

## CFD Investigation on Shape Effect of Helically Wrapped Wire Spacer in a Heat Pipe

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### 1. Introduction

Recently, the proportion of clean energy and distributed power is increasing in the global power market. The US, Canada, and the UK begin to develop micro-nuclear reactors for usage in places where there is no power grid. In Figure. 1, Westinghouse of the United States designed eVinci with 0.2~5MWe class heat pipe reactor. It is currently undergoing NRC licensing and is set to have its first demonstration in 2023. [1] In addition, Oklo has designed a 2MWe-class ultra-small reactor with metal fuel using sodium heat conduction tube technology, and is currently undergoing the NRC preliminary licensing process. In Korea, the Korea Atomic Energy Research Institute (KAERI) initiated a conceptual study with 10MWe-class ultra-small gas, and is developing the concept of a 20-year long-cycle core and an electric current in 2017. Since 2013, the Korea Advanced Institute of Science and Technology (KAIST) has been conducting a conceptual study of a 12MWe class sCO<sub>2</sub>-gas furnace type BOP-integrated ultra-small reactor. [2]

Heat pipe technology is a core technology for micro-nuclear reactors. In this study, a design method with a helically wrapped wire spacer is investigated to maximize the heat removal performance of the condensation section of the heat pipe of the micro-nuclear reactor. The pressure drop characteristics and heat transfer characteristics in the condensation section of the heat pipe have been analyzed with RANS based three-dimensional CFD(Computational Fluid Dynamics) simulation.

Furthermore, the geometric shape effect of wire diameter, wire winding pitch, heat pipe diameter and flow condition of Reynolds number(Re) has also been investigated.

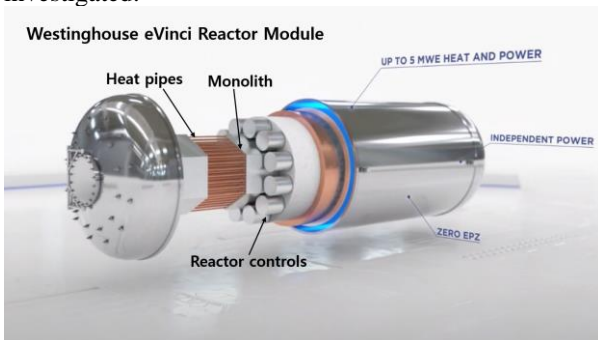


Fig. 1. Westinghouse eVinci Micro Reactor Module cutaway [1]

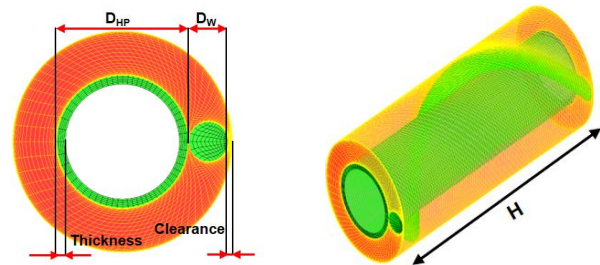
### 2. Numerical Method

#### 2.1. Computational grid system

The computational grid system consists of structured meshes as shown in Table 1. The computational grid system is composed of hexagonal meshes using the innovative grid generation methodology.

In the case of grid modeling for CFD analysis, a large-scale computational grid was required to simulate line contact between the wire and the heat pipe. Many researchers use a trimmed shape of wire spacer in a convenient for CFD simulation. [3] However, highly accurate CFD simulation has been performed with the innovative grid generation methodology. [4]

The grid is divided into the red fluid region and the green structure region, as shown in Fig. 2-(a), (b)



(a) Cross sectional view heat pipe with wire spacer (b) Perspective view heat pipe with wire spacer  
Fig. 2. Computational grid system

Table 1. Computational grid system of 8-pitch heat pipe

8-pitch	Cells	Nodes	Elements
Fluids	2,400,000	2,482,299	2,400,000
Structures	320,000	384,480	320,000
Total	2,720,000	2,866,779	2,720,000

#### 2.2. Modeling method

In order to compare the friction factor and Nusselt number according to the geometric shape, the geometric shape of the cases was shown in Table 2. The geometric shape variables were normalized and the characteristics according to the geometric shape change were compared.  $H/D_{HP}$  is wire lead pitch to rod diameter ratio and  $D_w/D_{HP}$  is wire diameter to rod diameter ratio.

Table 2. Heat pipe geometric shape characteristics

Geometric parameters	H/D <sub>HP</sub>	D <sub>w</sub> /D <sub>HP</sub>	Clearance [mm]
Case 1	4	0.3	0.1
Case 2	4	0.15	
Case 3	100	0.3	
Case 4	100	0.15	
Case 5	4	0.6	0.2
Case 6	4	0.3	
Case 7	100	0.6	
Case 8	100	0.3	

### 2.3. Boundary Condition

Table 3. describes the boundary conditions of CFD analysis. The inlet speed is set at various speeds according to the Reynolds number, and the outlet pressure is defined as relative pressure of 0 Pa. The surface of the outer rod and outer wire spacer is adaptive to no-slip boundary conditions with adiabatic conditions.

