A brief review of research on steam condensation heat transfer based on separate effect experiments and diffusion layer theory

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Abstract. Research on steam condensation in the presence of non-condensable gas is needed to support the thermal design of containment and capacity analysis of its cooling systems for nuclear power plants (NPPs). Based on classical and newly published literatures in related fields, the theoretical and experimental achievements are analyzed in this paper and research emphasis is consequently summarized. Considering the design and application characteristics of small-sized NPPs, several prospects of following-up study are proposed, which can be referenced in future work.

1. Introduction
Defense-in-depth is the fundamental safety philosophy of nuclear power plants (NPPs), which is known as an effective way to protect people and the environment. In practice, three physical barriers are used to prevent the radioactivity materials from releasing to the environment, namely fuel cladding, primary system pressure boundary and the containment. Under design basis accident, a large number of fluids with high enthalpy will break through the second barrier, enter the containment, and finally condense on the surface of containment or components inside containment. Failure of heat removal will definitely threaten the integrity of the third and also the last barrier. Thus, specified containment cooling systems, in active or/and passive ways, are installed to remove the excess heat. In order to aid the thermal design and capacity analysis of such cooling systems, targeted research on the characteristics of steam condensation should be carried out.

Nowadays, the research and development of small-sized NPPs have gradually become the hot spot in nuclear engineering area. Since there exists a thoroughly different operational condition compared with traditional NPPs, the thermal-hydraulic response of small containment under accident conditions will certainly be different, and this situation is also applied to the design of relevant containment and its cooling systems. In view of this, applicability study is needed to review the present research in the field of steam condensation. Considering the unique design of small-sized NPPs, an issues-to-be-solved list can be summarized consequently.

2. Separate effect experiments
Since the mid-1960s, a large number of small-scaled separate effect experiments are established to study the phenomenon of steam condensation and various heat transfer coefficient (HTC) correlations
are proposed by fitting of experimental data as follows, which are grouped according to the basic structure and fundamental purpose of the testing facilities.

2.1. Condensation on plates
A vertical flat plate, which width of 0.14m and length of 0.3m, is tested by Uchida et al.[1-2] to study the steam condensation in the presence of non-condensable gases on components inside containment or walls of containment, and a HTC correlation, depends only on the mass ratio of non-condensable gas (mostly air and hydrogen, and only the former one is considered in this paper) and steam, is obtained by experimental data fitting, as \( h_{\text{Uchida}} = 379 \eta^{-0.707} \). With the same test facility, a steam blow-down condition is simulated by Tagami et al.[1-2], and a set of time-dependent HTC correlations is gained, whose steady-state form is also a simple function of \( \eta \).

Furthermore, experiments on vertical plates have been carried on by Kataoka[3], Murase[4], and so on. Several Uchida-like HTC correlations are obtained by these experiments, and it is shown that the Uchida correlation is relatively conservative, especially in situation where the mass fraction of air is low (<0.5).

Because of this conservation, which is always emphasized by nuclear safety regulatory body in the process of safety review, the Uchida-Tagami correlations, though proposed over more than five decades, are still widely adopted in the engineering design of reactor containment and emergency core cooling system (ECCS) by different combinations, to obtain conservative calculation results.

It is worth noting that the steam condensation heat transfer is not only affected by mass ratio of air and steam, but also influenced by pressure of bulk gas mixture, sub-cooling of cold walls, and the test object itself. For AP600, a steel containment is designed to remove the excess heat through condensation inside and evaporation outside the wall. This advanced passive heat removal technique may be significantly undervalued utilizing correlations mentioned above. In order to study characteristic of heat transfer under similar condition in a best-estimate way, condensation on two scaled vessels have been analyzed by Anderson et al.[5], and the effect of different factors are summarized, with a vast database now used for model validations.

2.2. Condensation outside or inside tubes
While condensation on plates are mainly focus on the characteristics of steam condensation on surfaces or walls to support the thermal design of containment and safety analysis of LOCA, the research emphasis has been shifted to condensation outside or inside tubes in the mid-1990s, since the advent of passive containment cooling system (PCCS) with condenser pipes in advanced NPPs. Among the various researches, experiments by Dehbi[6] from MIT have been referenced the most.

