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Model application research for liquid entrainment through ADS-4 pipe in AP1000

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ABSTRACT

Application research of two new liquid entrainment models for separately predicting the beginning of entrainment and branch entrainment quality is performed which is a continuation of previous experimental and theoretical studies on the entrainment at T-junction. The new onset entrainment model and branch quality model are developed on the basis of the scaling experiment for studying ADS-4 entrainment phenomenon in AP1000 plant, and the two new models along with previously published entrainment models are compared. The results show that previous models in the background of entrainment through a small break of primary pipe are not suitable for predicting the entrainment through a large size branch (e.g. ADS-4 pipe), while the two new models have a larger applicability. Also, the new entrainment models are written into the RELAP5 code, and then a typical 2-in SBLOCA transient in AP1000 is simulated separately by the modified RELAP5 and the original RELAP5 to further discuss the applicability of new models for the simulation of entrainment through ADS-4. The results show that the modified RELAP5 can get more reasonable simulation results. In view of original RELAP5 overestimated core coolant inventory, the modified RELAP5 can get a conservative core coolant inventory. Hence we can conclude that the new entrainment models are more suitable for the simulation of entrainment through ADS-4.

1. Introduction

T-junctions consisting of main pipe and branch pipe (see Fig. 1) are widely existed in nuclear power plant, such as the joints between hot leg and ADS-4 (Fourth Stage Automatic Depressurization System) pipe or PRHRS (Passive Residual Heat Removal System) pipe. Also, the primary loop with a small break can also be regarded as a special kind of T-junction. Liquid entrainment through a branch pipe of T-junction can occur during a LOCA (Loss-of-coolant Accident), which has an adverse impact on coolant inventory in the core, thus affecting the reactor safety. Hence, research of liquid entrainment through a branch pipe of T-junction is an important study subject over the decades.

Since 1980s, many researchers have performed the studies for the liquid entrainment at T-junction. Many entrainment correlations were established, and even many classical entrainment models were adopted into some famous programs such as RELAP5 (RELAP, 2001) and CATHARE (Maciaszek and Micaelli, 1989). In a word, the previous entrainment research mainly focused on the small break entrainment phenomenon during a SBLOCA. The research of entrainment through a large size branch/break has attracted many researchers interest with the development of AP1000 plant in recent years. The liquid entrainment can occur along with the depressurization of ADS-4 pipe during the later stage of LOCA. However, latest research showed that the previous small break entrainment models cannot be suitable for the simulation of a large branch entrainment phenomenon like the

Abbreviations: ADS-1, First stage automatic depressurization system stage; ADS-2, Second stage automatic depressurization system stage; ADS-3, Third stage automatic depressurization system stage; ADS-4, Fourth stage automatic depressurization system stage; APEX, Advanced Plant Experiment; ATLATS, Air-water test loop for advanced thermal-hydraulic studies; CEA, Atomic Energy Commission; JAERI, Japan Atomic Energy Research Institute; KfK, Kernforschungszentrum Karlsruhe GmbH; NRC, US Nuclear Regulatory Commission; PRHRS, Passive Residual Heat Removal System; SBLOCA, Small break loss-of-coolant accident; OSU, Oregon State University; UCB, University of California Berkeley.

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Nomenclature

d	branch diameter/slot width
D	main pipe diameter
Fr	Froude number
g	gravitational acceleration
h	distance between interface and branch centerline (i.e. height of gas chamber)
h_b	critical gas chamber height at the onset of liquid entrainment
w_{3G}	gas mass flow rate at branch pipe
w_{3L}	liquid mass flow rate at branch pipe

Greek symbols

$\Delta\rho$	density difference
ρ_L	liquid phase density
ρ_G	gas phase density

Subscripts

G	gas
L	liquid

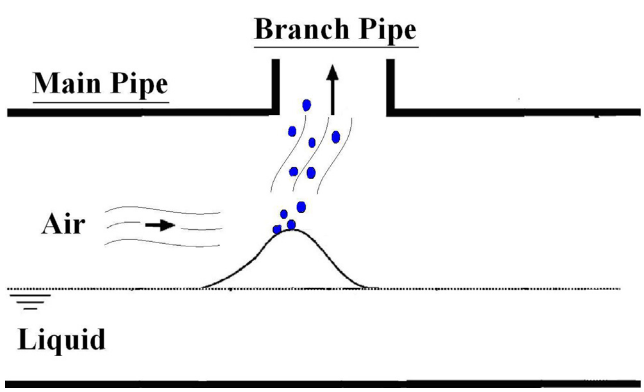

Fig. 1. Entrainment at T-junction.

entrainment through an ADS-4 pipe in AP1000 (Welter, 2001; Meng et al., 2014).