Because the heat pipe uses latent heat, the inner wall temperature is constant. Therefore, a constant temperature condition is set on the inner wall of the heat pipe.

Table 3. Boundary condition in Heat pipe 8-pitch

Boundary domain	Condition	Value
- Inlet	- Constant velocity	- Re=5000 - Re=10000 - Re=15000
- Outlet	- Relative Pressure	0 [Pa]
- Heat source	- Constant Temperature	953.15 [K]
- Rod outer - Wire outer	- Adiabatic	-
- Duct Wall	- No slip - Adiabatic	-

### 2.4. Turbulence Model

Numerical simulation techniques of a turbulent flow are typically divided into a DNS (Direct Numerical Simulation), LES (Large Eddy Simulation), and RANS (Reynolds Averaged Navier-Stokes simulation). LES cannot solve the full scale of turbulence and can only analyze large-scale turbulence models. DNS requires a fine grid and a small time interval. RANS solves the time averaged Navier-Stokes equation and models all scales of turbulence using turbulence models such as k-ε, k-ω and SST. In this CFD Investigation, the k-ε model was used. The high-resolution scheme was used for the convective term. The convergence of the simulation was judged by the velocity and temperature on the outlet domain on the 8-pitch heat pipe.

## 3. Result

### 3.1. Effect of Wire spacer

Research on the effect of wire spacer and research to improve fluid flow characteristics through various types of inserts is actively being conducted. [5] Mehedi Tusar et al. reported that the wire spacer increased the maximum heat transfer rate by 2.6 times in laminar flow. [6] In order to verify the effect of the wire spacer, the heat transfer performance when there is no wire in Case 1 as shown in Fig. 3-(b) was analyzed using the same methodology as above. As shown in Table 4, the result was Nu 1.25 times and Friction 2.28 times. Therefore, it is judged that there will be enough influence on the wire spacer effect as shown in Fig 4, 5, and 6. By changing the geometric shape variable, the characteristics of the fluid flow by the wire spacer were analyzed. The cross sections in Figs. 4, 5 and 6 were used at 4-pitch. Figs. 7 and 8 show the development of the friction factor and Nusselt number along the axial length.

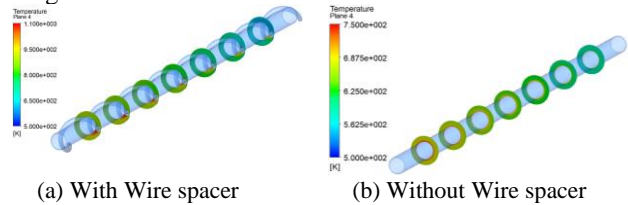


Fig. 3. 8-pitch heat pipe Perspective view

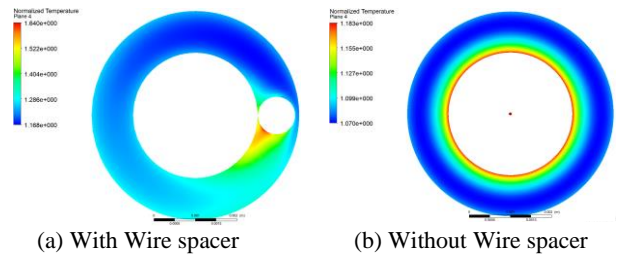


Fig. 4. Temperature field in cross sectional view

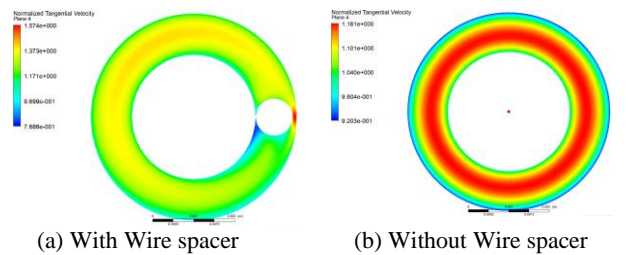


Fig. 5. Velocity field in cross sectional view

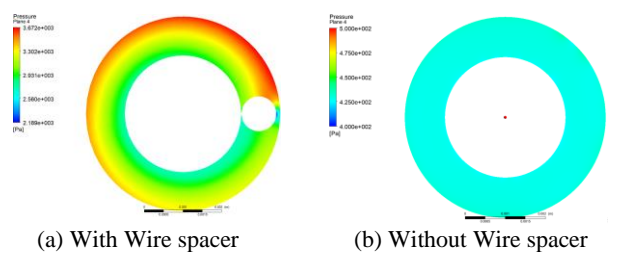


Fig. 6. Pressure field in cross section

Table 4. Comparison of heat transfer characteristics and coefficient of friction (Re=15000)

