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Dense gas dispersion for LNG plant

…. some recent findings

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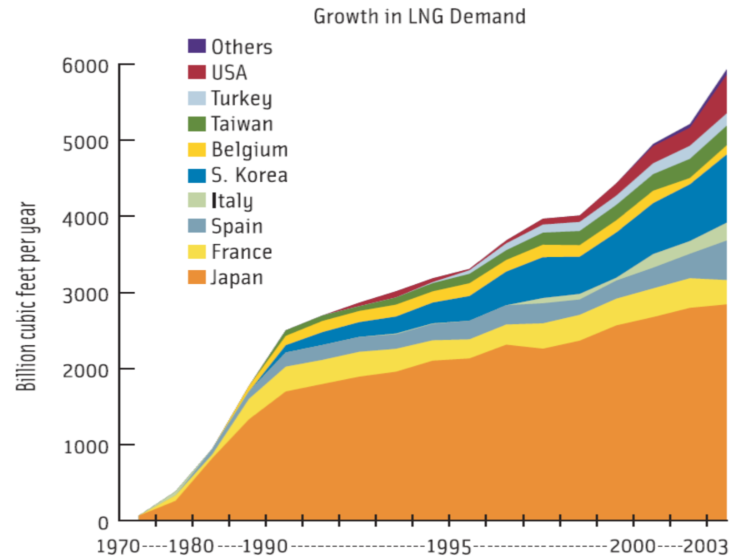
Plan Design Enable

Overview

- Introduction
- Dense gas dispersion – why is this unusual?
- What does "validation" mean ...
- How well does CFD model dense gas dispersion?
- Conclusions … ending with a question

Introduction – context for this talk

- Liquefied Natural Gas (LNG) is a booming market now.
- Large numbers of LNG plant are in design & construction around the world.



Introduction – context for this talk

- Assessment is required of these plant to gauge hazards to:
  - personnel working on the plant
  - public beyond the plant perimeter
  - the plant itself
- Wide range of consequence modelling is undertaken:
  - typically with integral or "box models"
  - … but increasingly with CFD.

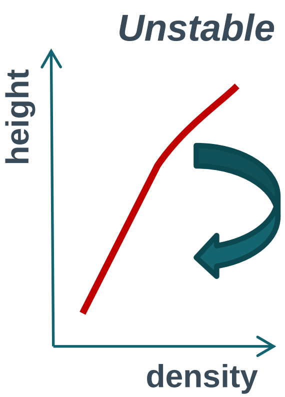
Introduction – context for this talk

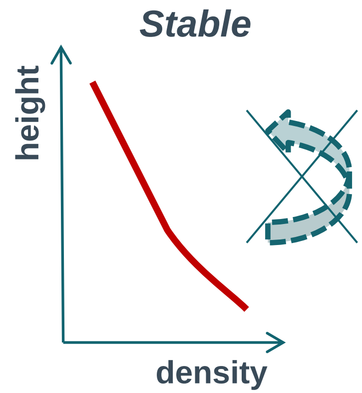
- In an LNG plant, there are large inventories of cold and heavy gases
- So many of the accidental releases are dense vapours:

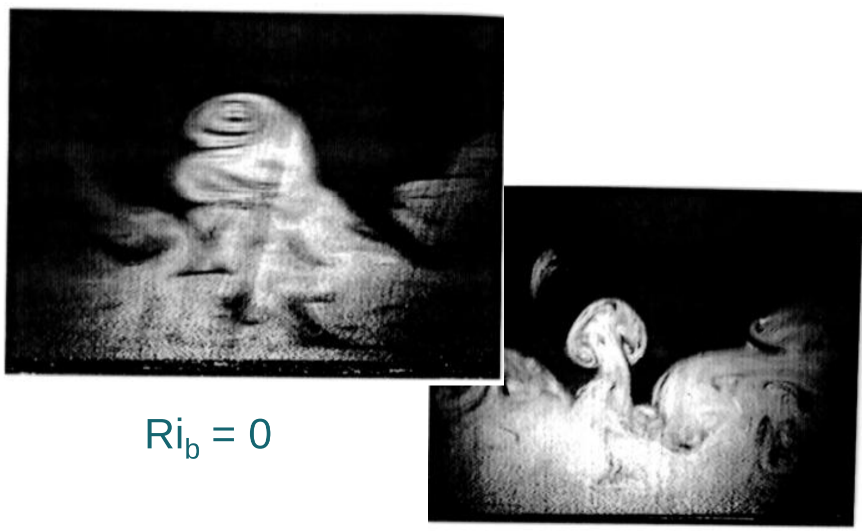
Material	Temperature	Molecular weight (kg/kmol)	Specific gravity (cf. ambient air)
LNG	~ -162ºC	18.5	1.7
LPG	~ -42ºC to -1ºC	44 – 58	2 – 2.2
Refrigerant	e.g. -50ºC	e.g. 30	1.4

