Liquid Impingement Erosion: Modeling Droplet Impacts onto Elastic Solids

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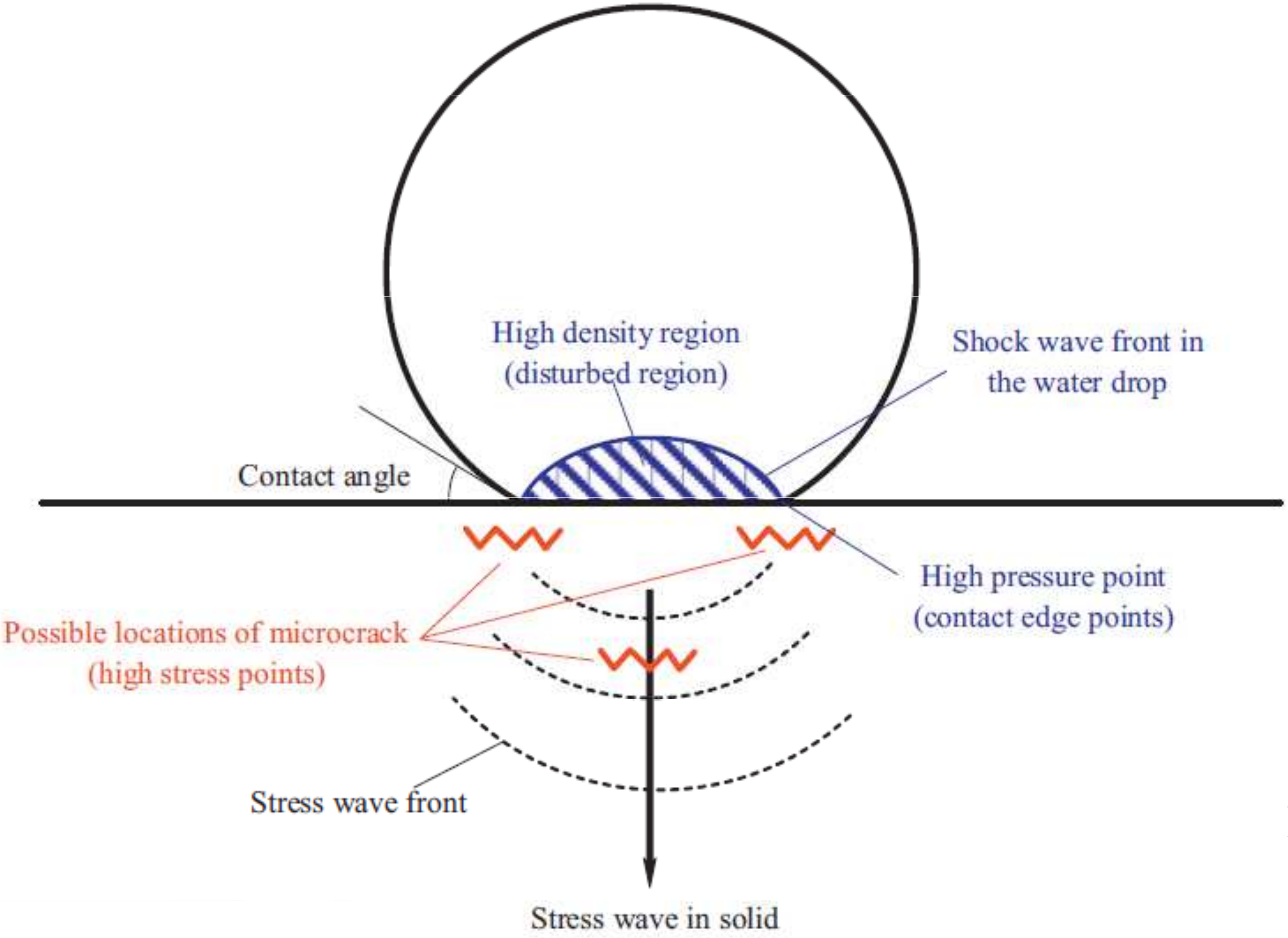
Outline

- Background
- Objectives
- Methodology
- Results
- Ongoing work and future plan

High speed drop impact



Li et al., 2008

Objectives

- Study the liquid impingement erosion problem
- Develop a 3-D coupled Fluid-Solid Interaction solver
- Model droplet impacts onto elastic solid substrates for a large range of impingement velocities
- Correlate the generated stress in the solid and the impinged droplet speed
- Find a correlation for liquid impingement erosion based on numerical modeling
- Validate the erosion correlation against experimental results available in the literature

Governing equations

Fluid

Continuity: $$\frac{\partial \rho_f}{\partial t} + \nabla \cdot \left(\rho_f V_f \right) = 0$$

Momentum: $$\frac{\partial \left(\rho_f V_f \right)}{\partial t} + \nabla \cdot \left(\rho_f V_f \otimes V_f \right) = \nabla \cdot \sigma_f + \rho_f g$$

Equation of state: $$\rho_f = \rho_{f_0} + p_f \psi$$

Solid

Elastic deformation: $$\rho_s \frac{\partial V_s}{\partial t} + \rho_s \nabla \cdot \left(V_s \otimes V_s \right) = \nabla \cdot \sigma_s + \rho_s g$$

Definition of equation terms

Fluid stress tensor: $\sigma_f = -p_f I + \mu_f \left(\nabla V_f + \nabla V_f^{\,T} \right)$

Solid stress tensor: $\sigma_s = \frac{1}{J} F \left(\lambda_s (trS) I + 2\mu_s S \right) F^T$

Deform. grad. tensor: $F = I + \nabla U_s$

St. Venant-Kirchhoff: $S = \frac{1}{2} \left(F^T F - I \right)$

Lamé coefficients: $\lambda_s = \frac{\nu_s E}{(1+\nu_s)(1-2\nu_s)}$ $\quad \mu_s = \frac{E}{2(1+\nu_s)}$

