International Institute for Cavitation Research

Different Modelling Approaches for Flash Boiling

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Presentation Layout

- **Problem Statement**
  - Effect of flash-boiling onset on Nozzle flows
  - Technological Applications/Experimental investigations
- **Modelling approaches**
  - Thermodynamic equilibrium or not
  - Suitable mass-transfer models
- **Benchmark cases**
  - Formulation of the numerical models
  - Comparison to experimental data
- **Liquid Oxygen Properties**
  - Tabulated Data based on the Helmholtz EoS
  - Preliminary Simulations
- **Concluding remarks**
  - Main findings
  - Open questions

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Effect of flashing

- **Flash boiling:** Intense nucleation occurring throughout the entire liquid volume and usually caused by a rapid depressurization process that leads to liquid superheat, i.e. $\mathbf{p=p_{sat}}$ yet $\mathbf{T>T_{sat}}$.

- **Jet atomization:** Rapid disintegration of the liquid bulk into small droplets; formation of a fine spray for flashing conditions

- **Occurrence of flashing in nozzle flows is associated to:**
  - Reduced penetration of the jet exiting the nozzle
  - Enhanced spray atomization efficiency
  - Increased spray angle
  - Complex pressure distribution at the spray region (formation of shockwave system)

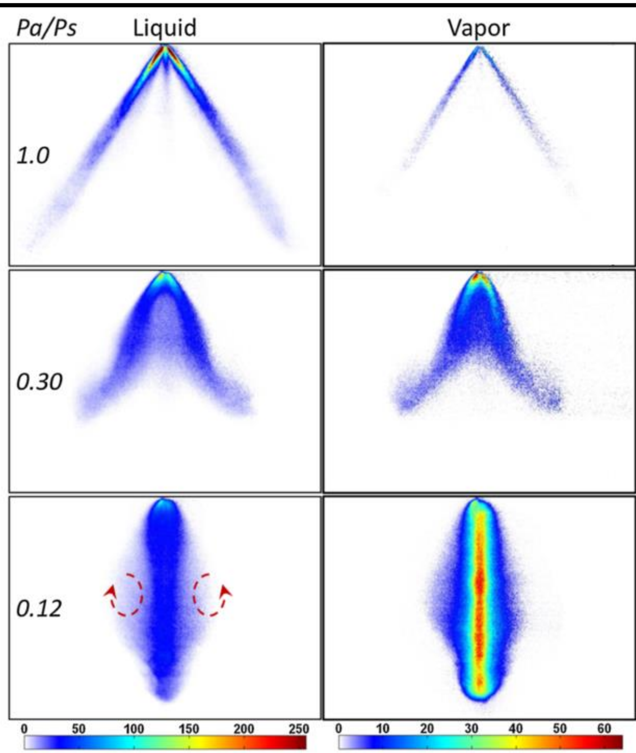
Exp. Investigations/Applications

Operation under (partial) vacuum conditions

- Gasoline engines
- Rocket engines

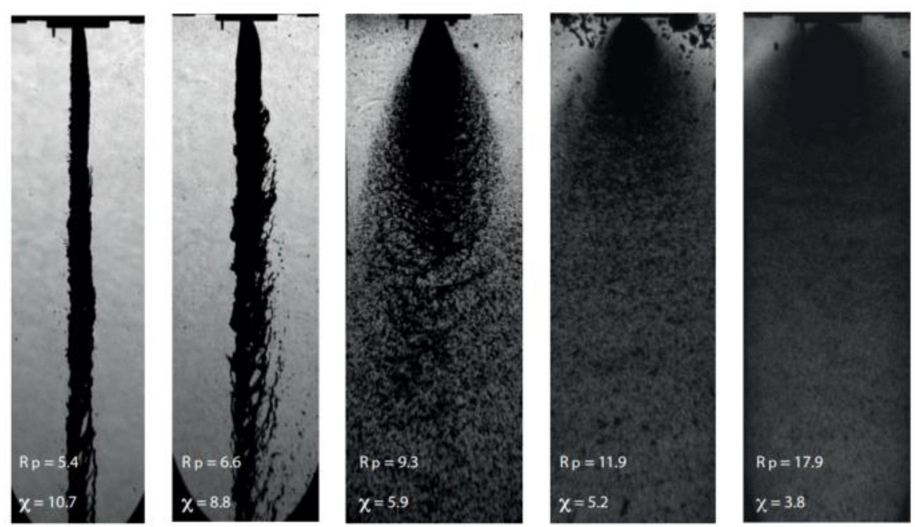
→ *Flashing is possible to occur in both applications yet the operation objectives are in fact opposite*

Zhang et al., 2014: n-hexane flashing at T_{inj}=298-358K (LIEF)



Common macroscopic flow features despite the difference in thermodynamic properties

Lamanna et al., 2015: LOX flashing at T_{inj}=94K (Shadowgraphy)



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Modelling Phase-Change

Two-phase models: **Finite mass-transfer rates associated with empirical quantities**

