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CFD analysis of 7-pin fuel bundle with new wire-wrapped pattern

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1. Introduction

Liquid-metal fast breeder reactor (LMFBR) has the attractive neutron utilization factor in comparison with one of the thermal reactors. Fast reactors could provide sustainable nuclear power with fissionable uranium resource. One of the noticeable difference between the fast reactor and the thermal reactor is the length of mean free path. Fast reactors has relatively short mean free path due to the use of a fast neutron. This characteristic was considered to design the reactor core which has the short pitch between the fuel pins. Therefore, many researchers have studied to remove the generated heat effectively under the geometrical limitation.

Wire-wrapped pins was presented as a solution to provide channels for coolant flow and enhance the heat transfer between the fuel pin and coolant. Related research has been performed in order to know the effect of wire-wrapped pin [1, 2, 3, 4, 5]. General idea is that helical wire-wrapped forces fluid to rotate around fuel pins. Swirl flow could be formed to decrease the temperature difference at same elevation. However, helical wire-wrapped could increase the pressure drop to maintain the constant flow condition in sub-channel. The efficiency of LMFBR could be enhanced when the goals which are low pressure drop and high heat transfer are simultaneously satisfied. In this work, new helical wire-wrapped arrangement was studied as part of an effort to improve the performance of the wire wrap based on the thermal hydraulics.

2. Wire wrap models

2.1 Characteristics of ordinary wire-wrapped pin

Figure 1 shows the ordinary geometry of wire-wrapped fuel pin in LMFBR. A number of fuel pins are located in the hexagonal walls. This wire wrap supports the separated geometry and make the specific coolant channel between the pins. The coolant would flow as shown in Fig. 2. The low velocity on the heated surface equipped with the wire wrap should be increased compared with the velocity on bare heated surface at same inlet flow condition. The swirl flow enhances mixing of the coolant which make to form the uniform coolant temperature. As a results of that, temperature of heated surface was decreased with enhanced heat transfer rate. Ultimately, it brings down the maximum temperature of a pin with proper cooling performance.

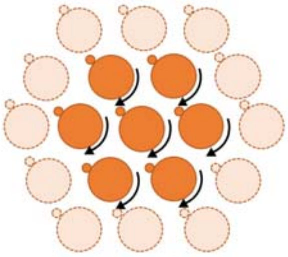
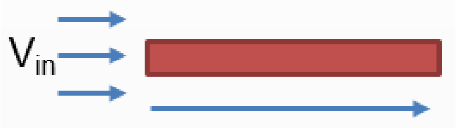
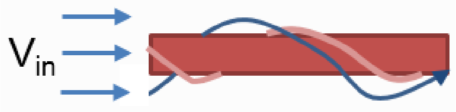


Fig. 1. Geometry of ordinary wire-wrapped pins and flow pattern on sub-channels.



(a) Bare surface conditoin



(b) Wire-wrapped surface condition
Fig. 2. Estimated different flow around a pin

2.2 New wire wrap arrangement and characteristics

Wire is wrapped on the ordinary fuel pin in LMFBR with same winding direction. The reason for this geometry is estimated due to the convenient manufacture and installation of wire wrap. However, a hydrodynamic issue could be detected in this arrangement. The flow direction rotating the pins could be predicted as shown in Fig. 1. After examining Fig. 3, some questions might arise about the flow pattern. The flow direction between the pins would be determined by the neighboring wire wrap. The position of the wire wrap is continuously changed along the axial direction. Unique flow pattern would be definitely formed in the fuel bundle corresponding to the elevation of the fuel pin. It is not fundamentally important to estimate the flow direction. Most critical point is that counter flow was formed in all interfaces in the fuel pins. In this counter flow regions, coolant flow is determined based on the velocity vector except axial direction. The coolant flow would be disturbed by counter flow. This phenomenon results in the negative effects on heat transfer and pressure drop.

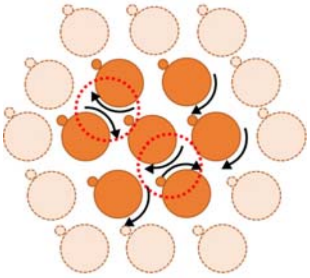
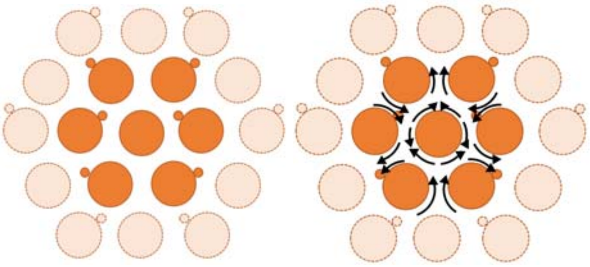