Dense gases – why so special?

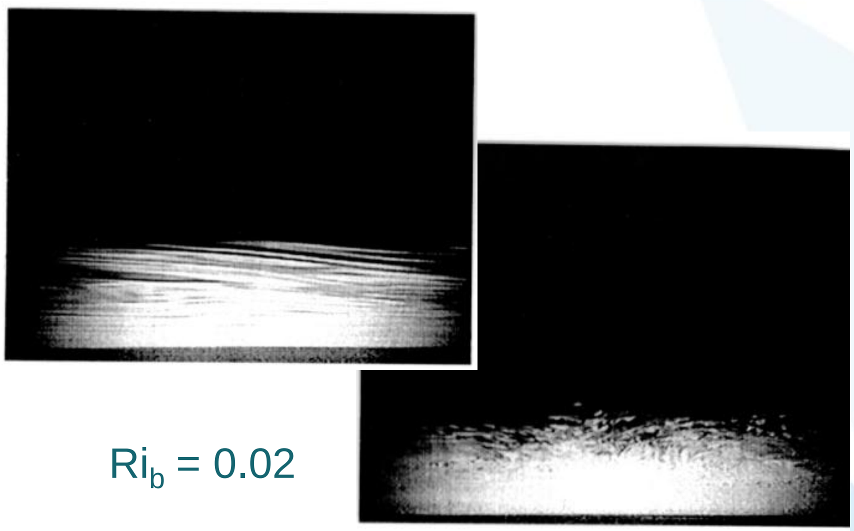
- Density gradients in a flow can have significant impact on the turbulence in the flow:







$Ri_b = 0$



$Ri_b = 0.02$

Cowan & Britter (1994)

Stable stratification – energy sink term

- Energy budget (with boundary layer approximation):

TKE

$$\frac{\partial \frac{1}{2}\overline{q^2}}{\partial t} = \mathcal{P} - \mathcal{B} - \mathcal{E} - \mathcal{A} - \frac{\partial}{\partial y}\left(\frac{1}{2}\overline{q^2 v} + \frac{\overline{pv}}{\rho_0}\right)$$

Shear production

Buoyancy sink

Viscous dissipation

Advection

Diffusion

$\mathcal{P} = -\overline{uv}\,\partial \bar{U}/\partial y$ is the production term

$\mathcal{B} = g\overline{\rho v}/\rho_0$ is the buoyancy consumption term

$\frac{1}{2}\overline{q^2} = \frac{1}{2}\overline{u_i^2}$ is the turbulent kinetic energy

Stable stratification – energy sink term

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- Energy budget (with boundary layer approximation):

TKE

$$\frac{\partial \frac{1}{2}\overline{q^2}}{\partial t} = \mathcal{P} - \mathcal{B} - \mathcal{E} - \mathcal{A} - \frac{\partial}{\partial y}\left(\frac{1}{2}\overline{q^2 v} + \frac{\overline{pv}}{\rho_0}\right)$$

Horizontal Re stress

$$\frac{\partial \frac{1}{2}\overline{u^2}}{\partial t} = \mathcal{P} + \Psi_{11} - \mathcal{E}_{11} - \mathcal{A}_1 - \frac{\partial \frac{1}{2}\overline{u^2 v}}{\partial y}$$

