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Experimental Analysis & Study of Intumescent Flame Retardant Coating for Polymeric Material Using LOI & Cone Calorimetry

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Abstract: The fire behavior of polymeric materials remains a critical concern in applications requiring enhanced safety against ignition and fire growth. Polyvinyl chloride (PVC), despite its widespread use, exhibits unfavorable fire characteristics under sustained heat exposure. This research paper presents an experimental evaluation of a surface-applied flame-retardant coating on PVC, with particular focus on the influence of coating thickness on fire performance. A comparative analysis between uncoated and coated PVC samples is conducted using cone calorimeter testing and Limiting Oxygen Index (LOI) measurements. Key fire parameters related to ignition resistance, heat release, and combustion stability are examined to assess the effectiveness of the coating. The results demonstrate a clear improvement in fire performance for coated specimens, including delayed ignition and reduced heat release. However, the enhancement does not increase proportionally with coating thickness, indicating diminishing returns beyond an optimal thickness. The findings emphasize the importance of thickness optimization in flame-retardant coatings and provide practical insight for improving passive fire protection strategies for polymeric materials in fire-sensitive applications.

Keywords: *Polyvinyl Chloride (PVC); Flame-Retardant Coating; Coating Thickness; Cone Calorimeter; Limiting Oxygen Index; Fire Performance.*

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I. INTRODUCTION

The extensive use of polymeric materials in modern engineering applications has significantly reshaped material selection practices across sectors such as construction, electrical engineering, transportation, and industrial manufacturing. Polymers are preferred due to their low density, corrosion resistance, electrical insulation properties, ease of processing, and economic viability. These advantages have led to their widespread application in cable insulation, conduits, wall panels, flooring systems, protective housings, and various structural and non-structural components. However, despite these benefits, the performance of polymeric materials under fire exposure remains a major concern in fire safety engineering [1].

Most polymeric materials are organic in nature and therefore act as combustible fuels when subjected to sufficient heat flux. Under fire conditions, polymers often exhibit rapid ignition, high flame spread rates, and elevated heat release rates, which contribute to fast fire growth. In addition, the combustion of polymers is typically accompanied by the generation of dense smoke and toxic gases, which significantly increases the risk to occupants and emergency responders [2]. Fire incident analyses consistently indicate that smoke inhalation and exposure to toxic combustion products are responsible for a majority of fire-related fatalities rather than direct flame contact, highlighting the importance of reducing smoke and toxic gas generation from polymeric materials [3].

Polyvinyl chloride (PVC) is one of the most widely used thermoplastic polymers globally and is extensively employed in electrical insulation, piping systems, wall coverings, flooring materials, and protective coatings. PVC is often considered comparatively flame resistant due to the presence of chlorine atoms in its molecular structure, which can inhibit flame propagation by scavenging free radicals during combustion. However, this inherent resistance does not ensure fire safety under realistic fire scenarios. When exposed to sustained thermal stress or high external heat flux, PVC undergoes thermal degradation, releasing combustible gases along with hydrogen chloride (HCl), carbon monoxide (CO), and other hazardous decomposition products [4].

The emission of hydrogen chloride during PVC combustion poses serious hazards. HCl is highly corrosive and toxic, causing severe irritation to the respiratory tract and eyes, thereby reducing visibility and impairing evacuation during fire incidents. Furthermore, HCl contributes to post-fire corrosion of electrical equipment, steel structures, and electronic systems, leading to extensive secondary damage even after the fire has been extinguished [5]. In addition to toxic gas release, PVC can exhibit considerable heat release and smoke production, particularly in enclosed or poorly ventilated spaces. These characteristics underline the need for supplementary fire protection strategies to enhance the fire performance of PVC-based materials used in fire-sensitive applications [6].

Among various approaches developed to improve the fire performance of polymeric materials, passive fire protection methods have gained significant attention due to their reliability and simplicity. Passive fire protection systems do not rely on mechanical activation or external energy sources; instead, they function by modifying the material response when exposed to fire. Surface-applied flame-retardant coatings represent one of the most effective passive fire protection strategies for polymeric substrates. Such coatings enhance fire resistance without altering the bulk mechanical or electrical properties of the base material, making them suitable for both new installations and retrofit applications [7].

Intumescent flame-retardant coatings constitute a specialized class of passive fire protection systems that respond dynamically to thermal exposure. When subjected to elevated temperatures, intumescent coatings undergo a sequence of chemical and physical reactions that result in volumetric expansion and the formation of a porous, carbonaceous char layer. This expanded char acts as a thermal insulation barrier, reducing heat transfer from the fire to the underlying substrate, limiting oxygen diffusion, and suppressing the release of flammable volatile products [8]. As a result, intumescent coatings effectively delay ignition, reduce flame intensity, and slow down fire propagation.

The fire-retardant mechanism of intumescent coatings is generally attributed to their multi-component formulation. Conventional systems consist of an acid source, a carbon source, and a blowing agent. Upon heating, the acid source decomposes to form acidic species that promote dehydration and charring of the carbon source. Simultaneously, the blowing agent releases non-flammable gases that cause the coating to expand, producing a multicellular char structure. This char layer is thermally stable and capable of maintaining its protective function over prolonged fire exposure durations [9]. Recent studies have shown that the incorporation of synergistic additives such as boron compounds, mineral fillers, and polymeric binders can further improve char strength, cohesion, and resistance to mechanical erosion under fire conditions [10].

The effectiveness of intumescent flame-retardant coatings is influenced by several factors, including chemical composition, substrate characteristics, heat flux intensity, and coating thickness. Among these parameters, coating thickness plays a critical role in determining the extent of char expansion and thermal insulation efficiency. While an increase in coating thickness generally enhances fire resistance by providing a larger volume of reactive material, excessive thickness may result in diminishing performance gains, increased material usage, and potential adhesion or cracking issues [11]. Therefore, understanding the relationship between coating thickness and fire performance is essential for optimizing intumescent coating systems for practical engineering applications.

Reliable evaluation of flame-retardant performance requires standardized fire testing techniques capable of characterizing ignition behavior, heat release, smoke generation, and toxic gas emission. The cone calorimeter is widely regarded as one of the most representative bench-scale fire testing instruments for assessing material fire behavior. Based on the oxygen consumption principle, cone calorimetry provides quantitative measurements of key fire parameters such as time to ignition, heat release rate, total heat release, mass loss rate, and smoke production rate [12]. These parameters show strong correlation with real-scale fire behavior, making cone calorimeter testing a valuable tool for comparative fire performance assessment.

In addition to calorimetric analysis, the Limiting Oxygen Index (LOI) test is commonly used to evaluate material flammability. LOI is defined as the minimum oxygen concentration required to sustain continuous combustion of a material under controlled laboratory conditions. Materials with higher LOI values exhibit greater resistance to ignition and flame propagation. LOI testing is particularly effective for comparing untreated polymers with flame-retardant-treated materials and for assessing the effectiveness of surface-applied fire-retardant coatings [13].

To complement macroscopic fire testing methods, spectroscopic techniques such as Fourier Transform Infrared (FTIR) analysis are increasingly employed to investigate chemical transformations during thermal degradation and char formation. FTIR spectroscopy enables identification of functional groups associated with dehydration, cross-linking, and phosphate-rich char structures, thereby providing insight into the underlying mechanisms responsible for improved flame retardancy [14].

In the present study, the fire performance of PVC sheets treated with surface-applied intumescent flame-retardant coatings is investigated using a combination of Limiting Oxygen Index testing, cone calorimeter analysis, and FTIR spectroscopy. Particular emphasis is placed on evaluating the influence of coating thickness on flame-retardant effectiveness, with the objective of determining whether increased coating thickness leads to proportional improvements in fire performance or primarily contributes additional mass with limited protective benefit. The findings of this research are intended to support the rational design and optimization of intumescent coating systems for polymeric materials used in fire-sensitive applications such as electrical installations, industrial facilities, and public infrastructure[15].