Fig. 3. Postulated counter flow between the pins in sub-channels

New wire-wrapped pin arrangement was presented to solve the problem related to counter flow. When the 7-pins are designated as one group without the hexagonal walls, the center pin has no wire wrap. The remainder surrounding the center pin has sequentially different winding direction. Although there is no wire wrap in the center pin, all pins are definitely separated each other. Figure 4 shows this arrangement and flow characteristics of pin arrangement. Ideal flow pattern could be formed in presented pin arrangement. Enhanced mixing effect and decreased pressure drop are predicted from stable flow pattern. The maximum temperature of fuel pin could be reduced due to well mixed coolant. Decreased pressure drop makes it possible to increase the coolant flow condition with the same performance of pumps. The range of plant operation condition could be extended to obtain improved efficiency and safety of LMFBR.



(a) New pin arrangement (b) Estimated flow pattern

Fig. 4. Presented new pin arrangement for stable coolant flow condition

3. CFD analysis

3.1 Geometry and boundary condition

CFD (ANSYS-CFX) simulation was conducted to analysis the presented pin arrangement. The dimension of the pin and pitch was determined with the reference about KALIMER-600 [6, 7] as shown in Table I. 7-pin fuel bundle is basic geometry. The option of volumetric heat generation was selected to simulate heat production caused by fission. The generated heat ratio was varied according to the elevation of fuel pin as shown in Fig. 5. This value was calculated from the neutron flux profile in axial direction. The geometry consists of metallic fuel (U-Pu-Zr), HT-9 cladding and sodium coolant. Constant thermal and physical properties were determined for each material by considering operation condition. The inlet velocity and temperature of sodium flow is 3.6 m/s and 390 °C, respectively. A k-ε turbulent model was selected to predict the behavior of sodium coolant. There are 3 types of geometry (fuel bundle without wire wrap, fuel bundle with ordinary wire wrap and fuel bundle with presented wire wrap). The effects of wire-wrapped pin arrangement could be distinguished through analysis of the 3 types of geometry

Table I: Geometry of bundle

	Dimension (mm)
Fuel slug length	940
Fuel pin diameter	6.96
Cladding thickness	1.02
Pin pitch	10.5
Wire wrap diameter	1.4
Wire wrap pitch	204.9

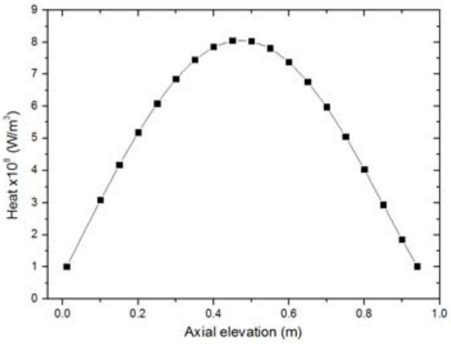
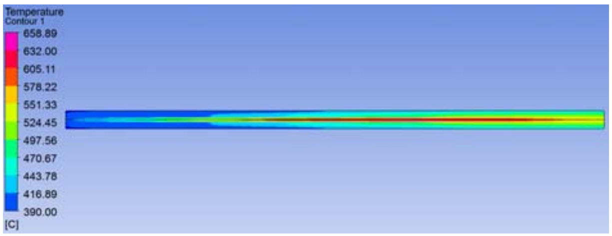


Fig. 5. Axial power distribution at peak assembly

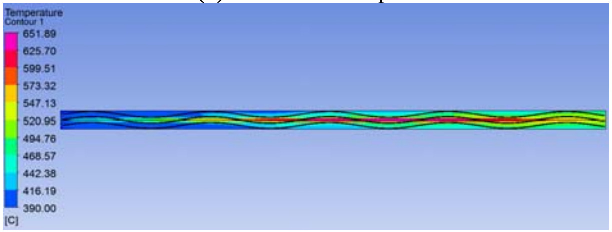
3.2 Temperature distribution in the bundle

Figure 6 shows the temperature distribution on perpendicular cross section for all geometries. The trend of temperature distribution was determined by neutron flux, coolant velocity and material of fuel. The loading of a metallic fuel is designed in KALIMER-600. The metallic fuel has high thermal conductivity in comparison with the oxide fuel. It is well known that the position of maximum temperature in the metallic fuel pin is higher than one of the oxide fuel because of considerable heat transfer in the axial direction. This characteristic was considered as one of the advantages for the metallic fuel at severe accidents. In all CFD results, the position of maximum temperature for fuel pin is about 60% of the total fuel height. The value of maximum temperature is different at same elevation. When the ordinary wire was wrapped around the fuel pin, temperature reduction is about 7 °C. Surprising result was indicated in Fig. 6 (c). Huge temperature reduction was observed at the position where the maximum temperature occurs. The temperature distribution at a height of 0.8 m. could give important information to understand this characteristic as shown in Fig. 7. Relatively high position was selected as the reference height to confirm the mixing effect of sodium coolant. Heated sodium coolant is concentrated in the center of fuel bundle at no wire wrap and the ordinary wire wrap cases. However, the maximum temperature regions were observed at some specific channels where is away from the center in the case of modified pin arrangement. The difference between maximum and minimum temperature is the smallest in this case. It means that mixing effect of the case is superior compared with other cases. The coolant flow direction could be estimated from analysis of the interesting temperature pattern indicated in Fig. 7 (c). The sub-channel around the center has the most dangerous condition by considering the heating boundary. Present pin arrangement is favorable to mix and dissipate the heated sodium coolant.

