REACTOR COOLANT JET VELOCITIES AND EXPANDING JET IMPINGEMENT MODELS FOR POTENTIAL CEDM MISSILES OF PWR

Tae Kyo Kang[1], Sung Jun Kim, Hyun Min Kim, Taek Sang Choi
[1]KEPCO Engineering & Construction Company, Inc.,
150 Deokjin-dong, Yuseong-gu, Daejon 305-353, Korea
E-mail of corresponding author: skylove@kepco-enc.com

ABSTRACT

Nuclear power plants are designed to protect their structures against potential missiles as one of the main safety features. Control element drive mechanism (CEDM) is a potential missile in the reactor head area of pressurized water reactors. In the postulated accident, the CEDM is propelled by reactor coolant jet discharged from a CEDM nozzle break, and it impacts on a missile shield. The missile shield should be qualified for the missile impact energies. The missile impact energies which damage structures are characterized by missile velocities depending on the jet velocities and jet expansion processes. The jet, which has mass and velocity, imparts an impulse to the missile. The jet velocities of reactor coolant are calculated using the conventional methods and applying Fauske slip equilibrium model herein. The conventional methods include Bernoulli's equations assuming that fluid in a vessel is in the liquid state, and semi-two-phase flow method based on the experimental data. They are simple methods to provide the jet velocities for design purpose with overestimation. In reality, the jet discharged from a sub-cooled hot water like reactor coolant will flash to two-phase flow of both vapor and liquid, and Fauske's model is applicable to calculate velocities of the jet in two-phase flow. The jet transfers energies to the missile, and the missile velocities depend on jet expanding processes involving jet expansion shapes, fluid properties, and distances from the jet throat. This paper provides various jet expansion shapes with angles, and their equations. In the equations, the fluid properties, such as densities, of jet are important to decide expansion angles and the missile velocities. It is assumed that they are constant while expanding, or have two-phase fluid properties. The equations for each jet expansion model are numerically integrated to calculate the missile velocities for the limited flight distances. The integrations are performed for the separated regions considering jet expansion angle, jet impingement area of missiles, and height of missiles. The investigation involves the comparison of numerical results from various jet impingement models.

INTRODUCTION

A control element drive mechanism (CEDM) is liable to become a potential missile in the reactor head area of pressurized water reactor nuclear power plants. In the postulated accident assuming circumferential break with full separation in the CEDM nozzle, the CEDM is propelled by reactor coolant jet discharged from a CEDM nozzle break. The jet gives a thrust force to the CEDM missile until it moves up and impacts on the missile shield. The missile shield is thick and strong enough to have structural strength to protect the primary system or containment structure [1]. Protection against the CEDM potential missile is one of the main safety features in the nuclear power plants. Since the overestimation of the missile impact energy can lead to difficulties in evaluating the missile shield, it is important to accurately estimate the impact energies for the missile.

The missile impact energies can damage a shielding structure and are characterized by missile velocities depending on jet velocities and jet expansion processes. The jet velocities of reactor coolant are obtained from conventional methods and Fauske slip equilibrium model [2] in this paper. In the conventional methods, the reactor coolant jet discharged from a reactor vessel has been assumed single-phase flow and a semi-two-phase flow described by Gwaltney [3]. Strictly speaking, semi-two-phase model does not represent the two-phase fluid, and is based on modified Bernoulli's equation and experimental data which can be applied to the limited areas. In reality it is known that the fluid becomes a two-phase flow of vapor and liquid in case that the vessel contains a liquid at saturation or superheated temperature. Many studies [4] have progressed on the two-phase critical flow since 1970's, and one of those theories, i.e., Fauske slip equilibrium model, has become acceptable for the engineering calculation for the jet velocities as described in ANS 58.2 [5].

Calculating the velocity of a jet impingement on a missile is so complicated due to many unknowns, it is, consequently, difficult to determine jet expanding process. The expanding process involves shapes of jet, jet expansion angles as well as state properties of the fluid as a function of distance from the jet throat. Although Gwaltney [3] provides information for missile velocity in the expanding jet impingement, there is no relation between equations and jet expansion mechanisms. Two-stage expansion models for jet geometry in two-phase mixture were presented in ANS 58.2 [5]. There is, however, no information relating to the missile velocity and jet geometry models. The relations between the jet expansion shapes and equations are presented by Kang, et al. [6] without presenting jet expansion angles. This paper deals with various jet expansion shapes with angles, and their equations as well as numerical solutions. The equations for each jet expansion model are numerically integrated to calculate the missile velocities for limited missile flight distances. The integrations are performed for the separated regions considering jet expansion angle, jet impingement area of missiles, and height of missiles. The investigation involves the comparison of numerical results from various jet impingement models.

