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Filmwise Reflux Condensation Length and Flooding Phenomena in Vertical U-Tubes

Moon-Hyun Chun and Jee-Won Park

Korea Advanced Institute of Science and Technology
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수직U-자관 속에서의 액체막 역류 응축 길이와 Flooding현상

전 문 헌 · 박 지 원

한국과학기술원
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Abstract

A two inverted U-tubes condenser was constructed from transparent materials to study the heat removal capability of steam generators under filmwise reflux condensation mode. Essentially, two sets of experiments were performed: (1) the first dealt with the reflux condensation length, and (2) the second dealt with the flooding points with and without the presence of a noncondensible gas in the steam flow, and the effect of the flooding time. In addition, experimental results are compared with the predictions of analytical models.

요 약

가압 경수로의 소형 냉각재 사고시 증기 발생기 U-자관 내에서의 역류 응축 현상(reflux condensation phenomena)은 주요한 열제거 수단이 된다. 열제거 Mechanism이 순수히 역류 응축 현상에 의할 때, 증기 발생기의 열제거 능력을 평가하기 위하여 원자로 증기 발생기의 U-자관을 모사하는 두 개의 U-자 관을 가진 증기응축 장치를 제작하여 다음 두 가지의 실험을 수행하였다. 첫째로, U-자 관속에서 역류 응축 현상이 일어날 때 증기의 유입량을 증가시켜 가면서 역류 응축이 일어나는 액체막 길이(filmwise reflux condensation length)를 측정하였다. 둘째로는 길이가 다른 두 개의 U-자관에 증기만을 유입시킬 때와 증기와 공기를 동시에 유입시킬 때에 대한 Flooding Point를 측정하여 U-자관의 길이와 비응축성 가스가 Flooding Point에 미치는 영향을 조사하였다. 그리고, 수학적 모델을 이용한 이론적 측정값과 실험 Data를 비교하였다.

Nomenclature

- A cross sectional area
- A_c cooling water flow area
- C_1 constant in Wallis flooding correlation
- C mass concentration of air
- C_f specific heat of water
- D inside diameter of U-tube
- g gravitational constant
- h_i condensation heat transfer coefficient
- h_o shell-side heat transfer coefficient
- h_{o1} shell-side heat transfer coefficient at the bottom of the condensation length

h_{o2} shell-side heat transfer coefficient at the top of the condensation length
h_{om} shell-side heat transfer coefficient between the top and the bottom of the condensation length
h_{fg} latent heat of steam
h_{fg}' a quantity defined by Eq. (5)
k_f thermal conductivity of water
k_t thermal conductivity of U-tube wall
L condensation length (two-phase condensing region shown in Fig. 1)
$\dot{m}_a$ air flow rate
$\dot{m}_c$ cooling water flow rate
$\dot{m}_f$ condensate flow rate
$\dot{m}_g$ steam flow rate
$\dot{m}_g^*$ steam flow rate at which flooding phenomenon occurs
P wetted perimeter
n constant in Wallis flooding correlation
q heat transfer rate
q'' heat flux
r_1 inside radius of U-tube
r_o outside radius of U-tube
T_b shell-side cooling water temperature
T_g steam temperature
T_w U-tube inside wall temperature
U overall heat transfer coefficient
μ_f viscosity of water
ρ_f density of water
ρ_g density of steam

Introduction

During a small break loss-of-coolant accident (LOCA) in a PWR, steam generators are expected to function as a primary heat sink. During the entire transient, different heat removal mechanisms, such as reflux condensation, single-phase and two-phase natural circulation, may be occurring in the steam generator U-tubes [1~5]. To evaluate the potential consequences of a small break LOCA, the flow regimes and heat removal mechanisms in a steam generator must be fully understood.

Owing to the previous studies [1~7] on the reflux condensation in a steam generator, the availability of reflux condensation cooling mode in the nuclear reactor primary heat transport system, under certain conditions, is now well established.

Weisshaupl and Brand [1] conducted a series of tests in the PKL test facility and demonstrated that the decay heat under a small break LOCA can readily be removed via the steam generator secondary side by single-phase and two-phase natural circulation, and more effectively by heat transfer in the reflux condensation mode. Also, they investigated the influence of the presence of noncondensible gases (N_2) on the reflux condensation mode. Their results showed that the addition of noncondensible gas in the steam generator resulted in the reduction of heat removal capability.

