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Modeling a Rubble Fire Consisting of Comingled Liquid and Solid Fuel

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Outline

- Introduction
  - Rubble Fire Scenario Interest
  - Existing Modeling Methods
- Approach
  - CPD for particle reactions, multi-component particles for epoxy/fiber
  - VOF capability for liquid layer
  - Verification of the liquid layer model
  - Introduction of validation test problem
- Validation test problem for liquid layer model
  - Selected data comparisons
- Outline of continuing effort

Motivation

- September 2014 test designed to mimic an airplane crash fire environment
  - 14+ hours of flaming
  - Very slow heating
- Co-mingled liquid and solid fuel, no models exist
  - Rubble fire has been studied
  - Moving particles in a flow (fluidized bed) methods exist
  - Liquid fuel burning models are not very mature
- This work represents the inception of an effort to achieve predictive models for this type of fire condition

Rubble Fire Test Arrangement

Composite Rubble Fire Test

Assembly Time Lapse

9/4/14

Rubble Fire Test Video

What do the results mean?

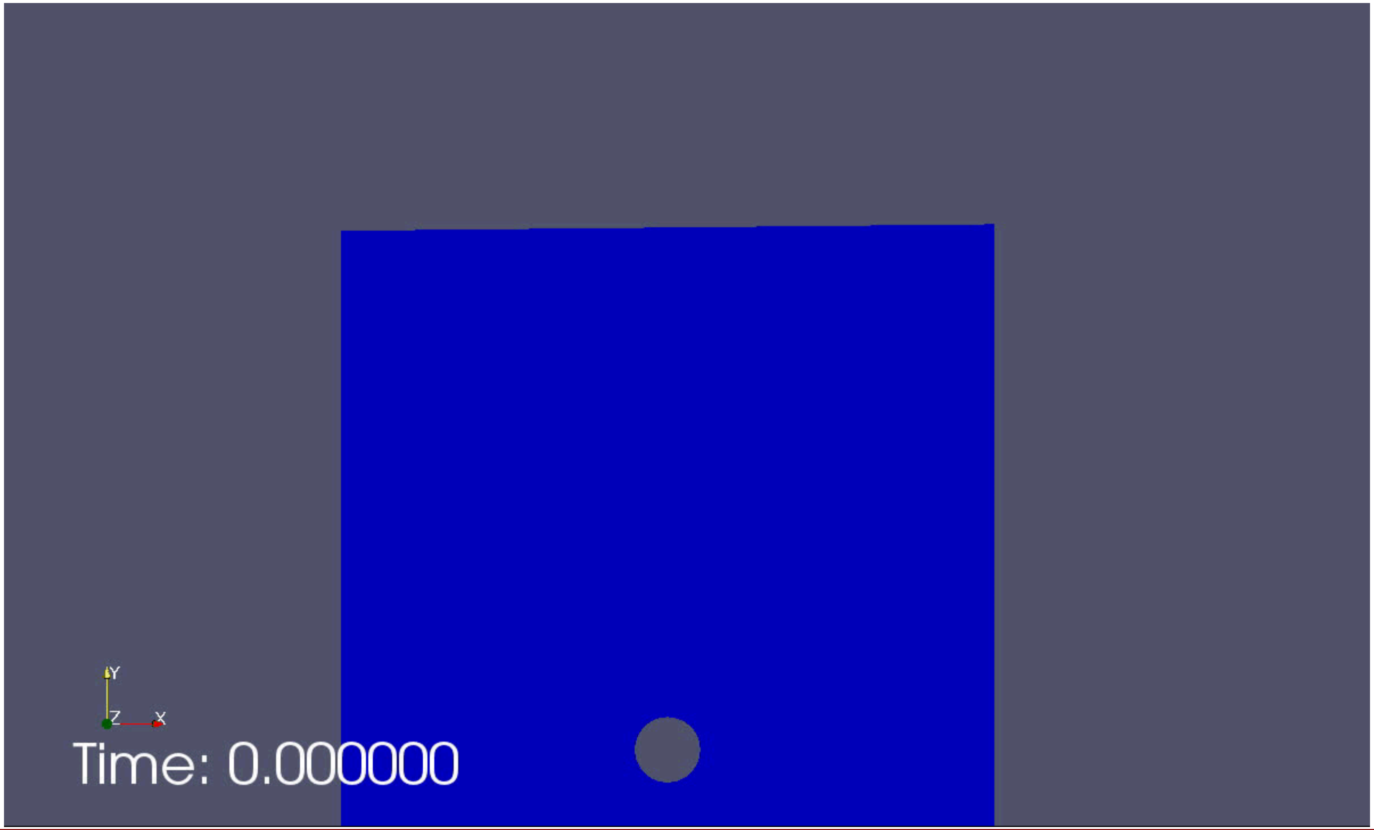
- A fire resulting from an aircraft crash can last an extraordinary length of time (hours to days) because of the reacting rubble
- It is possible to have a low-level burn with a significant increase in temperatures at later times
- Fibers may continue to react with no flaming present if there is sufficient material (i.e. at this scale)
- The epoxy never appeared to be a significant or distinguishing factor in this test as a fuel, is thought to be mostly consumed early in the burn
- Total composite mass loss is still not resolved for an unmitigated fire scenario, longer-term data would be helpful
  - Likely to exhibit significantly higher mass loss
  - Could use models that help define conditions

Existing Modeling Methods

- We generally lack the ability to model this scenario with existing tools
- I have not encountered a capability in any code for liquid soaked solid fuel fires
- We have performed some rubble soaked fuel tests in the past, but never had a scenario where the ‘rubble’ could also react

