Preliminary Assessment of Porous Gas-Cooled and Thin-Liquid-Protected Divertors

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Outline

- Porous Gas Cooled Divertors

- Thin-Liquid-Protected Divertors

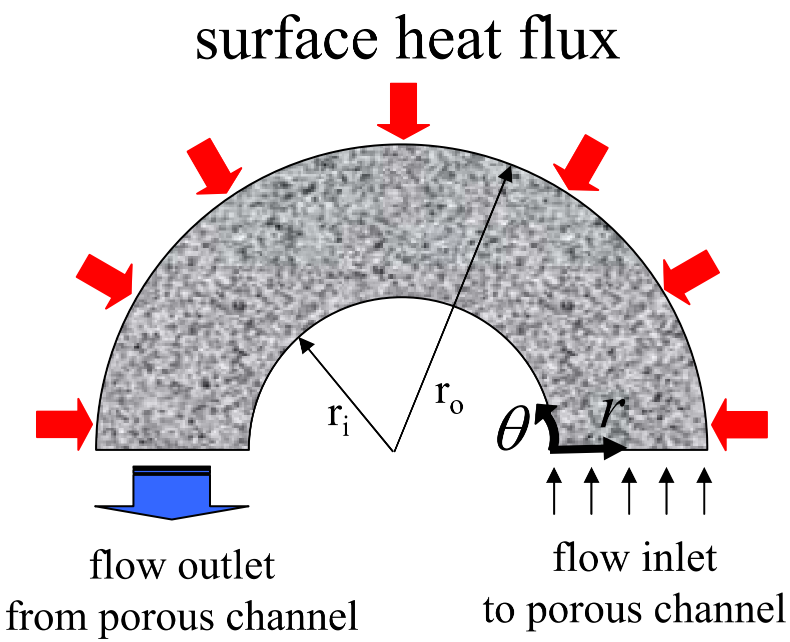
Porous Gas Cooled Divertors

Objective

- Compare predictions of the MERLOT code against FLUENT (6.1.22) predictions
  - Assess impact of using the incompressible fluid continuity equation on MERLOT's Predictions

Porous Gas Cooled Divertors

Test Problem Definition



r_o=12 mm, r_i=9 mm

- FLUENT has been used to solve the conservation equations (mass, momentum, and energy)
- Assumptions
  - Laminar flow
  - Isotropic porosity
  - Either incompressible or compressible flow
  - Local thermodynamic equilibrium between the gas and solid matrix
  - Two-dimensional (r, θ)
- 60×754 grid for r and θ directional resolution

Porous Gas Cooled Divertors
Effective Heat Transfer Coeffcient

T_{in}=823K, T_{out}=1423K

Heat input : Q''=30 MW/m^2,

Porous medium characteristic dimension : d_p=0.1 mm,

Porosity : ε=0.8

Coolant: Helium at 823K & 4.0 MPa

c_{pg}=5191 J/kg K, k_g=0.3 W/m K,

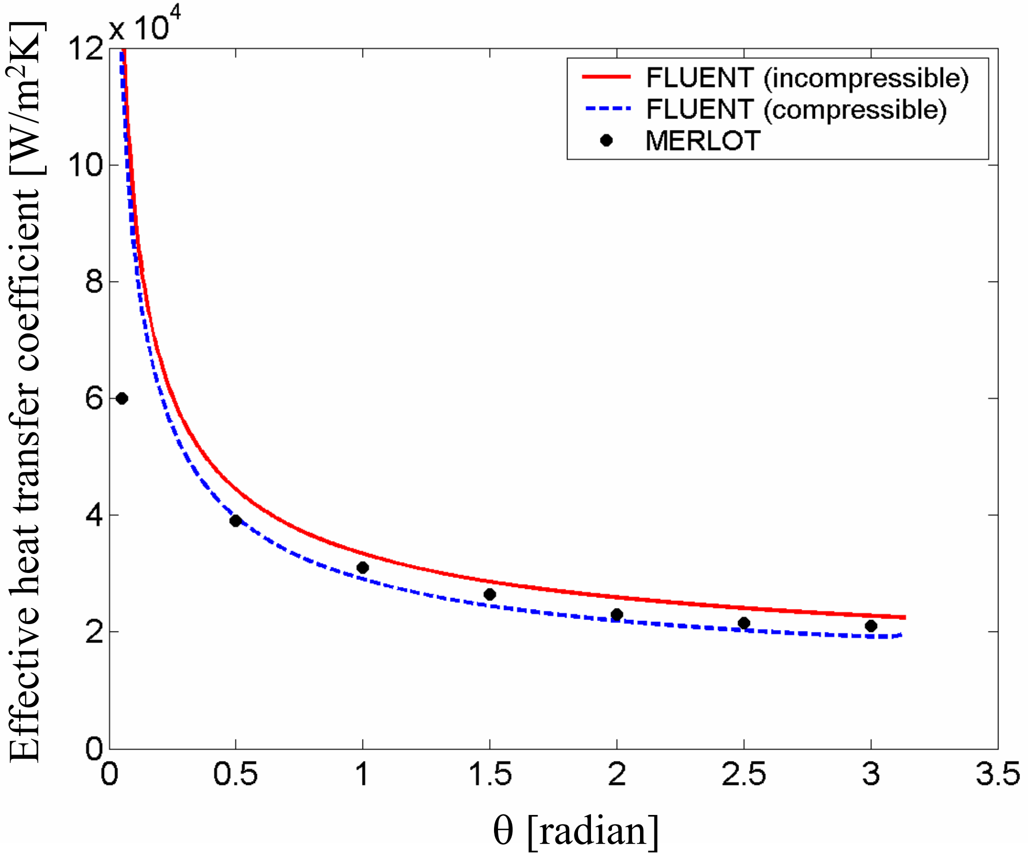
$\mu_g = 3.96\times10^{-5}$ kg/m s,

ρ_g=2.327 kg/m^3 (for incompressible)

