OpenFOAM Analysis on the Thermal-Hydraulics in the CANDU-6 Moderator

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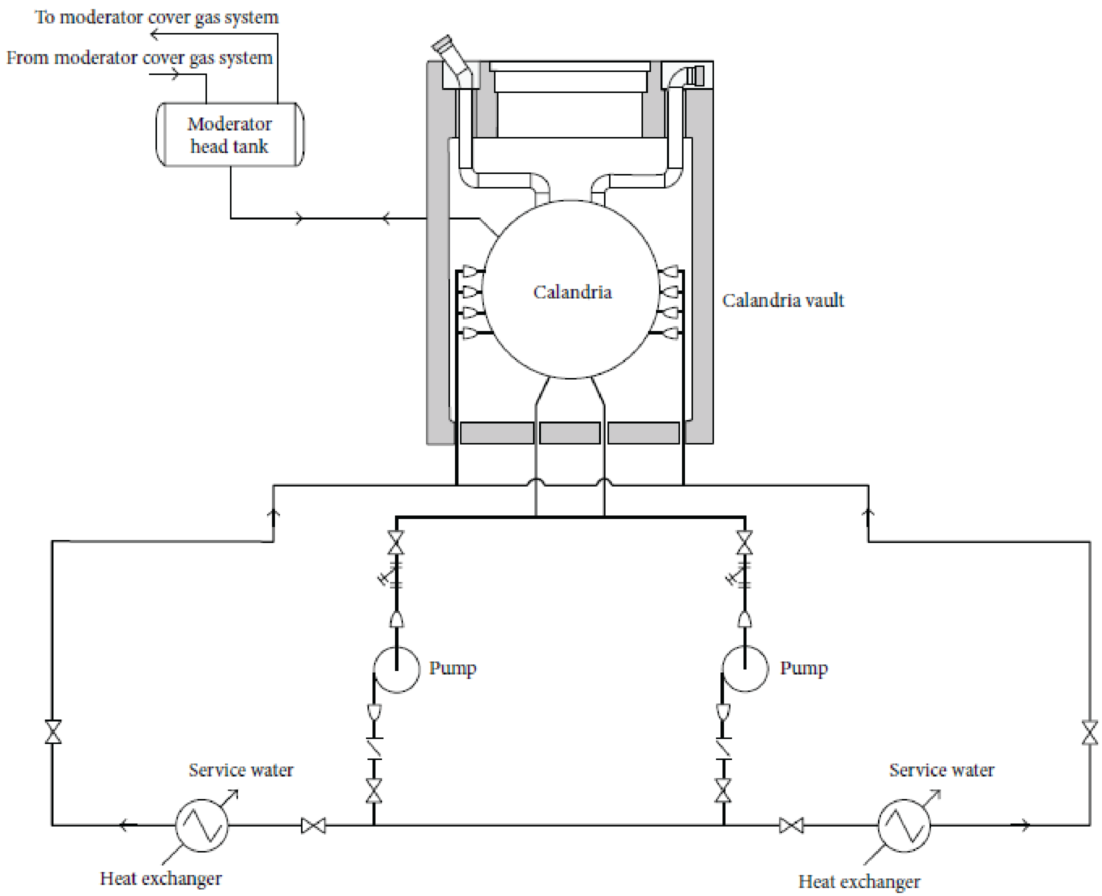
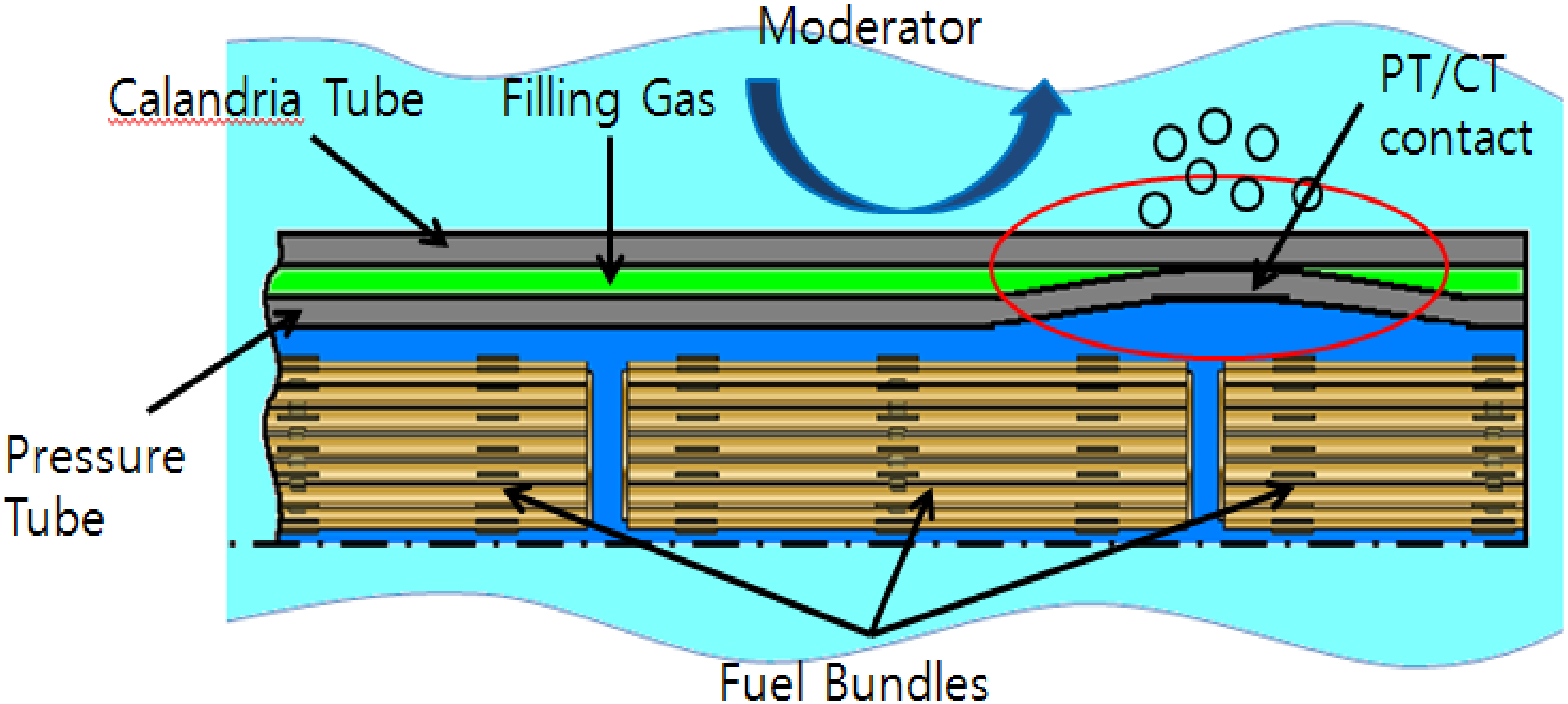
Contents

