



# Review and Prospect of the Measurement Technology of the Thickness of the Liquid Film on the Wall of the Corrugated Plate Dryer

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The corrugated plate dryer is an important steam-water separation device in the steam generator in the secondary loop of a light water reactor. It is essential to understand its steam-water separation mechanism. Most studies have shown that the separation efficiency of the corrugated plate is related to the thickness of the liquid film on the wall of the corrugated plate. We have studied the relationship between the thickness of the liquid film and the critical airflow velocity of the corrugated plate. At present, scholars mostly use the image method, ultrasonic method, and capacitance method to measure the thickness of thin liquid film. We have analyzed the application of these three methods in liquid film thickness measurement. Some important examples are listed. The results show that the capacitance method is recommended for liquid film thickness measurement experiments, whereas its accuracy is not particularly high. To pursue the higher accuracy, the image method is recommended. Planar laser-induced fluorescence (PLIF) technology is the first choice among image methods. The ultrasonic method is applicable in the case that the measurement data are large.

**Keywords:** liquid film thickness, corrugated plate, PLIF, steam-water separation, measurement

## INTRODUCTION

The corrugated plate dryer is an important steam-water separation device in the steam generator in the secondary loop of the nuclear power plant. It is important to understand its steam-water separation mechanism. The rupture and flow of the liquid film on the wall have a huge impact on the steam-water separation efficiency of the corrugated plate. The current research status of the corrugated plate is detailed in our previous review article in reference (Wang et al., 2019). We will not repeat them here. Most studies have shown that the separation efficiency of the corrugated plate is related to the thickness of the liquid film on the wall of the corrugated plate. We have studied the relationship between the thickness of the liquid film and the critical airflow velocity of the corrugated plate in reference (Wang and Tian, 2019b) [as shown in Eq. (1)]. The Navier-Stokes (N-S) equation and continuity equation of the two-dimensional boundary layer in the curvilinear coordinate system at the corrugated plate corner is established. The dimensionless method is used. Neglecting the higher-order terms, a simplified N-S equation and continuity equation in curvilinear

coordinate system can be obtained. A liquid film breakdown model at the corrugated plate corner is established according to boundary layer theory, thus Eq. (1) is obtained.

$$u_g = 2.4 \left( \frac{d \cos \theta \cdot \sigma \mu_{al}^2}{\rho_l \rho_g \mu_g} \right)^{\frac{1}{3}} \frac{1}{h} \quad (1)$$

where,  $d$ ,  $\theta$ ,  $\sigma$ ,  $\mu_{al}$ ,  $\rho_l$ ,  $\rho_g$ ,  $\mu_g$ ,  $h$  are linear distance between two plate walls, inflection angle of the corrugated plate corner, surface tension, liquid phase dynamic viscosity, liquid density, air density, dynamic viscosity of the air, and liquid film thickness, respectively.

Considering the important role of the measurement for liquid film thickness, many scholars currently have used the image method, capacitance method, and ultrasonic method to measure the thickness of liquid film. In the following, we analyze the application of these three methods in liquid film thickness measurement. Some important examples are listed. Prospects for future measurement methods of the thickness of the liquid film on the wall surface of the corrugated plate are given.

## MEASUREMENTS METHODS

### Ultrasonic Method

Wei et al. (2020) measured the free-falling film under the large Reynolds number and analyzed the volatility of the liquid film. The ultrasonic method was applied to the measurement the instantaneous thickness of the liquid film left on the wall of the square tube. Then they performed a power spectrum analysis on the curve of the instantaneous thickness of the liquid film (Wei et al., 2020). The ultrasonic method is very common, of which the principle is the doppler effect. During the measurement, the sensor emits ultrasonic waves to the measurement object at a certain Doppler angle. Ultrasound waves change their frequency when they encounter tiny particles (bubbles or solid particles). This makes the time of the reflected wave received by the sensors in different positions different, and the velocity of the liquid can be obtained.

