Mixing Processes in High-Level Waste Tanks

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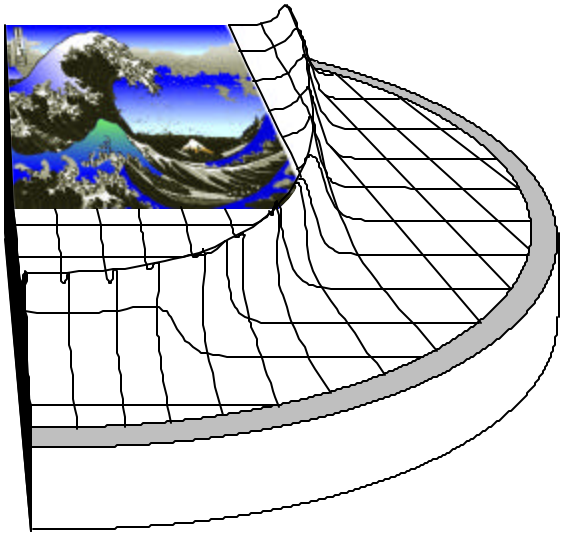


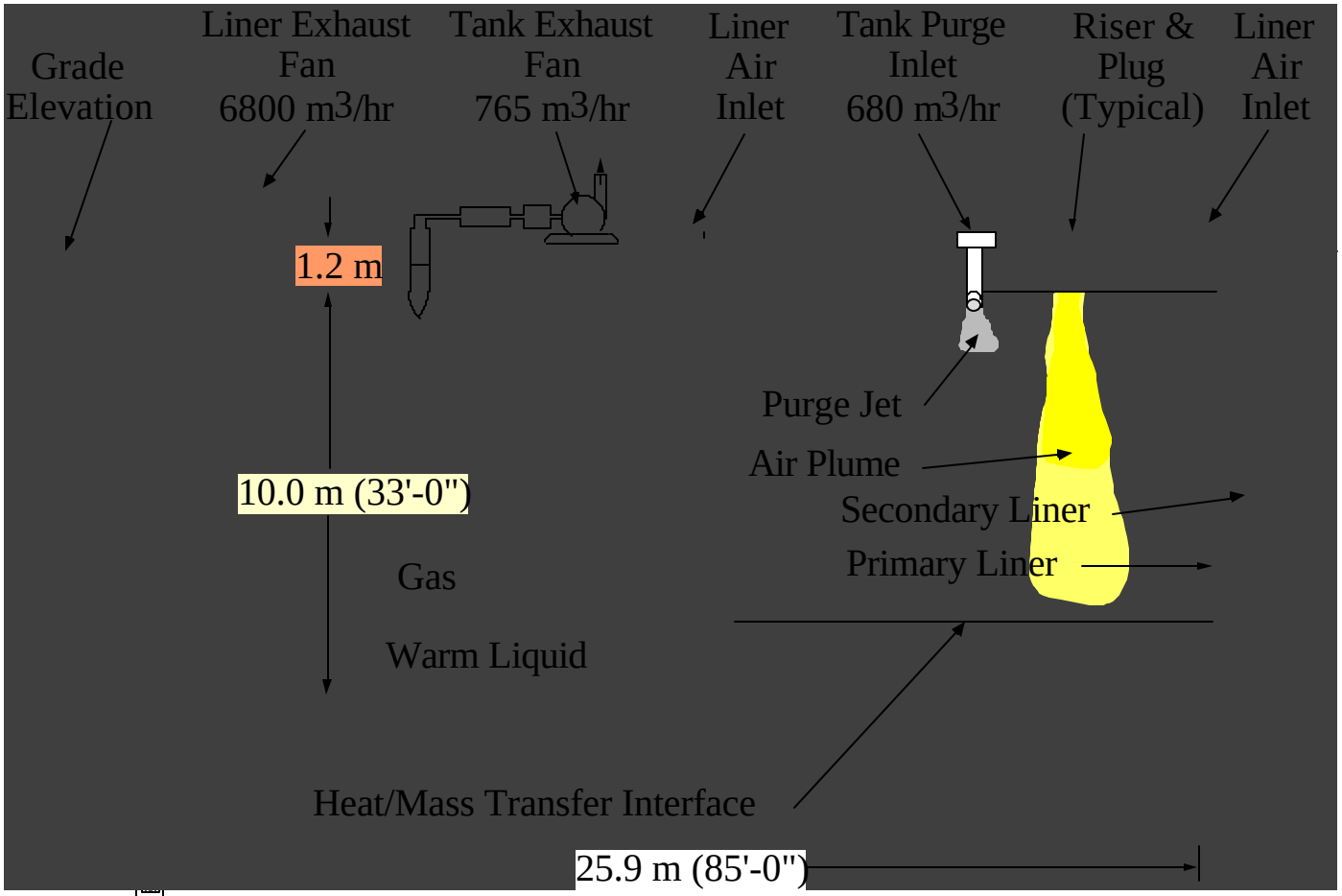
Environmental Management Science Program Workshop, April 24-27, 2000

- **Introduction**
- **Ceiling Air Ingress**
- **Mixed Convection from High-Velocity Purge Jets**
- **Modeling of Transient Density Evolution**

Introduction

- **Flammible gases can be produced in high-level radioactive waste tanks**
  - **Radiolytic hydrogen**
  - **Benzene (from cesium processing activities)**
- **UCB is studying the processes for mixing of flammible gases, to allow modeling of maximum concentrations**
- **Major topics:**
  - **Mass transfer and mixing augmentation by injected purge jets**
  - **Buoyancy-driven air exchange through tank roof**
  - **Modeling of stratification of heavy gases (benzene) following loss of ventilation**
- **Extrapolates from previous research for enclosure fires and reactor containments**

