Nuclear Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Measurements of local two-phase flow parameters in fuel bundle under BWR operating conditions

J.-M. Le Corre [a,*], U.C. Bergmann [a], A. Hallehn [a], H. Tejne [a], F. Waldemarsson [a], B. Morenius [b,1], R. Baghai [c]

[a] Westinghouse Electric Sweden AB, Sweden
[b] Nuclear Reactor Technology, Royal Institute of Technology, Sweden
[c] RBI Instrumentation, France

A R T I C L E I N F O

Article history:
Received 9 February 2017
Received in revised form 24 April 2017
Accepted 26 April 2017
Available online xxxx

Keywords:
Annular two-phase flow
BWR
Instrumentation
Rod bundle
Void fraction

A B S T R A C T

The Westinghouse FRIGG facility, in Västerås/Sweden, is dedicated to the measurement of critical power, stability and pressure drop in fuel rod bundles under BWR operating conditions (steady-state and transient). The facility is particularly relevant to test modern BWR fuel designs which typically have complex features, such as part-length rods and mixing vanes that make the flow heterogeneous and challenging to accurately simulate (e.g. using sub-channel analysis codes or CFD tools).

In order to support the validation of advanced thermal-hydraulics codes for detailed BWR fuel assembly simulation, new local instrumentation techniques have been tested at the FRIGG facility for the measurement of two-phase dynamic pressure (Pitot tubes) and high time resolution phase detection (optical sensor). The optical sensors were custom-made by RBI Instrumentation for the FRIGG facility and optimized for annular two-phase flow (drop/steam) under BWR operating conditions.

This new instrumentation was successfully tested and allows the first-time measurement, under BWR operating conditions, of relevant two-phase flow parameters such as the local void fraction in the steam core, the local drop/steam velocity, the volumetric interfacial area, the drop collision frequency and the assessment of drop size distribution during BWR steady-state and transient operations.

1. Introduction

The Westinghouse FRIGG facility has been used for nearly 50 years to perform full-scale BWR fuel thermal-hydraulic experiments under realistic steady-state and transient core conditions. The test results have supported the development of various successive BWR fuel designs and established the experimental basis for the development of Critical Power Ratio (CPR) correlations (Andersson et al., 2011). Beside dryout tests, the facility is also used for fuel assembly pressure drop measurements (single phase and two-phase) and stability tests.

In the past, the facility has been equipped with advanced instrumentation techniques to measure detailed void fraction distribution, e.g. using gamma tomography (Windecker & Anglart, 2001). However, the use of this type of instrumentation is often cumbersome and requires the use of a radiation source. As an alternative, and to obtain further insight in the thermal-hydraulic behavior of a BWR fuel assembly, new instrumentations were recently tested at the FRIGG facility. The new measurements can be used for the development and validation of advanced thermal-hydraulics codes for detailed fuel bundle simulations. This includes the validation of CFD codes and crossflow models for subchannel analysis codes in non-homogeneous BWR fuel lattice for which the measurement of local data are required.

2. Frigg facility

2.1. Test loop capabilities

The FRIGG facility is a full-scale BWR thermal-hydraulic test facility located in Västerås, Sweden. The facility has been operated since the 1960 s to qualify a long series of BWR fuel designs, starting from the early 8 × 8 fuel lattice until the latest 10 × 10 SVEA-96 fuel designs. The loop was modernized and upgraded in 1995 (Nylund, 1997).

The FRIGG test facility is designed to cover all requirements for BWR fuel heat transfer and pressure drop testing under BWR

* Corresponding author.
E-mail addresses: lecorrjm@westinghouse.com (J.-M. Le Corre), rbi.sarl@wanadoo.fr (R. Baghai).

[1] Currently: SKB (Swedish Nuclear Fuel and Waste Management Company) Stockholm, Sweden.

http://dx.doi.org/10.1016/j.nucengdes.2017.04.033
0029-5493/

Please cite this article in press as: Le Corre, J.-M., et al. Measurements of local two-phase flow parameters in fuel bundle under BWR operating conditions. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.04.033

two-phase flow conditions, including boiling transition (dryout) and thermal-hydraulic stability. The dryout tests are typically performed under a wide range of steady-state BWR operating conditions (flow, pressure, inlet temperature, axial power distributions). A wide range of variation in radial power distributions can also be achieved with the use of indirectly heated fuel rod simulators. In complement to steady-state tests, realistic transient dryout experiments can be performed with rapid power and flow variations.

The capability to measure cross-sectional void and radial void distributions during steady-state operation was considered when the facility was built in the late 1960s, using gamma transmission measurements. In the 1990s, redesigned equipment was installed to allow for full 2D tomography and some test campaigns were successfully run where the void was measured in the Westinghouse SVEA-96 fuel bundle geometry with and without part-length rods.

