Transactions of the Korean Nuclear Society Spring Meeting
Pyeongchang, Korea, May 27-28, 2010

Reduction of the Kinetic Energy of Potential CEDM Missile

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1. Introduction

A control element drive mechanism (CEDM) is considered to be a postulated missile in the reactor containment building. There is a missile protection system to absorb the missile kinetic energy from the CEDM missile during an accidental condition. Once a CEDM nozzle breaks, reactor coolant jet discharges from the nozzle, then it impinges on the bottom of the CEDM, and gives a thrust force to the CEDM missile until it impacts on the missile barrier.

The jet velocity has been previously calculated by Bernoulli's equation or experimental data so that it produced very conservative kinetic energy and caused difficulties in the design of the missile barrier. In order to reduce the excessive conservatism, the jet is assumed to be a two-phase critical flow with the Fauske slip model, and various jet impingement models on the CEDM are presented.

2. Methods and Results

2.1 Jet velocities with Classical Methods

The reactor vessel contains reactor coolant in a liquid state well below the saturation temperature (sub-cooled). If a CEDM breaks at the connection, the fluid will expand into the atmosphere and become a two-phase fluid, with vapor and liquid phases. Oak Ridge National Lab (ORNL) has provided several equations to calculate jet velocities in different fluid states based on classical theories [1]. Classical methods mean that jet fluids are assumed to be perfect gas or incompressible liquid and the velocities were driven from the Bernoulli's equation. Even though two-phase expansion of the fluid makes it very difficult to calculate the velocity because of many unknowns, such as quality and all other thermo-dynamic properties, the ORNL also has provided the only method to calculate the velocity of two-phase fluid based on the experimental data regardless the unknowns.

2.2 Jet velocities with Fauske's model

As a well-known non-homogeneous equilibrium theory for the two-phase critical flow, the Fauske's slip model can be utilized to calculate the velocity of the jet. Fauske suggested the use of experimental data for the ratio of critical pressure at the nozzle throat and stagnation pressure in the vessel as a function of ratio of nozzle length and diameter [2]. He also provided a plot of mass velocity as a function of stagnation enthalpy at various critical pressures for steam-water mixture [2]. For any enthalpy and pressure, one can immediately locate the mass velocity. Prior to using the plot, one should know the flow quality and the saturated liquid enthalpy of reactor coolant. On the other hand, mass velocity can be calculated by solving the differential equations defining the Fauske's model. The calculated values of mass velocity and flow quality turn out to be in good agreement with the data in the plot.

2.3 Jet Impingement Models for CEDM Missile

The ORNL report provides the equations to calculate the missile velocity but it should be applied in the condition that the cross section area of the missile is less than the size of the opening in the pipe or the vessel. It indicates the equations are applicable to limited conditions. In order to overcome the restrictions, three different models are presented depending on the jet expansion and the size of jet impingement based on the Newton's second law.

At the first model, it is assumed that the cross section area of a missile object is larger than that of the jet and the jet cross section maintains a uniform area when it impinges on the missile object. The missile velocity as a function of distance above the exit plane of the jet is given in

$$\left[\left(1-\frac{V_h}{V_e}\right)-\ln\left(1-\frac{V_h}{V_e}\right)\right]=1+h\left(\frac{\gamma_e A_e}{W}\right) \qquad (1)$$

,which is presented in Ref. [3,4].

