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Dynamic Meteorological Data Integration for Offsite Emergency Evacuation and Fire Hazard Modeling in LPG Terminals

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Abstract

Effective management of offsite emergencies in Liquefied Petroleum Gas (LPG) terminals hinges significantly on real-time access to meteorological data, particularly wind speed and direction. This study proposes an Internet of Things (IoT)-enabled system integrating a Bluetooth Anemometer with the ALOHA hazard modeling software to dynamically fetch and analyze wind data during LPG fire emergencies. Field testing involved real-time data collection using a mobile application connected to the anemometer, with immediate input into ALOHA to simulate threat zones. Results demonstrate that rapid data acquisition enables faster decision-making for evacuation strategies, potentially reducing response time and minimizing casualties. The proposed approach emphasizes proactive fire safety management by integrating dynamic environmental monitoring into emergency protocols.

Keywords LPG Fire, BLEVE, UVCE, IoT, Wind Speed Monitoring, ALOHA Modeling, Emergency Evacuation, Hazard Analysis

INTRODUCTION

The International Labour Organization (ILO) Convention C170 - *Chemicals Convention, 1990 (No.170)* emphasizes the responsibility of employers to ensure the safety and health of workers in environments where hazardous chemicals are used. Specifically, Article 13 mandates that employers must: Assess risks arising from the use of chemicals; Implement appropriate operational controls; Make arrangements to manage emergencies effectively.

These operational controls include, but are not limited to: (a) Selection of less hazardous chemicals to eliminate or minimize risk;(b) Adoption of technologies that inherently reduce risk; (c) Use of adequate engineering control measures; (d) Development of work practices and systems that reduce or eliminate exposure; (e) Implementation of occupational hygiene standards; (f) Provision and maintenance of personal protective equipment (PPE).

The **Factories Act** also reinforces the importance of **On-site and Off-site Emergency Preparedness** as an essential element in industrial risk management. However, despite regulatory frameworks and engineering advancements, high-risk environments such as **Liquefied Petroleum Gas (LPG) Storage Terminals** continue to experience serious incidents, notably **BLEVEs** (Boiling Liquid Expanding Vapor Explosions) and **UVCEs** (Unconfined Vapor Cloud Explosions).

Recent LPG Incident Highlights in India (2023–2025)

(i) Pune, Oct 2023 – Fire during illegal LPG transfer; 6 cylinders exploded, 2 injured. *(Unsafe practices; need for enforcement and training).* (ii) Pune, Dec 2023 – Explosion at unauthorized refilling unit; ~12 cylinders blasted (*Illegal setups pose major fire risks). (iii)* Coimbatore, Dec 2023 – LPG leak from parked tankers due to compound wall collapse. (*Site infrastructure maintenance is critical). (iv)* Coimbatore, Jan 2025 – Tanker overturned; gas leak forced school closures. (*Evacuation planning and tanker safety needed).* (v) Jaipur, Dec 2024 – Tanker crash and BLEVE; 11+ killed, 40 vehicles burned. (*Reinforced nozzle design, driver safety, and road risk control required).* (vi) Thrissur, Feb 2025 – Domestic LPG cylinder explosion due to leakage (*Manufacturer QC and public awareness **essential).***

These incidents point to **systemic safety gaps** not only in engineering design but also in operational discipline, emergency preparedness, and risk perception among employees.

Identified Challenges and Critical Observations

While many installations have basic engineering and firefighting systems in place, **real-world evacuation delays**, **insufficient meteorological risk assessment**, and **limited use of advanced predictive tools** continue to endanger lives. Key issues include: Inadequate **real-time risk communication** systems; Insufficient integration of **meteorological monitoring** into evacuation plans; Limited deployment of **hazard and consequence modeling software** (e.g., ALOHA, PHAST, SAFETI); Lack of **automated emergency response systems** (gas leak detection with AI-triggered alarms); **Poor community awareness** regarding off-site emergency protocols; Infrequent **emergency mock drills** or inadequate simulation of realistic scenarios; **Manual and outdated evacuation planning**, lacking data-driven modeling.