II. LITERATURE REVIEW

Fire safety remains a critical concern in the use of polymers, textiles, coatings, and bio-based materials due to their inherent combustibility. With the increasing application of polymeric and composite materials in construction, transportation, electronics, and consumer products, the consequences of fire incidents have become more severe in terms of human safety, property loss, and environmental impact. As a result, the development of effective flame-retardant systems has become a major area of materials research. Over the past several decades, significant progress has been made in understanding fire behavior, flame-retardant mechanisms, and formulation strategies aimed at reducing flammability while maintaining material performance.

Early flame-retardant technologies relied heavily on halogenated compounds due to their high flame-inhibition efficiency. However, these systems were later found to release toxic and corrosive gases during combustion, raising serious health and environmental concerns. Consequently, research focus shifted toward halogen-free flame retardants that are safer, environmentally acceptable, and compliant with evolving regulations. According to Horrocks and Price [3], this shift marked a fundamental transformation in flame-retardant science, encouraging the development of condensed-phase mechanisms rather than gas-phase flame inhibition. Alongi et al. [1] further emphasized that modern flame-retardant research prioritizes reduced smoke generation, lower toxicity, and improved sustainability alongside fire resistance.

Among halogen-free approaches, intumescent flame-retardant (IFR) systems have emerged as one of the most effective and versatile solutions. IFR systems function by forming an expanded, insulating char layer when exposed to heat, thereby protecting the underlying material from direct flame, oxygen, and heat flux. This mechanism significantly delays ignition and slows fire propagation. Jimenez et al. [2] described intumescence as a dynamic and complex process involving chemical decomposition, gas evolution, and physical expansion, resulting in a porous yet thermally stable char structure.

The classical intumescent system consists of three essential components: an acid source, a carbon source, and a blowing agent. Upon heating, the acid source decomposes to generate acidic species that catalyze dehydration of the carbon source, leading to char formation. Simultaneously, the blowing agent releases non-flammable gases that cause the softened char to expand and form a protective foam-like structure [4,8]. Gu et al. [4] demonstrated that the balance between these components plays a crucial role in determining the expansion ratio, char cohesion, and overall flame-retardant performance of IFR coatings.

Phosphorus-based compounds, particularly ammonium polyphosphate (APP) and monoammonium phosphate (MAP), are among the most widely used acid sources in IFR formulations. These compounds are favored due to their high phosphorus content, thermal stability, and compatibility with various polymer matrices. Kandola and Horrocks [8] showed that phosphorus promotes the formation of thermally stable char structures that act as effective barriers to heat and mass transfer during combustion. The presence of phosphorus also reduces the formation of flammable volatiles, thereby decreasing flame intensity.

In recent years, research has increasingly focused on enhancing the efficiency of IFR systems through synergistic additives. Boron-based compounds such as boric acid and borax have gained attention due to their ability to improve char strength, thermal stability, and oxidation resistance. Jin et al. [12] investigated the treatment of laminated bamboo lumber with MAP and boric acid/borax compounds and reported significant improvements in flame retardancy, as evidenced by higher limiting oxygen index values and reduced mass loss during burning. The authors attributed these improvements to the formation of a glassy boro phosphate char layer that enhanced the integrity of the protective barrier.

Synergistic effects involving boron compounds have also been explored in polymeric IFR systems. Suraj et al. [6] reported that the incorporation of ion exchange resins in combination with boric acid into MAP-based IFR systems resulted in improved flame retardancy and enhanced char cohesion. The study highlighted that ion exchange resins contributed to controlled decomposition behavior, while boric acid reinforced the char structure, leading to improved resistance against heat and flame penetration. These findings underscore the importance of multi-component interactions in designing advanced IFR formulations.

The influence of formulation additives on IFR coating properties has been further investigated in applied research. Suraj et al. [7] examined the effects of solvents and modifiers such as xylene, paraffin, and resin additives on the physical and fire-protective properties of IFR coatings. Their study revealed that these additives significantly affect coating viscosity, adhesion, expansion behavior, and thermal stability. Such formulation-level optimization is essential for translating laboratory-scale IFR systems into practical industrial applications.

In polymer science, IFR systems have been extensively studied for thermoplastics such as polypropylene, polyamide, and polylactic acid (PLA). Shen et al. [11] provided a comprehensive review of flame-retardant mechanisms in polymeric materials, highlighting that IFR systems primarily act in the condensed phase by promoting char formation and thermal insulation. The authors emphasized that proper dispersion and compatibility between IFR additives and polymer matrices are critical to achieving both flame retardancy and acceptable mechanical performance.

PLA, as a biodegradable polymer, presents unique challenges due to its inherent flammability and dripping behavior during combustion. Huang et al. [13] demonstrated that functionalizing ammonium polyphosphate with boron-based compounds significantly improved the flame retardancy and anti-dripping properties of PLA. The modified IFR system enhanced char formation and reduced melt flow during burning, addressing a key limitation of PLA in fire-sensitive applications. This study illustrates how chemical modification of IFR components can tailor fire performance for specific polymer systems.

The role of fillers in flame-retardant formulations has also received considerable attention. Calcium carbonate, traditionally used as a cost-effective filler, has been shown to influence both thermal degradation and combustion behavior. Ippolito et al. [15] investigated calcium carbonate as a functional filler in polyamide 12 and reported improvements in thermal stability and mechanical properties. When used alongside flame-retardant additives, calcium carbonate can contribute to enhanced char formation and heat absorption, thereby supporting the overall fire-retardant mechanism.

Textile applications pose additional challenges due to requirements for flexibility, breathability, and durability under washing and wear. Weil and Levchik [5] discussed practical flame-retardant solutions for textiles, emphasizing that IFR coatings are increasingly favored because they can be applied as surface treatments without significantly compromising fabric properties. Alongi et al. [1] further highlighted the development of advanced IFR systems for textiles, including hybrid and nano-structured formulations that improve wash durability and flame resistance.

Understanding and evaluating flame-retardant performance requires reliable and standardized testing methods. The Limiting Oxygen Index (LOI) test is widely used to assess the minimum oxygen concentration required to sustain combustion. ASTM D2863-19 [9] and ISO 4589-2:2017 [14] provide standardized procedures for conducting LOI tests under controlled conditions. These methods allow quantitative comparison of flame-retardant efficiency across materials and formulations. Internal standard operating procedures such as TD2863-19 [10] further ensure consistency and repeatability in experimental measurements, particularly in academic and industrial research laboratories.

Char formation is widely recognized as a key factor governing the effectiveness of flame-retardant systems. Kandola and Horrocks [8] emphasized that char morphology, continuity, and thermal stability directly influence heat and mass transfer during combustion. A dense and cohesive char layer can significantly reduce heat release rate and flame spread, whereas a fragile or cracked char provides limited protection. Consequently, recent research efforts focus on reinforcing char structure through synergistic additives, chemical modification, and filler incorporation.

Despite substantial progress, several challenges remain in the development of IFR systems. Issues such as moisture sensitivity, long-term durability, mechanical weakness of expanded char, and compatibility with different substrates continue to limit widespread application. Jimenez et al. [2] stressed the importance of achieving a deeper mechanistic understanding of intumescence to address these limitations. Current research trends emphasize multifunctional IFR coatings that not only provide flame retardancy but also offer additional benefits such as corrosion resistance, mechanical reinforcement, and environmental sustainability.

In summary, the reviewed literature demonstrates that intumescent flame-retardant systems represent a highly effective and environmentally favorable strategy for fire protection in polymers, textiles, and bio-based materials. Phosphorus-based acid sources, boron-based synergists, functional fillers, and formulation additives collectively enhance char formation, thermal insulation, and flame resistance. Standardized evaluation methods such as LOI testing provide reliable performance assessment, while recent advances continue to refine formulation chemistry and application techniques. Continued research in this area is essential to meet increasingly stringent fire safety standards and sustainability requirements.

III. MATERIALS AND METHODS

- ➤ *Polyvinyl Chloride (PVC) Substrate*

Polyvinyl chloride (PVC) was selected as the base polymeric material for the present investigation due to its extensive use in electrical insulation, interior panels, cable sheathing, and industrial components. From a fire safety perspective, PVC represents a material of practical relevance, as it is frequently involved in fire scenarios in both residential and industrial environments. Although PVC exhibits comparatively slower flame spread than some thermoplastics, its thermal degradation under sustained heat exposure leads to significant heat release, smoke generation, and emission of hazardous gases. These characteristics make PVC a suitable substrate for evaluating the effectiveness of flame-retardant surface treatments.