Cross Section of Typical Type IIIA SRP Waste Tank

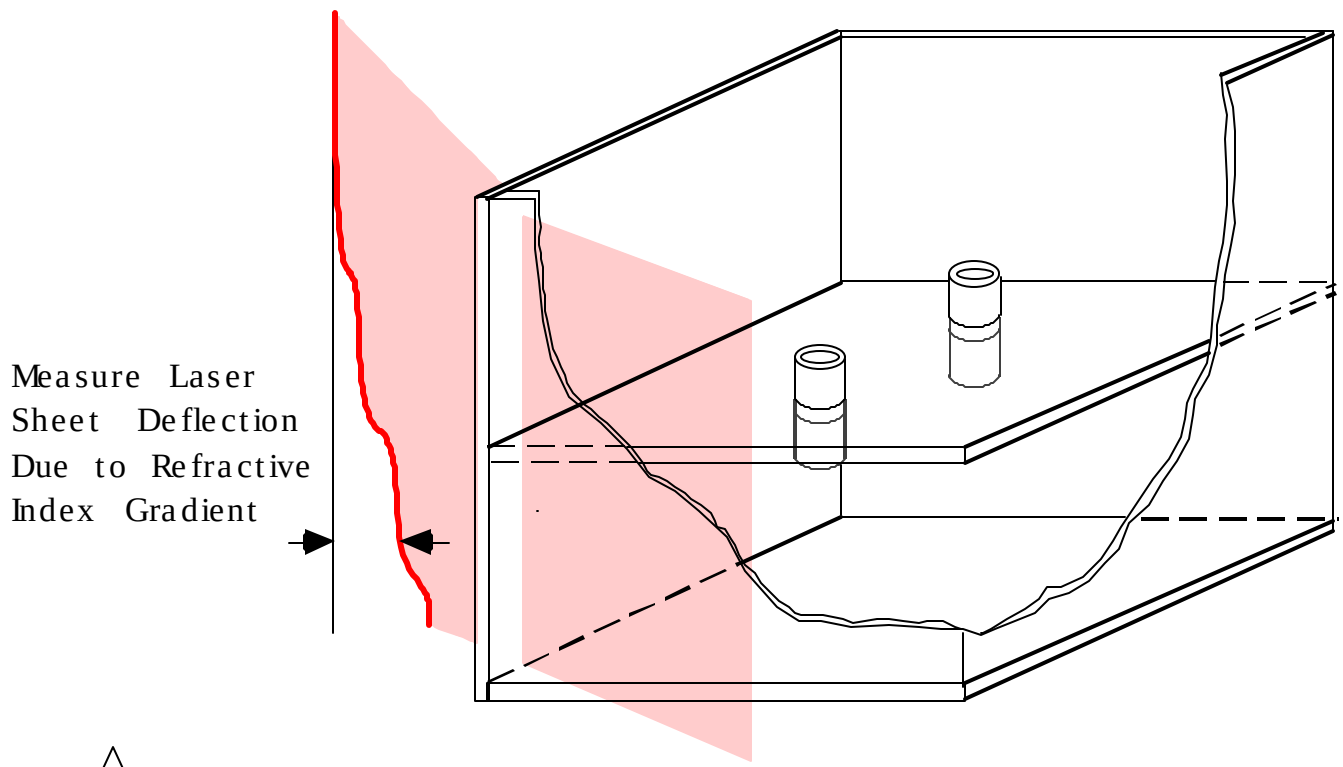


Exchange Flows Through Horizontal Partitions

- Buoyancy and wind-driven pressure oscillations drive air ingress into inerted tanks following loss of ventilation
- Previous experiments had incorrectly measured ingress rates, suggesting simple models were incorrect
- UCB developed laser diagnostic technique to measure transient ingress rate and density evolution
- Simplest models for exchange flows found to work well; suggests that current modeling of waste-tank loss-of-ventilation events is accurate