Equation of state

- Air: Ideal gas law @ isothermal condition

$$\rho_f = \rho_{f_0} + p_f \psi, \quad \psi : compressibility\ factor$$

$$\rho_{f_0} = 0, \psi = \frac{1}{RT} \approx 10^{-5} \Rightarrow p = \rho RT$$

- Water: Tait's equation of state

$$\frac{p_f + B}{p_a + B} = \left(\frac{\rho_f}{\rho_{f_0}} \right)^N$$

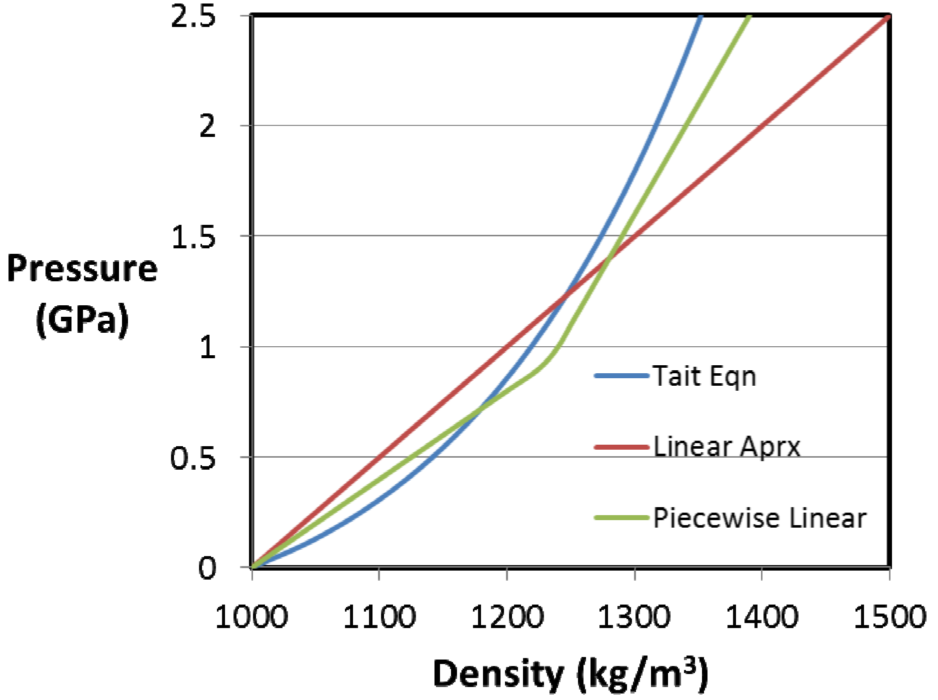
$$B = 300MPa,\ p_a = 0.1MPa,\ N = 7.415$$

- Linear approximation:

$$\rho_f = \rho_{f_0} + p_f \psi$$

$$\rho_{f_0} = 1000, \psi = 10^{-7}$$

$$\rho_f = \rho_{f_0} + p_f \psi$$



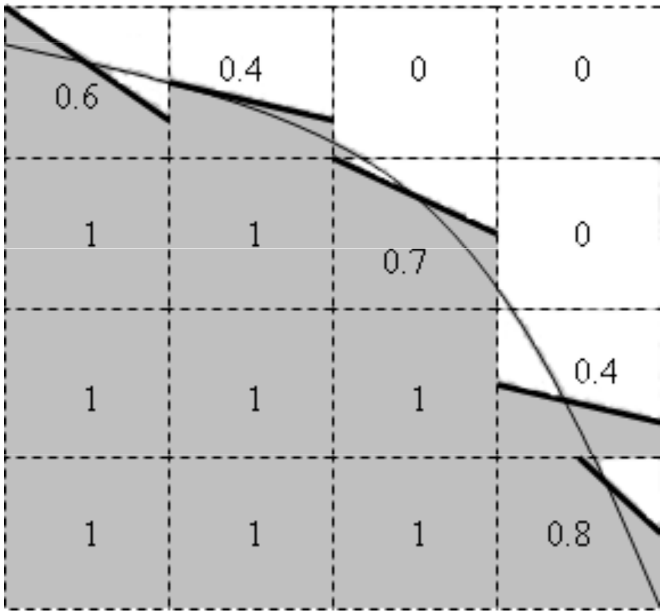
Volume of Fluid method

- Liquid volume fraction:

$$\begin{cases} \alpha_l = 0 & \textit{Gas phase} \\ 0 < \alpha_l < 1 & \textit{Interface} \\ \alpha_l = 1 & \textit{Liquid phase} \end{cases}$$

- VOF Advection:

$$\frac{\partial \alpha_l}{\partial t} + \nabla.(V_f \alpha_l) = 0$$



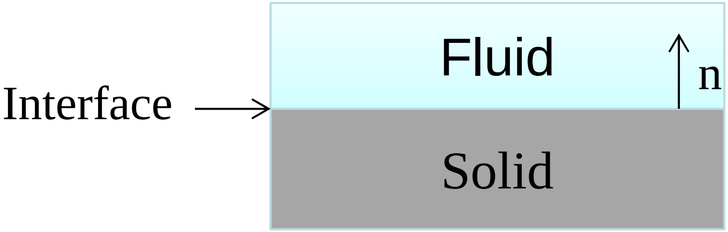
- Interface Reconstruction method:

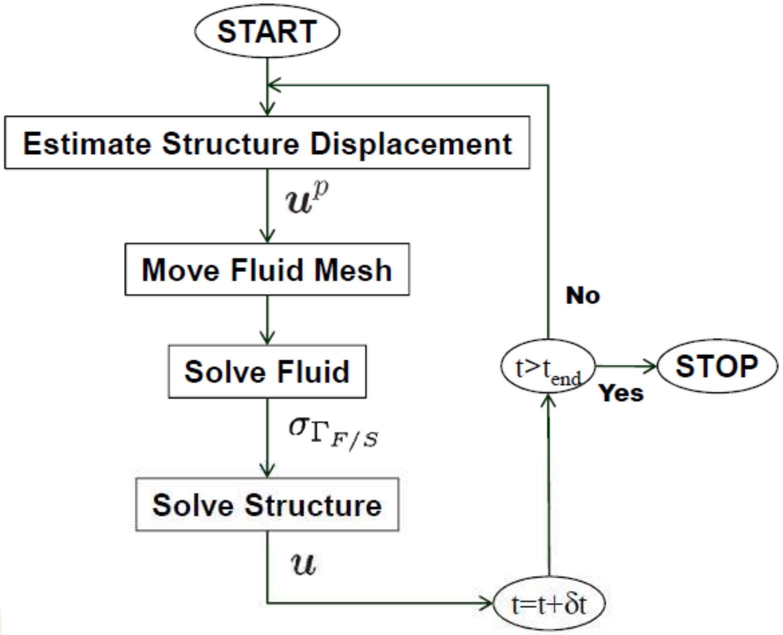
Piecewise Linear Interface Calculation (PLIC) of Youngs (1982)