Prior to specimen preparation, the PVC sheets were inspected visually to ensure uniform surface condition and absence of visible defects such as cracks, voids, or surface contamination, which could influence ignition behavior and combustion characteristics during testing.

- *Intumescent Flame-Retardant Coating*

A commercially available intumescent flame-retardant coating (Univolen Fire Retardant Coating) was used as the surface protection system in this study. Intumescent coatings are widely used as passive fire protection materials due to their ability to respond actively to heat exposure. When subjected to elevated temperatures, such coatings undergo a sequence of physical and chemical transformations, leading to the formation of an expanded, multicellular char layer. This char layer acts as a thermal barrier, reducing heat transfer to the substrate, limiting oxygen diffusion, and restricting the release of flammable decomposition products.

The selected coating was compatible with polymeric substrates and suitable for manual application, allowing controlled variation of coating thickness. The investigation focused on understanding whether increasing coating thickness leads to measurable improvement in flame retardancy or whether it primarily adds weight without proportionate fire performance benefits.

➢ *Specimen Preparation*

PVC sheets were cut into square specimens of uniform geometry to maintain consistency across all fire tests. Care was taken during cutting to ensure clean edges and flat surfaces, as surface irregularities can influence ignition time and flame spread behavior.

The prepared specimens were divided into four groups. One group was retained in the uncoated condition to serve as a reference sample for baseline fire behavior. The remaining three groups were coated with the intumescent flame-retardant coating at three different coating thickness levels, namely 250 µm, 350 µm, and 450 µm.

The coating was applied manually using a brush to ensure uniform coverage over the exposed surface. Multiple controlled brush strokes were used to avoid localized thickness variation and excessive accumulation at edges. Uniform application was essential to ensure that observed differences in fire performance could be attributed primarily to coating thickness rather than application inconsistency.

After coating, all specimens were allowed to dry under natural ambient conditions for a period of 24 hours. This drying period ensured adequate curing of the coating and complete evaporation of solvents, thereby preventing premature coating degradation during fire testing. Once dried, all specimens—both coated and uncoated—were weighed using a precision balance. The recorded mass values were later used to evaluate the contribution of coating thickness to overall specimen mass and to interpret mass loss behavior during combustion.

➢ *Experimental Program Overview*

The experimental program was designed to systematically evaluate the influence of flame-retardant coating thickness on the fire behavior of PVC materials. A comparative approach was adopted, in which uncoated specimens were tested first to establish baseline fire characteristics. Subsequently, coated specimens with increasing coating thickness were tested under identical conditions.

Two standardized fire testing techniques were employed: cone calorimeter testing and Limiting Oxygen Index (LOI) testing. Cone calorimetry was used to simulate realistic fire exposure conditions and to quantify fire growth behavior, while LOI testing was used to assess flammability under oxygen-controlled conditions. The combination of these techniques enabled a comprehensive understanding of ignition resistance, heat release behavior, combustion stability, and flame-retardant effectiveness.

➢ *Cone Calorimeter Testing*

• *Principle and Significance*

Cone calorimeter testing is based on the oxygen consumption principle, which states that a nearly constant amount of heat is released per unit mass of oxygen consumed during combustion. This principle allows accurate determination of heat release parameters, which are considered among the most important indicators of fire hazard.

The heat release rate (HRR) obtained from cone calorimeter testing is widely recognized as the single most important variable in fire hazard assessment, as it governs fire growth, flame spread, and the potential for flashover in enclosed spaces. A reduction in HRR directly indicates improved fire performance of a material.

• *Apparatus Description*

The cone calorimeter consists of an electrically heated conical radiant heater, a horizontal specimen holder, an ignition system, and an exhaust duct equipped with oxygen, carbon dioxide, and carbon monoxide analyzers. The exhaust system continuously measures oxygen depletion, enabling real-time calculation of heat release parameters. An FTIR (Fourier Transform Infrared Spectroscopy) system integrated with the exhaust duct was used for analysis of gaseous combustion product.

• *Test Conditions and Heat Flux Selection*

Each specimen was mounted horizontally in the standard specimen holder with the exposed surface facing the radiant heater. Prior to testing, the apparatus was calibrated to ensure accurate heat flux delivery and gas analyzer response.

All cone calorimeter tests were conducted at a constant external radiant heat flux of 50 kW/m². This heat flux level represents a severe fire exposure condition and is commonly used in bench-scale fire testing to evaluate fire growth behavior of polymeric materials. The selected heat flux provides sufficient thermal energy to initiate pyrolysis and flaming combustion within a reasonable time frame, allowing meaningful comparison of ignition behavior, heat release rate, and combustion stability among different specimens.

• *Test Procedure and Measured Parameters*

Once the specimen was positioned beneath the radiant heater, exposure to the heat flux was initiated. An electric spark igniter was used to ignite the specimen once sufficient volatile gases were released.

The following key parameters were recorded during cone calorimeter testing:

- ✓ *Time to Ignition (TTI):*

TTI represents the time required for a material to ignite under a specified heat flux. An increase in TTI indicates improved resistance to ignition, which is a desirable characteristic for flame-retardant materials.

- ✓ *Heat Release Rate (HRR):*

HRR represents the rate at which heat is released during combustion. Lower HRR values indicate reduced fire intensity and slower fire growth. The peak heat release rate (PHRR) is particularly significant, as it represents the maximum fire intensity reached during combustion.

- ✓ *Mass Loss and Mass Loss Rate:*

Mass loss measurements provide insight into the rate of material degradation during combustion. A lower mass loss rate indicates improved char formation and reduced fuel availability, both of which contribute to enhanced flame retardancy.

- ✓ *FTIR Gas Analysis:*

FTIR analysis was used to identify and monitor gaseous combustion products evolved during burning. This analysis provides valuable information regarding the nature and quantity of toxic and corrosive gases released, offering insight into combustion completeness and fire toxicity.

Each specimen was tested individually, and sufficient time was allowed between tests for the system to return to ambient conditions.

- ➢ *Limiting Oxygen Index (LOI) Testing*

- *Principle and Significance*

The Limiting Oxygen Index (LOI) test determines the minimum concentration of oxygen, expressed as a percentage by volume, required to sustain flaming combustion of a material in an oxygen–nitrogen mixture. LOI is a widely used indicator of material flammability. Materials with higher LOI values require higher oxygen concentrations to sustain burning and are therefore considered less flammable.

LOI testing is particularly useful for comparing flame-retardant effectiveness under controlled conditions, as it isolates the influence of oxygen concentration from external heat flux effects.

- *Apparatus and Test Setup*

The LOI apparatus consists of a vertical glass chimney mounted on a base equipped with gas mixing and flow control systems. Oxygen and nitrogen flow rates are regulated using calibrated rotameters to achieve the desired oxygen concentration. Specimens are mounted vertically at the center of the chimney, and ignition is achieved using a pilot flame introduced from the top.

- *Test Procedure*

An initial oxygen concentration was selected based on preliminary observations. The specimen was ignited at the top, and its burning behavior was observed. If sustained combustion occurred, the oxygen concentration was reduced incrementally in subsequent tests. If the flame extinguished prematurely, the oxygen concentration was increased.

This iterative process was continued until the minimum oxygen concentration that just supported continuous burning was identified. The corresponding oxygen concentration was recorded as the Limiting Oxygen Index value for the specimen.

- ➢ *Data Analysis and Interpretation*

All experimental data obtained from cone calorimeter and LOI tests were systematically recorded and analyzed. Cone calorimeter data included time to ignition, heat release rate curves, peak heat release rate, mass loss trends, and FTIR gas evolution profiles. LOI results were recorded as percentage oxygen concentration by volume.

Comparative analysis was performed between uncoated and coated specimens to evaluate the effectiveness of the intumescent coating. Particular emphasis was placed on correlating coating thickness with changes in fire performance parameters to determine whether increased coating thickness resulted in proportional improvement in flame retardancy.

