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Condensation and Hydrogen Risk Calculations in FCVS Pipe with Python

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1. Introduction

The explosion in Fukushima Nuclear Power Plant accident is due to high pressure, high temperature and high-volume fraction of hydrogen in containment vessel. Therefore, the Filtered Containment Venting System (FCVS) is introduced for preventing over-pressurization by venting the gas from containment to FCVS building. However, the hydrogen risk exists in FCVS pipe because the gas flowing into the FCVS pipe is mixture of air, steam and hydrogen. The high-pressure gas from the containment moves faster than speed of sound when it flows through the orifice in FCVS pipe. The supersonic flow of gas mixture can make condensation of steam and the changing of the composition ratio of gas can make hydrogen risk increase when the gas passes through the orifice.

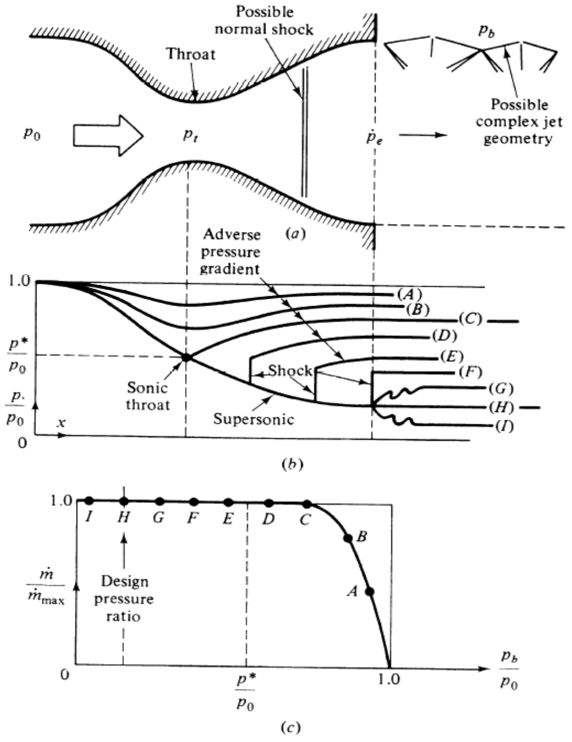

Fig. 1. Operation of a converging-diverging nozzle. [1]

In this paper, we will confirm the occurrence and hydrogen risk in FCVS pipe by using Python programming language.

2. Methods and Results

2.1 Initial Conditions

The gas mixture entering the pipe is steam-air-hydrogen mixture and among them, steam is only condensable gas. The behavior of condensed water is not considered in this paper and the condensation heat is considered. The pipe is assumed as cylindrical pipe and its diameter is 5cm. The orifice is assumed as hyperbolic nozzle with length of 10cm, and minimum diameter of 3.4cm. In this paper, we used the (H) state of Fig. 1.

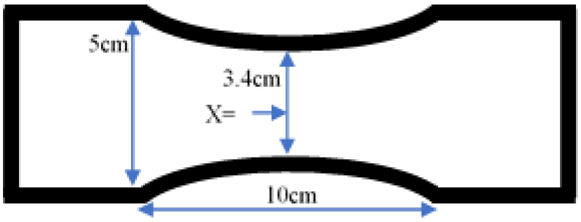

Fig. 2. Shape of postulated pipe.

2.2 Gas Flow

The parameter of gas is calculated by using Euler's equations and continuity equation. The differential equations are as shown below.

$$(1)\quad \frac{1}{M}\frac{dM}{dx}=\frac{1+\frac{k-1}{2}M^2}{M^2-1}\left[\frac{1}{A}\frac{dA}{dx}-\frac{(1+kM^2)}{2\left(1+\frac{q}{c_pT_0}\right)}\frac{d\left(\frac{q}{c_pT_0}\right)}{dx}\right]$$

$$(2)\quad \frac{1}{T}\frac{dT}{dx}=\frac{1}{1-M^2}\left[\frac{(k-1)M^2}{A}\frac{dA}{dx}+\frac{(1-kM^2)\left(1+\frac{k-1}{2}M^2\right)}{1+\frac{q}{c_pT_0}}\frac{d\left(\frac{q}{c_pT_0}\right)}{dx}\right]$$

$$(3)\quad \frac{1}{p}\frac{dp}{dx}=\frac{kM^2}{1-M^2}\left[\frac{1}{A}\frac{dA}{dx}-\frac{1+\frac{k-1}{2}M^2}{1+\frac{q}{c_pT_0}}\frac{d\left(\frac{q}{c_pT_0}\right)}{dx}\right]$$

