pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.25, No.2, (2023), pp.19~24 https://doi.org/10.9714/psac.2023.25.2.019

Pressure drop characteristics of concentric spiral corrugation cryostats for a HTS power cable considering core surface roughness

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(Received 8 June 2023; revised or reviewed 28 June 2023; accepted 29 June 2023)

Abstract

Recently, interest in renewable energy such as solar and wind power has increased as an alternative to fossil fuels. Renewable energy sources such as large wind farms require long-distance power transmission because they are located inland or offshore, far from the city where power is required. High-Temperature Superconducting (HTS) power cables have more than 5 times the transmission capacity and less than one-tenth the transmission loss compared to the existing cables of the same size, enabling large-capacity transmission at low voltage. For commercialization of HTS power cables, unmanned operation and long-distance cooling technology of several kilometers is essential, and pressure drop characteristic is important. The cryostat's spiral corrugation tube is easier to bend, but unlike the round tube, the pressure drop cannot be calculated using the Moody chart. In addition, it is more difficult to predict the pressure drop characteristics due to the irregular surface roughness of the binder wound around the cable core. In this paper, a CFD model of a spiral corrugation tube with a core was designed by referring to the water experiments from previous studies. In the four cases geometry, when the surface roughness of the core was 10mm, most errors were 15% and the maximum errors were 23%. These results will be used as a reference for the design of long-distance HTS power cables.

Keywords: CFD, corrugation tube, HTS power cable, pressure drop

NOMENCLATURE

ΔP = pressure drop due to the pipe friction
f = friction coefficient of pipe
L = length of HTS power cable
D_h = hydraulic diameter
A = cross section area of flow
ρ = density
$\dot{m}$ = mass flow rate
Re = Reynolds number
ε = sand roughness
D_o = outer diameter of corrugation flow
D_i = inner diameter of corrugation flow
D_c = core diameter of corrugation flow
p = pitch of corrugation flow
e = wave height of corrugation flow
a = wave angle of corrugation flow

1. INTRODUCTION

Global warming is intensifying due to greenhouse gas emissions from the continued use of fossil fuels, but energy demand in urban areas is still increasing. As an alternative to fossil fuels, there is a growing interest in renewable energy systems such as solar, hydrogen, geothermal, biomass and wind power [1, 2].

These renewable energy sources require long distance power transmission because they are placed inland or offshore that far from the downtown where power is needed.

Long-distance power transmission is used at extra high voltage to reduce electric loss. It caused troubles such as damage to the natural scenery, noise damage, and electromagnetic wave effects to the residents of the area around the extra high voltage transmission lines [3, 4].

As an alternative to extra high voltage transmission, high temperature superconducting (HTS) power cables have been researched and are currently in the development stage for commercialization [5-9]. The HTS power cable is a large power capacity, high efficiency power transmission device that generates more than 5 times the transmission capacity and less than 10 times the transmission loss compared to conventional cables of the same diameter. As for environmental advantages, it does not use any environmental pollutants such as insulating oil or SF6 gas used in ultra-high voltage power cable. And it has perfect magnetic shielding performance, so it can fundamentally solve the electromagnetic wave problem.

Korea Electric power Corporation (KEPCO) and LS Cable & System succeeded in commercial operation of 23 kV, 50 MVA single phase HTS power cable in the 1km long Singal-Heungdeok substations. The Jeju Smart Grid Demonstration Center has completed the 1 km, 154 kV, 600 MVA 3 phase HTS power cable test. Recently, the 3-phase coaxial HTS power cable of 23 kV, 60 MVA is being installed the Munsan-Seonyu substations of about 3 km long [10, 11].

For the commercialization of long distance HTS power cables, unmanned operation of the HTS power cable cooling system and long distance cooling technology are

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required. The forced circulation of subcooled liquid nitrogen removes the heat load generated during cable operation [12]. The cooling capacity of liquid nitrogen that flowing the cryostat of the HTS power cable grows as the mass flow increases, but the pressure drop due to friction in the cryostat also increases. Since the operating conditions of the HTS power cable cooling system are limited by the mechanical properties of the cryostat and the phase change of liquid nitrogen, a thermodynamic analysis is required considering the characteristics of the cryostat.