- ➢ *Experimental Reliability*

All experiments were conducted under controlled laboratory conditions following standardized procedures. Equipment calibration, consistent specimen preparation, and uniform test parameters were maintained throughout the study to ensure repeatability and reliability of results. The adopted methodology provides confidence in the observed trends and supports meaningful conclusions regarding the influence of coating thickness on fire performance

IV. RESULTS

- ➢ *Overview of Experimental Results*

Cone calorimeter testing at an external heat flux of 50 kW/m² was carried out on uncoated PVC and intumescent-coated PVC specimens with coating thicknesses of 250 µm, 350 µm, and 450 µm. The recorded outputs include ignition characteristics, heat release parameters, mass loss behavior, smoke production, carbon monoxide evolution, and FTIR absorbance spectra of combustion gases. In addition, time-based observations such as shutter opening time, ignition delay, flame initiation, flame extinction, and total burning duration were recorded for coated samples.

The results are presented sequentially for the uncoated PVC specimen followed by coated specimens with increasing coating thickness. This arrangement enables direct comparison of fire behavior before and after coating application and facilitates assessment of thickness-dependent performance.

➢ *Results of Uncoated PVC Specimen*

- *Ignition and Burning Characteristics*

The uncoated PVC specimen ignited under the applied heat flux after a time to ignition of 435.90 s. Once ignition occurred, flame development was rapid and continuous flaming combustion was observed until flame extinction at 539.00 s, resulting in a burning duration of approximately 103 s. The short burning duration combined with intense flame activity indicates rapid fuel consumption and uncontrolled combustion.

- *Heat Release Characteristics*

The uncoated PVC specimen exhibited the most severe heat release behavior among all tested samples. The maximum heat release rate ($q_{A,max}$) reached 78.89 kW/m², while the maximum average rate of heat emission (MARHE) was recorded as 34.88 kW/m². These high values indicate rapid fire growth and intense combustion.

Heat release values at specific intervals remained high throughout the test, with $q_{A,180} = 30.71$ kW/m² and $q_{A,300} = 32.98$ kW/m², confirming sustained fire intensity. The total heat release (THR) was measured as 14.56 MJ/m², reflecting a large cumulative energy output and high fire load contribution.

- *Mass Loss, Smoke, and Gas Emission*

The uncoated PVC specimen experienced extensive degradation, with a mass loss rate (MLR) of 9.95 g/m²·s and a total mass loss (TML) of 926.87 g/m². Smoke production was significant, with a smoke production rate (SPR) of 0.182 m²/s. The peak carbon monoxide concentration recorded was 0.18, indicating incomplete combustion and hazardous gas release.

➢ *Results of PVC with 250 µm Intumescent Coating*

- *Ignition and Flame Development*

The PVC specimen coated with a 250 µm thick intumescent layer showed delayed flame development compared to the uncoated sample. Flame initiation occurred at 282 s, and flame extinction was observed at 674 s, resulting in a total burning duration of 392 s. The longer burning duration reflects moderated combustion behavior rather than rapid fire growth.

- *Heat Release Characteristics*

The application of the 250 µm coating resulted in a substantial reduction in heat release. The maximum heat release rate decreased to 11.10 kW/m², while the MARHE reduced to 2.97 kW/m². Heat release at fixed intervals also remained low ($q_{A,180} = 1.81$ kW/m², $q_{A,300} = 2.28$ kW/m²).

The total heat release for this specimen was 2.00 MJ/m², representing a drastic reduction compared to the uncoated PVC.

- *Mass Loss, Smoke, and Gas Emission*

For the 250 µm coated specimen, mass loss was negligible, indicating effective protection of the PVC substrate. The smoke production rate was 0.159 m²/s, lower than that of uncoated PVC. The CO peak concentration was 0.16, reflecting reduced toxic gas evolution.

➢ *Results of PVC with 350 µm Intumescent Coating*

- *Ignition and Burning Behavior*

The 350 µm coated specimen exhibited the longest delay in flame initiation among all samples. Flame appearance occurred at 610 s, and flame extinction at 940 s, resulting in a burning duration of 330 s. This behavior indicates extended resistance to flame development under sustained heat exposure.

- *Heat Release Characteristics*

The maximum heat release rate for this specimen was 9.02 kW/m², and the MARHE was 1.64 kW/m², the lowest recorded among all samples. Heat release values at 180 s and 300 s were 0.80 kW/m² and 1.57 kW/m², respectively.

The total heat release was measured as 1.53 MJ/m², representing the minimum cumulative energy output among all tested specimens.

- *Mass Loss, Smoke, and Gas Emission*

Mass loss for the 350 µm coated specimen was negligible, similar to the 250 µm sample. The smoke production rate was 0.1556 m²/s, slightly lower than thinner coatings. The CO peak concentration remained at 0.16.

- *FTIR Gas Analysis*

FTIR absorbance spectra for the 350 µm coated specimen showed low absorbance intensity across the entire wavenumber range. Peaks observed in the 2300–2400 cm⁻¹ and 3500–3900 cm⁻¹ regions were present but limited in magnitude, indicating reduced gaseous emission during combustion.

➢ *Results of PVC with 450 µm Intumescent Coating*

- *Ignition and Burning Behavior*

For the 450 µm coated specimen, the shutter opening time was 385 s, with ignition occurring 17 s later. Flame initiation was observed at 402 s, and flame extinction occurred at 908 s, resulting in a total burning duration of 506 s, the longest among all specimens.

- *Heat Release Characteristics*

The maximum heat release rate was 6.18 kW/m², the lowest peak HRR recorded. The MARHE value was 2.61 kW/m². Heat release at fixed intervals remained low ($q_{A,180} = 1.97$ kW/m², $q_{A,300} = 2.16$ kW/m²).

The total heat release was 2.34 MJ/m², slightly higher than that of the 350 µm coated specimen.

- *Mass Loss, Smoke, and Gas Emission*

Unlike thinner coatings, the 450 µm specimen showed measurable degradation, with a mass loss rate of 8.65 g/m²·s and total mass loss of 1660 g/m². The smoke production rate was 0.1492 m²/s, the lowest among all samples. The CO peak concentration was 0.15, also the lowest recorded.

- *FTIR Gas Analysis*

FTIR spectra for the 450 µm coated specimen showed similar peak locations to the 350 µm sample but with slightly higher absorbance intensities, indicating increased gas evolution relative to the optimal coating thickness.

➢ *Consolidated Comparative Results and Thickness-Dependent Trends*

The uncoated PVC specimen exhibited rapid fire growth, high heat release, extensive mass loss, and significant smoke and gas emission. Application of intumescent coating resulted in a marked reduction in all fire performance parameters.

The 250 µm coating produced a substantial improvement compared to uncoated PVC, significantly reducing HRR and THR while minimizing mass loss. Increasing the coating thickness to 350 µm further improved performance, yielding the lowest MARHE and THR values and minimal gas evolution. The 450 µm coating achieved the lowest peak HRR and smoke production but showed increased mass loss and slightly higher cumulative heat release.

These results indicate that while increasing coating thickness enhances fire resistance, the improvement is not proportional beyond a certain thickness. The 350 µm coating demonstrated the most balanced fire performance across all measured parameters.

➢ *Summary of Key Experimental Results*

Uncoated PVC showed the highest fire hazard characteristics.

Intumescent coating significantly reduced ignition intensity, heat release, and smoke generation.

- The 250 µm coating provided major improvement over uncoated PVC.
- The 350 µm coating yielded the lowest cumulative heat release and most stable combustion behavior.
- The 450 µm coating minimized peak HRR and smoke but introduced higher mass loss.

Overall results confirm the effectiveness of intumescent coatings and highlight the importance of coating thickness optimization.

V. DISCUSSION

The experimental results clearly indicate that the application of an intumescent flame-retardant coating significantly improves the fire performance of PVC substrates. However, the degree of improvement is strongly influenced by coating thickness, and the enhancement does not increase linearly with increasing thickness.