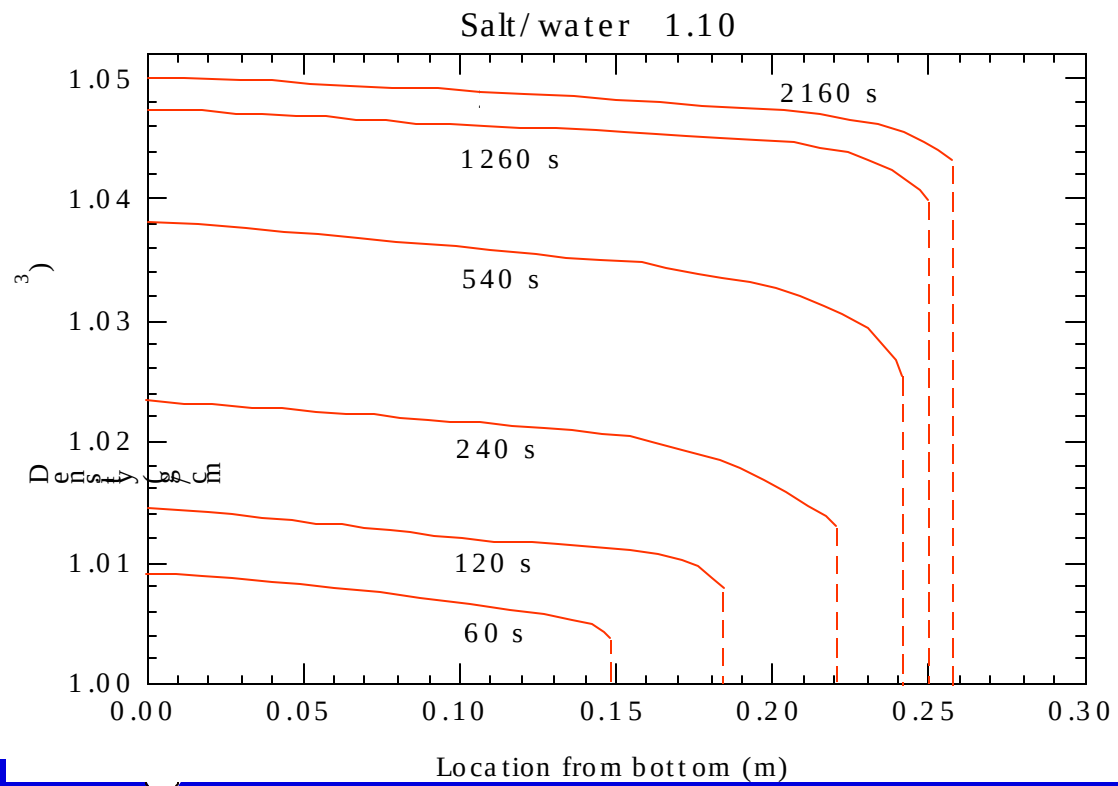
Exchange Flow Experiments

- **Experiments with dyed salt water and fresh water to study buoyancy driven exchange flows through perforated horizontal partitions**



Laser Diagnostics

- **Developed new method to use laser sheet to measure vertical refractive index (i.e. density) distribution**
- **Previous experiments have measured only the surface density, giving inaccurate results**
- **Typical results:**



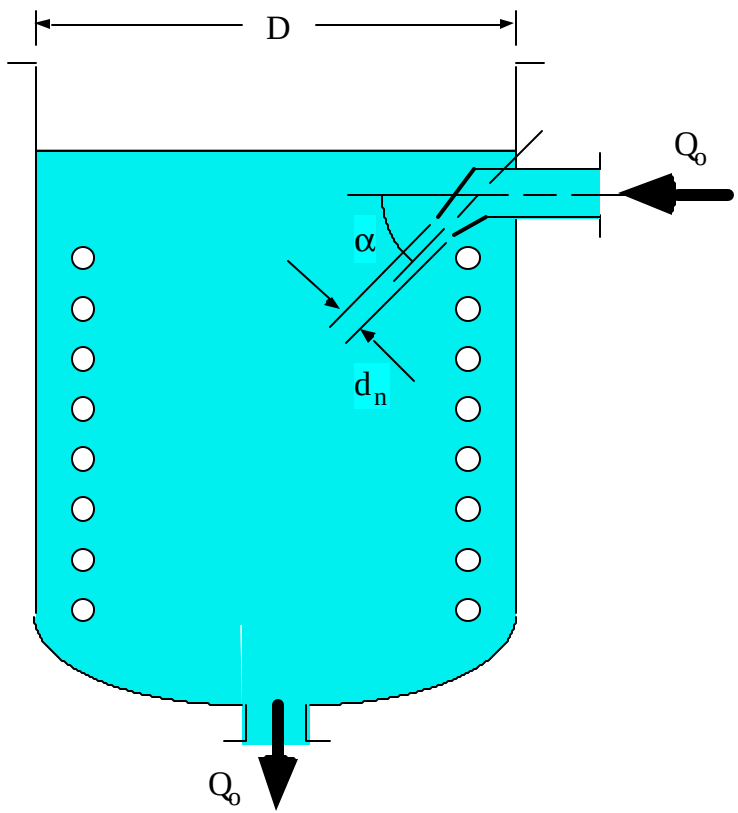
Forced Convection in Jet-Agitated Enclosures

- Important for understanding benzene/hydrogen mass transport from liquid surface in inerted tanks
- Chemical process industry experience
  - jacket and helical-coil heat exchangers for heating and cooling fluids in agitated tanks.
- Paddles and propellers most commonly studied due to higher mechanical efficiency
- However, agitation by injected jets has also been studied for mixing and for heat-transfer augmentation

Hsu and Shih Correlation

$$\mathrm{Nu}_{Df} = \frac{h_f D}{k} = f\,\mathrm{Re}_{d_n}^{0.65}\,\mathrm{Pr}^{0.37}\left(\frac{d_n}{D}\right)^{0.09}\left(\frac{m_w}{m}\right)^{-0.14}$$

- **Study average helical-coil heat transfer in a jet-agitated tank**
- **Studied several liquids**
- **Weak effect of nozzle diameter d_n to tank diameter D ratio**
- **Weak effect of jet orientation**
- **Re coefficient 0.65 matches most values found for paddle-agitated vessels**



Jet diameter/orientation

- **Effect is weak: Hypothesize average Nu depends on enclosure bulk velocity induced by jet**
- **For bulk scales use jet velocity/diameter impacting wall**
  - **Velocity Scale**
    - » **Jet entrainment:** $\frac{Q - Q_o}{D} = a_T \sqrt{8p\,M}$
    - » **Jet momentum flux:** $M = \frac{p\,d_w^2 U_w^2}{4} = \frac{4Q^2}{p\,d_w^2} = \frac{p\,d_n^2 U_o^2}{4} = \frac{4Q_o^2}{p\,d_n^2}$
    - » **Re at wall:** $\mathrm{Re}_D = \frac{r\,U_w D}{m} = \frac{r\,U_o d_n / m}{4\sqrt{\frac{2}{p}}\,a_T + \frac{d_n}{D}} = \frac{\mathrm{Re}_{d_n}}{4\sqrt{\frac{2}{p}}\,a_T + \frac{d_n}{D}}$
  - **Length Scale**
    - » **Jet diameter at wall** $\frac{d_w}{D} = 4\sqrt{\frac{2}{p}}\,a_T + \frac{d_n}{D}$ — **Small**
- **Jet Momentum—not KE—is most important**