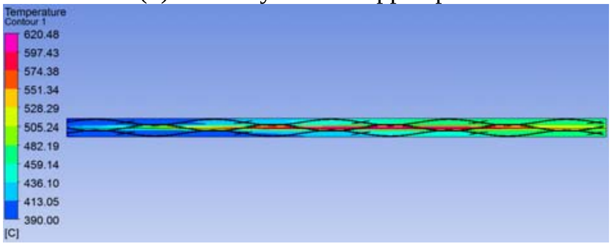
CFD simulation was conducted with only 7-pin fuel bundle geometry. The obtained results and insight could be limited to understand the performance of wire wrap. One thing is for sure-without concerns, presented wire wrap would could reduce the maximum temerapter in the core of KALIMER-600. It is possible to ensure the safety of LMFBR by decreasing the maximum temperature or enhance the efficiency of LMFBR by increasing the operation temperature.



(a) Plain surface pin

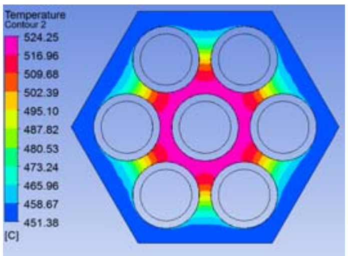


(b) Ordinary wire-wrapped pin

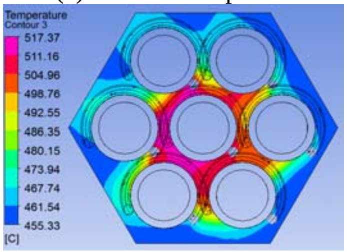


(c) Modified wire-wrapped pin

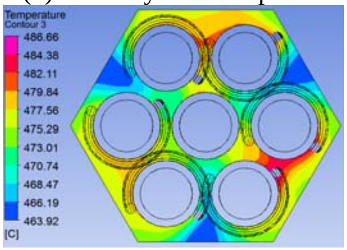
Fig. 6. Temperature distribution on perpendicular cross section at different sub-channel condition



(a) No wire wrap case



(b) Ordinary wire wrap case

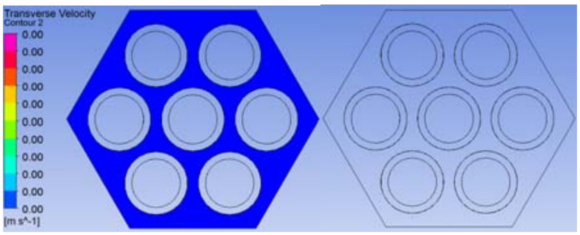


(c) Modified wire wrap case

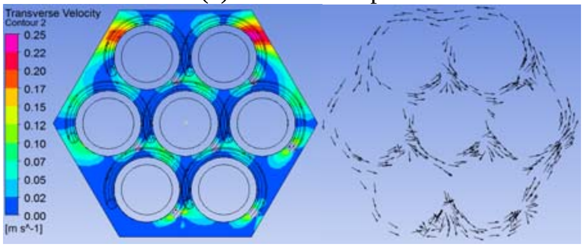
Fig. 7. Temperature distribution on cross section (Z=0.8m) at different sub-channel condition

