



Development of A Novel Turbulence Model for Multiphase and Hypersonic Flow Problems

**H. Q. Yang – CFDRC/Amentum, Fluid Dynamics Branch (MSFC-ER42)
NASA Marshall Space Flight Center, AL**

**Presented at
JANNAF Conference
January 26-30, 2026
Spokane, WA**

Multiphase and Hypersonic Flows: A Common Modeling Challenge



Multiphase Flow

- Gas-liquid Interface
- Sharp density jump
- Turbulence on both sides of the interface

Supersonic and Hypersonic Flow

- Shock wave near wall
- Abrupt density increase
- Turbulent boundary layer

Key Physical Challenges in Numerical Modeling

- Multiphase flows: density discontinuity at material interfaces
- Hypersonic flows: density discontinuity across shock waves
- In both cases:
 - Turbulence interacts with strong density gradients
 - Conventional models exhibit nonphysical behavior

Key Takeaway

Sharp density gradients—not the flow regime—are the root cause of turbulence modeling failures

Multiphase Problem: Cryogenics Fluid Management (CFM)



Why Accurate Turbulence Modeling Matters at Density Discontinuities

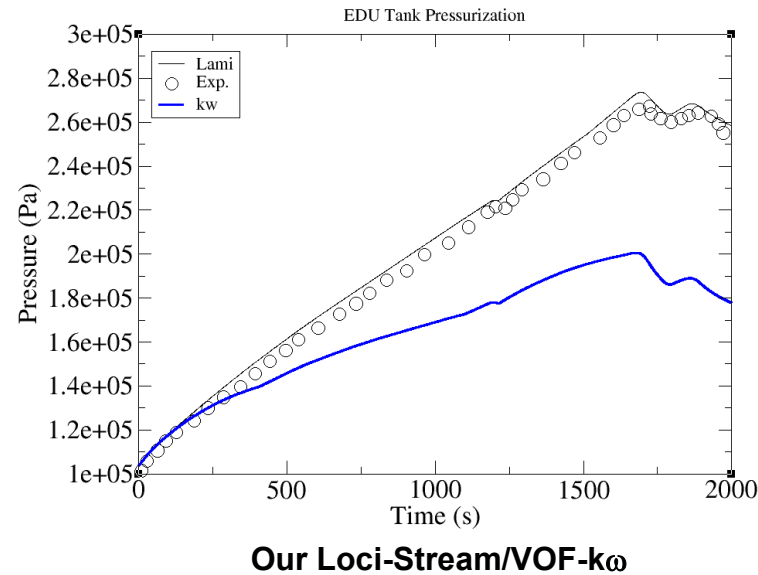
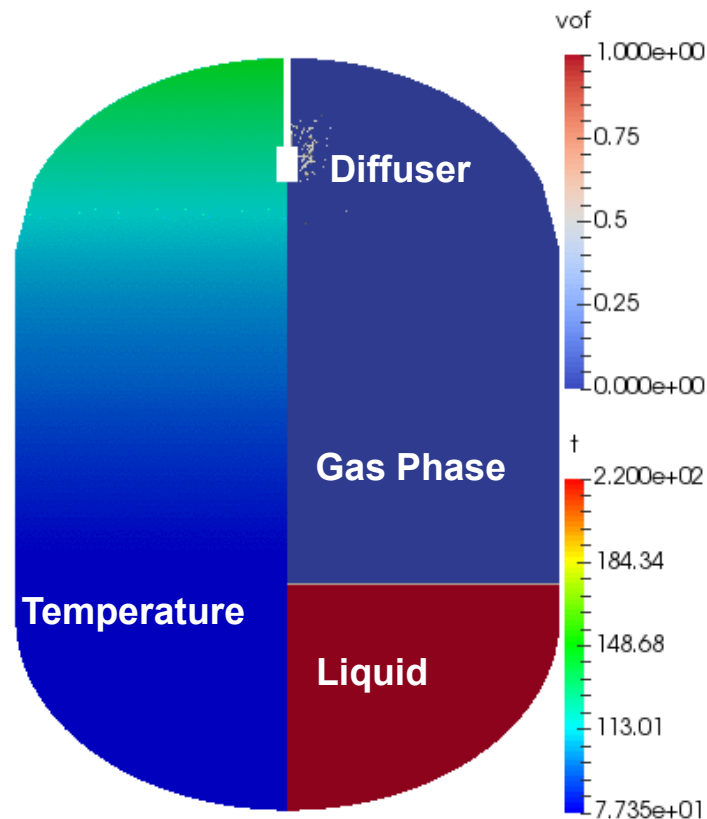
- **For CFM, turbulence controls:**
 - heat transfer across liquid–vapor interfaces,
 - vapor generation and condensation rates,
 - pressure rise and venting behavior,
 - propellant mass loss
- **Conventional turbulence models:**
 - were developed for single-phase flows, and originated for incompressible flow.
 - require empirical corrections at interfaces,
 - can produce nonphysical results in cryogenic systems.
- **Previous Attempts at Interface Turbulence Modeling: Damping Models of Egorov-type**
 - Add source terms to the dissipation (ω) equation
 - Suppress nonphysical turbulence amplification caused by k -based models
 - Strongly dependent on mesh resolution and tuning parameter B
 - Limited predictive capability outside calibrated conditions

Known Modeling Difficulties for Autogenous Pressurization



LN2 Tank Autogenous Pressurization

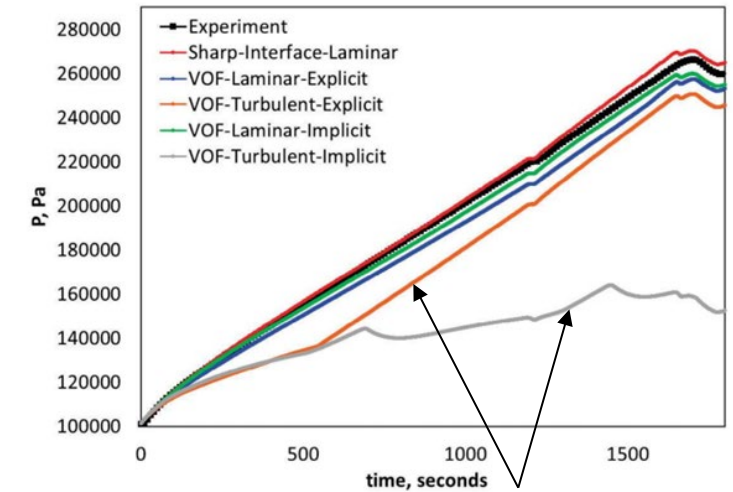
- Pi-sector of 1 degrees, VOF.
- No wall heat fluxes.
- Conjugate heat transfer
- Turbulence models: Laminar. k- ω SST



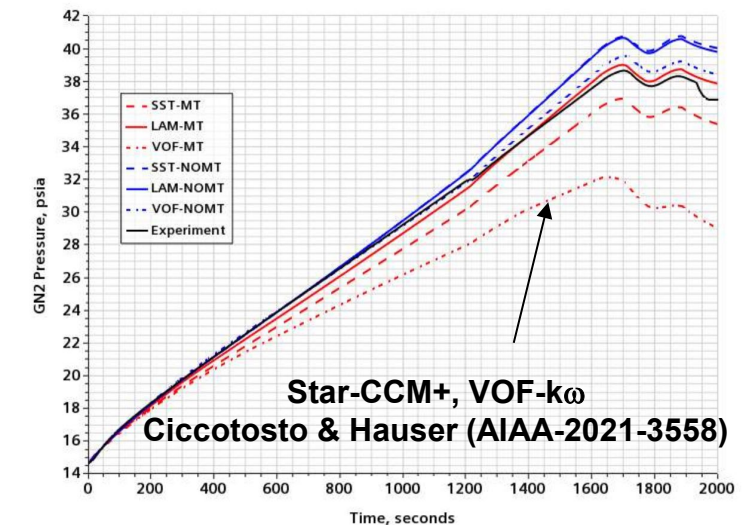
Key Observations:

- Laminar flow simulations show excellent agreement
- Conventional turbulence models fail
- Discrepancies are reported across multiple CFD codes and platforms.