Key Recommendations and Enhanced Risk Mitigation Measures

Based on a detailed review of case studies and regulatory obligations, the following strategies are vital for ensuring comprehensive emergency preparedness: (i) **Routine Monitoring and Inspection Programs**: Frequent testing & maintenance of safety interlocks and pressure relief valves on LPG bullets and Periodic inspection of LPG pipelines, joints, hoses, and valves for early leak detection. (ii) **Advanced Risk Control Implementation**: Installation of **automated leak detection & isolation systems** and Use of **predictive hazard modeling software** to simulate BLEVE/UVCE scenarios for better preparedness. Deployment of **drones and thermal cameras** for high-risk zone monitoring. (iii) **Enhanced Worker Training and Awareness**: Regular and scenario-based training programs for handling LPG emergencies and Competency checks and safety drills for both routine and emergency tasks. (iv) **Meteorological Risk Integration**: Real-time weather monitoring & plume dispersion modeling to guide safe evacuation directions and Incorporating wind speed/direction data into fire and vapor cloud spread simulations. (v) **Robust On-site and Off-site Emergency Response Systems**: Clearly demarcated **evacuation routes** and assembly points with real-time alert systems. Integration of **GIS-based mapping** and **mass notification systems** for immediate alerts and Engagement with local authorities and hospitals to establish a **coordinated Off-site Emergency Plan**. (vi) **Community and Stakeholder Engagement**: Periodic awareness campaigns for surrounding communities on emergency response procedures. Liaison with disaster management authorities for rapid coordination. (vii) **Post-Incident Learning and Safety Culture**: Root Cause Analysis (RCA) of all near misses and incidents. Continuous improvement through lessons learned and implementation of corrective actions.

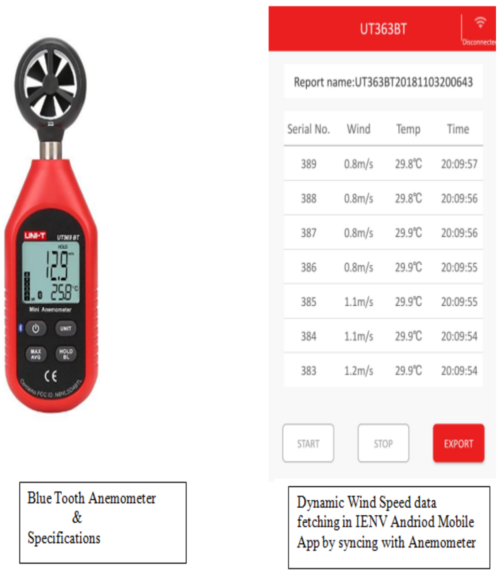
Despite compliance with existing safety norms, the persistence of LPG-related incidents reveals the need for a **proactive and integrated safety management approach**. Real-time risk assessment, advanced emergency modeling, and dynamic evacuation planning—combined with consistent training and community engagement—are critical to minimizing the catastrophic potential of LPG storage terminal accidents.

The following sections will delve into the technical aspects of **On-site and Off-site Emergency Evacuation Enhancement**, supported by a **Working Model** and **Hazard Simulation Software** outputs for effective implementation.