Uncoated PVC exhibited rapid fire growth once ignition occurred, accompanied by high heat release rate and extensive mass loss. This behavior is consistent with the known thermal degradation mechanism of PVC, where dehydrochlorination under sustained heat exposure leads to volatile release and intensified combustion [1]. The high heat release and smoke generation observed for uncoated PVC confirm its contribution to fire severity despite its comparatively slow flame spread.

All coated specimens demonstrated delayed flame initiation and substantial reduction in heat release parameters. This improvement can be attributed to the intumescent action of the coating, which undergoes endothermic decomposition and expands to form a protective char layer when exposed to heat. The expanded char acts as a thermal barrier, limiting heat transfer to the PVC substrate and restricting oxygen diffusion and volatile fuel release [2]. Similar ignition delay and fire suppression effects have been widely reported for intumescent systems applied on polymeric materials [3].

Among the tested thicknesses, the 350 µm coating exhibited the most balanced fire performance, showing the lowest MARHE and total heat release. This suggests that at this thickness, the char layer formed is sufficiently thick, cohesive, and thermally stable to maintain its protective function throughout the fire exposure. Previous studies have emphasized that char quality and integrity are more critical than coating thickness alone in determining fire-retardant efficiency [4].

Although the 450 µm coating resulted in the lowest peak heat release rate and smoke production, it also showed increased mass loss and slightly higher total heat release compared to the 350 µm coating. This behavior indicates that excessive coating thickness may introduce instability in the expanded char structure, leading to cracking or partial collapse during prolonged exposure. Such degradation can expose the substrate and allow renewed pyrolysis, a phenomenon reported in earlier investigations on thick intumescent layers [5].

Smoke and carbon monoxide generation were significantly reduced for all coated specimens compared to uncoated PVC. This reduction is critical from a life-safety perspective, as smoke inhalation and toxic gas exposure are primary causes of fire-related fatalities [6]. The further reduction in smoke and CO observed for thicker coatings reflects improved suppression of volatile release, although this benefit must be balanced against the accompanying increase in mass loss.

FTIR gas analysis supported these observations by showing reduced absorbance intensities for coated specimens, indicating lower emission of decomposition products. The similarity in peak positions across coated samples suggests that the decomposition pathways remain unchanged, while differences in intensity reflect variations in gas quantity rather than chemistry [7].

Overall, the results demonstrate that increasing intumescent coating thickness enhances fire resistance only up to an optimal level. The 350 µm coating provided the most effective balance between ignition resistance, heat release suppression, mass stability, and reduced toxic emissions. These findings highlight the importance of coating thickness optimization rather than excessive material application for effective passive fire protection of PVC materials [8].

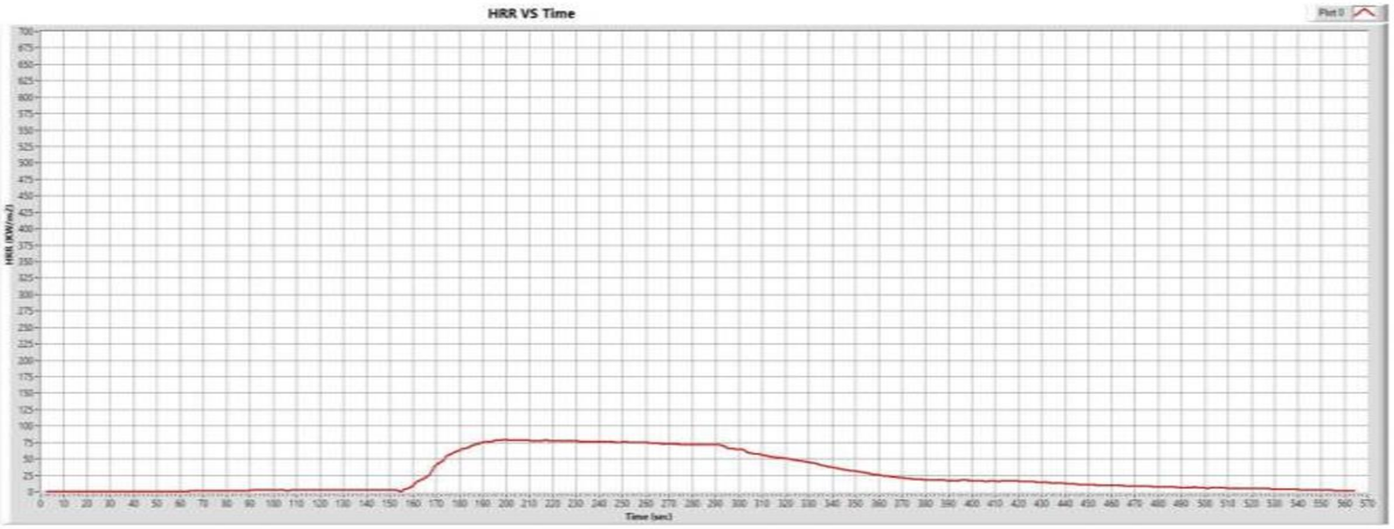
VI. TABLES AND GRAPHS

- *Comparative Cone Calorimeter Results of Uncoated and Intumescent-Coated PVC at Different Coating Thicknesses*

Comparative Cone Calorimeter Results of Uncoated and Intumescent-Coated PVC at Different Coating Thicknesses

Factors	Before Coating	After coating 250µm	After Coating 350µm	After Coating 450µm
E	13.1 MJ/Kg	13.1 MJ/Kg	13.1 MJ/Kg	13.1 MJ/Kg
Thickness	10 mm	10+250µm	10+350µm	10+450µm
Initial mass	14 g	14.16g	14.22g	14.31g
Surface area	0.00884 m^2	-	-	-
Heat flux	50 kw/m^2	-	-	-
Separation	25 mm	-	-	-
Flow	24 I/s	-	-	-
Calibration factor	0.03800	-	-	-
Test standards	ISO 5660	-	-	-
Date/time	26-09-2025 17:32	25-11-2025 03:01pm	25-11-2025 03:28pm	25-11-2025 4:02pm
Time to ignition	435.9 sec	389.30sec	328.5sec	503.1sec
Time to flame in	103 sec	284.00sec	611.00sec	407sec
Time to flameout	539 sec	673.00sec	940sec	901sec
Max average rate of heat Emission(MARHE)	34.88 kw/m^2	2.97kw/m^2	1.64kw/m^2	2.61kw/m^2
Qa, max	78.89 kw/m^2	11.10kw/m^2	9.02kw/m^2	6.18kw/m^2
qA, 180	30.71 kw/m^2	2.21kw/m^2	0.80kw/m^2	1.97kw/m^2
Qa, 300	32.98kw/m^2	2.97kw/m^2	1.57kw/m^2	2.16kw/m^2
Total hear release	14.56 MJ/m^2	2.00MJ/m^2	1.53MJ/m^2	2.34MJ/m^2
Mass loss rate	9.95 g/m^2.s	0.00g/m^2.s	0.00g/m^2.s	0.00g/m^2.s
Total mass loss	926.87g/m^2	0.00g/m^2	0.00g/m^2	0.00g/m^2
SPR(m^2/s)	0.182346m^2/s	0.159440m^2/s	0.155m^2/s	1660m^2/s
Flux(kw/m^2)	14.60	2.01	1.54	2.53

