Discussion on the Flashing Phenomena of High Pressure Break Flow

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1. Introduction

There are several words to indicate the phase change of liquid (water) to gas (vapor).

- The word 'vaporization' seems the most general expression of phase change from liquid to gas regardless of it mechanism.
- 'Evaporation' seems to include the meaning of the phase change at 'liquid-gas interface'.
- 'Boiling' is usually used when heat is added to the liquid to form bubbles.
- 'Flashing' refers to the vaporization of highly pressurized liquid water of high energy when suddenly expands to low pressure condition.

Flashing phenomena are frequently observed in nuclear system both in a reactor coolant system and in a reactor containment system during accident such as LOCA (Loss Of Coolant Accident). And most of the nuclear thermal-hydraulic codes have the relevant models (USNRC, 1979; Ha et al., 2011; Hong et al., 2015; OECD NEA, 2014). In the flashing process, excess latent heat is consumed to evaporate some portion of the hot water, and the treatment of flashing in containment is very important to determine the pressure and temperature during accident.

Recently integral type SMRs(Small Modular Reactors) based on light water including i-SMR (innovative SMR) are under development. In this kind of SMR the containment is very small compared to the large dry containment of conventional reactor. Thus the containment code upgrade is essential including flashing model for the performance and safety analysis. In spite of the importance of the flashing in containment pressure and temperate, there are not so many discussions on the model and its effect.

Thus, the objective of this study is to discuss several aspects of flashing phenomena to provide the theoretical basis for the code upgrade.

2. Review of Thermal-hydraulic Code Models

2.1 Containment Codes

In CONTEMPT-LT code, the flashing model is applied to ME(mass and energy) before putting them into the containment region. The flashing options are two: one is temperature flashing(T-flash) and the other is pressure flashing(P-flash).

Temperature flashing (T-flash)

This is a kind of thermal equilibrium model. That is, the ME is assume to be well mixed with the containment atmosphere and then the phase separation is calculated based on the at atmosphere temperature.

This model is known, in most cases, to produce the highest containment atmosphere energy during the blowdown process and, therefore, generally the highest atmospheric pressure and temperature, assuming saturation conditions.

Pressure flashing (P-flash)

The flashed mass is calculated using following equation on the base of the total pressure of containment atmosphere.

$$M_{flash} = M_{in} \frac{h_{in} - h_f}{h_g - h_f} \tag{1}$$

where

M_{flash} = mass of blowdown liquid which flashes
M_{in} = mass of blowdown fluid which enters the drywell
h_{in} = specific enthalpy of blowdown fluid which enters the drywell (containment)
h_f = specific enthalpy of fluid
h_g = specific enthalpy of vapor.

If the total pressure is corresponding to the atmosphere temperature of saturation, the T-flash and P-flash generate the same flashed mass. CAP code has these two models in general source term when treating ME.

2.2 Reactor Codes

Reactor analysis codes such as SPACE usually use following interfacial phase change term (vapor generation rate).

$$\Gamma_{ig} = -\left[\frac{\frac{P_s}{P} H_{ig}\left(T^s - T_g\right) - H_{if}\left(T^s - T_f\right)}{h_g^* - h_f^*}\right] \tag{2}$$

where

Γ_{ig} = volumetric vapor generation rate
P_s *or* P = steam partial pressure and total pressure
H_{ig} *or* H_{if} = volumetric interfacial heat transfer

T_f or T_g = phasic temperature
$h_g^* or h_f^*$ = phasic enthalpy

The phasic enthalpies are based on the steam partial pressure. For the superheated liquid, that will surely undergoes the flashing process, the volumetric heat transfer coefficient (H_{if}) includes liquid superheat (ΔT_{sf}) term according to the flow regime, and this makes H_{if} very large. Resultantly a violent mass transfer between gas and liquid phases occurs. In this volumetric heat transfer correlations, all the properties are based on total pressure.

