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Thermal-hydraulic analysis of a 7-pin sodium fast reactor fuel bundle with a new pattern of helical wire wrap spacer

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ABSTRACT

Thermal-hydraulic analysis was performed with a 7-pin fuel bundle by using CFD. The ordinary wire-wrapped spacers are wound on the fuel pins in the same direction. Counter flow is predicted to occur in all sub-channels due to this pattern. This flow was confirmed in this analysis work. A new type of arrangement for wire-wrapped spacers, called the U-pattern, is presented to provide favorable flow for coolant mixing. In this pattern, 7 pins are designated in a group, the center pin has no wrapping spacer, and the pins surrounding the center pin have alternate winding directions of the spacer. Superior mixing effect and the uniform flow were confirmed in this pattern. This pattern has about 30 °C cooler than that of the ordinary wire-wrapped fuel bundle pattern in the maximum temperature region. Pressure drop of the U-pattern was reduced about 10% compared with the ordinary pattern. The new pattern of the fuel pins enhances the heat transfer and reduces pressure drop simultaneously.

1. Introduction

A liquid-metal fast breeder reactor (LMFBR) has an attractive neutron utilization factor, in comparison with thermal reactors. Fast reactors could provide sustainable nuclear power and effective actinide management by using the fissionable uranium resource and fast neutrons. One of the noticeable differences between the fast reactor and the thermal reactor is the length of the mean free path. A fast reactor has a relatively long mean free path, or low macro absorption cross-section. The core geometry is small for the continuous reactions. The sub-channels between the fuel pins are narrow due to the geometric characteristic.

Wire-wrapped pins have been presented as a solution to provide the enhanced heat transfer in the sub-channel between the fuel pins. Related research has been performed in order to understand the effects of wire-wrapping on the fuel pin. The general idea is that a helical wire wrapping forces the fluid to rotate around fuel pins. A swirling flow could remove the heat from the pin effectively. However, a helical wire wrapping could increase the pressure drop. Many researchers have studied about the wire wrapping effects.

Novendstern developed a semi-empirical model to predict pressure drop in a wire-wrapped fuel pin bundle (Novendstern, 1972). This model is able to predict the value of pressure drop within 14% over a wide range of geometries in the turbulent flow regime.

Cheng and Todreas developed hydrodynamic models of wire-wrapped rod bundles to calculate sub-channel friction factors and mixing parameters for use in sub-channel analysis codes (Cheng and Todreas, 1986). Both flow regime and geometry effects were taken into account in these models. Correlations based on the models for the sub-channel friction factor and mixing parameters were calibrated with the available data at that time. These correlations provide some background information suitable for validation.

Gajapathy et al. investigated the sodium flow and temperature distributions in heat generating fuel pin bundles with helical spacer wires (Gajapathy et al., 2009). The characteristics of 7, 19, and 37 fuel pin bundles were analyzed by using a commercial computational fluid dynamics (CFD) code. It was found that the normalized outlet velocities were nearly equal to unity, even in the peripheral and central zones (in the range 0.9–1.1), and there was good agreement with published hydraulic experimental measurements.

Hamman and Berry evaluated a CFD model and simulation for large-scale problems of a fast reactor with wire-wrapped pin bundles (Hamman and Berry, 2010). Three-dimensional flow distributions of sodium in the sub-channels of a 19-pin fuel bundle were

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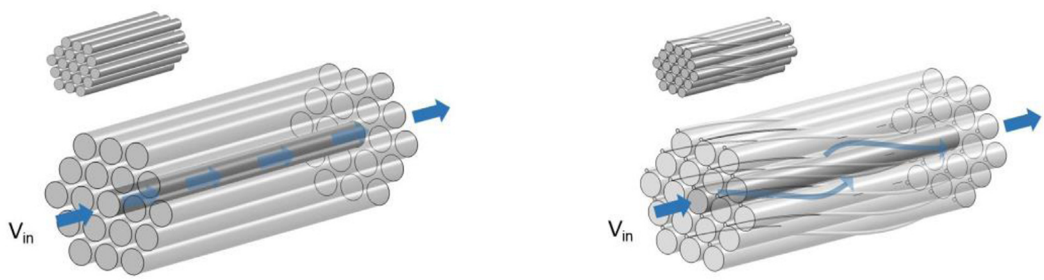
(a) Full sized dimension of the pin bundle (b) Flow pattern in present design