Extension to Mixed Convection

- **Model transition to natural convection following loss of ventilation**
- **Assume form for mixed convection correlation**

$$\mathrm{Nu}_D = \left[\mathrm{Nu}_{Dn}^n + \mathrm{Nu}_{Df}^n\right]^{1/n}$$

- **Plug in jet correlation and standard natural convection correlation $\mathrm{Nu}_{Dn} = C\,\mathrm{Gr}^{1/3}$**

$$\frac{\mathrm{Nu}_D}{\mathrm{Nu}_{Dn}} = \left\{1 + C_2\left[\frac{\mathrm{Re}_{d_n}^{0.65}}{\mathrm{Gr}_D^{1/3}\,\mathrm{Pr}^{1/3}}\left(\frac{d_n}{D}\right)^{0.09}\right]^n\right\}^{1/n}$$

- **But the Archimedes Number $\mathrm{Ar}=\mathrm{Re}^2/\mathrm{Gr}$**

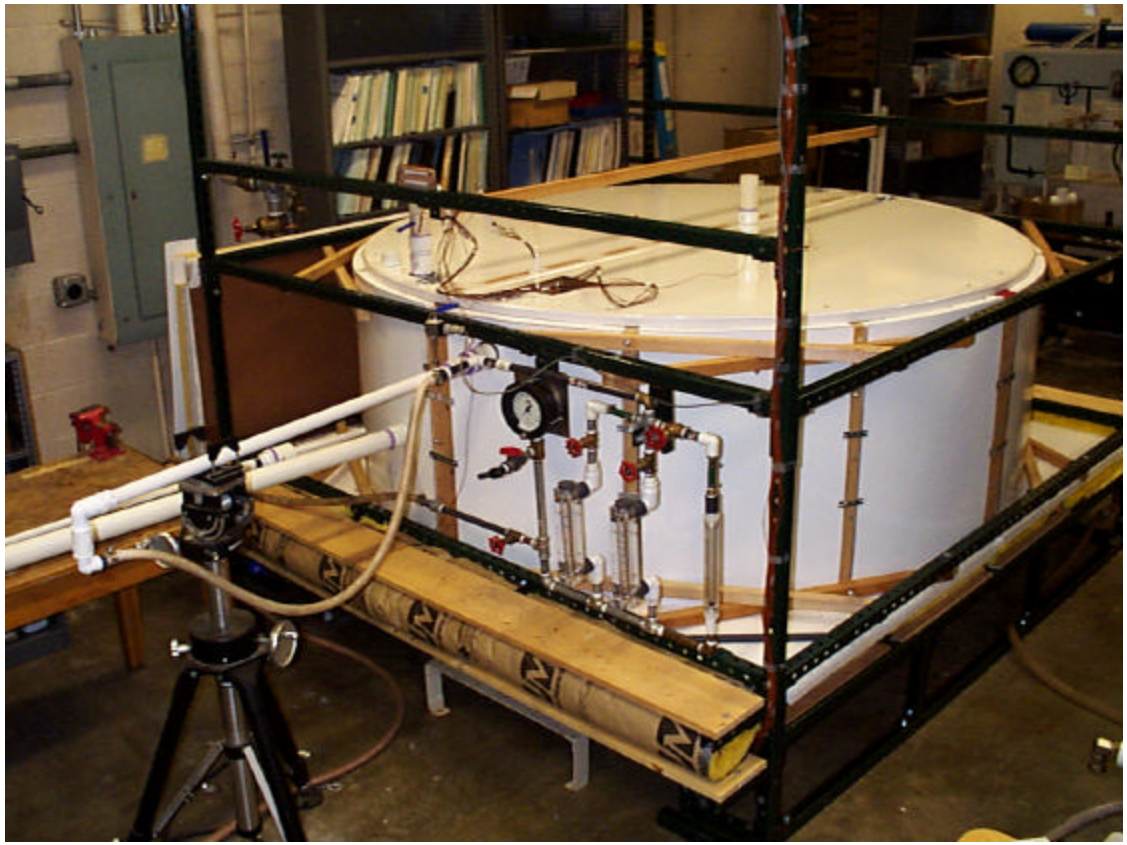
$$\frac{\mathrm{Nu}_D}{\mathrm{Nu}_{Dn}^n} = \left\{1 + C_2\left[\frac{\mathrm{Ar}^{1/3}}{\mathrm{Pr}^{1/3}}\left(\frac{d_n}{D}\right)^{0.09}\right]^n\right\}^{1/n}$$

Jet Mixing (1)

- **Jet diameter/orientation have little effect on average forced-convection augmentation**
- **Archimedes number is most important parameter**
  - **characterizes augmentation**
  - **previously shown to characterize onset of stratification**
- **Scaled waste-tank experiment to study forced/natural convection heat and mass transfer from horizontal surfaces in a cylindrical enclosure**