The ultrasonic reflected wave and incident wave of the liquid film can be obtained by using the ultrasonic transducer. Fast Fourier Transform is performed on the two through an oscilloscope to obtain the reflection coefficient spectrogram and frequency, and then to obtain the thickness of the liquid film (Wei et al., 2020). The above measurement process can all be completed by using an oscilloscope and through computer programming, thus achieving the acquisition of liquid film thickness. The above process does not require post-processing. Therefore, the ultrasonic method is suitable for the measurement of large amounts of data. However, the shortcomings of ultrasonic method could be described as follows: The velocity of the fluid particles on the ultrasonic motion path can be obtained based on spectrum analysis. The fluid particle velocity is assumed to be the fluid velocity at that location. Of course, there must be a difference between the speed of a single particle and the speed of fluid. This assumption is accepted by the academic community, and there is currently no very good solution to this.

### Capacitance Method

The basic principle of the capacitance method to measure film thickness is as follows: When the medium or plate distance between two parallel metal electrodes changes, the output voltage changes. Within a certain range, the voltage change of the capacitor has a linear relationship with the change of the liquid film thickness. The thickness of the liquid film can be measured by obtaining the voltage signal.

He et al. (2019) conducted an experimental study on the liquid film behavior of the two-phase circulation on the rod bundle. They conducted cold experiments on the circulation in a  $3 \times 3$  fuel bundle in a pressurized water reactor. Air-water circulation is used to simulate the flow of hot steam. In the test, the local liquid film thickness of the rod bundle needs to be measured. They developed a method for measuring the thickness of the liquid film based on the capacitance method.

When the capacitance method is used for measurement, the liquid film thickness can be automatically measured directly through the combination of capacitance sensors, National Instruments (NI) data collectors, and computers. Thus, the measurement speed is very good.

### Image Method

Ye et al. (2020) conducted an experimental study on the transmission of the liquid surface around the bubbles in the microchannel with cavitation. High-speed cameras are used to capture the shape of bubbles. The gray-scale image of bubbles can be obtained based on the processing of image pixels based on MATLAB (Ye et al., 2020). In the experiment, they needed to measure the thickness of the thin liquid film under Taylor flow (Ye et al., 2020). But in Taylor flow, the bubble keeps in contact with the liquid film. The irregular shape of the bubbles will be irregular in the shape of the liquid film.

Chinnov et al. (2019) also applied the image measurement method. High-speed infrared cameras and fluorescence methods were used to measure the thickness and temperature field of the vertically dropped heated liquid film on the flat plate at a Reynolds number of 50. Liu et al. (2020) conducted an experimental study on the interface fluctuation and liquid film thickness of the swirling gas-liquid flow. Image analysis is used to measure the thickness of the liquid film.

Wang and Tian (2019a; 2019c) and Wang et al. (2020a) measured the thickness of the liquid film on the wall surface of the corrugated plate based on the planar laser-induced fluorescence (PLIF) method. Their measurement accuracy can reach  $1 \mu\text{m}$ . Before the experiment, a few milligrams of rhodamine B was put into the liquid. The narrow-slit method is applied to generate a stable flowing liquid film on the wall surface (Wang and Tian, 2019a; Wang et al., 2020a). The PLIF measurement needs to keep the surrounding environment in a dark state (Wang and Tian, 2019a). The wavelength of the light emitted by the solid-state laser is 532 nm. The maximum absorption wavelength of rhodamine B is 555 nm. Therefore, the rhodamine B particles irradiated by the solid-state laser will be excited. The excited particles are unstable, so they return to the ground state and release visible light. This light can be captured by a high-speed

camera. A liquid film surface profile can be captured through acquisition of the horizontal cross-section image of water film by high-speed camera, thus obtaining average water film thickness by application of liquid film image processing software.

Yang et al. (2020) measured the liquid film thickness based on the diode-laser absorption spectroscopy (DLAS) method. Guo et al. (2020) conducted an experimental measurement of transient liquid film during micro-channel flow boiling based on the laser confocal displacement meter (LFDM) method.

## ANALYSIS AND DISCUSSION

According to He et al. (2019), the capacitance method is a contact measurement method. This will inevitably affect the flow of the liquid film. Therefore, this will affect the accuracy of the measurement.