Linear mass-transfer rate (Knudsen)

$$\dot{R} = C_{evap} A_{int,tot} \alpha_l \rho_l \Delta p$$

$A_{int,\,tot} = n_0 \, A_{bubble}$

Hertz-Knudsen Equation

$$\dot{R} = \frac{\lambda (p_{sat} - p)}{\sqrt{2\pi R_g T_{int}}}$$

λ<1: departure from equilibrium

Homogen. Relaxation Model (HRM)

$$\dot{R} = -\rho_{mix} \frac{Y - Y_e}{\Theta} \quad \begin{cases} Y_e = \dfrac{h_{mix} - h_{sat,l}}{h_{sat,v} - h_{sat,l}} \\ \Theta = \Theta_0 a^m \phi^n \end{cases}$$

Homogen. Equilibrium Model (HEM)

$$p(\rho,T) = \begin{cases} B\left[\left(\rho / \rho_{sat,L}(T)\right)^n - 1\right] + p_{sat}(T), & \rho \geq \rho_{sat,L}(T) \\ p_{sat}(T), & \rho_{sat,V}(T) < \rho < \rho_{sat,L}(T) \\ \rho R T, & \rho < \rho_{sat,V}(T) \end{cases}$$

Numerical Formulation/ Bubble dynamics models

2D, transient flow simulations

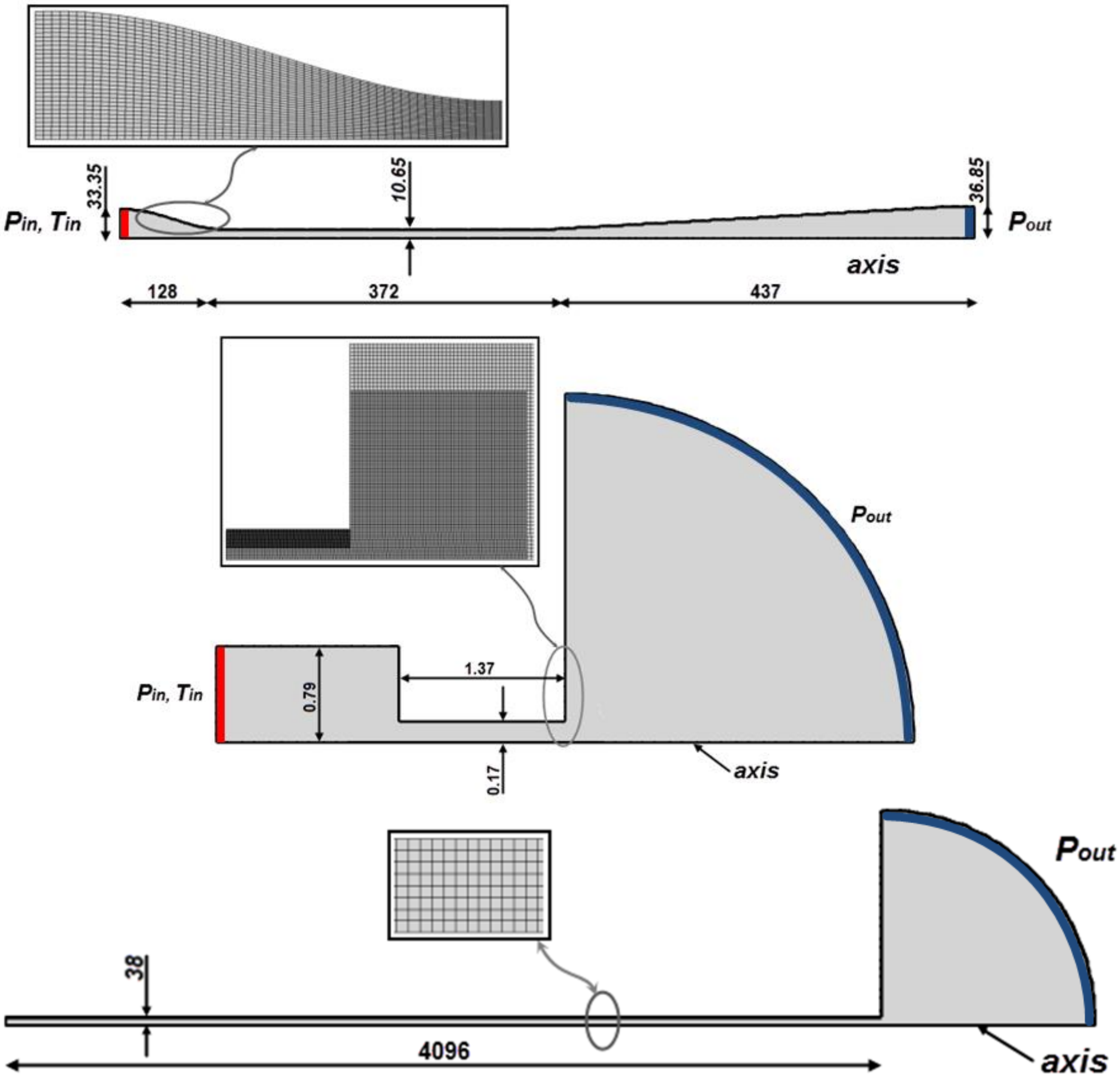
- Mixture two-phase model: mechanical equilibrium between the phases
- Liquid: Tait equation of state
- Vapour: ideal gas
- Mixture compressibility: $$\frac{1}{\rho} \cong \frac{1-a}{\rho_l c_l^2} + \frac{a}{\rho_v c_v^2} - \frac{\delta m}{\delta p}\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)$$