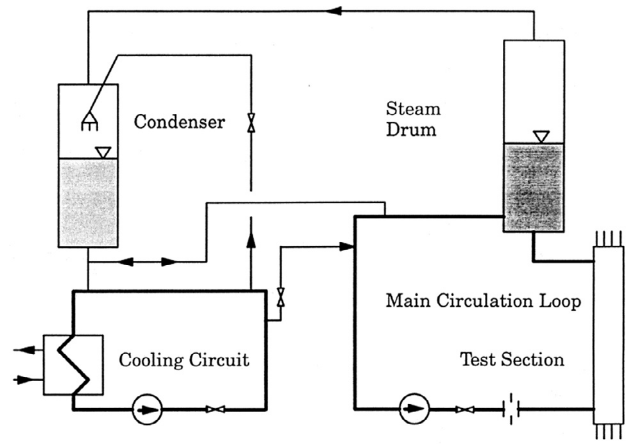

Fig. 1. FRIGG test loop.

2.2. Test loop design and instrumentation

The FRIGG loop is designed to operate at maximum of 10 MPa and 15 MW, sufficient for full-size BWR fuel assembly testing. The Westinghouse SVEA quarter-assembly can also be tested. Data collection of all relevant parameters is typically performed at 25 Hz. The FRIGG test section consists of a pressure vessel, a flow channel and a fuel bundle consisting of electrically heated fuel rod simulators and spacer grids. Pressure sensors are connected to the flow channel at different elevation taps. A schematic of the FRIGG test loop can be found in Fig. 1.

The flow channels are manufactured in normal fuel channel production and are hence realistic (apart from the pressure taps). The same applies to the spacer grids, which are entirely without reinforcements. Use of standard components is possible in FRIGG due to the use of the indirect heater rods that eliminates the need for electrically insulating flow channel ceramics. More detailed information regarding the FRIGG loop design can be found in Andersson et al. (2011).

Rapid control of power and flow is possible, to simulate typical limiting safety-related BWR transients, such as flow reduction during a pump trip, rapid power increase transients or a combination of both. The transient forcing functions are introduced from precalculations via a control computer.

The FRIGG data acquisition system consists of a main computer and a number of scanners, allowing the simultaneous collection of up to 830 signals at 25 Hz. The data recording and control systems have been continuously upgraded to meet current standards.

Void measurement using gamma tomography has been a very important testing objective, from the early HWR and BWR lattices, until the current 10×10 lattices. A new tomography system was developed and used for advanced 10×10 fuel validation (Windecker & Anglart, 2001), including to investigate the effects of part-length fuel rods (Ahnesjö et al., 2015). The databases from void measurements have been used to validate the void correlations needed in the core design methods. The early HWR FRIGG data were published and are available in the open literature (e.g. in Nylund et al., 1970).

3. New local instrumentation

3.1. Objectives

Modern BWR fuel assemblies include features that can make the flow inhomogeneous and challenging to simulate with available TH simulation tools (validated mainly in single channels and homogeneous fuel lattices). At the end of the part-length rods, typical of modern BWR fuel designs, sudden expansions of the flow area are created, leaving place to empty regions within the fuel lattice. This can lead to significant cross flows which can be challenging to simulate accurately, in particular when considering separately the film, drop and steam fields, typical of annular two-phase flow.

The measurement of relevant local flow information is required to validate sub-channel and CFD codes. Under typical BWR conditions, the flow regime of interest is annular flow where a thin liquid film flows over the walls and the steam core is mixed with liquid droplets. The liquid film flow would be very challenging to measure in a high pressure/high temperature test rig. However, it is possible to position local probes for the measurement of relevant two-phase flow parameters in the steam core (i.e. away from the rods and channel box). For that purpose, The FRIGG facility has been equipped with Pitot tubes (Section 3.2), for two-phase dynamic pressure measurement, and optical sensors (Section 3.3), for local phase detection and local void fraction. When used together, these instruments also allow for the measurements of local flow velocity and drop diameter distribution in the two-phase steam core.

Both instruments are intrusive and perform local measurements. They were placed downstream of, but close to, the end of heated length (EOHL) and hence had no effect on dryout and pressure drop measurements within the heated length. In the results presented in this work, both instruments were placed near the center of the open region above part-length rods where the two-phase flow fields are considered to be nearly uniform.

3.2. Pitot tubes

3.2.1. Measurement principles

Pitot tubes are commonly used to measure local dynamic pressure and fluid velocity in liquid, air and gas flow for many industrial applications (e.g. aircraft or boat speed). Though most applications are performed under single-phase flow conditions, applications to two-phase flow are also possible under specific assumptions. Some applications under gas/liquid and liquid/liquid two-phase flows can be found in Hau and Banerjee (1981), Hamad and He (2010) and White and Young (1997).

A Pitot tube is composed of 2 ports, the first port faces the flow direction and measures the stagnation (total) pressure of the fluid (P_t, static + dynamic). The second port is typically perpendicular to the flow direction and measures the static pressure (P_s). In two-phase flow, the pressure difference between the two ports is hence