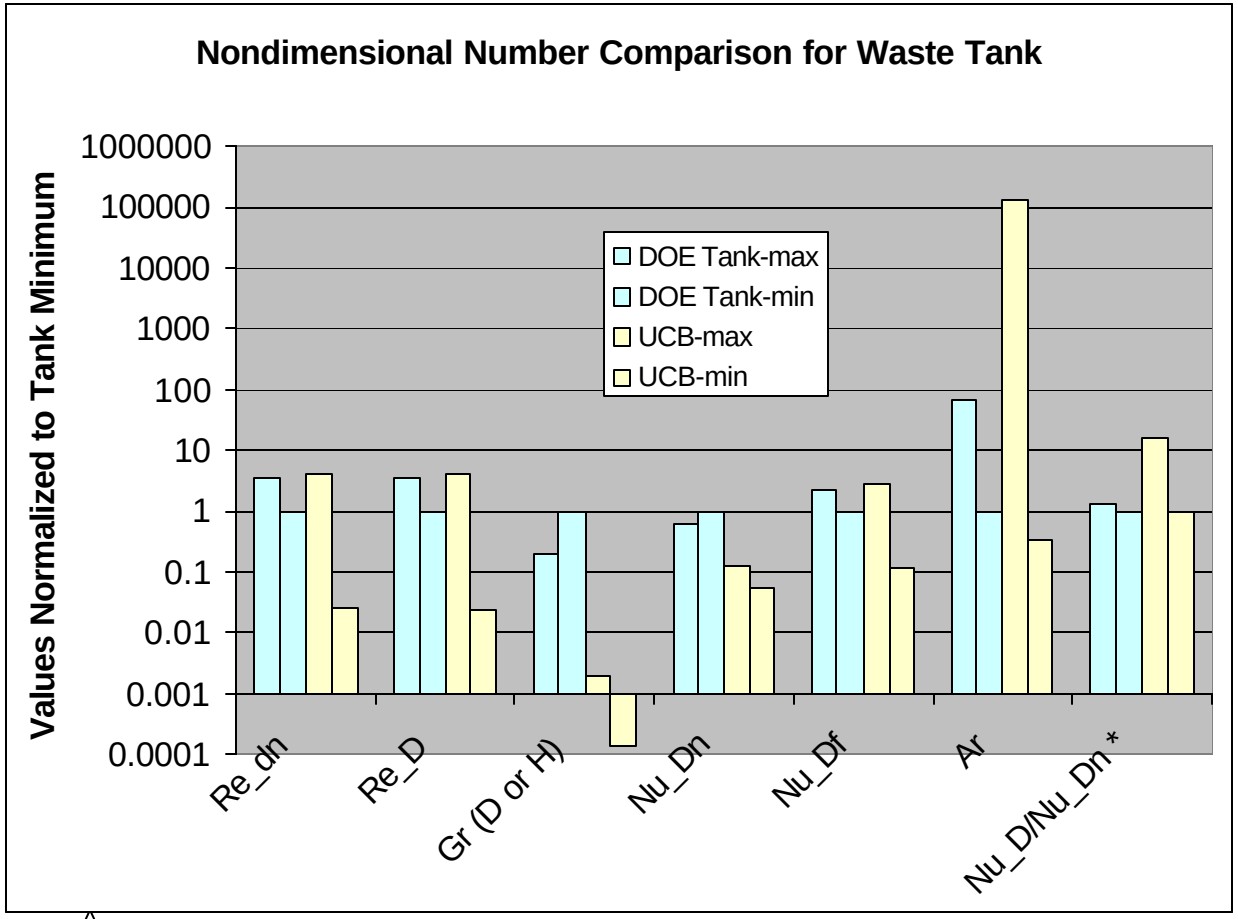
Jet Mixing (2)

Cylindrical Enclosure Experimental Setup



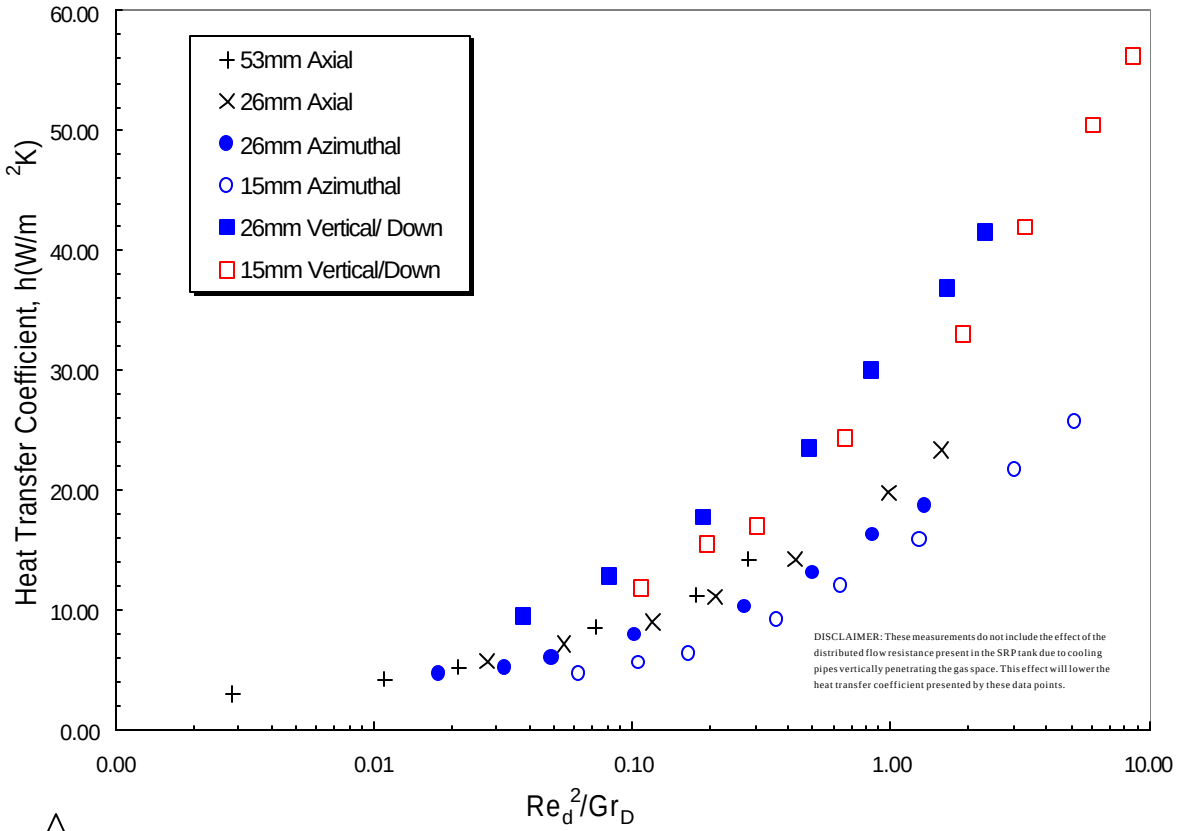
Jet Mixing (3)