A vertical tube, which diameter of 38mm and length of 3.5m, inside a cylindrical vessel is tested, and the condensation heat is removed by coolant inside the tube. Compared with previous studies, influence factors in Dehbi’s experiments are relatively complete and the major parameters discussed in chapter 2.1 are certainly involved in the empirical correlation of HTC, which is now widely used to validate a new theoretical or experimental model. This benchmarking HTC correlation is as follows

\[
\frac{h_{\text{Dehbi}} L^{0.05}}{T_{b}^{0.25} - T_{w}^{0.25}} = \frac{(3.7+28.7P) \cdot (2438+458.3P) \log X_{\text{air}}}{T_{b}^{0.25}}
\]

Furthermore, condensation outside tubes have been continued studied by researchers like Liu[7], Kawakubo[8], Lee[9], and so on, to support the design of PCCS in pressurized water reactor (PWR) NPPs. The correlation of HTC concluded differed from each other, and partial results obtained by Liu is in contradiction with counterpart by Dehbi. But collectively, the principal factor in condensation on plates or tubes are basically the same, namely mass fraction of non-condensable gas, pressure of bulk gas mixture, sub-cooling of cold surfaces, and so on. Therefore, apart from the dimensionless form consists of Nu, Gr, and Ja, and derived by Lee[9] lately, the HTC correlation for condensation on tubes share almost the same format: \( h = f(P; X_{\text{air}} \text{ or } X_{\text{st}}; T_{b} - T_{w}) \).
Besides, research on condensation inside tubes is also needed to aid the design of PCCS\[10\], which always has a condenser with coolant inside, for boiling water reactor (BWR), or residual heat removal system\[11\], which may contain inclined tubes, for either PWR or BWR. In contrast to condensation on external surfaces (plates or tubes), forced convection is more common inside tubes vertically or horizontally, and the convection HTC is generally higher than its counterpart under natural convection. Also, it is customary to utilize dimensionless number, like Nu, Re and Ja, to formulate the condensation HTC, with a generalized form like: \( \text{Nu} = f(\text{Re}; \text{X}_{\text{air}}; \text{Ja}) \).

### 2.3. Summary of experimental investigations

It can be known that the condensation heat transfer is highly dependent on the geometry (inside or outside, horizontal or vertical, plates or tubes) and the thermal condition (pressure, mass fraction, subcooling and so on) of the test facility. Limited to the device and condition of the experiment, a large difference exists in the empirical correlation proposed by different researchers, in which partial results are even contradictory. Though each HTC correlation is in good agreement with its relevant experiment, it is not easy to predict the heat transfer for other experiments, and considering the lack of theoretical foundation, these correlations cannot be applied to a wider range. Therefore, the pioneered, conservative Uchida-Tagami correlations are still used in licensing analysis of an engineering object.

With the development of small-sized reactor, various novel techniques have been created, such as integral arrangement, marine application, and so on. Still, in face of functions and conditions that may not be considered before, much work remains to be done. Limited to free volume in containment, the design pressure of containment of small-sized NPPs is probably much higher than traditional ones. Since present study are mainly focus on low pressure (<0.5 MPa) condition, further research is needed to analyze the condensation under high pressure and the applicability of present achievements. For marine ones, the sea conditions, especially the rolling motion, should be considering as a design basis condition in experiment. Besides, a licensed model is also needed to eliminate the unnecessary burden by excessive conservatism to the design of small containment.

### 3. Diffusion layer theory

Up to now, various theoretical models have been established to explain the physical essence behind the phenomena of steam condensation in the presence of non-condensable gas, which can been roughly divided into three groups: (1) solve the field equation in boundary layer, (2) apply the mass and heat transfer analogy (HMTA)\[12\], and (3) analyze the diffusion layer model (DLM) based on HMTA. Developed from the second theory, the third one, diffusion layer model has a more physical meaning and is ideally suitable to be implemented into a computer code for containment analysis due to its relatively simple structure. Take the case of condensation on vertical surfaces (mostly in natural convection), the DLM and its modifications, which are widely studied and applied in relevant research, are analyzed in following chapters.

Generally speaking, the condensation process involves four parts: cold wall, liquid film, gas diffusion layer, and bulk gas mixture. Applying the concept of thermal resistance, the total HTC can be formulate as follows:

\[
\frac{1}{h_{\text{tot}}} = \frac{1}{h_{\text{film}}} + \frac{1}{h_{\text{gas}}} = \frac{1}{h_{\text{convection}}} + \frac{1}{h_{\text{condensation}}} + \frac{1}{h_{\text{radiation}}}
\]

Where, \( h_{\text{film}} \) is always solved utilizing the classical Nusselt’s theory or its modification, \( h_{\text{convection}} \) is always solved utilizing the McAdams’ theory, \( h_{\text{radiation}} \) is always ignored under relatively low temperature, and \( h_{\text{condensation}} \) is calculated as follows.

