CFD modelling of liquid pressurized water and phase change through leaks in micro-cracks

Quantitative estimates - comparison with analytical solutions

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64th IUVSTA Workshop

Introduction (1)

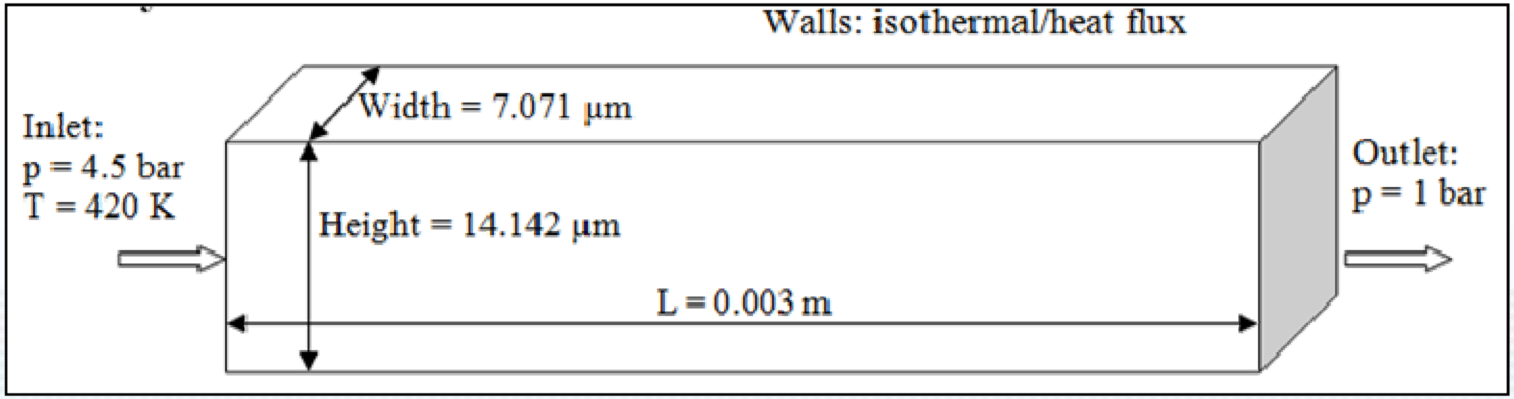
- Vapour leak in the vacuum vessel of ITER
- Detection of leaks and determination of the fastest method to pinpoint the leak location
- FLUIDYN mandated for 2 tasks :
  - Model the spatial distribution of water vapour from a leak in the BSM according to the leak type, operational state and location
  - **Model the liquid water behaviour flowing through a crevice into the vacuum according to the type of crevice**

Introduction (2)

- Preliminary studies :
  - Analytical tool based on Sharipov (99) and Sharipov et al (2010)
  - CFD modeling of He flowing into crevice (pure gas+ heat exchange)

- CFD modeling for water leaks (with phase change)
  - Use of Homogeneous Equation Model (HEM)
  - 4 cases :
    1. Isothermal fluid : all heat needed is available
    2. Isothermal wall boundary : maximum heat from the wall
    3. Adiabatic wall boundary : no heat from the wall
    4. Conjugated Heat Transfer (1D) in the wall : more realistic

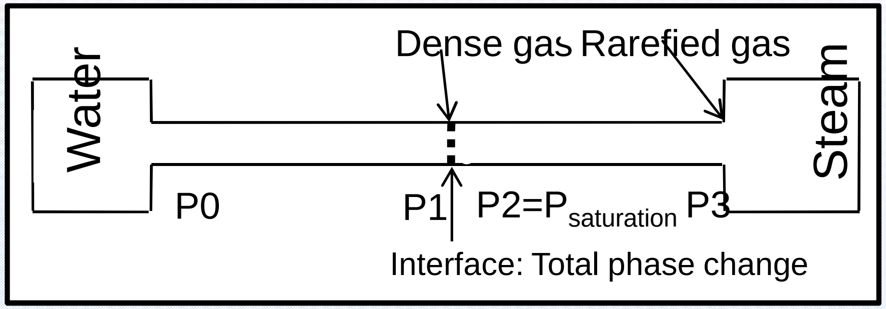
Geometry and case definition



- Length of 3 mm or 1cm depending on case
- H/w = 2
- Inlet pressure of 4.5E+05 Pa
- Outlet pressure of 1.0E+05 Pa
- Rarefaction parameter at outlet $\delta \sim 80$
- Temperature of fluid (or wall) = 420 K
- Computational domain : ¼ of the cross-section
- 16000 hexahedral elements.

Brief description of the analytical tool

- Sharipov model :
  - Isothermal flow
  - Total evaporation
  - Laminar liquid flow
  - Sharp interface between liquid and steam
  - Whole range of rarefied gas (slip to free molecular regime)



- Methodology :
  - Initialization : First guess of the mass flow rate
  - Based on rarefied gas solution, pressure profile upstream reconstructed up to the saturated pressure. Gaseous and liquid lengths estimated.
  - Liquid mass flow rate from Poiseuille solution estimated with liquid length.
  - Convergence criteria: balance between liquid and gas flow rate.

