Progress in Nuclear Energy 105 (2018) 21–28

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Experimental investigation of bottom reflooding and modeling of quench velocity in a narrow rectangular channel

Wei Xu[a], Jianhua Xia[a], Xiaojing Liu[a,*], Xu Cheng[a], Wei Zeng[b]

[a] School of Nuclear Science and Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Minhang District, Shanghai, China
[b] Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institute of China, Cheng Du, 610041, China

ARTICLE INFO

Keywords:
Narrow rectangular channel
Bottom reflooding
Temperature variation speed
Quench velocity
Model development

ABSTRACT

For the purpose of figuring out the thermal-hydraulic behaviors during bottom reflooding in the narrow rectangular channel of plate-type fuel reactor, experimental apparatus 'THERMAL' was established to simulate the bottom reflooding process, with different inlet velocities and initial surface temperatures. The narrow channel was formed between a heating plate made of stainless steel and a heat-proof glass. Thermocouples (TCs) were fixed to measure the solid temperature in vertical and horizontal directions, and a high-speed camera was used to record flow regime near the quench front. Based on experimental results, conclusions can be drawn that quench velocity increases with increasing inlet velocity and decreasing initial solid temperature. The quench temperature, which is strongly affected by the initial wall temperature, is almost independent of the inlet velocity. A new method is utilized to determine rewetting front and quench front from 'temperature variation speed' curve. Moreover, an analytical model of quench velocity in narrow rectangular channel is discussed and proposed, which can predict quench velocity more precisely in 'THERMAL' facility.

1. Introduction

As is known that blowdown, refilling, reflooding and long-term cooling are continuous sequences when large break loss of coolant accident (LBLOCA) occurs. Due to break of the pressure boundary, coolant is expelled out of the primary loop in a very short time. Even though reactor can be shut down in a short time, stored energy and decay heat in the fuel elements still need to be removed urgently in case of severer consequence. Reflooding is not only an important phase to guarantee the integrity of core, but also a very complicated process, during which various thermal-hydraulic phenomena exist.

The phenomenon of rapid cooling of an overheated solid is recognized as quenching. However, when the surface temperature is higher than some threshold values, coolant can't contact and cool the surface directly. The reason is that the formation of steam film prevents the contact between coolant and hot solid surface and cooling effect is very limited when this steam film exists. As time passing, the steam film gradually collapses. Once coolant contacts the surface, the solid can be cooled acutely with much higher heat transfer ability. The phenomenon of establishment of the contact between liquid phase and solid phase is known as rewetting. Because of the complexity and significance of reflooding phenomena, experimental and theoretical studies on quenching and rewetting have been performed by many researchers.

Murao (1978) defined the quench front as the leading edge of two-phase contact area. The advancing velocity of quench front is called quench velocity (or rewetting velocity). The apparent temperature, at which the surface of fuel rods begins to be cooled rapidly and falls down to nearly saturated, is called quench temperature.

Rewetting is characterized by a highly transient heat transfer process. When the coolant enters an overheated channel from the bottom side (known as bottom reflooding), the advancing tip of the liquid is called reflooding front, which is shown as point X in Fig. 1 (Paul et al., 2016). The location at every instant where the solid-liquid contact exists is known as rewetting front, which is indicated by point Y. The temperature at which the transition between the dry region (film boiling) and wet region (transition and nucleate boiling) takes place is called the rewetting temperature.

Barnea et al. (1994) conducted an experimental and theoretical study during quenching of an annular channel. The experimental program covers the range of parameters applicable to the accident scenario of LOCA in research reactors. The quantitative data and observations were used to predict the rate of quench front velocity. Based on observations, Barnea defined rewetting temperature as the highest temperature at which the slope of the surface temperature versus time curve first exceeds an arbitrary value of 500 °C/s.

The determinations of the quench temperature and rewetting

---

[*] Corresponding author.
E-mail address: xiaojingliu@sjtu.edu.cn (X. Liu).

https://doi.org/10.1016/j.pnucene.2017.12.008
Received 14 August 2017; Received in revised form 16 November 2017; Accepted 25 December 2017

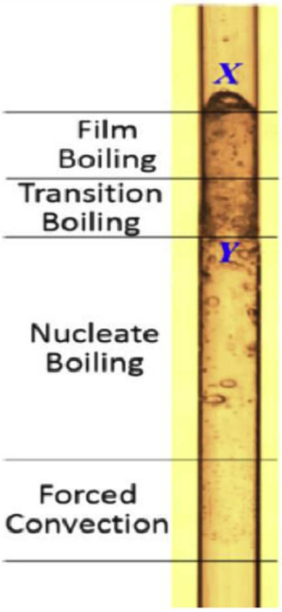

Fig. 1. Photographic representation of reflooding and rewetting front.

temperature are important for limiting the extent of core damage when severe accident occurs, and they are essential for predicting the propagation rate of quench front. Takrouri et al. (2017) defined quench temperature as the onset of the rapid decrease in surface temperature. Meanwhile, quench temperature corresponds to the onset of destabilization of vapor film that exists between the hot surface and liquid. Rewetting temperature is the one at which the liquid establishes wet contact with the hot surface.