Objective of Research

3-D Analysis with CFD(Computational Fluid Dynamics code and consideration of its feasibility in the moderator system of heavy-water CANDU reactors: Calandria tank



Introduction: Calandria Tubes



LOCA: Loss Of Coolant Accident
CHF: Critical Heat Flux
Codes: MODTRUC/MODTRUC_CLAS, CATHENA, CUPID

Key Physics

Primary Physical Phenomena

1) Incompressible flow solver + turbulence model
2) Heat transfer: energy equation
3) Buoyancy term: source terms in N-S equation
4) Porous media: modeling of porosity, permeability
5) Heat source model: energy equation

Boundary conditions

No-slip (wall), adiabatic, inlet/outlet, ……

Governing Equations

$$\nabla \cdot \mathbf{V} = 0$$

$$\rho \left\{ \frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} \right\} = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{V} + \rho_0 \mathbf{g} \beta (T_0 - T)$$

$$\rho C_p \left\{ \frac{\partial T}{\partial t} + (\mathbf{V} \cdot \nabla) T \right\} = \sigma \nabla^2 T + Q_s$$

$$\rho \left\{ \frac{\partial k}{\partial t} + (\mathbf{V} \cdot \nabla) k \right\} = \frac{\partial}{\partial x_j} \left\{ \left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right\} + P_k + P_b - \rho \varepsilon - Y_M + S_k$$

$$\rho \left\{ \frac{\partial \varepsilon}{\partial t} + (\mathbf{V} \cdot \nabla) \varepsilon \right\} = \frac{\partial}{\partial x_j} \left\{ \left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right\} + C_{1\varepsilon} \frac{\varepsilon}{k} (P_k + C_{3\varepsilon} P_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon$$

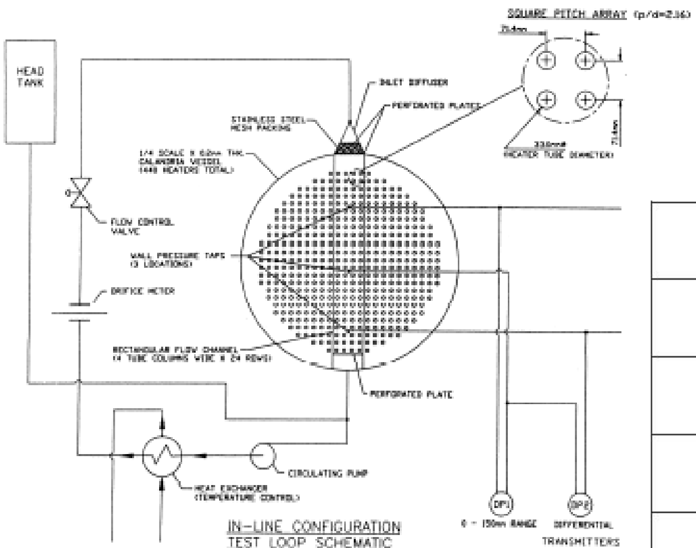
$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad C_{1\varepsilon} = 1.44, \ C_{2\varepsilon} = 1.92, \ C_\mu = 0.09, \ \sigma_k = 1.0, \ \sigma_\varepsilon = 1.3$$

Solvers

Table 1. OpenFOAM solvers used in the present computation.

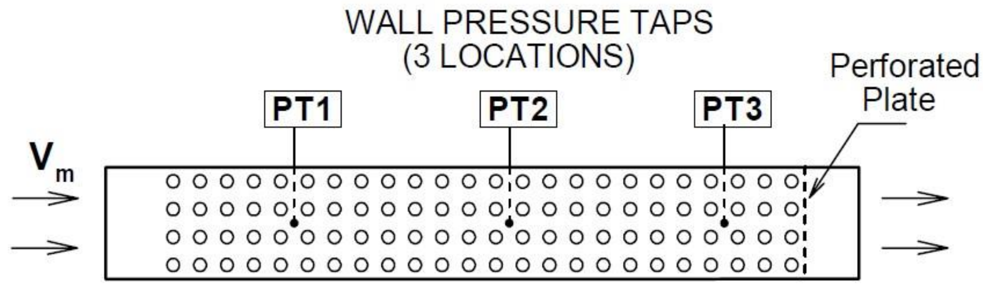
Types	Name of solver	Related physics
Incompressible (isothermal)	(porousSimpleFoam) simpleFoam/pimpleFoam	(Prorous media) Steady/Unsteady-state Incompressible Turbulent (model)
Heat Transfer	buoyantBoussinesqSimpleFoam/ buoyantBoussinesqPimpleFoam	Steady/Unsteady-state Buoyant: free convection Incompressible Turbulent (model)

Benchmark: STERN Lab. Exp.



(a) 압력강하 측정을 위한 실험장비 (Hadaller et al. 1996

(b) 검증을 위한 계산 영역



(a) In-Line Configuration

Table I Comparison of Measured and Predicted Pressure Drops

		STERN T.P. 326	STERN T.P. 299	STERN T.P. 306
Mass Flow [kg/s]		3.089	3.904	5.734
Temp. [°C]		39.5	63.6	79.8
V_m [m/s]		0.054	0.070	0.103
Reynolds Number		2746	5237	9392
ΔP [Pa]	Measurement, **A**	28.2	41.3	78.7
	CFX-4, **B**	27.6	41.2	79.3
	MODTURC	30.5	44.9	87.3
	| A – B | / A	2.13 %	0.242 %	0.762 %

Material Properties

Case	Vm [m/s]	Density [kg/m³]	Viscosity [kg/(m s)]	Re_d
1	0.054	992.25	0.000653	2,709
2	0.070	981.00	0.000440	5,153
3	0.103	971.60	0.000355	9,308