Solid Structure :

k_s=100W/m K,

ρ_s=19300 kg/m^3, c_{ps}=132 J/kg K

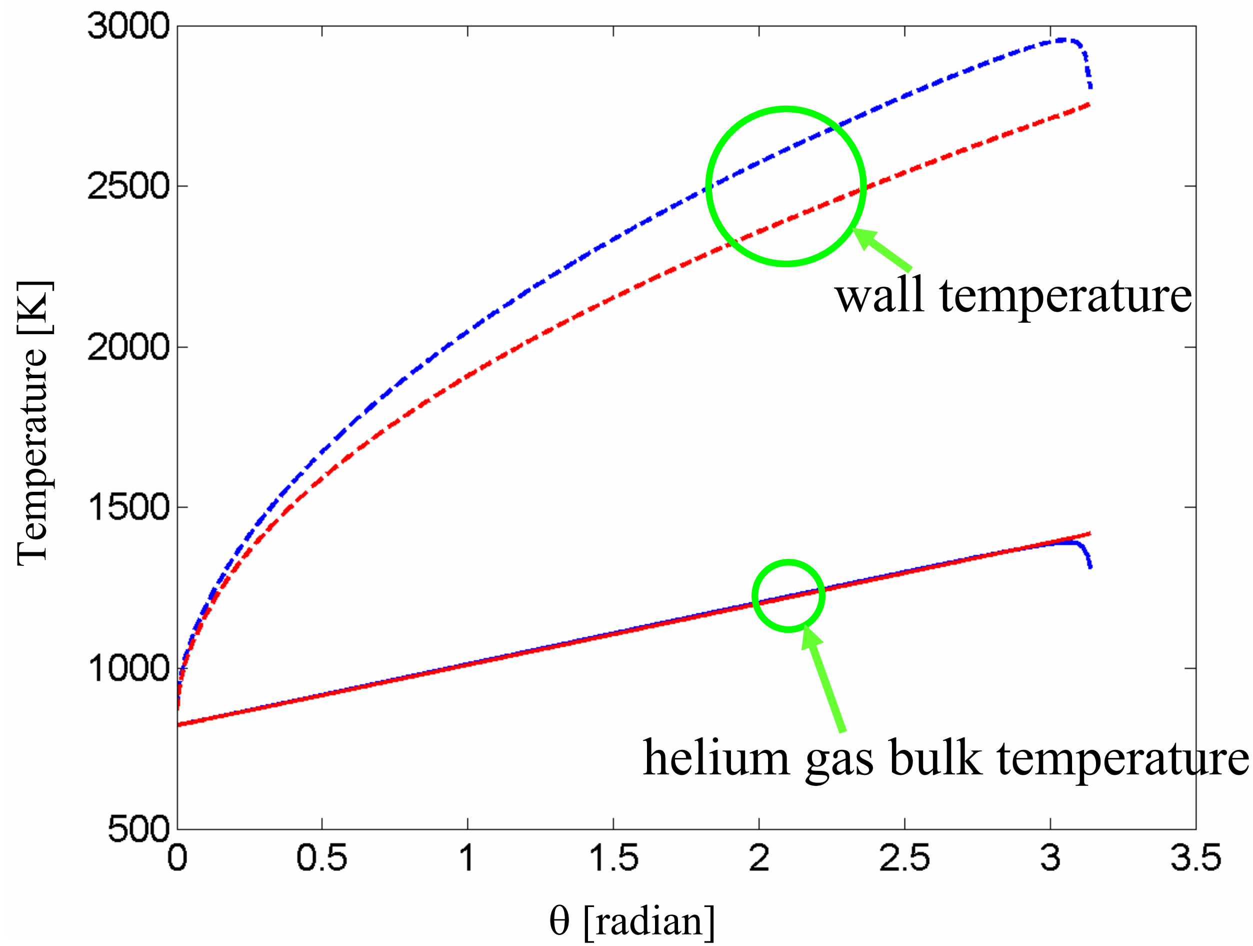


Porous Gas Cooled Divertors

Temperature Distribution

Incompressible

Compressible



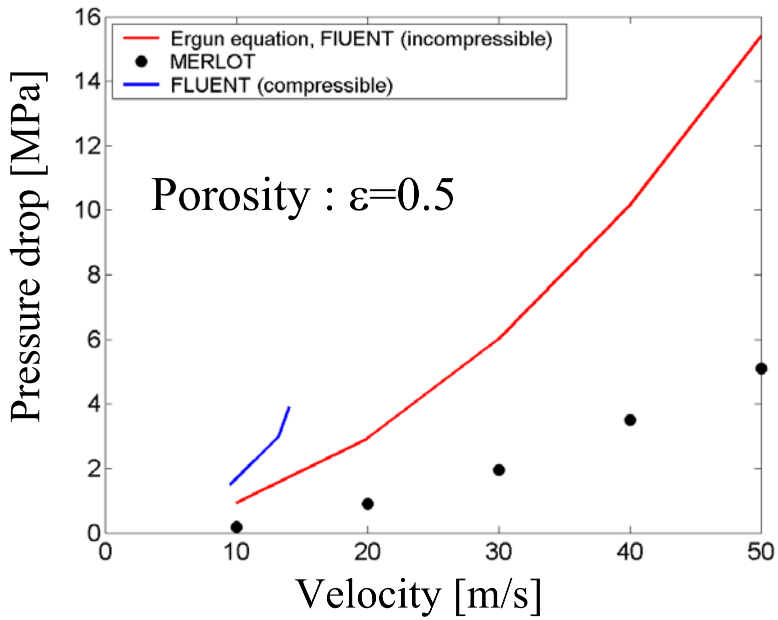
Porous Gas Cooled Divertors

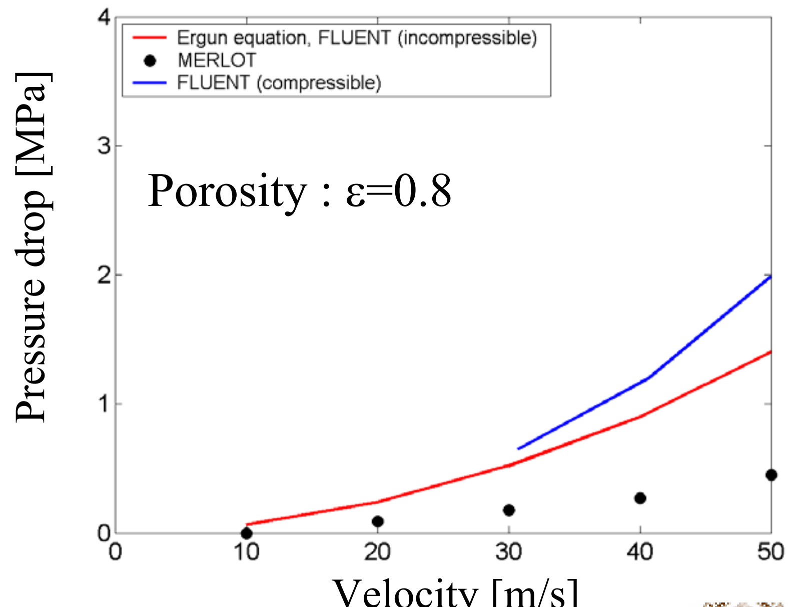
Pressure Drop

Ergun equation $$\frac{dP}{ds} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_g V_o}{d_p^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_g V_o^2}{d_p}$$

Pressure drop $$\Delta P = \int_{\theta=0}^{\theta=\pi} \frac{dP}{ds} \cdot r d\theta$$

T_{in}=823K, Q''=5 MW/m^2, d_p=0.1 mm





Porous Gas-Cooled Divertors

Preliminary Conclusions

- **Heat transfer coefficients predicted by MERLOT and FLUENT appear to be consistent**

