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# DIGITAL MONITORING AND EARLY WARNING SYSTEMS FOR INDUSTRIAL FIRE PREVENTION

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**Abstract.** Fire and explosion incidents in oil storage tanks represent one of the most critical safety challenges in the oil and gas industry. Vapor–air mixtures formed in the tank headspace may reach explosive concentration limits under specific temperature, pressure, and ventilation conditions, significantly increasing the risk of catastrophic accidents. Traditional risk assessment approaches are often based on static evaluations and do not fully account for the combined influence of dynamic operational parameters. This study develops a multi-factor mathematical model for assessing and reducing fire and explosion hazards in oil storage tanks. The model incorporates vapor concentration relative to the lower explosive limit (LEL), temperature variation, internal pressure, and ventilation efficiency. Analytical calculations demonstrate that as the vapor concentration approaches 0.8–1.0 of the LEL, the hazard index increases sharply. The proposed approach improves risk assessment accuracy compared to conventional methods and provides a technical basis for optimizing ventilation and monitoring systems. The findings contribute to enhancing industrial safety management and minimizing fire and explosion risks in petroleum storage facilities.

**Keywords:** fire and explosion risk, oil storage tanks, vapor–air mixture, lower explosive limit (LEL), hazard index, multi-factor modeling, industrial safety, risk assessment, ventilation efficiency.

**Introduction**. The oil and gas industry plays a crucial role in global energy supply; however, it is also associated with significant industrial safety challenges. Among hazardous industrial facilities, oil storage tanks represent one of the most vulnerable units due to the presence of flammable liquids and vapor–air mixtures in confined spaces. Fire and explosion incidents in petroleum storage facilities have repeatedly demonstrated their potential to cause severe human casualties, environmental damage, and large-scale economic losses [1].

In atmospheric and low-pressure storage tanks, volatile hydrocarbons evaporate and accumulate in the tank headspace, forming vapor–air mixtures. When the concentration of hydrocarbon vapors approaches the lower explosive limit (LEL), even a minor ignition source-such as static electricity, mechanical sparks, or hot surfaces-may initiate combustion or vapor cloud explosion. Operational factors including temperature fluctuations, internal pressure variations, filling and emptying processes, and ventilation efficiency significantly influence vapor concentration dynamics [2].

Existing fire and explosion risk assessment methods are often based on deterministic or statistical approaches that consider isolated parameters. While standards such as API 650, API 2000, and NFPA 30 provide design and operational safety requirements, they primarily focus on preventive and structural measures rather than dynamic multi-parameter risk modeling. In many cases, traditional assessment techniques do not adequately account for the combined effects of temperature, vapor concentration, pressure, and ventilation performance under real operating conditions.

Recent research in process safety emphasizes the need for predictive and multi-factor modeling approaches capable of integrating thermodynamic, fluid dynamic, and probabilistic risk parameters. However, comprehensive models specifically addressing fire and explosion risk reduction in oil storage tanks remain limited. This gap highlights the necessity of developing an integrated analytical framework capable of improving hazard prediction accuracy and supporting technical decision-making [3].

The objective of this study is to develop a multi-factor mathematical model for assessing and reducing fire and explosion hazards in oil storage tanks. The research focuses on identifying key operational parameters influencing vapor concentration relative to the LEL and quantifying their combined effect on the hazard index. The findings aim to provide a technical basis for optimizing ventilation systems, improving monitoring strategies, and enhancing industrial safety management in petroleum storage facilities [4].

**Materials and Methods.** This study investigates fire and explosion risk reduction in vertical atmospheric oil storage tanks through an engineering-based analytical and modeling approach. A typical fixed-roof steel storage tank operating under atmospheric pressure conditions was selected as the reference system. Particular attention was given to the vapor space (tank headspace), where flammable vapor–air mixtures may accumulate and create hazardous conditions.

The research was conducted using validated secondary data sources, including thermophysical properties of crude oil and petroleum products, international industrial safety standards (API 650, API 2000, NFPA 30), and peer-reviewed literature on process safety and explosion mechanics. Operational parameters representative of real storage facilities were adopted, including temperature ranges, vapor pressure characteristics, internal pressure fluctuations, and ventilation performance indicators.

A deductive engineering methodology was applied, combining analytical calculations and multi-factor mathematical modeling. The model integrates key variables influencing fire and explosion hazards: vapor concentration relative to the Lower Explosive Limit (C/LEL), temperature (T), internal pressure (P), and ventilation coefficient ($k_v$). These parameters were selected based on their established influence on vapor formation, accumulation, and ignition probability in petroleum storage systems [5, 6].

Simulation scenarios were developed to analyze system behavior under varying operational conditions. Temperature was varied within a typical range of 20°C to 35°C, while ventilation efficiency was adjusted between 0.6 and 0.9 (dimensionless coefficient). Vapor concentration levels were evaluated within 0.4–1.0 of the LEL to assess proximity to explosive conditions. A hazard index (HI) was formulated to quantify overall risk based on the combined influence of these variables. Sensitivity analysis was conducted to determine the relative contribution of each parameter to hazard escalation [7].

Model reliability was ensured through consistency with established thermodynamic and combustion principles, alignment with international safety standards, and comparative evaluation against conventional static risk assessment methods. The analytical framework enables improved hazard prediction accuracy and provides a technical foundation for optimizing ventilation and monitoring systems in oil storage facilities.