Dia. of tube: 0.03302 m
X = 2 m
Y = 0.02856 m
Z = 0.2 m

Boundary Condition / Grids

Inlet Boundary Condition: fix volume flow rate

Turbulence Intensity: assume 5%

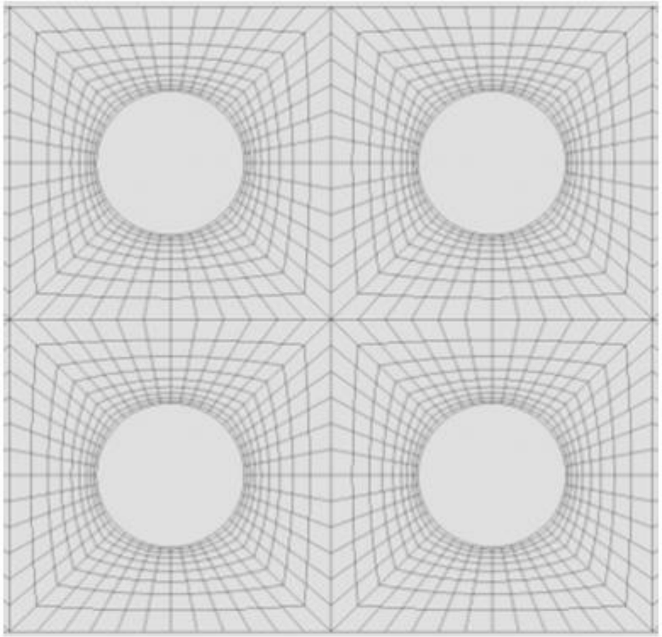
$$k = \frac{1}{2}\left\|\mathbf{V}'\right\|^2$$

$$\varepsilon = \frac{C_\mu^{0.75} k^{1.5}}{l}$$

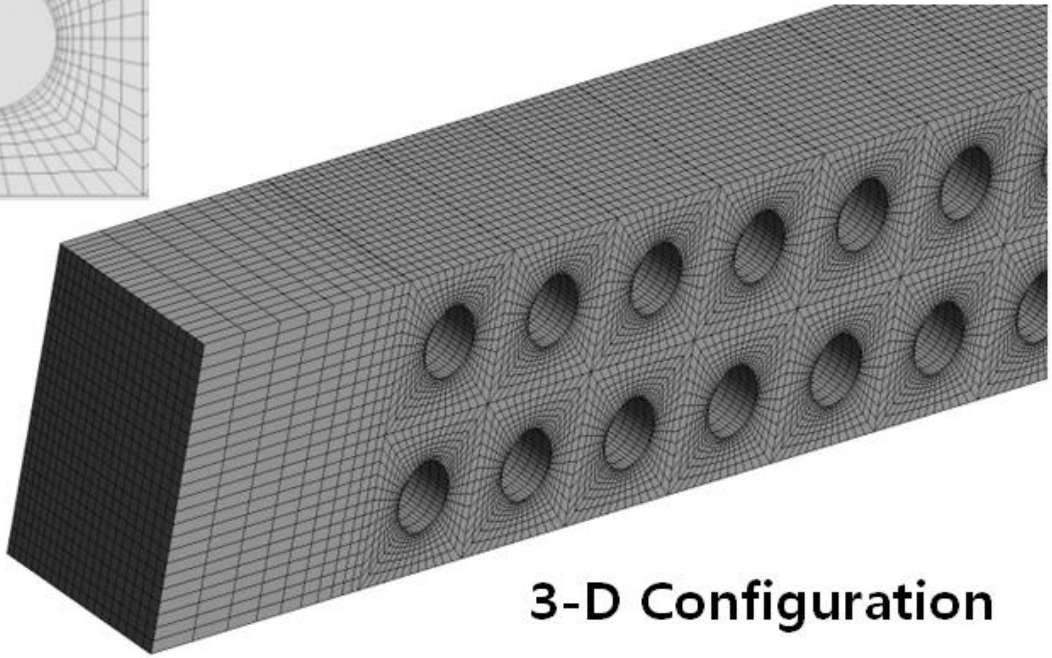
Outlet Boundary Condition: const pressure