JET VELOCITY IN SINGLE AND TWO-PHASE FLOWS

When the fluid expands after pipe rupture, the expansion process depends on the state of the fluid in the container. If the fluid is in a gaseous state, it will expand very rapidly and be dispersed quickly in the air. Fluid in the liquid state which is below the saturation temperature or sub-cooled temperature, will also expand quickly but not disperse in large angles like gas, and will become a two-phase flow of vapor and liquid.

For a liquid jet, the jet velocities can be estimated by

$$V_T = \left[V^2 + 2g\left(\frac{P}{w} - H_L \right) \right]^{1/2}, \tag{1}$$

where, V_T is the jet velocity, V is the liquid velocity in the container, g is the gravitational constant, P is the pressure in the vessel, w is a specific weight of the liquid, and H_L is energy loss, based on Bernoulli's equation. If the energy loss, H_L, is assumed to be zero and V is zero, we have upper limits of jet velocities. The jet velocities are calculated for the fluid properties of the reactor coolant using Eq. (1), and the results are presented in Table 1.

In a flashing jet, reactor coolant jet becomes a two-phase flow of both vapor and liquid. Gwaltney [3] describes a method to calculate jet velocities as a semi-two-phase flow without using of a computer program. It combines equations and experimental data to get the jet velocities. For a given length-to-diameter ratio (L/D) of a short circular tube, the value of V/V_o can be obtained from experimental data, where V is the actual velocity and V_o is the average velocity of two-phase fluid. V_o can be estimated from

$$V_o = C_d \left[\frac{2g}{\rho_i} \left(P_i - P_e \right) \right]^{1/2}, \tag{2}$$

where, P_i and ρ_i are the initial pressure and the density of the liquid in the vessel, P_e is the exit pressure of the fluid, C_d is the Euler number. Euler number (C_d) is obtained from experimental data which provide usual range of the Euler number for circular orifice. The assumed value for the exit pressure (P_e) is used to calculate ($P_i - P_e$). After calculating V_o, actual velocity (V) can be determined from the ratio of V/V_o. The ratio of V/Vo relates to the length-to-diameter ratio of the tubes. With the method, the calculated jet velocity is given in Table 1 for most conservative case assuming that exit pressure is zero. Furthermore, once V is determined, the Reynolds number can be calculated. Using the graph to show correlation between the Reynolds number and cavitation number [3], we can update the assumed fluid exit pressure. The procedure can be repeated until correct exit pressure is obtained.

The semi-two-phase flow has no theoretical background and no consideration of fluid state with vapor and liquid, so it is difficult to represent reactor coolant jet as two-phase flow. A specific volume of the vapor and liquid mixture attains a maximum value at the jet exit. Since the specific volume (υ) is a function of both quality and void fraction, it must be a function of the slip ratio (S). Different values of slip ratio result in different value of flow velocity (G). Maximum G is therefore obtained at a slip ratio when $\partial\upsilon/\partial S = 0$. This model, called the slip equilibrium model, is suggested by Fauske [2] and formulated by

$$G_{\max}^2 = -g_c S^* \Big/ \left\{ \left[(1 - x + S^* x) x \right] \frac{d\upsilon_g}{dP} + \left[\upsilon_g (1 + 2S^* x - 2x) + \upsilon_f \left(2xS^* - 2S^* - 2xS^{*2} + S^{*2} \right) \right] \frac{dx}{dP} \right\}, \tag{3}$$

where, G_{max} is the maximum mass flow rate, g_c is the gravitational constant, S* is the maximum slip ratio, x is the void fraction (or quality), υ_g is the specific volume of vapor, υ_f is the specific volume of the liquid, and P is the pressure. In Eq. (3), derivatives ($d\upsilon_g/dP$ and dx/dP) can be obtained from El-Wakil [7]. The value of x, quality, is obtained from the energy equation which is based on the specific volume and enthalpy evaluated at the critical pressure. The critical pressure can be determined from the experimental data by Fauske. The experimental data show critical pressure ratio of approximately 0.55 for long channels in which the L/D ratio exceeds 12. Solutions for the set of complicate equations defining the Fauske slip-equilibrium model have been prepared by Fauske [2]. The solutions are a plot of mass velocity as a function of stagnation enthalpy at various critical pressures for steam-water mixture. For any enthalpy and pressure, one can immediately locate the mass velocity if flow quality and saturated liquid enthalpy of reactor coolant are available. The jet velocity applied to Fauske's model, is presented in Table 1 for the reactor coolant jet. From the results of Table 1, we can have the lowest jet velocity when two-phase flow model, Fauske's model is applied to jet velocity calculation.