Vapour fraction transport equation

$$\frac{\partial(a\rho_v)}{\partial t} + \nabla(a\rho_v \boldsymbol{u}) = \dot{R}$$ → **Mass-transfer term modelled**

- SST k-ω turbulence model
- Implicit, coupled solver
- Second order schemes for momentum and turbulence advection
- Time step of 1μs corresponding to CFL numbers ~4-5 in the nozzle

Benchmark Geometrical Layouts



Moby Dick nozzle

- Water, steady problem
- T_{in}=Tsat-2K
- P_{in}=20bar, P_{out} =5bar

Reitz nozzle:

- Water, steady problem
- T_{in}=360-427
- P_{in} =7.97bar, P_{out}=1bar

Edwards' pipe:

- Water, transient problem
- T_{in}=502K
- P_{in}-P_{out} =70bar

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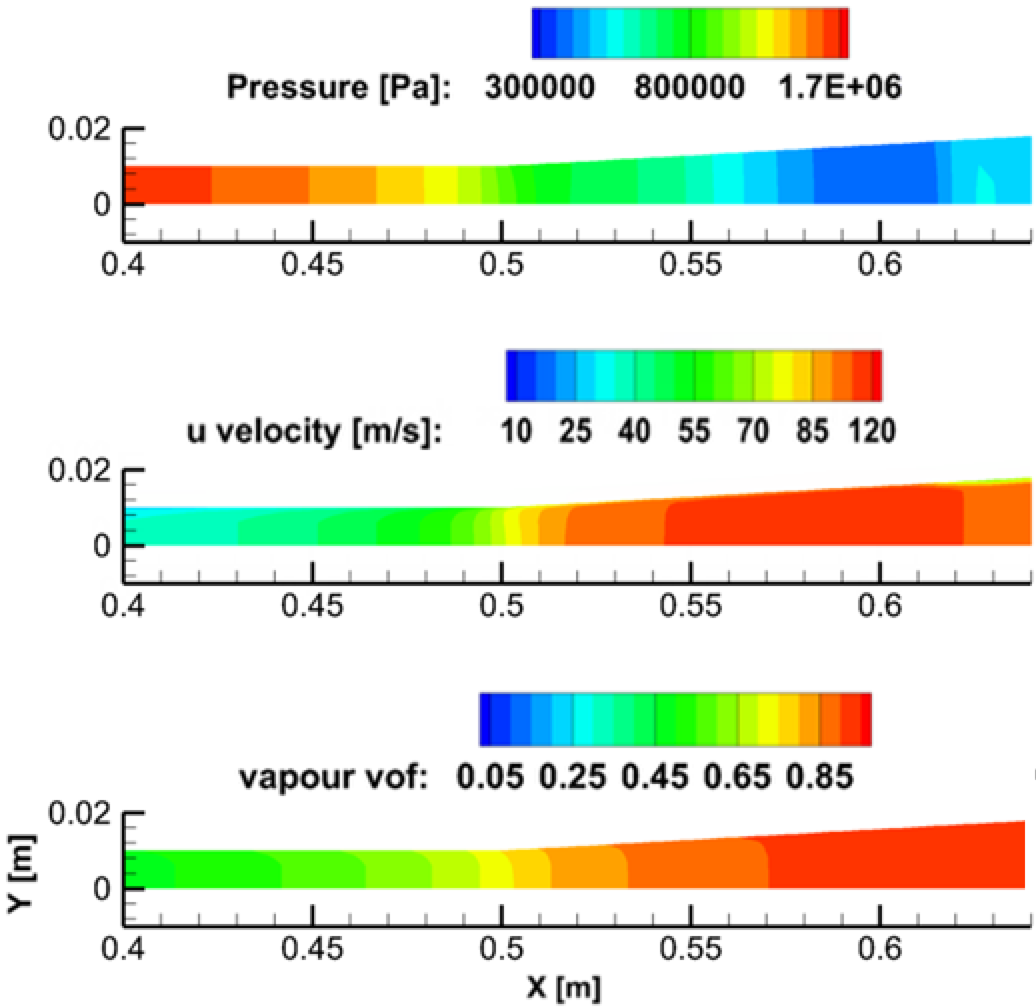
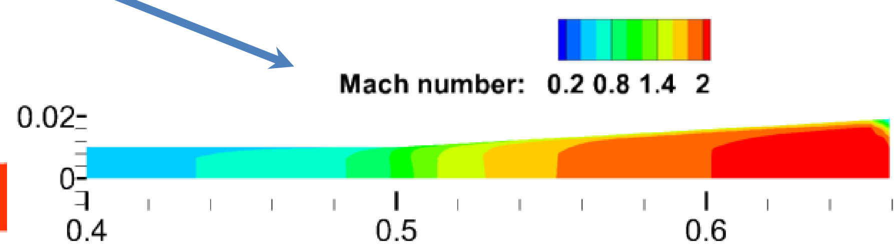
Moby-Dick Nozzle (1)