Based on the conditions of core spraying, a 36-rod assembly was heated to different temperatures and then cooled by top spraying, Yamanouchi (1968) derived velocity correlation of wet front out of one-dimensional heat conduction equation, which is shown as Eq. (1):

$$u_r^{-1} = \rho_w C_{p,w} \left(\frac{\delta_w}{h\lambda_w} \right)^{1/2} \frac{(T_w - T_{sat})^{1/2}(T_w - T_0)^{1/2}}{T_0 - T_{sat}} \tag{1}$$

T_0, the critical wall temperature below which effective cooling by wall-to-fluid heat transfer takes place, is considered to be around 150 °C, at which the water droplets starts to adhere to the surface, accompanied by intense boiling. The heat transfer coefficient$h$, in turn, can be calculated from the test data of front velocity.

Duffey and Porthouse (1973) found that the physical processes involved in the rewetting have been shown to be identical for falling water films and bottom reflooding. According to the two-dimensional heat conduction problem during rewetting of a thin slab, and based on several additional assumptions, the authors obtained the rewetting velocity correlation for low refilling rate ($Bi < 1$) is the same as Eq. (1). And the approximate solution for high refilling rate ($Bi > 1$) is given as Eq. (2):

$$u_r^{-1} = \frac{\pi \rho_w C_{p,w}}{2h} \frac{T_w - T_{sat}}{T_0 - T_{sat}} \tag{2}$$

It can be concluded that major definitions of quench temperature and rewetting temperature in literature are limited to literal state. In addition, previous theoretical models of rewetting velocity (or quench velocity) cannot be applied to different situations. The mentioned experiments above were designed for rods and annual channel, while thermal hydraulic phenomena in narrow rectangular channel are totally different. In this study, bottom reflooding experiments in a narrow rectangular channel were carried out over ranges of initial parameters. Visualization results of boiling phenomena in the narrowly confined channel were obtained by utilizing a high-speed digital camera. Besides, a more specific method of 'temperature variation speed' is proposed to determine locations of rewetting front and quench front. Based on this method, quench velocity can be calculated from experimental data. Last but not least, a suitable quench velocity model deduced from energy conservation, which can be applied in a narrow rectangular channel, is also proposed.

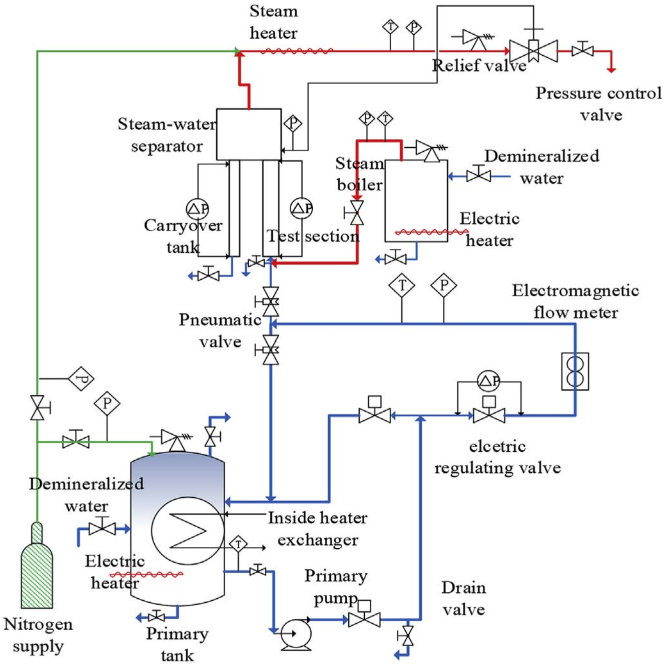

Fig. 2. Schematic of THERMAL experimental apparatus.

2. Experimental facility and results analysis

The bottom reflooding experimental facility is named THERMAL, which is the abbreviation of **T**hermal-**h**ydraulic h**e**at t**r**ansfer experi**m**ent for the narrow rect**a**ngular channe**l**. THERMAL facility is built for studying bottom reflooding phenomena in a narrow rectangular channel. Reflooding test is different from others because it is a once -through system rather than a circulation system. Referred to the design of NEPTUN-III facility (Dreier et al., 1987), which is established for carrying out reflooding experiments, THERMAL apparatus consists of the following three main components: water loop system, test section system and auxiliary system. The schematic diagram is shown in Fig. 2 with detail.

2.1. *Description of experimental facility*

The water loop system is composed of primary loop and cooling loop. An inside coil cooler heat exchanger is installed in the primary tank. Coolant is circulated in the cooling loop. Eventually, redundant heat of primary loop is discharged by means of an air cooling tower. The primary loop is used for adjusting the initial situations, such as water temperature, volume flow rate and systematic pressure, to meet the desired test conditions. The working fluid in the primary loop is demineralized water, whose electric conductivity must be larger than $5\mu s/cm$, otherwise the electromagnetic flow meter can't function normally.

The test section system consists of main test section, steam-water separator and water entrainment tube. Through the separator, two-phase mixture expelled from the test section is divided into water and steam. The separated water flows down into the entrainment tube and the entrainment integral effect can be deduced from a pressure