- **Pressure drop predicted by MERLOT is significantly lower than that predicted by FLUENT for either compressible or incompressible assumption**

- **Acceleration pressure drop due to gas compressibility effects can not be ignored**

Thin-Liquid-Protected Divertors

Objective

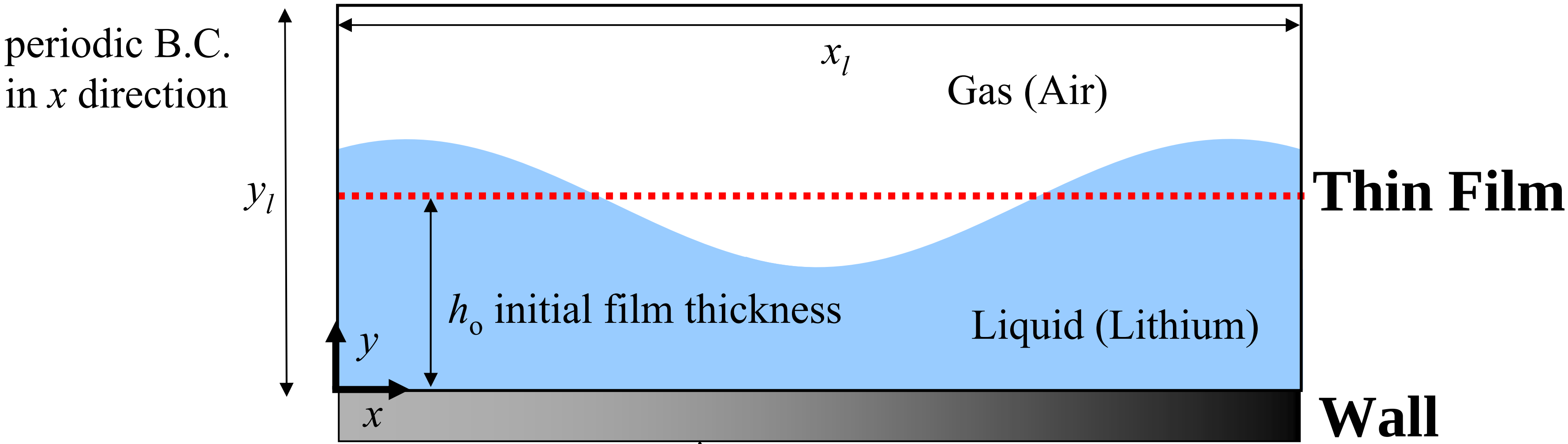
A maximum allowable surface temperature has been established to limit liquid evaporation and plasma contamination (~380 ^{o}C for Li)

- This work is aimed at establishing limits for the maximum allowable temperature gradients (i.e. heat flux gradients) to prevent film rupture due to thermocapillary effects

Thin-Liquid-Protected Divertors

Problem Definition

open B.C. at top, $\frac{\partial u}{\partial y} = \frac{\partial v}{\partial y} = \frac{\partial T}{\partial y} = 0$