Wall Boundary Condition: no slip

3-D Grids System

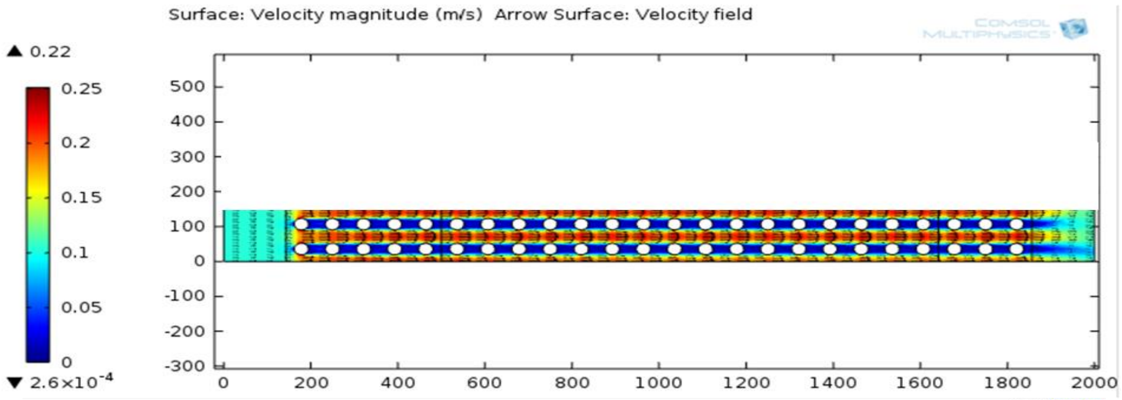


Tube Channel

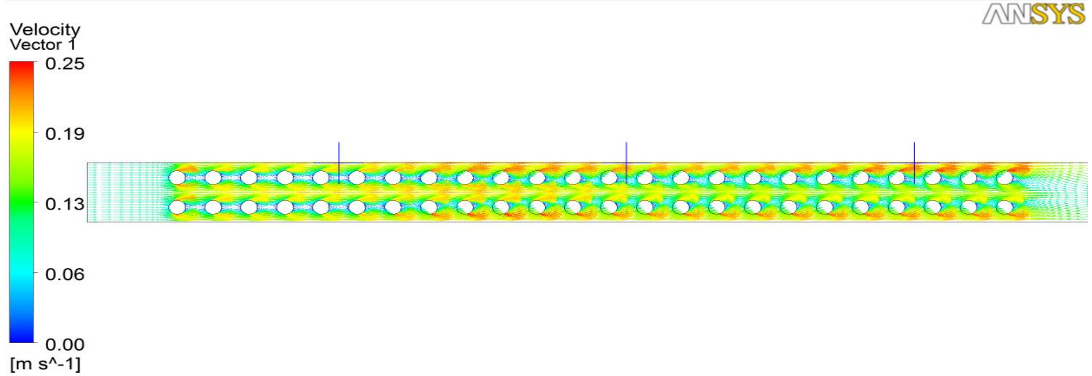


3-D Configuration

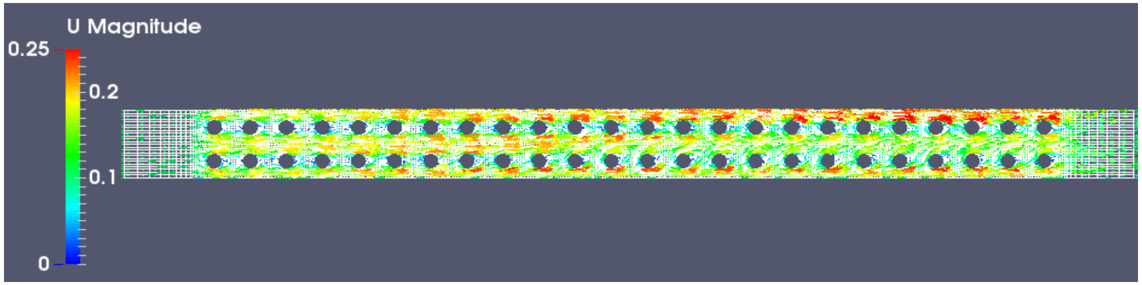
Comparison of Result



COMSOL Multiphysics

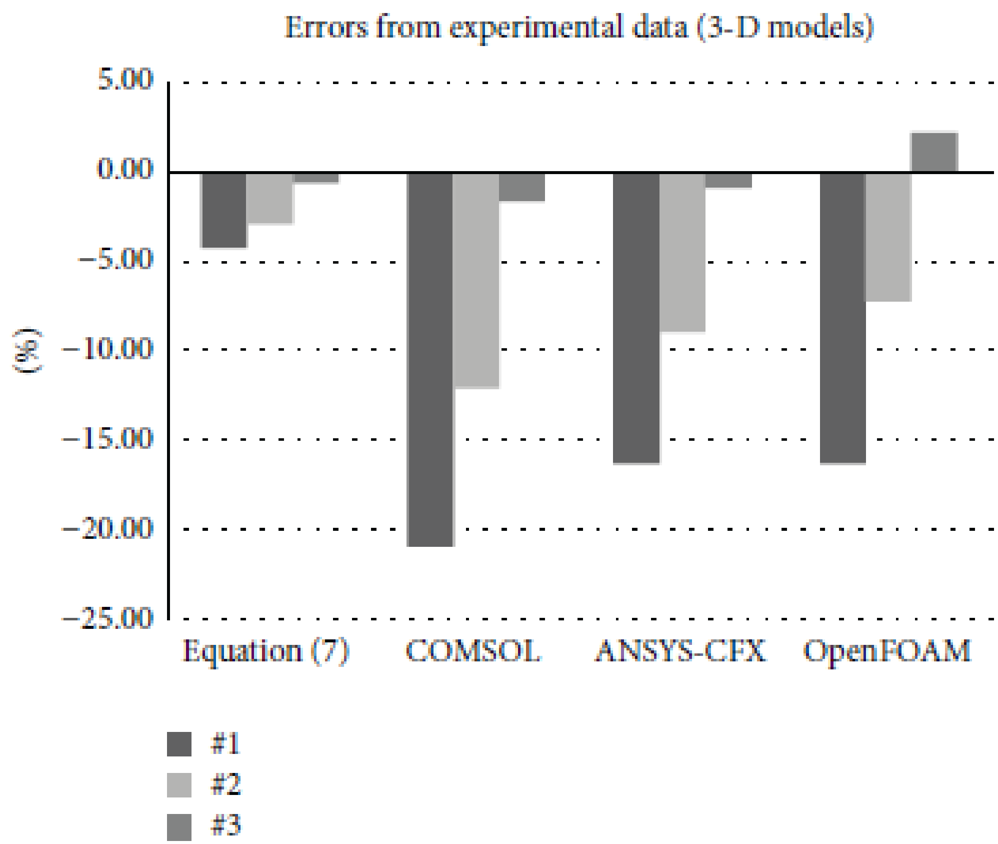


ANSYS-CFX



OpenFOAM

Comparison of Results (I)



<u>Cause of error:</u>

1) Turbulence Intensity:
   - Intake Turbulence
   - Surface Roughness
2) 3-D Effect:
   - Axial Flow along the Cylinder Surface
   - Relaxation of Flow Instability

Comparison of Results (II)

2-D

Case	Δp (Pa)			
	Experiment (STERN)	COMSOL (2D)	ANSYS-FLUENT (2D)*	OpenFOAM (2D)
#1	28.2	15.0	16.0	14.0
#2	41.3	22.5	20.3	21.4
#3	78.2	45.2	36.4	38.0

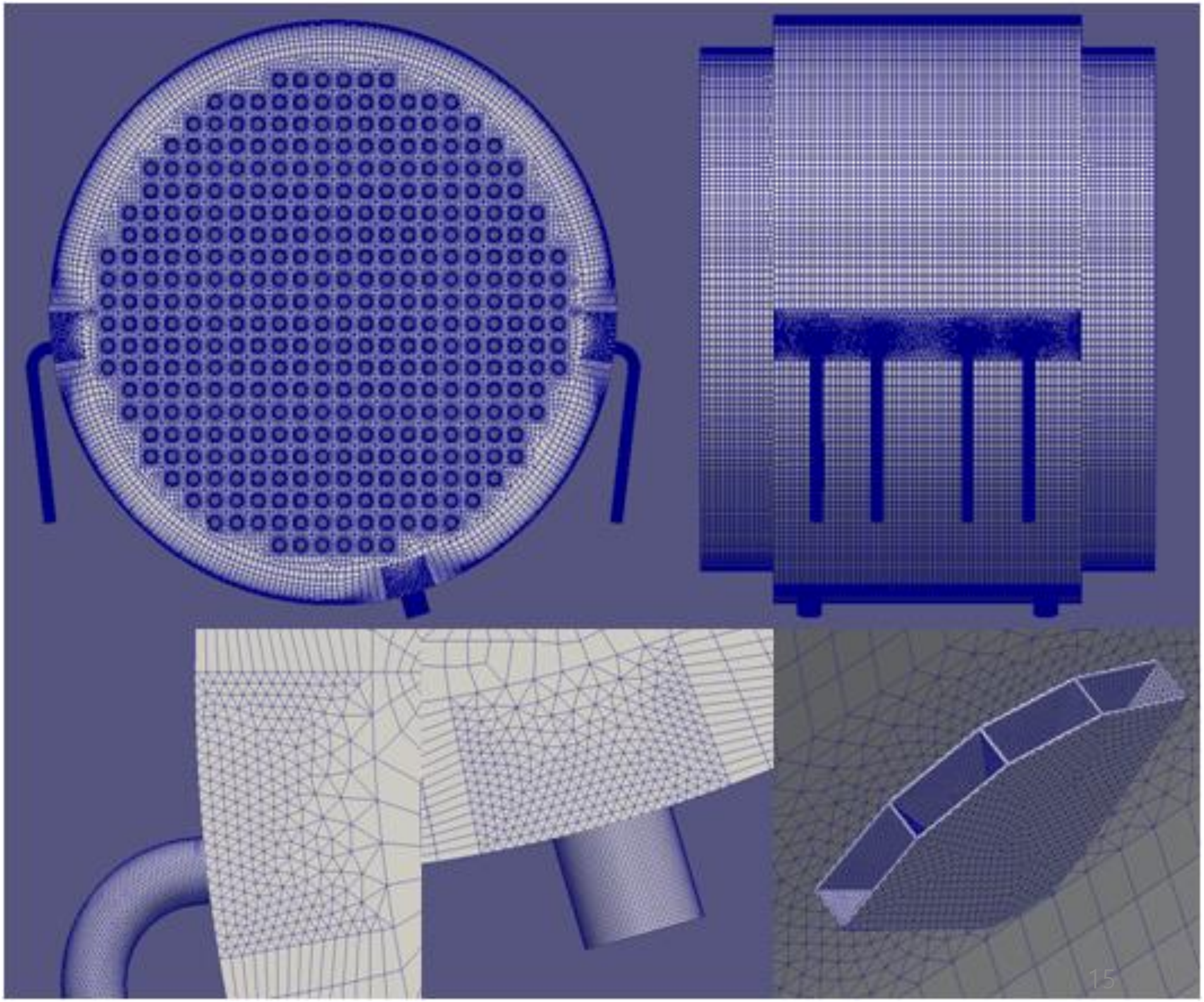
* Quoted for the data with k-ε turbulence model in FLUENT version 15 [10].