Fluid-solid coupling at interface

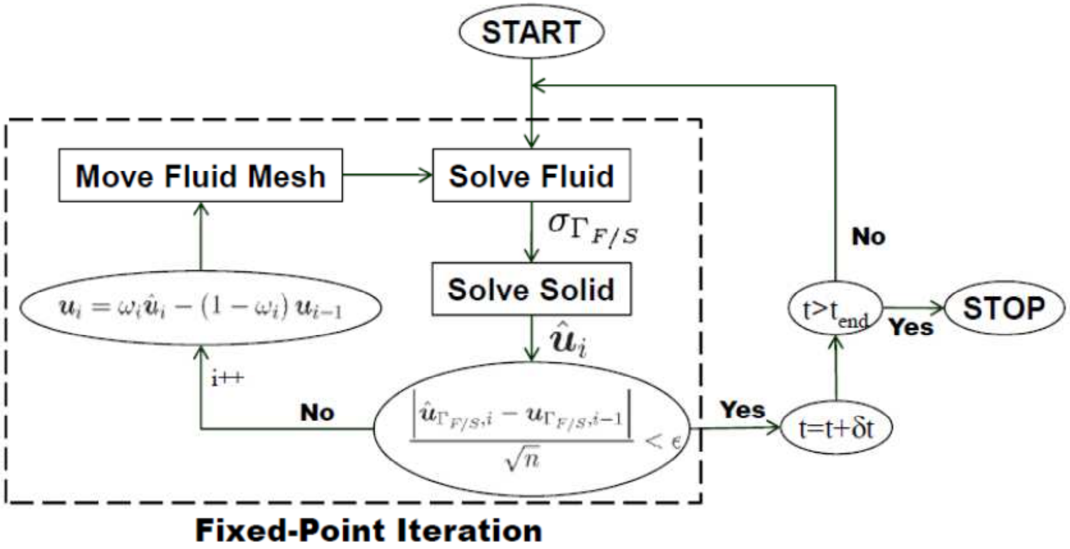
Force balance: $\sigma_s n = \sigma_f n$

No-slip condition: $V_s = V_f$





1-way coupling



2-way coupling

Numerical scheme

Fluid solver:

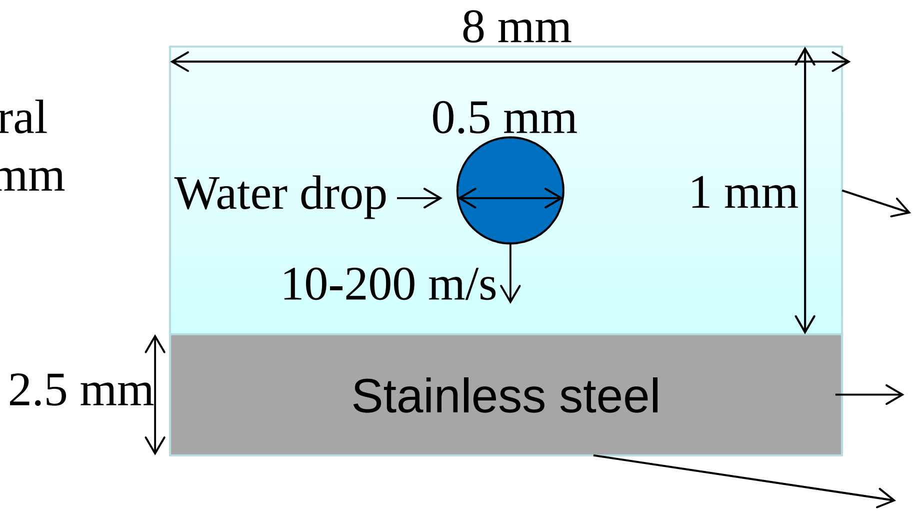
- Finite Volume Method (FVM) to solve integral form of eq'ns
- Solved over a fixed system of grids in a segregated manner
- 2nd order accuracy in space and time
- Pressure-velocity coupling: Pressure-Implicit with Splitting of Operators (PISO) method
- Adaptive time step based on CFL initially set to 0.1
- OpenFoam solver: interFoam

Solid solver:

- Finite Element Method (FEM) to solve elastic structure
- OpenFoam solver: stressedFoam

