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Analysis and Evaluation of Separation Efficiency on Mass Flow of Mini Hydro Cyclone Separator Manufactured by 3D Printing

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3D 프린팅을 적용한 미니 하이드로 싸이클론 분리기의 질량유량을 통한 분리효율 해석 및 평가

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ABSTRACT

In this study, a mini hydro cyclone was designed and manufactured to achieve an inlet flow rate of 2 L/min in the experiment, which was conducted using alumina powder with a specific gravity of 3.97. This hydro cyclone was studied for using in steam and water analysis system (SWAS) of thermal power plant and was manufactured by 3D printing. Numerical analysis was performed with Solidworks Flow Simulation, utilizing the reynolds stress method (RSM) of fluid multiphase flow analysis models. Experimental and numerical analysis were performed under the three conditions of inlet velocity 2.0, 4.0, and 6.0 m/s. The separation efficiency was over 80% at all inlet velocity conditions. At the inlet velocity 4m/s, the separation efficiency was the best, and it was confirmed that the efficiency was more than 90%.

Key Words : 3D Printing(3D프린팅), Hydro Cyclone(하이드로 싸이클론), Separation Efficiency(분리효율), Mass Flow Rate(질량유량), Mini Cyclone Separator(소형 싸이클론 분리기)

1. Introduction

Hydro cyclone separators refer to cyclone separators that separate particles contained in water using centrifugal force. In a hydro cyclone separator, a mixture of water and particles is injected through the inlet, and the particles are separated from the water using centrifugal force. Large and heavy particles are discharged through the outlet at the bottom (underflow), whereas small and light particles are discharged through the outlet at the top (overflow).[1] Cyclone separators have been widely used in various appliances such as household cleaners and air purifiers because they have no separate driving devices and are easy to construct and manufacture.[2]

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The efficiency and performance of a cyclone separator are expressed through the prediction and verification of the cut-off size, which is the criterion for dividing the flow into overflow and underflow, i.e., the outlets of the cyclone separator. d_{50} is generally used as a coefficient to represent the efficiency of such separation. Actually, however, some of the heavy particles are erroneously placed into overflow, and the coefficient that corrects this error is expressed as d_{50c}.[4] The value of d_{50c} is dominantly determined by the geometry of the cyclone separator, but it is also significantly affected by the density and velocity of the mixture introduced through the inlet. The pressure drop at the inlet is also known to significantly affect the performance of the separator. Therefore, the efficiency of separation is significantly affected by the characteristics of the flow at the inlet as well as the geometry of the cyclone separator.[2–4]

Meanwhile, water is used in various processes, including in steam turbines and as cooling water in the course of producing electricity in thermal power plants. The steam and water analysis system (SWAS) is generally used to analyze the real-time water quality of such water and steam. In the case of old thermal power plants, however, when the water is sent to the SWAS through long pipes, foreign substances present in the pipes frequently flow into the process water, thereby damaging the measuring instruments and adversely affecting the operation of the entire power generation equipment. At present, 150-μm (primary) and 100-μm (secondary) particles are filtered by installing strainer-type filters in double layers, but the particle size of 50 μm or less, as required by the actual water quality analyzer, cannot be achieved. The main foreign substances that block the filters are hematite and magnetite, and a technique capable of separating more than 90% of the foreign substances larger than 100 μm is required. The purpose of this study is to analyze and evaluate the separation efficiency of a cyclone separator for application to the SWAS. As the SWAS requires a small amount of water (1–2 L/min), a very small hydro cyclone separator, compared to existing commercial cyclone separators, is required. As the typical manufacturing method requires considerable cost and time, complex geometry can be produced easily and rapidly using a three-dimensional (3D) printer with high efficiency.

Therefore, in this study, flow analysis was conducted to predict the internal flow, the flow rates of underflow and overflow, and the mass flow rate according to the inlet velocity for the designed cyclone separator. In addition, an actual cyclone separator was fabricated using the 3D printer, and its separation efficiency was compared and evaluated.

2. Structure and Analysis Conditions of Hydro cyclone Separator

2.1 Structure of hydro cyclone separator

The structure of the hydro cyclone separator consists of a cylindrical section at the top and a conical portion at the bottom. The cylindrical section includes an inlet for the injection of a mixture and an outlet at the top for the overflow. The conical portion includes an outlet at the bottom for the underflow.[5–8]

Fig. 1 presents the schematics of the main parts that affect the geometry and performance of the cyclone separator, and Table 1 summarizes the specifications of the cyclone separator. Fig. 2 presents the schematic of the water quality analyzer of a power plant system. When the process water enters the system, it is cooled down to a safe level in the first chiller, and foreign substances are removed in the cyclone separator to produce the sample water. The sample water is then supplied to the water quality analyzer through the second chiller.

Table 1 Specification of hydro cyclone

I	De	S	h	H	B
2	2	8	12.5	39	2

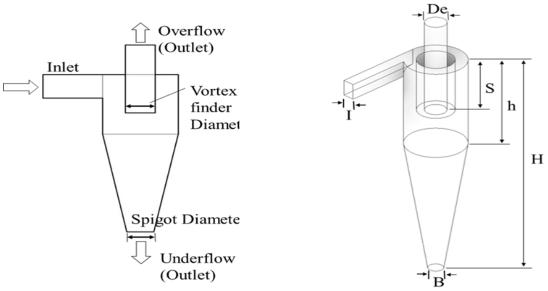

Fig. 1 Hydro cyclone design and parameter

Table 2 Specification of hydro cyclone

Flow type	Reynolds stress method
-Analysis type	-Inside
-Wall boundary	- No slip condition
- Solver	-Steady state
-Inlet velocity (m/s)	-2.0, 4.0, 6.0
-Inlet pressure (kPa)	-0
-Solid volume	-6.4853e-05 m^3
-Fluid volume	-0.000478921 m^3