The cryostat of HTS power cable is made of spiral corrugated tube because it is easy to bend according to the geographical characteristics of the installation site. These complex three dimensional geometry make it difficult to predict pressure drop using a Moody Chart. In addition, the irregular and rough surfaced core protection layers that fasten the multi layered cable cores make the pressure drop more difficult to predict.

Many researchers, including E.A.M. Elshafei and Yang Dong, conducted research on the pressure drop characteristics in various types of corrugation tube without a core, but could not analyze the effect of the core [12-14]. O Maruyama compared the experimental and analysis results of the pressure drop of the spiral corrugation cryostat with a core, but conducted only for a one shape and did not consider the effect of surface roughness of the cable core [15].

In this study, to analyze the characteristics of pressure drop in spiral corrugation cryostat with various diameter of cable core, CFD analysis was performed on the flow shape of 4 cases of the previous water similarity experiment, and the friction factor was compared according to the surface roughness of the cable core. This paper can be used as a reference when designing a long distance HTS power cable for commercialization.

2. High Temperature Superconducting power cable

2.1. Structure of HTS power cable

Fig. 1 shows the structure of single phase HTS power cable. The HTS power cable classified into a cable core that flows current and a cryostat section for maintaining a cryogenic environment.

The cable core is composed of a copper former, a conducting layer, a semiconducting layer, an insulating layer, a shield layer and a core protection layer from the inside. The copper former supports the shape and becomes a passage that fault current flows at the fault occurred the conducting layer stacked with superconducting tapes placed in parallel is the passage that current flows during normal operation. The semiconducting layer is made of carbon black paper to even out the charge distribution of the conductor. The insulating layer is made of PPLP(Polypropylene laminated paper) to ensure the insulation performance between the conducting layer and the shielding layer in liquid nitrogen. The shielding layer shields the magnetic field generated by the conductive layer and consists of several stacked superconducting tapes placed in parallel. A core protection layer is wound on the outermost layer to fasten the multi layered cable core. The cryostat section is composed of spiral corrugation cryostat, multi-layer insulation (MLI), vacuum vessel and PVC(Poly vinyl chloride) jacket.

The spiral corrugation cryostat is a passage that liquid nitrogen flows to cool the cable core. MLI reduce radiative heat intrusion into liquid nitrogen from room temperature. A vacuum vessel is used to remove convective heat transfer. A PVC jacket protects the cable from external impact and corrosion.

The HTS power cables have various type and sizes depending on the purpose of use and the power capacity [16, 17]. Power transmission, which is the bulk movement of electrical energy from power plant to substation, generally uses a three phase cable that is more efficient than single phase cable. Power distribution that supplies electrical energy from substations to individual consumers is used as single phase or three phase cable as needed. A single phase power cable has one cable core that current flows. On the other, a three phase power cable has three cable cores to flow current in each phase, so it needs a relatively large cryostat. As another type of three phase power cable, there is a coaxial three phase power cable that forms three phases in one core by insulating between phases. The diameter of the cable core depends on the amount of power delivered, and the diameter of the cryostat depends on the mass flow of liquid nitrogen that is determined by the cable length and heat load.

2.2. Spiral corrugation cryostat and core protection layer

The cryostat of HTS power cables is a passage for subcooled liquid nitrogen and is exposed to cryogenic and high-pressure environments. Since the cryostat should not be broken under the liquid nitrogen temperature, it is made of an aluminum ally having sufficient strength. The spiral corrugation tube is used as a cryostat, because it is easier to install than a round tube when a curved shape is required according to the installation condition.

Fig. 2 shows the geometry of spiral corrugation cryostat and core protection layer. For a general round tube, the

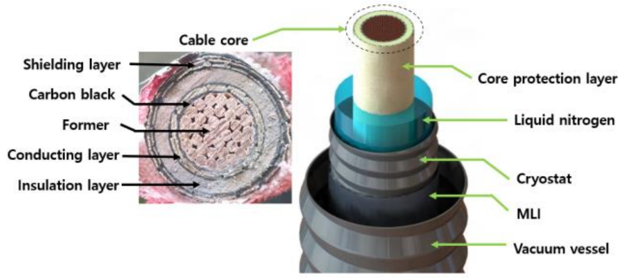

Fig. 1. Structure of single phase HTS power cable.

