CHAM Limited

Pioneering CFD Software for Education & Industry

Natural Convection Flow in a Nuclear Reactor

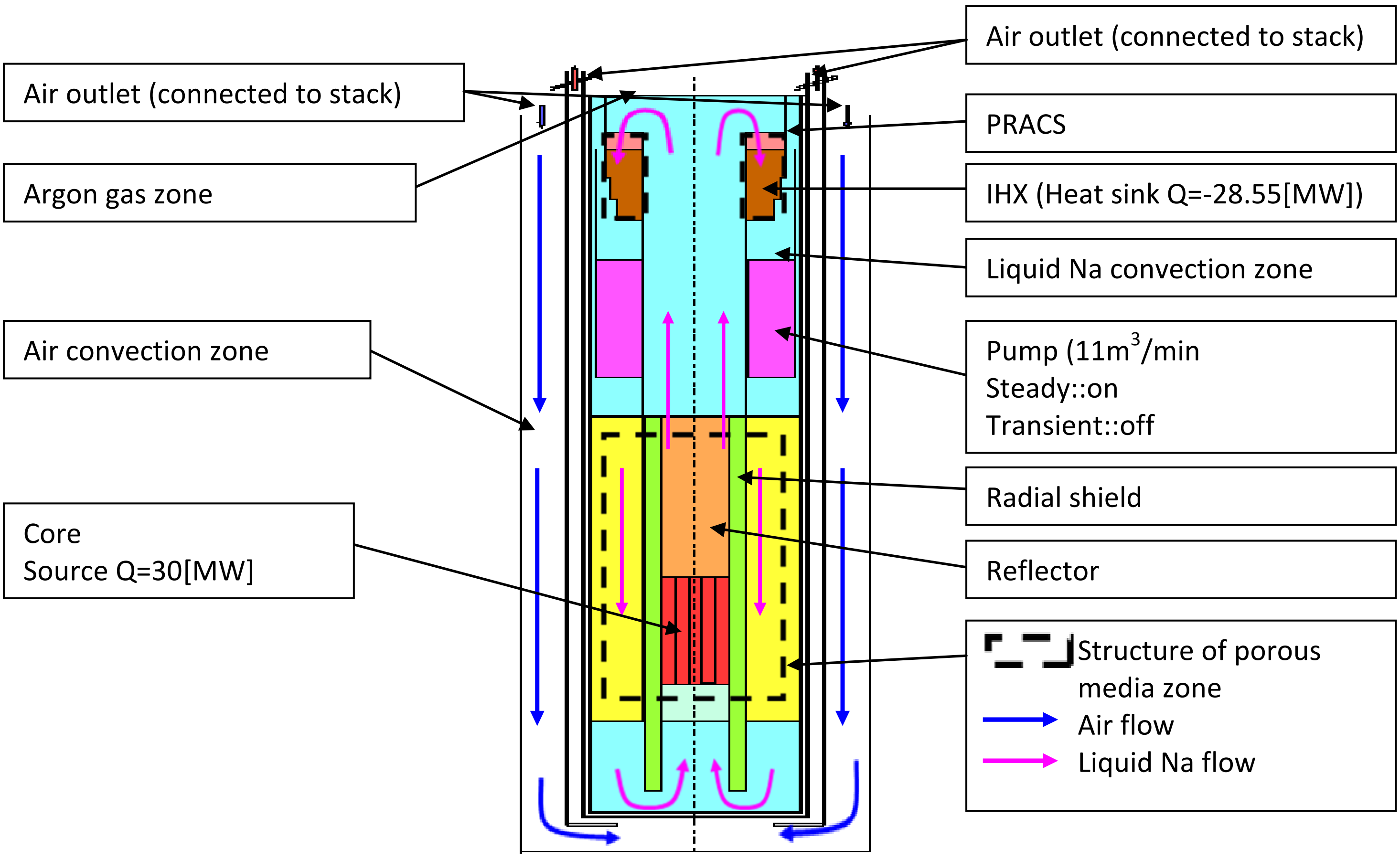
A PHOENICS Version 3.6 Application by CHAM Japan

The following represents part of a consulting project undertaken by CHAM Japan on behalf of Denchuken. The problem considered is a simulation of the heat release from a nuclear reactor following an unexpected failure of its cooling system. When an accident happens in the nuclear reactor system - eg a cooling system failure - heat will be released solely by natural convection of air flow. The purpose of this model is to establish the distribution of temperature and the air flow rate under these circumstances.