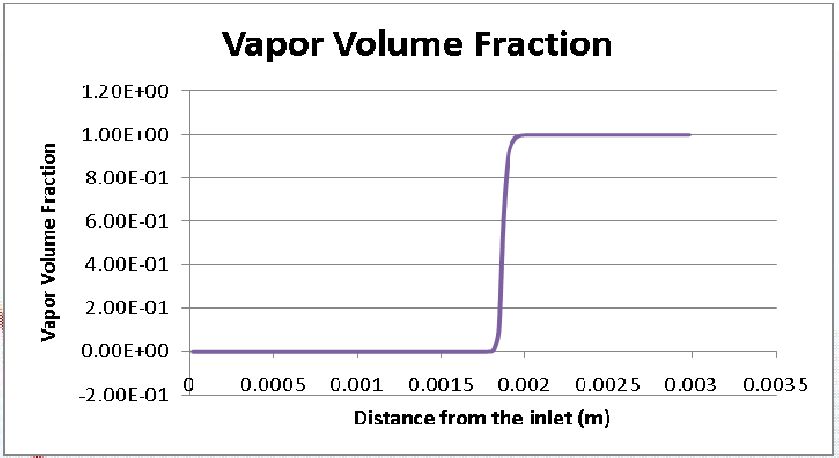
CFD model : HEM & 1D conduction model

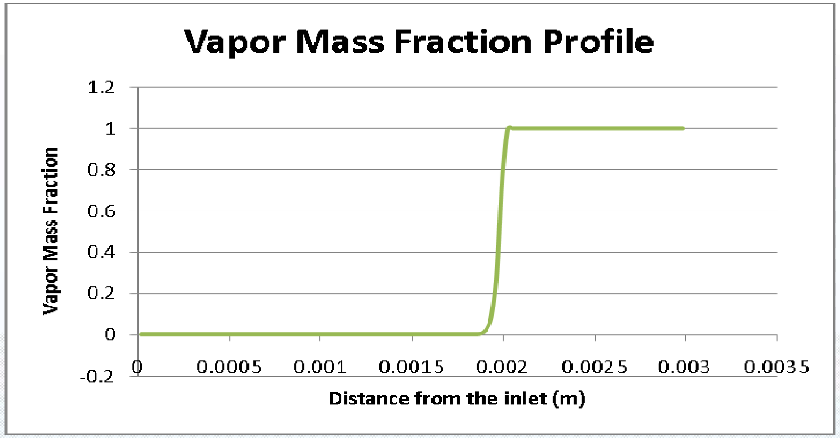
- Fluidyn-MP-NSNT

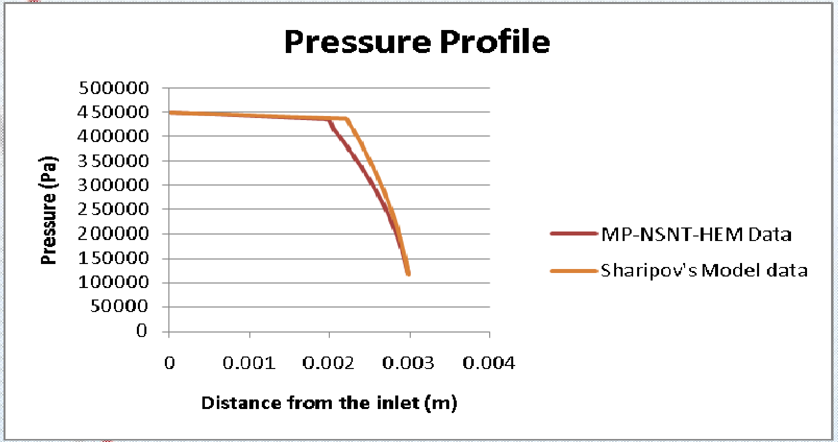
Equation for mixture	EOS
$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$ $\frac{\partial(\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{UU}) = \nabla \cdot \tau - \nabla p + S_{\mathbf{U}}$ $Cp\left[\frac{\partial(\rho T)}{\partial t} + \nabla \cdot (\rho \mathbf{U} T)\right] = \nabla \cdot \mathbf{q} - \left[\frac{\partial(\ln \rho)}{\partial(\ln T)}\right]_p \left[\frac{\partial p}{\partial t} + \mathbf{U} \cdot \nabla p\right] + S_T$ Transport equation for the gas phase $\frac{\partial(\rho \phi)}{\partial t} + \nabla \cdot (\rho \mathbf{U} \phi) = \nabla \cdot \mathbf{J} + S_\phi$	$p = \frac{T \sum_i^{i \neq h2ol} R_i \rho_i}{\theta} = \frac{\rho T \sum_i^{i \neq h2ol} R_i X_i}{\theta}$ Source term for evaporation $S_{h2og} = \left(\rho_{sat} - \rho_{h2og,gas}\right) / t_{pc}$

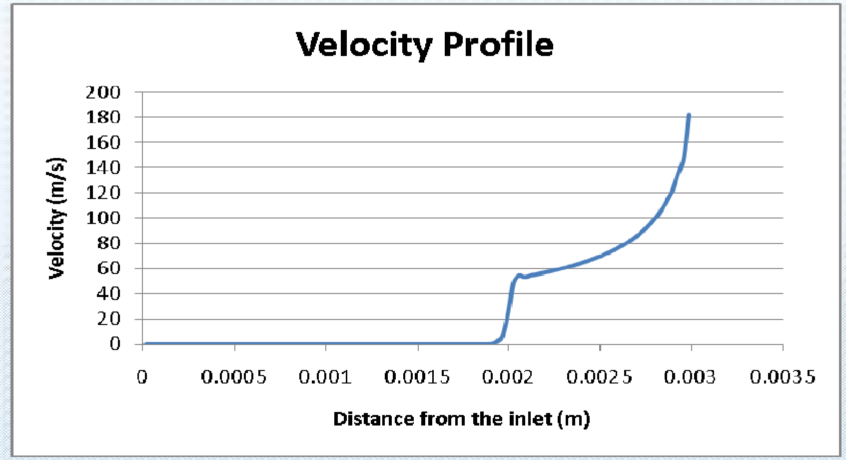
- Boundary Conditions:
  - Inlet: Liquid+ 10-8 mass fraction of gas
  - Outlet: Open at pressure 1bar
  - Structure: Adiabatic or isothermal or solution 1D conduction heat transfer in steel