3-D

Case	Δp (Pa)				
	Experiment (STERN)	Equation (7)*	COMSOL (3-D)	ANSYS-CFX (3-D)	OpenFOAM (3-D)
#1	28.2	27.0	22.3	23.6	23.6
#2	41.3	40.1	36.3	37.6	38.3
#3	78.2	77.7	76.9	77.5	79.9

* The porous model is used with the experimental correlation [15].

Full 3-D CANDU-6 Grids



Total = 6.74 M
Hexa = 5.11 M
Pyramid = 0.013 M
Tetra = 1.62 M

Boundary/Initial Conditions

- Massflow rate at each inlet = 127.4 kg/s.
  (Total Massflow = 1,019 kg/s)
- No-slip at the wall.

- Outlet pressure: fixed, & zero-gradient otherwise.

- Inlet temperature = 47.3 degC.
- Adiabatic at the wall.

- Initially stationary & isothermal.

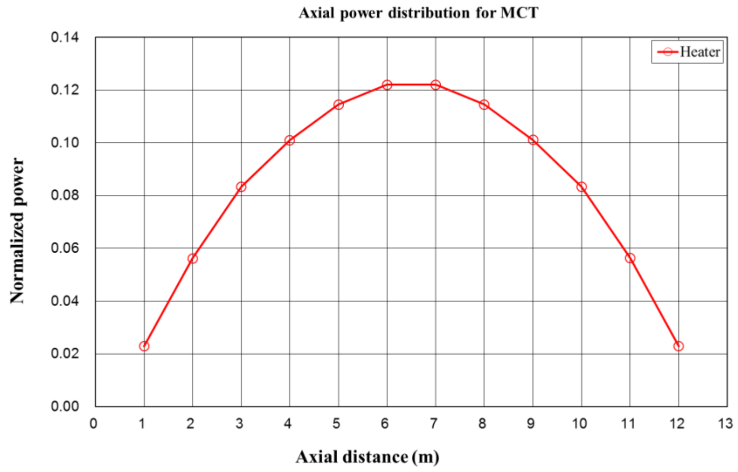
Modeling of the Heat Source

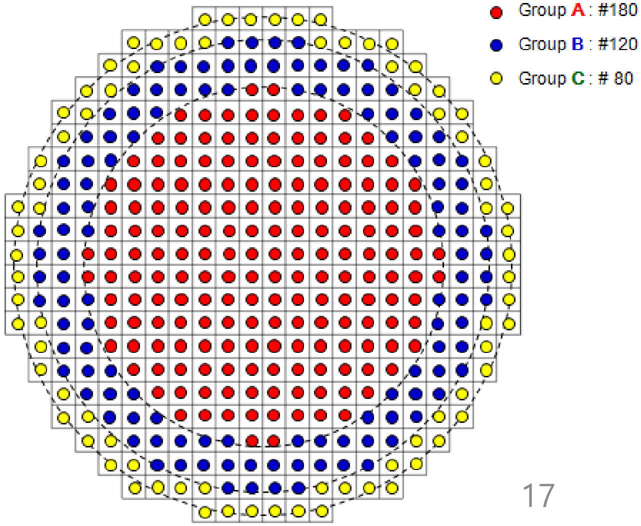
Total Thermal Power = 100 MW
Correction Factor for the Volume of Tube Bundle
= 1.089

$$Q_s(r,z) = Q_s\, f_r(r)\, f_z(z)$$

$$f_r(r) = 0.94588 - 0.01989\,r + 0.0995\,r^2 - 0.03888\,r^3 - 0.00256\,r^4 \quad (0.0 \le r \le 3.38\ m)$$

$$f_z(z) = 1.0 - 0.1111\,z^2 \quad (-3.0 \le z \le 3.0\ m)$$





Implementation with OpenFOAM

File Name: fvOption

```
energySource1
{
        type scalarCodedSource;
        active true;
        selectionMode all;
        #{
                ...
                forAll(cc,celll)
                {
                        ...         //define the source terms
                }
        #};
}
```

Turbulence Model: Realizable k-ε

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k+P_b-\rho\epsilon-Y_M+S_k$$

$$\frac{\partial}{\partial t}(\rho\epsilon)+\frac{\partial}{\partial x_j}(\rho\epsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right]+\rho\, C_1 S\epsilon-\rho\, C_2\frac{\epsilon^2}{k+\sqrt{\nu\epsilon}}+C_{1\epsilon}\frac{\epsilon}{k}C_{3\epsilon}P_b+S_\epsilon$$