EMERGENCY EVACUATION CHALLENGES

INDOSHNEWS Journal Vol.6 published by DGFASLI clearly presented the Survey of Risk from Storage tanks at sites. The fire and explosion in LPG storage system is likely to start with the leakage or release of gas either from the storage tanks or from the distribution system with the following possibilities like Gas release from the top fittings of the tank, Liquid release from the bottom fittings of a tank Gas release from vapor line from the decanting platform to the tanks or from the tanks to the plant, Liquid release from the pipeline from the pump to the tanks or from the tanks to the vaporizer or from the drain line. It has mentioned that the ultimate damage to property and life due to an unconfined vapor cloud explosion depends upon the mass of gas within explosive range. It was found that under stability conditions for 2 m/Sec wind speed these values were 887 kg from 20 Tonne LPG Bullet and at higher wind speed (5 m/Sec) these values changed to 404 kg. Wind speed. Thus, having the installation at a place which has more average wind speed is advantageous. As per the Emergency Risk Assessment document, published by Ministry of Environment, Government of India, it is evident that they are so many challenges in ON SITE and OFF-SITE Emergency evacuation. It clearly explains that the Wind Sock should be installed at the top of the building to indicate wind direction. In case of emergency building occupants / workers should evacuate by running at 90 degrees to wind direction (and not opposite to wind direction). In case of Hazardous /Toxic gas release, Offsite emergency plan would be triggered. Along with many factors, Arrangements should be made in obtaining details of weather conditions prevailing at the time of emergency and subsequent weather forecasts to be fetched through Wind Socks and Meteorological Department. Fetching of the meteorological data like Wind Speed and Direction is one the important factor for effective OFF SITE Emergency Evacuation. The effective implementations have not found in Indian LPG storage terminals to dynamically fetch this data from the Fire incident spot and dependency on Meteorological Department may delay the evacuation process. This key challenge has identified and enhancement has recommended. While the Factories Act and ILO Convention C170 stress the importance of emergency preparedness, most LPG installations rely on static data or delayed updates from external sources. This research bridges that gap by integrating IoT-based real-time wind speed monitoring with hazard modeling to dynamically support offsite emergency planning.

Fig. 1 Bluetooth Anemometer & iEnv Android App



MATERIALS AND METHODS

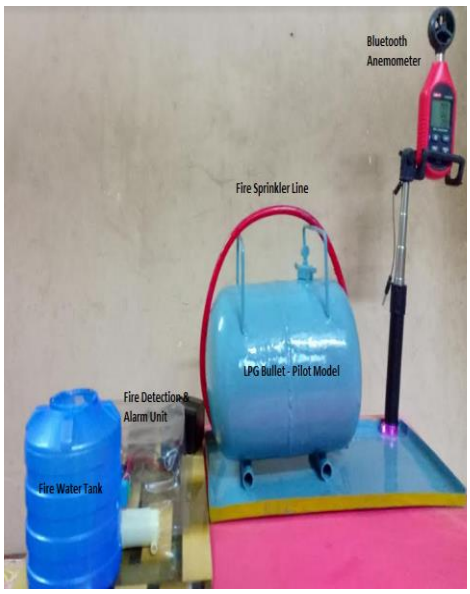
Materials

Bluetooth Anemometer which has used to measure wind speed is the light weight device is equipped with the latest magnetic sensing technology, which can directly display the air flow speed on LCD. Bluetooth function is added for data transfer and analysis on mobile App, iENV (Fig 1) which can be downloaded from Google Play or Apple Store.

The features of Bluetooth Anemometer as follows:

- Dual display of wind speed and temperature.
- 5 Units switching: m/s, km/h, ft/min, knots, mph.
- 12 level Beaufort scale indicator.
- Wind chill index (condition: ambient temperature below 0°C, wind speed higher than 5m/s).
- Special fan structure design, can detect startup wind speed as low as 0.1m/s.

Fig. 2 LPG Fire Detection with Dynamic Wind Speed Monitoring Anemometer



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The overall working model assembly (Fig 2) consist of a LPG bullet, Fire water tank, Fire water sprinkler circuit system and the anemometer assembly. The current set up has been arranged only to find the wind speed and direction. For further research improvement, thermocouple can be arranged to find out the temperature near the LPG bullet during the fire which will be helpful for further analysis.