$$(4)\quad \frac{1}{\rho}\frac{d\rho}{dx}=\frac{1}{1-M^2}\left[\frac{M^2}{A}\frac{dA}{dx}-\frac{1-\frac{k-1}{2}M^2}{1+\frac{q}{c_pT_0}}\frac{d\left(\frac{q}{c_pT_0}\right)}{dx}\right]$$

$$(5)\quad \frac{1}{u}\frac{du}{dx}=-\frac{1}{1-M^2}\left[\frac{1}{A}\frac{dA}{dx}-\frac{1+\frac{k-1}{2}M^2}{1+\frac{q}{c_pT_0}}\frac{d\left(\frac{q}{c_pT_0}\right)}{dx}\right]$$

Eq.1. Flow equation from Euler equations

In these equations, when Mach number(M) is 1, term $\frac{1}{1-M^2}$ goes to infinity, therefore the value of square bracket in equations (1) to (5) should be 0. For that reason, Mach number is 1 at bottleneck of orifice at non-condensable state. If heat 'q' is given, second term in square bracket has opposite sign of first term. Therefore, the variation of parameter value at condensable state is smaller than non-condensable state.

2.3 Condensation Model

The number and size of water droplet in pipe increase as gas mixture fluid passes orifice. The condensation rate is related with water properties, temperature and supersaturated state.

$$(1)\quad r^* = \frac{2\sigma_\infty}{\rho_c \tilde{R} T_v\, ln(S)}$$

$$(2)\quad J = \frac{\rho_v^2}{\rho_c} \cdot \sqrt{\frac{2\sigma_\infty}{\pi M_p^3}} \cdot exp\left(-\frac{16\pi}{3}\frac{\sigma_\infty^3}{M_p \rho_c^2 \tilde{R}^3 T_v^3 (ln(S))^2}\right)$$

$$(3)\quad B_x = A \cdot K$$

$$(4)\quad K = \begin{bmatrix} \frac{4}{3}\pi\rho_c\left(r^{*3}J + 3\frac{d\bar{r}}{dt}\rho Q_2\right) \\ r^{*2}J + 2\frac{d\bar{r}}{dt}\rho Q_1 \\ r^{*}J + \frac{d\bar{r}}{dt}\rho Q_0 \\ J \end{bmatrix}$$

$$(5)\quad B = \begin{bmatrix} \rho u A g \\ \rho u A Q_2 \\ \rho u A Q_1 \\ \rho u A Q_0 \end{bmatrix}$$

$$(6)\quad \bar{r} = \sqrt{\left(\frac{Q_2}{Q_0}\right)} \quad , \quad q = g \cdot l$$

Eq.2. Equation of Condensation model [2,3]

2.4 Programming

In this paper, the Python ver.2.7.13 is used with numpy module and gnuplot to calculate the steam condensation and hydrogen risk. The calculation methods refer to preceding research [4]. From the condensation model calculation, the point when nucleation rate is 10^{50} is assumed to be condensation, I_{start}. The calculation algorithm is separated as one adiabatic part and two diabetic parts; The first one is adiabatic part which defines from inlet to I_{start} point of condensable condition. Second one is diabetic_1 part which is from I_{start} point to 5 nodes after I_{start} point of condensable condition. The last one is diabetic_2 part which is from $I_{start} + 6$ point to last point of condensable state. The number of cells is 16000. The Euler method is used for calculating differential equation.

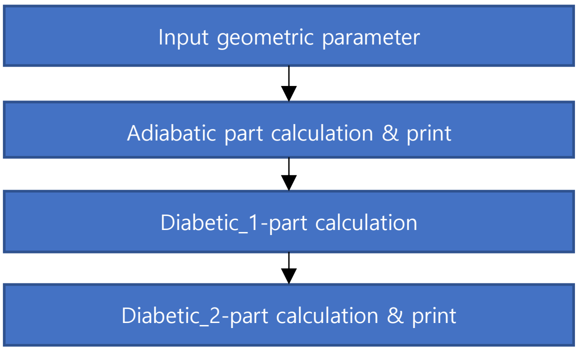

Fig.3. Algorithm of calculation.

2.5 Results

Condensation occurs when volume fraction of H_2O=0.4, volume fraction of H_2=0.4, T0=180°C and P0=5bar [case (a)] and volume fraction of H_20 = 0.4, volume fraction of H_2 = 0.2, T0 = 180°C and P0 = 5bar [case(b)].