Why does a laminar model outperform turbulence models?



Fluent, VOF-k ω
Olga Kartuzova (CFM-RPT-007)



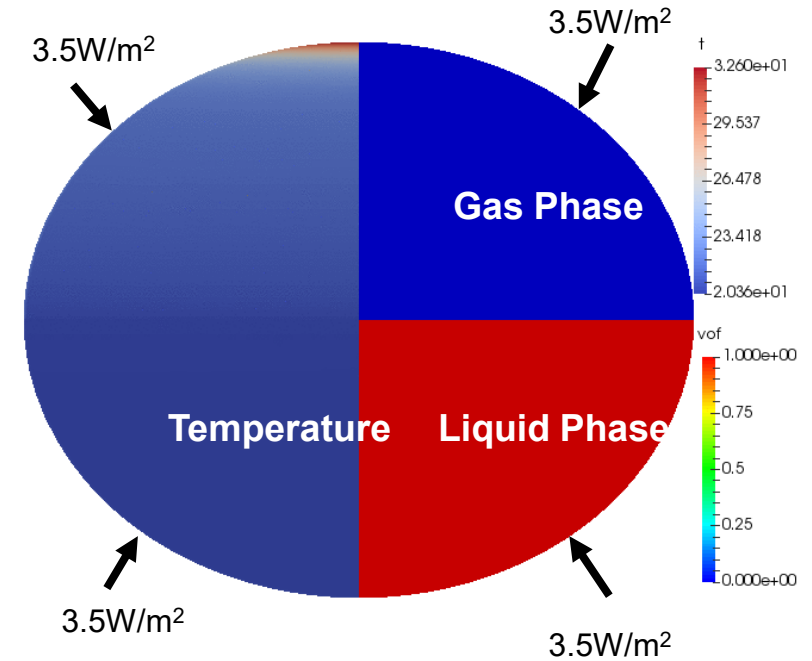
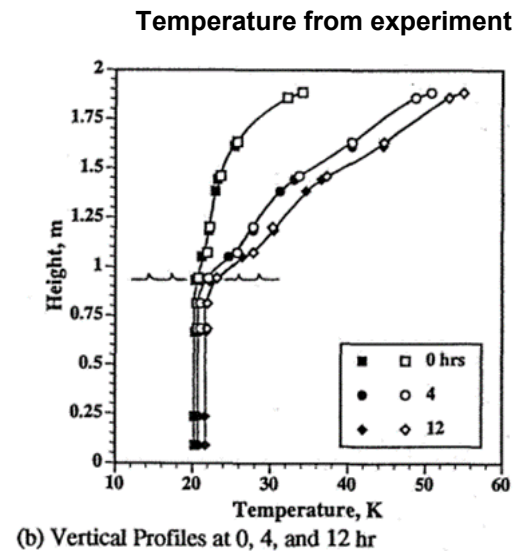
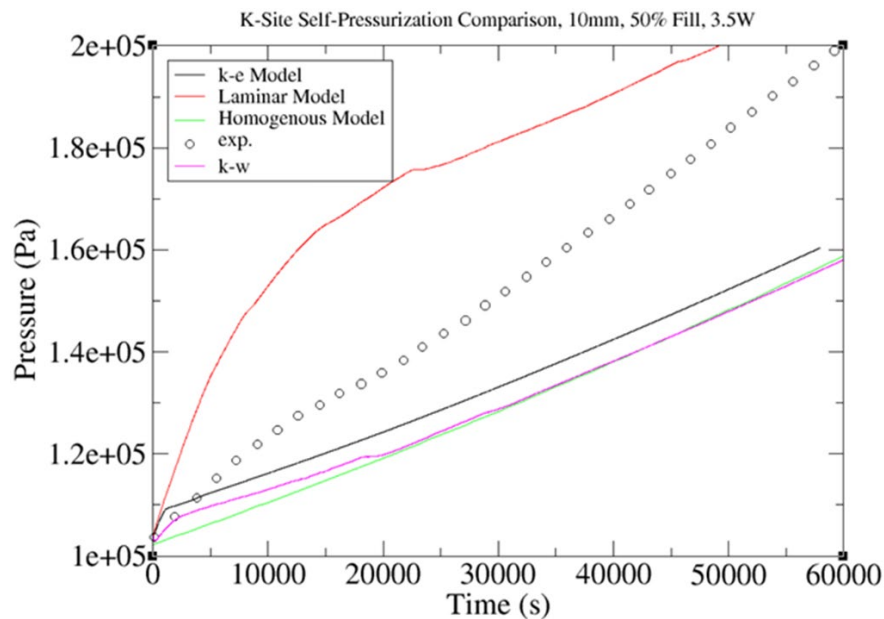
Star-CCM+, VOF-k ω
Ciccotosto & Hauser (AIAA-2021-3558)

Known Modeling Difficulties for Self-Pressurization



LH2 Spherical Tank (K-site)

- Pi-sector of 1 degrees, sharp interface
- Heat fluxes: 3.5W/m^2
- Liquid Volume Fill: 29%, 49%, 83%.
- Turbulence model: Laminar, $k-\omega$ SST, $k-\varepsilon$