Domain & boundary conditions

Uniform hexahedral mesh with 0.025 mm sizing for both domains



8 mm

0.5 mm

Water drop

1 mm

10-200 m/s

2.5 mm

Stainless steel

Note: not to scale

Pressure outlet

Zero displacement

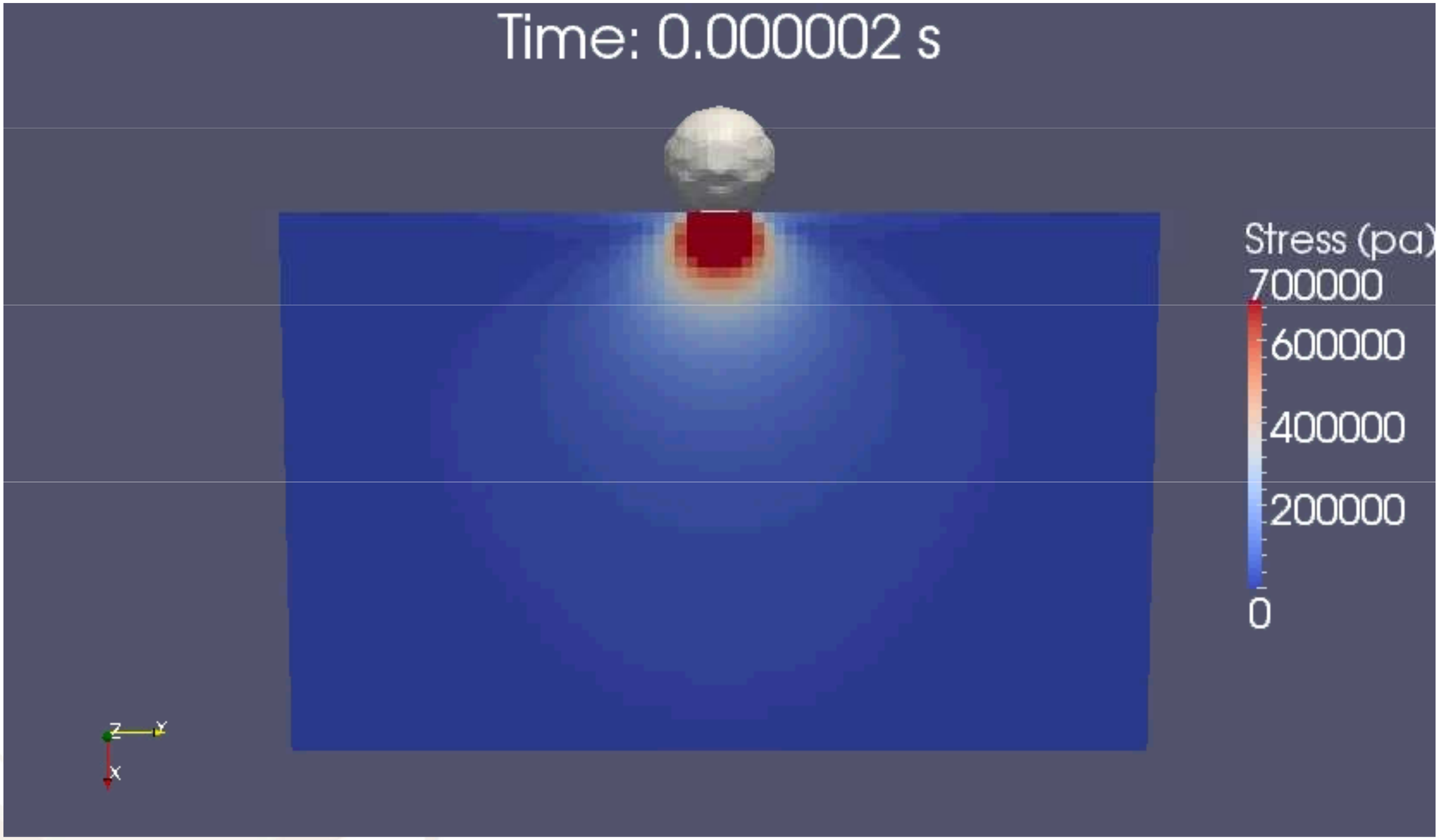
Zero stress

Fluid properties	Air	Water
Density (kg/m^3)	1	1000
Kinematic viscosity (m^2/s)	1.48e-05	1e-06
Surface tension (N/m)	-	0.07

Solid properties	Stainless Steel
Density (kg/m^3)	7850
Poisson ratio	0.3
Young’s modulus (GPa)	200