Results for isothermal fluid for 3mm tube

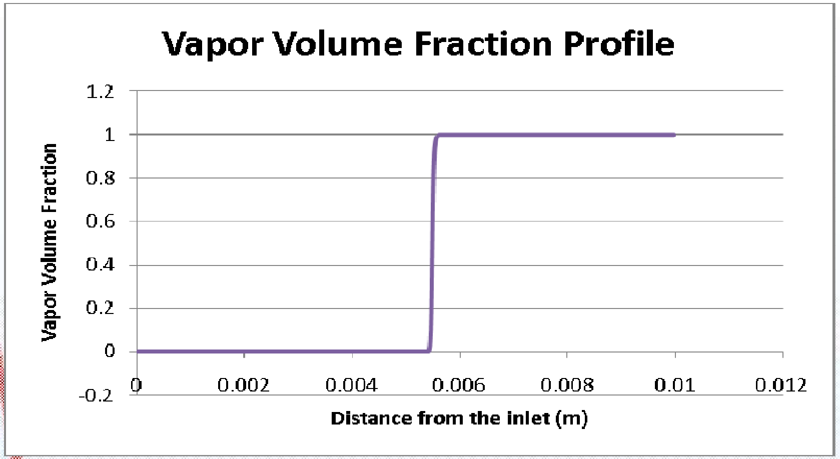


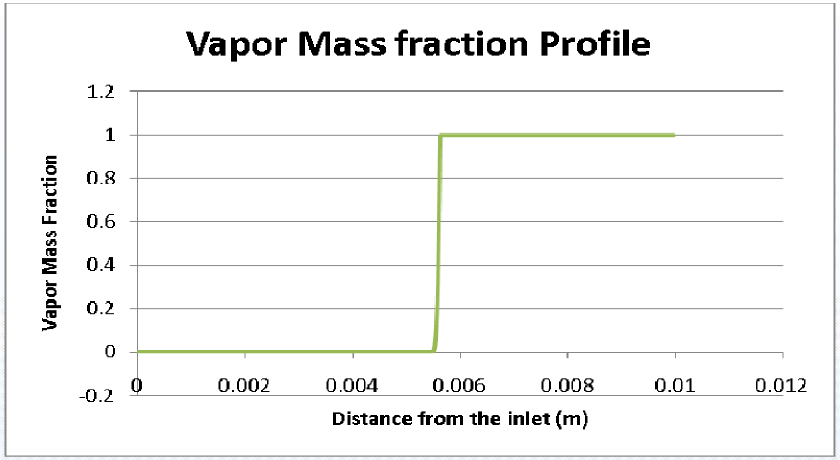


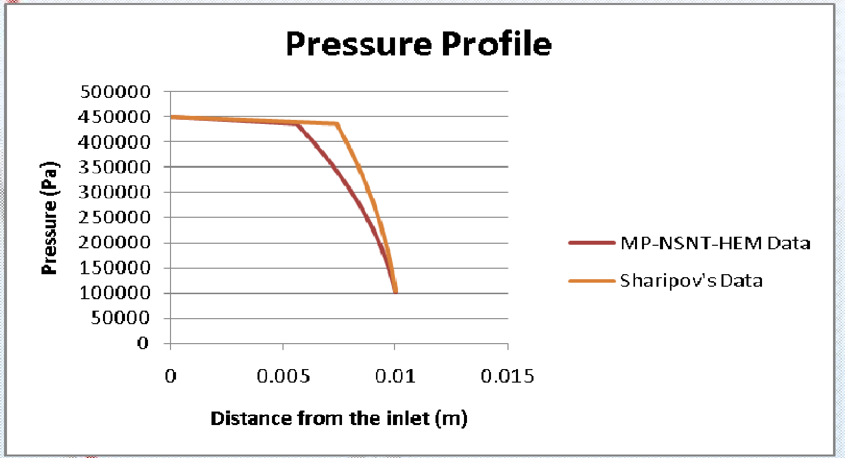


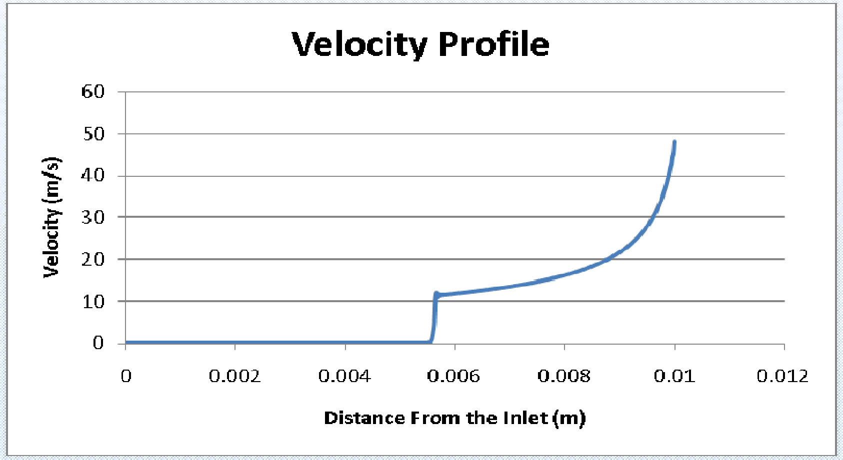


Results for isothermal fluid for 1cm tube









Isothermal fluid case

	Mass flow rate (kg/s)		Distance to Psat (m)	
	Sharipov	HEM	Sharipov	HEM
3mm	1.2E-08	1.13E-08	2.21E-03	1.97E-03
1cm	3.7E-09	2.55E-09	7.37E-03	5.51E-03

- CFD-HEM and analytical solution are matching.
- Differences may be due to:
  - non-slip conditions for this case (rarefaction order of 100).
  - different EOS laws for both Psat(T) and viscosities(T) liq and gas.