Model details

- Cylindrical-polar grid
- Three-Dimensional steady or transient flow with heat transfer
- Buoyancy-influenced flow
- Surface to surface radiation included
- NX*NY*NZ=40*45*80=144,000

Geometry

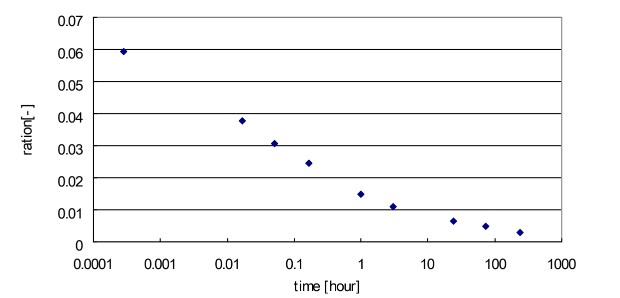


Boundary Conditions

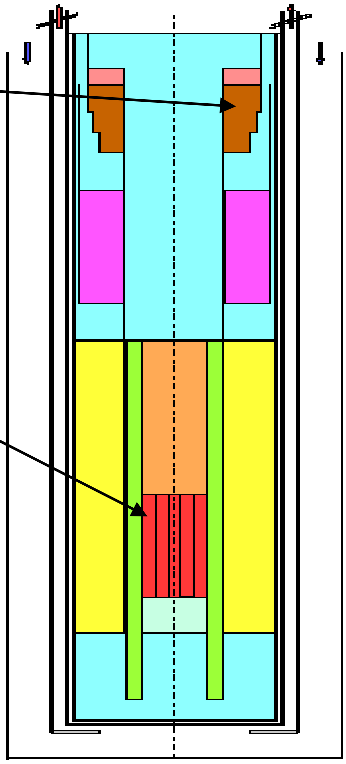
Heat source and heat sink

Steady: -28.55 [MW]
Transient: 0 [MW]

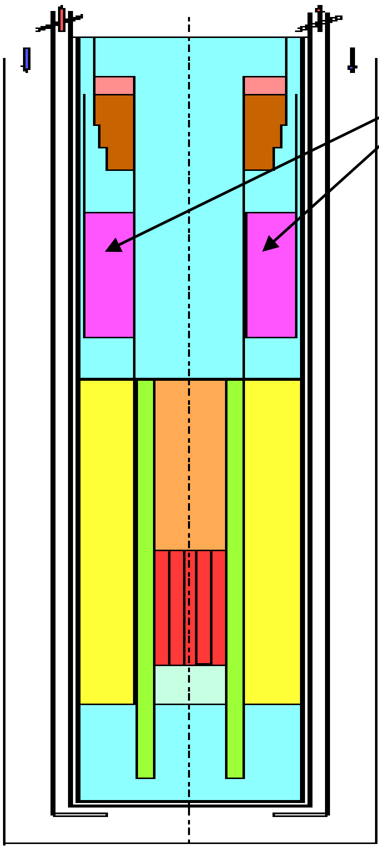
Steady: 30[MW]
Transient: change profile