Level-set methods for Liquids

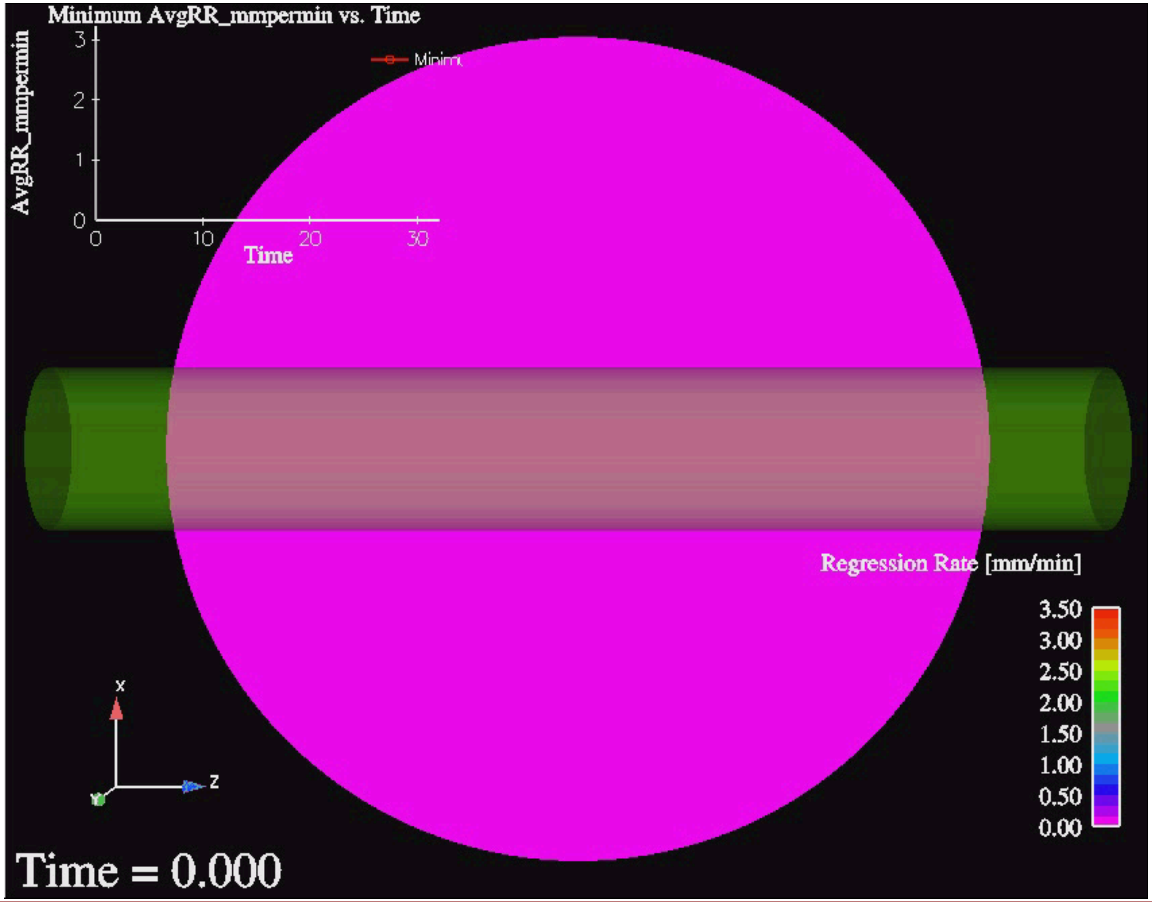
- CDFEM methods were recently implemented for resolving level-set multi-fluid interfaces
- The below video exhibits a 2-D prediction of a boiling drop rupturing on the surface of a liquid
- Level-set is not adequately mass conservative for predictive simulations



This video shows a 2D rising bubble through a liquid surface breaking at the surface with level-set

1-D Liquid Pool Model

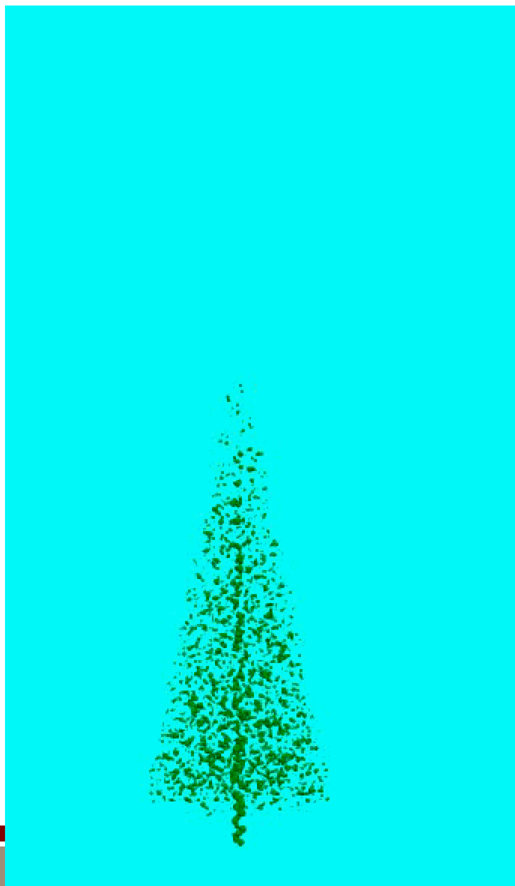
- Historical model for predicting the burn rate for pool fires given heat transport from the flames (based on legacy SINTEF codes)
- Others have also employed 1-D models, which do not level the surface or transport heat via convection

