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# Prediction of rod film thickness of vertical upward co-current adiabatic flow in rod bundle

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ABSTRACT

Prediction of rod film thickness and its distribution in annular flow in rod bundle is of essential importance to nuclear power industry. This is attributed to the possible film dryout on fuel rods under certain conditions, which will result in a drastically increasing cladding temperature and possible fuel damage. Though there exist a lot of models or correlations to predict film thickness for annular flow in pipes, there are few models to predict rod film thickness inside rod bundle. The one-dimensional models or correlations for pipe flow cannot be used for rod bundle directly due to different geometry and flow dynamics. In relation to this, a new approach to predict the rod film thickness inside rod bundle has been developed. This approach first divides the rod bundle cross-section into three regions according to their characteristic length scales. Then, the gas and liquid flow distribution inside rod bundle has been given with reasonable assumptions. Based on the flow distribution profile, the sub-channel area-averaged gas and liquid volumetric fluxes have been given. Finally, the correlation developed for pipe flow is adopted for each sub-channel based on the local two-phase parameters in the rod bundle. Compared to experimental data obtained in-house and found in the literature, the newly proposed approach can predict rod film thickness with satisfactory accuracy.

## 1. Introduction

Annular flow exists widely in many industrial applications, such as heat exchangers in refrigeration system, reactor core of boiling water reactor and natural gas pipelines, etc. It is characterized by a gas core flowing in the channel center and liquid film flowing on the side wall (Hewitt and Hall-Taylor, 1970). Annular flow transfers high heat flux from wall to fluid inside the channel by the liquid film (Butterworth and Hewitt, 1977), making the liquid film thickness a primary safety concern for gas-liquid annular two-phase flow. Accurate prediction of post-dryout regime is needed for safety analysis of light water reactors (Becker et al., 1983).

In nuclear industry, the reactor core of both the boiling water reactor (BWR) and pressurized water reactor (PWR) consists of many fuel rods from where the fission energy is released to the coolant channel. For BWR, annular flow exists in the core exit region during normal operation condition. For PWR, annular flow can happen during the accident conditions. For both reactor types, the film thickness distribution on fuel rods in rod bundle geometry is of critical importance to reactor design and safety analysis. One particular concern is the possible film dryout phenomenon under certain conditions, which will result in a drastically increasing cladding temperature and possible fuel damage. From Nishida et al. (1994), the film thickness generally shows strong distribution and the minimum film thickness happens on center rods in a rod bundle. Thus, the rod film thickness and its distribution should be carefully studied given its safety significance.

Many studies on average film thickness have been performed in the literature as mentioned in Ju et al. (2015). However, all of these models or correlations are for film thickness in pipes. The film thickness inside rod bundle, which is much more complex than that in pipe, has not been modeled or correlated yet. The major challenge comes from the complex geometry of rod bundle. Film thickness on different locations of rods is different while most of the film thickness correlations or models in pipe are one dimensional. The film thickness correlations or models in pipe cannot be implemented to rod bundle directly.

The main objective of this paper is to provide a prediction method for rod film thickness in rod bundle. In order to achieve this goal, three steps are required. First, experiments have been performed for film thickness in rod bundle. Also, available datasets

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## Nomenclature

| | |
|---|---|
| $B$ | half of the box length |
| $D$ | pipe inner diameter |
| $F$ | dimensionless group containing flow rates and fluid properties |
| $Fr$ | Froude number |
| $g$ | acceleration due to gravity |
| $j$ | volumetric flux |
| $N$ | non-dimensional number |
| $p$ | pressure |
| $Re$ | Reynolds number |
| $v$ | velocity |
| $We$ | Weber number |
| $x$ | quality, x direction |
| $y$ | y direction |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density |
| $\sigma$ | surface tension |
| $\delta$ | film thickness |
| $\tau$ | interfacial shear stress |
| $\mu$ | dynamic viscosity |

*Subscripts*

| | |
|---|---|
| $c$ | characteristic length |
| $f$ | liquid phase |
| $g$ | gas phase |
| $H$ | hydraulic diameter |
| $i$ | interface |

from literature have been collected to expand the current database. Secondly, the strategy on transforming correlations developed for pipe to that for rod bundle has been established. Finally, the correlations have been compared with the experimental database and the comparison results have been discussed. There are three steps to transform correlations developed for pipe to that for rod bundle. First, the cross-section of rod bundle has been divided into different sub-regions based on different characteristic length. Then, the local volumetric flux averaged by sub-channel flow area for both air and water in rod bundle have been given. Finally, the correlation developed for pipe flow is adopted for each sub-channel based on area-averaged local two-phase parameters in sub-channel. Based on the above discussion, the correlations of pipe flow can be applied to rod bundle geometry.