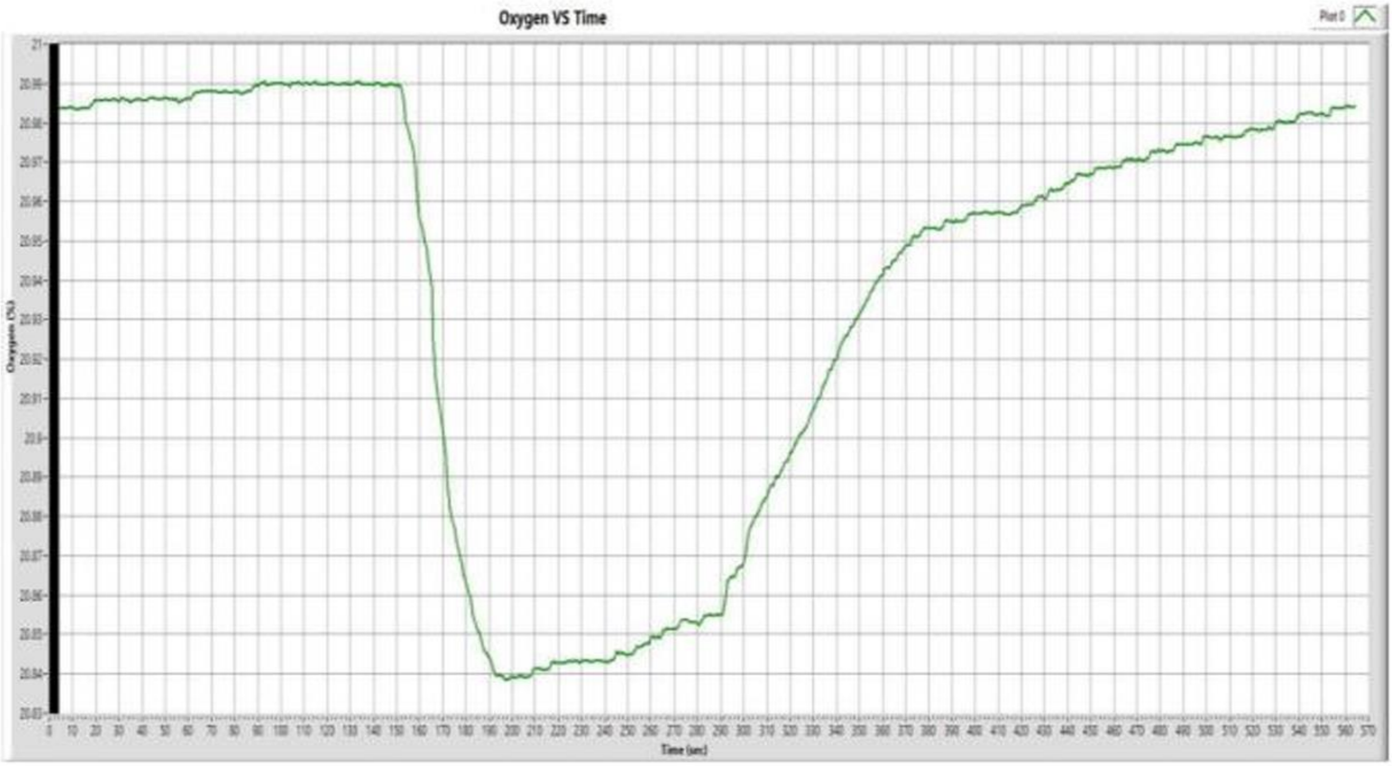
- *Heat Release Rate (HRR) Versus Time for Uncoated PVC*



graph of uncoated PVC (HRR vs Time)

Fig 1 Heat Release Rate (HRR) Versus Time for Uncoated PVC

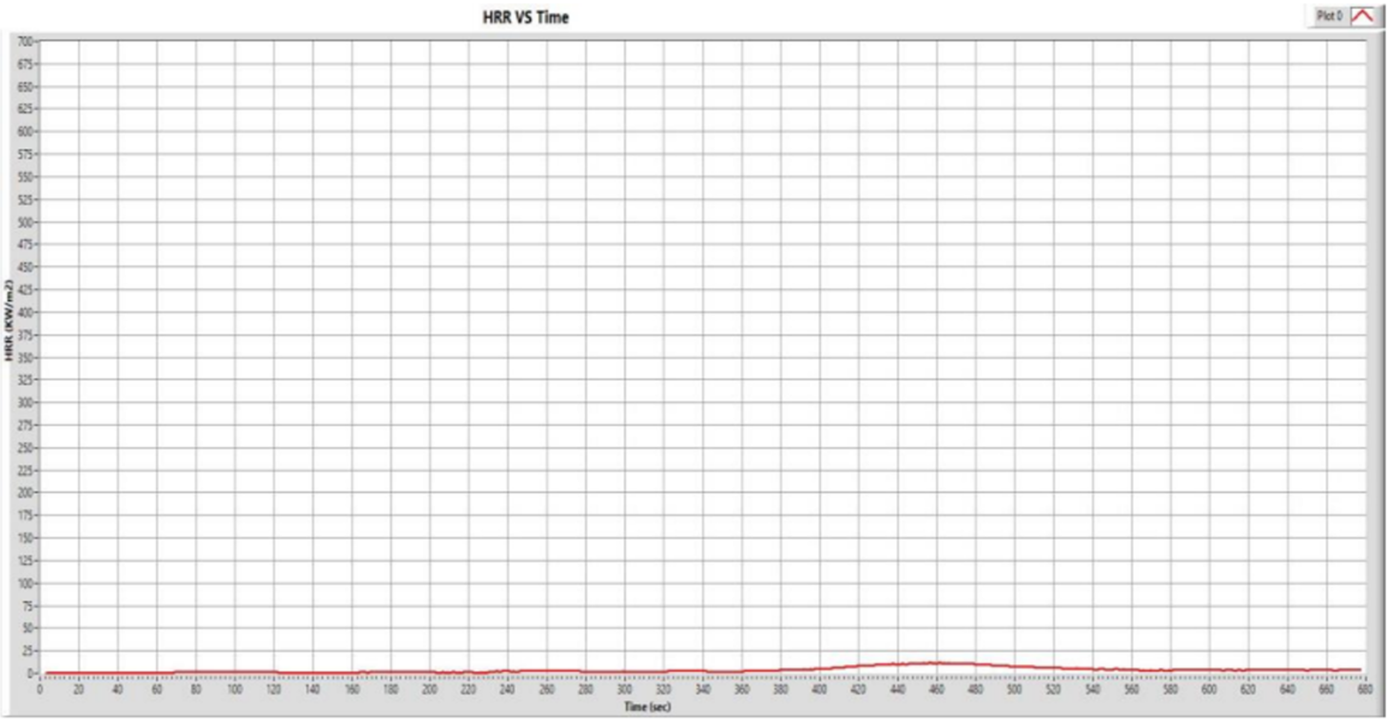
- *Oxygen Concentration Versus Time for Uncoated PVC*



graph of uncoated of PVC (oxygen vs time)

Fig 2 Oxygen Concentration Versus Time for Uncoated PVC

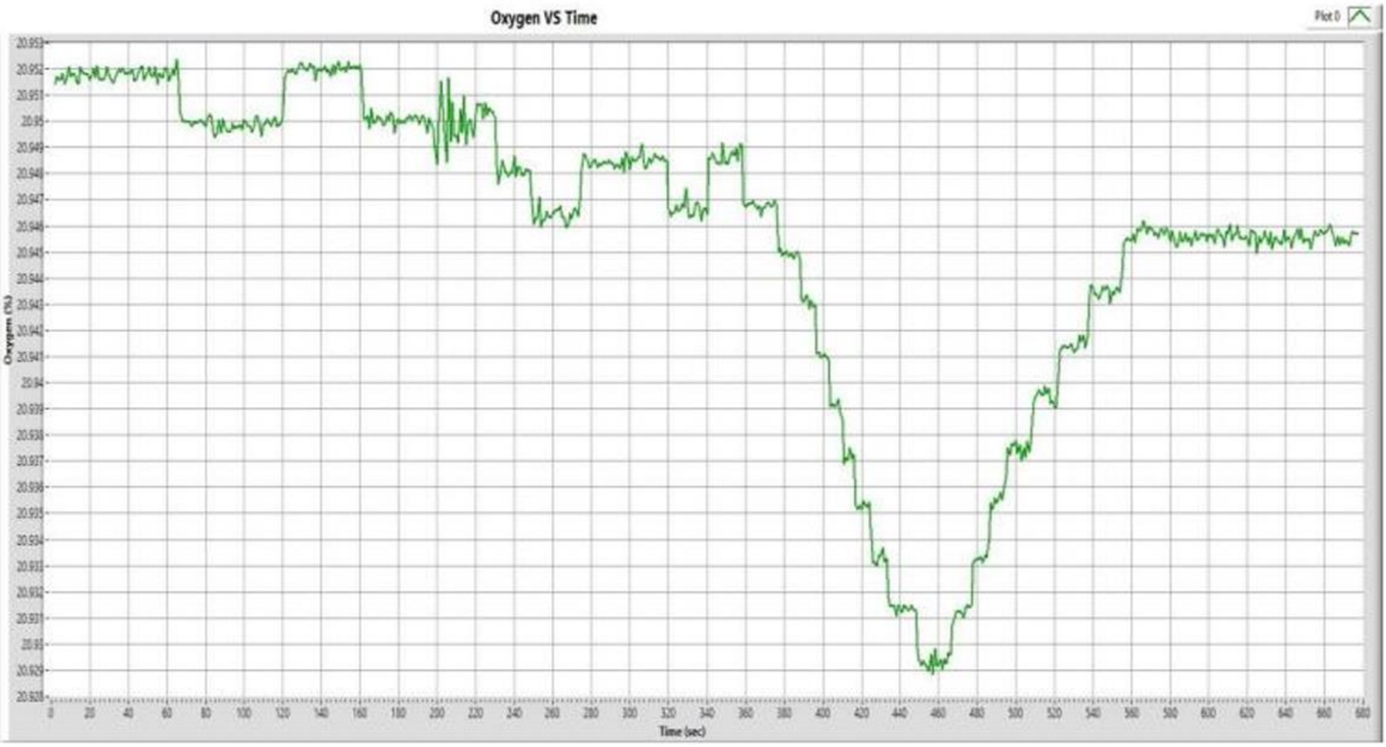
- *Heat Release Rate (HRR) Versus Time for PVC with 250 µm Intumescent Coating*