For bubbly flow, which includes the case that all the fluid is just liquid, the minimum seed void fraction 10E-5 is assumed to avoid zero interfacial heat transfer area in the volumetric heat transfer coefficient. So the liquid superheat can easily make the volumetric heat transfer coefficient very large. For vertically stratified flow the liquid volumetric heat transfer coefficient takes the value when the flow regime is not vertically stratified flow (i. e. the previous flow regime).

CAP code also takes this kind of interfacial mass/heat transfer calculation. However, CAP code only considers a flow regime of a kind of horizontally stratified flow, and the interfacial heat transfer area is very small. So the other special flashing calculation model was built in based on the liquid superheat.

3. Thermodynamic Process and Sample Calculation

3.1 Isentropic process

The flashing phenomena progresses very (or relatively fast, and it is very reasonable to assume that the entropy is assume to be constant for during short period. The final state of the quality is given by

$$x_2 = \frac{s_2 - s_{2f}}{s_{2fg}} \quad ,\text{where } s_2 = s_1 \tag{3}$$

In order to determine the final state ('2' in above equation), the reference pressure is to be determined: one is total pressure and the other is partial pressure based on steam (air mixture, saturated) temperature.

$$p = \begin{cases} Total\ pressure \\ Partial\ pressure \end{cases} \tag{4}$$

Actually the high pressure break flow can interact with ambient atmosphere or surrounding solid structures. In this case the final entropy can increase.

$$s_2 \begin{cases} = s_1,\ isentropic\ process \\ > s_1,\ entropy\ increase \end{cases} \tag{5}$$

3.2 Isenthalpic process (Throttling)

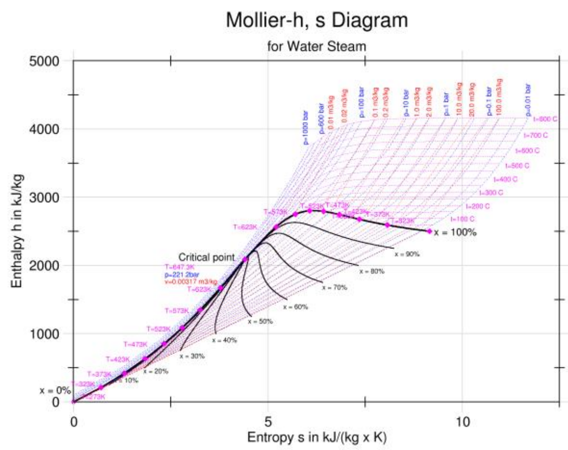
When pipe break, the break flow discharges through a long pipe or an orifice-like geometry. In this case the break flow can undergo the throttling process (Isenthalpic process).

$$x_2 = \frac{h_2 - h_{2f}}{h_{2g} - h_{2f}} \tag{6}$$

This equation is identical to the P-flash in Eq. (1). This process also requires the reference pressure: total pressure or steam partial pressure. In this case the final entropy is given by

$$s_2 = x_2 s_{2g} + (1 - x_2) s_{2f} \tag{7}$$

As can be seen in Mollier diagram in Fig. 1, the entropy increases as the pressure drops for this process. For easier perception of temperature change according to the pressure change Fig. 2 of P-T diagram is presented.



(from Wikipedia)

Fig. 1. Mollier h-s Diagram for Water

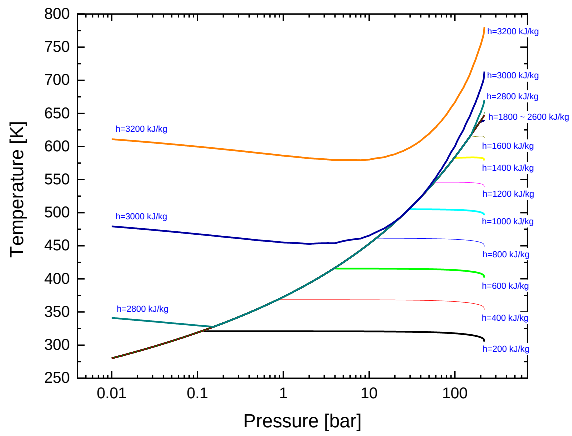


Fig. 2. Isenthalpic T-P Diagram for Water

4. Sample Calculations

4.1 Sample Calculations for each Thermodynamic Process

For a sample calculation following assumptions were used.