Banerjee et al. [2] studied factors affecting reflux condensation in a single vertical tube using constant inlet and outlet pressure boundary conditions. Using a single inverted U-tube steam condenser, Nguyen and Banerjee [3] investigated the flow regimes and the parametric effects of input power, noncondensible gas, and cooling water flow rate on the heat removal process.

Calia and Griffith [4] used a four tube inverted U-tube condenser to determine the modes of flow that can exist as the rate of steam flow into the condenser is reduced: noncondensable gases were found to substantially alter the plenum pressure difference and aid flow instability.

Tien et al. [5] analyzed reflux condensation heat transfer in a vertical closed thermosyphon under constant wall temperature condition using the Nusselt film condensation theory.

Chang et al. [6] studied experimentally the effects of system pressure, cooling water temperature, length of the single-phase region and tube diameter on the heat removal capacity of a single tube under complete reflux. Wan et al. [7] investigated the role of flooding on reflux condensation in a single inverted U-tube.

Current research efforts on the reflux condensation are directed toward the study of the more detailed parametric dependence of its heat removal capability and its mechanisms.

In the present work, a two inverted U-tubes condenser was constructed from transparent material to study the heat removal capability of steam generators under filmwise reflux condensation mode, Essentially, two sets of experiments were carried out: (1) the first dealt with the reflux condensation length measurement, and (2) the second dealt with the effect of the U-tube length on the flooding time.

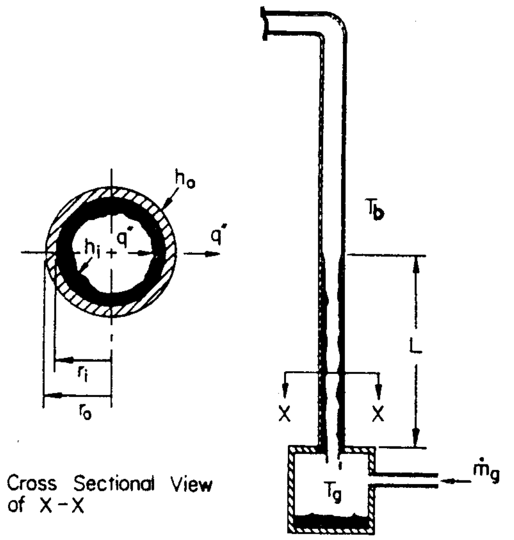

Fig. 1. Filmwise Reflux Condensation in a Vertical U-Tube Showing Flow Patterns in Inner Tube

Theory and Analysis

1. A Governing Equation for the Filmwise Reflux Condensation Length L

The flow patterns observed in reflux condensations (counter-current steam-condensate flow) have the general character shown in Fig. 1. Above the inlet of the tube, a two-phase condensing region is formed. Assuming there is no single-phase region above the two-phase region and under steady operating conditions, an expression for the length of the two-phase region L, where reflux condensations occur, for a given steam flow rate $\dot{m}_g$ can be obtained from the consideration of the heat removal rate of the U-tube shown in Fig. 1.

In the derivation of a governing equation for L, the following assumptions and simplifications are made:

1. The liquid film and the steam are at the saturation temperature.
2. The U-tube wall temperature is uniform.
3. No shear stress exists at the liquid-vapor interface.
4. Momentum effects are neglected.

The heat transfer rate from the reflux condensation film to the shell side water can be expressed as

$$q = UA(T_g - T_b) \tag{1}$$

In this case, the overall heat transfer resistance consists of three resistances in series, that is, (1) the reflux condensation heat transfer, (2) the U-tube conductive wall, and (3) the shell side convection.