Fig. 1. Geometry of typical pin arrangement and flow pattern in arbitrary sub-channels.



(a) Bare surface condition (b) Wire-wrapped surface condition

Fig. 2. Estimated different flows around a pin.

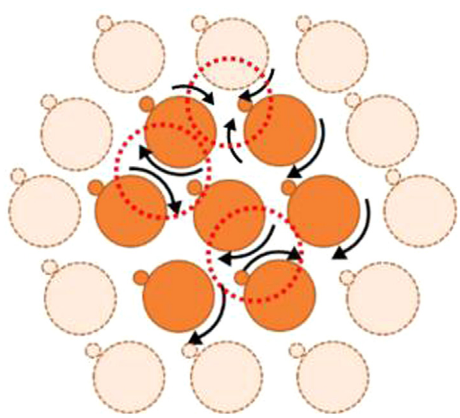


Fig. 3. Postulated counter flow between the pins in sub-channels. (clockwise rotation, anticlockwise rotation).

simulated by using a commercial CFD code. Their results have a difference of 9–15% in comparison with some correlations.

Volkov et al. developed a CFD model of a 19-rod wire-wrapped pin fuel bundle (Volkov et al., 2013). They found that the use of the high-Reynolds k-ε turbulence model for simulating the flow in the pin fuel bundle made it possible to reduce the dimension of the computational mesh, and hence perform a full-scale simulation of a fuel bundle. The obtained results are in good agreement with the empirical dependences and international calculations.

Talebi et al. conducted a parametric study of the Rayleigh number, inlet temperature and heat fluxes on the fluid flow and heat transfer inside the sub-channel with a CFD code that solves the governing equations with a finite volume method and SIMPLE algorithm (Talebi et al., 2014). The wire wrapped spacers created a uniform fluid velocity and temperature in the cross-section of the channel.

The wire-wrapped spacers are wound in the same rotating direction. It might be estimated the counter flow in this pattern. In this work, a new helical wire-wrapped pattern was studied to improve the thermal hydraulic performance such as the temperature and the pressure drop.

2. Wire wrap models

2.1. Characteristics of ordinary wire-wrapped pin

Fig. 1 shows the ordinary pattern of wire-wrapped fuel pin in an LMFBR. A number of fuel pins are arranged in the hexagonal walls. This wire wrap makes the coolant channels between the pins without the direct contact. Fig. 2 shows an estimated flow of the coolant in the fuel pins. The swirl flow is generated around the pins. This flow enhances mixing of the coolant. The temperature of the pin surface is decreased due to an enhanced heat transfer. Ultimately, the wire wrapping lowers the maximum temperature of a pin with the wire-wrapped surface compared with the model of the bare surface condition.

2.2. New wire-wrap arrangement and characteristics

The Wire wrapping, it is called as the spacer, is wrapped on an ordinary fuel pin with the same winding direction. A hydrodynamic issue can be considered in this arrangement. The flow direction rotating around the pins could be predicted as shown in Fig. 1. After examining Fig. 3, some concerns might arise about the flow pattern. The counter flow is formed in all sub-channels. The coolant flow would be disturbed by this counter flow. This phenomenon is negative on the heat transfer and pressure drop. A new wire-wrapped pin arrangement is presented to solve a problem of the counter flow. 7 pins are designated as one group. This pattern can be extended to the fuel assembly. The center pin has no wire wrap, and the pins surrounding the center pin have