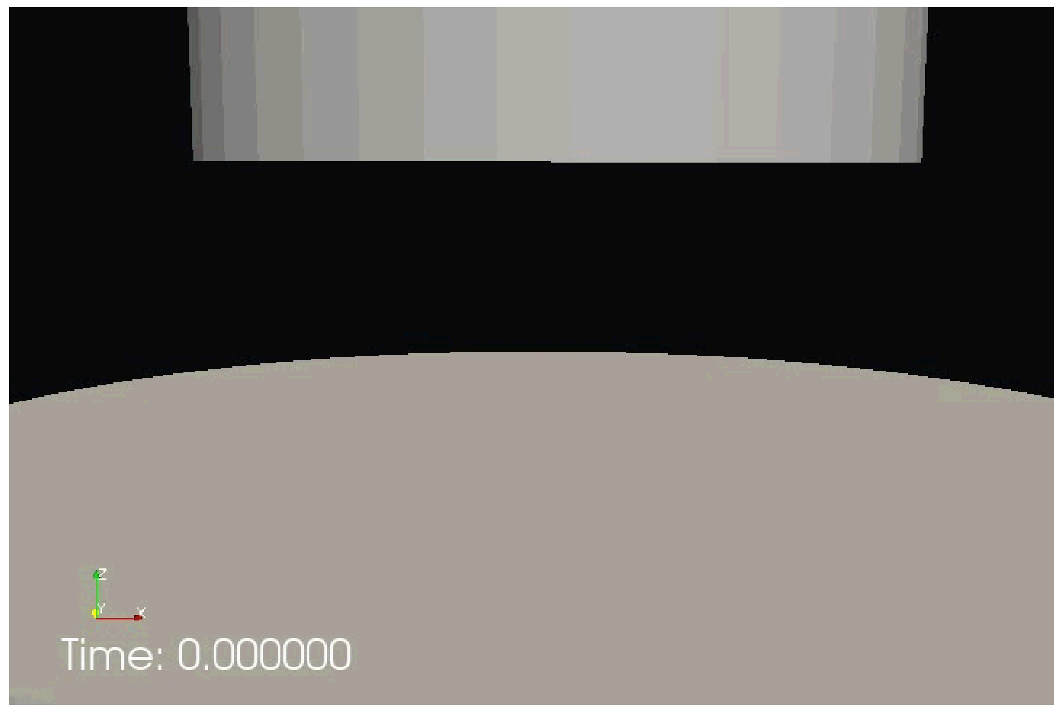


This video shows a 1D pool regression rate prediction based on thermal feedback from a fire

Particle Combustion Model

- Primarily used in the past for two applications:
  - Wildland fire predictions for idealized trees
  - Aluminized propellant reactions





Approach

- Implement a volume of fluid capability to model the receding fuel layer
  - Better mass conservation
  - Established models for evaporation, surface tension
- Abstract the existing solid fuel modeling capabilities to predict the reactions in a rubble fuel bed
  - We leveraged this component of development to incorporate the CPD model for percolation theory based reaction kinetics
  - We recently added capability for oxidative surface reactions
  - Heat transfer approximations are being made for conduction
- Link the capabilities in Sandia's SIERRA/Fluid Mechanics code Fuego that has participating media radiation capability and generalized transport solvers
  - Enable combustion and evaporation from the liquid surface

VOF Theory

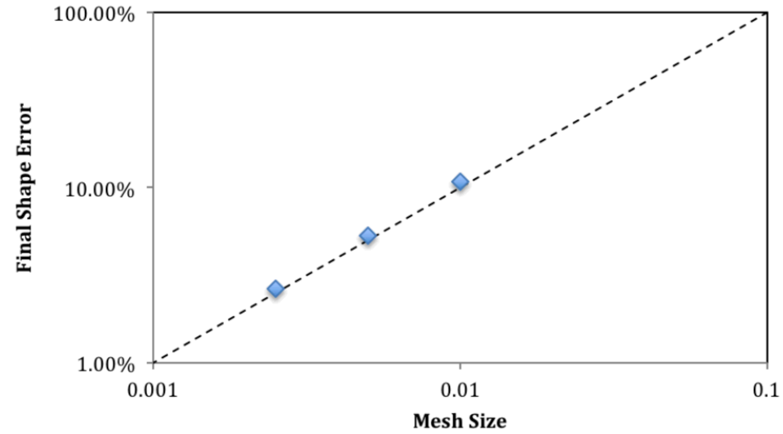
- At its core, VOF conserves a scalar for phase:

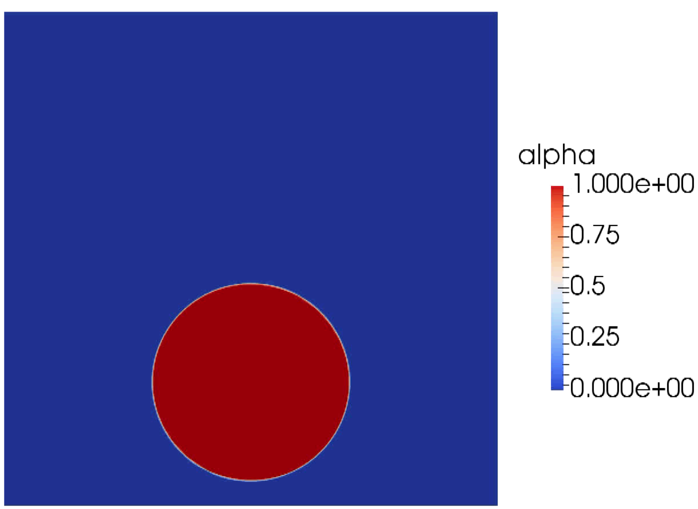
$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial x} + v\frac{\partial F}{\partial y} + w\frac{\partial F}{\partial z} = 0$$

- Right hand of equation modified for forces and effects such as surface tension, gravity, and evaporation
- Existing models leveraged for the formulation:
  - Geometric advection using interface compression for improved surface definition
  - Evaporation by deviation from saturation temperature method (Hardt and Wondra, 2008)
  - Pressure stabilization through a pressure diffusion term (Tukovic and Jasak, 2012)
  - Surface tension and gravity body forces, using a velocity correction factor (Francois et al., 2006)
- We are implementing a radiative transport coupling capability