graph of coated PVC 250 (HRR vs time)

Fig 3 Heat Release Rate (HRR) Versus Time for PVC with 250 µm Intumescent Coating

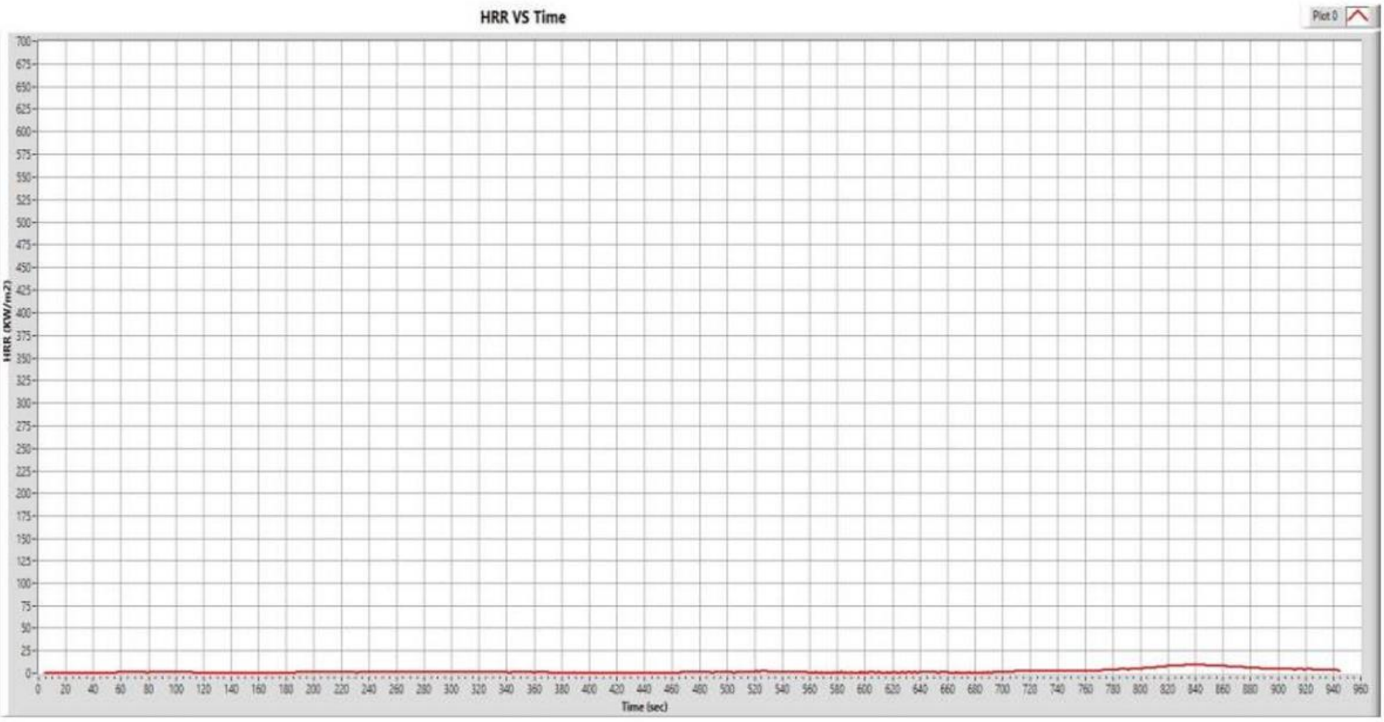
- *Oxygen Concentration Versus Time for PVC with 250 µm Intumescent Coating*



graph of coated PVC 350 (oxygen vs Time)

Fig 4 Oxygen Concentration Versus Time for PVC with 250 µm Intumescent Coating

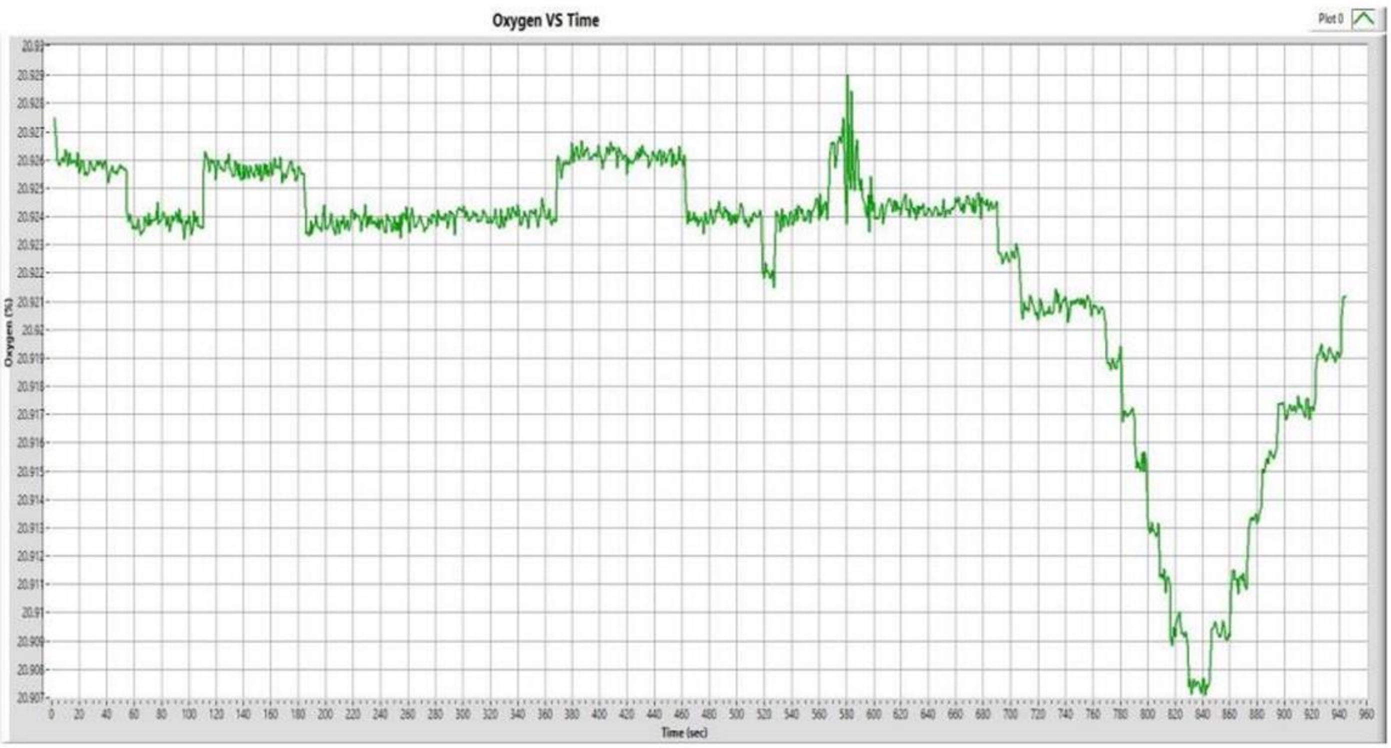
- *Heat Release Rate (HRR) Versus Time for PVC with 350 µm Intumescent Coating*



graph of coated PVC 350 (HRR vs time)