Hertz-Knudsen model, λ=0.1



- Flow acceleration at the divergent region → expansion of initially choked two-phase flow
- Supersonic flow downstream the throat
- Almost full liquid vaporization has occurred at an axial distance X=0.65m

Mach number distribution



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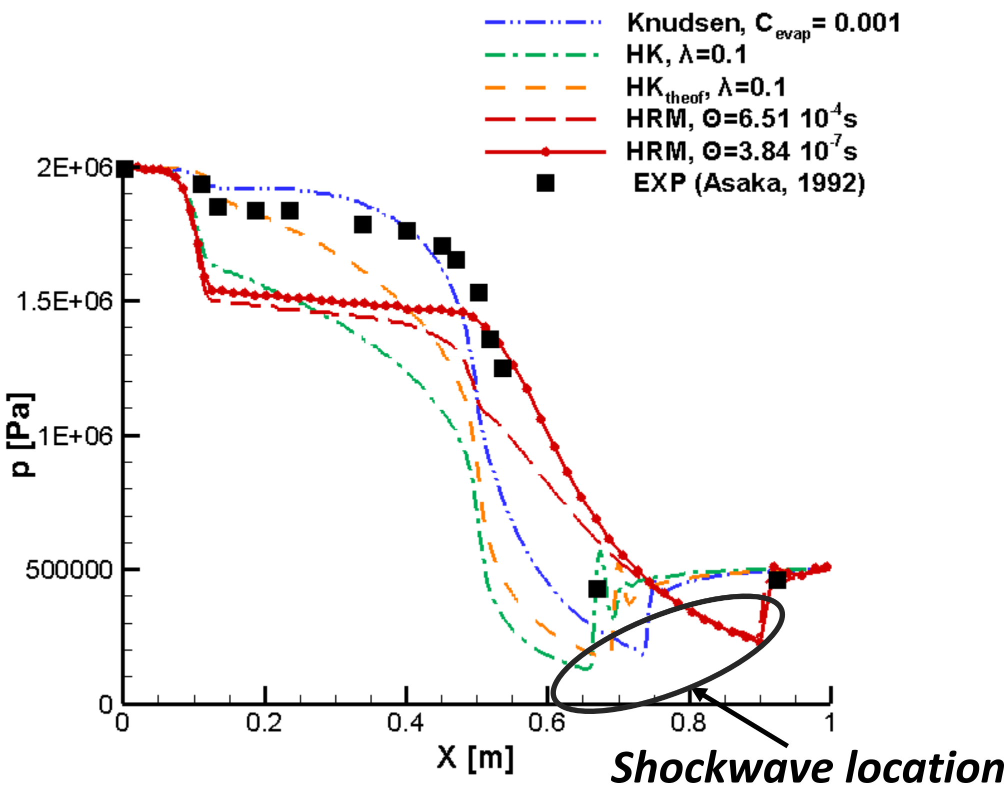
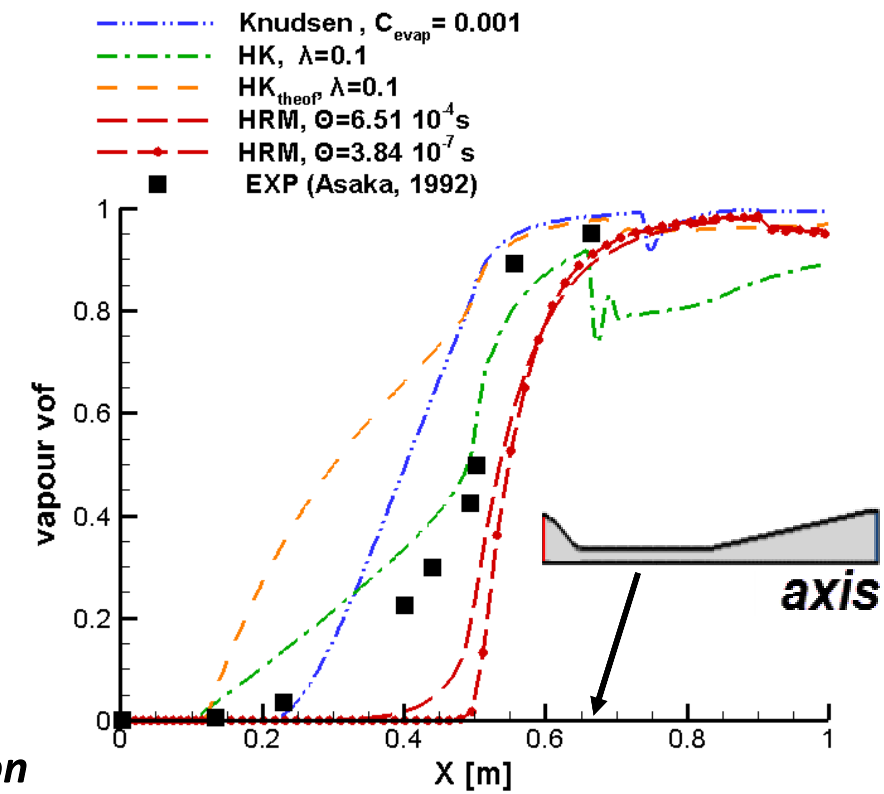
Moby-Dick Nozzle (2)