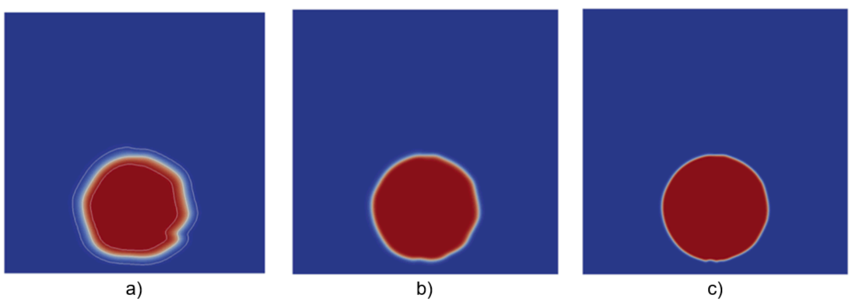
Verification

- Methods employed:
  - Basic advection
  - Planar advection
  - Circle advection
  - Hollow square advection
  - Shearing advection
- u =< cos(πx) sin(πy), -sin(πx) cos(πy) >





Time: 0.0 ms

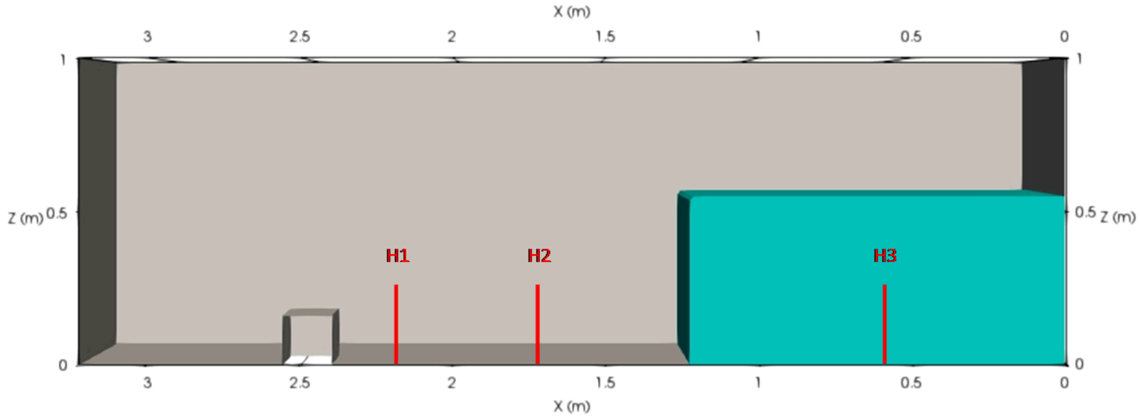


	Mesh	Time Step	CFL	Final Shape Error
a	100x100 (001 m)	2.5 ms	0.25	10.85%
b	200 x 200 (0.005 m)	1.25 ms	0.25	5.29%
c	400 x 400 (0.0025 m)	0.625 ms	0.25	2.64%

Validation Scenario

- Dam burst scenario was created experimentally
- Provides a good test of the advection and surface models
- References:

- K. Kleefsman, G. Fekken, A. Veldman, B. Iwanowski, and B. Buchner. A volume-of-fluid based simulation method for wave impact problems. Journal of Computational Physics, 206(1):363-393, JUN 2005.
- C. Crespo, J. M. Dominguez, A. Barreiro, M. Gomez-Gesteira, and B. D. Rogers. GPUs, a new tool of acceleration in CFD: Efficiency and reliability on smoothed particle hydrodynamics methods. PLOS ONE, 6(6), JUN 2011.



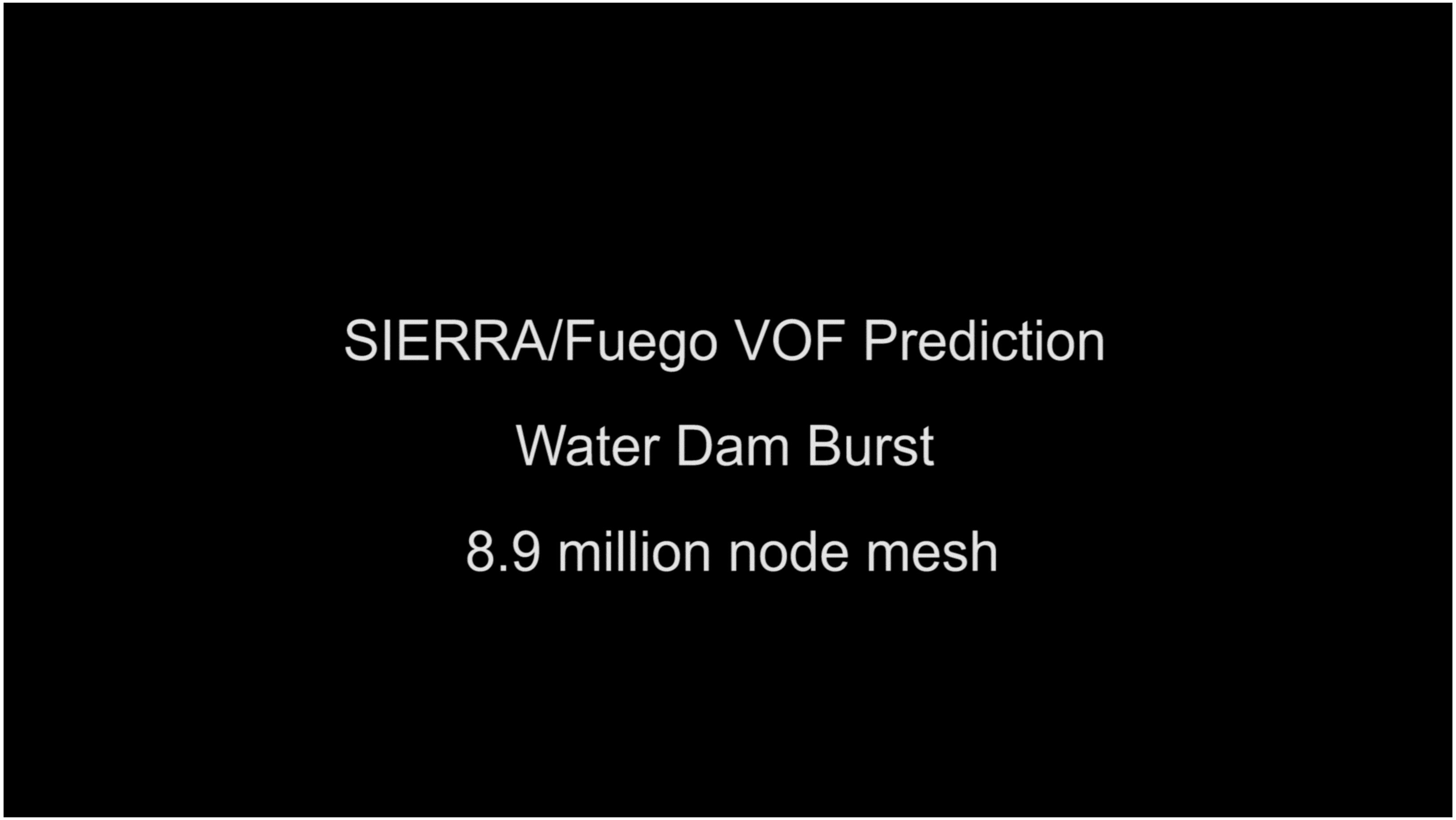
Dam burst scenario (initial configuration above)
Blocking obstacle
Three measurement points where data were extracted