Thermal budget

A Posteriori analysis of energy requirement:

- Mass flow rate Q_m=1.2 10^{-8} kg/s
- Heat for evaporation L_v = 2.1 10^6 J/kg
- Q_w= 0.0256 W to be distributed on a equivalent surface (of wall)
- S= 42x10^{-6} m x 0.003m = 0.126 10^{-6} m^2

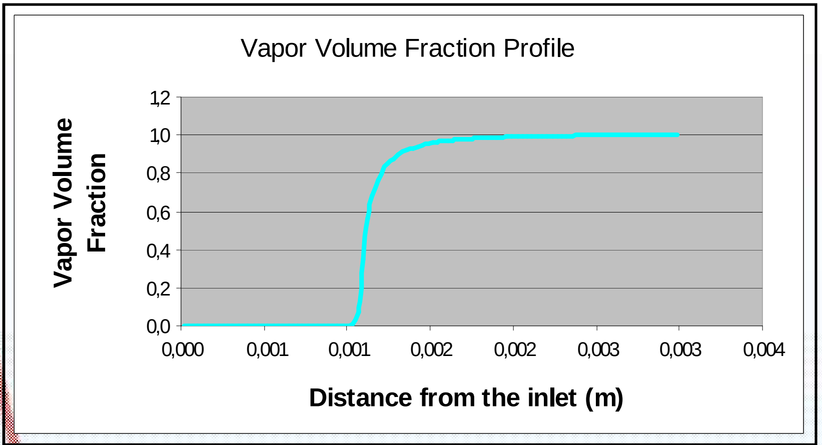
➢Average surface heat flux to be injected= ***203kW/m²***

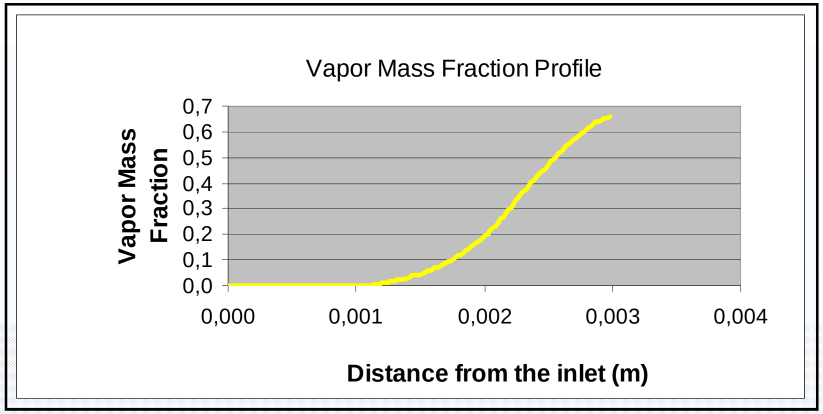
Can the Wall provide such heat flux (even worse on a sharp interface) ????

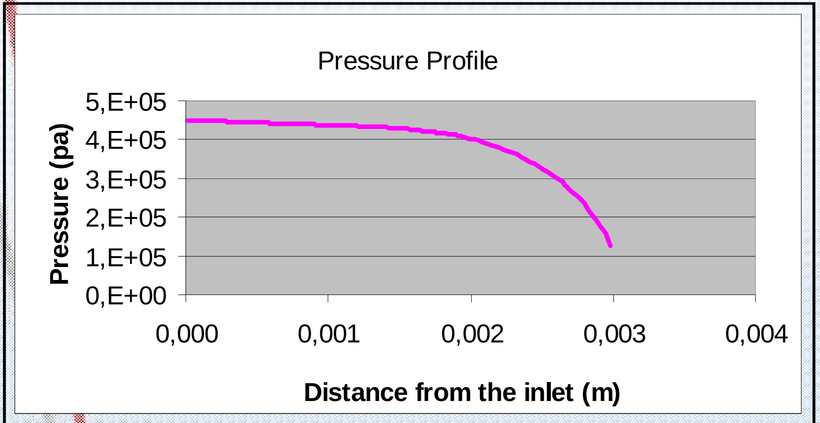
➢***Analysis with 3D CFD HEM and heat transfer in fluid and structure***

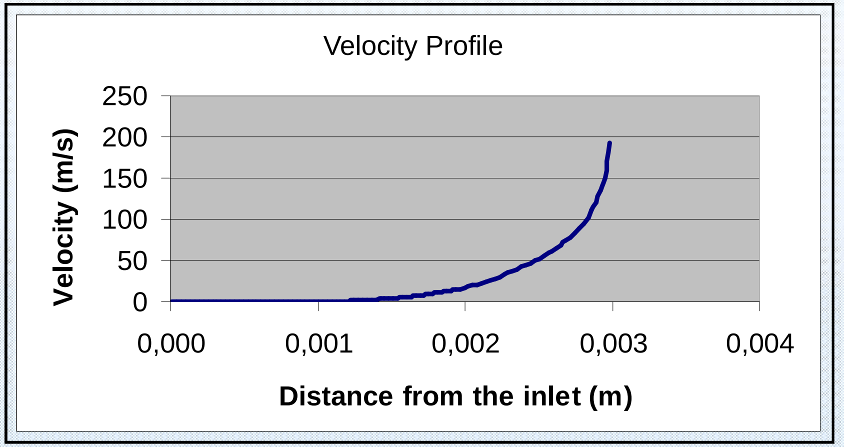
- Isothermal wall boundary (maximum heat flux from wall)
- Adiabatic wall boundary (no heat flux from wall)
- Conjugated Heat Transfer (1D-CHT) in the wall (conduction limited heat flux from wall = most realistic)

Results for isothermal wall (1/2)