## 2. Existing work

### 2.1. Film thickness modeling

As mentioned in Ju et al. (2015), there are many studies on average film thickness inside pipes and they are summarized in Table 1. However, the film thickness inside rod bundle has not been correlated yet due to the complex geometry of rod bundle. Though the film thickness correlations or models in pipe cannot be used to rod bundle directly, these correlations or models can be used for the film thickness in sub-channel with proper description of local flow conditions and characteristic length scale. In this way, the correlations or models for pipe flow can be used for film thickness prediction in rod bundle. The models from Tatterson et al. (1977), Hori et al. (1978), Fukano and Furukawa (1998), Macgillivray (2004), Berna et al. (2014) and Ju et al. (2015) have been used for film thickness prediction in the current study.

### 2.2. Film thickness data

There are a few databases available from literature on rod bundle film thickness. Some researchers studied the spacer effect on film thickness in rod bundle. Tomiyama and Yokomizo (1988) carried out experiment on a 3 × 3 rod bundle to study the spacer effect on film thickness. Nishida et al. (1994) conducted air-water two-phase annular flow experiment in both 4 × 4 and 9 × 9 rod bundles for the spacer effect. However, very few people studied the film thickness distribution inside the rod bundle. Of them, Ju (2015) performed air-water two-phase flow in an 8 × 8 rod bundle. The research provided detailed information on the film thickness inside rod bundle, especially on the rod film thickness distribution.

A rod bundle test section has been constructed and instrumented in order to measure the film thickness in rod bundle for air-water annular flow. The schematic of the 8 × 8 rod bundle facility used for these experiments is shown in Fig. 1.

The test section consists of a square stainless steel shell and 64 stainless steel rods with diameter of 10.3 mm. The rods are arranged in an 8 × 8 square lattice configuration, which is similar to the typical BWR fuel assemblies. The side of the shell has a length of 140 mm and the pitch between rods is 16.7 mm. Four measurement ports are located along the test section with axial distance of $z/D_H = 8.7$, 80.6, 89.4 and 141, respectively and they are marked as red lines in Fig. 1. Inside the test section, there are seven grid spacers with axial distance of $z/D_H = 24.3$, 45.4, 66.4, 86.2, 107, 126, 146. The blue boxes in Fig. 1 represent the locations of these grid spacers.

**Table 1**
Previous models and correlations on film thickness in pipes (Ju et al. ,2015).

| Reference | Correlation |
|---|---|
| Ishii and Grolmes, 1975 | $\delta = 0.347\mathrm{Re}_f^{2/3}\sqrt{\frac{\rho_f}{\tau_i}\frac{\mu_f}{\rho_f}}$ |
| Hori et al. (1978) | $\frac{\delta}{D} = 0.905Re_g^{-1.45}\mathrm{Re}_f^{0.90}Fr_g^{0.93}Fr_f^{-0.68}\left(\frac{\mu_f}{\mu_{f,ref}}\right)^{1.06}$ |
| Henstock and Hanratty (1976) | Vertical flows<br>$\frac{\delta}{D} = \frac{6.59F}{(1+1400F)^{0.5}}$<br>Horizontal flows<br>$\frac{\delta}{D} = \frac{6.59F}{(1+850F)^{0.5}}$<br>$F = \frac{1}{\sqrt{2}Re_g^{0.4}}\frac{\mathrm{Re}_f^{0.50}}{Re_g^{0.5}}\frac{\mu_f}{\mu_g}\frac{\rho_g^{0.5}}{\rho_f^{0.5}}$ |
| Tatterson et al. (1977) | Vertical flows<br>$\frac{\delta}{D} = \frac{6.59F}{(1+1400F)^{0.5}}$<br>Horizontal flows<br>$\frac{\delta}{D} = \frac{6.59F}{(1+850F)^{0.5}}$<br>$F = \frac{\gamma(\mathrm{Re}_f)}{Re_g^{0.9}}\frac{\mu_f}{\mu_g}\frac{\rho_g^{0.5}}{\rho_f^{0.5}}$<br>$\gamma(\mathrm{Re}_f) = \left[\left(0.707\mathrm{Re}_f^{0.5}\right)^{2.5} + \left(0.0379\mathrm{Re}_f^{0.9}\right)^{2.5}\right]^{0.4}$ |
| Fukano and Furukawa (1998) | $\frac{\delta}{D} = 0.0594\exp\left(-0.34Fr_g^{0.25}\mathrm{Re}_f^{0.19}x^{0.6}\right)$<br>$x = \frac{\langle j_g\rangle\rho_g}{\langle j_g\rangle\rho_g+\langle j_f\rangle\rho_f}$ |
| Macgillivray, 2004 | $\frac{\rho_f\langle j_f\rangle\delta}{\mu_f} = 39\mathrm{Re}_f^{0.2}\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_f}\right)^{0.5}$ |
| Berna et al. (2014) | $\frac{\delta}{D} = 7.165Re_g^{-1.07}\mathrm{Re}_f^{0.48}\left(\frac{Fr_g}{Fr_f}\right)^{0.24}$ |
| Ju et al. (2015) | $\frac{\delta}{0.071D} = \tanh\left(We_f^{0.24}We_g^{-0.47}N_{\mu_f}^{0.21}\right)$ |