In reference (Ye et al., 2020), Ye et al. gave a novel calculation method for the thickness of the liquid film. For bubbles with a longer length, the shape of the liquid film in contact therewith is generally more regular. Its shape is mostly rectangular. Its thickness is the width of the rectangle. Measurements can be achieved using optical image methods such as PLIF technology. For irregularly shaped bullet bubbles and short bubbles, they used an integral method to measure the thickness of the liquid film. We have also used the idea of integration to calculate the average liquid film thickness when using the moving particle semi-implicit method to simulate the shape of the liquid film rupture (Wang et al., 2020b).

The study of the volatility of the liquid membrane with such a small Reynolds number is rare in academia because the formation and control of liquid film with a small Reynolds number is difficult. Therefore, the research is very innovative. The experiment in reference (Chinnov et al., 2019) outcomes the results in the case that the Reynolds number is 50. Experiments with a larger range of Reynolds numbers are encouraged. The general conclusion is expected to be presented.

Besides, the PLIF method is different from other image measurement methods in that PLIF uses fluorescent substances, because in general experiments, the boundary of the liquid film and the surrounding environment are not much different under high-speed camera shooting. Therefore, there are difficulties and certain errors for the subsequent image processing. Because all the use of images to measure the thickness of the liquid film needs to identify the boundary of the liquid film. The principle of boundary differentiation is applied. The determination of the boundary threshold is one of the main sources of error. If a fluorescent substance such as rhodamine B is added and the surrounding environment is kept in a dark state, the boundary image of the liquid film is clearer under a high-speed camera. This is very beneficial for reducing errors. Adding a few milligrams of rhodamine B has almost no effect on the physical properties of the liquid film. Therefore, the measurement will not be affected in any way. Obviously, if it is extremely precise measurement, such as the measurement accuracy is about a few nanometers, the fluorescent substance is not recommended to be used. Of course, this kind of high-accuracy measurement is not common

for the measurement of the thickness of the liquid film on the wall surface of the corrugated plate.

According to references (Yang et al., 2020) and (Guo et al., 2020), both DLAS and LFDM are optical imaging methods. No fluorescent agent is used in these methods. Therefore, this is not conducive to eliminating the reflected light generated by the high-speed camera shooting the liquid film image.

According to above, the following conclusions can be obtained:

- (1) The accuracy of the image method depends on the resolution of the high-speed camera. The measurement accuracy is generally a few microns, but the measurement speed is slow (Wang and Tian, 2019a,c; Wang et al., 2020a), because in the PLIF method, a high-speed camera is required to obtain the image of the liquid film. It is necessary to write a program based on the principle of boundary differentiation to identify the boundary of the liquid film. Finally, the number of pixels corresponding to the thickness of the liquid film is measured by the image processing software, and the thickness of the liquid film is calculated according to the scale.
- (2) The capacitance method is a contact measurement. When the capacitance method is used for measurement, the liquid film thickness can be automatically measured directly through the combination of capacitance sensors, NI data collectors, and computers. Thus, the measurement speed is very good. However, the contact measurement will affect the flow field and temperature field of the liquid film, which will inevitably produce measurement errors.
- (3) The accuracy ultrasonic method is able to reach tens of microns. The measurement accuracy is not as good as the image method, but it is suitable for the measurement of large amounts of data.

Therefore, for the experiments that do not require very high accuracy, the capacitance method is recommended. For higher measurement accuracy, the image method is recommended. PLIF technology is the first choice among image methods. PLIF can effectively improve the recognition accuracy of liquid film boundary. The ultrasonic method is suitable for measuring the thickness of the liquid film when there are many measurement data.

## CONCLUSION

The corrugated plate dryer is an important steam-water separation device in the steam generator in the secondary loop of the nuclear power plant. Since the separation efficiency of the corrugated plate is related to the thin thickness of the liquid film on the wall surface of the corrugated plate, the measurement methods of the thickness of the thin liquid film such as the image method, the ultrasonic method, and the capacitance method are summarized.

For the experiments that do not require very high accuracy, the capacitance method is recommended. The ultrasonic method is suitable for measurement when the amount of data is large. For higher measurement accuracy, the image method is

recommended. The study is expected to provide reference for liquid film measurement in nuclear engineering.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

BW designed this study. Besides, BW, BC, JW, CL, and RT contributed to the investigation on the related references. BW

mainly co-wrote most of the manuscript. All authors contributed to writing the manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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