Table 1: Calculated jet velocities for reactor coolant using the single-phase flow, semi-two-phase flow, and two-phase flow

Types of Flow	Single-Phase Flow	Semi-Two-Phase Flow	Two-Phase Flow
Jet Velocity, m/sec	240.7	147.3	70.2

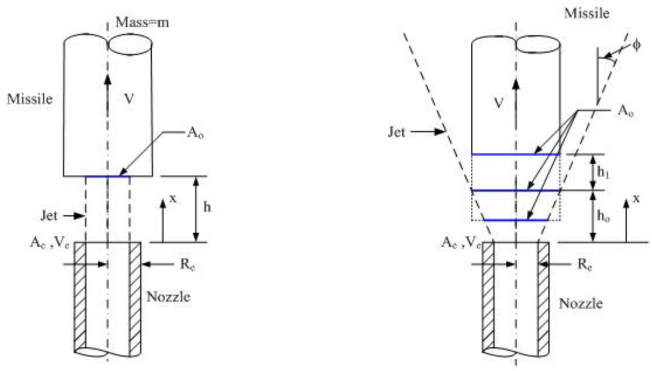
JET IMPINGEMENT MODELS

Simple Jet Expansion Models

In case that the cross-sectional area of the missile object is assumed to be larger than that of jet, all of the jet impinges on the missile. Flow exit model in the uniform jet impingement with constant area is shown in Fig. 1-(a). Based on the Newton's second law, the missile velocity at height (h) for uniform jet is given by [8]

$$\left[\left(1-\frac{V_h}{V_e}\right)-\ln\left(1-\frac{V_h}{V_e}\right)\right]=1+h\left(\frac{\omega A_e}{W}\right)\ , \tag{4}$$

where, V is the missile velocity, V_e is the jet velocity impinging on the missile, ω is the specific weight of the fluid, A_e is the jet area at the throat, W is the weight of missile, and x is the distance from the jet throat. Eq. (4) is obtained from assuming that a missile is resting, $V/V_o=0$ at $x = 0$), where V_o is the initial jet velocity, and final jet velocities are same as the initial jet velocity ($V_e=V_f$). From Eq. (4), missile velocities in uniform jet impingement model are varied only depending on the missile traveling distance if the specific weights of fluid are constant for any locations in the jet.



(a) (b)

Fig. 1: Jet impingement models for (a) uniform constant jet impingement and (b) expanding jet impingement on a missile

For the expanding jet, the cross-sectional area of a missile is equal to or larger than that of the jet. The flow exit model for the expanding jet impinging is shown in Fig. 1-(b). The amount of jet fluid intercepted by a missile (β) is given by

$$\beta = \frac{A_0}{A_h} = \frac{A_0}{\pi(R_e + x\tan\phi)^2} \ , \tag{5}$$

where, A_h is the cross-sectional area of jet at height (x), A_o is the jet impingement area in the missile, R_e is the radius of jet exit, and ϕ is the jet expansion angle. Based on the Newton's 2nd law, missile and jet thrust forces for the expansion jet are formulated by

$$\frac{V}{V_e^2(1 - V/V_e)} dV = \frac{\omega A_e A_o}{W\pi} \left[\frac{1}{(R_e + x\tan\phi)^2} \right] dx \ . \tag{6}$$

Integrating from 0 to h, and from V=0 to V=V_h, Eq. (6) yields

$$\left[\left(1 - \frac{V_h}{V_e}\right) - \ln\left(1 - \frac{V_h}{V_e}\right) \right] = 1 + \left(\frac{\omega A_e A_0}{W\pi\tan\phi} \right) \left(\frac{1}{R_e} - \frac{1}{(R_e + h\tan\phi)} \right). \tag{7}$$

Jet velocities (V_e) are assumed to be constant from the jet exit to the missile for the calculation. Eq. (7) shows specific weight (ω), and jet expansion angles (ϕ) decrease jet velocities as the jet expands farther and broadly.

