

CFD Review of Pure-Steam External Condensation on Horizontal Tubes

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1. Introduction

Following the Fukushima Daiichi accident, the necessity of passive safety in nuclear power plants has been underscored, and the implementation of such systems has effectively become a prerequisite for licensing. Passive safety aims to achieve post-accident core cooling independently of offsite power and human error, relying instead on natural forces—gravity, natural circulation, and heat transfer in phase change—for system actuation and heat removal.

In current conventional light-water reactors, decay heat is removed passively through multiple paths: the Passive Auxiliary Feedwater System (PAFS) cools the reactor through the steam generator (SG) secondary side; the Passive Containment Cooling System (PCCS) condenses steam that leaks into containment; and the Passive Containment Cooling Tank (PCCT) serves as the ultimate heat sink, sustaining heat removal and natural circulation in the long term.

Emerging Small Modular Reactors (SMRs)—promoted for flexible load-following, compactness, and improved constructability—also adopt passive safety features. In case of innovative-SMR (iSMR), integral PWR-type SMRs developing in Korea, the reactor pressure vessel (RPV) is arranged with an inner vessel housing the core and an outer vessel that contains helical-coil steam generators. During an accident, opening of the emergency depressurization valves (EDV) and emergency recirculation valves (ERV) effectively extends the reactor coolant system boundary to the containment vessel (CNV), reduces the RPV water level, and establishes natural circulation: decay-heat-generated steam rises in the inner vessel, while a descending path is formed across the SG region in the outer vessel. Condensation then occurs on the exterior of the helical SG tubes (see Fig 1.).

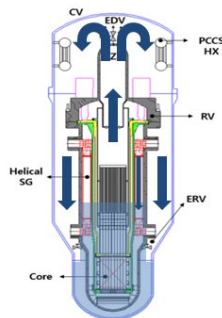


Fig 1. Condensation Scheme at iSMR in accident

During normal operation, the containment is maintained at vacuum. Consequently, in an accident, the high-pressure steam circulates by natural convection and condenses on the exterior of SG, removing decay heat. Because non-condensable gases (NCG) are absent, this mechanism can achieve higher heat removal performance than condensation in large LWR accidents where NCGs degrade interfacial heat and mass transfer [1]. Accordingly, rigorous evaluation of external condensation heat transfer under these conditions is essential. The classical foundation is Nusselt's laminar film-condensation model for a single tube [2], which has been extended to include interfacial shear effects—most notably by Shekrladze and Gomelaury—yielding improved agreement with experiments [3]. Nevertheless, the existing body of work on pure-steam condensation has been developed pressure close to atmosphere and for regimes unlike the natural-circulation, high-pressure environment expected in vacuum containments. Systematic studies for external condensation on tubes under such conditions remain limited, leaving important questions regarding correlation applicability and model fidelity.

Accordingly, as a preparatory step, the assessments of condensation heat transfer of pure, high-pressure steam using CFD is needed. To establish a modeling basis, this paper reviews prior CFD studies of pure steam external condensation on tubes, identifies the key modeling choices; interface analysis method and phase-change closures.

2. Literature Reviews

The CFD studies of pure steam external condensation on tubes have simulated only horizontal tubes, which from on a single tube to an inline arrangement of two cylinders. Their flow domain, conditions and physical models are given in Table 1. When using CFD to simulate condensation on tubes, there are two key approaches for modeling the film condensation: interface analysis method and phase change model.

2.1 Interface Analysis Method

External condensation on tubes is a two-phase flow with phase change; in two-phase CFD of such problems, resolving the liquid-vapor interface is critical. Broadly, interface treatment follows either (i) Lagrangian approaches, which explicitly advect a discretized surface but can lose fidelity for thin films when coupled to cell-

Table 1. Prior CFD studies of pure steam external condensation on tubes

Reference	Interface analysis method	Mass transfer model	Working Fluid	Pressure	U_{∞}	ΔT	Fluid Domain
Kleiner et al. [4]	VOF	Numerical iteration scheme	Water, pentane	1atm	-	10 - 50K	Cylindrical Geometry - radius: 9.525-10.5 mm
Minko et al. [5]	VOF	Lee model	Water, pentane	1atm	0-3 m/s	20 - 30K	Cylindrical Geometry - radius: 12.7-38.1 mm
Minko et al. [6]	VOF	Modified Lee model	R-113	0.1MPa	3-6 m/s	20K	Cylindrical Geometry - radius: 6.25-18.75 mm
Kumar et al. [7]	CLSVOF	Heat flux model	R-123	3.6MPa	~0.1m/s	3 - 9K	Inline arrangement of two tubes in cuboid

centered property averaging—making them less suitable for laminar film condensation [8]—or (ii) interface-capturing approaches. Among the latter, the Level-Set (LS) method represents the interface as the zero contour of a signed-distance function but is not strictly mass-conservative and may accumulate mass errors during reinitialization [9]. By contrast, the Volume of Fluid (VOF) method advects a bounded volume fraction and is intrinsically mass-conservative. Using VOF, Kleiner performed the first 2D and 3D simulations of condensation around horizontal tubes [4]. This study reported deviations within approximately 5% against Reif's experiments [10] (see Fig 2). These results motivate VOF-based frameworks for assessing pure, high-pressure steam film condensation relevant to vacuum-containment conditions.