Vertical Re stress

$$\frac{\partial \frac{1}{2}\overline{v^2}}{\partial t} = -\mathcal{B} + \Psi_{22} - \mathcal{E}_{22} - \mathcal{A}_2 - \frac{\partial}{\partial y}\left(\frac{\overline{v^3}}{2} + \frac{\overline{pv}}{\rho_0}\right)$$

$\mathcal{P} = -\overline{uv}\,\partial \bar{U}/\partial y$ is the production term

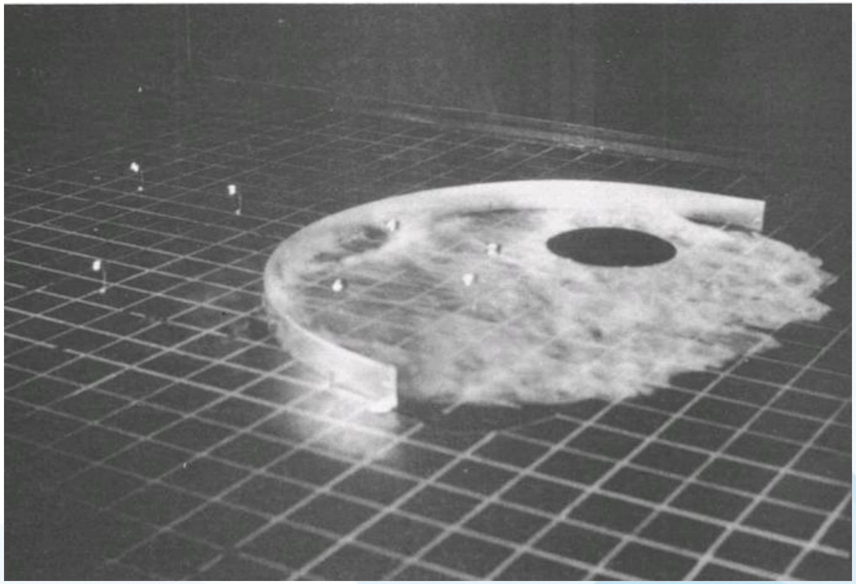
$\mathcal{B} = g\overline{\rho v}/\rho_0$ is the buoyancy consumption term

$\frac{1}{2}\overline{q^2} = \frac{1}{2}\overline{u_i^2}$ is the turbulent kinetic energy

- Anisotropy increases with stability : ⇩ $-\overline{uv}\,/\,k\ (\sim C_\mu^{1/2})$

Research in dense gas dispersion

- Is prodigious and long-established!
- For example (to name just a few):
  - Britter (1974), McQuaid (1976)
  - Maplin Sands and Burro full-scale trials (1980)
  - Wheatley & Webber review (1985)
  - Britter McQuaid workbook, HSE (1988)
  - König-Langlo & Schatzmann wind tunnel tests (1990)
  - Cleaver review paper (2007)
  - Ivings et al (2007) HSE report