Pressure/VOF distribution at the nozzle axis

- **Adequate agreement achieved by all models.**
- **Higher mass transfer rate accompanied by increased in-nozzle pressure**
- **Shockwave predicted by all models however at different locations**



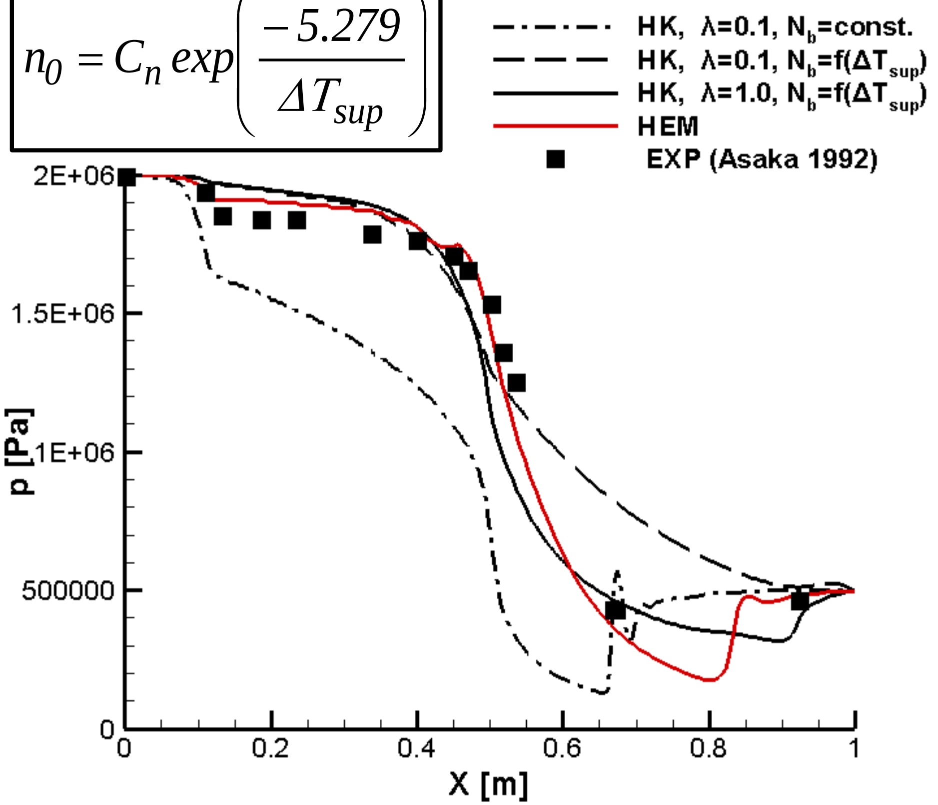


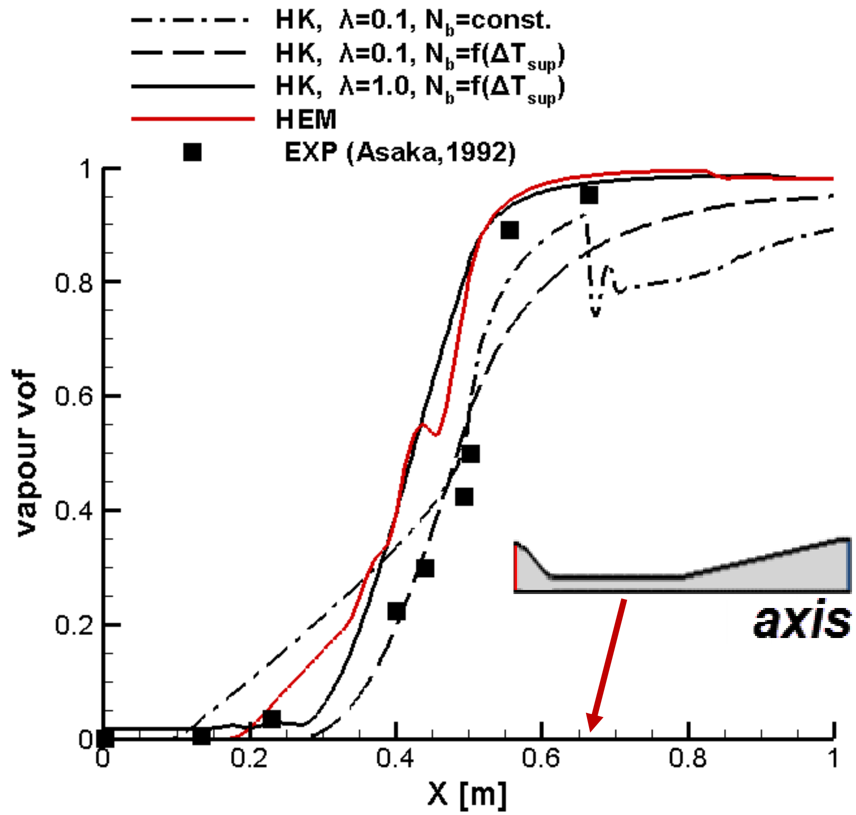
Effect of nucleation-site density