Scaling for Cylindrical Tank Experiment



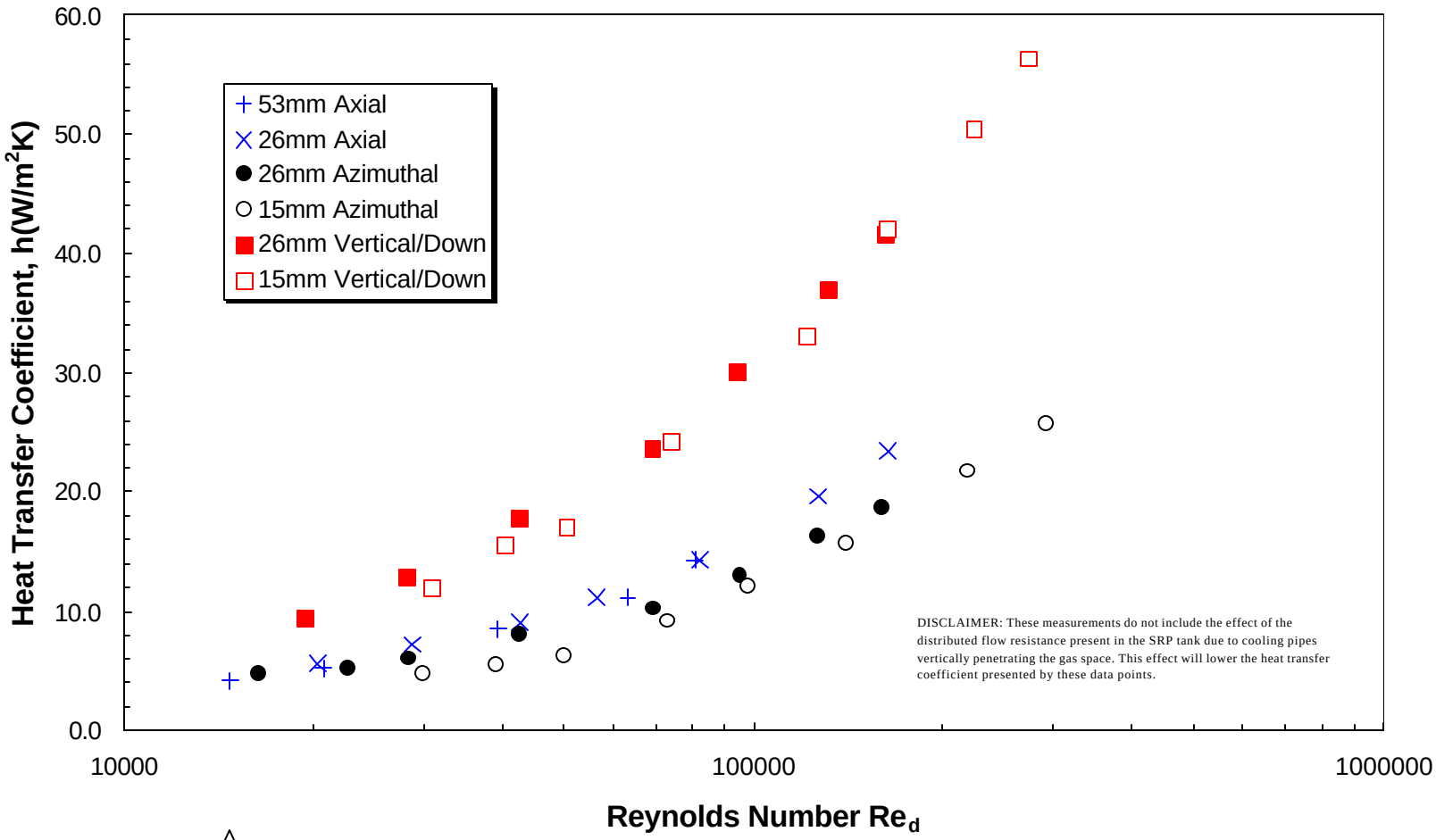
Jet Mixing (4)