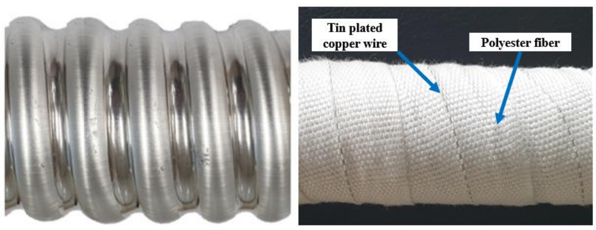

Fig. 2. Geometry of spiral corrugation cryostat and core protection layer.

pressure drop can be readily estimated by Moody chart, but for a corrugation tube, it is difficult to use Moody chart. For this reason, the pressure drop through the spiral corrugation tube can only be estimated by the experimental approach.

The core protective layer is wound on the outside of the core. it is a tape in which tin plated copper wires are arranged on polyester fibers, which has sufficient mechanical properties to bind the cable core at the cryogenic environment. It has a rough surface by the weaving structure of the fiber and the tin-plated copper wire, and has more irregular roughness because the core protection layer is overlaid. This geometrical shape makes it more difficult to predict the pressure drop in the cryostat of the HTS power cable.

2.3. HTS power cable operating limit condition

Working temperature and pressure are important factors in designing the HTS power cable cooling system. The optimal operating conditions should be determined in considering the safety and economy aspects of the cooling system as well as the electrical performance of the HTS cable.

The freezing point of liquid nitrogen (1 atm, 63.2 K) should be avoided for stable fluid flow in the cryostat, and the boiling point of liquid nitrogen (1 atm, 77.3 K) should also be avoided to suppress bubble generation that cause dielectric breakdown. Higher operating pressure in the cooling system can prevent bubble generation by increasing the boiling temperature of liquid nitrogen. But the operating pressure should not exceed the allowable pressure of the cryostat [18, 19].

Fig. 3 shows an example of operating limiting condition of the HTS power cable cooling system. This cooling system was utilized for a three-phase coaxial HTS power cable with operating voltage of 23 kV, a power capacity of 60 MVA and a cable length of 3 km. At any point in the HTS power cable and cooling system, it is operated within the limit condition.

As liquid nitrogen cools the cable core, the pressure decreases and the temperature increases. For unmanned operation, it is circulated as an initial condition through a pump and cryocooler. The change of elevation due to the vertical installation of the HTS power cable causes hydrostatic pressure on the liquid nitrogen. Therefore, underground installations experience rapid pressure changes due to elevation changes.

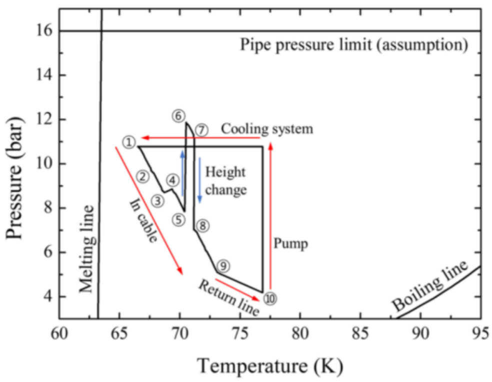

Fig. 3. Example of operating limit condition for HTS power cable cooling system [19].

2.4. Pressure drop of HTS power cable

The pressure drop (ΔP) due to friction in the tube that flowing the liquid nitrogen can be calculated by

$$\Delta P = f \frac{L}{D_h} \frac{\dot{m}^2}{2\rho A^2} \tag{1}$$

where f, L, D_h, A, ρ and $\dot{m}$ are the friction factor, the tube length (m), the hydraulic diameter of flow (m), flow cross sectional area (m^2), the density of liquid nitrogen (kg/m^3) and the mass flow rate of liquid nitrogen (kg/s).

According to The Colebrook-White equation (2) [19], the friction factor is related to the Reynolds number (Re) and the surface roughness (ε).

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\frac{\varepsilon}{D_h}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad (Re > 4000) \tag{2}$$

where ε (mm) is mean equivalent sand grain roughness.

The mass flow rate of the liquid nitrogen is affected by the roughness of the core protection layer as well as the height and pitch of the spiral corrugation shape.