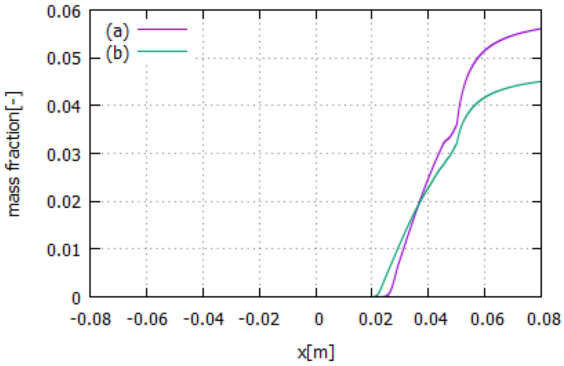

Fig.4. Mass fraction in pipe.

As shown in Fig.4, in both (a) and (b) cases, condensed water mass fraction reaches about 5% at the outlet of pipe. Therefore, the volume fraction of gas is changed slightly.

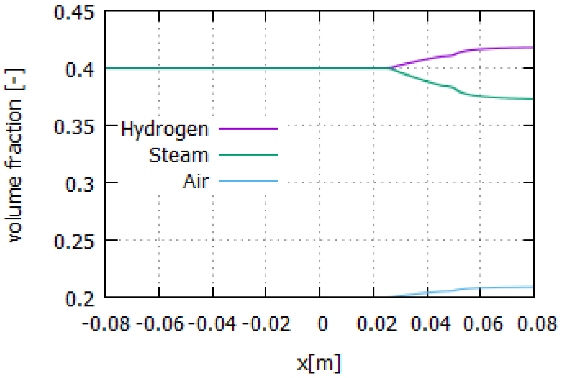

Fig.5. Change of volume fraction in pipe [case(a)].

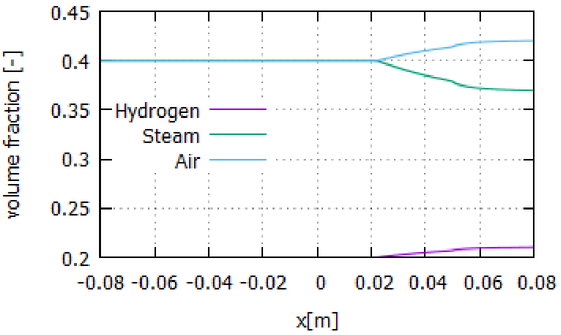

Fig.6. Change of volume fraction in pipe [case(b)].

As shown in Fig.5&6, in both cases, volume fraction of steam increased while others decreased. In Case (a), the increase of hydrogen volume fraction is bigger than others, however, in Case (b), the increase of volume fraction of air is the biggest. In addition, the change of volume fraction for both cases are not small.

2.6 Gas Composition Change

With a linear equation using gas composition at FCVS pipe inlet and outlet, we calculated the shift of mixed gas composition in Shapiro-diagram as steam volume fraction changes.

Table I: Case(a)

Fluid	Inlet	Output	H_2O=1	H_2O=0
H_20	0.4	0.3730528	1	0
H_2	0.4	0.4179648	0	0.667
Air	0.2	0.2089824	0	0.333

Table II: Case(b)

Fluid	Inlet	Outlet	H_2O=1	H_2O=0
H_20	0.4	0.3697417	1	0
H_2	0.2	0.2100861	0	0.333
Air	0.4	0.4201722	0	0.667

In table I and II, when volume fraction of steam is 1, hydrogen and air volume fraction is 0. However, when volume fraction of steam is 0, other volume fraction is calculated from equation 3.

$$(1)\quad \mathrm{NowH_2VolumeFraction} = \frac{\mathrm{OldH_2VolumeFraction}}{\mathrm{OldH_2Volume\ Fraction{+}OldAirVolume\ Fraction}}$$

$$(2)\quad \mathrm{NowAirVolumeFraction} = \frac{\mathrm{OldAirVolumeFraction}}{\mathrm{OldH_2Volume\ Fraction{+}OldAirVolume\ Fraction}}$$

Eq.3. Hydrogen and air volume fraction when water volume fraction is zero.