Case	Friction factor (Average)	Nusselt number (Average)
With Wire spacer	$1.94 \times 10^{-2}$	$2.84 \times 10^1$
Without Wire spacer	$8.51 \times 10^{-3}$	$2.27 \times 10^1$

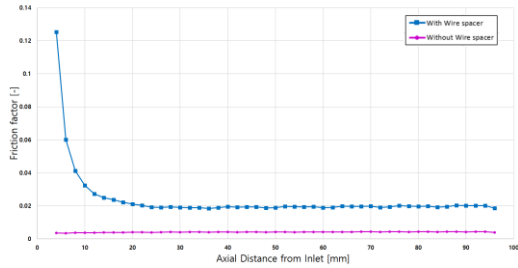


Fig. 7. Friction factor comparison of with wire spacer and without wire spacer in the axial direction (Re=15000)

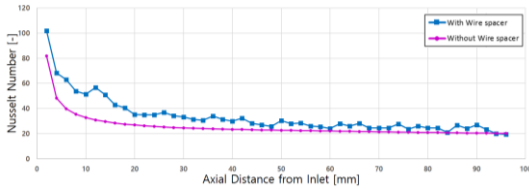


Fig. 8. Nusselt number comparison of with wire spacer and without wire spacer in the axial direction (Re=15000)

### 3.2. Effect on Pressure drop due to Heat pipe shape

The CFD simulation results with 8-pitch of wire spacer were equally divided into 48 regions to calculate the friction factor in the axial direction to see the change in the friction factor due to the pressure drop. The pressure drop on fully developed flow is calculated as follows:

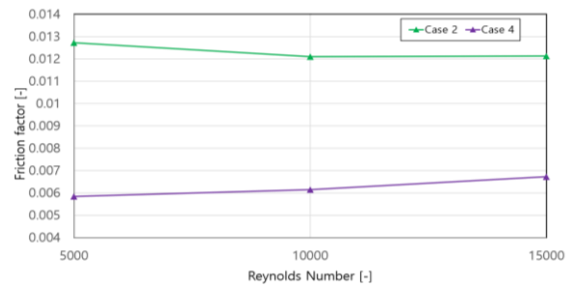
$$f = \Delta P \frac{D_h}{L} \frac{2}{\rho V^2}$$

Sivashanmugam and Suresh reported that the friction factor decreases with increasing Reynolds number. [7] Fig. 9. shows the comparison results of the friction factor according to the geometric shape change.

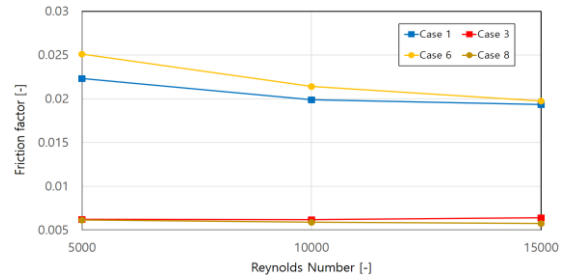
### 3.3. Effect on heat transfer due to Heat pipe shape

Thermal energy is transferred to the coolant by convection. The coolant, fluid Nitrogen Pr, is typically about 0.73. Convective heat transfer is amplified when the turbulence strength and speed increase by the wire spacer geometric shape. Fig. 10. shows the comparison results of the Nusselt number according to the geometric shape change. The Nusselt number is used to determine the local heat transfer coefficient. The Nusselt number is defined as follows:

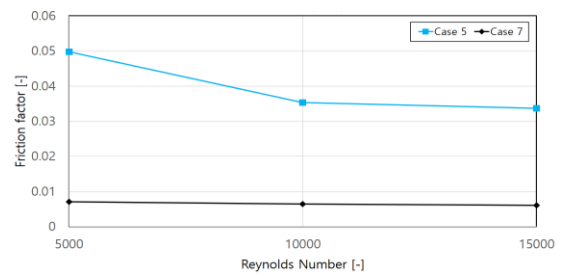
$$Nu = \frac{hD_h}{k_f}$$



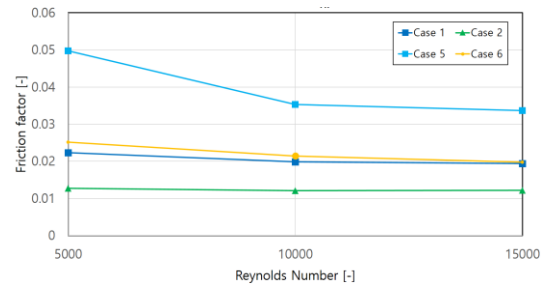
(a) Geometric shape of  $D_w/D_{HP} = 0.15$