Liquid entrainment model can divided into onset entrainment model and branch quality model. Some previous liquid entrainment models are summarized in the Table 1. Onset entrainment model of Smoglie et al. and branch quality model of Schrock et al. have been adopted into REALP5 code (RELAP, 2001). Smoglie and Reimann (1986) established the entrainment model on the basis of a point mass sink assumption (i.e. the break is assumed into a point sink), even without branch diameter d in the expressions of model. So Smoglie et al' model did not take the effect of branch size into account. Similarly, the effect of branch size was also not considered into Schrock et al' model. Maciaszek and Micaelli (1989)) and Welter (2001) and Welter et al. (2004) developed respectively entrainment models by the method of theoretical analysis, and even Welter et al.' model could be further simplified into Maciaszek and Micaelli's model. The Welter et al.' model considered the effect of branch diameter d, but applicability of this model still need to be further discussed, especially for the branch quality model (Welter et al., 2004). Also, Sun et al. (2015) conducted scaled experimental research for the entrainment through ADS-4 pipe in AP1000 plant and developed a new entrainment model considering the effect of surface tense, but this model was not verified by any experimental data.

In our early research, a scaled entrainment experiment was performed referring to the ADS-4 entrainment, which had a great difference with the Welter et al.' (2004) and Sun et al.' experiments (Sun et al., 2014). The main pipe of T-junction test section in our experimental facility was longer enough to ignore the entrance effect, while the main pipe length in Welter et al.' and Sun et al.' experiments was obtain by the scale-down of hot leg length of AP1000 plant, so the entrance effect cannot be ignore. That is, the Welter and Sun et al.' experiments were designed for the research of practical engineering problem including the entrance effect. However, our experiment was designed on the purpose of model research of entrainment through a large size branch excluding the entrance effect.

In a word, the research of entrainment through a large size branch mainly focuses on the ADS-4 entrainment phenomenon, but the existing research is in a serious shortage. Based on early experimental and theoretical studies, the applicability of two new liquid entrainment models including onset entrainment model and branch quality model is analyzed in this paper. The new models are compared and discussed with the previous

Table 1
Previously published entrainment models.

Author	Organization	D/d	Onset entrainment model	Branch quality model
Smoglie and Reimann (1986)	KfK	34,26, 17,10	$h_b = \frac{1.67W_{3G}^{0.4}}{[g\rho_G\Delta\rho]^{0.2}}$	$x = 1 - x_o^{2R}[1 - 0.5(1+R)x_o^{(1-R)}]^{0.5}$ $R = \frac{h}{h_b}, x_o = \frac{1.15}{1+(\rho_L/\rho_G)}$
Schrock et al. (1986)	UCB	31,25, 17,10	$Fr_G\left(\frac{\rho_G}{\Delta\rho}\right)^{1/2} = 0.395\left(\frac{h_b}{d}\right)^{2.5}$ $Fr_G = \frac{V_{3G}}{\sqrt{gd}}$	$x = R^{3.25(1-R)^2}$ $R = \frac{h}{h_b}$
Maciaszek and Micaelli, (1989)	CEA	7	$h_b = 0.88\left(\frac{W_{3G}^2}{g\rho_G\Delta\rho d^2}\right)^{1/3}$	$x = 0.98\left(\frac{\alpha}{\alpha+\sqrt{\rho_L/\rho_G}(1-\alpha)}\right)$ $\alpha = 0.441\left(\frac{D}{d}\right)^{2/3}\left(\frac{h}{h_b}\right)$
Welter (2001) and Welter et al. (2004)	OSU	2,3, 4.4	$\frac{w_{3G}^2}{gd^5\rho_G(\rho_L-\rho_G)} = 0.636\left(\frac{h_b}{d}\right)^3\left[0.22\left(\frac{h_b}{d}\right)+1\right]^2\cdot\left[1-\left(\frac{h_b}{d}\right)^2\right]^{-1}$	$x = \frac{1}{1+W_{3L}/W_{3G}}$ $\frac{W_{3L}}{W_{3G}} = 3.0\frac{\left(1-\frac{h}{h_b}\right)\sqrt{\left(\frac{\rho_L h}{\rho_G h_b}\right)}}{\left(\frac{h}{h_b}\right)(0.22\frac{h}{h_b}+1)}\cdot\left[\left(\frac{h_b}{h}\right)\left(\frac{\alpha_{1b}}{\alpha_1}\right)^2-1\right]\left(1-\left(\frac{h}{h_b}\right)^2\right)$
Yonomoto and Tasaka (1988)	JAERI			$x = \frac{R}{R+(1-R)\left(\frac{\rho_L}{\rho_G}\right)^{0.5}}$ $R = A\left(\frac{h}{h_b}\right)^{1.25} + B$