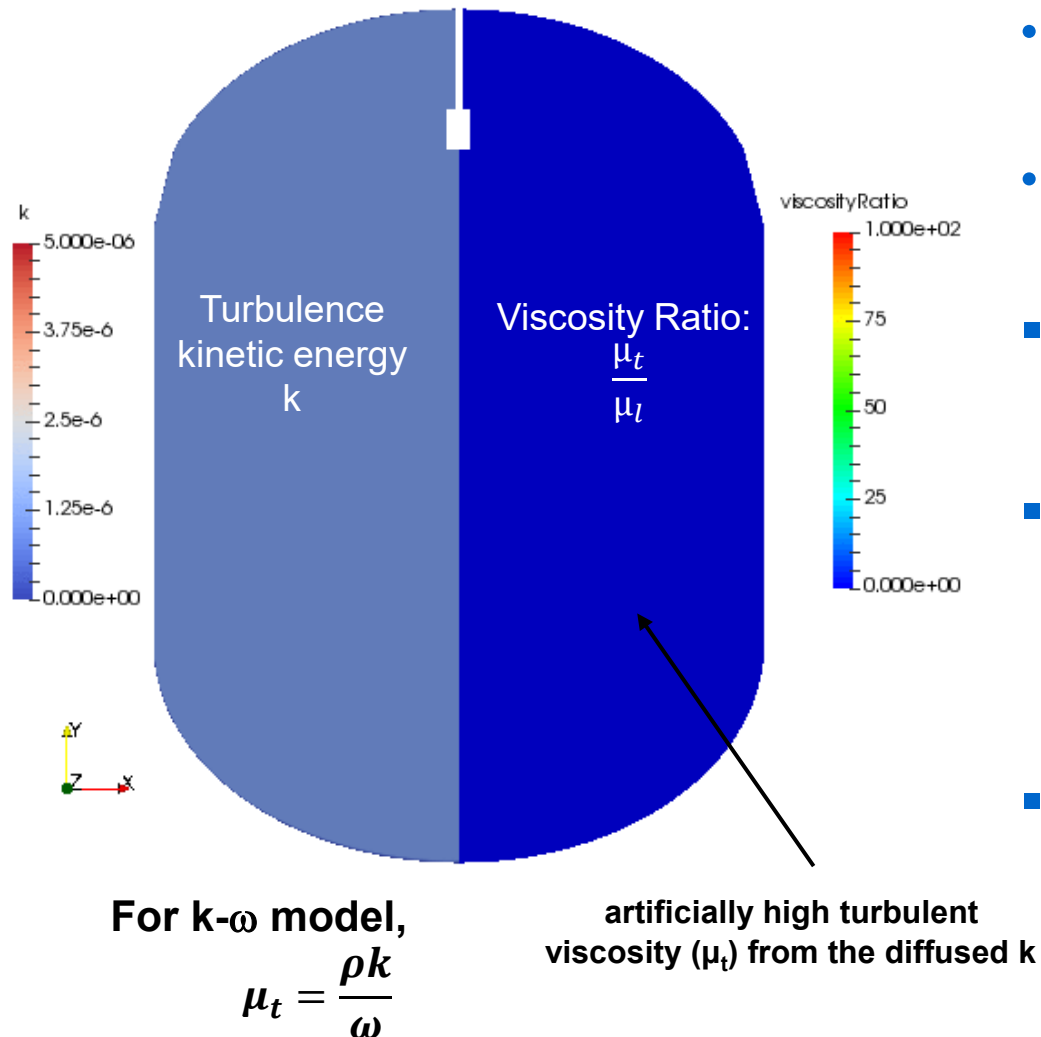


- **Key Observations** :Turbulent mixing is systematically overpredicted; Thermal stratification is completely lost.
- **Root cause**: Excessive interfacial turbulence transport dominates thermal and pressure errors.
- **Bottom line**: The problem is not turbulence itself, but how it is transported across the interface.

Diagnosis: Why Existing Turbulence Models Fail



Using Standard k formulation



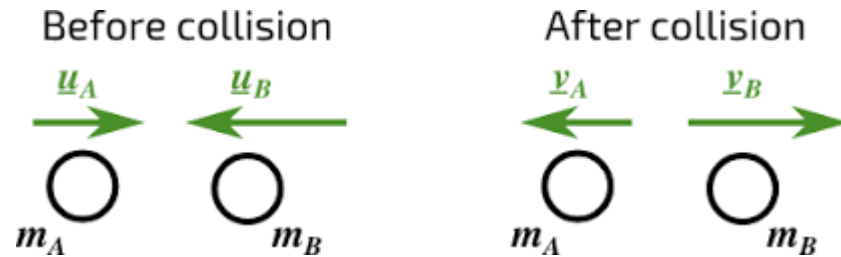
- **Code Independence:** This behavior appears across different CFD codes: From Fluent, Star-CCM+, to Loci/STREAM-VOF.
- **Root Cause#1:** VOF turbulence models implicitly assume continuity of k , ω , ϵ across interfaces
- **Why μ_t becomes nonphysical?** $\mu_t = \rho \frac{k}{\omega}$, liquid density amplifies μ_t by orders of magnitude.
- **Why Laminar Sometimes Works?** The laminar model avoids transporting nonphysical turbulence across the interface.
- **Summary of Diagnosis**
 - Mass-specific k is transported across density jumps
 - This produces artificial μ_t in the liquid
 - Interface damping method treats symptoms, not the cause
- **Resolution:**
 - What is the turbulence boundary condition across the interface?

Turbulence Model Correction: Interfacial Continuity of k and ω ?



For the turbulence quantities, what is the interfacial condition?

(a) Particle and Particle Interaction with Different Mass



For the Lagrangian Particles Dynamics:

$$\text{Total Kinetic Energy} = \frac{1}{2} m_A u_A^2 + \frac{1}{2} m_B u_B^2$$

(b) Gas and Liquid Interaction with Density Jump (right)

- The energy conservation gives us: $\frac{1}{2} \rho_g V_g^2 = \rho_l g h$;

$$h = \frac{\rho_g V_g^2}{2 \rho_l g}$$

- From Bernoulli's Equation: $\rho_l g h = \frac{1}{2} \rho_l V_l^2$;

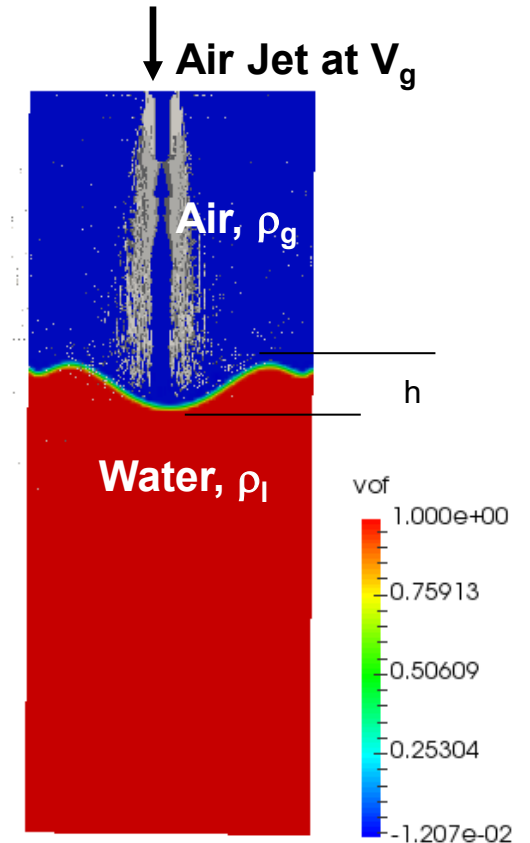
$$\frac{1}{2} \rho_g V_g^2 = \frac{1}{2} \rho_l V_l^2$$

- Turbulent Flow: $\frac{1}{2} \rho_g (V_g^2) = \frac{1}{2} \rho_g (\bar{V}_g + V_g')^2$

- Interfacial continuity: $\frac{1}{2} \rho_g V_g'^2 = \frac{1}{2} \rho_l V_l'^2$

$$\rho_g k_g = \rho_l k_l$$

- For the turbulence kinetic equation: ρk should be continuous, rather than k itself.



Turbulence Model Correction: Interfacial Continuity of ρk



Which turbulence-model equations must be modified?

- as interfacial continuity requirement: $\rho_g k_g = \rho_l k_l$

For k- ω model, $\mu_t = \frac{(\rho k)}{\omega}$;

- Modify only the k -equation $\rightarrow$ transport ρk
- No change needed for the ω -equation, since ω is treated as continuous across the interface

For k- ε model, $\mu_t = \rho C_\mu f_\mu \frac{k^2}{\varepsilon} = C_\mu f_\mu \frac{(\rho k)^2}{(\rho \varepsilon)}$

- Both the k - and ε - equations must be reformulated.

Turbulence Modeling Strategies

- **For simplicity and minimal code changes**, we adopt the k - ω framework and **reformulate** only the **TKE equation** using ρk .
- **Eliminate** empirical interface turbulence damping while remaining consistent with physical jumps in turbulence quantities.
- **Retain** existing calibrated model constants and code structure for straightforward implementation
- **Applicable** to single phase and incompressible flows.