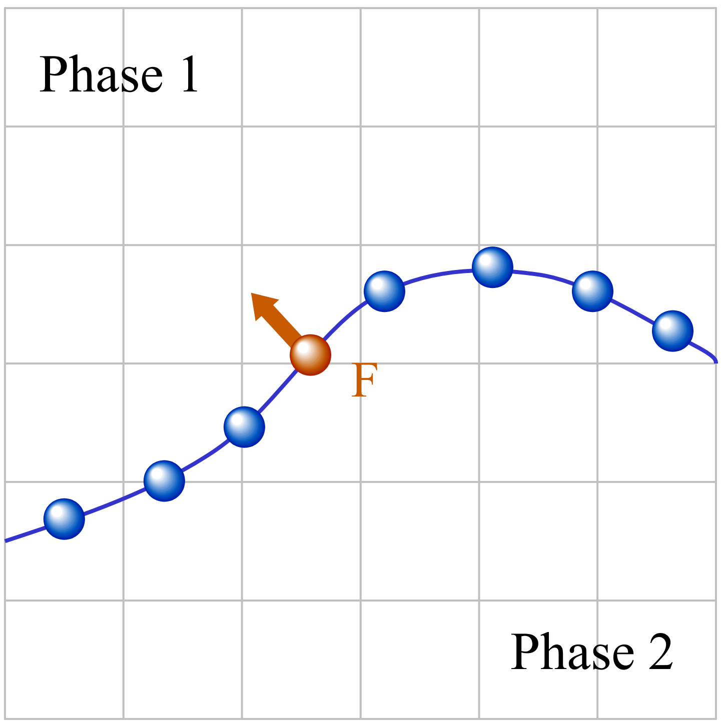


Non-uniform wall temperature $T_s(x) = T_m + \Delta T_s \cos\left[\frac{2\pi}{x_l}(x - \frac{x_l}{2})\right]$

- Initially, quiescent liquid and gas (u=0, v=0, T=T_m at t=0)

Thin-Liquid-Protected Divertors

Numerical Method



- Evolution of the free surface is modeled using the Level Contour Reconstruction Method

- Two Grid Structures
  - Volume - entire computational domain (both phases) discretized by a standard, uniform, stationary, finite difference grid.
  - Phase Interface - discretized by Lagrangian points or elements whose motions are explicitly tracked.

Thin-Liquid-Protected Divertors

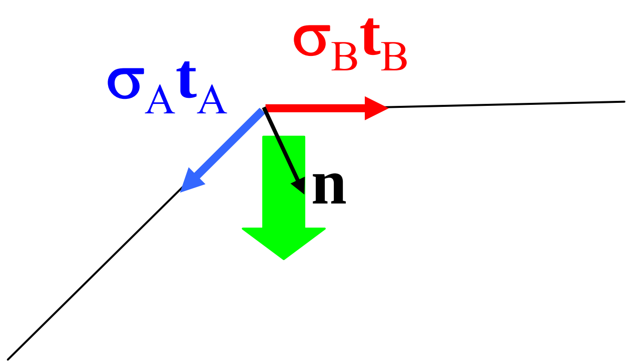
Governing Equations

- Conservation of Mass $\nabla \cdot \mathbf{u} = 0$
- Momentum $\rho\left[\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right] = -\nabla P + \rho \mathbf{g} + \nabla \cdot \mu(\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathrm{T}}) + \int_{\Gamma(t)} \sigma \kappa \mathbf{n} \delta(\mathbf{x} - \mathbf{x}_f) \mathrm{d}s$
- Energy $\rho\left[\frac{\partial (cT)}{\partial t} + \mathbf{u} \cdot \nabla (cT)\right] = \nabla \cdot k \nabla T$

  - A single field formulation
  - Constant but unequal material properties
  - Surface tension included as local surface delta function sources

Thin-Liquid-Protected Divertors

Variable Surface Tension Source Term



n : unit vector in normal direction

t : unit vecotr in tangential direction

κ : curvature

- Variable surface tension : $\sigma = \sigma_o + \gamma_o (T - T_m)$

  $\sigma_o = 6.62 \times 10^{-2}$ N/m

  $\gamma_o = 1.74 \times 10^{-4}$ N/m°C

  $T_m = 573$ K

- Force on a line element

$$\delta F_e = \int_{\Delta s} \sigma \kappa \mathbf{n} \, \mathrm{d}s = \int_A^B \frac{\partial(\sigma \mathbf{t})}{\partial s} \mathrm{d}s = (\sigma_B \mathbf{t}_B - \sigma_A \mathbf{t}_A)$$

$$\therefore \frac{\partial(\sigma \mathbf{t})}{\partial s} = \sigma \frac{\partial \mathbf{t}}{\partial s} + \frac{\partial \sigma}{\partial s} \mathbf{t} = \sigma \kappa \mathbf{n} + \frac{\partial \sigma}{\partial s} \mathbf{t}$$

normal surface tension force

thermocapillary force

Thin-Liquid-Protected Divertors

Material Properties

- Material property field (Liquid=>Lithium, Gas=>Air*)

$$\rho \equiv \rho(\mathbf{x},t) = \rho_G + (\rho_L - \rho_G) I(\mathbf{x},t)$$ (ρ_L=504.8 kg/m^3, ρ_G=1.046 kg/m^3)

$$\mu \equiv \mu(\mathbf{x},t) = \mu_G + (\mu_L - \mu_G) I(\mathbf{x},t)$$ (μ_L=4.51×10^{-4} kg/ms, μ_G=2.0×10^{-5} kg/ms)

