

Investigations of single-phase flow mixing characteristics in a wire-wrapped 37-pin bundle for a sodium-cooled fast reactor



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ARTICLE INFO

Article history:

Received 6 March 2015

Received in revised form 21 September 2015

Accepted 24 September 2015

Keywords:

Sodium-cooled fast reactor (SFR)

Core thermal design

Flow mixing

A wire-mesh sensor (WMS)

A wire-wrap effect

Electro-tomography

ABSTRACT

Flow mixing characteristics inside a wire-wrapped 37-pin bundle were measured using a wire-mesh sensing system. The subchannel flow mixing within a sodium-cooled fast reactor (SFR) core subassembly is an important phenomenon to predict temperature distributions for the core thermal design and safety analysis. To identify the mixing characteristics experimentally, a dedicated test facility including the wire-mesh sensor system and tracing liquid injection system was developed. The conductivity fields at the end of a 37-pin bundle were visualized in several different flow conditions which are corresponding to 20–115% flow of the prototype reactor nominal flow based on the Reynolds number. A CFD preliminary analysis under pre-determined boundary conditions was also performed to verify the design parameters and range of various operating values of the current mixing test. The experimentally identified mixing characteristics were compared with the CFD results, which show reasonable agreements with each other. The current experimental work includes the uncertainty evaluation by performing the separated test for the elementary parameters.

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1. Introduction

Mixing of coolant flows inside fuel rod bundles have been of significant interest for nuclear safety (Walker et al., 2009) and core thermal design. In the design of a sodium-cooled fast reactor (SFR) developed by the Korea Atomic Energy Research Institute (KAERI), mixing characteristics in an SFR fuel assembly are also considered as an important issue for a core thermal design and for assessing a safety issue as a temperature limitation in a fuel assembly in spite of the heat flux limitation in a pressurized water reactor (PWR). An SFR fuel assembly has many fuel rods with wrapped wires which act as both a spacer with adjacent wires and a flow mixer. Because an SFR fuel assembly has much smaller hydraulic diameters than those of PWR, only a simple wrapped wire lets the spacing between fuel rods keep the minimum gap without any grid structures. In addition, the wrapped wire on a rod can generate a circumferential swirl flow around the rod for an enhancement of subchannel flow mixing. The mixing characteristics should be assessed through subchannel flow mixing experiments in a core thermal fluidic design.

To measure the flow mixing characteristics in a wire-wrapped rod bundle, several representative experimental studies have been conducted by measuring the electric conductivities. Lorenz and Ginsberg (1977) conducted measurements of flow mixing in a 91-pin wire-wrapped fuel assembly using an electrolytic tracer. Cheng (1984) conducted a similar work on a 37-pin wire-wrapped bundle using a salt tracer injection method, and Cheng and Todreas (1986) suggested consistent hydrodynamic models for mixing parameters in wire-wrapped rod bundles. They used a simple subchannel-based sampled measurement of electric conductivity, and these methods can have a coarse resolution and inaccuracy in an uncertainty analysis.

A wire-mesh sensor (WMS) is an intrusive device for measuring the local electric conductivity level. The technique was developed in HZDR, Germany (Prasser et al., 1998), and can be regarded as an effective method for identification of a local phase for multi-phase flows; in addition, WMSs have been usually adapted for visualization of two-phase flows (Abdulahi and Azzopardi, 2014; Krepper et al., 2007; Lucas et al., 2013; Manera et al., 2006; Monni et al., 2014). The recent reports show the feasibility of a WMS for a single phase flow (Kliem et al., 2008; Bertolotto et al., 2009; Ylönen et al., 2011; Prasser and Kliem, 2014). Although subchannels in an SFR are located with hexagonal arrays unlike PWR type having rectangular arrays, flow mixing can be effectively

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measured using the custom designed WMS and an appropriate post-processing to achieve a higher spatial and temporal resolution with a good accuracy. A CFD preliminary analysis under pre-determined boundary conditions was also performed to verify the design parameters and range of various operating values of the current mixing test. The experimental results are thus compared with computational fluid-dynamic (CFD) results to cross-check our methodology.

2. Methods

2.1. A wire-mesh sensor and a test assembly

A wire-mesh sensor (WMS) has both a transmitting electrode layer and a receiving electrode layer with a short distance and a cross angle of 90°. As a driving voltage is supplied to the transmitting electrodes in order, a current count is derived in the receiving electrodes (see Fig. 1). In other words, according to the electric conductivity level of the liquid path between two different layered wires, the derived current counts are varied. Using this sensing mechanism, a difference in the electric conductivity level of the liquid across the cross points can be measured. Although the fabricated WMS can have own unwanted offset values at each cross point in a manufacturing phase, the offset values show good repeatability and robustness. In other words, uneven offsets should be removed by the proper post-processing method.

The test section of 1.5-m in height was fabricated including 37 rods with wrapped wires in a hexagonal arrangement. The pitch to rod diameter ratio (P/D) and wire lead length to rod diameter ratio (H/D) were preserved with our prototype SFR design (i.e., P/D of 1.13, H/D of 27.7). According to these geometry parameters, a WMS had been designed for the flow experiments. The cross points were set at the center of each subchannel. To match the location between the cross points of WMS and the subchannels of a 37-pin bundle, the WMS has been fabricated having irregular rectangular cells (Fig. 2).