3.3 Velocity distribution in the bundle

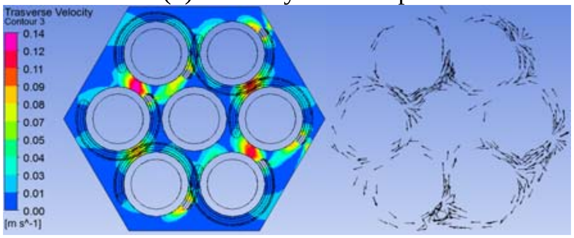
Sodium velocity distribution and the velocity vector at a height of 0.8m was shown in Fig. 8. The velocity is transverse velocity to distinguish the normal velocity to the inlet surface. This velocity is related to coolant mixing. The maximum transverse velocity of the ordinary wire-wrapped pin case is higher than one of the presented wire-wrapped pin case. The average transverse velocity for the cases of no wire wrap, ordinary wire wrap and new wire wrap is 0, 0.038, 0.019 m/s, respectively. The moment of inertia for sodium coolant is generated by wire-wrapped pin geometry. In the ordinary wire wrap geometry, counter flow could be schematically generated in all sub-channels as shown in Fig. 3. This prediction was confirmed by observing the velocity vector. Although the value of flow velocity is high, the flow pattern is complicated in the sub-channels around the center pin. Fast and stable flow pattern could be observed near the hexagonal walls. The direction of this rotated flow is dependent on winding direction of wires. Sodium coolant which is adjacent to the hexagonal walls is relatively cold. This coolant should flow into the sub-channels around the center pin. However, this flow is limited due to the reverse flow caused by wire-wrapped center pin. The temperature reduction of coolant with the ordinary wire wrap is insufficient compared with one of no wire-wrapped fuel pin because of this flow pattern. The flow pattern of the fuel pin geometry with modified wire-wrapped pin arrangement is different. Anticipated flow pattern which is presented in Fig. 4 was observed. Mixing of coolant would be maximized in this condition. Uniform temperature distribution results in this flow pattern. Although locally fast velocity region are generated in Fig. 8 (b), modified wire-wrapped pins make suitable coolant flow to remove the heat from the fuel pins as shown in Fig. 8 (c). The stable coolant flow was observed in all sub-channels regardless of the elevation.



(a) No wire wrap



(b) Ordinary wire wrap



(c) New wire wrap

Fig. 8. Transverse velocity distribution and velocity vector on cross section (Z=0.8m) at different sub-channel condition

3.4 Heat transfer coefficient and Pressure drop

Table II shows the calculated heat transfer coefficient and the pressure drop. Heat transfer coefficient was increased due to the wire wrap. The geometry of wire wrap makes the turbulent flow in the sub-channels. The value of heat transfer coefficient for geometry of ordinary wire wrap and modified wire wrap is similar. Although the average transverse velocity for geometry of ordinary wire wrap is higher, heat transfer would deteriorate due to locally complicated flow pattern.

Equation (1) expresses the heat flow in the fuel. Suppose that the temperature of sodium coolant is fixed. When the heat transfer coefficient is increased, the temperature difference could be reduced. The maximum fuel temperature could be reduced in the geometry which has the ordinary wire wrap. The case of geometry which has the modified wire pin arrangement is different. If there is considerable mixing effect in the sub-channels, the temperature of coolant could be decreased. This phenomenon could be applied in the modified wire wrap geometry. Ultimately, maximum fuel temperature could be reduced by considering enhanced heat transfer and relatively cold coolant.

The value of heat transfer coefficient is uncertain because temperature influence on the change of thermal and physical properties is not considered. Obtaining accurate thermal and physical property of ternary metallic fuel (U-Pu-Zr), HT-9 cladding material and sodium is limited. Although the modified thermal and physical properties will be reflected in CFD simulation, it is anticipated that the overall trend of flow and heat transfer is permanent when the arrangement of the wire wrap is modified.

Table II. Result of heat transfer coefficient and pressure drop according to condition of wire wrap

	Heat transfer coefficient (W/m^2K)	Pressure drop (Pa)
No wire wrap	3.565	22864
Ordinary wire wrap	3.878	34790
New wire wrap	3.893	31321

$$T_m - T_f = \frac{q'''R^2}{4\pi k_f} + \frac{q'''R^2}{2}\left[\frac{1}{k_c}\ln\frac{R+c}{R} + \frac{1}{h\left(R+c\right)}\right] \qquad (1)$$

where T_m is maximum fuel temperature. T_f is coolant temperature. q"' is volumetric thermal source. k_f and k_c are thermal conductivity of fuel and cladding respectively. R is radius of fuel. c is the thickness of cladding. h is heat transfer coefficient on the wall.

One of the disadvantage for wire wrap is the increase of pressure drop. About 50% of addition pressure drop was calculated in CFD simulation due to the ordinary wire wrap. Relative high performance pump would be required to maintain the coolant flow at normal operation condition. Increased pressure drop could shorten the rotation time of pump which is generated by pump moment of inertia in response to a loss of flow accident. Modified wire wrap geometry could reduce the pressure drop in comparison with one of the ordinary wire wrap geometry. There is no wire in the center pin. There is stable flow pattern. These two reasons make to lower the pressure drop in modified wire-wrapped pin geometry.

4. Conclusions

Modified wire wrap geometry was presented to increase the heat transfer from heated fuel pins. Combination of the pin which has no wire wrap and the pins which have the reverse winding direction makes to form the uniform temperature distribution. The reduction of maximum temperature was observed in CFD results due to the enhanced mixing of coolant. Presented unique pattern make to lower the pressure drop compared with one of the ordinary wire wrap geometry. The efficiency of LMFBR could be enhanced by simultaneously satisfying low pressure drop and high heat transfer.

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