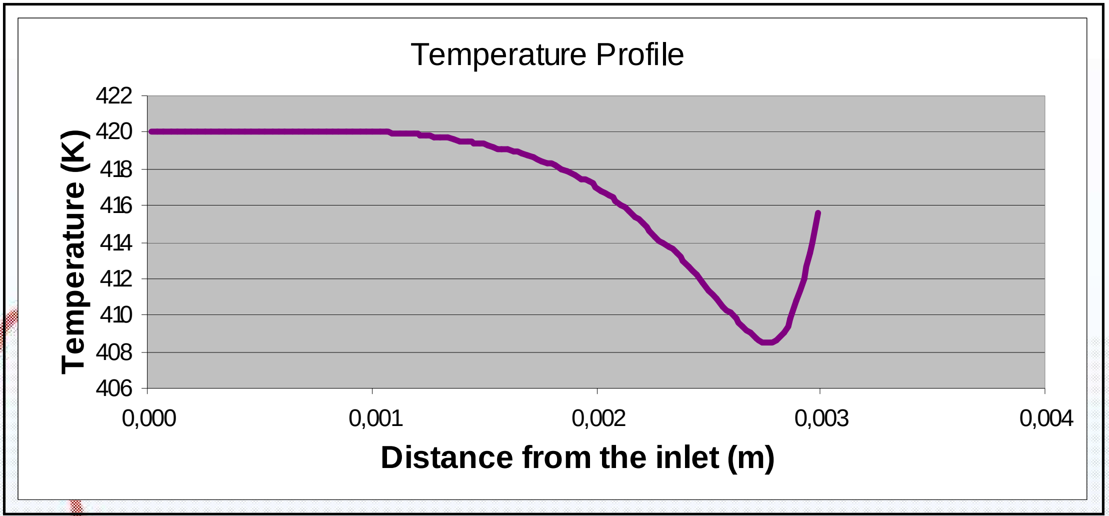


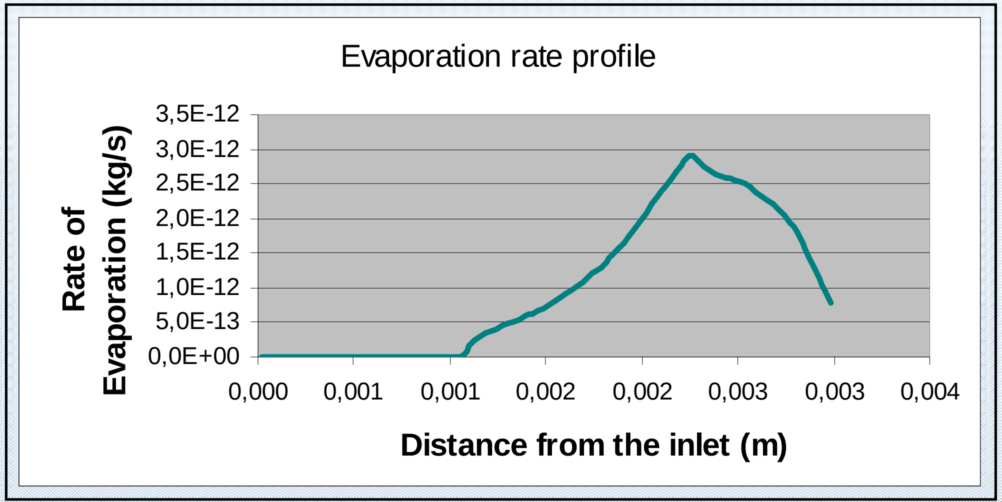




- Sharp Interface lost, pressure drop smoother, 30% mass fraction of liquid at outlet
- In relation with temperature drop (not maintained by heat flux from wall)

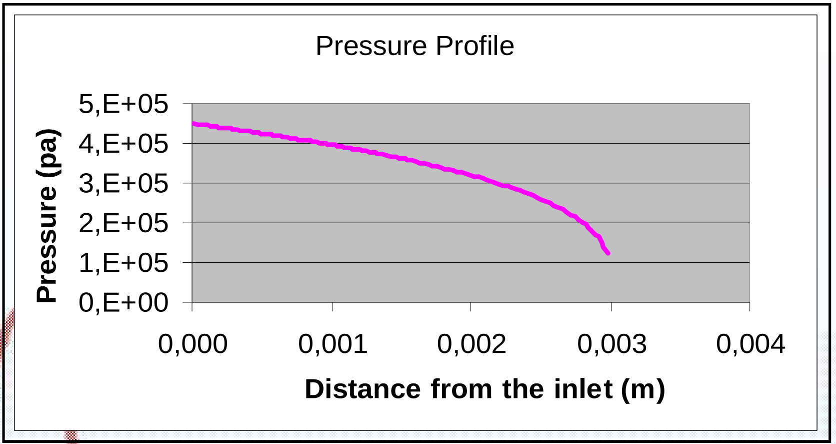
Results for isothermal wall (2/2)