Jet Impingement Model Based on Two-Stage Jet Expansion of ANS 58.2 [5]

An acceptable shape of the jet is presented in ANS 58.2 [5], which includes two-stage expansion model with different dispersion angles for each region. The shape of jet is divided into three regions, and the cross-sectional areas for each region depend on the fluid conditions. The applicable shape of the jet is shown in Fig.2.

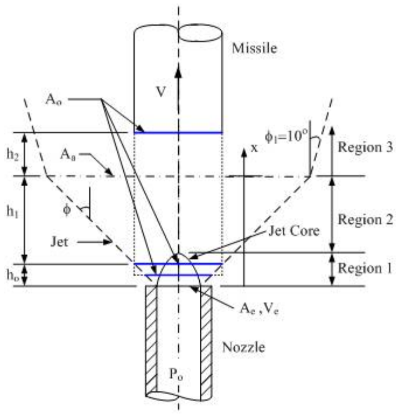


Fig. 2: Jet impingement model for circumferential break with full separation

In order to determine the expansion angle of Regions 1&2, we have to calculate an asymptotic plane area (A_a) defined by [5]

$$\frac{A_a}{A_e} = \left[\frac{Ge^2}{g_c \rho_{ma} C_T P_o} \right], \tag{8}$$

where, A_e is the break plane area as described in Fig. 2, G_e is mass flow rate, g_c is the gravitational constant, C_T is the steady-state thrust coefficient, P_o is the initial pressure, and ρ_{ma} is the density for two-phase flow given by

$$\rho_{ma} = 1/\lfloor x/\rho_g + (1-x)/\rho_f \rfloor \ , \qquad (9)$$

where, x is the quality of the mixture, ρ_g is the saturated liquid density, and ρ_f is the saturated vapor density. For the Region 3, expansion angle of 10° is designated in Fig. 2 [5]. Fauske's model is useful to use Eq. (8) because it produces mass flow rate.

NUMEREICAL RESULTS

Numerical solutions for missile velocities are calculated using fluid properties of reactor coolant in normal operating conditions and geometries of the CEDM nozzle. Missile-traveling height is limited considering the locations of the missile shield and the CEDM. The jet velocity and mass flow rate obtained from Fauske's model are used for missile velocity calculation. The jet velocity and specific weight are assumed to be constant while the jet is being discharged.

For the uniform jet impingement, missile velocities are obtained from Eq. (4) at any height. In case of expanding jet, jet impingement areas (A_o) and intercepted jet area (β) are varied as the jet expands, then Eq. (6) has to be integrated for the ranges of h_o and h_1, respectively. Since the expansion angles are unknown for the Eq. (6), we change the jet expansion angles from 10° to 50° to find the effects of missile velocities depending on expansion angles. The missile velocity profiles are presented in Fig. 3 depending on the missile height ratio (H/L) and expansion angles ranged from 10° to 50°. For the H/L, h is the height of missile, and L is the limited height of missile traveling by missile shield. The jet velocities for uniform jet are included in Fig. 3.

Fig.3 shows that the reductions of jet expansion angles decrease the missile velocities and lessen the slops of curves. The sharp changes of velocities occur in the lower height, less than 0.2 of H/L, comparing to those for higher height. All of the jet impinge on the missile in the region of h_0, and it causes sudden increase in missile velocities in the region. In the higher region of h_1, there are increases of escaping jet without impinging on the missile, so it results in reducing the velocity increase of missile.

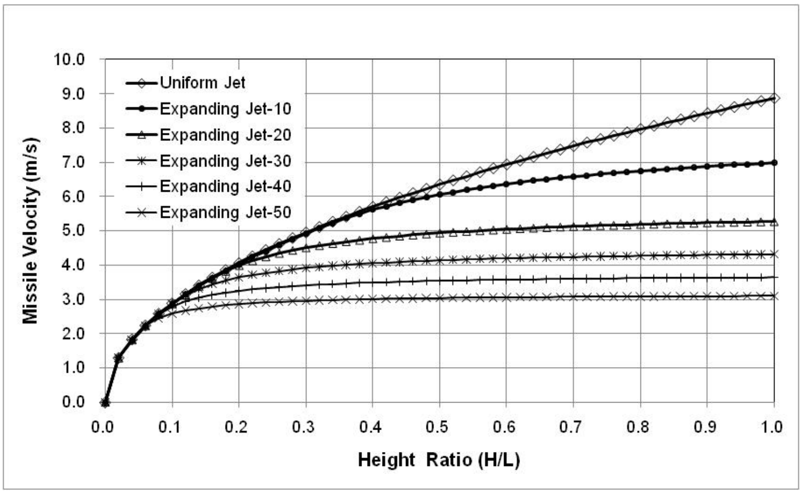


Fig. 3: CEDM missile velocities profiles for uniform and expand jet impingement models depending on the height ratio (H/L) and expansion angles with 10° through 50°