#### 3.1. DLM

The total heat flux equals the sum of the latent heat and the sensible heat through the film/gas interface. Using Fick’s law and modified Clausius-Clapeyron equation in condition of idea gas behavior, the total heat flux and condensation velocity can be written as:
\[
q_{\text{cond}} = q_{\text{cond}} + q_{\text{sen}} = -h_p c M_{\text{g}} v_i + k_u \frac{\partial T}{\partial y} v_i = \frac{D h_p M_{\text{g}} x_{n,av}}{R T_{av} x_{g,av}} \delta_y (T_{i,s} - T_{b,s})
\] (3)

Defining condensation thermal conductivity, the condensation HTC can be developed, by Peterson[13], in a simple form:

\[
h_{\text{cond}} = \frac{S h_k k_{\text{cond}}}{L}, \quad k_{\text{cond}} = \frac{1}{\phi R_{av}} \left( \frac{h^2 P_{M} M_{\text{g}} D_{0}}{R T_{i,s}^2} \right)
\] (4)

3.2. Improved DLM

In Peterson’s model, the specific volume is assumed to be a constant in the given temperature range, which, in fact, is inaccurate since large temperature gradient may exist in large-scale space especially in containment of AP600 NPPs. Thus, the Clausius-Clapeyron equation is revised through describing the steam volume by ideal gas law, and an improved DLM is thus proposed by Anderson[14] and Herranz[15], with the condensation thermal conductivity yields the following:

\[
k_{\text{cond}} = \frac{C M_{\text{g}} h_{\text{sh}} D}{\phi R_{c} T_{i,s}}
\] (5)

3.3. Generalized DLM

Those DLMs mentioned above are developed on the molar basis, whose calculation of condensation mass turned to be relatively conservative by some researchers. A generalized DLM, developed from Fick’s law on the mass basis, is proposed by Liao[16], with a more complicated condensation thermal conductivity:

\[
k_{\text{cond}} = \phi_1 \phi_2 \frac{h_{\text{sh}} h_{\text{su}} P_{D M} M_{\text{g}}}{R^2 T^2}, \quad \phi_1 = \frac{\ln \left( 1 - m_{\text{po}} / (1 - m_{\text{po}}) \right)}{m_{\text{p}} / m_{\text{po}}}, \quad \phi_2 = \frac{M_{\text{m}}^2}{M_{\text{p}} M_{\text{po}}}
\] (6)

Where, the factor numbered 1 stands for the effect of non-condensable gas and the suction on steam condensation, and the factor numbered 2 explain the effects of variable mixture molecular weights on steam diffusion. Though complex, this model can predict the HTC more realistically.

3.4. Summary of theoretical investigations

Compared with the experimental researches, the DLM shows a better understanding of the physical phenomenon behind steam condensation and can be applied in a wider range. Certainly, some models are simplified and transformed to obtain a relatively simple equation, which can thus be incorporated into a containment analysis tool and be solved in an economically feasible way.

Because of these simplifications, the DLM should be carefully used for a newly designed NPPs and key models should be re-derived according to the specific conditions, just as Herranz et al. developed for the AP600 with a passive containment and Wu[17] developed for the small-sized NPPs under high pressure condition.

4. Conclusions

Classical and newly research achievements in the field of steam condensation based on separate effect experiments and diffusion layer theory have been summarized briefly in this paper. Considering the novel research and development of several small-sized NPPs, relevant conclusions are drawn as follows: (1) High pressure, tilt and roll motion conditions should be emphasized in following-up experimental research as design basis. (2) Mathematically, the DLM is suitable for the small-sized NPPs while certain modifications should be developed according to the detailed design of specific type, and verification by relevant experiments is also necessary. (3) A licensing condensation model or set of models is needed to absorb the achievements made in recent decades.
Appendices

Table 1. Nomenclature

| Symbols       | Subscripts | Description                      |
|---------------|------------|----------------------------------|
| c             | m          | molar density                    |
| C             |            | concentration                    |
| D             |            | diffusion coefficient            |
| Gr            |            | Grashof number                   |
| h             |            | heat transfer coefficient        |
| hfg           |            | latent heat of vaporation        |
| h             |            | heat transfer coefficient        |
| h             |            | Reynolds number                  |
| k             |            | thermal conductivity             |
| L             |            | length                           |
| m             |            | mass fraction                    |
| M             |            | molecular weight                 |
| Nu            |            | Nusselt number                   |
| Pr            |            | Prandtl number                   |
| Pr            |            | pressure                          |
| q''           |            | heat flux                        |
| Rc            |            | gas universal constant           |
| Re            |            | Reynolds number                  |
| Sc            |            | Schmidt number                   |
| Sh            |            | Sherwood number                  |
| T             |            | temperature                      |
| X             |            | mass fraction                    |
| x             |            | coordinate                       |
| y             |            | coordinate                       |
| v             |            | velocity                         |
| tot           |            | total                            |
| st            |            | steam                            |
| wall          |            | wall                             |

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