Therefore, $1/(UA)$ is given by

$$\frac{1}{UA} = \left[\frac{1}{2\pi r_i h_i} + \frac{l_n(r_o/r_i)}{2\pi k_t} + \frac{1}{2\pi r_o h_o} \right] \cdot \frac{1}{L} \tag{2}$$

Combining Eqs. (1) and (2) and solving for L

$$L = \frac{q}{(T_g - T_b)} \left[\frac{1}{2\pi r_i h_i} + \frac{l_n(r_o/r_i)}{2\pi k_t} + \frac{1}{2\pi r_o h_o} \right] \tag{3}$$

Using the results of a modified Nusselt analysis of laminar film condensation on a vertical plate, h_i can be obtained from the following equation [8].

$$h_i = 0.943 \left[\frac{g\rho_f(\rho_f - \rho_g) k_f^3 h_{fg}'}{L\mu_f(T_g - T_w)} \right]^{1/4} \tag{4}$$

where

$$h_{fg}' = h_{fg} + 0.68 C_f (T_g - T_w) \tag{5}$$

The rate of heat transfer from the condensation of rising vapor to the reflux film and the U-tube wall, on the other hand, may be expressed as

$$q = 2\pi r_i h_i L (T_g - T_w) \tag{6}$$

Substituting Eq. (4) into Eq. (6) and solving for $(T_g - T_w)$,

$$T_g - T_w = \left(\frac{q}{1.886\pi r_i} \right)^{4/3} \left[\frac{\mu_f}{g\rho_f(\rho_f - \rho_g) k_f^3 h_{fg}'} \right]^{1/3} \frac{1}{L} \tag{7}$$

By substituting Eq. (7) into Eq. (4) and using this result for h_i in Eq. (3), one can obtain an expression for L as follows:

$$L = \left(\frac{q^{4/3}}{T_g - T_b} \right) \frac{\mu_f^{1/3}}{(1.886\pi r_i)^{4/3} [g\rho_f(\rho_f - \rho_g) k_f^3 h_{fg}']^{1/3}} + \frac{q}{T_g - T_b} \left[\frac{l_n(r_o/r_i)}{2\pi k_t} + \frac{1}{2\pi r_o h_o} \right] \tag{8}$$

At the steady state filmwise reflux condensation, i.e., when the amount of heat flux to the tube wall from the condensing steam is equal to the amount of heat removal from the shell side convection.

$$q = \dot{m}_g h_{fg}' \tag{9}$$

For pure steam condensations, if the tempearture of the liquid film inside the U-tube is at the saturation tempearture, h_{fg}' can be replaced by h_{fg}.

The filmwise reflux condensation length L can be obtained from the Eq. (8) by the following procedure:

1. Measure the steam flow rate $\dot{m}_g$.
2. Assuming a steady state (i.e., assuming that the amount of heat added to the tube wall by steam is equal to the amount of heat removal), obtainn q by substituting $\dot{m}_g$ into the Eq. (9).
3. Actually the outer heat transfer coefficient h_o in Eq. (8) can be obtained from the Dittus-Boelter type correlation since the range of the Reynolds number of the cooling water in the condenser varied from 3630 to 33,000 depending on the axial position. However, based on the experimental observation of the cooling water flow in the condenser, the average value of h_o is found from the following equation

$$h_o = \frac{1}{L} \int_0^L h_o(L)\, dL \tag{10}$$

assuming that the heat transfer coefficient decreases from h_{o1} (at $L=0$, i.e., at the bottom) to h_{om} (at $L=0.3$m) by 80% of the total difference between the values of h_{o1} at the bottom and h_{o2} at the top of the condensation length i.e., $\left(\frac{h_{o1} - h_{om}}{h_{o1} - h_{o2}} = 0.8 \right)$. Here, h_{o1} and h_{o2} are calculated by the Dittus-Boelter correlation using the equivalent diameter, $De = \frac{4A_c}{p}$.

4. Substitute q, thermo-physical properties, and other data into Eq. (8), and solve for L.

2. Steam Flow Rate Equation for the Flooding Point

Using an empirical correlation for flooding in vertical tubes suggested by Wallis [9], the following expression for a steam flow rate corresponding to the point of flooding can be obtained:

$$\dot{m}_g^* = \frac{\pi D^2}{4} \frac{c_1^2 \sqrt{gD\rho_g(\rho_f - \rho_g)}}{[1 + n(\rho_g/\rho_f)^{1/4}]^2} \tag{11}$$

where C_1 varies between 0.725 and 1.0 depending on the design of the ends of the tubes and the way in which the liquid and gas are added and extracted and the value of n is equal to unity when the Reynolds number of the steam flow is greater than 3600.