Mixed Convection Augmentation Measurements

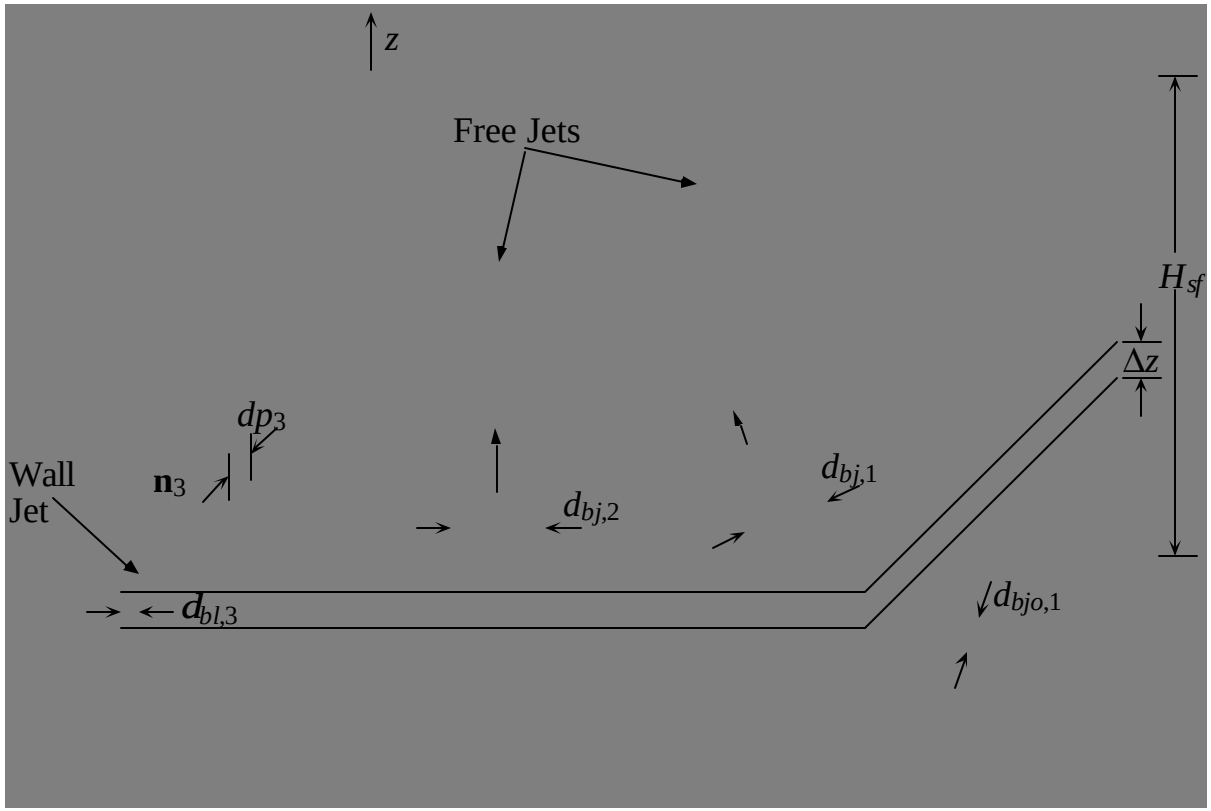


Jet Mixing (5)

Mixed Convection Augmentation Measurements



1-D/Zero-D Large Enclosure Modeling



Key Features (1)

- **Foundation from previous work**
  - **Zuber scaling methodology (see Peterson, *IJHMT*, 1996)**
  - **Enclosure Fire Modeling (Jalaria *et al*.)**
- **1-D Large Enclosure Model Fundamentals**
  - **Vertical gradients described by differential equations**
    - » **temperature, species concentration, density, turbulent kinetic energy and dissipation rate, aerosol concentration**
  - **Horizontal gradients small in ambient volume**
  - **Horizontal gradients in wall and free jets described by integral correlations**
    - » **Follows from Zuber method scaling, short residence times**
    - » **Better description than 3-D CFD can provide, due to grid size limitations**

Key Features (2)

- **Apply correct heat/mass transfer B.C.s at liquid surface and structures**
  - **Temperature, concentration, turbulent kinetic energy known at all elevations**
- **Apply 1-D k-e model in large enclosures**
  - **Turbulent kinetic energy sources/sinks**
    - » **Convected in by inlet flows (i.e. break flow)**
    - » **Generated by buoyancy in free plumes and wall jets**
    - » **Convected out by enclosure discharge flows**
    - » **Dissipated in ambient volume**
  - **Advantages of tracking vertical distribution of k and e**
    - » **Best estimate modeling of forced-convection augmentation of heat and mass transfer at surfaces**
    - » **Augment vertical mixing (another way to predict transition from mixed (zero-D) to stratified (1-D) conditions?)**

Key Features (3)

- **Key models/features**
  - **Quasi-incompressible stratified ambient model**
    - » **Lagrangian treatment to minimize numerical diffusion/permit front/pool surface tracking**
  - **Wall jet integral entrainment models**
    - » **vertical mixing by boundary layers on vertical cooling tubes**
    - » **turbulent kinetic energy generation, discharge elevation**
  - **Free jet entrainment models**
    - » **jet trajectory, impingement/discharge elevation**

1-D Enclosure modeling:

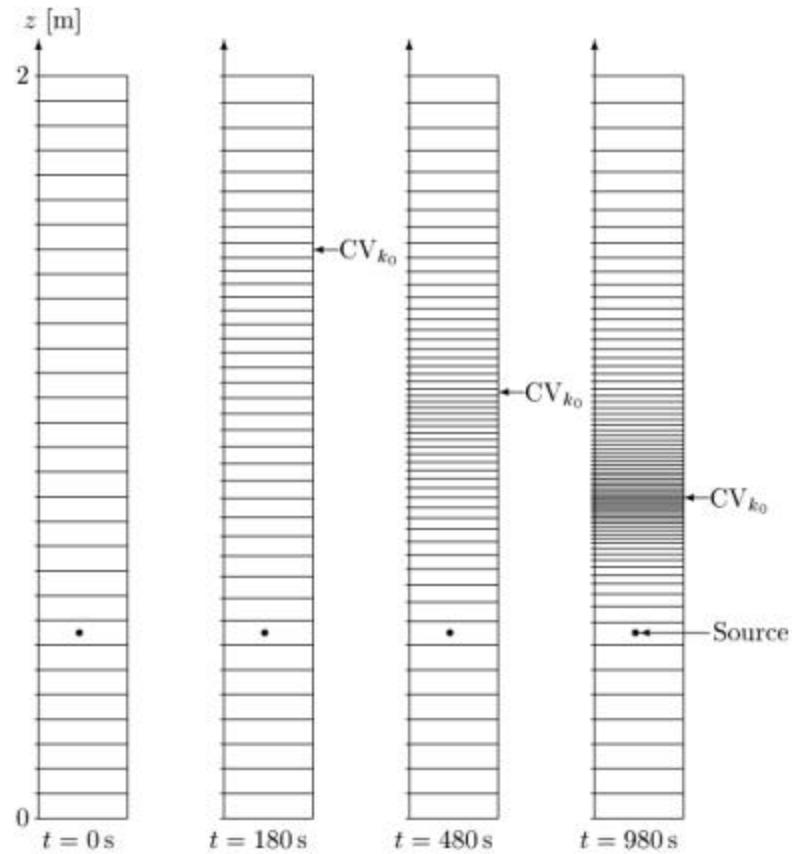
The BMIX code v1.0

First version in Matlab with features:

