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Review

# Review: Condensation regime maps of steam submerged jet condensation

Quanbin Zhao[a,*], Takashi Hibiki[b]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, 47907-2017, USA

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ABSTRACT

Steam submerged jet condensation has been widely used in many industry applications, especially in nuclear engineering. Since the heat and mass transfer varies with the condensation patterns as well as steam-water interface shapes, the identification and classification of the condensation regime is indispensable to conduct thermal-hydraulic analyses and to select adequate constitutive equations such as heat transfer coefficient. Different definitions and criteria have been used to classify the steam jet condensation regime. Due to the different transition criteria of condensation regime and multi-parameters' effect, existing condensation regime maps do not agree each other. In this paper, unified criteria and definitions for each regimes have been proposed based on the dynamic behavior and geometrical shape of steam-water interface. The re-classified condensation regimes are chugging regime, hemispherical bubble oscillation regime, condensation oscillation regime, stable condensation regime and steam escape regime. The existing analytical model, empirical correlations and empirical map developed under different test section designs and test conditions failed to predict the existing experimental condensation regime transition boundaries. The discrepancy in the transition boundaries among existing experimental data is significant due partly to the subjective classification and complicated dependence on multiple parameters. Further efforts on both analytical and experimental researches are encouraged in the future.

## 1. Introduction

Direct contact condensation is an important phenomenon in many industrial applications. The direct contact condensation has a great advantage in mass and heat transfer in comparison with a wall condensation-type heat and mass transfer. Submerged steam jet condensation as a typical operation mode of direct contact condensation has great efficiency in heat transfer due to the high heat transfer coefficient. The introduction of steam jet into a pool agitates water resulting in increased turbulence, which enhances the heat and mass transfer between steam and water significantly. Due to its high efficiency, steam submerged jet condensation is widely used in various industrial fields such as gas welding, rocket fuel system and pressure relief system in nuclear reactors (Gamble et al., 2001; Chong et al., 2015a,b).

In the nuclear reactor system, steam jet condensation is used to mitigate nuclear reactor accidents such as the loss of coolant accident and loss of condenser vacuum. In boiling water reactor (BWR) system, once loss of coolant accident happens, steam is released from dry well to wet well (suppression pool) through connected pipes to suppress pressure. Steam submerged jet condensation occurs in the wet well. In pressurized water reactor (PWR) system, pressure in a primary circulation loop is maintained by a pressurizer. When the pressure in the pressurizer exceeds a critical pressure, a safe valve installed in a pressure release pipe line is opened to release steam to water tank through spargers. Especially, for an advanced nuclear reactor, which is characterized with the passive pressure release system, steam jet condensation and thermal mixing characteristics significantly affects the performance of the pressure suppression system (Song and Kim, 2011). As exemplified above, the research on the steam jet condensation is important in nuclear safety researches.

In two-phase flow, mass, momentum and energy transfer between two phases are governed by two-phase interface structure. The topological two-phase interfacial structures are used to identify flow regimes (Ishii and Hibiki, 2011; Lokanathan, and Hibiki, 2016; Mao and Hibiki, 2017; Liu and Hibiki, 2017). However, in steam submerged jet condensation, the steam-water interface structure or condensation regime is not only governed by typical two-phase flow parameters such as steam velocity, but also steam condensation rate in water. Because of a strong coupling of fluid dynamics and heat transfer process in the condensation process, condensation regime map is more complicated. Accurate identification of the condensation regime is a key factor in

* Corresponding author.
*E-mail address:* zqb8031110.com@stuxjtuedu.cn (Q. Zhao).

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**Nomenclature**

| | |
|---|---|
| $A_i$ | interfacial area |
| $C_1$, $C_1$, $C_2$ | constant number |
| $c_p$ | water specific heat |
| $D$ | pipe/nozzle diameter |
| $D_b$ | bubble diameter |
| $g$ | gravitational acceleration |
| $h$ | interfacial heat transfer coefficient |
| $h_{fg}$ | steam latent heat |
| $P$ | pressure |
| $R_n$ | nozzle radius |
| $T_{sat}$ | saturated steam temperature |
| $T_w$ | water temperature |
| $\Delta T$ | water subcooling |
| $u_t$ | turbulent intensity of interfacial eddy |
| $V$ | volume of steam bubble formed at pipe/nozzle exit |
| $\upsilon_s$ | steam jet speed at nozzle exit |

*Greek symbol*

| | |
|---|---|
| $\delta_w$ | thermal layer thickness |
| $\lambda$ | thermal conductivity coefficient |
| $\delta_t$ | eddy size at steam-water interface |
| $\mu_l$ | kinematic viscosity of water |
| $\rho_l$ | water density |
| $\rho_s$ | steam density |
| $\sigma$ | surface tension of water |