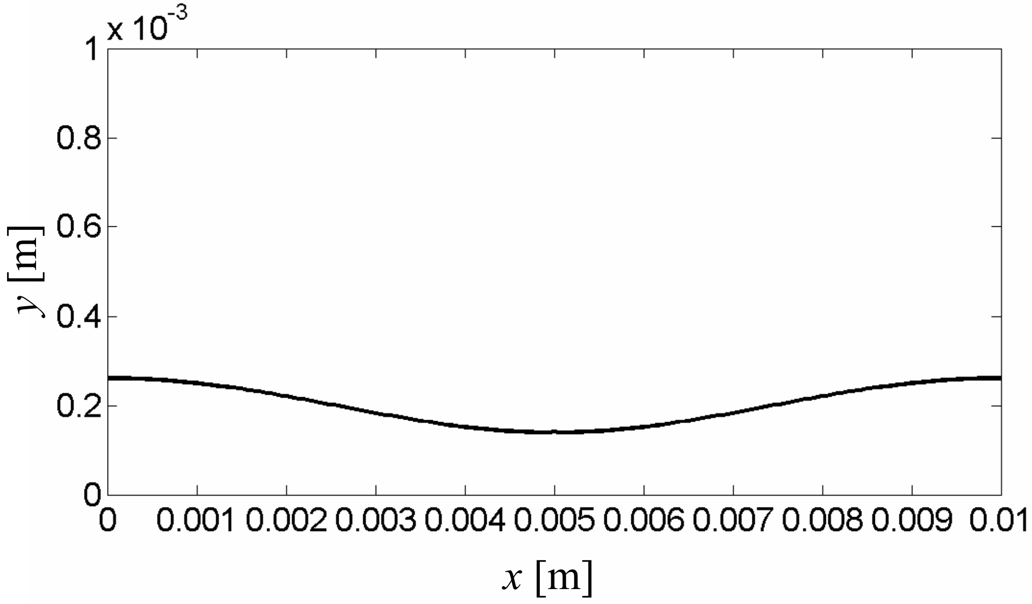
$$c \equiv c(\mathbf{x},t) = c_G + (c_L - c_G) I(\mathbf{x},t)$$ (c_L=4287 J/kg^{o}C, c_G=1008 J/kg^{o}C)

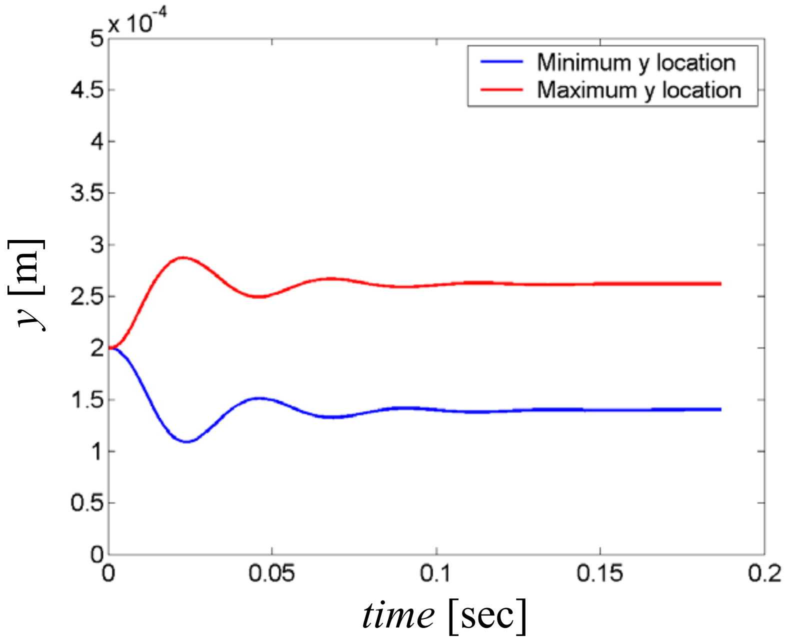
$$k \equiv k(\mathbf{x},t) = k_G + (k_L - k_G) I(\mathbf{x},t)$$ (k_L=46.6 W/m^{o}C, k_G=0.029 W/m^{o}C)