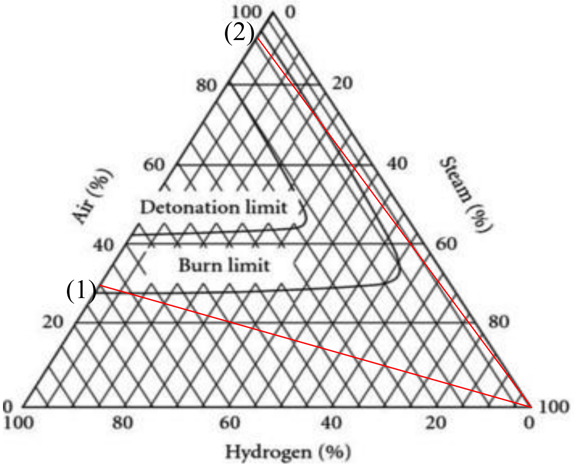

Fig.7. The boundary where hydrogen burning can appear when steam is condensed in Shapiro-diagram [5].

As shown Fig.7, if the ratio of air to hydrogen volume fraction is lower than 3/7 (1) or higher than 9/1 (2), there is no hydrogen risk.

2.7 Hydrogen Risk

When the hydrogen risk is assumed to be appeared in FCVS pipe, the Case (c) is calculated. The initial condition of Case (c) is safe but close to the burn limit. The initial condition of Case (c) is T0=180°C, P0=5bar, volume fraction of steam is 0.575 and hydrogen volume fraction is 0.125.

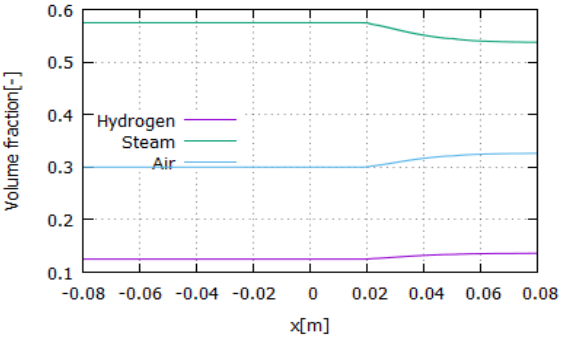

Fig.7. Change of volume fraction in pipe [Case (c)].

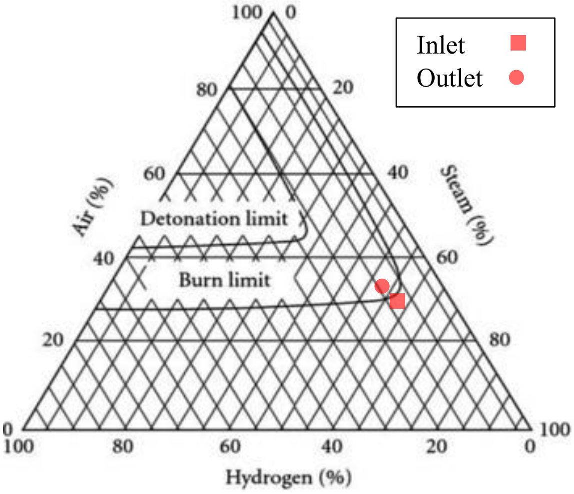

Fig.8. Gas composition shift in shapiro-diagram

As shown in Fig.8, hydrogen burning is appeared in Case (c). Therefore, the hydrogen risk can be increased when mixed gas pass through FCVS pipe.

3. Conclusions

Through the results from the calculations, if steam is condensable, the composition of gas can be changed through the line that passing initial point and a point where volume fraction of steam is 1 in Shapiro-diagram. In addition, change of gas composition is not small. However, the amount of gas composition change may depend on the temperature or pressure. Therefore, to clarify the appearance of hydrogen risk in FCVS pipe, further researches that consider various temperature and pressure are needed.

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REFERENCES

[1] J. M. Cimbala, “Compressible Flow in a Converging-Diverging Nozzle”, Penn State University, pp.2, 19 January 2012
[2] D W Oxtoby, “Homogeneous nucleation: theory and experiment”, Journal of Physics: Condensed Matter, Vol. 4, No. 38, July 1992
[3] N. H. Fletcher, “Size Effect in Heterogeneous Nucleation”, The Journal of Chemical Physics, Vol. 29, No. 3, August 2004
[4] Jea-Ho Park, Dong Kyu Lee, Yang Su Song, Seong Yong Lee and Jong Hwa Jeong, “Development of 1-d Code to estimate Condensation in FCVS Duct”, KoFONS Technical Report No. NSTAR-17NS22-06, 2017.
[5] Mahdi Saghafi, Faramarz Yousefpour, Kaveh Karimi and Seyed Mohsen Hoseyni, “Determination of PAR configuration for PWR containment design: A hydrogen mitigation strategy”, International Journal of Hydrogen Energy, Vol. 42, No. 10, pp.7105, 9 March 2017