Methods

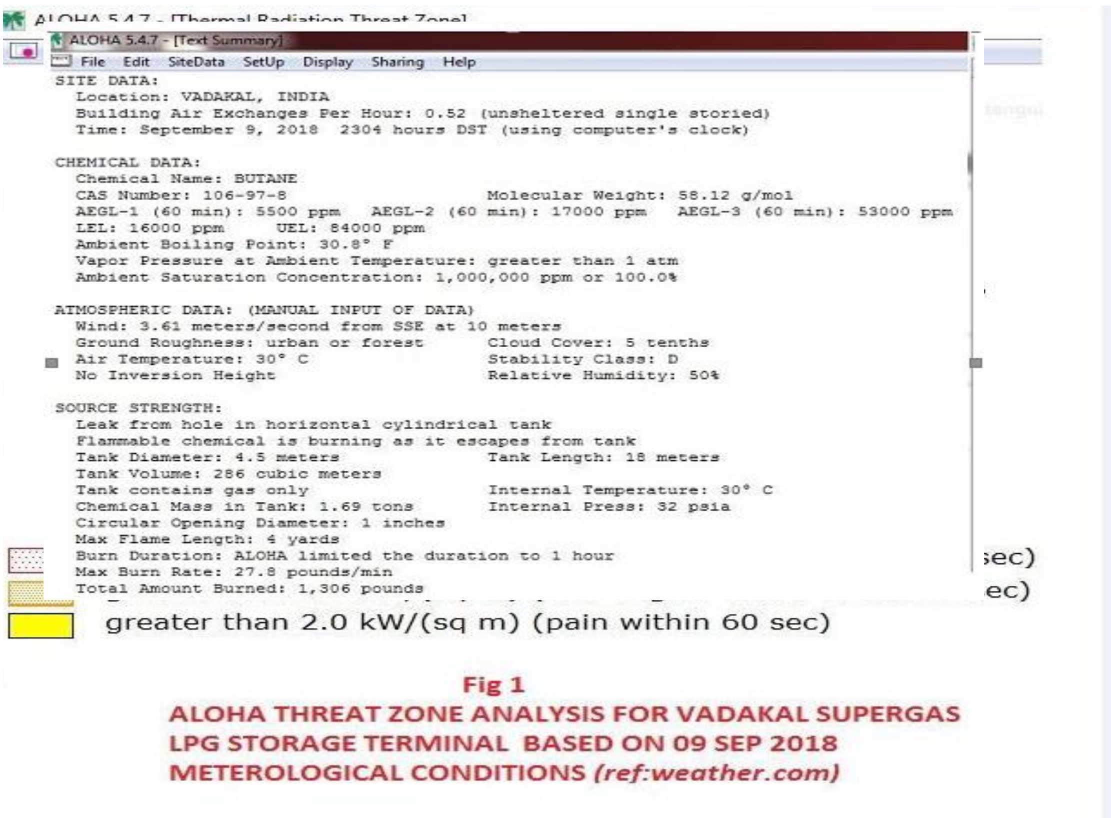
If the Wind Speed and Direction data fetched dynamically, emergency evacuation plan that is moving towards Upwind / Cross Wind or to the safe assembly point can be decided quickly. To attain this, Blue tooth Anemometer have incorporated in the working model and then through IENV Android App, the Wind Speed has fetched immediately during emergency. The dynamic wind speed data has fed in ALOHA Software for Fire Hazard Modeling. In this model, only Wind Speed data has fetched

ALOHA – LPG Storage Terminal – Site Data

This Anemometer would measure the Wind speed range 0 to 45 m/s. It measures the Wind Temperature ranges between -10 to 50 °C. In case of LPG Fire Emergency, the wind speed data would be helpful to understand the intensity of fire spread that can be expected and this By feeding this data into ALOHA – Hazard modeling software the threat zone can be found out instantly and emergency evacuation can be planned accordingly

<u>**LPG TERMINAL THREAT ZONE ANALYSIS**</u>

ALOHA can be abbreviated as Area Locations of Hazardous Atmosphere. To develop fire & explosion and dispersion model using ALOHA software, the following data is required : Location: Latitude and Longitude, Wind speed for the given location and Elevation of the location. ALOHA can be used as modeling software to analyze the toxicity, flammability, The specific data related to LPG Terminal data (Fig 3) has entered and Threat Zone modeling has done . The Wind speed data (3.61 m/s) which has dynamically fetched from Bluetooth Anemometer and synchronized with iENV Mobile app has entered in ALOHA for Threat Zone analysis.