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right],\qquad \eta=S\frac{k}{\epsilon},\qquad S=\sqrt{2S_{ij}S_{ij}}$$

$$\mu_t=\rho C_\mu\frac{k^2}{\epsilon}$$

$$C_\mu=\frac{1}{A_0+A_s\frac{kU^*}{\epsilon}}$$

$$U^*\equiv\sqrt{S_{ij}S_{ij}+\tilde{\Omega}_{ij}\tilde{\Omega}_{ij}};$$

$$\tilde{\Omega}_{ij}=\Omega_{ij}-2\epsilon_{ijk}\omega_k;$$

$$\Omega_{ij}=\overline{\Omega_{ij}}-\epsilon_{ijk}\omega_k$$

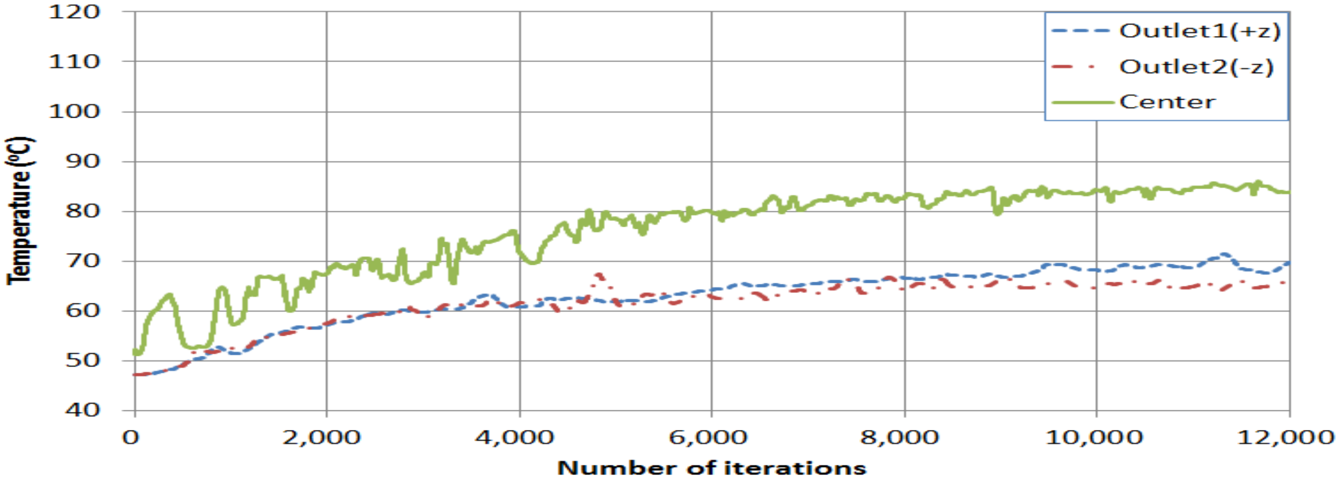
$$A_0=4.04,\quad A_s=\sqrt{6}\cos\phi$$

$$\phi=\frac{1}{3}\cos^{-1}(\sqrt{6}W),\quad W=\frac{S_{ij}S_{jk}S_{ki}}{\tilde{S}^3},\quad \tilde{S}=\sqrt{S_{ij}S_{ij}},\quad S_{ij}=\frac{1}{2}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)$$

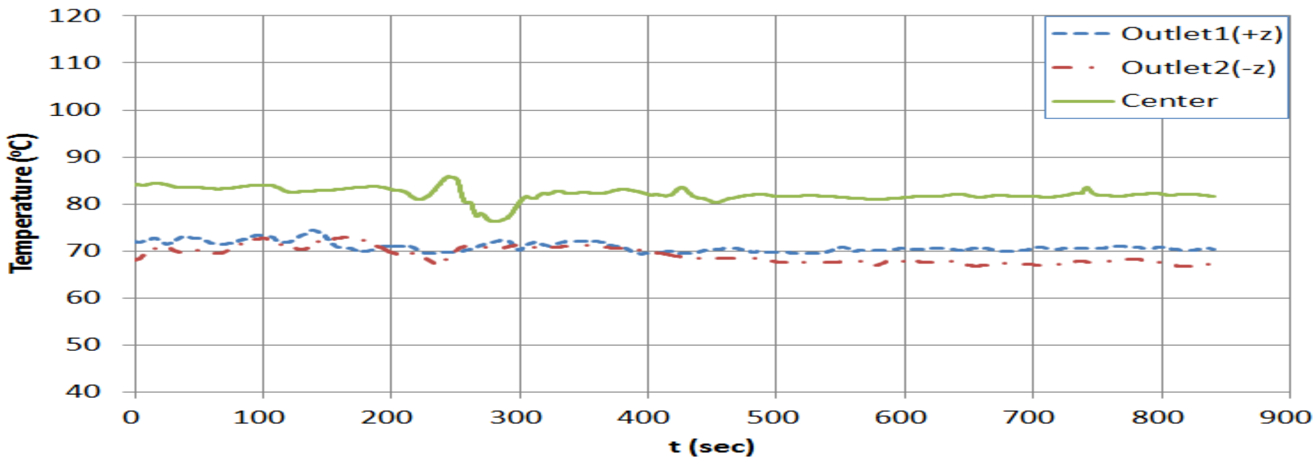
$$C_{1\epsilon}=1.44,\quad C_2=1.9,\quad \sigma_k=1.0,\quad \sigma_\epsilon=1.2$$