#	Mesh	Nodes	Nominal Mesh Spacing	Time Step (s)
1	coarse	28,600	0.05000 m	0.00250
2	med	216,400	0.02500 m	0.00125
3	fine	716,500	0.01667 m	0.00100
4	xfine	1,682,000	0.01250 m	0.00100
5	xxfine	3,266,300	0.01000 m	0.00050
6	xxxfine	5,622,400	0.00833 m	0.00050
7	xxxxfine	8,903,500	0.00714 m	0.00050

Study consisted of mostly mesh refinement variations

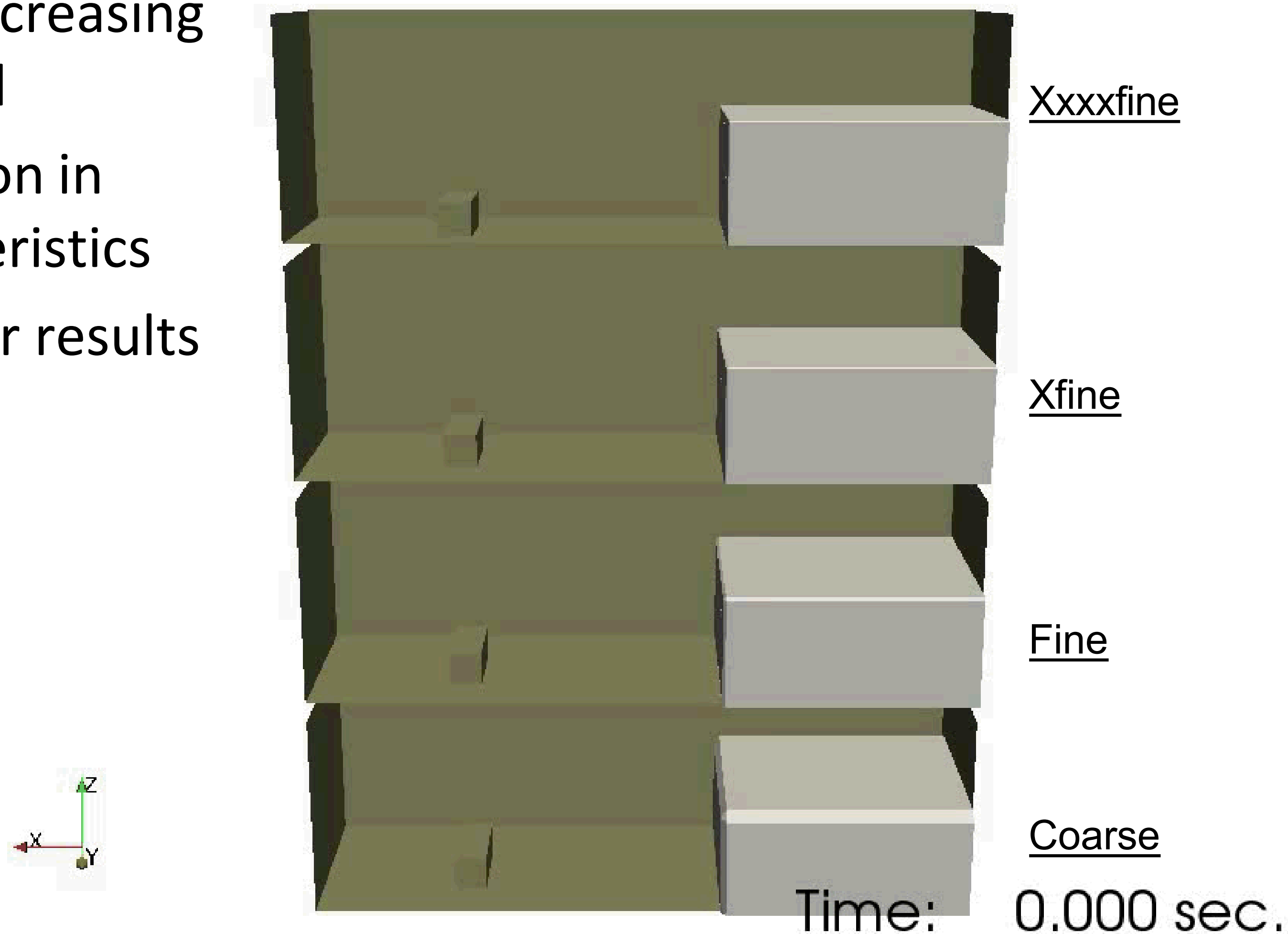
Highest Resolution Video

- The highest resolution case results in a very complex surface flow



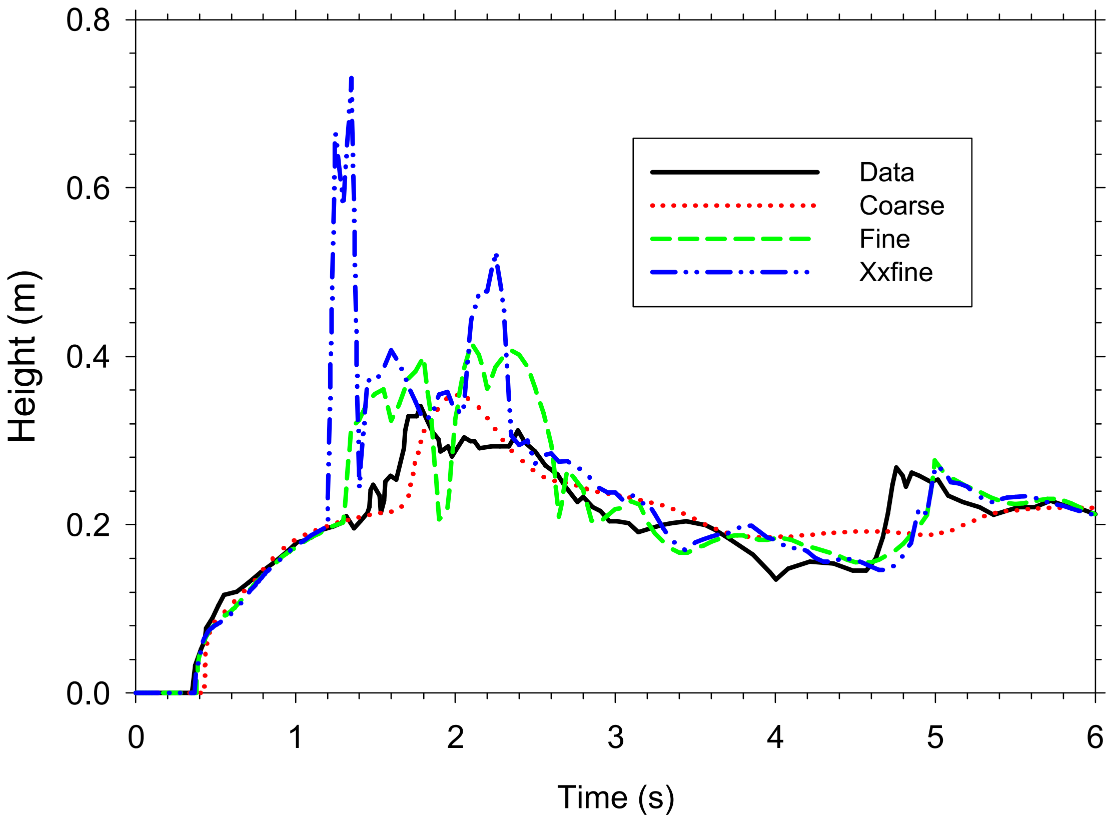
Resolution Comparison Video

- With improved resolution, increasing surface detail
- Some variation in flow characteristics
- Mostly similar results