power ration=Q/30



Pump Power



Steady: 11[m^3/s]
Transient: change profile

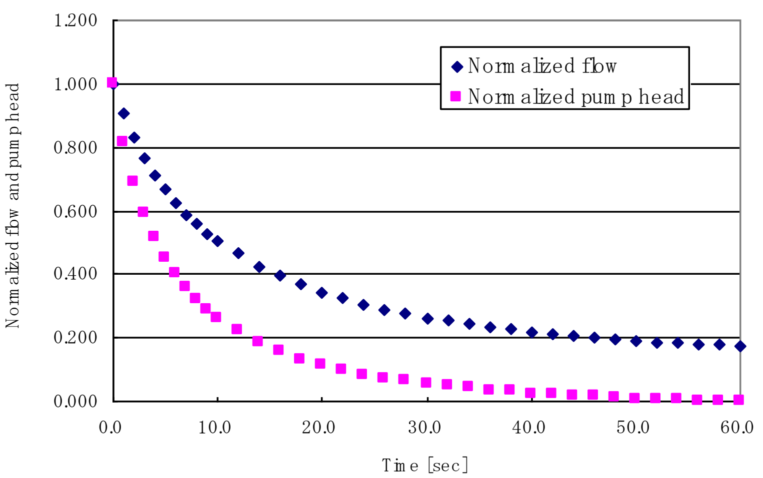


Fig. Pump coastdown curve

Body Force (Buoyancy)

Liquid Na convection zone

$$F = \beta \rho g (T - T_\infty)$$

Air convection zone

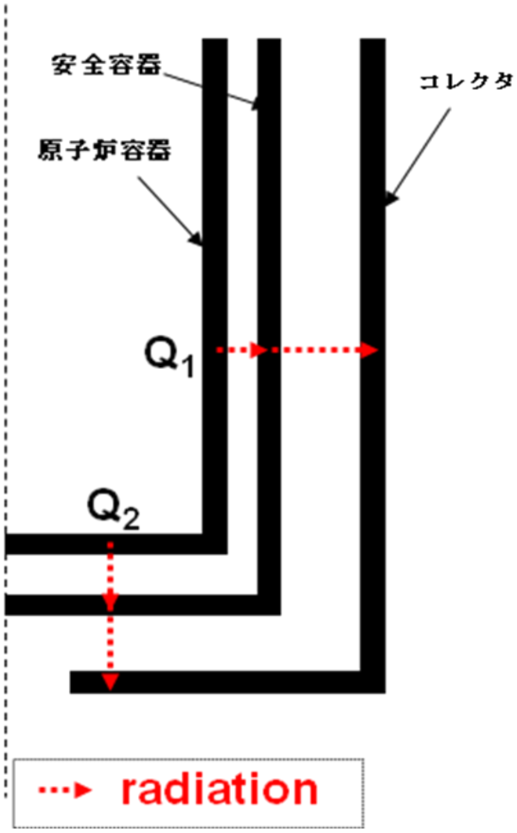
$$F = \rho g$$

Resistance force in the porous medium zone:

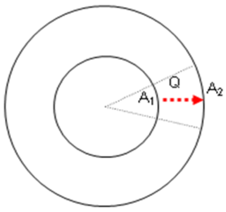
$$F = K \rho U^2$$

where
K: Pressure resistance coefficient. (This is different in each zone.)
p: density
U: velocity

Radiation

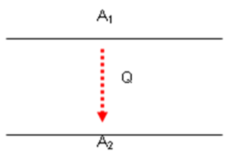


$$Q_1 = \sigma (T_1^4 - T_2^4) A_1 \frac{A_2}{\frac{A_2}{\varepsilon_1} + \frac{A_1}{\varepsilon_2} - A_1}$$



$$A_1 \neq A_2$$

$$Q_2 = \sigma (T_1^4 - T_2^4) A_1 \frac{A_2}{\frac{A_2}{\varepsilon_1} + \frac{A_1}{\varepsilon_2} - A_1}$$



$$A_1 = A_2$$

Energy source in the porous medium zone

$$\frac{\partial (\rho Cp)_{ef} T}{\partial t}+\frac{\partial(\rho_{liq} U_i Cp_{liq} T)}{\partial x_i}-\frac{\partial}{\partial x_i}\left(k_{ef}\frac{\partial T}{\partial x_i}\right)=S$$