Experimental Apparatus

A two inverted U-tubes condenser was constructed from transparent material to study (1) the condensation length under reflux conditions,

(2) the flooding point with and without the presence of flowing noncondensible gases in the flowing steam, and (3) the effect of the U-tube length on the flooding time.

The apparatus along with the steam supply system and various measuring points are shown in Figs. 2 and 3. The experimental apparatus consists of (1) two electric steam boilers connected in parallel, (2) steam preheating section,

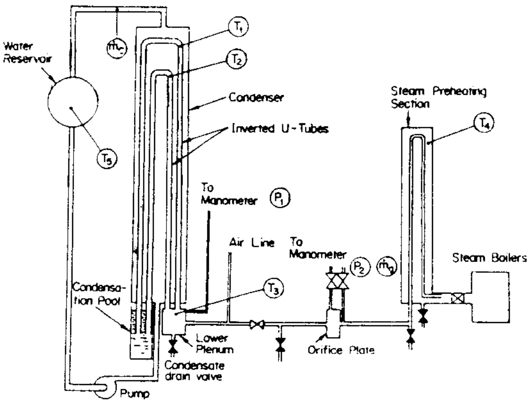

Fig. 2. Schematic Diagram of Experimental Apparatus

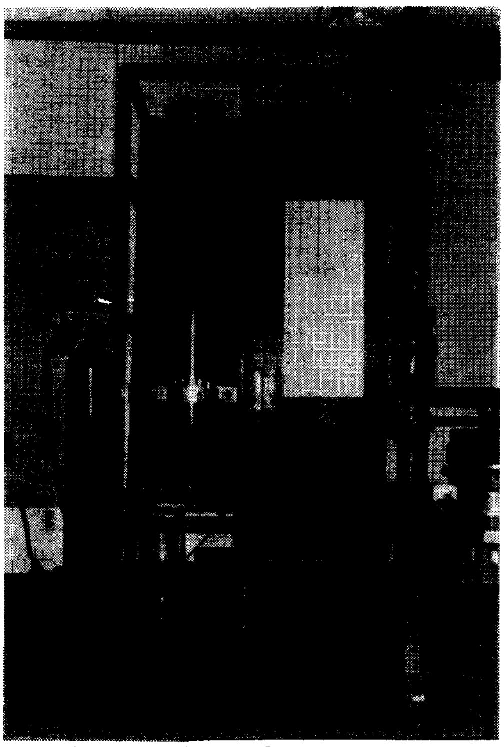

Fig. 3. Close-up View of the Experimental Setup

(3) lower plenum and condenser with two inverted U-tubes of transparent material, (4) a water reservoir and a circulation pump, (5) an air tank and a rotar meter, and (6) associated sensors or devices to measure flow rates of steam and air, pressure, and temperatures.

Each steam boiler (Chromalox model CMB-3L, 3 Watt operating at 100V) can produce steam at a steady flow rate of 4kg/hr for more than 5 minutes.

The preheating section was used to slightly superheat the steam (typically 1.7～7.8°C). An inverted copper U-tube is housed in a stainless steel enclosure (O.D.=76mm, Length =1,400mm). The outside of the whole preheating section is fully insulated with asbestos and glass wool. A manometer and a temperature sensor at the lower plenum were both used to determine the degree of superheating.

The lower plenum is a connection between the steam inflow and the U-tube test sections. The lower plenum is connected between the steam inflow tube and the U-tube test section to play the role of making a uniform distribution of steam flow to two U-tubes test section.

The condenser, on the other hand, consists of two U-tubes (pyrex glass I.D.=1.55cm, O.D.=1.80cm, length=1.9m and 1.63m) and a cooling jacket (an acryle resin).

The two U-tubes, in which condensation of steam takes place, are made of pyrex glass, and they are designed to simulate the steam generator U-tubes; one is used to simulate the shortest steam generator U-tube and the other is used to simulate the longer one. The linear scaling factor is 5.6. Since the diameter of the tube is roughly the same as that of the nuclear steam generator U-tubes, the scaling factor of the heat transfer area is 5.6 for each tube.

A water reservior and a circulation pump are used to circulate the cooling water (13°C) to the cooling jacket and to cool the U-tubes while flowing cocurrent to the steam flow.

