A Review of the Q9 Equivalent Cloud Method for Explosion Modelling

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These slides and the work they describe were funded by the Health and Safety Executive (HSE). Their contents, including any opinions and/or conclusions expressed, are those of the author(s) alone and do not necessarily reflect HSE policy.
Contents

• Motivation & Background
• Probabilistic ERA & the Equivalent Cloud Concept
  – Overview
  – Equivalent cloud metrics
• Validation of Q9 Approach
• Key Issues to Consider
  – Model sensitivity & user-induced variability
  – Pre-ignition turbulence
  – Suitability of Modelling Guidance
• Next Steps & Potential Future Work
Motivation & Background
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• Probabilistic Explosion Risk Assessments (ERA) are used to characterise risks of accidental ignition of unintended release of flammable gases on/offshore

• ERA are a requirement of the NORSOK Z-013 [1] industry standard, with further guidance given by Lloyds Register [2]

• The primary outputs of these types of study are overpressure exceedance curves

• Used to inform design decisions relating to pressure loading on structures and safety critical plant
Motivation & Background

• Some concern over whether or not the modelling approaches used give sufficiently conservative results

• Also uncertainty over the extent of user-variability and how ‘expert judgment’ affects the ERA process

• Aim was to review the Q9 equivalent stoichiometric cloud approach to evaluate:
  – The scientific basis of the method
  – The extent to which it has been validated
  – How consistently the approach is applied by different users
Probabilistic Explosion Risk Assessment (ERA) & the Equivalent Cloud Concept
ERA & Equivalent Cloud Concept

Wind Speed  Wind Direction  Release Scenario  

Dispersion Simulations

Pragmatic simplification

Translate to Equiv. Clouds

Cloud Size  Cloud Position  Ignition Probability  Ignition Location

Explosion Simulations

Results brought together to produce overpressure exceedance curves
ERA & Equivalent Cloud Concept

Inhomogeneous cloud from realistic release

Equivalent stoichiometric gas volume

Apply scaling

LFL
UFL
>UFL

Most reactive
ERA & Equivalent Cloud Concept

• Equivalent cloud metrics in FLACS $^{[3]}$:
  – ERFAC (kg)
  – FLAM (m$^3$) [equivalent to ΔFL below]
  – Q5 (m$^3$)
  – Q9 (m$^3$) most commonly used
  – Q8 (m$^3$)

• Other options also used $^{[4]}$:
  – >LFL (m$^3$) conservative
  – ΔFL (m$^3$) [equivalent to FLAM]

• Ratio of volumes between ΔFL:Q8:Q9 is approx. 3:2:1
ERA & Equivalent Cloud Concept

1995

Gexcon introduce first equivalent cloud metric with parameter ERFAC

1999

Introduction of Q8 & Q9 to account for fuels where max. flame speed and expansion occur at different equivalence ratios

2005

Q5 proposed to include gas expansion effects – aim was to eliminate ERFAC bias towards fuel-rich clouds

No change to methods & limited changes to modelling guidance

2019

What now & next?

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• Methods are designed to give a reasonable approximation of expected overpressures in the context of a probabilistic assessment

• Based on two key assumptions:
  – Explosion models (and modellers!) accurately predict overpressures in uniform clouds
  – Scaling gives a uniform cloud generating a similar overpressure to the corresponding inhomogeneous cloud
Validation of the Q9 Approach
Validation of Q9 Approach

• Two main (publically-available) evaluations of Q9
  – Tam et al. (2008) [4]
  – Hansen et al. (2013) [5]

• Both works compare model predictions to data from the BFETS Phase 3B experiments
  – Natural gas
  – Full-scale offshore module (28 x 12 x 8 m)
  – Full and partial fill tests with near-stoichiometric concentration
  – Ignited jet release tests (~33/43 mm orifice)
Validation of Q9 Approach

• Tam et al. [4] compared FLACS-predicted overpressures to data from the BFETS Phase 3B tests using Q9, >LFL and ΔFL equivalent clouds

• The equivalent cloud volumes used were estimated from the gas concentration measurements made during the BFETS tests

• This approach separates out the dispersion and explosion elements of the study in an attempt to quantify the performance of the equivalent cloud metrics used

• The cloud position and ignition location were varied in an approach consistent with that used in a probabilistic ERA
Tam et al.\textsuperscript{[4]} showed that for measured overpressures $> 0.1$ bar, FLACS under-predicted by more than a factor of two (on average) using Q9 clouds.

Using the other two equivalent cloud metrics, FLACS gave conservative predictions of the overpressure in the BFETS tests.

The Tam et al. results showed that using Q9 gave the largest scatter in predictions, and therefore least consistent performance.

Tam et al. concluded:

\textit{“This study does not support the use of Q9.”}
The Hansen et al. [5] study first examined the performance of the FLACS dispersion model for predicting Q9 cloud size.

The authors compared predicted Q9 cloud size to values estimated from BFETS Phase 3B concentration measurements.