ρk Based Turbulence Model Equation



Revisit the derivation of turbulence kinetic energy equation for incompressible flow

- Decomposition: $u_i = \bar{u}_i + u_i'$; $p_i = \bar{p}_i + p_i'$;
- Instantaneous Navier-Stokes Equation: $\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2}$
- Define: $k = \frac{1}{2} \overline{u_i' u_i'}$; by: $u_i' * [Instantaneous NS - RANS]$

$$\frac{Dk}{Dt} = P_k - \epsilon + T_k + \Pi$$

P_k : Turbulent production due to mean shear;
 ϵ : Dissipation (loss of TKE due to viscosity at small scales);
 T_k : Transport term (diffusion of TKE by turbulence and viscosity);
 Π : Pressure-related terms (pressure diffusion + pressure-strain correlation)

Derivation of turbulence kinetic energy equation for compressible flow using ρk

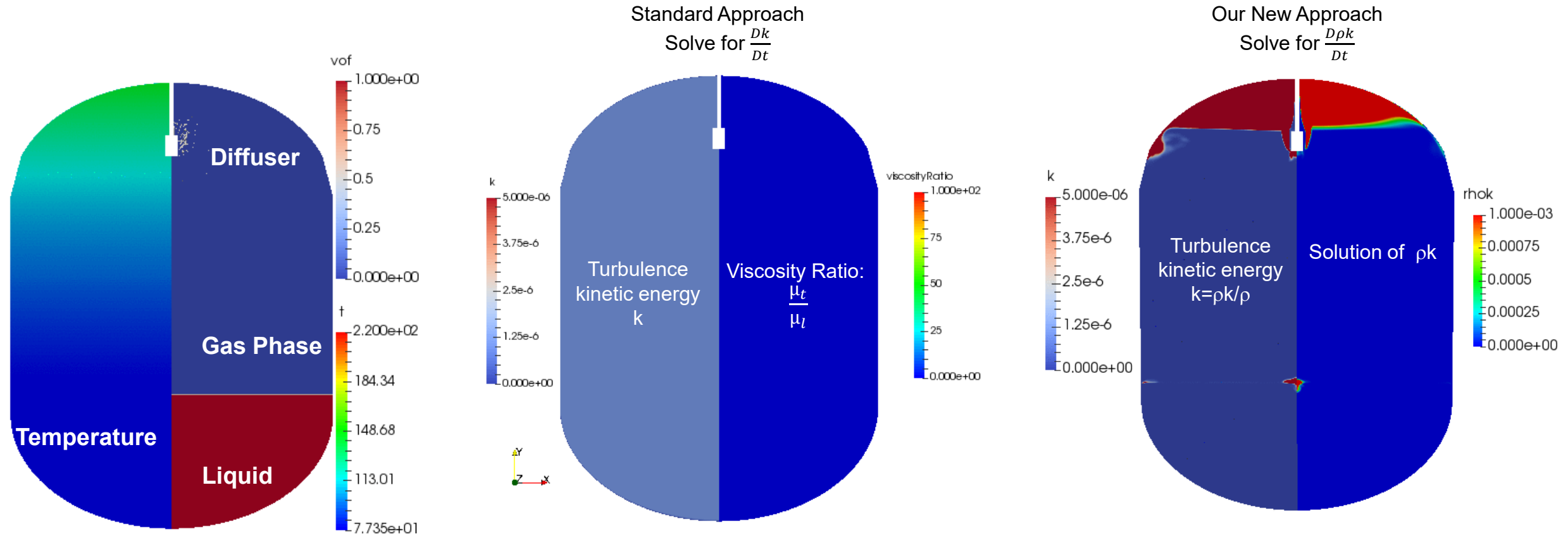
- Define: $k = \frac{1}{2} \overline{u_i' u_i'}$; by: $\bar{\rho} u_i' * [Instantaneous NS - RANS]$

$$\frac{D\rho k}{Dt} = P_k^* - \epsilon^* + T_k^* + \Pi^*$$

Turbulence Model Improvement Using ρk Formulation



EDU Tank Autogenous Pressurization



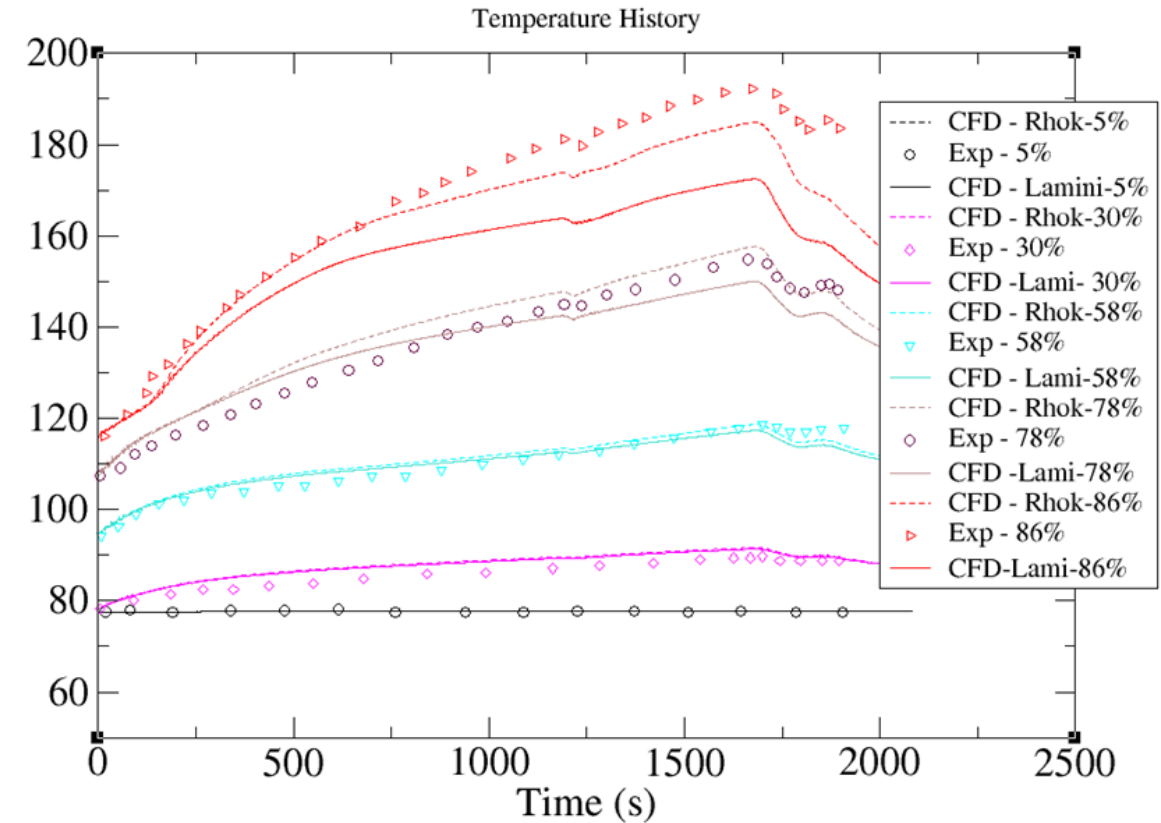
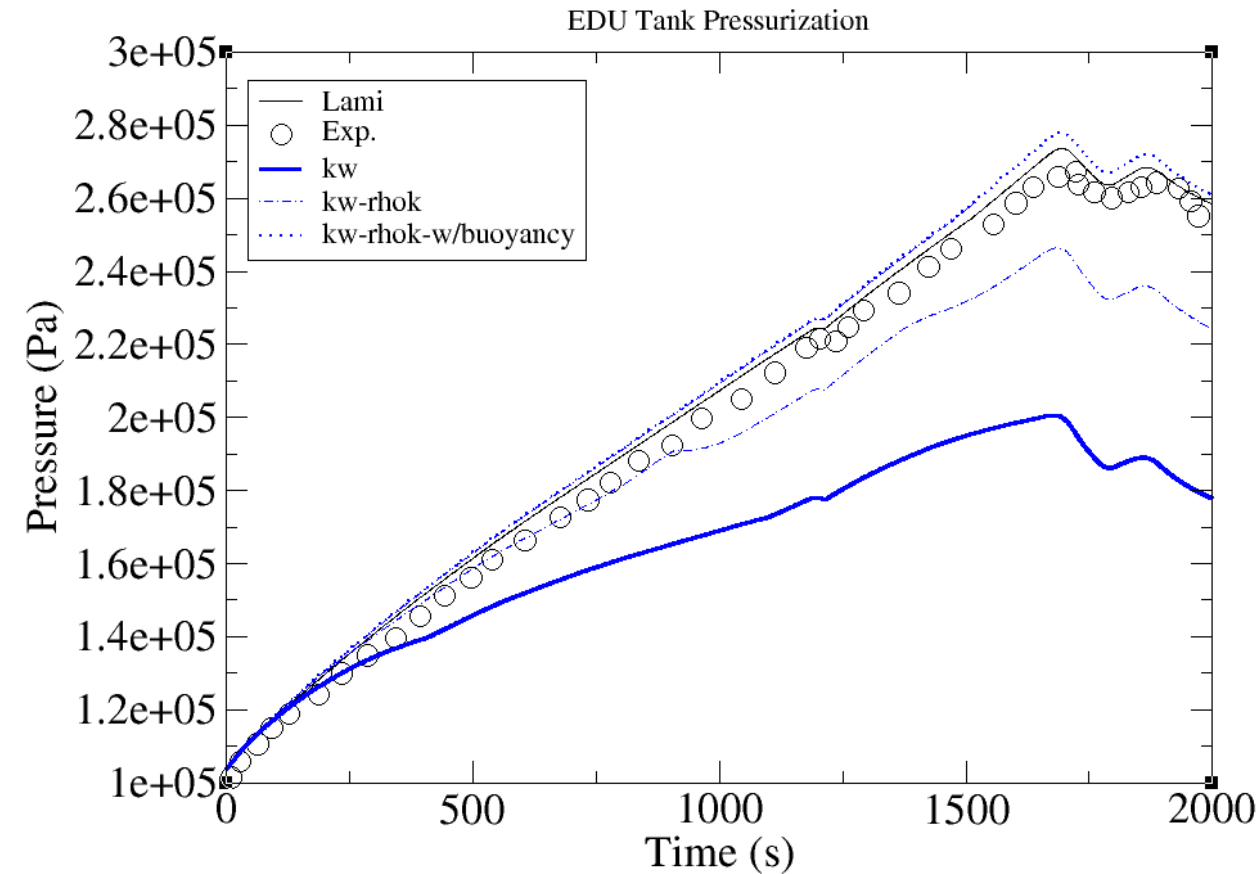
Key Observations