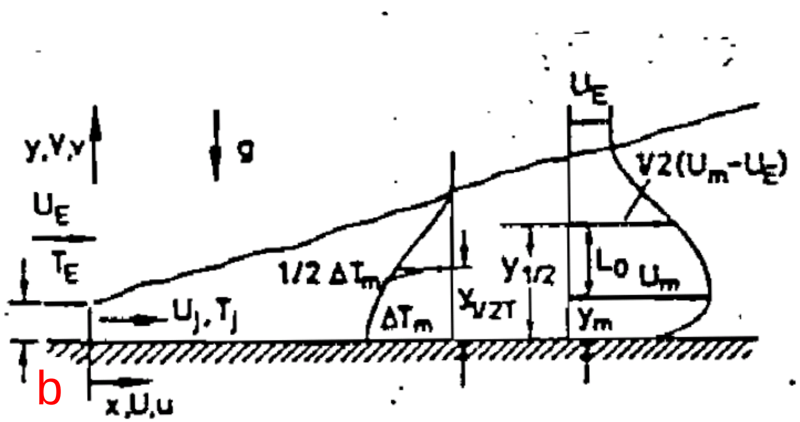


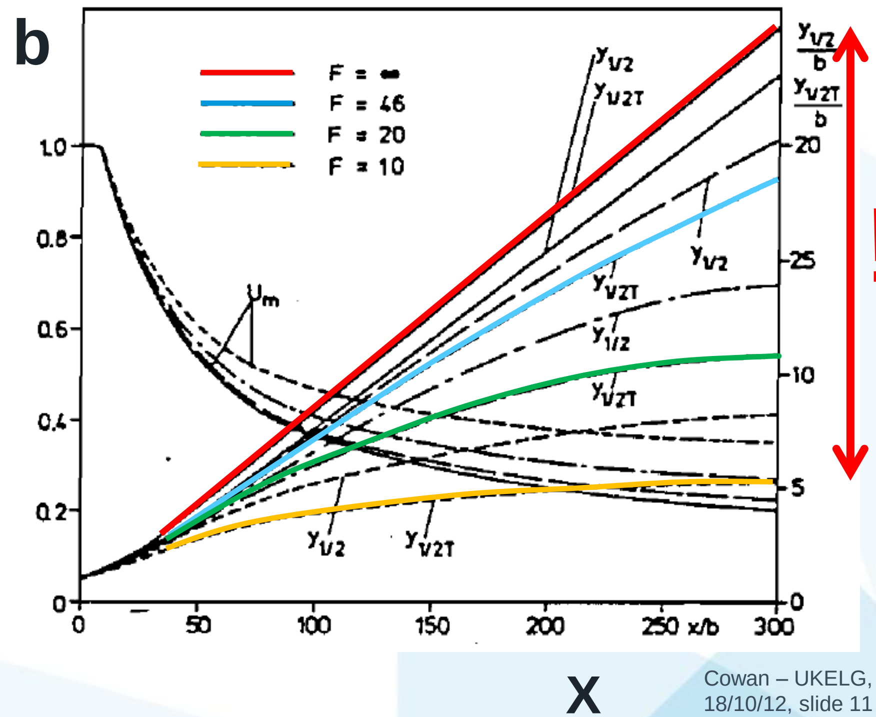
What does “validation” mean?

- Press article from one of the Commercial CFD code vendors:
  - Code X has been “validated” against 33 dense gas experiments
  - Scenarios that can be modelled using X include … dispersion from LNG spills
- This code is based on a simple linear-EVM k-epsilon turbulence closure model.
- Validated?
- Really?

Simple test case

- Ljuboja and Rodi (1980)
  - 2D jet spreading along a wall – lab tests
  - Isothermal (constant density) case:
    - similarity arguments – can prove: b ~ X
  - Increasing stability:
    - reduced turbulence levels
    - reduced entrainment
    - reduced spreading rate