Large uncertainty in experimental values due to sparse array of gas sensors used in the tests – approx. one every 60 m³ on average.

Predicted Q9 volumes were calculated in two ways:
- From predicted concentrations at experimental sensor locations
- From FLACs internal calculation of Q9 (over all mesh cells)

Some large deviations between prediction/experiment and between two methods used to determine predicted cloud size.
Validation of Q9 Approach

• Hansen et al. then used equivalent stoichiometric clouds with sizes ranging from 2% to 100% fill of the BFETS module in an explosion modelling study

• Cloud position and ignition location was varied and results were presented both with/without pre-ignition turbulence

• The results showed FLACS gave comparable overpressures to the measurements without pre-ignition turbulence and slightly conservative results with pre-ignition turbulence included in the model
## Validation of Q9 Approach

<table>
<thead>
<tr>
<th></th>
<th>Tam et al. (2008)</th>
<th>Hansen et al. (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q9 size from dispersion simulation results?</td>
<td>✗</td>
<td>?</td>
</tr>
<tr>
<td>Most reactive gas concentration used?</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cloud position &amp; ignition location varied?</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td>Significant under-prediction</td>
<td>Agreement within a factor of 2</td>
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</table>
Validation of Q9 Approach

- Tam et al. (2008) and Hansen et al. (2013) studies lead to opposing conclusions on suitability of Q9
- Highlights the importance of having clear guidance on how equivalent clouds should be used in ERA
- Ongoing JIP AIRRE looking at ways of updating and improving equivalent cloud approaches
- “better guidelines are required to avoid arbitrary results depending on the settings defined by individual users of the CFD software”, Skjold et al. [6]
Key Issues Associated with use of Equivalent Clouds
Model Sensitivity & User Variability

- Significant model and user-induced variability for predictions of overpressure for ignited homogeneous clouds
- Factor of 23 variation in predictions across all models/users for vented H₂ deflagrations
- Model sensitivity for natural gas simulations has been shown to be much smaller [7]
- Blind-prediction study for full-scale NG explosions in congested modules needed to assess user effect
Pre-Ignition Turbulence

• Pre-ignition turbulence can significantly affect overpressures generated in gas explosions

• For highly congested scenarios, the effect is modest in comparison to the turbulence generated by obstacles during the explosion \[^6\]

• For moderate levels of congestion, e.g. BFETS, it is important that turbulence generated by the release is accounted for in any explosion model

• A consistent methodology and/or clearer guidance on how to include the effects of pre-ignition turbulence in an ERA is needed
Pre-Ignition Turbulence

- BFETS Phase 3B data
  - Significant scatter for ignited jet release scenarios
  - Trend for increase in overpressure with increasing homogeneous gas cloud volume
  - Jet release cases give higher overpressure than homogeneous stoichiometric cases with similar Q9 volume
Pre-Ignition Turbulence

- Hansen et al.\textsuperscript{[5]} study illustrates that including pre-ignition turbulence gives more conservative results when using Q9.
- Tolias et al.\textsuperscript{[8]} showed that FLACS-predicted overpressure in uniform H\textsubscript{2} clouds varied by a factor of 2.5 as a result of changes (within the user guidelines for the model!) to initial turbulence length scale.
- The FLACS User Manual \textsuperscript{[3]}, Hansen et al.\textsuperscript{[5]} paper, NORSOK Z-013 \textsuperscript{[1]} and Lloyds Register \textsuperscript{[2]} guidance all suggest including pre-ignition turbulence in an ERA study.
- None of these documents says how, yet it is clear that it can have a significant impact on model predictions.
Conclusions of Q9 Review
Conclusions

- The Q9 method is an engineering approach designed for use within the framework of a probabilistic ERA.
- Use of equivalent cloud methods are based on assumptions that:
  - The explosion model used can accurately predict overpressure in homogeneous stoichiometric clouds.
  - The scaling between inhomogeneous and equivalent stoichiometric clouds gives volumes generating similar overpressures.
- Neither assumption is valid consistently, with evidence for and against each.
Conclusions

• Published research demonstrates that inconsistent results can be produced by different experts undertaking ERA

• There is a strong reliance upon expert judgment in the process with detailed modelling choices made regarding:
  – Choice of equivalent cloud method
  – Pre-ignition turbulence
  – Choice of cloud size categories and locations
  – Choice of ignition locations
  – Ignition probability modelling
  – CFD model set up – e.g. grid resolution

• Improved guidance is needed to reduce the inconsistency across studies
Next Steps & Potential Future Work
Aims of future work on the topic should focus on:

- Characterising the level of uncertainty in probabilistic ERA studies
- Reducing model sensitivity and user variability
- Developing clearer guidance and good practice guidelines for undertaking probabilistic ERA
- Working towards providing greater transparency in the ERA process to harmonize approaches/results

A possible way forward would be a JIP involving consultants, model developers and regulators to undertake an ERA inter-comparison exercise.

A similar exercise was performed nearly 20 years ago[^9] in the Norwegian sector.
References


References


Questions?