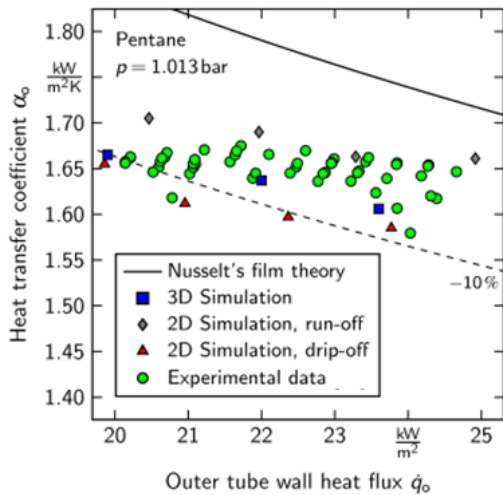


Fig 2. Comparison of outer heat transfer coefficients between the measurements of Reif [10], Nusselt's film theory and the different simulation approaches

2.2 Phase Change Models

The phase-change rate directly determines the source terms in the continuity and energy equations. Two principal approaches are commonly used. The first

computes the condensation rate from the interfacial heat-flux continuity, whereby the condensed amount is governed by the temperature gradients on the liquid and vapor sides and by the saturation temperature. However, within a numerical framework such as VOF that employs a single temperature field for both phases, the two-sided interfacial heat fluxes must be reconstructed and separated [11], [12]. The second approach is the Lee model [13]. Grounded in the molecular-kinetic theory of Hertz–Knudsen equation, the Lee model prescribes a volumetric mass-transfer rate that relaxes the cell temperature toward the saturation temperature at the cell pressure (see Eq. 1).

$$\dot{m} = \begin{cases} r\alpha_l\rho_l \frac{T-T_{sat}}{T_{sat}} & \text{if } T \geq T_{sat} \\ r\alpha_v\rho_v \frac{T-T_{sat}}{T_{sat}} & \text{if } T < T_{sat} \end{cases} \quad (1)$$

where r is coefficient of Lee model, with unit of s^{-1} , and unit of temperature is kelvin.

Minko et al. studied free convection film condensation over a cylinder with an VOF method and Lee model [5]. However, this model include an arbitrary coefficient, which has to be calibrated for simulations. The main disadvantage of the Lee model is that coefficient is not limited to a maximum value. Thus, Minko used modified Lee model, simulated forced convection film condensation, which was downward flow moving at a velocity up to 6m/s at a pressure close to atmosphere [6]. Also, Thomas et al suggested the mass transfer rate model using the iterative scheme for the evaluation of the energy balance [4].

3. Conclusions

External condensation of high-pressure pure steam on horizontal tubes represents a key heat-removal mechanism for accident analysis of vacuum-containment SMR designs. A review of prior work indicates that most correlations and datasets were established near atmospheric pressure, leaving the applicability at high pressure insufficiently validated.

From a CFD standpoint, VOF-based interface

capturing is supported by prior successes in thin-film condensation due to its intrinsic mass conservation and topological robustness. For the phase-change closure, interfacial heat-flux continuity methods enforce energy conservation but demand careful reconstruction of two-sided gradients, whereas Lee-type volumetric models offer robustness at the expense of a tunable relaxation coefficient. For practical application to iSMR-relevant conditions, a calibrated Lee-type approach anchored by canonical benchmarks (the 1D Stefan problem) and selected tube-condensation data is recommended, with iterative energy-balance checks to bound the coefficient and preserve physical consistency.

A modeling framework for subsequent iSMR studies should therefore include: (1) VOF interface capturing with documented grid/time-step independence and interface-thickness control; (2) thermophysical properties consistent with high-pressure steam and subcooled condensate; (3) explicit specification of wall subcooling, wetting/contact angle, and gravity orientation; and (4) verification against canonical problems and targeted validation against tube-condensation measurements extended to elevated pressures. Within this framework, parametric studies in pressure, subcooling (Jakob number), vapor shear, and geometry (tube diameter and pitch for bundles) can quantify the regime map and inform the selection or modification of heat-transfer correlations vacuum-containment SMR applications.

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