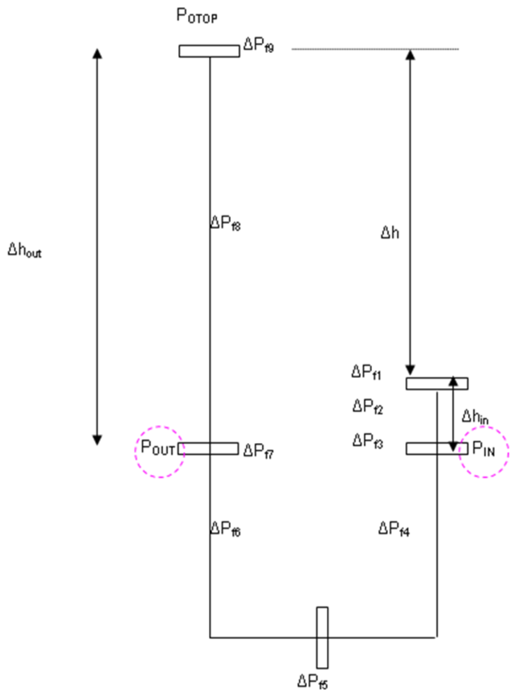
$$\frac{\partial (V_{liq}\rho_{liq} Cp_{liq} T)}{\partial t}+\frac{\partial(\rho_{liq} U_i Cp_{liq} T)}{\partial x_i}-\frac{\partial}{\partial x_i}\left(k_{ef}\frac{\partial T}{\partial x_i}\right)=S-\frac{\partial (V_{solid}\rho_{solid} Cp_{solid} T)}{\partial t}$$

where

$$(\rho Cp)_{ef} = V_{liq}\rho_{liq}Cp_{liq} + V_{solid}\rho_{solid}Cp_{solid}$$
$$k_{ef} = V_{solid}k_{solid} + V_{solid}k_{liq}$$
$$V_{sol} = 1 - V_{liq}$$

Pressure value in the air convection zone boundary

The value of pressure in the air convection zone boundary is renewed while it is calculated from the next experience equation.



$$P_{out} = \rho_{out} g \Delta h_{out} + \sum_{i=1,9}\Delta P_{fi} - \sum_{i=1,7}\Delta P_{fi}$$

$$P_{in} = \rho_{out} g (\Delta h + \Delta h_{in}) + \sum_{i=1,9}\Delta P_{fi} - \sum_{i=1,2}\Delta P_{fi}$$

i=1 to 5

$$\Delta P_{fi} = \frac{0.5}{n}\frac{k_i}{\rho_{out}}\frac{\dot{m}}{A_i^2}$$

i=6 to 10

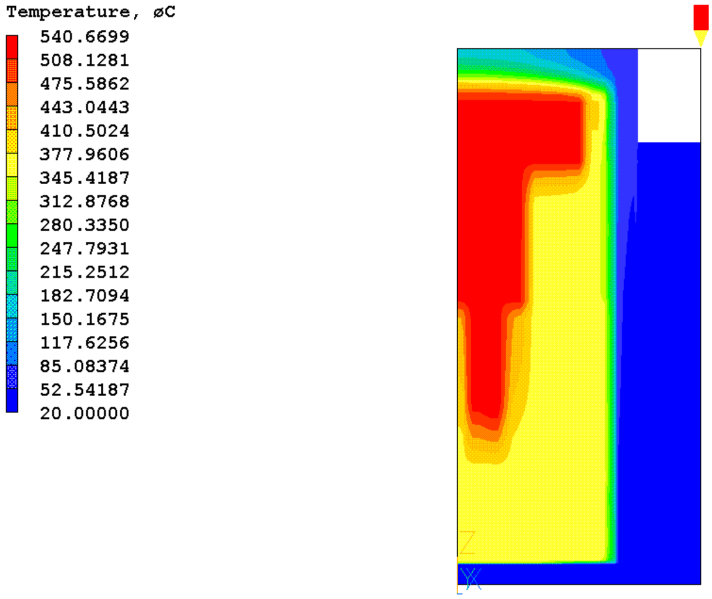
$$\Delta P_{fi} = \frac{0.5}{n}\frac{k_i}{\rho_{in}}\frac{\dot{m}}{A_i^2}$$