* Effect of Liquid/Gas density ratio becomes insignificant for values ≥ 100

Thin-Liquid-Protected Divertors

Steady State Results, very thin films

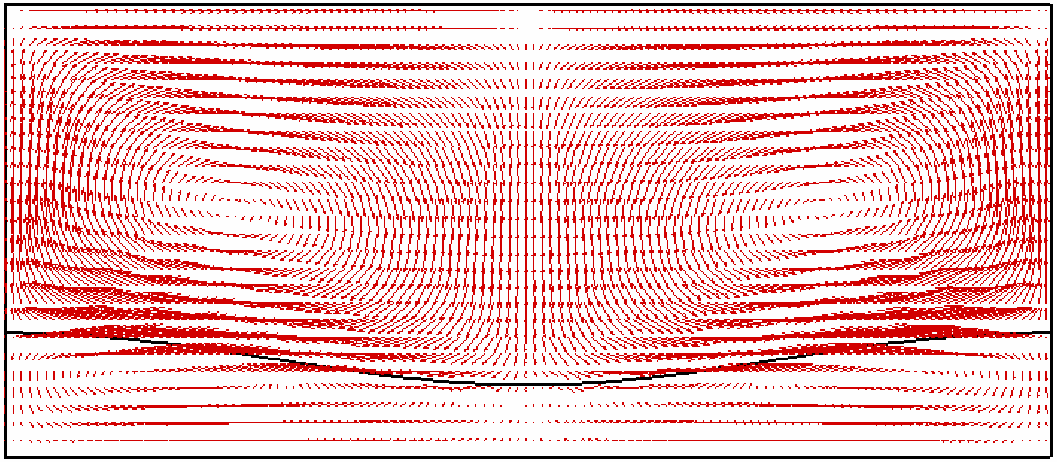




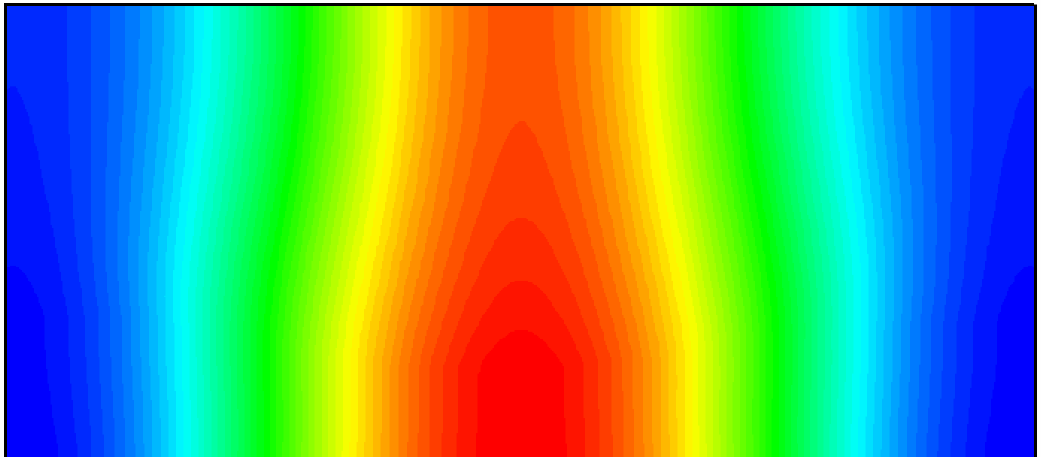
- Two-dimensional simulation with 0.01[m]×0.001[m] box size and 250×50 resolution
- h_o=0.2 mm, ΔT_s=10 K

Thin-Liquid-Protected Divertors

Steady State Results, very thin films



velocity vector plot

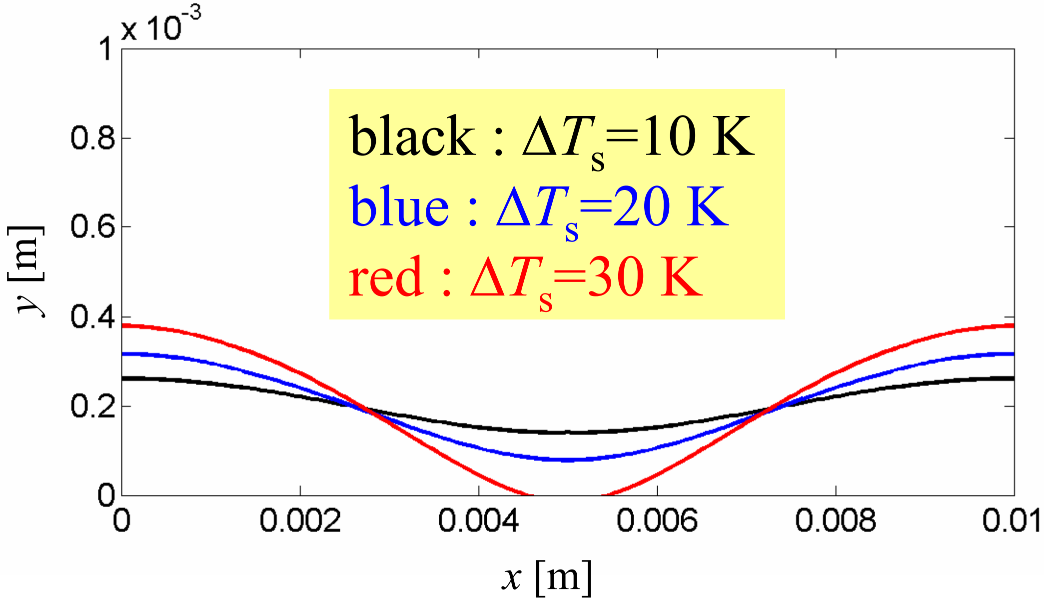


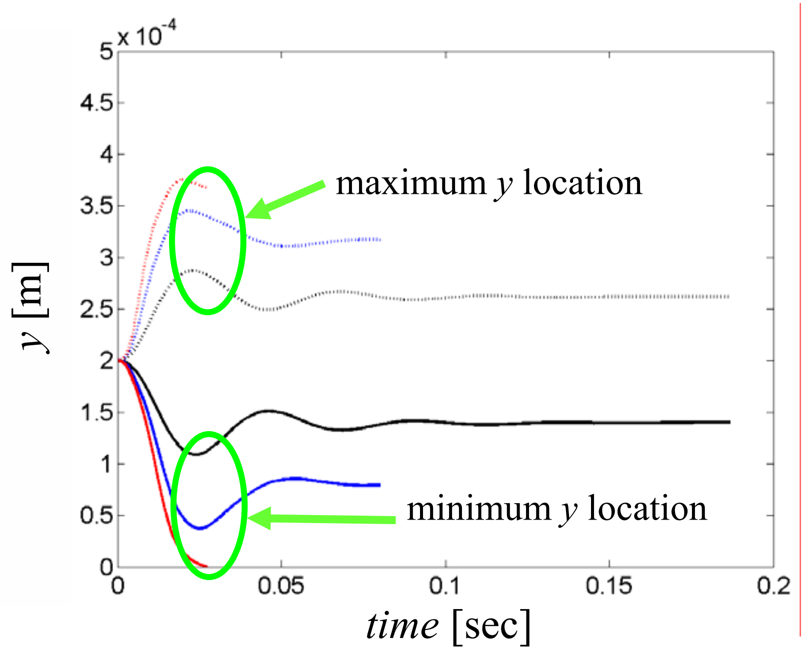
temperature plot

- Two-dimensional simulation with 0.01[m]×0.001[m] box size and 250×50 resolution
- h_o=0.2 mm, ΔT_s=10 K