The effect of complex turbulent flow due to spiral corrugation tube can be analyzed into CFD, However, the increase in pressure drop due to the irregular and rough surface of the core protection layer is difficult to predict. The equivalent sand grain roughness of the core protection layer will be defined by comparing the experiment and analysis.

3. CFD simulation of HTS power cable

3.1. Flow passage on HTS power cable

To design the CFD simulation model of flow into the HTS power cable, the flow shape of the previous water similarity experiment was referred to [20]. Fig. 4 shows the flow zone of a spiral corrugation cryostat and its dimensions are shown in Table 1. The cable cores are arranged concentrically with the spiral corrugation cryostat using a spacer, with two cores of different diameters in two spiral corrugation cryostats with different outer diameters.

The core wall is irregular and has a surface due to the existence of core protection layer, and the spiral corrugation cryostat wall has a smooth surface. Near the cryostat wall, the flow is greatly affected by the spiral corrugation shape, and the closer it gets to the core wall, the weaker the effect is.

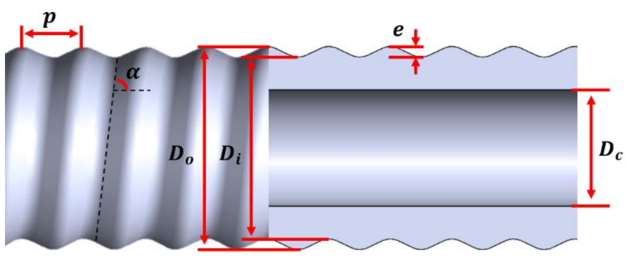

Fig. 4. Flow zone of spiral corrugation cryostat.

TABLE 1
DIMENSION OF SPIRAL CORRUGATION CRYOSTAT.

Parameter	Value			
	Case 1	Case 2	Case 3	Case 4
D_o (mm)	85.6		108.7	
D_i (mm)	76.6		99.7	
D_c (mm)	49	61	77	90
P (mm)	25.5		28.5	
e (mm)	4.5			
α (deg)	83			

3.2. Boundary condition and mesh independency test

Table 2 shows the boundary conditions for CFD simulation of HTS power cable. The working fluid is water at a standard ambient temperature and pressure. Since the cryostat was manufactured through extrusion processing, a smooth wall was applied. The equivalent sand grain roughness of 1, 5 and 10 mm was applied to the core protection layer. In order to analyze the fully developed flow excluding the entrance region of the flow, the model length was set to 1 m.

The k-ε turbulence model was used with scalable wall function. The scalable wall function is used to simulate the relationship between velocity distribution and wall shear in a turbulent boundary layer. y^+ is a dimensionless parameter that relates to the grid size near a solid wall. The first mesh of the fluid at the wall should be made when y+ is greater than 11.225 in order to use the logarithmic overlap law that simulates the turbulent boundary layer well.

It is necessary to create a mesh that can obtain a result suitable for the purpose of analysis. To create a suitable mesh for analyzing the pressure drop characteristics of a flow in spiral corrugation cryostat having a concentric core, a mesh independency test should be performed as shown in Fig. 5. In the mesh independency test, the equivalent sand grain roughness of the cable core was 10 mm, and the element size was applied from 1×10^{-1} m to 1×10^{-3} m. The results of the mesh independent test show that the pressure drop per unit length converges when the element size is less than 1.3×10^{-3} m of all cases.

Fig. 6 shows the 3D mesh of flow region and cross section for spiral corrugation cryostat. The size of the mesh element is 1.3×10^{-3} m, and the corrugation tube wall and the cable core wall were created more densely considering the velocity boundary layer.

To analyze the pressure drop in the fully developed flow,

TABLE 2
BOUNDARY CONDITIONS FOR CFD SIMULATION

Parameter	Condition
Working fluid	Water
Temperature	Standard ambient temperature
Outlet pressure	Standard ambient pressure
Model length	1 m
Wall roughness	Cryostat – smooth wall
Wall condition	No-slip condition
Turbulence model	*k-ε*

a pressure drop per unit pitch was checked as shown in Fig. 7. The equivalent sand grain roughness of the cable core is 10 mm. At the entrance region, the pressure drop was small compared to fully developed flow regime because the flow did not completely follow the spiral corrugation shape. The pressure drop in the fully developed flow is almost constant in all cases.