- The ρk formulation substantially reduces turbulent kinetic energy (k) near the liquid–gas interface.
- This reduction prevents nonphysical turbulence penetration into the liquid phase.
- As a result, interfacial transport is governed by physical shear rather than numerical diffusion.

Improved Solution: # 1 Autogenous Pressurization



Improved solution with the use of (ρk) as dependent variable, and source term due to buoyance.

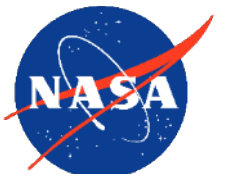


Key Observations

- ρk yields pressure predictions comparable to the laminar model.
- Temperature fields are more accurate than laminar results due to realistic localized turbulence.
- Consistent ρk transport is critical for reliable pressure-thermal coupling.

Improved Solution: # 2 Benchmark

Validation of Stratified Parallel Flow



Experimental evidence of ρk continuity across the interface

- The experiment conducted by Fabre et al. [*Multiph. Sci. Technol.* 1987, 3, 285–301]. Air–water stratified flows in a rectangular channel
- Widely used as the test case for the development of interface damping models
- CFD model; 1001x121 non-uniform cells;
- VOF: k- ω SST with and without using ρk formulation;
- Sharp Interface: different boundary conditions: slip; no slip; continuity condition across interface of ρk .

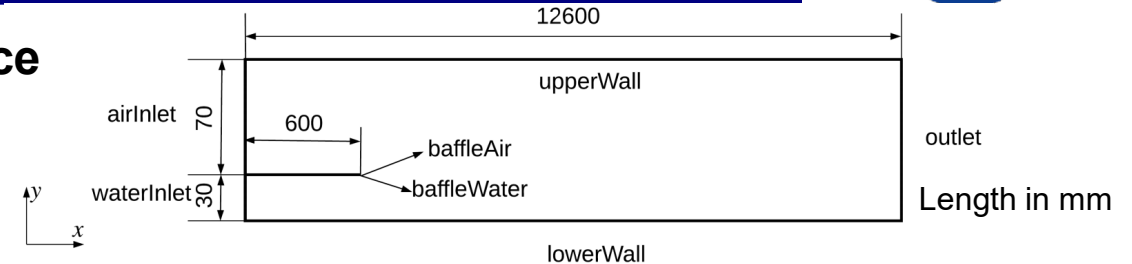
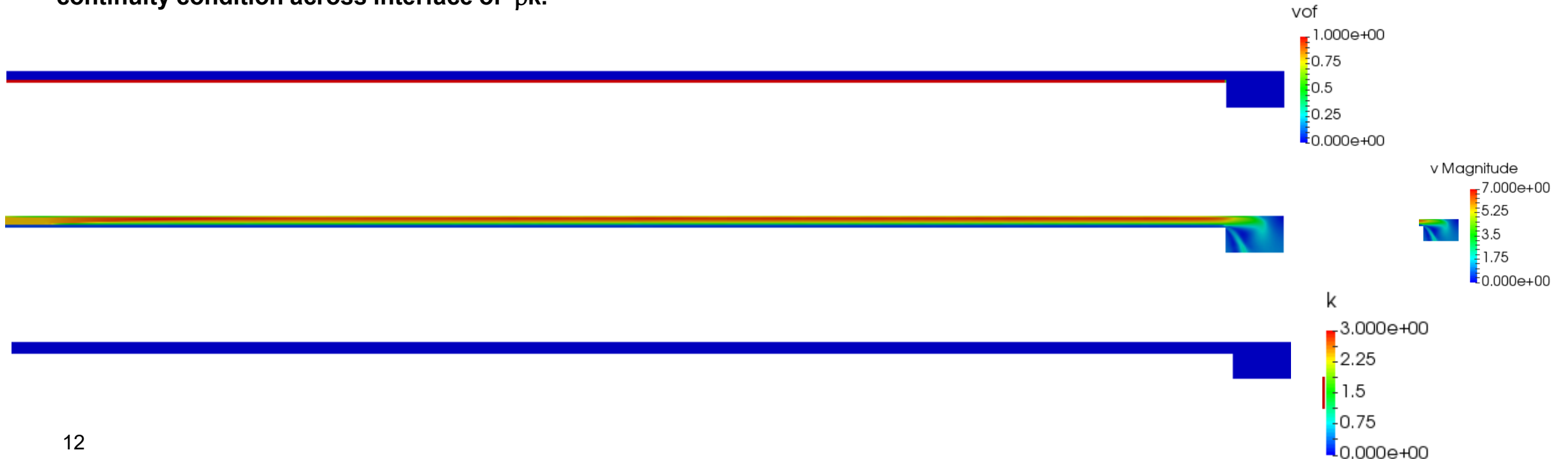


Table 1. Flow conditions and experimental data [4].