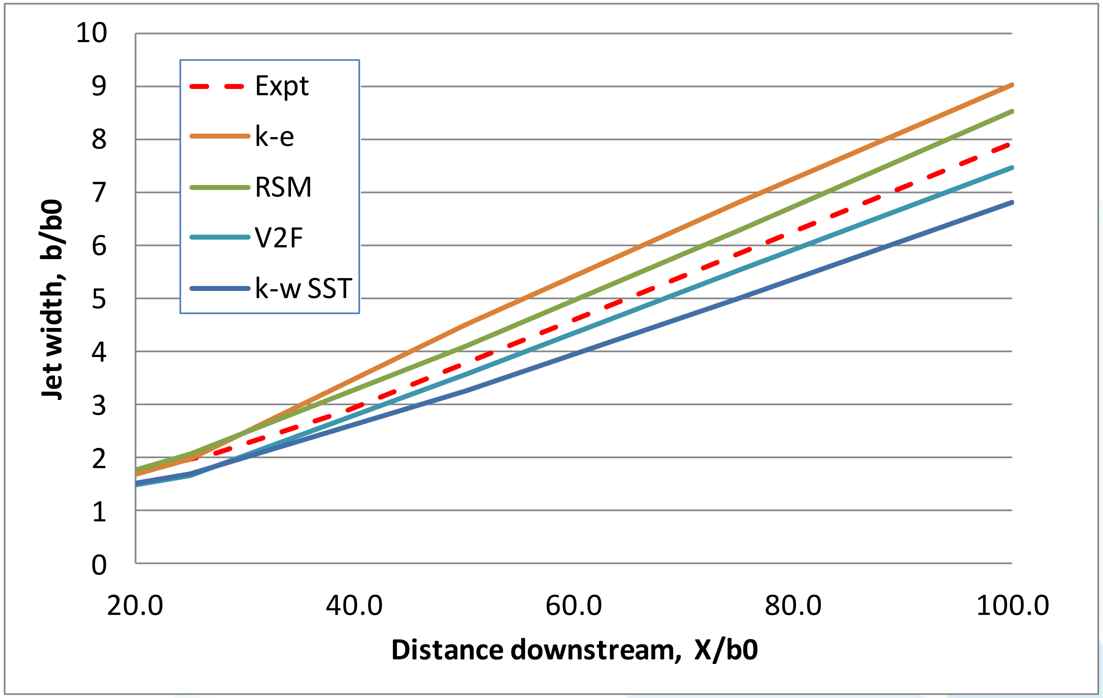




Can CFD reproduce this?

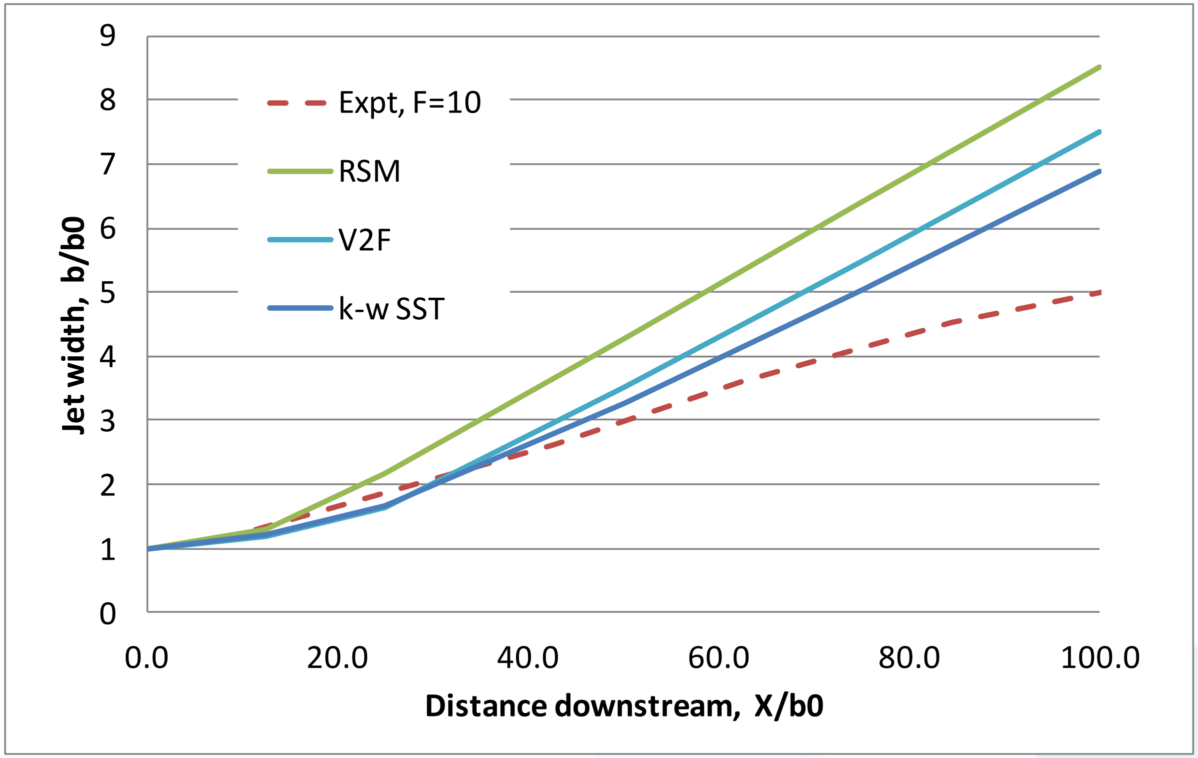
- Start with isothermal case
  - actually fairly challenging
  - presence of wall damps vertical turbulence
  - linear growth well captured, though
  - results broadly acceptable

Closure scheme	Spread rate cf. expts
Std k-ε	+22%
Non-lin. k-ε	+15%
RSM	+15%
V2F	+3%
k-ω SST	-5%



Can CFD reproduce this?