3.3. Friction factor according to surface roughness of cable core

Fig. 8 shows the friction factor according to the equivalent sand grain roughness of each case. As the Reynolds number increased, the friction factor decreased gradually. As the equivalent sand grain roughness of the cable core increased, the friction factor also increased.

The friction factor of a round tube with a smooth surface with the same hydraulic diameter is less than 0.05 obtained

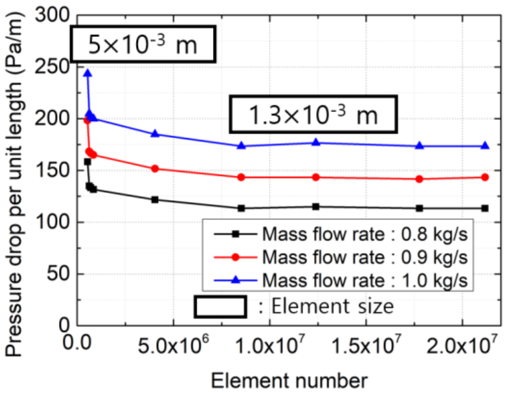

Fig. 5. Mesh independent test results.

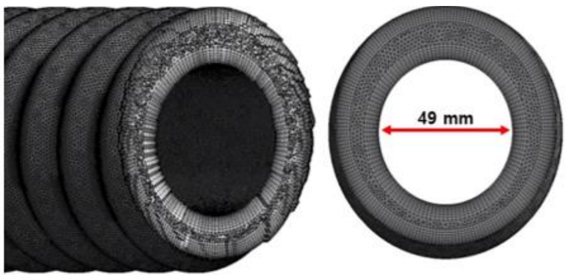

Fig. 6. 3D mesh of flow region and cross section for spiral corrugation cryostat in case 1.

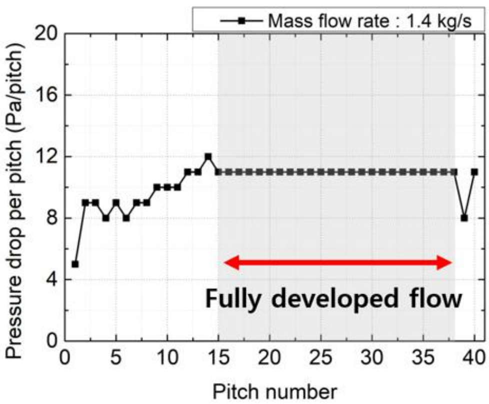

Fig. 7. Fully developed flow in case 1.