Variable nucleation site density (Senda et al., 1994)

- Excellent agreement obtained for λ=1 (thermodynamic-equilibrium)
- No clear distinction of the effects of nucleation-site density and actual thermodynamic conditions on phase-change rate

$$n_0 = C_n \, exp\left(\frac{-5.279}{\Delta T_{sup}}\right)$$

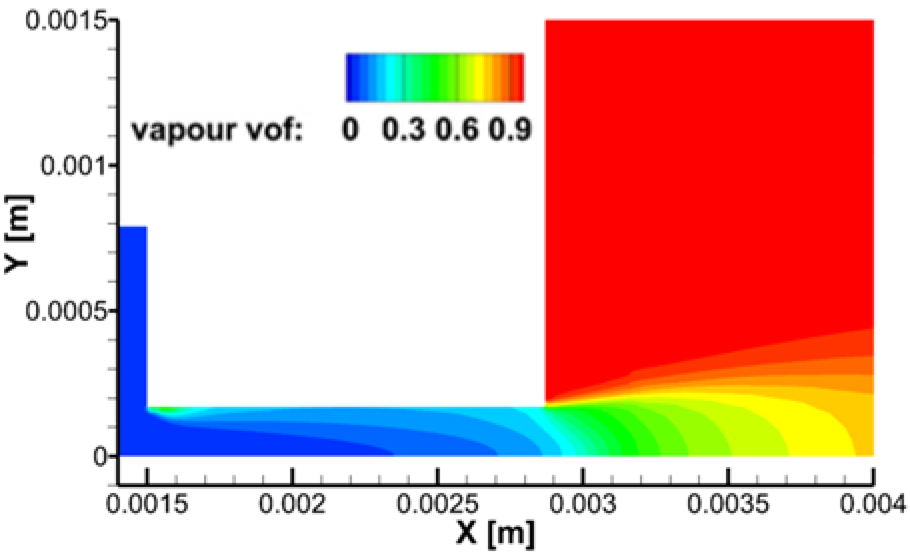




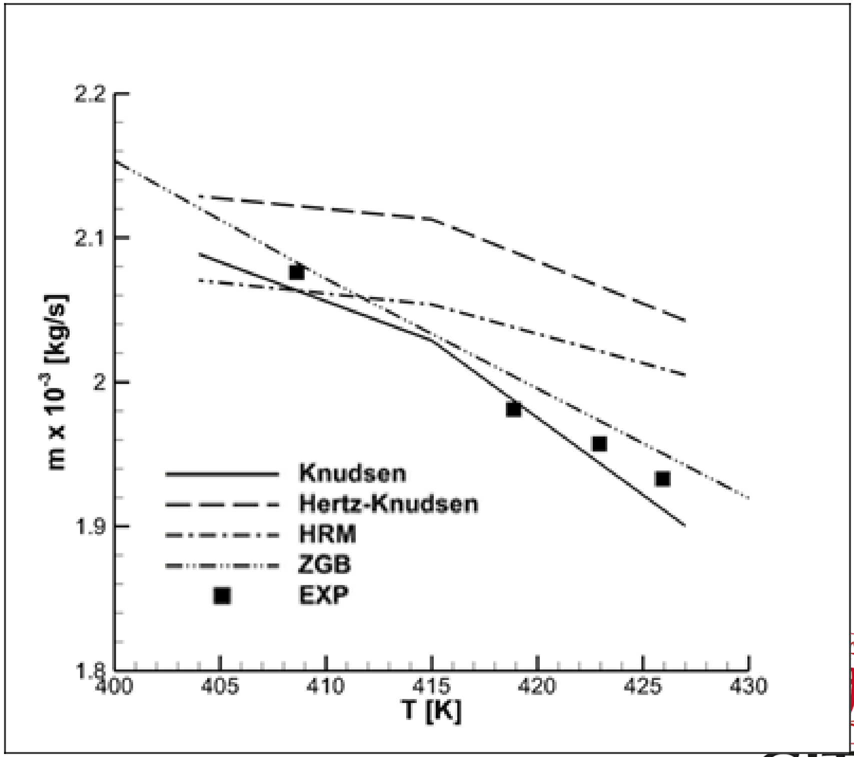
Reitz nozzle(1)