An air tank and an air regulator were used to supply noncondensible air to the test section. Air flow from the air tank is finely controlled by two needle valves and measured by a rotar meter.

The steam flow rate is measured using aU-tube manometer connected to the flange taps of the orifice plate.

The condensation length measurements under filmwise reflux condition are made at various steam flow rates ($\dot{m}_g$): i.e., the steam flow rate is varied from 0.75kg/hr to 3.3kg/hr.

Experimental Results and Comparison with Theory

Essentially two sets of experiments wer performed. The first part of the test dealt with the measurement of reflux condensation length (L), whereas the second part of the test dealt with the flooding points with and without the presence of noncondensible gases in the steam flow, and the effect of the length of a U-tube on the flooding time.

1. Filmwise Reflux Condensation Length

The coodensation length measurement tests were conducted, under the condition of constant steam flow input for a given test. At the steam flow rates used in the test, flooding did not occur; a stable condensate film flow was observed and the condensate was all refluxed, i.e., a steam-water countercurrent annular flow occurred in all the tests. A remarkable fact is that there was a dropwise condensation at the top region of the condensation length.

Experimentally obtained condensation lengths are compared with predictions of the modified Nusselt analysis of laminar film condensation on a vertical plate, Eq. (8), and they are shown in Fig. 4.

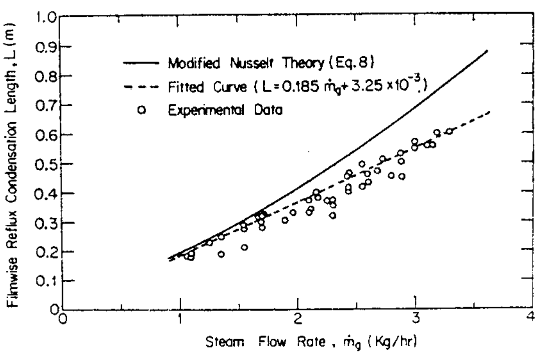

Fig. 4. Comparison of Experimental Data and Theory for Steam Flow Rate vs. Filmwise Reflux Condensation Length

As may be observed in Fig. 4 the modified Nusselt theory overestimates the condensation length, and the deviation between the experimental data and the theory becomes larger as the steam flow rate is increased.

This may be attributable to the following factors:

(1) The Nusselt theory is for the stagnant steam condensation, while the present result is for the flowing steam condensation. This fact partly explains the reason for an increasing deviation between the present experimental data and the Nusselt theory at higher steam flow rate.

(2) Another factor is the dropwise condensation that occurred locally in the upper region of the condensation area (which may be due both to the effect of the condensing surface and to deficiency of the steam flow).

The heat transfer rates for dropwise condensation are, in general, between 2 and 20 times larger than that for film condensation at the same temperature difference. Therefore, in the present work, where local dropwise condensation occurred, the smaller condensation length should have been required to condense the same amount of steam flow. This fact agrees with the results shown in Fig. 4.

The experimental data shown in Fig. 4 have been fitted by the least square method, and the expression is given by

$$L=0.185\dot{m}_g+3.25\times10^{-3} \quad (12)$$

This empirical equation is used here to obtain a reference curve and to examine the degree of deviation between the modified Nusselt theory and the present experimental results. Since this equation represents only a limited set of experiments, it should not be used in prediction other condensation experiments.

2. Flooding Test

As described by Wallis [9], unlike the phenomena which occur in dispersions of drops or bubbles, the flooding point is not approached as the limit of a continuous process but is the result of a sudden and dramatic instability which increases the pressure gradient by an order of magnitude.

experimentally obtained flooding points (i.e., the steam flow rates at which flooding phenomena occur, $\dot{m}_g$*) with and without the presence of a noncondensible gas are summarized in Table 1, along with the test conditions and predictions based on the Wallis correlation (Eq. 11). From the results shown in Table 1 it can be observed that $\dot{m}_g$* decreases as $\dot{m}_a$ is increased. This means that the presence of a noncondensible gas, in this case air, promotes the flooding.