ALOHA 5.4.7 - [Text Summary]
File Edit SiteData SetUp Display Sharing Help

```
SITE DATA:
  Location: VADAKAL, INDIA
  Building Air Exchanges Per Hour: 0.52 (unsheltered single storied)
  Time: September 9, 2018  2304 hours DST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: BUTANE
  CAS Number: 106-97-8                    Molecular Weight: 58.12 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 53000 ppm
  LEL: 16000 ppm     UEL: 84000 ppm
  Ambient Boiling Point: 30.8° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3.61 meters/second from SSE at 10 meters
  Ground Roughness: urban or forest       Cloud Cover: 5 tenths
  Air Temperature: 30° C                  Stability Class: D
  No Inversion Height                     Relative Humidity: 50%

SOURCE STRENGTH:
  Leak from hole in horizontal cylindrical tank
  Flammable chemical is burning as it escapes from tank
  Tank Diameter: 4.5 meters               Tank Length: 18 meters
  Tank Volume: 286 cubic meters
  Tank contains gas only                  Internal Temperature: 30° C
  Chemical Mass in Tank: 1.69 tons        Internal Press: 32 psia
  Circular Opening Diameter: 1 inches
  Max Flame Length: 4 yards
  Burn Duration: ALOHA limited the duration to 1 hour
  Max Burn Rate: 27.8 pounds/min
  Total Amount Burned: 1,306 pounds
```


Fig. 3

In this modeling, prevailing Wind Speed has entered by referring the web site weather.com. By implementing Bluetooth Anemometer, in case of LPG fire Emergency, Wind Speed can be fetched dynamically through IENV app in Android Mobile .The Threat Zone (Fig 4) can be graphed immediately and evacuation can be done immediately instead of waiting for Meteorological reports. ALOHA simulations indicated significant shifts in threat zone radii corresponding to dynamic wind speedsAt 3.6 m/s, the red zone radius extended approximately 200 meters, while a 5 m/s input produced a more elongated dispersion profile. These real-time

Fig. 4 Threat Zone Analysis

visualizations allowed for immediate determination of evacuation direction, improving overall response time by an estimated 30 to 45 seconds when compared to conventional methods relying on static meteorological forecasts.

RESULTS AND DISCUSSIONS

This study demonstrates that integrating IoT-based meteorological monitoring systems, specifically dynamic wind speed sensors, into offsite emergency protocols offers the following advantages:

(a) Improved Decision-Making During Emergencies: Real-time wind speed data, when linked to hazard modeling software (such as ALOHA), enables rapid simulation of vapor cloud dispersion or thermal radiation impact zones. Operators can quickly identify safe zones, danger zones, and optimal evacuation paths based on live data, rather than relying on fixed or outdated assumptions. **(b) Reduction in Evacuation Delays:** Traditionally, evacuation protocols often rely on fixed wind assumptions or historical averages. The deployment of IoT-based anemometers (wind sensors) allows near-instant updates to response teams, thus reducing the time needed to validate evacuation decisions. **(c) Enhanced Offsite Community Protection:** For terminals located near residential or commercial zones, wind data plays a crucial role in offsite emergency planning. Real-time alerts can be extended to municipal authorities, traffic control, and nearby schools or hospitals, guiding them on whether to evacuate or shelter in place. **(d) Validation of Emergency Drill Models:** Integration of real wind speed data into post-drill analysis helps validate the accuracy and realism of mock drills. This improves emergency preparedness and enables data-driven updates to existing SOPs.

CONCLUSION

Meteorological data play a critical role in shaping the effectiveness of fire emergency evacuation strategies in LPG storage terminals. Among these, wind speed and direction are especially significant, as they directly influence the dispersion of vapor clouds, flame spread, and thermal radiation zones during incidents. This study demonstrates that the integration of IoT-based real-time wind speed monitoring into off-site emergency response protocols can substantially improve evacuation planning and execution. By feeding live meteorological data into hazard modeling software, such as ALOHA, facility operators are empowered to make informed, data-driven decisions during fire emergencies. This not only minimizes evacuation delays but also enhances personnel and community safety.

Furthermore, the system's ability to dynamically adjust evacuation routes based on changing wind conditions ensures a more adaptable and effective response. Future enhancements may include the incorporation of wind direction sensors, AI-based predictive modeling, and automated alert systems to forecast plume trajectories and optimize real-time evacuation strategies. These advancements hold significant potential for transforming emergency preparedness in high-risk LPG facilities.

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