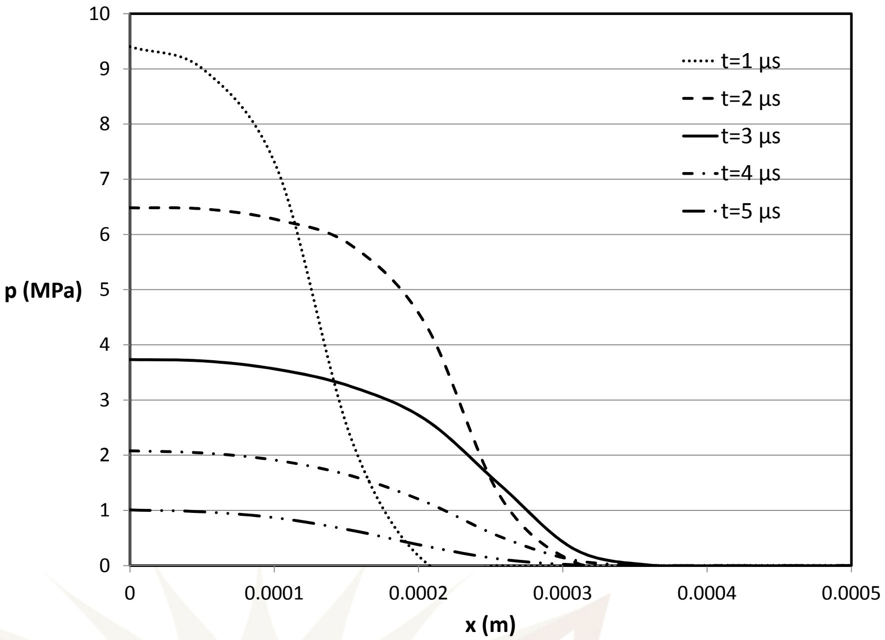
Preliminary results

Droplet impact @ 40 m/s



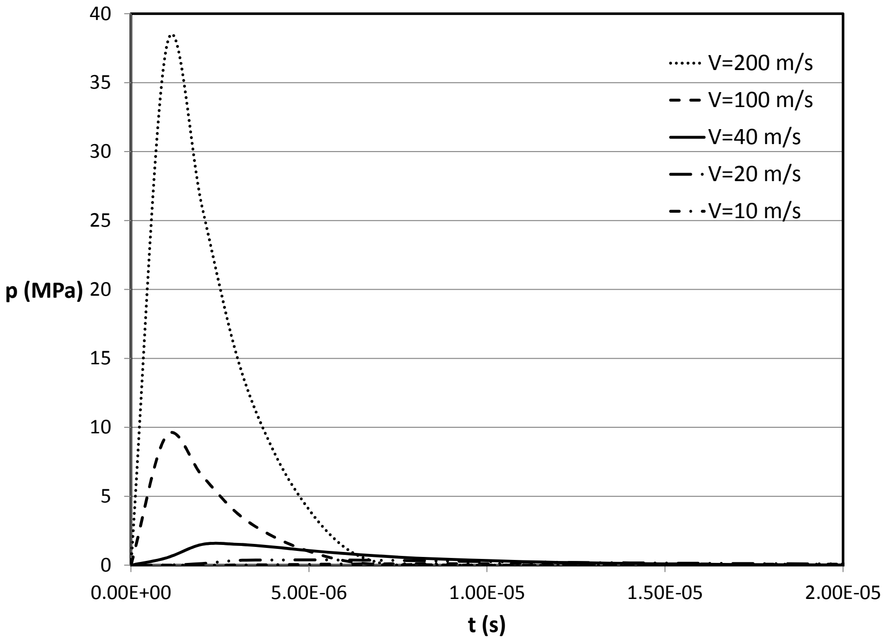
Pressure field in fluid domain

Pressure distribution in the liquid
along the fluid-solid interface



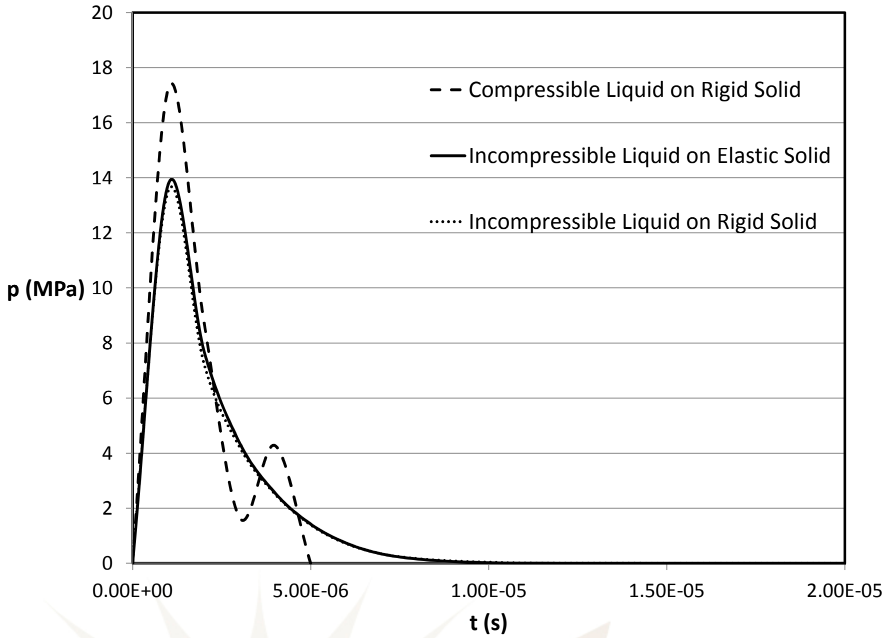
SS, V=100m/s, D=0.5mm,
Incomp.

Peak transient pressure in the liquid
along the fluid-solid interface

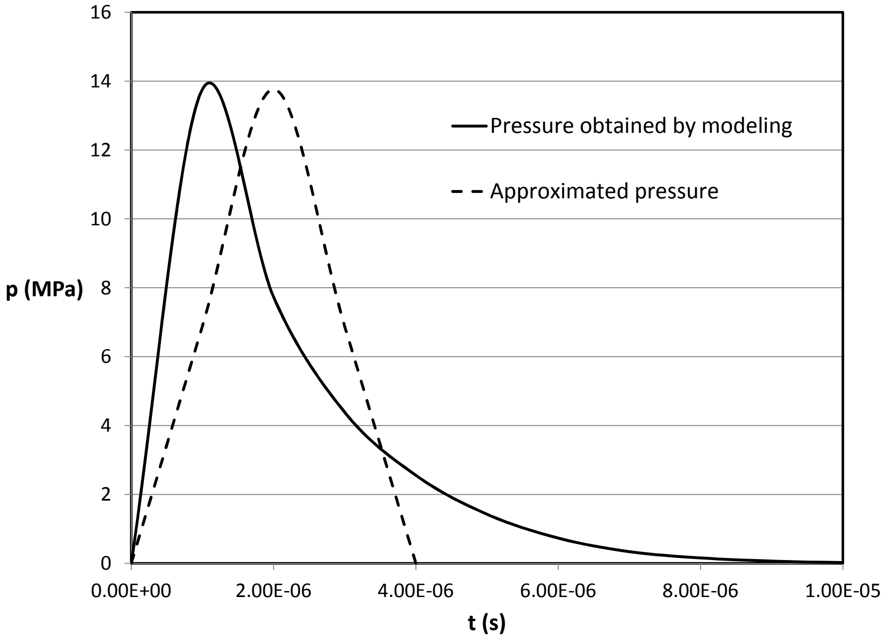


Pressure field in fluid domain, Con’d

Effect of fluid compressibility on the pressure variation



Pressure approximation as a triangular pulse

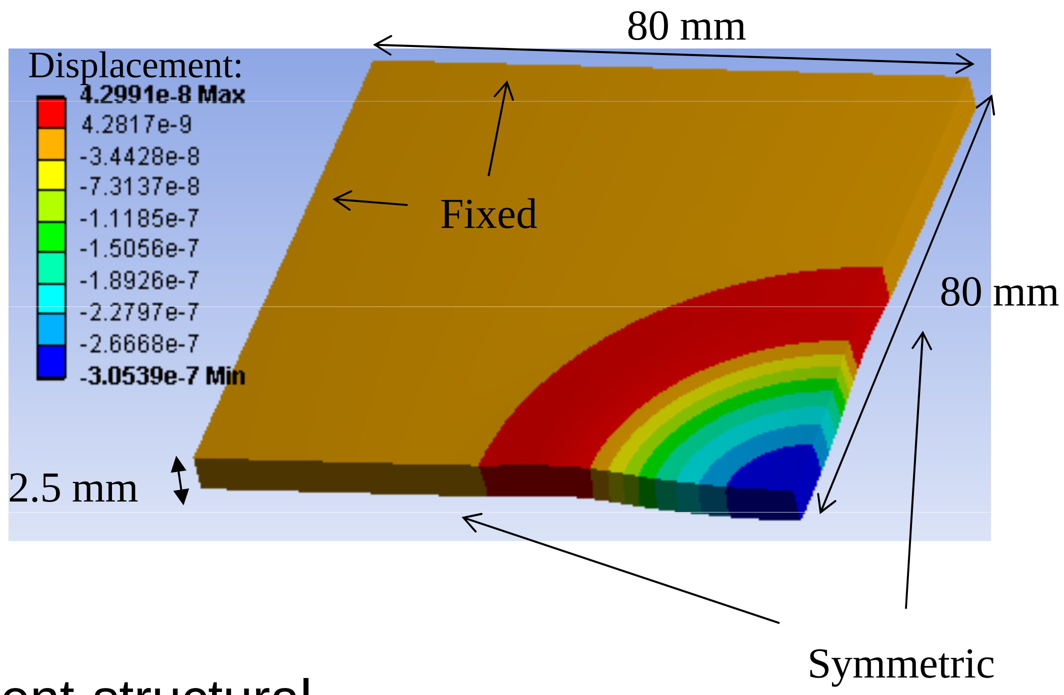


SS, V=100m/s, D=0.5mm,
Incomp./Comp.