For the two-stage expansion model shown in Fig. 2, we calculate asymptotic plane area to obtain the jet expansion angle in regions 1&2 using Eq. (8). The calculation for the plane area considers the fluid density of Eq. (9) of two-phase flow. As a two-stage expansion model, forty five degrees (45°) are obtained from the asymptotic area for regions 1&2, and ten degrees (10°) [5] in region 3 are given by Fig. 2. Since the expansion angles are known from Eq. (8), these are used for integrating Eq. (6). With the different expansion angles and the jet impingement areas, Eq. (6) is integrated for three regions, respectively. Fig. 4 shows the missile velocity profiles depending on height ratio (H/L) based on the two-stage expansion model of Fig. 2 as well as that based on assumptions that the jet expands in 40° and 50°. The curve for two-stage expansion model is bounded by the curves of 40° and 50° jet expansions because the expansion angle for two-stage expansion model is 45° in regions 1&2. It is observed that the increasing rate of the velocities for two-stage expansion model is greater than the other expansion models, wherein this is caused by the decrease in expansion angle to 10° above asymptotic plane.

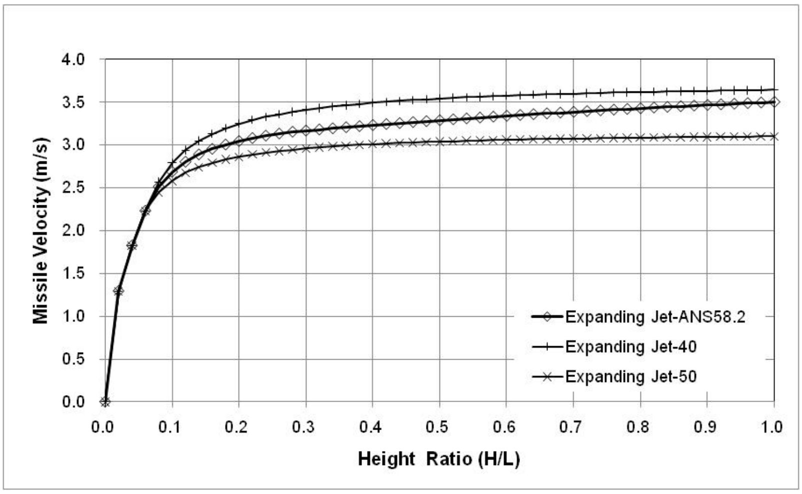


Fig. 4: CEDM missile velocities profiles for expanding jet models with expansion angles of 40° and 50°, and expanding jet based on ANS 58.2 [5] depending on the height ratio (H/L)

CONCLUSIONS

This paper deals with the missile impact energies which damage a shielding structure, and those are characterized by missile velocities depending on jet velocities and jet expansion processes. The jet velocities of reactor coolant are obtained from conventional methods and Fauske slip equilibrium model. The conventional methods, which are applied to current engineering practices, include the single-phase flow and semi-two-phase flow. Fauske's model for the reactor coolant jet provides the lowest jet velocities comparing to the results from conventional methods, and the jet velocity and mass flow rate are used for determining missile velocities for various jet expansion models. This paper provides the jet expansion models and their equations as well as numerical solutions. Correlations of jet expansion angles and missile velocities are provided, where missile velocity profiles are changed depending on the jet impingement areas and size of missile objects. In the CEDM missile velocity profiles, it shows sharp increase in the missile velocities until height is 0.3 when it starts a moderate increase. Two-stage expansion model is applied for calculating the jet expansion angles, and the missile velocities for two-stage expansion models are bounded by results of simple jet impingement models with 40° and 50° jet expansion angles. According to the equations, missile velocities also depend on densities of the fluid along with jet pressure. But this study assumes that the densities are constant while the jet is being discharged. Further investigations considering the changes of jet fluid densities are needed.

Finally, conservatism in jet velocities can be reduced as Fauske's model is applied to determine two-phase jet characteristics, and missile velocities are more accurately estimated by using two-stage-expansion model. The reduced missile velocities will help missile shield design to ensure structural integrity avoiding overestimated missile impact energy.

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