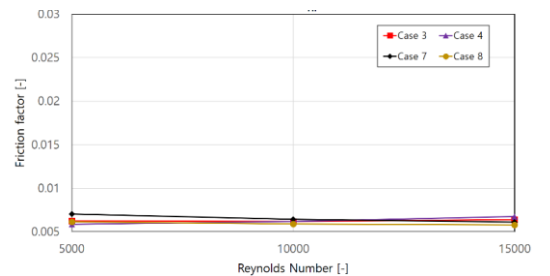
(b) Geometric shape of  $D_w/D_{HP} = 0.3$



(c) Geometric shape of  $D_w/D_{HP} = 0.6$

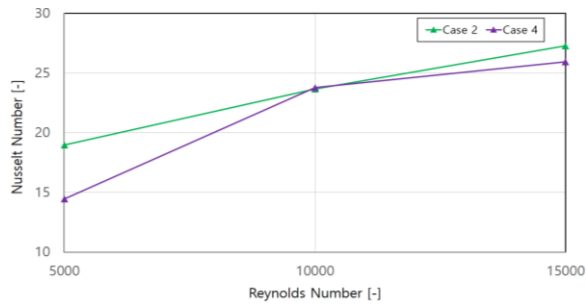


(d) Geometric shape of  $H/D_{HP} = 4$

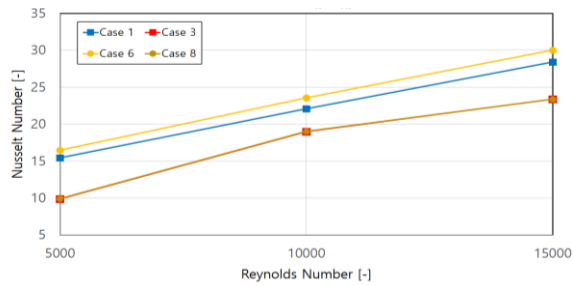


(e) Geometric shape of  $H/D_{HP} = 100$

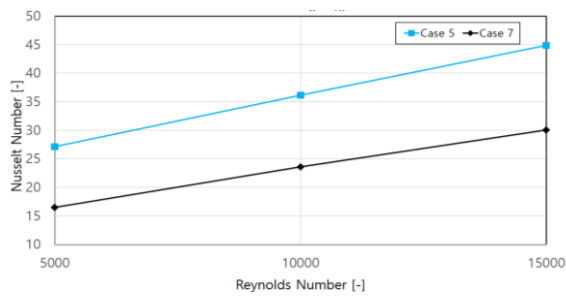
Fig. 9. Friction factor with geometric shape difference by CFD



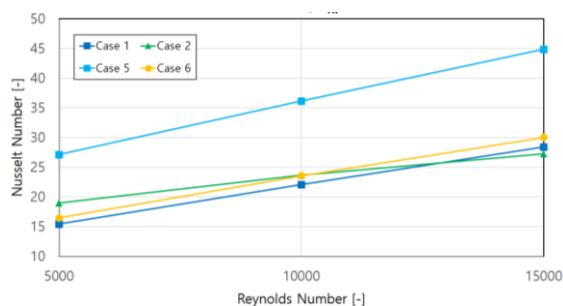
(a) Geometric shape of  $D_w/D_{HP} = 0.15$



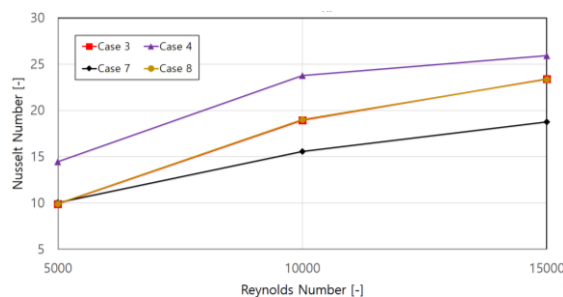
(b) Geometric shape of  $D_w/D_{HP} = 0.3$



(c) Geometric shape of  $D_w/D_{HP} = 0.6$



(d) Geometric shape of  $H/D_{HP} = 4$



(e) Geometric shape of  $H/D_{HP} = 100$

Fig. 10. Nusselt number with geometric shape difference by CFD

#### 4. Conclusion

CFD simulation has been conducted to understand characteristics of friction factor and Nusselt number with the difference of geometric shapes of wire diameter, wire winding pitch, heat pipe diameter. According to the results of the CFD Investigation, the conclusions are as follows.

1. Heat pipe with wire spacer is effective for enhancing heat transfer.
2. Furthermore, geometrical shapes of wire spacers are sensitive for friction factor and Nusselt number.
3. In the next stage, CFD simulation with various turbulent models and geometric shape will be performed.

#### ACKNOWLEDGEMENTS

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