FSI Validation with ANSYS

Impact conditions:

- V=100m/s
- D=0.5 mm
- SS plate



80 mm

80 mm

Fixed

2.5 mm

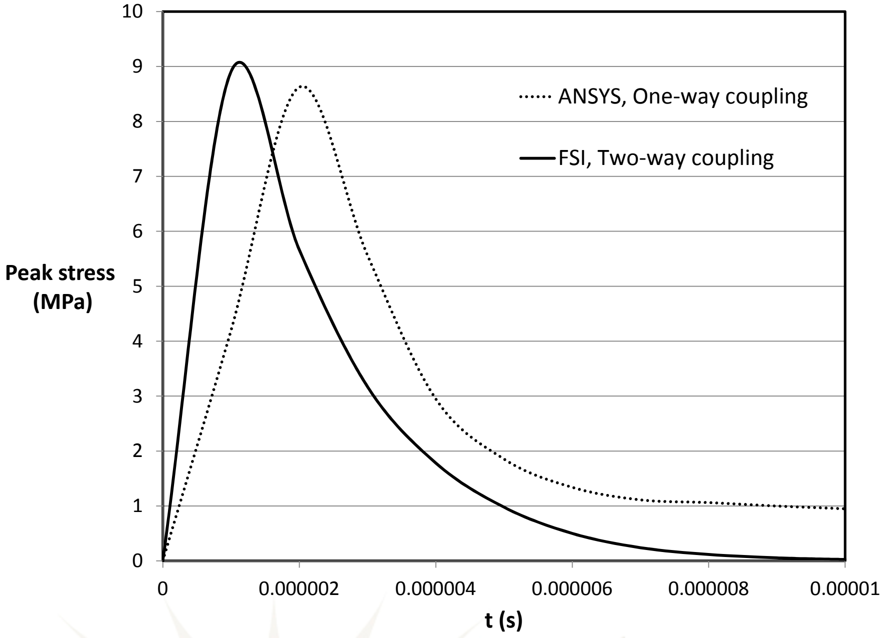
Symmetric

Solver parameters:

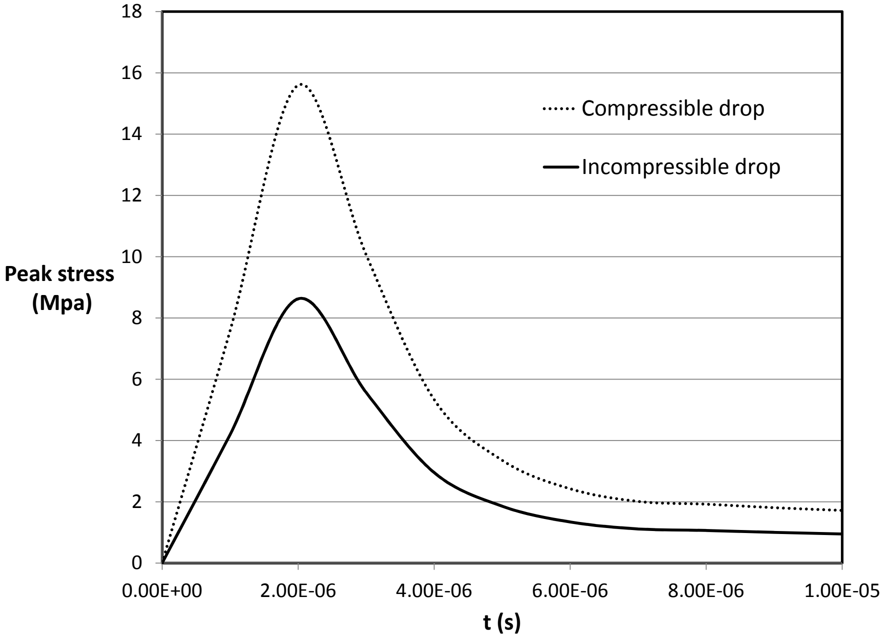
- Mesh size: 0.25 mm
- Time step: 1 µs
- Solver: ANSYS 3D Transient-structural

Stress field in the solid domain

Validation of FSI solver with FEM solver ANSYS



Increase in the peak stress due to fluid compressibility



SS, V=100m/s, D=0.5mm,
Incomp./Comp.

Progress to date

Incompressible FSI Model:

- incompressible VOF coupled with elastic solid solver
- 1-way and 2-way coupling methods
- Pressure field in liquid domain, stress field in the structure are obtained simultaneously

Compressible FSI Model:

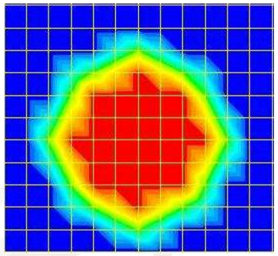
- compressible VOF solver with a rigid substrate
- 1-way coupling method
- Pressure field in liquid domain is obtained first and imposed on an elastic substrate to calculate the stress

Ongoing work

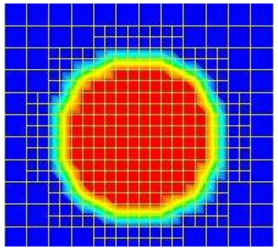
- Model the impact of a compressible droplet at high impingement velocities on regid substrates
- Couple the compressible VOF solver with structural solver to create a 3-D coupled compressible FSI solver
- Validate the FSI solver utilizing commercial FEM codes e.g. ANSYS
- Add Adaptive Grid Refinement to the VOF solver
- Develop a correlation to predict the generated stress in the solid based on the impingement velocity
- Use the correlation in a liquid impingement problem to calculate erosion rate
- Compare the obtained erosion rate with existing experimental results

Challenges and limitations

- High computational cost due to single processing → Parallelization of the FSI solver
- Modeling fluid compressibility coupling with solid elasticity→ Creating a compressible FSI model based on compressible VOF and structural elastic solvers with a 2-way coupling
- Mesh refinement limitation → Adding adaptive grid refinement



10 cells per diameter



20 cells per diameter

Thank you!

Questions?

