Hydrogen stratification breakup model with modified Froude number

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1. Introduction

Recent study observed experimentally the breakup process of a stratified light gas to assess the behavior of hydrogen distribution that could be generated in an upper containment during a severe accident [1]. They simulated that helium stratified in an upper test vessel was mixed by an impinging jet. The stratification breakup model was developed by the dimensional analysis and experimental results [2]. It was based on the SPARC and PANDA tests that injected vertically an air into the stratified air-helium. The previous model does not consider the effect of steam flowing through an inner compartment of a test vessel on the breakup behavior. In a severe accident, a large amount of coolant could be converted into steam, and it could be then released into the atmosphere through compartments in the inner containment. Steam moves upward due to buoyancy, and it could be condensed by the difference in temperature. This study modifies Froude number that is a ratio of inertia to buoyancy in the stratification breakup model from expanding the experimental database that injects steam into a stratified He through an inner cylinder.

2. Methods and Results

2.1. Previous stratification breakup model

In the experimental database regarding the breakup of a stratified gas by an impinging jet, as shown in Fig. 1 (a), there are 8 key variables, such as a breakup distance (Δz), an initial distance between the start of the concentration gradient and the exit of a jet pipe (z_0), a diameter of a jet pipe (d), a test vessel diameter (D), a jet velocity at the exit of a pipe (U_0), a jet density (ρ_j), buoyancy of a stratified gas ($\Delta\rho \cdot g$), and time (t), which are representing a test scale, flow, and fluid properties.

Previous study grouped the eight variables into the four dimensionless numbers, as shown in Table I, by Buckingham's PI theorem [2]. The dimensionless degree of stratification breakup ($\Delta z/z_0$) depends on the dimensionless test scale (δ), the dimensionless time scale (τ), and Froude number (Fr_0) that is a ratio of the initial momentum of an impinging jet to buoyancy of a stratified gas. A functional relationship between the four dimensionless numbers, as shown in Eq. (1), was determined by the experimental database for the erosion of stratified helium by an impinging air jet. The SPARC and PANDA results in the different conditions, as shown in Table II, converges on the stratification breakup model, Eq. (1), as shown in Fig. 2. The coefficients and powers of Eq. (1) can be modified by widening the experimental database.

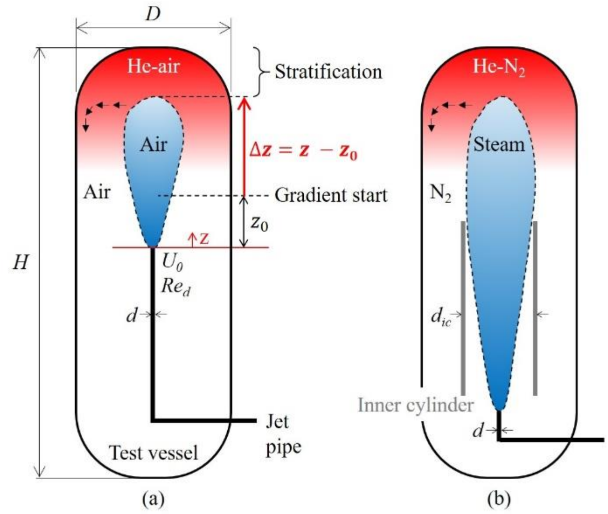

Fig. 1. Key variables of the erosion of a stratified gas by impinging jet: (a) SPARC and PANDA, (b) THAI.

Table I: Dimensionless numbers of stratification breakup

#	Definition	#	Definition
1	$\frac{\Delta Z}{Z_0}$	3	$\delta = \frac{d}{D}$
2	$Fr_0 = \frac{U_0}{\sqrt{(\Delta\rho g/\rho_j)Z_0}}$	4	$\tau = \frac{tU_0}{Z_0}$

$$\left(\frac{\Delta Z}{Z_0}\right)(Fr_0^{-0.8})(\delta^{-1.1}) = 1.6\tau^{0.4} \quad (1)$$

Table II: Test conditions of SPARC, PANDA, and THAI

	SPARC	PANDA	THAI
D/H (m)	3.4/9.5	4/8	3.2/9.2
d (mm)	100	75	138
d_{ic} (mm)	-	-	1380
Re_d (test case)	20000(SM 13)	14000(E 20)	17600 (HM1)
	30000(SM 17)	26000(E 23)	
He(Vol.%)	30	40	36

A THAI test injected steam into He-N_2 stratification through an inner cylinder, as shown in Fig. 1 (b), which was distinct from SPARC and PANDA tests [2]. This study applied the THAI result to Eq. (1) with the same dimensionless numbers in Table II. In Fig. 2, it seems that the duration of stratification in the THAI test is much shorter than those in SPARC and PANDA tests. It is expected that the reason of difference between HM1 and the other tests comes from buoyancy of a steam jet, flow through an inner compartment, and steam condensation.