Thin-Liquid-Protected Divertors

Steady State Results, very thin films

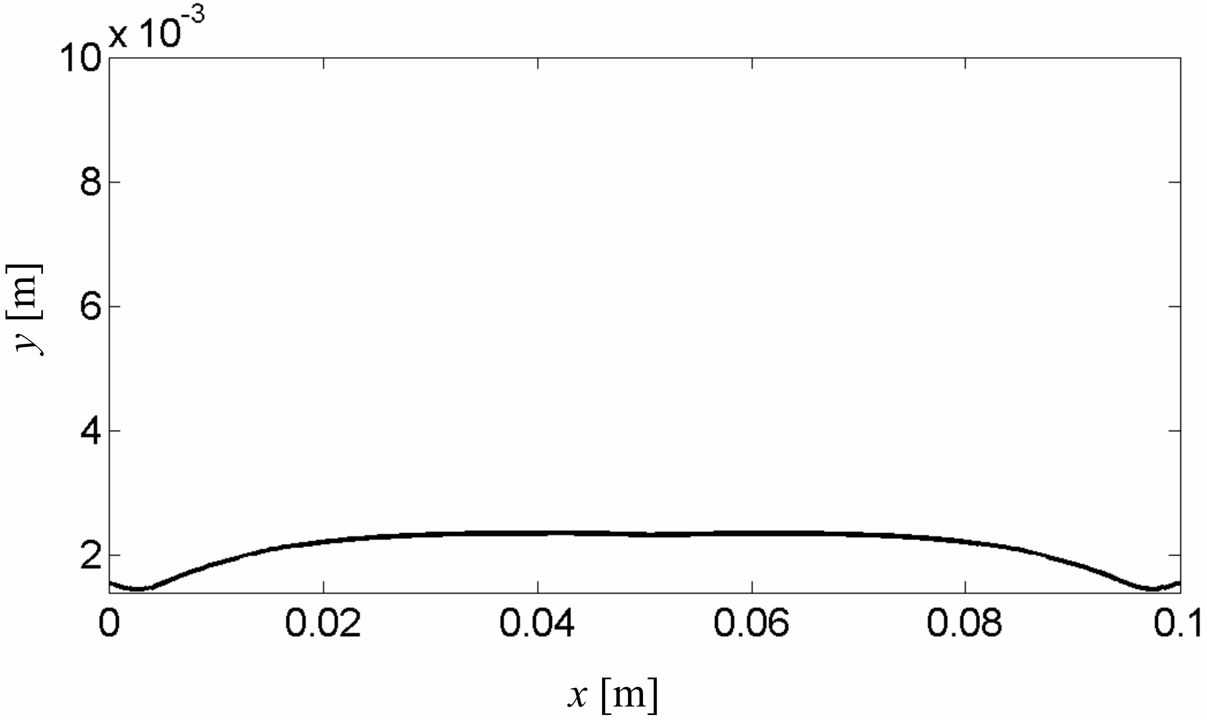




- Two-dimensional simulation with 0.01[m]×0.001[m] box size, 250×50 resolution, and h_o=0.2 mm

Thin-Liquid-Protected Divertors

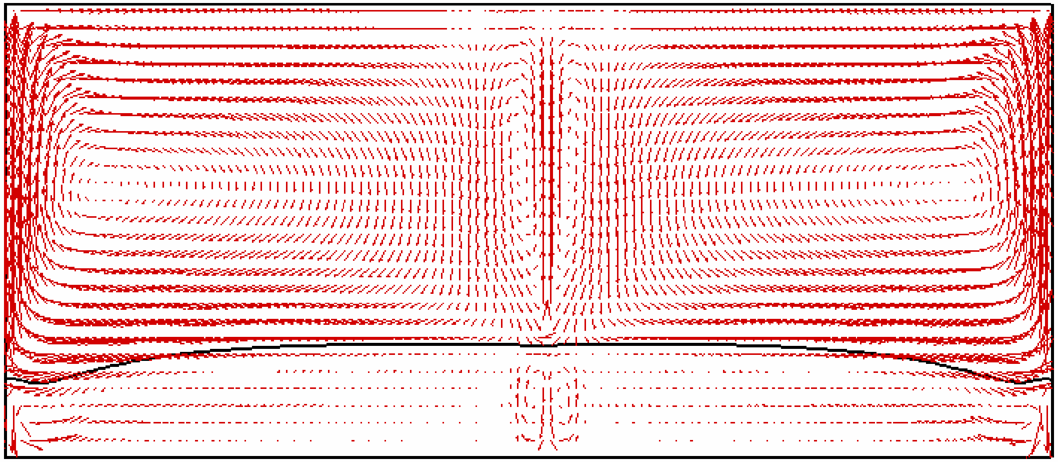
Steady State Results, moderate film thickness