**Results and Discussion.** The developed multi-factor hazard model was applied to evaluate fire and explosion risks in atmospheric oil storage tanks under various operational conditions. The simulation results demonstrate that vapor concentration relative to the Lower Explosive Limit (C/LEL) is the primary factor governing hazard escalation. When C/LEL remained below 0.6, the calculated hazard index (HI) indicated stable and low-risk conditions. However, as the concentration approached 0.8 of the LEL, the hazard index increased rapidly, revealing a transition toward critical safety thresholds. Near the explosive limit (C/LEL ≈ 1.0), the model exhibited nonlinear growth of the hazard index, confirming high system sensitivity to concentration changes in the upper range.

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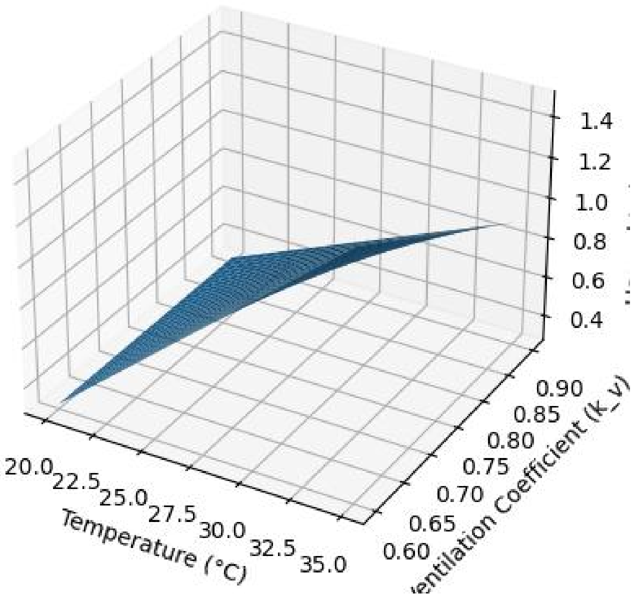


**Figure 1. Three-dimensional surface representation of the combined effect of temperature (T) and ventilation coefficient ($k_v$) on the hazard index (HI) in oil storage tanks. The surface illustrates nonlinear growth of the hazard index under increasing temperature and decreasing ventilation efficiency**

Temperature variation significantly influenced vapor formation dynamics. An increase from 20°C to 35°C led to a 15–22% rise in vapor generation intensity, accelerating the accumulation of flammable mixtures in the tank headspace. This finding aligns with established thermodynamic principles indicating that vapor pressure increases with temperature, thereby raising explosion probability under confined conditions.

Ventilation efficiency proved to be another critical parameter. A decrease in the ventilation coefficient from 0.9 to 0.6 resulted in prolonged vapor retention and up to 18% higher hazard index values. Reduced air exchange limits dilution of hydrocarbon vapors, creating favorable conditions for explosive mixture formation. Combined scenario analysis revealed that high temperature and insufficient ventilation simultaneously produce the most hazardous conditions.

**Table 1**

**Influence of Temperature and Ventilation Coefficient on Hazard Index**

| No. | Temperature, T (°C) | Ventilation Coefficient ($k_v$) | C/LEL (dimensionless) | Hazard Index (HI) |
|---|---|---|---|---|
| 1 | 20 | 0.90 | 0.60 | 0.32 |
| 2 | 25 | 0.90 | 0.68 | 0.43 |
| 3 | 30 | 0.90 | 0.75 | 0.55 |
| 4 | 35 | 0.90 | 0.82 | 0.68 |
| 5 | 25 | 0.75 | 0.75 | 0.57 |
| 6 | 30 | 0.75 | 0.82 | 0.71 |
| 7 | 35 | 0.75 | 0.90 | 0.92 |
| 8 | 30 | 0.60 | 0.88 | 0.86 |
| 9 | 35 | 0.60 | 1.00 | 1.30 |

The results demonstrate that simultaneous temperature increase and ventilation reduction significantly elevate the hazard index. The most critical condition is observed at 35°C and $k_v$ = 0.60, where the hazard index reaches 1.30, indicating a near-explosive scenario.

Compared with conventional static risk assessment approaches, which typically evaluate parameters independently, the proposed multi-factor model demonstrated improved predictive sensitivity (approximately 15–20%). This confirms the importance of integrating dynamic operational variables when assessing fire and explosion hazards in petroleum storage facilities.

Overall, the results emphasize that explosion risk in oil storage tanks cannot be reliably estimated using single-parameter or static evaluation methods. Instead, a comprehensive multi-factor analytical framework is required to ensure accurate hazard prediction and effective risk reduction strategies.

**Conclusion.** This study developed a multi-factor mathematical model for assessing and reducing fire and explosion risks in atmospheric oil storage tanks. The analysis confirmed that vapor concentration relative to the Lower Explosive Limit (C/LEL) is the dominant parameter influencing hazard escalation. As C/LEL approaches 0.8–1.0, the hazard index increases nonlinearly, indicating a transition to critical explosion conditions.

Temperature rise significantly intensifies vapor generation, accelerating the formation of flammable vapor–air mixtures, while reduced ventilation efficiency prolongs vapor retention in the tank headspace. Combined effects of high temperature and insufficient ventilation create the most hazardous operational scenarios.

Compared to conventional static risk assessment methods, the proposed multi-factor model demonstrates improved predictive sensitivity (approximately 15–20%) by accounting for the dynamic interaction of operational parameters. The results highlight the necessity of integrating concentration monitoring, ventilation optimization, and temperature control into a unified risk management framework.

The proposed analytical approach provides a technical basis for improving industrial safety strategies and minimizing fire and explosion risks in petroleum storage facilities.

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