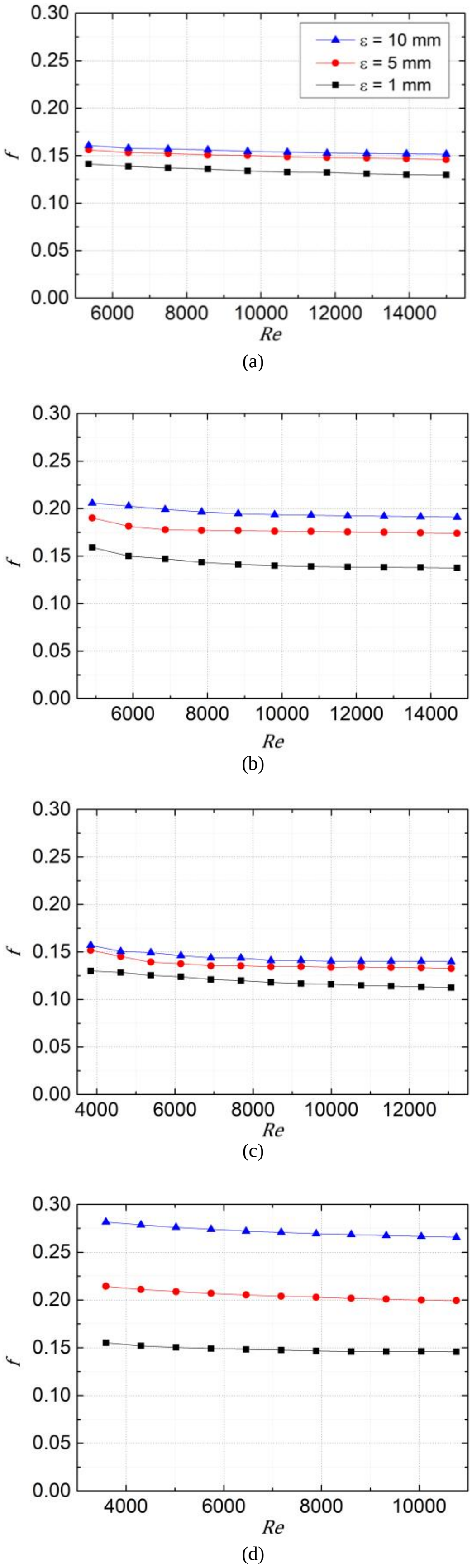

Fig. 8. Friction factor according to the equivalent sand grain roughness (a) case 1, (b) case 2, (c) case 3, (d) case 4.

from the Moody chart. The spiral corrugated cryostat has a friction factor about 3 times greater than the round tube.

Cases 1 and 2 have the same diameter cryostat and have different diameter cable cores. Similarly, cases 3 and 4 have the same diameter cryostat and have cable cores of different diameters. When the diameter of the cryostat is the same, the equivalent sand grain roughness of the cable core greatly affect on the friction factor as the diameter of the core increases.

It is shown that the closer between the cable core and the spiral corrugation wall are, the more affected by the surface roughness of the cable core. If the diameter of the cryostat is sufficiently larger than the cable core, the effect of the cable core surface roughness is be insignificant.

3.4. Comparison with previous experimental results.

Liquid nitrogen has a density about 20% smaller than that of water and a viscosity coefficient about 5 times lower, but the pressure drop characteristics can be analyzed through water experiments using the dimensionless Reynolds number and friction coefficient. In addition, subcooled liquid nitrogen, which is a working fluid, does not cause an immediate phase change, rapid volume increase due to evaporation can be ignored.

Fig. 9 shows the comparison between the friction factor obtained from the previous experiment [20] and the CFD simulation result with 10 mm equivalent sand grain roughness of the cable core. In all cases, most of the errors were within 15%, except for Case 3.

The error would be originated from the winding of the protection layer that is made by human work.

4. Conclusion

We compared the results of CFD simulation with the previous experiment and confirmed the most similar to the experiment result when the cable core has a 10 mm equivalent sand grain roughness in CFD simulation.

As a study on the pressure drop characteristics of HTS power cables, we designed an appropriate CFD model of a spiral corrugation cryostat having a core of various diameters by comparing the results of the previous water similarity experiment.

The CFD simulation results show in all cases, the friction factor decreases gradually as the Reynolds number increases. As the diameter of the cable core increases and is closer to the corrugation tube, the surface roughness has a greater effect on the pressure drop. If the spiral corrugation cryostat is sufficiently larger than the core, the effect of the surface roughness is negligible. This study shows that the unknown surface roughness of a cable core with a wound core protection layer can be predicted by applying an equivalent sand grain roughness of 10 mm to the cable core in the CFD simulation.

This paper will be referenced in the analysis of the pressure drop characteristics of the cooling system using CFD simulation when designing long distance HTS power cables.

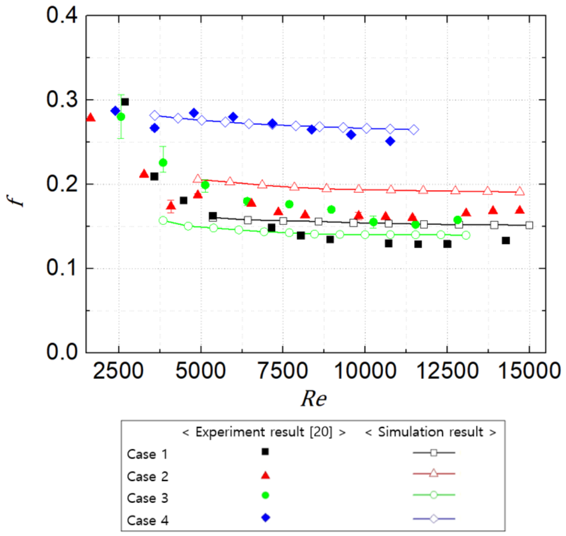

Fig. 9. Comparison of the friction factor of the previous water similarity experiment and the CFD simulation result.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(No. 2019R1A5A8083201) and the Basic Research Program funded by the Korea institute of Machinery and Materials (grant number : NK237B).

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