Phase field for T=427K

- Liquid core could evident at the nozzle outlet and severe atomization sets in immediately downstream the nozzle outlet
- Mass flow rate decreases due to the increasing part of nozzle cross section occupied by vapour



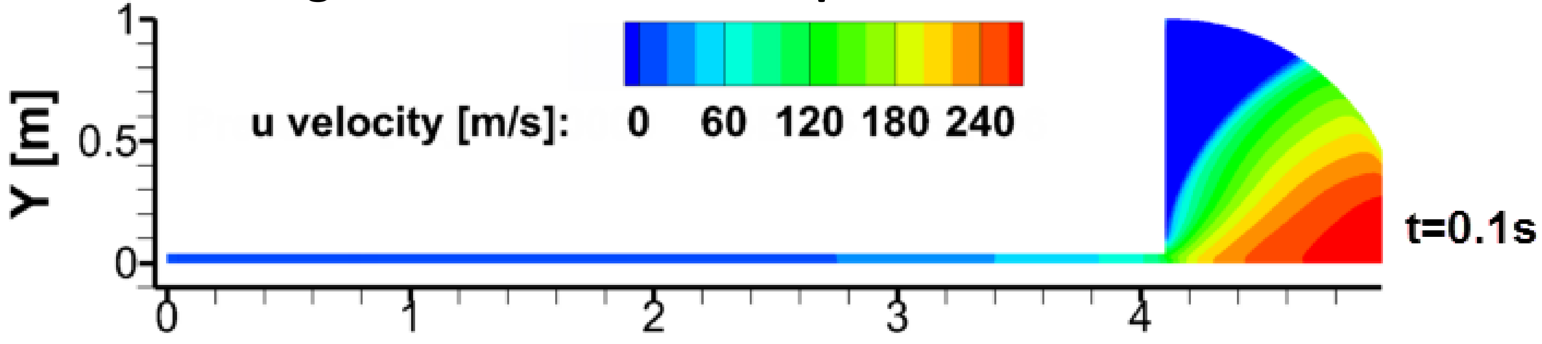
T=427K, HRM (Θ=6.51·10^{-4}s)

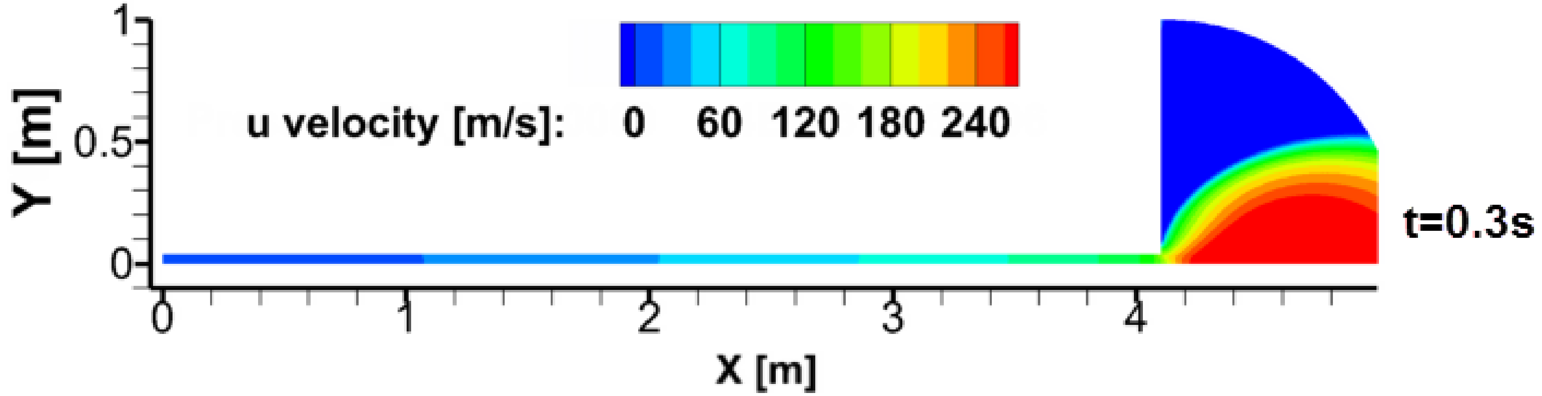


Edwards' pipe (1)

Velocity field (Hertz-Knudsen, λ=0.1)

- Flow acceleration towards the pipe outlet as the phenomenon evolves
- Increased cone angle due to flow over-expansion