i	$A_i[m^2]$	$k_i[-]$	n
1	1.0	0.3	2
2	1.0	0.25	2
3	-	0.657	2
4	5.28	1.3	1
5	3.48	0.76	1
6	1.26	2.6	1
7	-	0.3174	2
8	1.0	1.5	2
9	1.0	7.0	2

Result

Maximum temperature [C˚]

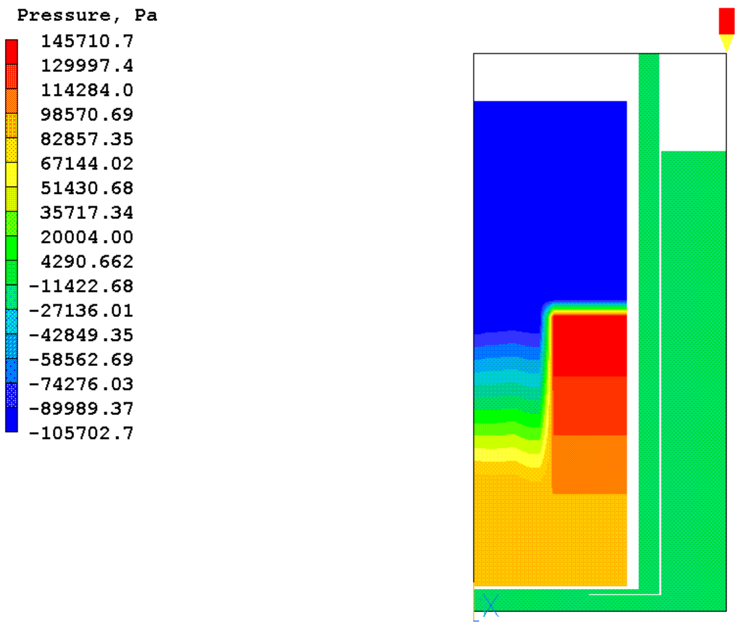
Experimental data: 550 ˚C
PHOENICS result: 540.6699 ˚C



Temperature distribution (steady)

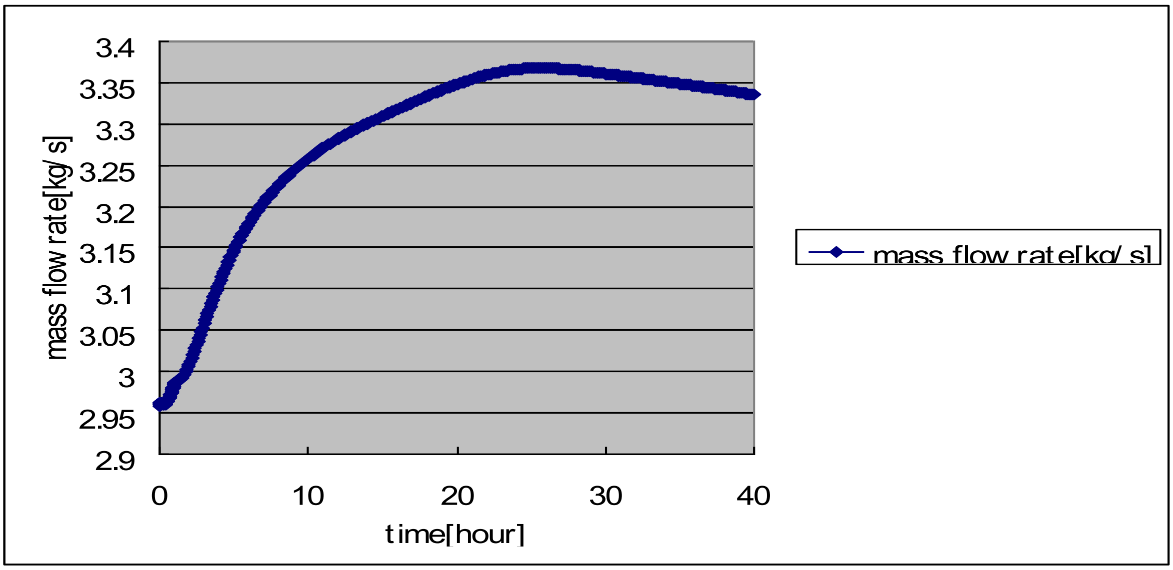
Pressure drop [MPa] in Na convection zone

