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Uncertainty analysis on droplet size measurement in dispersed flow film boiling regime during reflood using image processing technique

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ABSTRACT

In the dispersed flow film boiling (DFFB) regime during the reflood stage of a postulated loss of coolant accident (LOCA), liquid droplets are entrained by a continuous vapor phase moving upward within the rod bundle. The liquid droplets may interact strongly with the vapor flow and the resulting thermal–hydraulic behavior of the two-phase mixture could significantly affect the evolution of peak cladding temperature (PCT). Therefore, a clear and comprehensive understanding of liquid droplet behavior is crucial for reactor safety analysis. As an attempt to visualize and quantify the droplet behavior during reflood, an advanced image processing technique is used in the present study to capture the distributions of droplet size and velocity at the RBHT test facility. In order to ensure that the experimental droplet data obtained is reliable as well as to better utilize the data for subsequent thermal–hydraulic analyses, the image processing based measurement uncertainties have to be investigated and analyzed. In this paper, various statistical methods are explored to determine the minimum droplet sample size required as a function of standard deviation at a given confidence level. Accordingly, an appropriate droplet count lower limit is selected. Based on this lower limit, the 95% confidence intervals are determined for two typical reflood tests. In addition, the repeatability in droplet measurement of Rod Bundle Heat Transfer (RBHT) reflood tests is carefully examined by comparing data sets from two identical tests. Results show that a lower required level of precision and a smaller scattering in the measured droplet data generally require a smaller sample size. For typical RBHT reflood tests, it is found that the droplet size measured downstream of a spacer grid near the peak power location always has better accuracy compared with that at the upstream location. For the tests investigated, the maximum relative error in the liquid droplet Sauter mean diameter is found to be generally smaller than 0.15 (15%) when the droplet count lower limit is 30. Comparison of the results from two identical tests indicates that the RBHT reflood test results are highly repeatable.

1. Introduction

As one of the most important nuclear reactor safety management and accident mitigation measures, emergency core cooling system (ECCS) is activated to inject subcooled water directly into the reactor pressure vessel (RPV) through both hot and cold legs of the primary system when a postulated loss of coolant accident (LOCA) occurs. A pressurized water reactor (PWR) typically operates at the system pressure of 15.5 MPa while the initial pressure within reactor containment may only be one atmospheric pressure. Because of the large pressure difference, under the LOCA scenario, a break on the boundary of reactor primary loop could lead to significant loss of coolant. This process is called blow-down and it generally lasts for several minutes until the pressure difference inside and outside the primary system becomes sufficiently small. Following the LOCA with the system coolant inventory being constantly depleted, if no protective actions are taken to remedy the situation, the integrity of the active core would be challenged due to excess decay heat generation and inadequate heat removal capability. Further evolution of such an accident will eventually lead to core component degradation and release of radioactive materials to the environment. In order to prevent uncovery of the nuclear fuel rods and to maintain the peak cladding temperature (PCT) well below the regulatory limit of 1477.6 K (2200 $^\circ F$), emergency water injection is initiated by ECCS immediately after the safety injection signal is received from reactor control systems. The reactor core refilling stage is referred to as the reflood stage and it constitutes an

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important part of the reactor thermal–hydraulic and safety analysis. During this period, whether the rod bundle can be completely re-submerged by water before incurring potential damage is the key to maintaining the safety of nuclear power plant and thus needs to be studied thoroughly.

Dispersed flow film boiling (DFFB) regime is typically expected during reflood. Its corresponding flow pattern is usually called dispersed, mist or liquid deficient flow, in which dispersed liquid droplets are entrained by superheated vapor. Since the DFFB heat transfer processes are closely related to the evolution of rod bundle PCT for a given accident scenario, development of accurate prediction models for the thermal–hydraulic behaviors in DFFB is of crucial importance. Unfortunately, due to the co-existence of both liquid and vapor phases and their thermal–hydraulic non-equilibrium states, the actual mass and heat transfer processes involved in DFFB are very complicated and interactive. Key mechanisms for heat transfer include the following: laminar and turbulent convection between single-phase vapor and the rod surface, direct heat transfer between liquid droplets and the superheated rod surface (dry wall contact), interfacial heat transfer between vapor and liquid droplets and radiation heat transfer from the rod to the vapor, droplets and other surrounding structures. The problem is further complicated by the presence of spacer grids (SGs), especially when taking different SG thermal–hydraulic conditions (whether it is a dry-grid, partially wet grid or wet-grid) into consideration. It has been observed in many previous studies (Bajorek and Cheung, 2009; Srinivasan, 2010; Cho et al., 2011; Sharma et al., 2011, etc.) that SGs have a significant effect on the two-phase thermal–hydraulic behavior and subsequent heat transfer enhancement in DFFB regime.