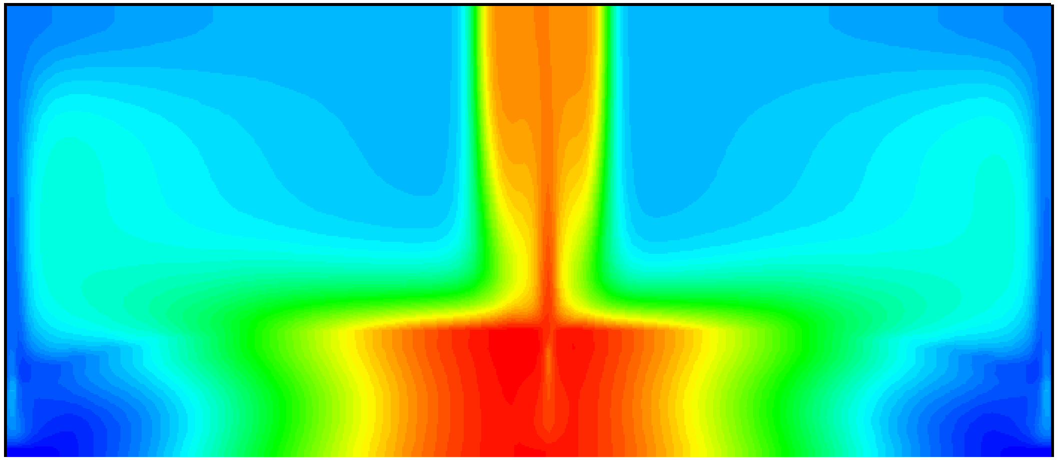
- Two-dimensional simulation with 0.1[m]×0.01[m] box size and 250×50 resolution
- h_o=2 mm, ΔT_s=100 K

Thin-Liquid-Protected Divertors

Steady State Results, moderate film thickness



velocity vector plot

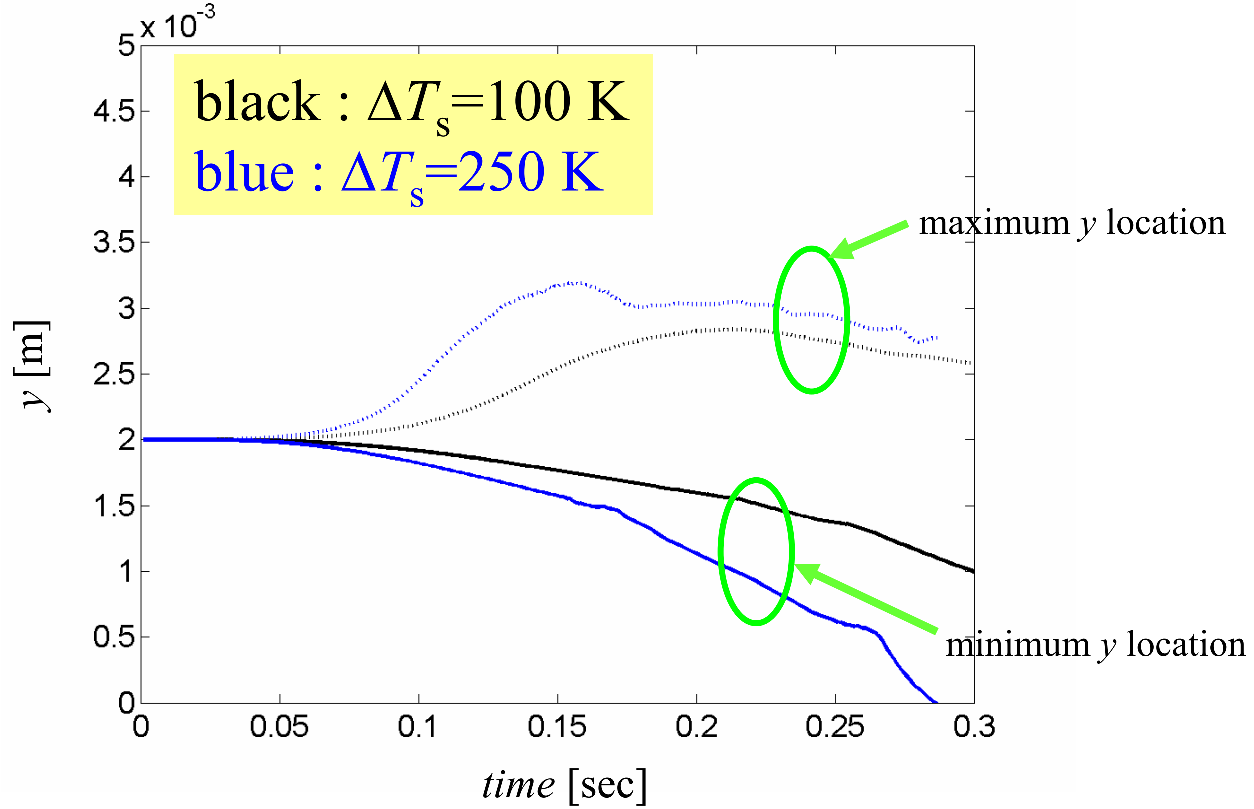


temperature plot

- Two-dimensional simulation with 0.1[m]×0.01[m] box size and 250×50 resolution
- h_o=2 mm, ΔT_s=100 K

Thin-Liquid-Protected Divertors

Steady State Results, moderate film thickness



- Two-dimensional simulation with 0.1[m]×0.01[m] box size, 250×50 resolution, and h_o=2 mm

Thin Liquid-Protected Divertors

Preliminary Conclusions

- **Methodology can be used to determine the Limiting values for temperature gradients (i.e. heat flux gradients) necessary to prevent film rupture**

- **In some cases (very thin films), limits may be more restrictive than surface temperature limits**

- **Path Forward:**

  - Generalized charts will be developed to determine the temperature gradient limits for different fluids and film thickness values