Run Reference	Air Average Velocity (m/s)	Water Average Velocity (m/s)	Pressure Gradient (Pa/m)
250	3.66	0.395	2.10
400	5.50	0.476	6.70
600	7.56	0.698	14.80



Improved Solution: # 2 Benchmark Validation of Stratified Parallel Flow

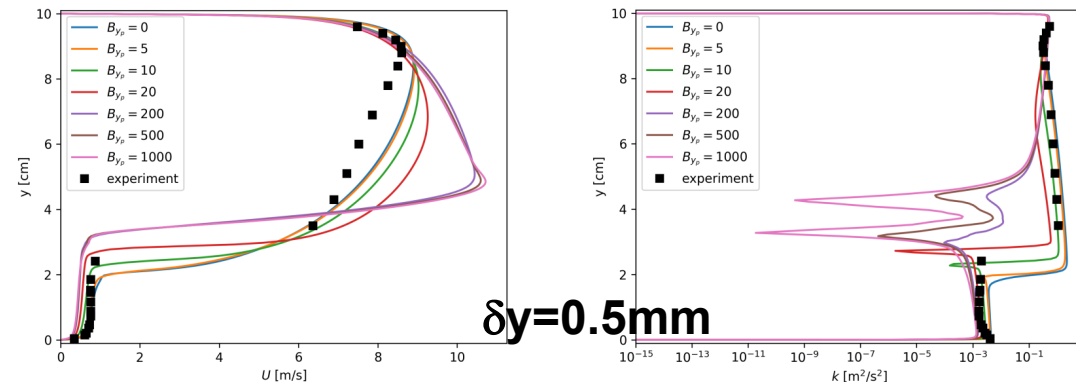
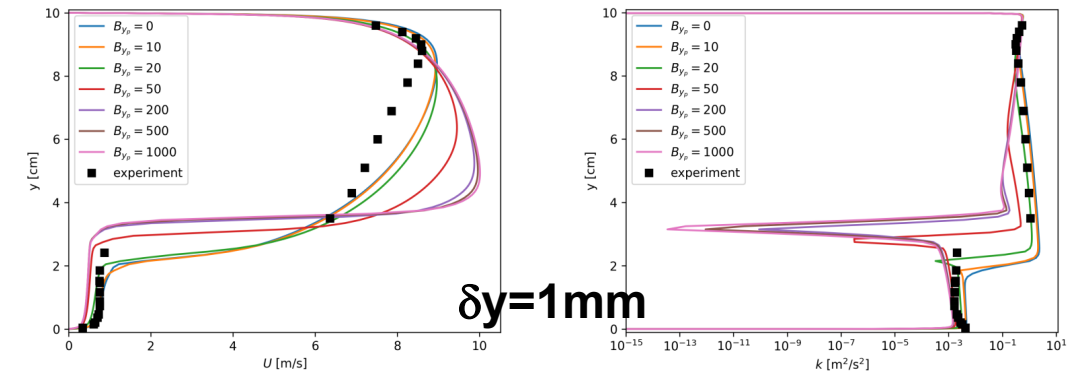
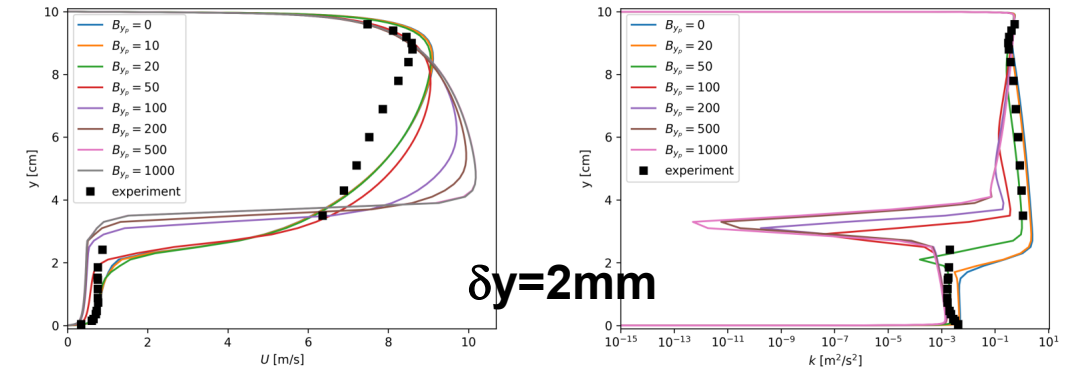


Limitation of Interface Turbulence Damping Method

- Fan and Anglart, 2019 (the improved Egorov interface turbulence damping model), Run-600
- Add source term to ω equation; $S_{\omega,i} = \frac{36A_i\mu_i^2}{\beta\rho_i} \frac{B^2}{\Delta n^3}$.
as ω BC near wall: $\omega = 10 \frac{6\nu}{\beta_1\Delta y^2}$
 - In Star-CCM+, $\Delta n = \sqrt[3]{V}$,
 - In Fluent: Δn is the normal distance to interface
 - B: tuning parameter
- Issues:
 - Cell size and/or shape dependent.
 - As mesh is refined, the solution becomes unstable.
 - Calibrated B number is not universal.

Calibrated B number for different flows and mesh sizes

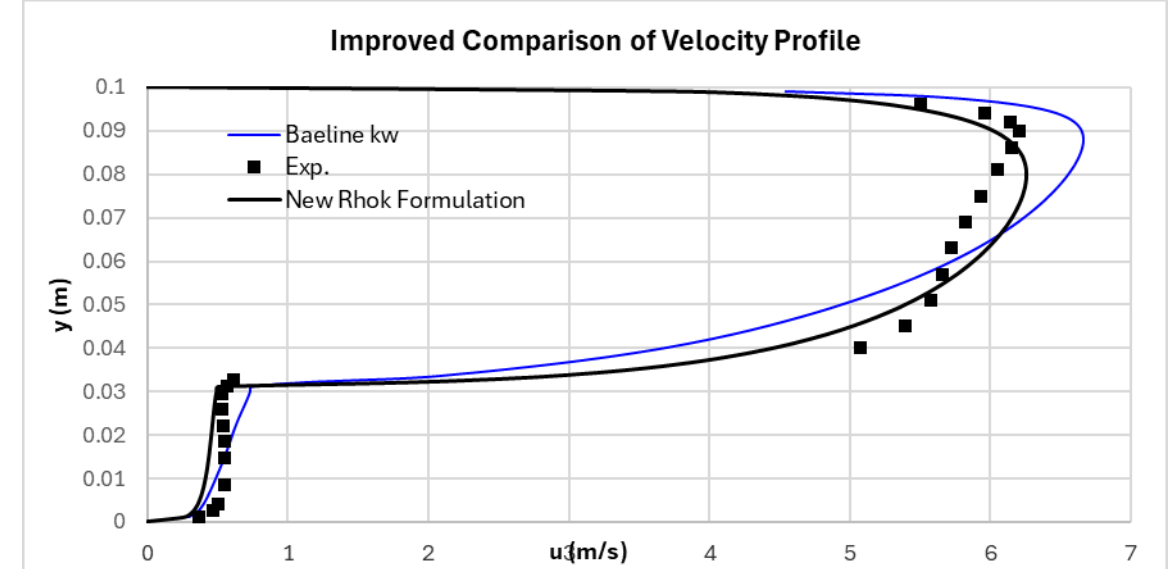
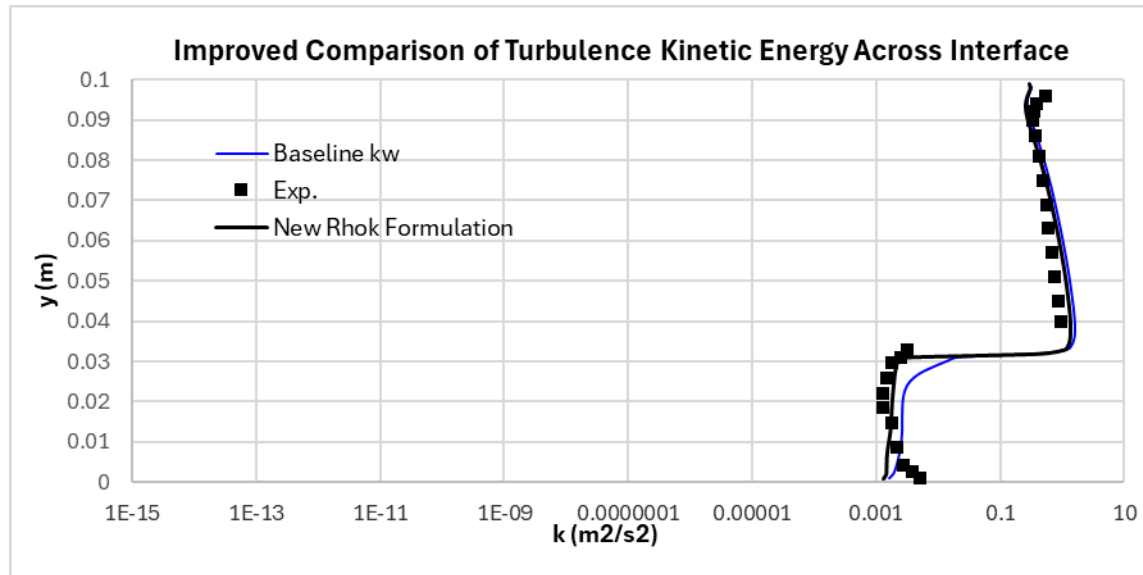
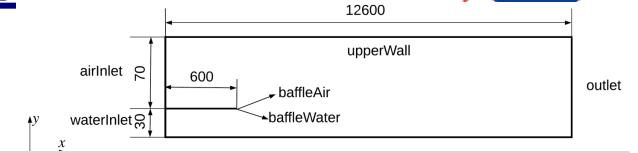
	$\delta y=2\text{mm}$	$\delta y=1\text{mm}$	$\delta y=0.5\text{mm}$
Run600	50	20	10
Run400	20	10	5
Run250	20	10	10