In order to accurately model the mass and heat transfer processes within the DFFB regime, many researches focused their studies on the behavior of liquid droplets as well as the interactions of droplets with surrounding vapor. Representative experimental and theoretical works include: Ganic and Rohensow (1977), Adams and Clare (1984), Lee et al. (1984), Sugimoto and Murao (1984), Paik et al. (1985), Yao et al. (1988), Unal et al. (1991), Ireland et al. (2003), Cheung and Bajorek (2011) and Cho et al. (2011). Previous studies indicate that the liquid droplet size in DFFB can be adequately represented by a log-normal distribution, despite that Sugimoto and Murao (1984) assumed a Γ-distribution function to describe the droplet size. The log-normal distribution is a very important distribution in probability theory and statistics due to its extensive applications in scientific researches and engineering fields from human biology to environment radiation measurement. For example, in spray process involving droplet impacts, the size distribution of atomized droplets can be described by a log-normal distribution (Wu, 2003). As a result, many studies of the sample size and confidence interval were based on log-normal distribution, including Finney (1941), Hale (1972), Cochran (1977), Pashchenko (1996), Zhou and Gao (1997) and Olsson (2005).

The log-normal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. Occasionally, it is also called Galton distribution (Johnson et al., 1994). Eq. (1) below gives the general probability density function for this type of distribution.

$$PDF\,(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right) \tag{1}$$

where x is the droplet size, μ and σ are the mean and standard deviation of the variable's natural logarithm, respectively.

In the present reflood experiment, the droplet behaviors as well as their size and velocity distributions are captured and analyzed using an advanced image processing technique. An Oxford Lasers Firefly Imaging System is adopted for droplet measurement in the RBHT test facility (Hochreiter et al., 2010a,b). A series of reflood tests have been performed at this test facility in order to investigate the effects of droplets on the rod bundle thermal-hydraulics under post-CHF conditions. The measured droplet images are analyzed by a software called VisiSize (also developed by Oxford Lasers) to obtain droplet size and velocity distribution information. In order to analyze and interpret the experimental results in an appropriate manner, measurement uncertainties involved in obtaining the droplet size and velocity information for subsequent determination of averaged droplet size and velocity need to be adequately quantified.

The individual droplet size measurement uncertainty has been investigated in detail by Todd (1999) using the method for determining 95% confidence level. In his study, a measurement bias was observed in the VisiSize system. That is, the small particles captured by the system appear to be smaller than their actual size. Such bias in individual droplet measurement results from the laser light diffracting around the particles. The effect of laser diffraction is more profound with decreasing size. However, this problem is found to be insignificant. For small droplets (0.1 mm), the uncertainty is determined to be about 3.2% while for large droplets (2 mm), the uncertainty is only about 0.03%. In addition, a correction factor specifically accounting for laser diffraction is used to obtain the final droplet size measured by VisiSize. Therefore, this problem is not a concern in the current study. Discussion can be also found in the work by Ireland et al. (2003).

In the present study, the uncertainties involved in obtaining the averaged values from a set of limited droplet data are quantified. The minimum droplet sample size required to satisfy a specified accuracy as well as confidence level is determined based on different variable distributions: normal distribution, T-distribution and log-normal distribution. Sample sizes determined from different statistical methods (Cochran, 1977; Hale, 1972; Pashchenko, 1996; Olsson, 2005) are compared. Based on the results obtained, the 95% confidence intervals are thus determined for each droplet data point during reflood, taking both the arithmetic mean and Sauter mean as reference values. Finally, the repeatability of the RBHT tests is examined and discussed. It should be noted that the current study mainly focuses on the droplet size uncertainty quantification. Nevertheless, the same approach can be used to quantify the liquid droplet velocity measurement as well. The current analysis serves as a basis for future experimental data reduction and theoretical model development.

2. Description of test facility and droplet measurement

2.1. RBHT test facility

The Rod Bundle Heat Transfer (RBHT) test facility at the Pennsylvania State University was specifically designed for conducting systematic separate effects tests under well controlled reflood conditions.

The general configuration of the RBHT test facility is shown in Fig. 1. The inlet and outlet of the vertical test section are connected to a water supply tank and carryover tanks followed by steam separator, respectively. It is a once-through test facility. Water is stored and preheated in the supply tank and pumped into the test section via the lower plenum at the bottom. The flow mixture coming out of the test section is separated and collected in different stages. The first liquid–vapor separation takes place in the upper plenum. The liquid droplets are directed into the small and large carryover tanks for liquid carryover measurement. The steam, after going through a steam separator, is eventually vented into the atmosphere. In addition, a pressure oscillation damping tank is used to stabilize the system pressure. The test section has a 7 × 7 rod bundle assembly. Of the total 49 rods, 4 unheated support rods are located at corner locations. The remaining 45 rods are electrically heated with a heated length of 3.66 m (12 ft). Each rod has an outer diameter of 9.49 mm (0.374 in) and rod pitch of 12.6 mm (0.496 in). The test facility is heavily instrumented and is capable of capturing transient variations of various flow quantities during reflood period (Hochreiter et al., 2010a,b).