As previously mentioned, the WMS also has its own geometrical characteristics and hence several preliminary tests were conducted before the main experiments. First, the stability test without flows was performed. The WMS showed very good robustness with no change with varying time. Then the effects by change of temperature were studied by experiments with flow conditions.

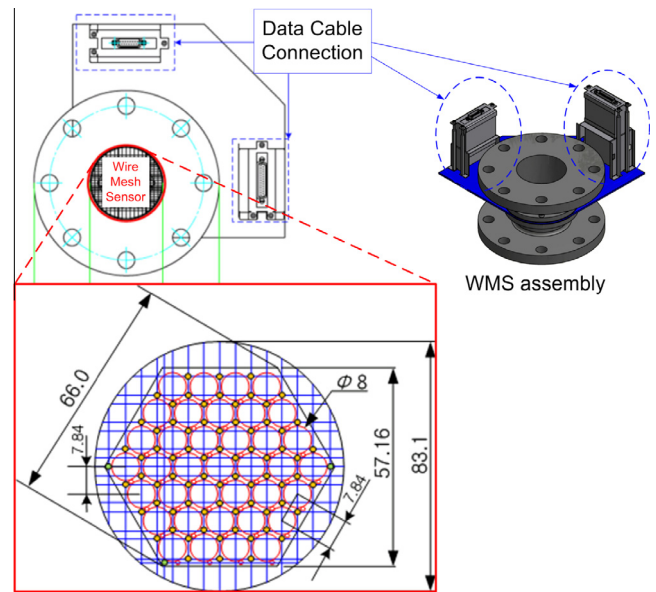


Fig. 2. The design of a wire-mesh sensor (WMS) and a WMS assembly. It contains flanges for connecting to our experimental loop system, and every cross point are matched to the center of subchannels.

As temperature or flow rate were raised, the obtained current counts showed the tendency of increase. The temperature effect tests were conducted at around 60 °C (from 58 °C to 62 °C), and the flow rate effect tests were performed at the range from 1.098 kg/s to 6.316 kg/s. From these tests, the coefficients of every points were obtained, for example $\delta\theta_{x,y,h}/\delta T$ (at ~60 °C) and $\delta\theta_{x,y,h}/\delta M$ where $\theta_{x,y,h}$ is measured value at each point. The $\delta\theta_{x,y,h}/\delta T$ showed a range from -0.714 to 2.16 with an average value of 1.408, and the $\delta\theta_{x,y,h}/\delta M$ represented a range from 0.00296 to 0.00873 with an average value of 0.00502. As a result, controls of temperature are more important than those of flow rate in the main experiments.

2.2. Test loop and experimental set-up

The experiments were conducted at the FIFFA (Flow Identification test loop for Fast reactor Fuel Assembly) test facility at KAERI (Korea Atomic Energy Research Institute). The test loop consists of a main water tank, a pump, a tracing liquid injection fluid system (including a tracing liquid tank, injecting tubes, and flow control valves) and several instruments such as a flow meter and a pressure gauge (Fig. 3). All experiments were carried out under a pressure of 10 bar as a system pressure of the loop. Temperature (60 °C) and flow rates (from 1.098 kg/s to 6.316 kg/s) were controlled to maintain experimental conditions as shown in Table 1 during the experiments. The main loop was filled with deionized (DI) water as the background liquid, and tap water was used as the tracing liquid. The tracing liquid was injected using a rod consisting of rod bundle, inside which a tracing tube were connected exquisitely. Two rods were selected for the injection at two different elevations. Therefore, there are four different points for injection: upper (1L) and lower (1S) holes for an interior subchannel, and upper (25L) and lower (25S) holes for an edge subchannel. The numbers 1 and 25 mean identification of the rod of the bundle.

The intake of the test rig includes a flow regulator to make the flow uniformly, and the experimental hydraulic conditions are fully turbulent. The WMS was installed at the exit of the subchannels of the wire-wrapped 37-pin bundle with a 5-mm gap from the end of the rods.

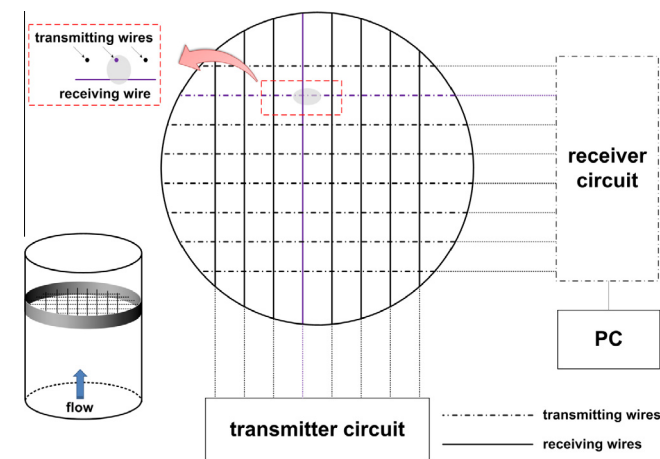


Fig. 1. A measurement system using a wire-mesh sensor (WMS). A WMS consists of two separated wire layers as transmitting and receiving wires. Receiving wires receive signals from transmitting wires, and transmitting wires send signals in order. The measured current count means a relative conductivity of a small gap between the transmitting wire and the receiving wire at each cross-point.

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