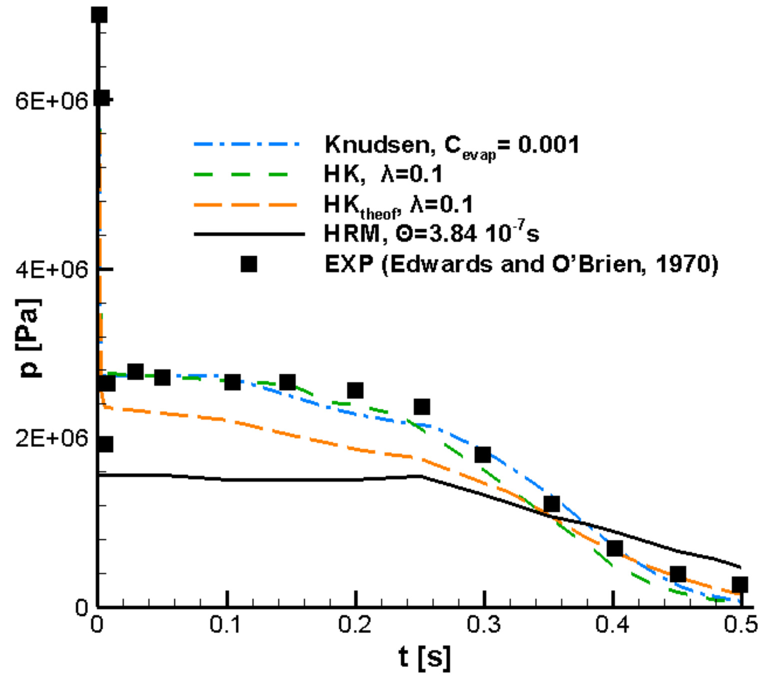


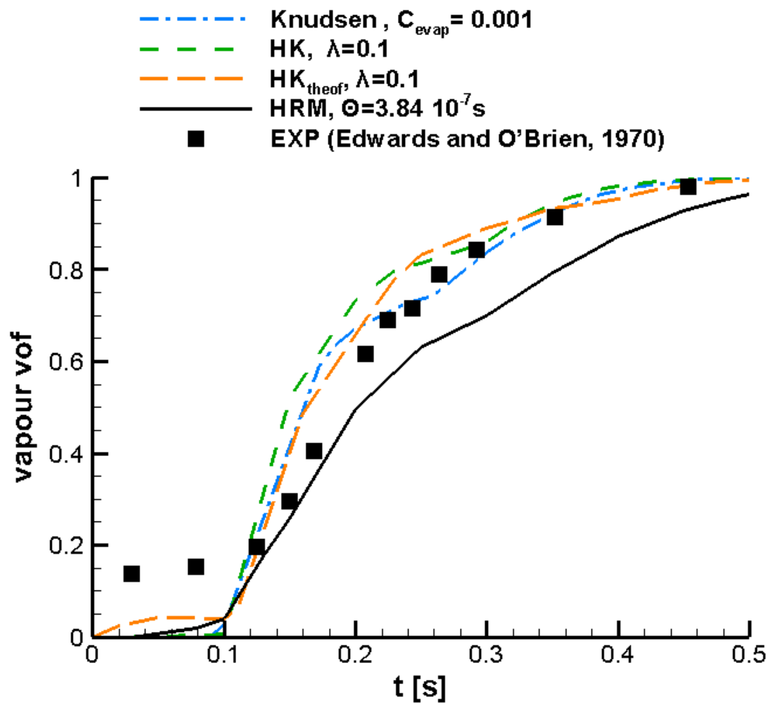


Edwards' pipe (2)

Pressure at the pipe left wall/Vapour vof at the pipe mid-section

- **Knudsen and Hertz-Knudsen equations produce accurate predictions**
- **Liquid vaporization caused due to rarefraction wave**
- **Vaporization occurs at a sharp interface reaching left wall at ~0.5 s**
- **Calibration of HRM parameters for externally flashing flows needed**





Conclusions

- Accurate predictions of Hertz-Knudsen models for all examined cases. Possible HRM tuning for mass transfer through sharp interphase
- Information of nucleation-site density is vital for accurate predictions.
- Flashing within the nozzle is accompanied with choked flow and increased spray cone angle of the expanding jet.
- LOX thermodynamic properties successfully predicted using Helmholtz EoS; Good agreement with NIST REFPROP
- Preliminary simulations verified the robustness of the implemented methodology for predicting flashing of cryogenic fuel

Open Questions/ Future research

- **Clear identification of the flashing regimes, i.e. internal or external and effect of orifice manufacturing characteristics (L/D, roughness etc.)**
- **Characterization of the inception-point distribution in the liquid bulk- Methods to avoid model tuning**
- **Effect of heat-transfer rate & Jacob number on mass-transfer rate**
- **Explicit correlation between the expanding-jet characteristics (velocity, cone angle, droplet size) and the phase-change rate within the nozzle**
- **Experimental studies needed to designate HRM coefficients for hydrocarbon and cryogenic fuel**

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