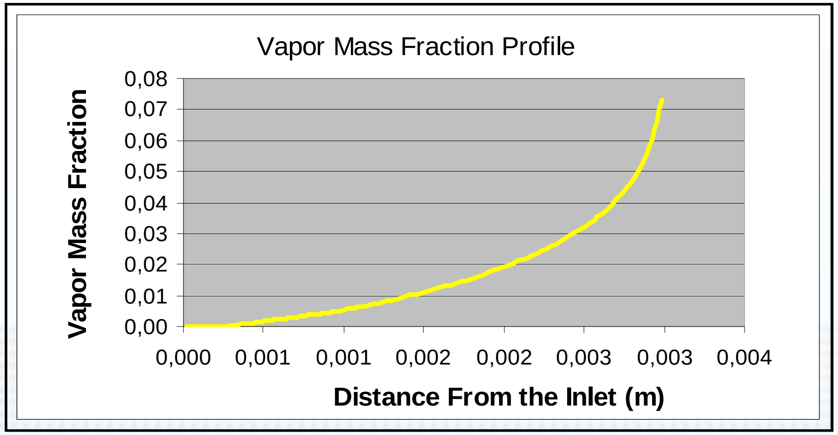


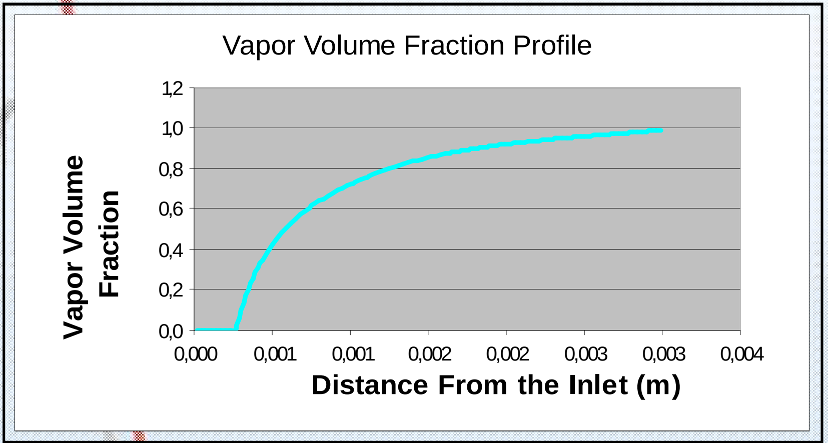


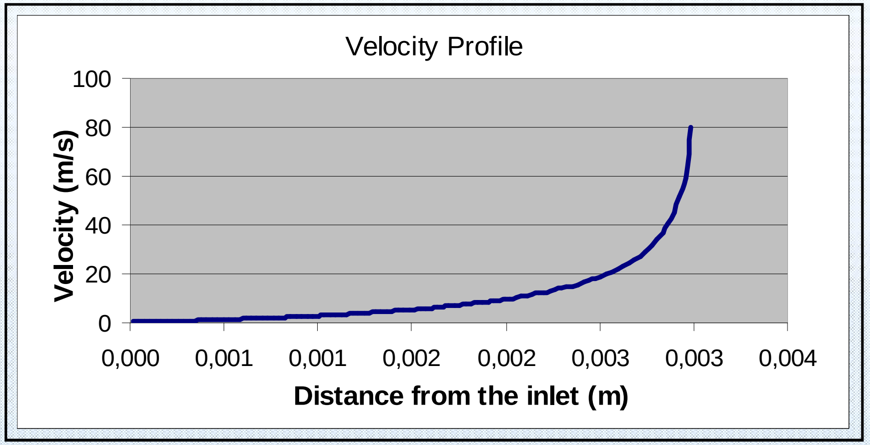
Results for adiabatic wall (1/2)

Fluidyn FRANCE



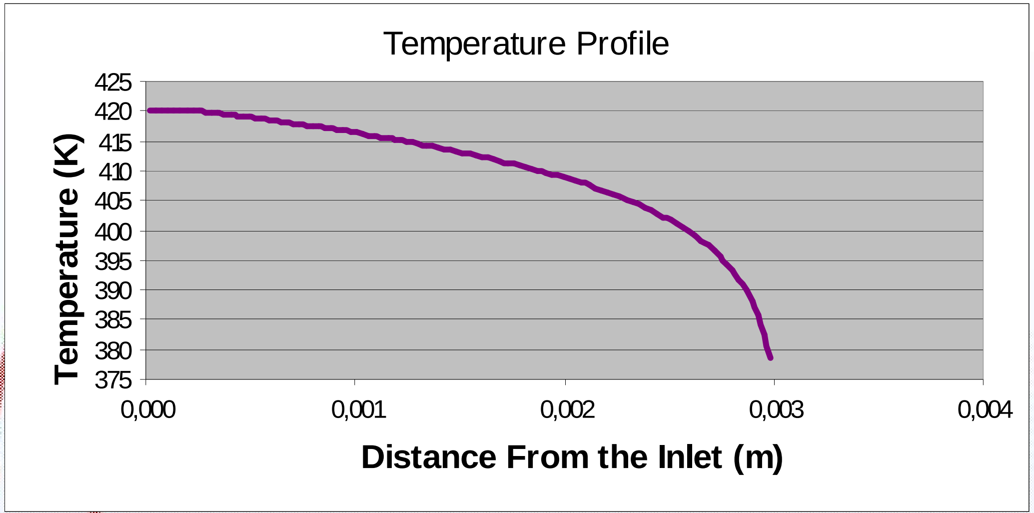


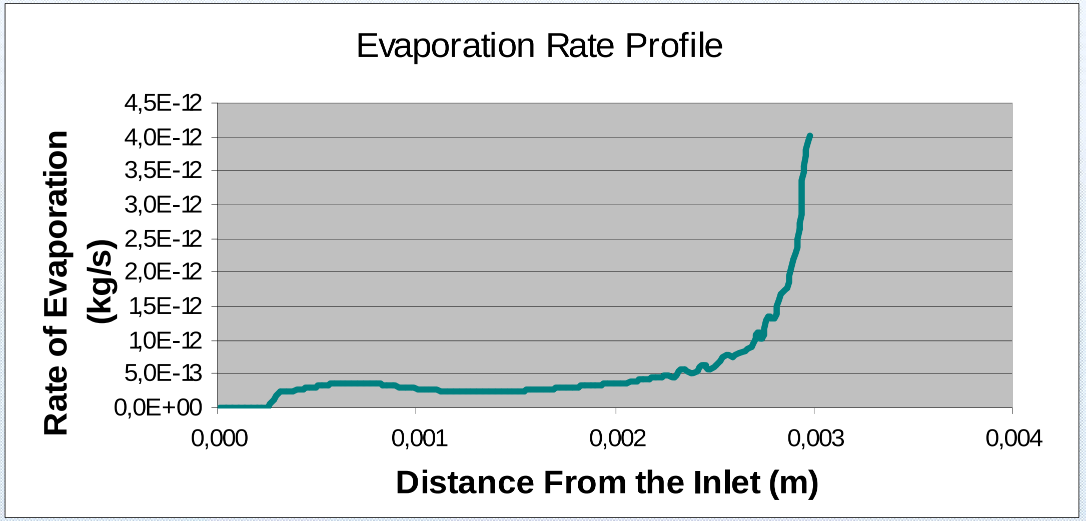




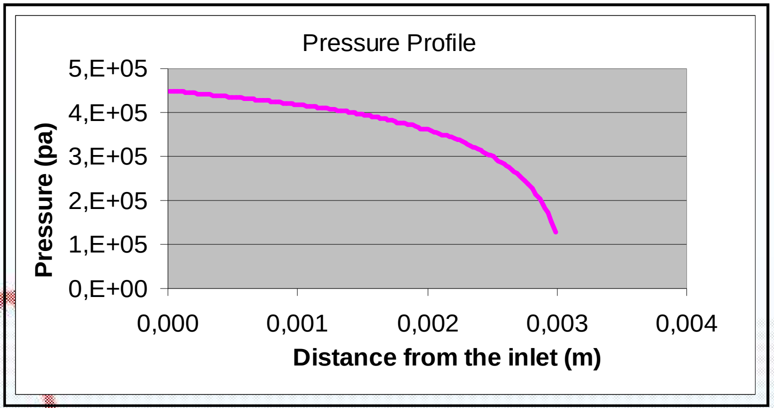
- Sharp Interface lost, pressure drop smoother, 93% mass fraction of liquid at outlet
- In relation with strong temperature drop (latent heat pumping and no heat at all from the wall)