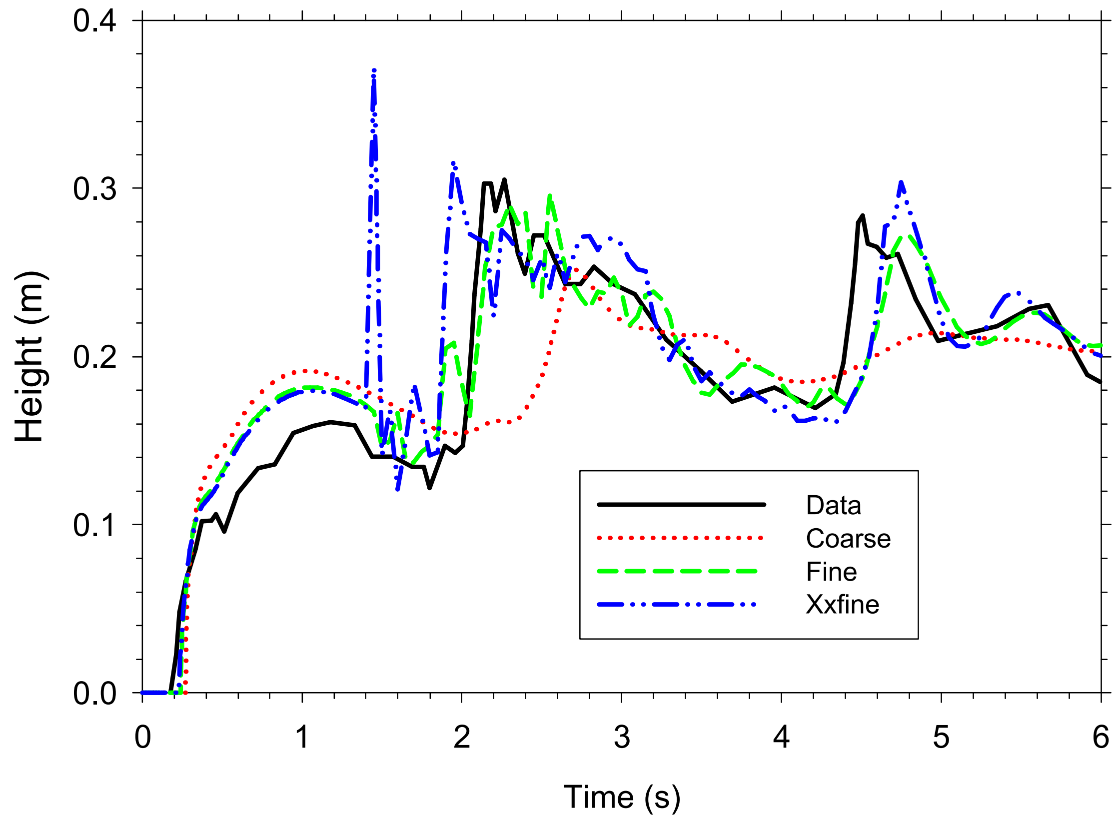
Fluid Height at H1

- Increased resolution generally matches the data peak heights better



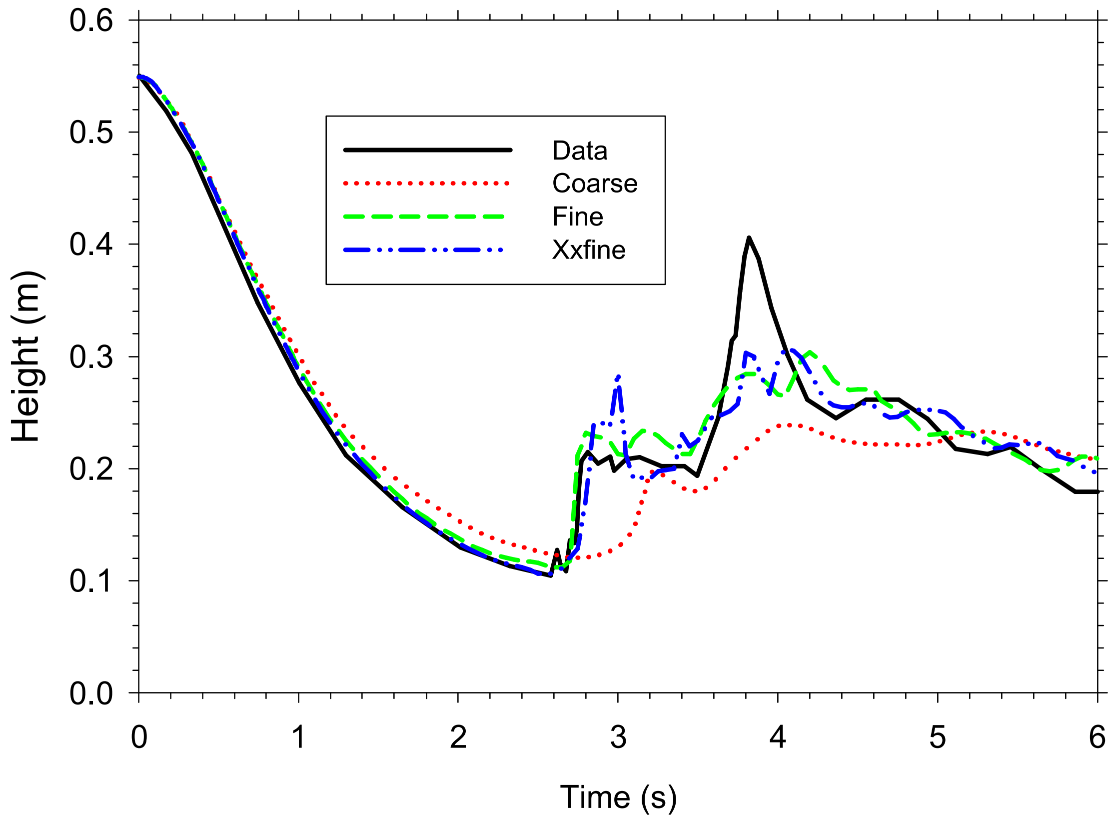
Fluid Height at H2

- Coarse calculation is appreciably worse than the fine and xxfine