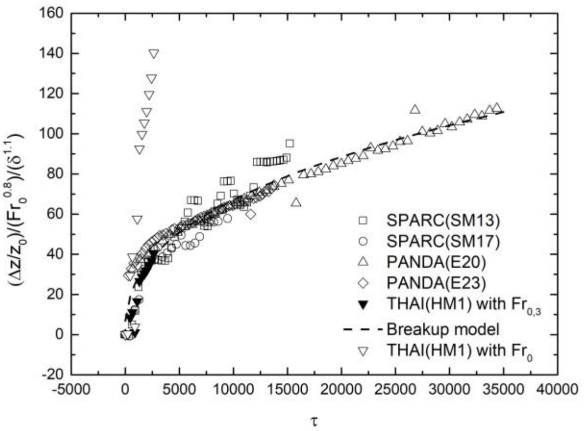

Fig. 2. Stratification breakup model applied to SPARC, PANDA, and THAI tests.

2.2. Modified Froude number

Firstly, to consider buoyancy of a steam jet, this study modified Froude number, as shown in Eq. (2). The initial inertia of a jet is affected by buoyancy ($\Delta\rho_j \cdot g \cdot d$) from the density difference between steam and the around atmosphere (N_2), as well as a jet velocity (U_0) at the exit of a jet pipe.

$$Fr_0 = \sqrt{\frac{U_0^2 \rho_j}{\Delta\rho g z_0}} \rightarrow Fr_{0,1} = \sqrt{\frac{U_0^2 \rho_j + \Delta\rho_j g d}{\Delta\rho g z_0}} \quad (2)$$

Secondly, a steam jet moves upward through an inner cylinder of a THAI vessel. A rise velocity of a jet depends on the diameter of an inner cylinder. This study added a correction factor (C_{ic}) of a jet velocity to Froude number, as shown in Eq. (3). The correction factor (C_{ic}) is the ratio of an average velocity through an inner cylinder in diameter of d_{ic} to an average velocity through a test vessel in a diameter of D at the same volume flow rate, as shown in Eqs. (4). It is assumed that a velocity (U_0) at the exit of a jet pipe affects the breakup of stratification by a velocity ratio (C_{ic}) depending on the diameter of an inner cylinder. Here, diameter of an inner cylinder should be more than that of a jet pipe, and it should be less than that of a test vessel.

$$Fr_{0,2} = \sqrt{\frac{(C_{ic} U_0)^2 \rho_j + \Delta\rho_j g d_j}{\Delta\rho g z_0}} \quad (3)$$

$$C_{ic} = \frac{V_{d,ic}}{V_D} \quad (4)$$

Thirdly, steam condensation influences the mass and buoyancy of a steam jet rising upward. This study added a correction factor (C_{sc}) of jet inertia to Froude number, as shown in Eq. (5). The correction factor (C_{sc}) is the ratio of the atmospheric temperature (T_a) averaged during jet release to the jet temperature ($T_{j,0}$) at the exit of a jet pipe, as shown in Eq. (6). For an ideal gas, the temperature ratio is the same with the density ratio. Jet temperature should be more than the around temperature.

$$Fr_{0,3} = \sqrt{\frac{C_{sc}\{(C_{ic} U_0)^2 \rho_j + \Delta\rho_j g d_j\}}{\Delta\rho g z_0}} \quad (5)$$

$$C_{sc} = \frac{T_a}{T_{j,0}} \quad (6)$$

Finally, the THAI test using modified Froude number ($Fr_{0,3}$) converged on SPARC and PANDA tests, as shown in Fig. 2. Stratification breakup model with modified Froude number can be applied to the experimental database for injecting steam into a stratified gas through an inner compartment. In SPARC and PANDA tests, the correction factors in Eqs (4) and (6) are unity, because it could assume that diameter of an inner cylinder is the same with that of a test vessel, and there is no difference in temperature.

3. Conclusion

This study expanded the prediction range of the previous stratification breakup model to consider the effects of a steam jet flowing through an inner compartment. In the stratification breakup model, Froude number originally defined by a ratio of the initial momentum of an impinging jet to buoyancy of a stratified gas was modified by adding the correction factors regarding buoyancy, flow through an inner cylinder, and steam condensation. In the future, it is necessary to apply the various experimental database simulating the complex phenomena of a severe accident to the stratification breakup model.

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