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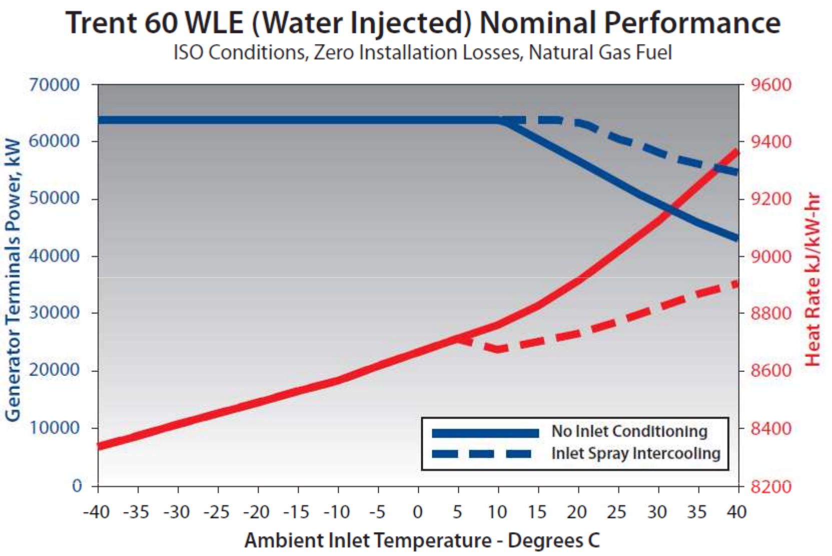
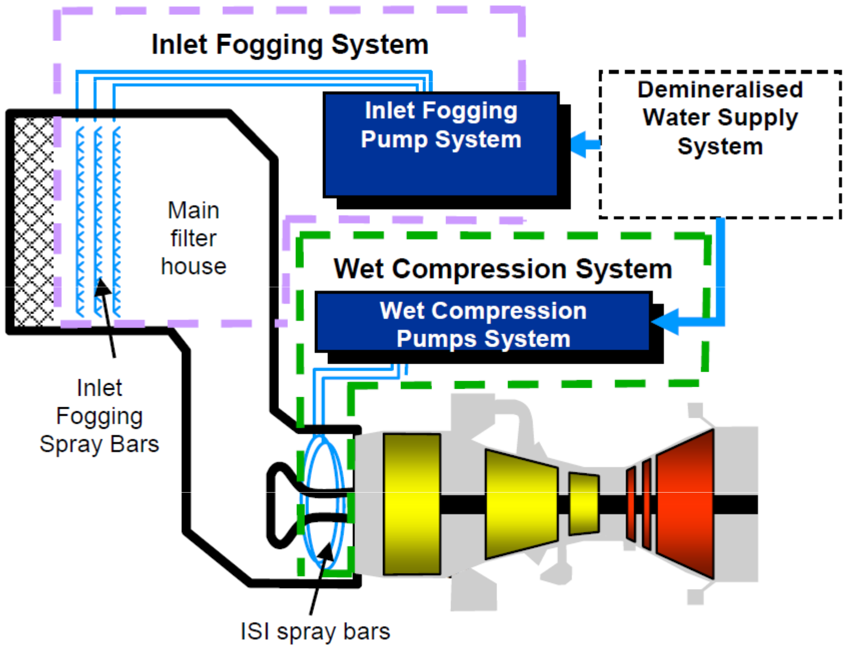
Spray intercooling system

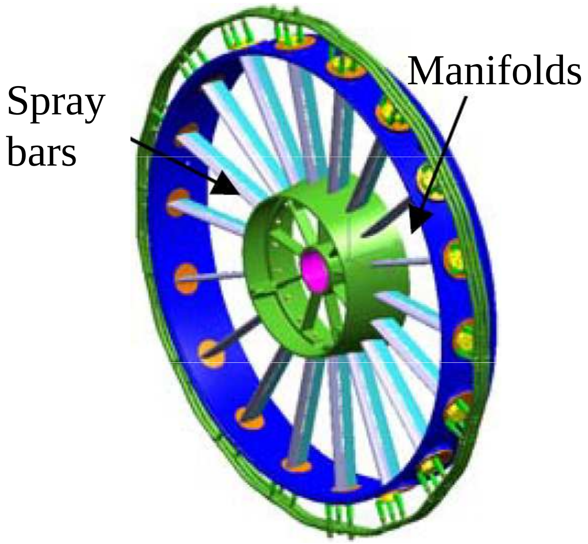


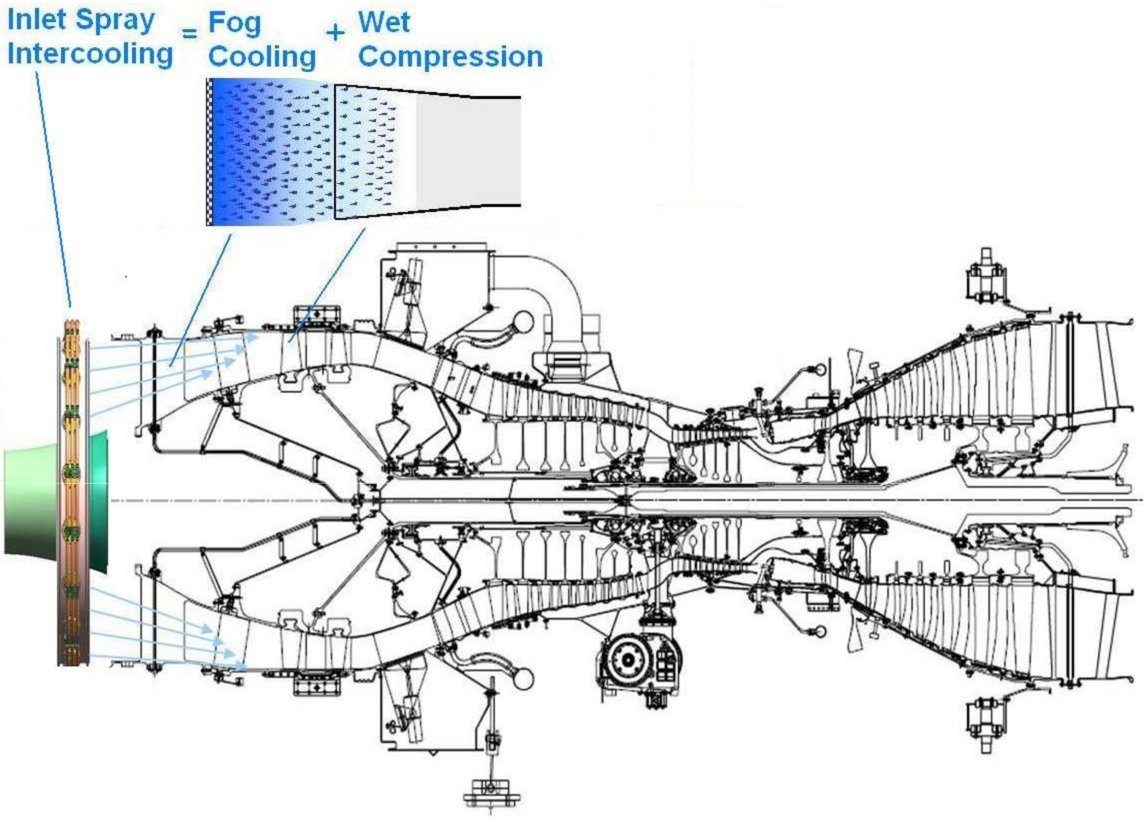


- ➢ 15-30 % gain in power at high ambient temperatures
- ❖ Reduce the blade life considerably