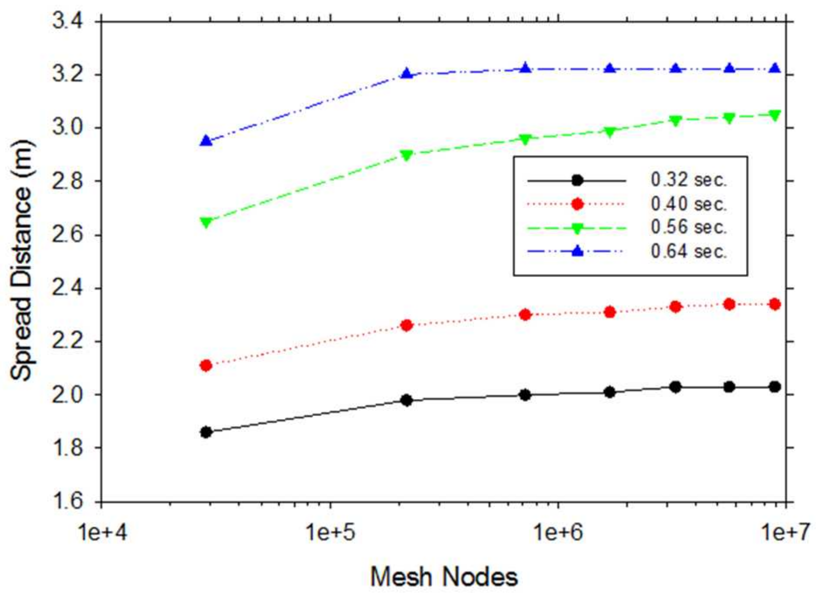
Fluid Height at H3

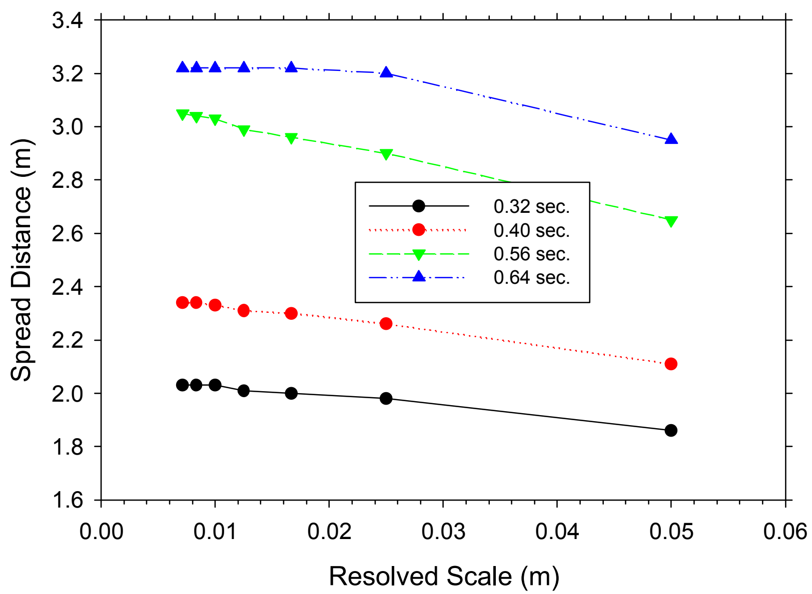
- Very good temporal predictions for higher resolution models, moderate difference in peak magnitudes