- ❑ Buoyant jets modeled by integral correlations.
- ❑ Lagrangian method eliminates false diffusion from the discretized equations.
- ❑ Gives physically acceptable solutions even for very coarse computational grids.
- ❑ Very lax stability requirement *independent* of spatial steplength.
- ❑ High accuracy with low computational cost.
- ❑ Arbitrary number of plumes and jets.
- ❑ Heat and mass diffusion included.
- ❑ Multi-component incompressible fluid.
- ❑ Accommodates varying cross-sectional area.

The BMIX code v1.0

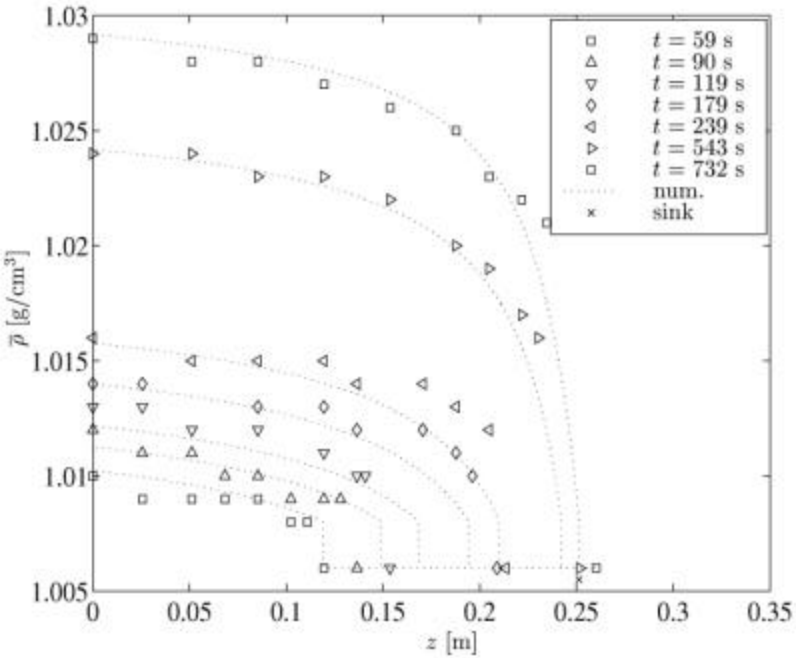
The numerical model illustrated on grid level.



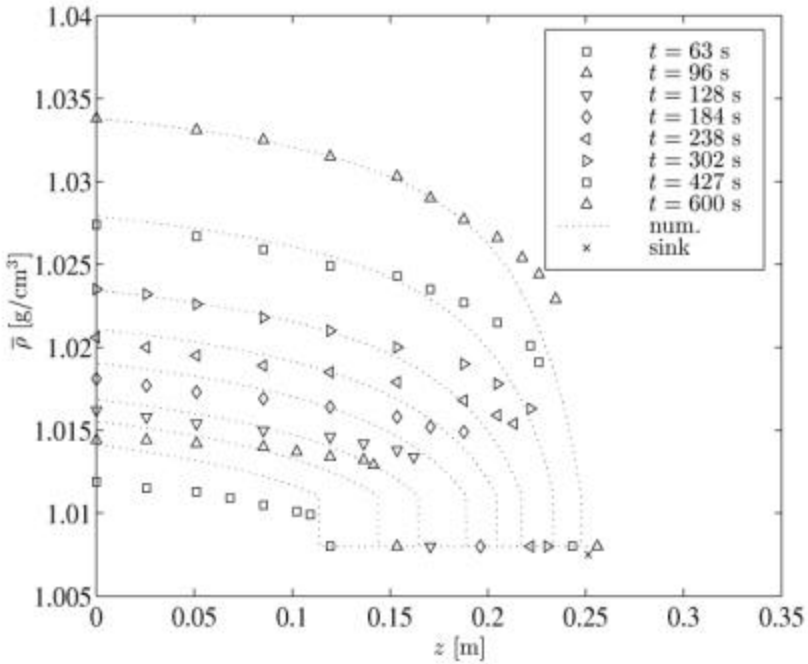
Movement of the warm front for a heat source in water.
The horizontal lines separate individual control volumes.

The BMIX code v1.0

Summary of salt/water flow exchange results



Predicted and experimental density distribution from water tank experient. Prediction generated with the Lagrangian BMIX code developed at UC Berkeley (54656).



Comparison of the numerical model with experimental data points for fixed flow rate with $Q_{in} = 11.19 \cdot 10^{-6}$ kg/s.

Conclusions

- Current results contribute to understanding of tank gas-space mixing processes and air infiltration
- 1-D treatment of a stratified enclosure has been shown to accurately predict the time wise evolution of species mass and energy.
- Ongoing work will focus on scaled tank experiments to study jet-induced forced-convection and heat/concentration induced natural convection mixing processes
- 1-D enclosure modeling work in progress to allow for compressible multi-component fluid and more complex modeling for the buoyant jets.