Courtesy of Rolls-Royce Canada

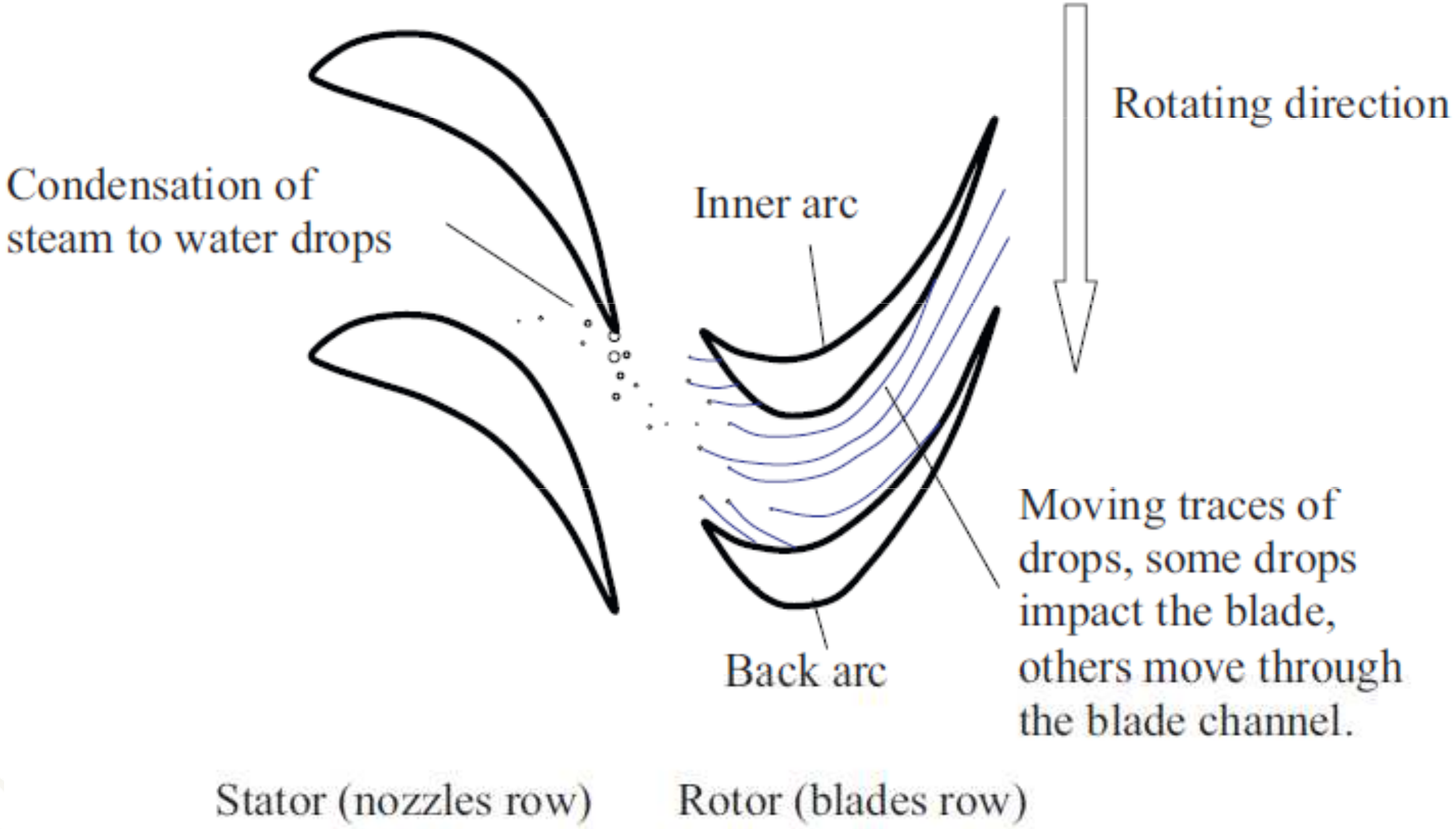
Cooling mechanism





Courtesy of Rolls-Royce Canada

Droplet shedding on rotor blades



Li et al., 2008

Liquid Impingement Erosion

Consequences of LIE on blades:

- Drop in aerodynamic performance (due to geometry change)
- Engine instability due to loading change
- Reduction in life time of rotor blades
- Unscheduled maintenance
- Engine shut-off/power loss
- Destruction of engine components
- Engine explosion in severe cases
- **High Cost**

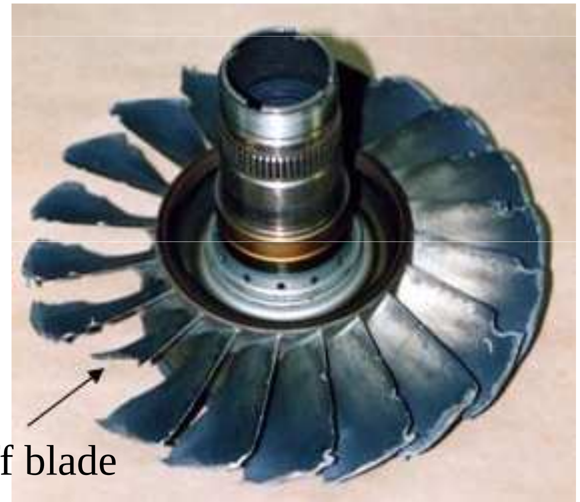

Chopped off blade

Photo courtesy: Australian Transport Safety Bureau

Significance of the work

1. Liquid Impingement Erosion

- encountered in gas turbine engines used in power generation and aerospace industries
- high stresses generated due to high speed impact
- repetitive impacts cause severe damage on the blade
- replacing the compressor blades is costly and it requires the whole engine to be shut down for overhaul

2. Thermal spray and plasma spray coatings

- Coating metal substrates with melted metal particles