Convergence Check

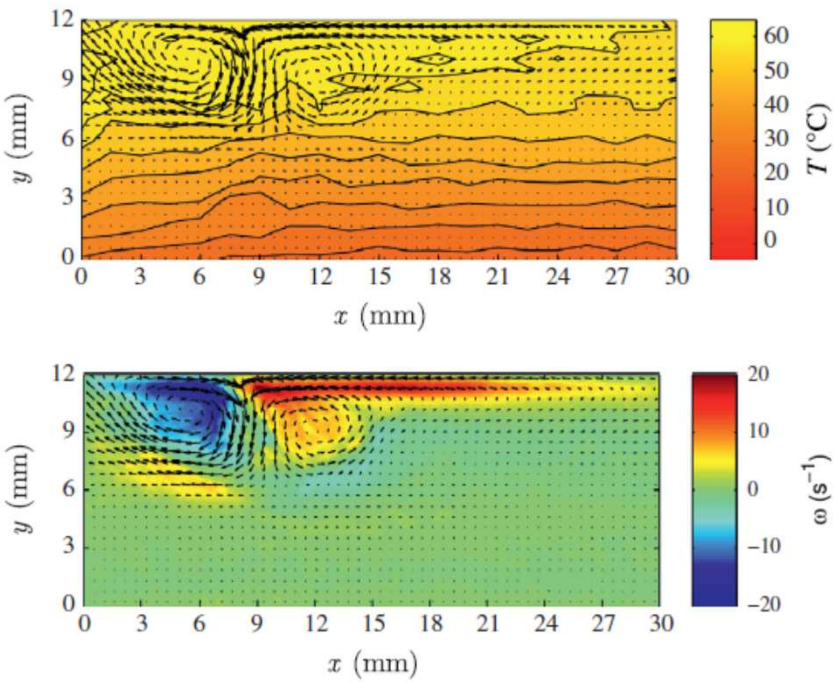
- The convergence is evaluated based on the liquid spread distance
- Convergence appears good at early times
- Some lack of convergence is apparent (0.56 sec.)
- 0.64 sec. result appears converged, but is reflective of the spread arriving at the wall



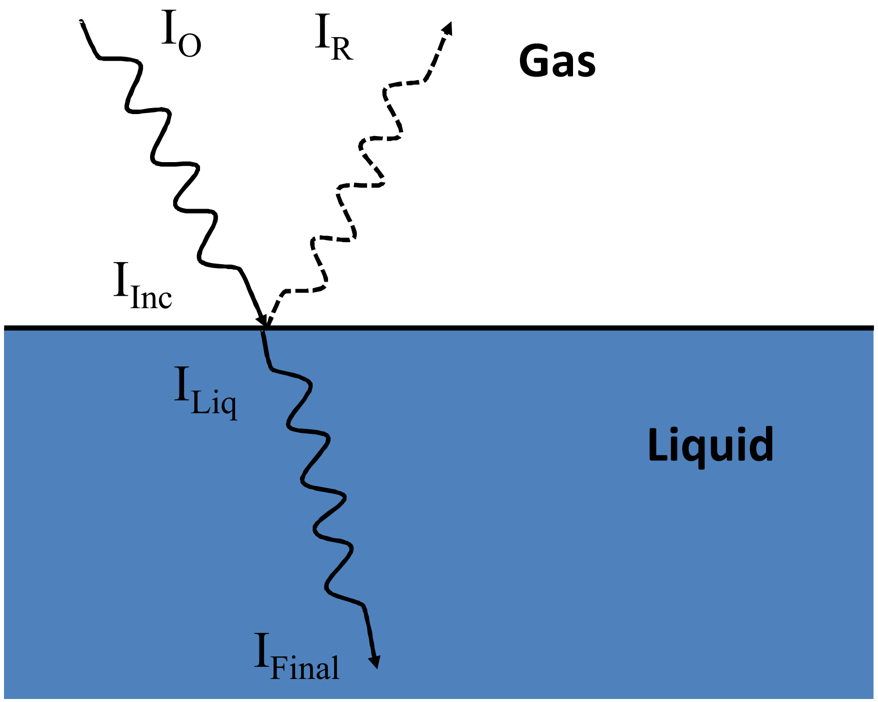


Path Forward

- For our application, this wasn't the best validation test
- Vali et al (2014) have flow data for a burning pool
- This will be a more relevant test problem
- Radiation transport coupled to multi-phase model



Vorticity and temperature from Vali et al. 2014



A schematic of radiation transport in a fire

Vali, A., Nobes, D.S., and Kostiuk, L.W., "Transport phenomena within the liquid phase of a laboratory-scale circular methanol pool fire," Combustion and Flame, 161, pp. 1076-1084, 2014.

Discussion

- Results aren't exact to the data, but deemed good:
  - Removal of the dam induces some initial condition not captured in the model
  - Moving forward with confidence in the model
- Liquid pool fire simulation alone will be novel
  - Vali et al. 2014 don't show model comparisons
  - Can't find other instances of similar models
- Liquid pool model combined with rubble model will enable unique simulations

Summary

- Model development for mixed liquid and solid fuel fires is in progress
  - We illustrated verification and validation of the VOF model for liquid transport
- Outstanding activities
  - Particle burn model for laminate rubble
  - Radiation coupling and combustion working with VOF
  - Coupling the two together in a simulation
  - Validation
- New (novel) capabilities:
  - Burning 3D pool model
  - Rubble fire
  - Multiphase radiation transport

Acknowledgements

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