \text{CH}_2 \text{)}_y + \text{NH}_2 \right] \\
\downarrow & \quad \downarrow \\
\text{Hydrocarbons,} & \quad \text{cyclic ketones, esters,} & \quad \left[ \text{C-(CH}_2\text{)}_y \quad + \text{CO}_2 + \text{NH}_3 \text{-NH} = \text{CH}_2 \text{)}_y + \text{NH}_2 \right] \\
\downarrow & \quad \downarrow \\
nitriles, carbon char
The reactions (a) and (b) lead to the formation of poly(vinyl ketone) (3) as a final product of oxidation of the substrate. Poly(vinyl ketone) was isolated and identified by microanalysis and spectral data [17].

Preliminary cone calorimeter tests for PVA and PVA oxidized by KMnO$_4$ were carried out at heat fluxes of 20, 35 and 50 kW/m$^2$ (Table 2) [18-20]. The carbon residue (wt. %) and peak of heat release rate (Peak R.H.R. kW/m$^2$) suggest substantial improvement of fire resistance characteristics for PVA oxidized by KMnO$_4$ in comparison with PVA. PVA oxidized by KMnO$_4$ gives about half the peak of heat release rate (Peak R.H.R. kW/m$^2$), when compared with pure PVA. Even at 50 kW/m$^2$, the yield of char residue for PVA oxidized by KMnO$_4$ was 9.1%. One reason for this phenomenon may be the ability for PVA oxidized by KMnO$_4$ (polyvinyl ketone structures) to act as a neutral (structure 1) and/or monobasic (structure 2) bidentate ligand [21].

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Bibliography and Suggestions for further study

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