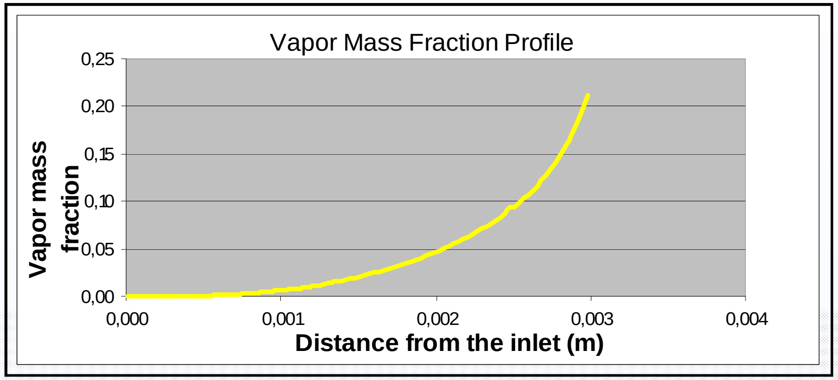
Results for adiabatic wall (2/2)

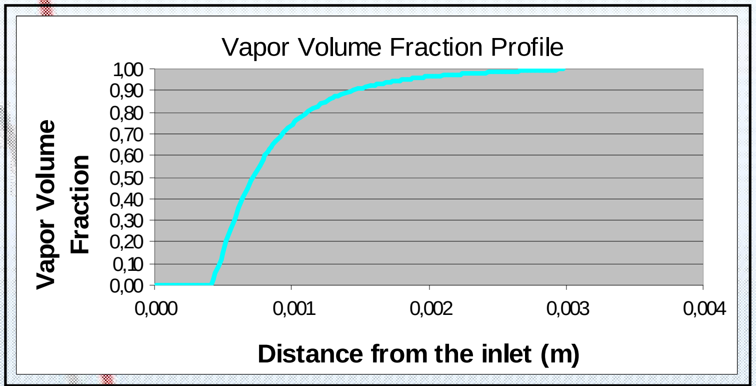


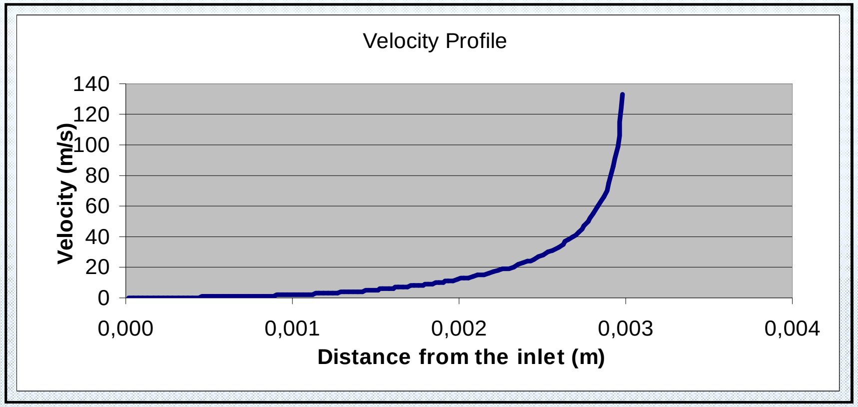


Results for conducting wall (1/2)