- How about stably stratified cases?
- All available closure models in commercial CFD codes: unabashed linear jet growth.
- Significant under-prediction of hazards from this scenario.
- None can reproduce the “stabilising” effect of the stratification.
- Why?



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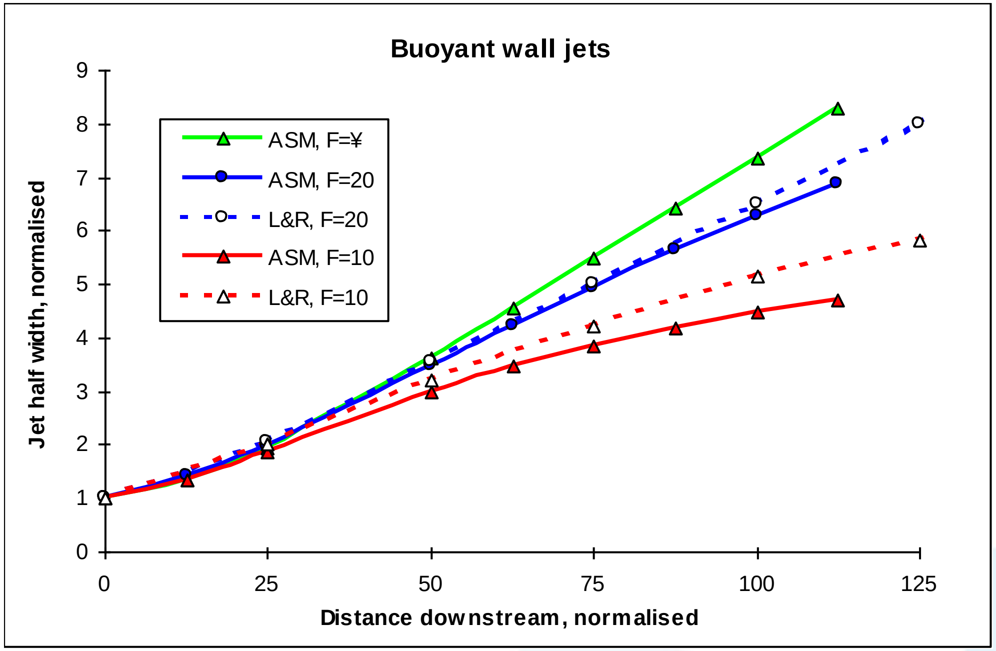
Why is CFD struggling here?

- Standard turbulence closure models are missing the key physics
- … the stabilising effect of the dense gas.
- Closure model needs to:
  - Allow for anisotropy
  - Reduce vertical diffusivity
  - Dampen turbulence production rate
- These features are not present in standard isotropic gradient diffusion eddy viscosity models.

Why is CFD struggling here?

- Solutions:
  - Algebraic stress model is a cheap way forward:
    - eddy viscosity model with constants (C_μ, σ_t etc) that change with stability – e.g. Ljuboja & Rodi (1980)
  - Full Reynolds stress model (6 stresses + 3 scalar fluxes)
- Also, but impractical:
  - LES (but not DES … unless based on above ASM)



Conclusions

- Standard CFD closure models cannot reproduce the stabilising effect of density gradients.
- These will provide non-conservative predictions of gas concentration in the mid to far-field.
- For correct prediction:
  - an advanced closure model must be used,
  - that accounts for turbulence anisotropy
  - and the dampening effect of stability.
- None of the commercial codes currently provide this.
- Despite this, some codes are “validated” for these flows – what does this mean?