Experimental data: 2.5
PHOENICS result: 2.51

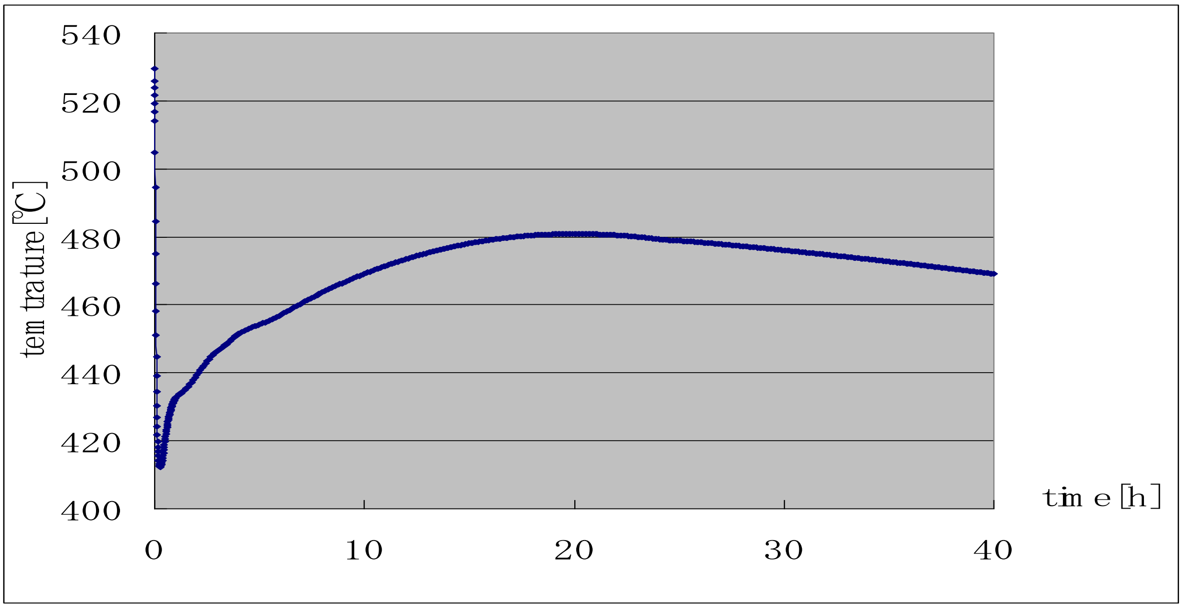


Pressure distribution (steady)

Air flow rate in the air convection zone



Maximum temperature in the liquid Na convection zone



Conclusion

Such is the flexibility of PHOENICS that a model capturing the major components of the nuclear reactor system was able to be constructed from built-in objects. Additional user-defined functionality was introduced via GROUND coding. The final model performed well against experimental data both for its normal steady-state operation and its transient predictions agreed well with data gathered from a controlled and monitored cooling-system failure.