To examine the effect of the length of a U-tube on the flooding time, on the other hand, a set of qualitative two U-tubes (short and long tubes) flooding experiments was performed. The test method is to observe which of the two U-tubes encounters the flooding point first, for different exit conditions, while gradually increasing the steam flow rates in the U-tubes from zero to the flooding point $\dot{m}_g$*. The results are summarized in Table 2.

This result shows that the flooding times are different when the U-tube lengths are different. Also, the flooding point arrives first in the longer tube when the exit conditions of the two tubes are closed. The reason for this may partly be attributable to the fact that the amount of pressure buildup by noncondensible gases in the longer tube is smaller than in the shorter tube. This allows a larger steam flow rate in the longer tube, and this, in turn, causes the flooding to occur in the longer tube earlier than in the shorter tube.

Table 2. Comparison of the Time of Flooding for Two U-tubes

Exit Conditions of U-tubes		The U-tube that Encountered Flooding Point First
long tube	short tube	
open*	open	simultaneously
open	close*	long tube
close	open	short tube
close	close	long tube

* open : atmospheric pressure
close : with 15cm water head

Table 1. Experimental Values of Steam Flow Rates at the Point of Flooding $\dot{m}_g$*(kg/hr), with and without a Noncondensible Gas

Run No.	Test Conditions			$\dot{m}_g$(kg/hr)	$\dot{m}_g$*(kg/hr) by Wallis Correlation (Eq. 11)
	$\dot{m}_a$(ml/min)	$\dot{m}_c$(kg/hr)	T_b(°C)		
1	0 (pure steam)	4,300	12.2	3.41	2.47~4.70
2	400	4,300	12.2	3.33	—
3	950	4,300	12.2	3.29	—
4	1,450	4,300	12.2	3.23	—

Conclusions

From the foregoing results, the following con clusions may be made:

1. The modified Nusselt analysis of laminar film condensation on a vertical plate (Eq. 8) overestimates the reflux condensation length and the deviation between the present experimental data and the theory becomes larger as the steam flow rate is increased. This is mainly due to the difference in the conditions of condensing steam. That is, the Nusselt theory is applicable to the stagnant steam condensation, while the present data is obtained for the flowing steam condensation. In addition, dropwise condensation was present locally in the reflux condensation of this work.

2. The presence of flowing noncondensible gases promotes flooding phenomena.

3. The flooding point arrives first in the longer tube when exits of both short and long tubes are closed.

References

1. H. Weisshaupl, and B. Brand, "PKL Small Break Tests and Energy Transport Mechanisms," *ANS Specialists Meeting on Small Break Loss of Coolant Accident Analyses in LWRs Confenrence*, Aug. 1981, Monterey California.
2. S. Banerjee, J-S. Chang, R. Girard, and V.S. Krishnan, "Reflux Condensation and Transition to Natural Circulation in a Vertical U-tube," *Journal of Heat Transfer*, Vol. 105, 1983, pp. 719-727.
3. O.T. Nguyen and S. Banerjee, "Flow Regimes and Heat Removal Mechanisms in a Single Inverted U-tube Steam Condenser," *Transactions of American Nuclear Society*, Vol. 43, 1982, pp. 788-789.
4. C. Calia and P. Griffith, "Modes of Circulation in an Inverted U-tube Array with Condensation," *Journal of Heat Transfer*, Vol. 104, 1982, pp. 769-773.
5. C.L. Tien, T. Fukano, K. Hijikata, and S.J. Chen, "Reflux Condensation and Operating Limits of Countercurrent Vapor-Liquid Flows in a Closed Tube," EPRI-N-2648, 1982.
6. J-S. Chang, R. Girard, S. Revankar, and P.T. Wan, "Heat Removal Capability of Steam Generators under Reflux Cooling Modes in a CANDU-PHT System," *4th Canadian Nuclear Society Conference*, 1983.
7. P.T. Wan, R. Girard, J-S. Chang, "The Role of Flooding Phenomena in Reflux Condensation in a Vertical Inverted U-tube," *3rd Multiphase Flow and Heat Transfer Symposium Workshop*, 1983.
8. W. Rosenow and H. Choi, "*Heat, Mass and Momentum Transfer*," Prentice-Hall, Inc. 1961.
9. G.B. Wallis, "One-dimensional Two-Phase Flow," McGraw-Hill, Inc. 1969.