- RCS (Break source) state: 150bar 286℃ (Enthalpy is 1263.7kJ/kg)

- Containment (Reservoir) state: 1.0bar 50℃ and relative humidity 100% (Corresponding saturation pressure is 0.1234bar)

The calculation results are summarized in Table I.

Table I: Calculation Results based on Thermodynamic Process

Process	Reference pressure	Result (Static quality)
Isentropic process	Total pressure	0.296
	Gas temperature	0.324
Isenthalpic process	Total pressure	0.375
	Gas temperature	0.443

The final entropies for isenthalpic process are 3.573 kJ/kg-K and 3.967 kJ/kg-K, respectively. Similar results can be checked using the h-s Mollier diagram in Fig. 1.

4.2 Computer Code Calculations

MARS-KS 2.0 and CAP3.1 calculation were conducted. Absolutely the same simulation of subsection 3.1 is impossible. Rather, hot water is assumed to flow into a chamber atmosphere as outlined in Fig. 3. So, the calculation results must be different from the thermodynamic process calculation.

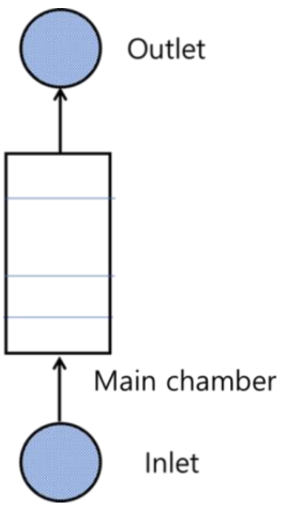


Fig. 3. Conceptual Nodalization for MARS-KS and CAP Calculations

Inlet, chamber, and outlet which controls the chamber pressure were set to be same conditions to the subsection 4.1. 10kg/s hot water during 10s was injected at very slow speed. Upper volumes above the bottom volume were kept quality 100%. The bottom volume static qualities calculated were arranged in Table 2.

MARS-KS and CAP 3.1 resulted in slightly increased chamber pressure. And they are believed caused by the head. In CAP calculation T-flash resulted in more phase change than P-flash because of the lower pressure of the steam partial pressure than total pressure. And the P-flash case is same to boundary flow case, as the special flashing model, which is not P-flash nor T-flash models, is based on total pressure. In spite that the phasic enthalpies are based on partial pressure, the static quality shows no more increase differently from MARS-KS because of artificial suppression of interfacial area of horizontally stratified flow in CAP.

In MARS-KS calculation, the initial flashing is governed by the liquid superheat and relevant volumetric heat transfer coefficient model which is based on the total pressure. After this initial flashing the static quality showed continuous increase, even though the rate is very slow, because of the partial pressure based phasic enthalpy difference.

Table 2: Calculation Results using Thermal-hydraulic Code

Code	Option	Result (Static quality)
MARS-KS 2.0	Boundary flow	0.560*
CAP 3.1	Boundary flow	0.560
	(ME) P-flash	0.560
	(ME) T-flash	0.569

* This value is initial changed one, and it increases continuously and slowly.

5. Conclusions

In this study, fundamental mechanism of flashing was discussed and example calculations were presented using hand calculation and code calculations. As expected the isentropic process produced the least phase change amount and the T-flash yielded more phase change than P-flash and isentropic process. And it was found that there is some difference between codes because of the different treatment of flow regime and relevant interfacial models.

This study is expected to give a fundamental understanding of the flashing phenomena and relevant code models

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