The second model provides a missile velocity equation when the jet expands with an angle and the cross section area of an object is equal to or smaller than that of the jet. It is assumed that some of the exit flow does not impinge on the missile object. We can use the missile velocity equation (2) for expanding jet fluid in the Ref. [3,4],

$$\left[\left(1-\frac{V_h}{V_e}\right)-\ln\left(1-\frac{V_h}{V_e}\right)\right]$$
$$=1+\left(\frac{\gamma_e A_e A_0}{W\pi\tan\phi}\right)\left(\frac{1}{R_e}-\frac{1}{(R_e+h\tan\phi)}\right) \qquad (2)$$

The last model considers a large object which can envelope the expanding jet area at a certain height. This case can be evaluated in two parts: In the first part all of the jet fluid is intercepted by the object. The second part of the evaluation is similar to the concept in the second model. The missile velocity at a height h_a in the first part can be formulated as the following equation,

$$\ln\left[\left(\frac{1-V_{ma}/V_a}{1-V_{mb}/V_a}\right)\right]-\frac{1}{V_a}(V_{mb}-V_{ma}) = \left(\frac{\gamma_e A_a^2}{W\pi\tan\phi}\right)\left(\frac{1}{R_a}-\frac{1}{(R_a+h_b\tan\phi)}\right) \tag{3}$$

,which is presented in Ref. [3,4].

The missile velocity at height h_b in the second part can be formulated by the following equation,

$$\left[\left(1-\frac{V_{mb}}{V_a}\right)-\ln\left(1-\frac{V_{mb}}{V_a}\right)\right] = 1+\left(\frac{\gamma_e A_a^2}{W\pi\tan\phi}\right)\left(\frac{1}{R_a}-\frac{1}{(R_a+h_b\tan\phi)}\right) \tag{4}$$

,which is provided in Ref. [3,4].

2.4 Results

The jet velocities were driven from the classical methods and Fauske's slip equilibrium model as stated in Sec. 2.1 and 2.2. Therefore, the missile velocities were calculated depending on the models in Sec.2.3 and the results are summarized in Table 1.

Table 1. Jet and Missile Velocities of CEDM Missile

Jet Models	Jet Impingement Models	Jet Velocity (m/sec.)	Missile Velocity (m/sec.)	Kinetic Energy (kJ)
Classical Method 1[(a)]	-	240	-	-
Classical Method 2[(b)]	[1]	150	18	78
Fauske's Model	Uniform Jet [(c)]	70	9	19
	Expanding Jet - CASE1[(d)]	70	6	9
	Expanding Jet - CASE2[(e)]	70	5	7

Notes ;

(a) The jet is in a liquid state.
(b) The jet is in a flashing jet of two-phase.
(c) Calculated by equation (1)
(d) Calculated by equation (2)
(e) Calculated by equation (3) and (4)

3. Conclusions

With the Fauske's slip equilibrium model and jet impingement models, the missile kinetic energy and velocities are considerably reduced comparing with the results of the classical methods.

From an engineering point of view, the ORLN report, which was issued on 1960s, has been used for calculation of jet and missile velocities even though it is based on the classical theories and is only applicable to a small missile size. Considering many studies on the two-phase critical flow, it is believed that the two-phase models including the Fauske's model are applicable to calculate the jet velocity for engineering design. Therefore, three jet impingement models based on the Newton's second law would be helpful to determine the missile velocity for different missile sizes and jet expansions.

By applications of Fauske's model and three jet impingement models, overestimation of kinetic energy and velocity of the missile in the classical methods can be reduced for optimizing the design of missile barrier under CEDM missile impact.

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Nomenclature

A_a = Cross section area of the jet at the elevation, h_a
A_e = Cross section area of the jet at the exit plane
A_o = Cross section area of the missile object jet impinged
g_c = Acceleration of the gravity
h = Elevation from jet exit plane along jet travelling path
m = Mass of the object weight (W), $m = W / g_c$
R_a = Radius of the jet at the elevations, h_a and h_b, respectively
R_e = Radius of the jet at the exit plane, same as the radius of nozzle
V_a = Jet velocity at the elevation, h_a
V_e = Jet velocity at the exit plane
V_h = Jet velocity at the elevation, h
V_{ma}, V_{mb} = Missile velocity at the elevations, h_a and h_b, respectively
ρ_e = Mass density of fluid at the jet exit, $\rho_e = \gamma_e / g_c$, where γ_e is the specific weight of fluid.
ϕ = Angle of the jet expansion