*Dimensionless numbers*

| | |
|---|---|
| $Bo$ | Bond number, $\frac{gR_n^2(\rho_l-\rho_s)}{\sigma}$ |
| Fr | modified Froude number, $\frac{\rho_s \upsilon^2}{gD(\rho_l-\rho_s)}$ |
| $Ja$ | Jacob number, $\frac{\rho_l C_p \Delta T}{\rho_s h_{fg}}$ |
| $Nu_t$ | Nusselt number, $\frac{h\lambda_t}{\lambda}$ |
| Pr | Prandtl number $\frac{\mu_l c_p}{\lambda}$ |
| Re | Reynolds number $\frac{\rho \upsilon D}{\mu}$ |
| $Re_f^s$ | Reynolds number based on steam velocity and water viscosity, $\frac{\rho_s \upsilon_s D}{\mu_l}$ |
| $Re_t$ | turbulent Reynolds number at interface, $\frac{\rho_s \upsilon_s \lambda_t}{\mu_f}$ |
| $We$ | Weber number associate with water density, $\frac{\rho_l \upsilon_s^2 D}{\sigma}$ |

**Table 1**
Existing condensation regime maps.

| Authors | Nozzle Diameter [mm] | Water Temperature [°C] | Steam Mass Flux [$kg{\cdot}m^{-2}{\cdot}s^{-1}$] | Criteria and Method | Steam Jet Orientation | Identified Condensation Regime |
|---|---|---|---|---|---|---|
| Arinobu (1980) | 16.1, 27.6 | 20–92 | 5–100 | 1) Steam cavity shape<br>2) Pressure oscillation | Vertical downward | I, II (Chugging), III, IV (CO), V, VI |
| Chan and Lee (1982) | 38.1 | 40–90 | 1–175 | 1) Steam cavity shape<br>2) Steam bubble detachment position<br>3) Location of steam cavity from pipe exit<br>4) Pressure oscillation | Vertical downward | EJ, EOB, OB, OJ, ECEB, ECDB, IC, OI |
| Aya et al. (1980, 1983), Narria and Aya (1986) | 18, 29<br>15.9 | 10–90<br>10–100 | 0–40<br>0–200 | 1) High-frequency pressure oscillation<br>2) Temperature wave<br>3) Steam cavity shape | Vertical downward | La-C, Sm-C, CO, T, B |
| Lahey and Moody (1993) | | 0–100 | 0–150 | Steam cavity shape | | OI, C, CO Quasi-Steady Oscillation, T |
| Chun et al. (1996) | 4.45<br>7.65<br>10.85<br>10.85 | 17–83<br>12–82<br>20–82<br>16–81 | 200–700 | Steam cavity shape | Horizontal<br><br><br>Vertical Downward | CO, SC, BCO, IOC |
| Cho et al. (1998) | 5, 10, 15, 20 | 0–100 | 45–450 | Steam cavity shape | Horizontal | C, TC, CO, SC, BCO,IOC |
| De With et al. (2007) | 10–50 | 10–90 | 0–1500 | Steam cavity shape | | ICO, C, B,<br>Co, El, Di |
| Wu et al. (2007, 2009) | $D_{cr}$ = 8,<br>$D_e$ = 8, 8.8, 9.6, 10.4, 11.2, 12 | 20–70 | 298–865 | Steam cavity shape | Horizontal | UJ, Con, Ex-Con, Double-Ex-Con, Double-Ex-Div, Con-Ex-Con, Con-Ex-Div |
| Gregu et al. (2017) | 27 | 0–70 | 0–20 | Steam cavity shape<br>Pressure oscillation | Vertical downward | SEB, BEB, BEEB, NEB, Sm-C |
| Liang (1991), Liang and Griffith (1994) | 10.9, 19.1 | 60–90 | 0–50 | Steam cavity shape | Vertical upward | C, Bubbling, Jet |
| Xu et al. (2013), Xu and Guo (2016) | 8 | 20–70 | 110–500 | Steam cavity shape | Vertical upward<br>Vertical Crossflow | Hem, Co, Cy, El, Div<br>C, CO, S-co, S-ex, S-cy |
| Zong et al. (2015) | $D_{cr} = 8 \times 8$<br>$D_e = 10 \times 10$<br>$D_{cr\text{-}w} = 8 \times 10$<br>$D_{e\text{-}w} = 10 \times 10$ | 20–60 | 200–650 | Steam cavity shape | Horizontal | Bubble, OJ, Co, El, Di |