Improved Solution: # 2 Benchmark Validation of Stratified Parallel Flow



Run 400: Experimental evidence of ρk continuity across the interface



Key Observations

- Experiments confirm a density-jump in k across the interface.
- Baseline models overpredict interfacial turbulence by $\sim 5\times$.
- ρk restores correct turbulence and velocity behavior.

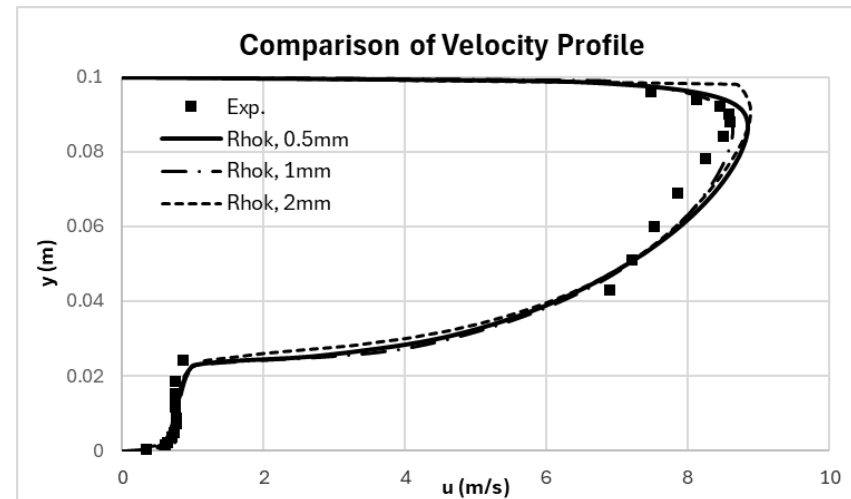
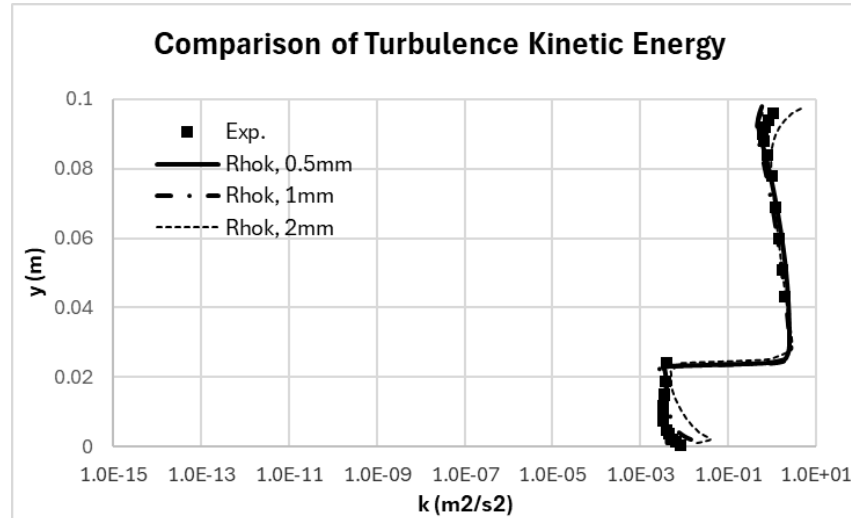
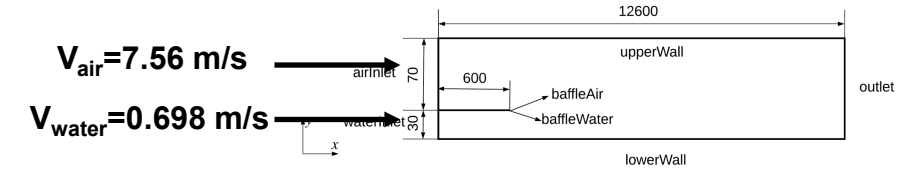
These results confirm that enforcing physically consistent turbulence transport across density interfaces is essential for accurate interfacial momentum and energy transfer.

Improved Solution: # 2 Benchmark Validation of Stratified Parallel Flow



ρk Formulation

Run 600



New ρk Model Advantages:

- Simulations were performed using three mesh resolutions: 0.5 mm, 1 mm, and 2 mm. For the 2 mm mesh, the near-wall non-dimensional distance (y^+) is approximately 20.
- With the 2 mm mesh, the conventional $k-\omega$ SST turbulence model shows degraded performance in the near-wall region, but it still reproduces the turbulence kinetic energy (TKE) jump across the interface.
- The proposed ρk -based formulation demonstrates greater robustness, accurately resolving interface turbulence effects across all mesh resolutions tested.
- In contrast to the interface turbulence damping model, which is highly sensitive to both flow condition and mesh size, the ρk formulation remains independent of mesh resolution and flow condition, ensuring more reliable predictions.

Implications for Hypersonic Turbulence Modeling



- **Shock waves introduce abrupt density jumps**
- **K-based turbulence transport violates conservation across shocks**
- **ρk formulation enforces physically consistent transport**
- **Expected benefits:**
 - Improved shock–boundary-layer interaction modeling
 - Improved heat-flux prediction robustness



Conclusions

- Conventional k -based turbulence models fail at sharp density interfaces, leading to excessive turbulent mixing, loss of thermal stratification, and nonphysical pressure behavior in CFM simulations.
- The root cause is the transport of mass-specific turbulent kinetic energy k across interfaces, which is inconsistent for large density ratios.
- A physics-based reformulation using turbulent kinetic energy density (ρk) was developed, enforcing correct interfacial behavior by construction.
- The ρk formulation:
 - naturally limits turbulent viscosity near the liquid–gas interface,
 - eliminates the need for empirical interface damping,
 - provides mesh-robust and numerically stable solutions.
- Validation against Fabre stratified flow experiments and cryogenic tank pressurization benchmarks demonstrates:
 - correct turbulence behavior across interfaces,
 - improved velocity, temperature, and pressure predictions,
 - consistency with laminar trends where appropriate.
- These results establish the ρk formulation as a robust foundation for predictive turbulence modeling in multiphase and hypersonic flows, with CFM serving as a representative multiphase application.

