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SHELTER MODELS FOR CONSEQUENCE ANALYSIS AND RISK ASSESSMENT OF CO$_2$ PIPELINES

J.M. Race$^a$, K. Adefila$^a$, B. Wetenhall$^b$, H. Aghajani$^b$, B. Aktas$^b$

$^a$ Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde
$^b$ School of Marine Science and Technology, Newcastle University
Requirement for a shelter model

Description of models developed
  – Analytical model
  – Computational Fluid Dynamics (CFD) model

Model validation – single room

Sensitivity study

Effect of partitions and half height clouds

Conclusions and recommendations
What is the CCS transportation challenge?

To transport anthropogenic CO$_2$ of varying composition from multiple capture sites (power plant and industrial) to multiple storage sites in a safe, reliable and efficient manner in compliance with appropriate design standards and regulatory requirements.
Consequences of CO$_2$ pipeline failure

• CO$_2$ is not explosive or inflammable like natural gas and is odourless.
• CO$_2$ is denser than air and might accumulate in depressions or valleys.
• CO$_2$ is toxic and above concentrations of ~10% can have long term effects or cause fatality.

Therefore

• Need to be able to calculate CO$_2$ concentrations around a failure in order to define separation distances from pipelines using a Quantitative Risk Assessment approach.
• Requires a pragmatic infiltration model to predict effect CO$_2$ exposure on humans in buildings.
Consequences of CO$_2$ pipeline failure

- CO$_2$ concentration profile outside the building
- CO$_2$ concentration profile within the building
Analytical model description

- Based on the principles of natural building ventilation (Etheridge and Sandberg, 1996).
- Model described in outline in Lyons et al 2015 and in detail in future publications.
- Considers wind driven and buoyancy driven air flow.

**Assumptions:**
- Initial concentration of CO$_2$ in building is same as atmosphere.
- Building is engulfed in a cloud of CO$_2$ following a release.


Air flow – wind driven

- Wind blowing outside.
- Pressure difference between internal and external environments.
- Air flows from high to low pressure - in at front face, out at rear.
- Air flow straight through building.
Air Flow – buoyancy driven

In the absence of a release:

- Increased internal air temperature reduces internal air density.
- Steeper pressure gradient outside the building than inside (as density is greater outside).
- Creates pressure difference across openings at top and bottom of building.
- Warm, less dense air leaves and is replaced by colder more dense air at base, with upward drift of warmer air inside.
Based on conservation equations for mass, momentum, energy and chemical species

$k - \epsilon$ turbulence model was corrected to incorporate the effect of buoyancy driven flows with low Reynolds number

Four different models tested - Lag Elliptic Blending (EB) $k - \epsilon$ model gave best results relative to the experimental data

Meshed using polyhedral mesh within solution domain with a prism layer mesher used to improve the CFD simulation in near-wall regions
Model input data

**Cloud conditions**
- CO₂ concentration profile
- Temperature profile

**Atmospheric conditions**
- Wind speed
- Wind incident direction
- Internal temperature
- Internal CO₂ concentration

**Building geometry**
- Area of openings
- Spacing of openings
- Volume of building
Model comparison – single room totally engulfed

Room dimensions: 6x6x3m
Wind speed = 5m/s
Window area = 0.02905m²
Initial internal temperature = 293K
Toxic dose

• A generalised equation for toxic dose of exposure to some contaminant is given by:

\[ D = \int c(t)^n \, dt \]

Where
- \( c(t) \) is the concentration of the contaminant a person is exposed to in parts per million (ppm),
- \( t \) is the time of the exposure in minutes
- \( n \) is the toxic index = 8 for CO\(_2\)

• Dangerous Toxic Loads
  - The Specified Level of Toxicity (SLOT). The SLOT dose for CO\(_2\) is 1.5 x 10\(^{40} \) ppm\(^8\)min.
  - The Significant Likelihood of Death (SLOD). The SLOD dose for CO\(_2\) is 1.5 x 10\(^{41} \) ppm\(^8\)min.
Model comparison – single room totally engulfed

Room dimensions: 6x6x3m
Wind speed = 5m/s
Window area = 0.02905m²
Initial internal temperature = 293K
Sensitivity study – wind speed dependence

Room dimensions: 6x6x3m
Wind speed = variable
Window area = 0.02905m²
Initial internal temperature = 293K
Partitions and half height clouds

- Room dimensions: 6x6x6m
- Wind speed = 5m/s
- Window area = 0.02905m² for each window
- Initial internal temperature = 293K

**Graph:**
- CFD analysis - top floor
- Analytical model - top floor
- CFD analysis - bottom floor
- Analytical model - bottom floor

**Graph Details:**
- CO₂ concentration within the building (%)
- Time from release event
Conclusions

- Two shelter models have been developed as part of this work; an analytical and a CFD model.
- The models compare favourably with experimental test data.
- It has been demonstrated that the ability of buildings along a pipeline route to provide shelter can be determined using these models.
- The wind speed has been shown to have the greatest impact on concentration profiles within the building.
Conclusions

- Calculations have been conducted for worst case direction.
- SLOD times would be different (and less severe) for different directions throughout the cloud.
- In conducting a full QRA a failure frequency analysis would be incorporated with these results to calculate the risk at any particular location.
- However, it has been shown that dose received by an individual in a building would not reach the levels of toxicity experienced in shelter were not considered.
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