Fig 5 Heat Release Rate (HRR) Versus Time for PVC with 350 µm Intumescent Coating

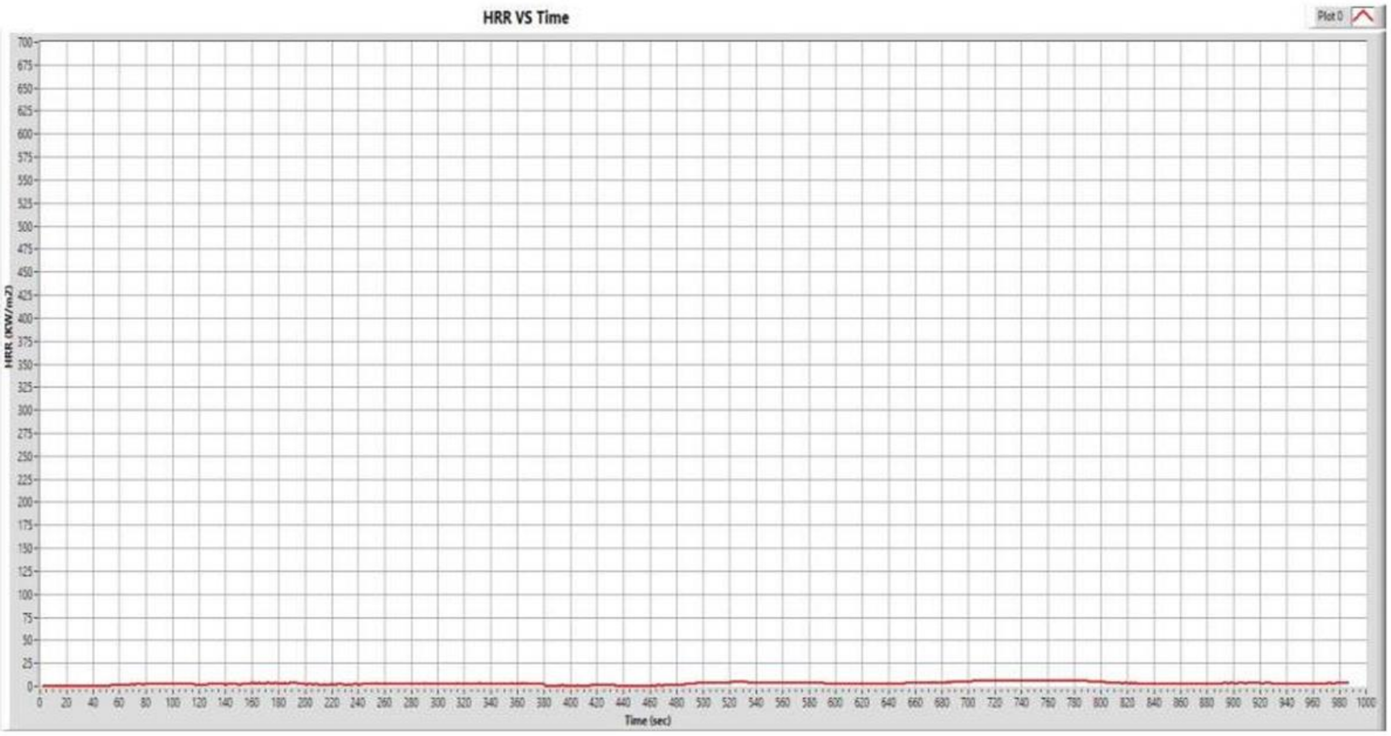
- *Oxygen Concentration Versus Time for PVC with 350 µm Intumescent Coating*



graph of coated PVC 350 (oxygen vs Time)

Fig 6 Oxygen Concentration Versus Time for PVC with 350 µm Intumescent Coating

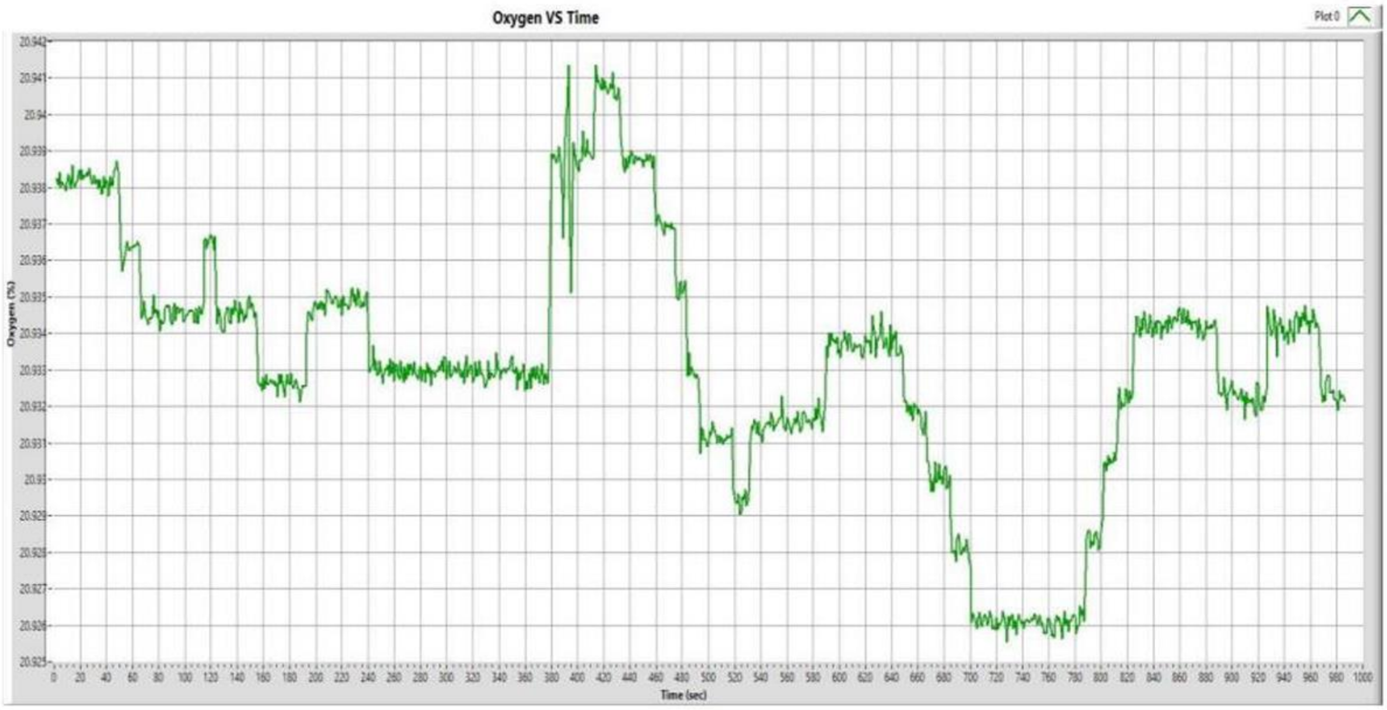
- *Heat Release Rate (HRR) Versus Time for PVC with 450 µm Intumescent Coating*



graph of coated PVC 450 (HRR vs time)

Fig 7 Heat Release Rate (HRR) Versus Time for PVC with 450 µm Intumescent Coating

- *Oxygen Concentration Versus Time for PVC with 450 µm Intumescent Coating*



graph of coated PVC450 (oxygen vs time)

Fig 8 Oxygen Concentration Versus Time for PVC with 450 µm Intumescent Coating

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