Future Work



- **Extension to compressible flows**
 - Apply the pk formulation to **variable-density compressible turbulence**
 - Assess behavior across **shock waves and expansion fans**, where density jumps also violate conventional k-transport assumptions
 - Evaluate shock–turbulence interaction without empirical damping
- **Hypersonic flow applications**
 - Incorporate the pk formulation into **hypersonic CFD solvers**
 - Study turbulence behavior in:
 - boundary layers with strong density gradients,
 - shock–boundary-layer interactions,
 - high-enthalpy, thermally nonequilibrium flows
 - Examine robustness for **Mach 5+ regimes** relevant to defense and space access
- **Advanced CFM simulations**
 - Apply the model to **full cryogenic tank configurations**, including:
 - self-pressurization,
 - noncondensable gas effects,
 - sloshing and drain scenarios
 - Quantify improvements in pressure, temperature, and phase-change prediction
- **Model generalization and validation**
 - Extend to additional turbulence closures (e.g., Reynolds stress models)
 - Validate against **additional experimental datasets** and flight-relevant conditions
 - Assess performance on **unstructured and adaptive meshes**

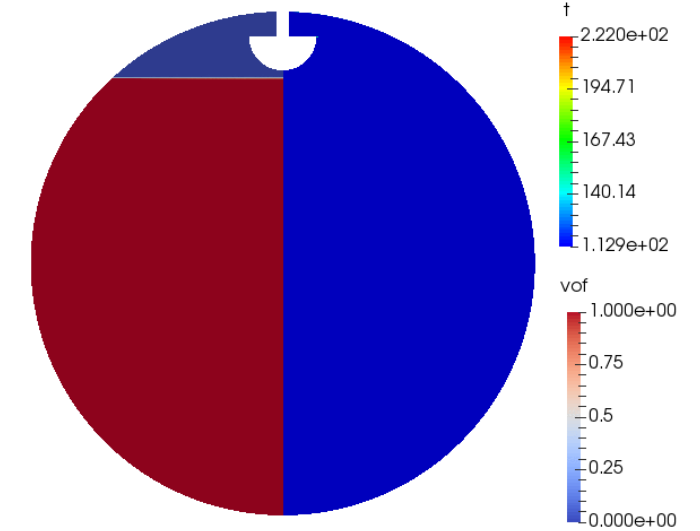
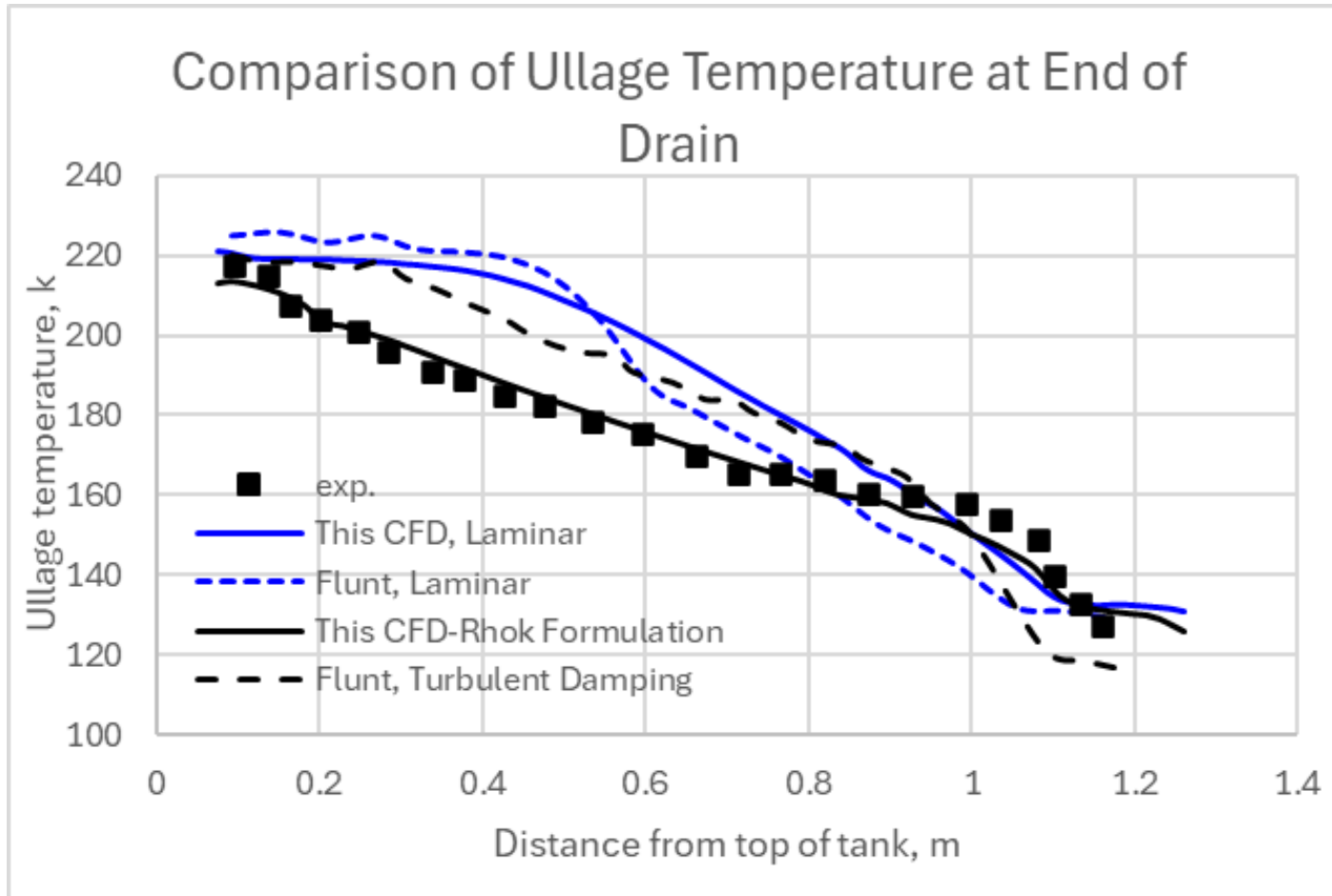


Back up

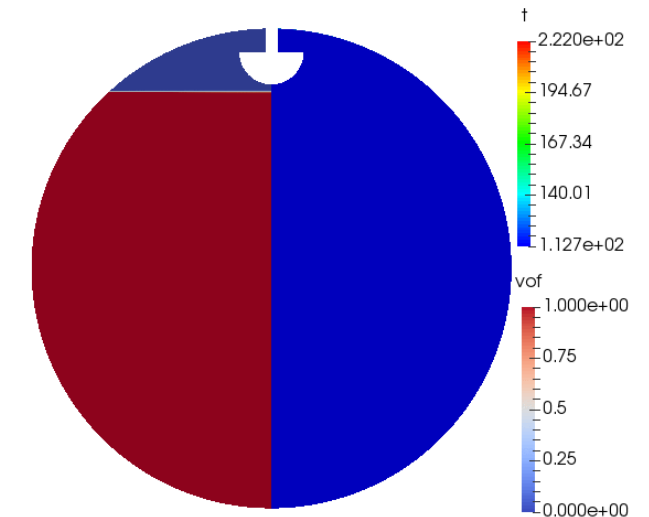
Improved Solution: # 3 Tank Pressurization, Hold and Drain



Validation for Tank Pressurization, Hold, Drain.



Stream/VOF, Laminar



Stream/VOF, New ρ_k Formulation



Improved Solution: # 4 Self-Pressurization

Tank Self-Pressurization due to Heating