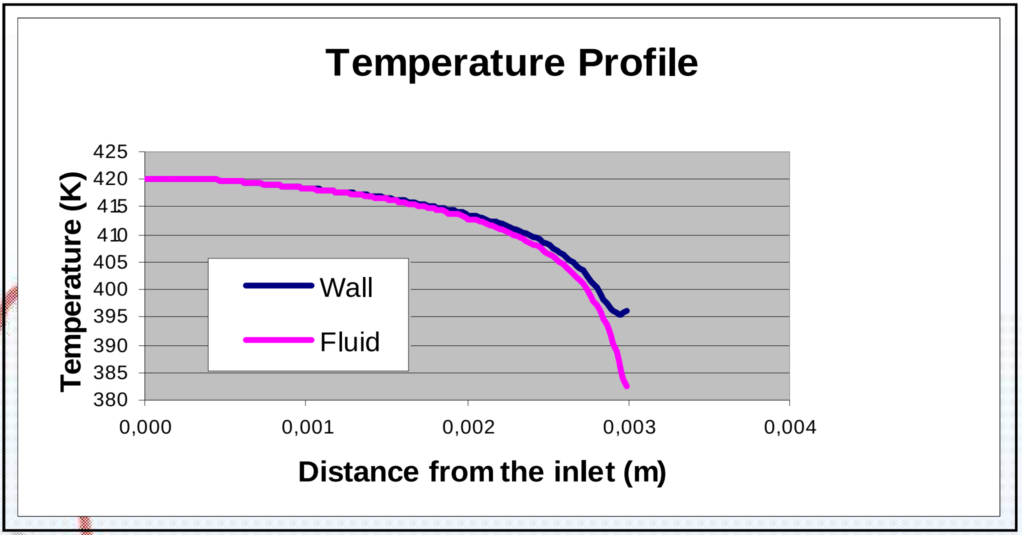


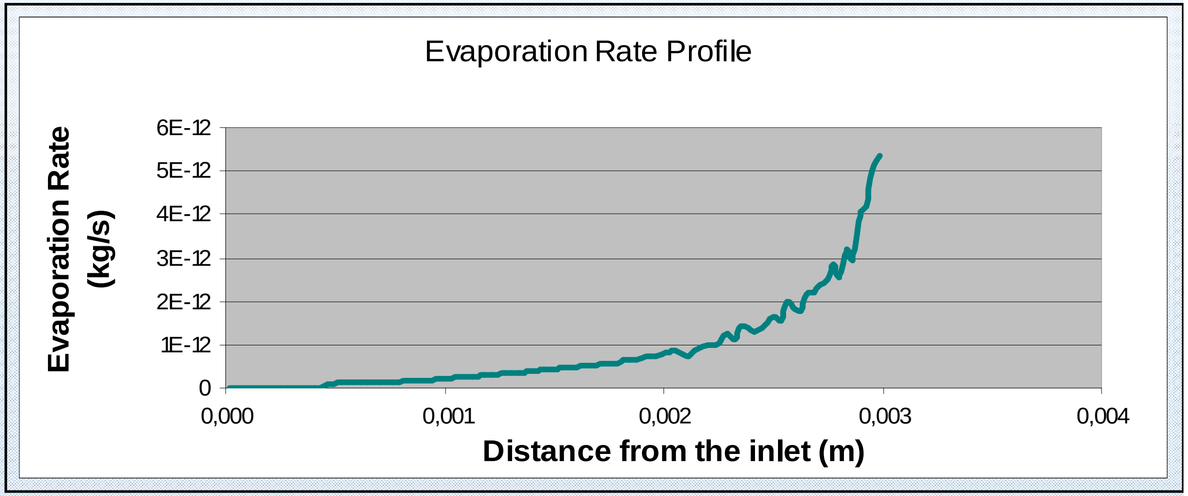




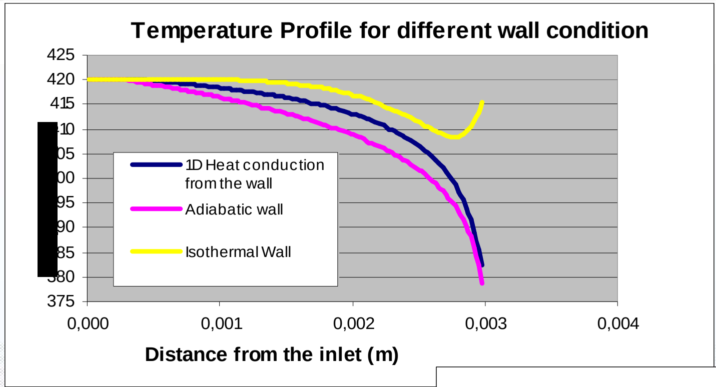
- Sharp Interface lost, pressure drop smoother, 80% mass fraction of liquid at outlet
- In relation with strong temperature drop (limited heat from wall conduction)
- Results at 70ms transient: wall keeps on cooling

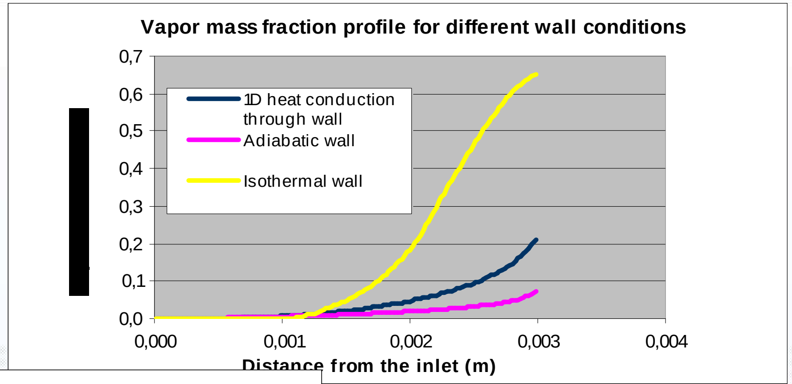
Results for conducting wall (2/2)

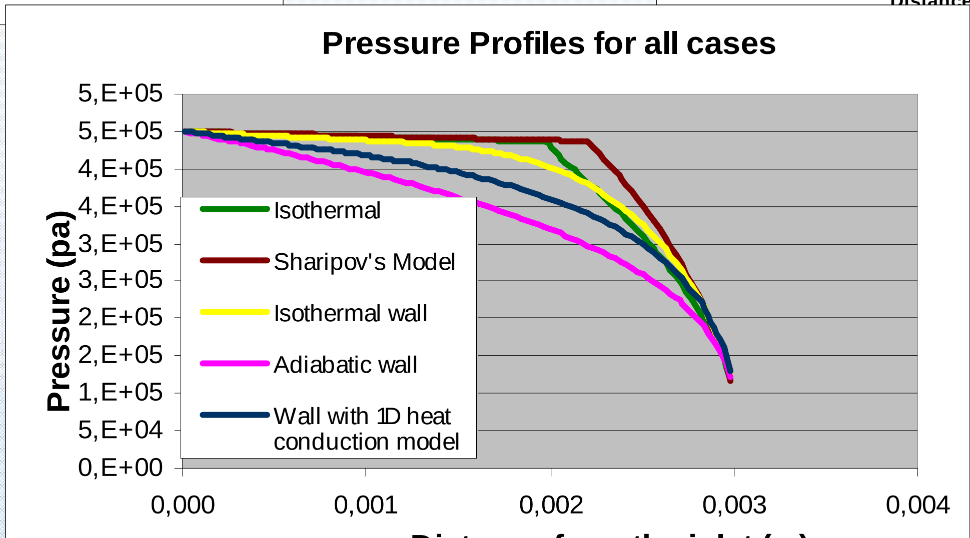




Comparison of all non-isothermal cases







CFD-HEM adiabatic (kg/s)	CFD-HEM 1D heat conduction (kg/s)	CFD-HEM isothermal wall (kg/s)	CFD-HEM isothermal flow (kg/s)	Sharipov's model (kg/s)
8.0E-08	4.96E-08	1.98E-08	1.13E-08	1.2E-08

Conclusions

- In similar conditions, fair agreement of CFD-HEM with Sharipov's model.
- For non-isothermal flows :
  - mass flow rate higher than isothermal flow.
  - only partial evaporation
- 1D heat conduction between that of the isothermal wall and adiabatic case.
- Area of phase change ?
- ITER cases