Complex rotational flow

Temperature at the Inlet/Outlet



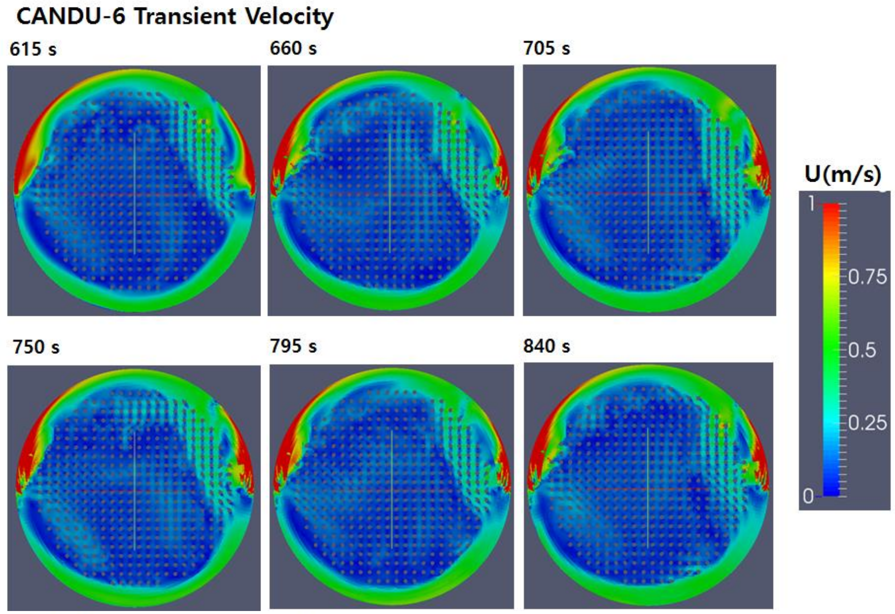
Stage 1



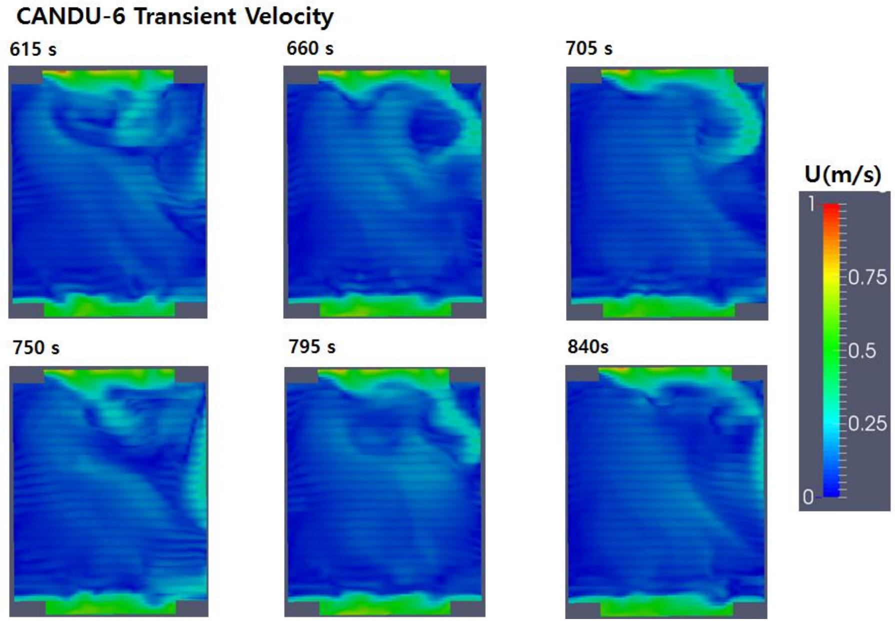
Stage 2

Velocity Profiles

Cross-sectional

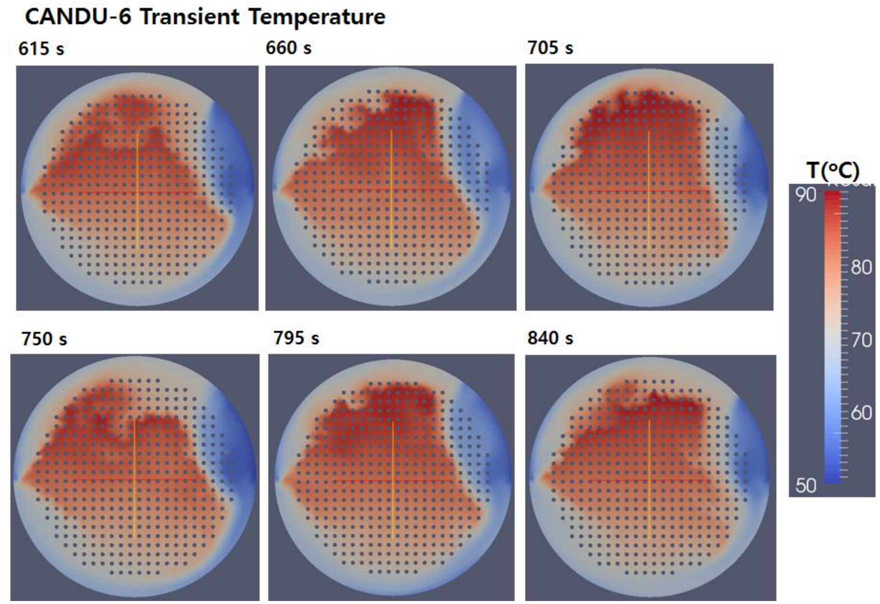


Axial

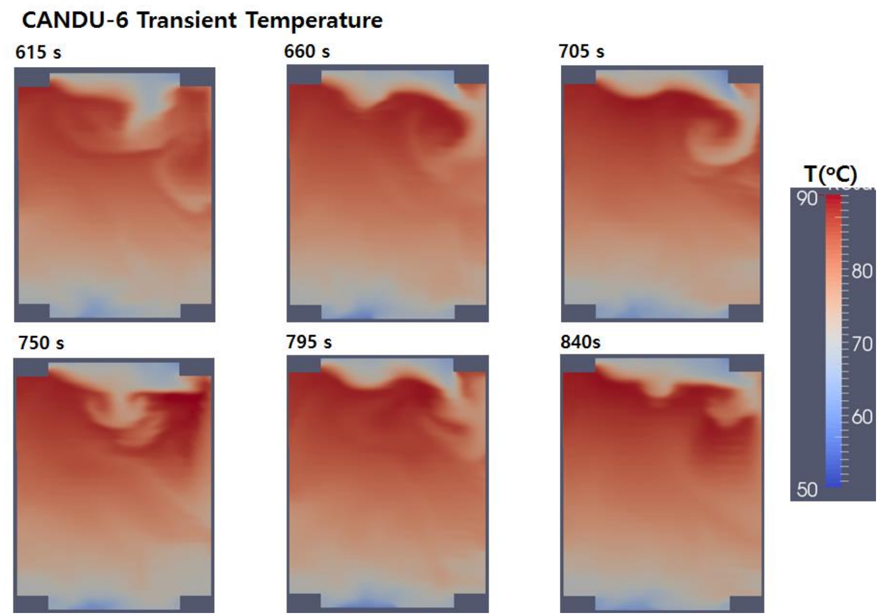


Temperature Profiles

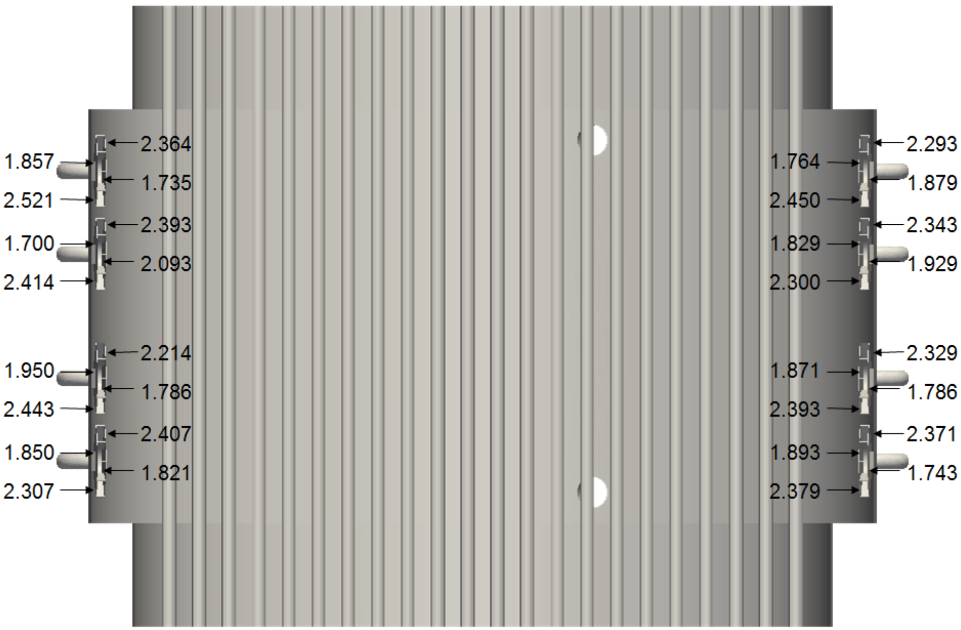
Cross-sectional

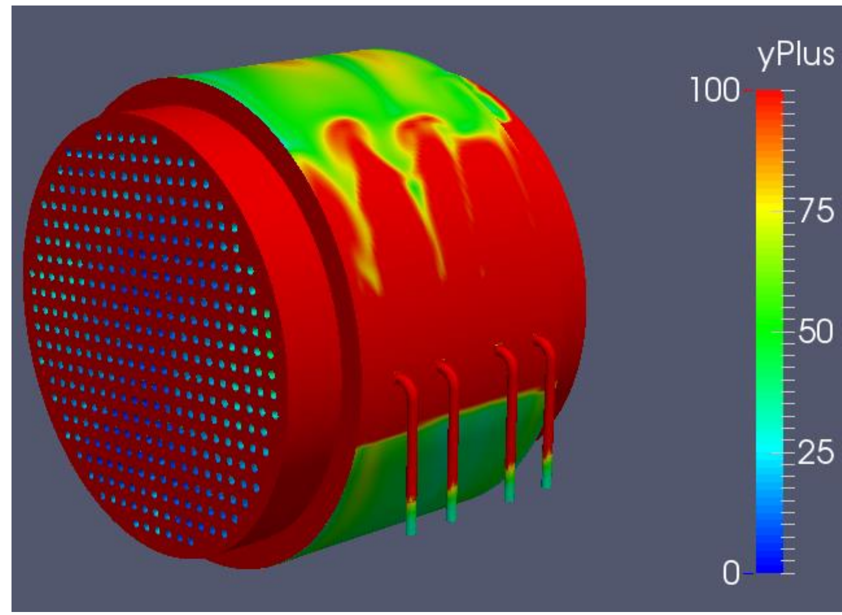


Axial

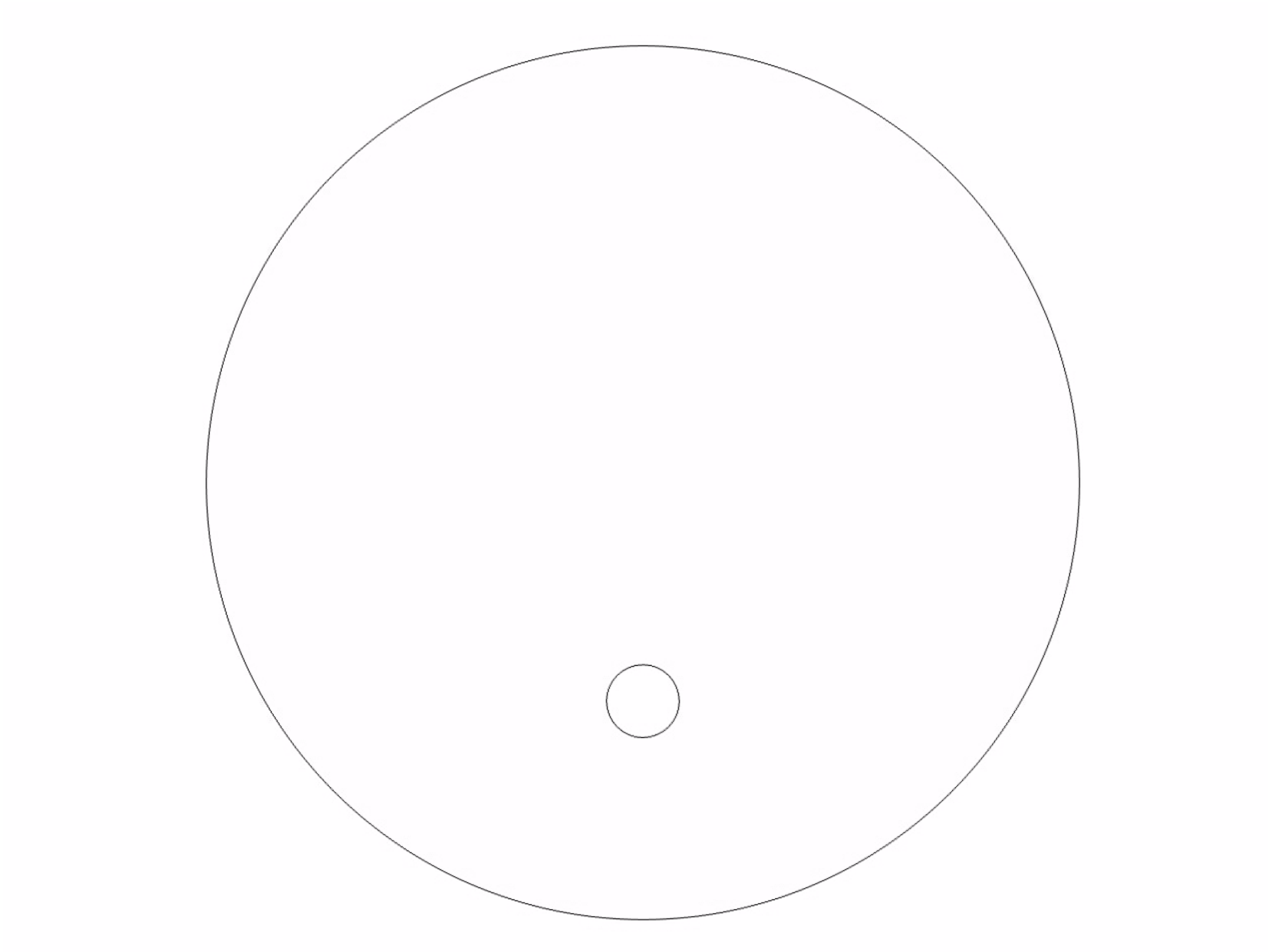


Velocity at Nozzles & y⁺





Animation: Natural Convection



Summary and Conclusion

1) 1-D System Code(RELAP/MARS)
   → 3-D CFD Code
   (In-House/Commercial/Open Source)

2) Validation of STERN Lab. Exp.: Feasibility O.K.

3) Simulation of Full-scale CANDU-6 Moderator:
   - Two-stage computation/pseudo-steady
   - Use of SIMPLE and PIMPLE Foams
   - Realizable k-ϵTurbulence Model
   - No Converged Solution: Natural Characterisitcs of N-S Equations
   - Max. temperature: 89 degC

Q & A

Thank you for your attention!