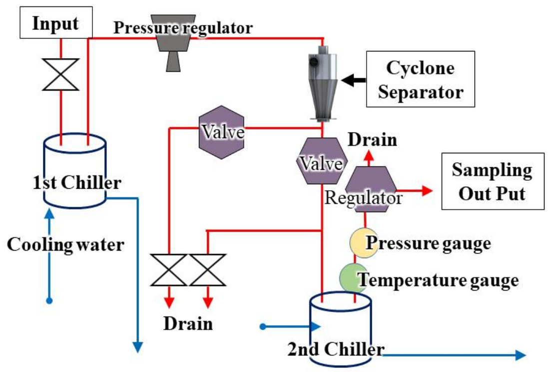

Fig. 2 Schematic diagram of water sampling system

2.2 Analysis model of hydro cyclone separator

The mass flow rate of the hydro cyclone separator was analyzed using Solidworks Flow Simulation, a 3D design and analysis software program. For the flow analysis of the designed modeling, a simulation using "geometry inspection," which is a function of Flow Simulation, confirmed that there was no problem with the geometry. An internal flow field was then formed by blocking the outlets and inlet using the lid function, and the fluid and solid volumes of the modeling were examined. In general, the flow inside the hydro cyclone separator is laminar and turbulent. Both the water and particles are regarded as a continuum. Therefore, the Reynolds stress method (RSM) model was used in this study. The analysis conditions are summarized in Table 2. The flow inside the cyclone separator was assumed to be in a steady state, and the temperature was assumed to be constant. The liquid used was water, and the properties of the input constants in the program were set. Fig. 3 depicts the boundary conditions used. The particles introduced through the inlet pass through the vortex finder and perform swirl motion. As the feed rate at the inlet increases, the particles are separated by size and weight owing to the increase in the centrifugal force inside the hydro cyclone separator. In this study, analyses were conducted under the conditions of 2 and 4 m/s, which satisfy the actual flow rate at the inlet, and the condition of 6 m/s, which causes an excessive flow rate.

3. Experimental Setup and Method

3.1 Fabrication of cyclone separator using 3D printing

As for the fabrication of the cyclone separator using the 3D printer, the sizes of the inlet and outlets were designed based on the Stairmand model to meet the target flow rate and pressure conditions. The cyclone separator was designed as a flange type for easy pipe connection in the case of performance evaluation, and a natural flow could be formed inside the cyclone separator. A transparent liquid-type PC-like material was used for 3D printing so that the normal formation of the internal flow field could be easily confirmed from the outside. Fig. 4 depicts the fabricated cyclone separator.

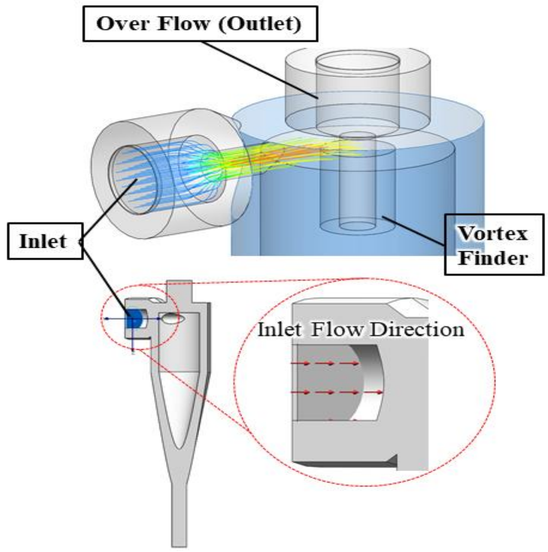

Fig. 3 Boundary condition of flow simulation

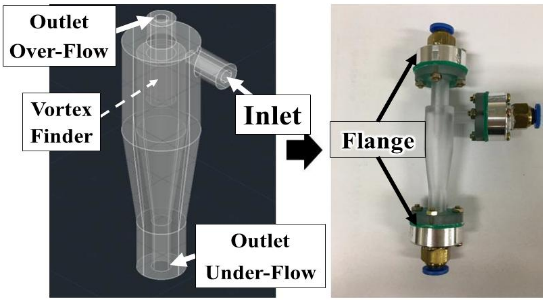

Fig. 4 Experimental setup - Hydro Cyclone photo

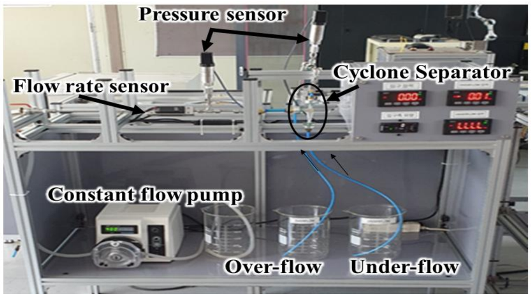

Fig. 5 Experimen equipment setup photo

3.2 Experimental setup and method

In this study, the process of separating hematite and magnetite, which are foreign substances found in the sample water, in the water quality analyzer of a power plant system was assessed. To this end, a performance evaluation device was constructed as illustrated in Fig. 5.

First, a constant-flow pump was used to maintain a constant flow rate, and pressure and flow sensors were installed at each inlet and outlet to monitor the flow rate. Alumina particles with a density similar to those of hematite and magnetite were used. The physical properties of the particles are listed in Table 3. 2,000 ml of water and 50 g of 53–75 μm alumina particles were mixed using a stirrer, and the flow rate was measured as the motor rpm of the pump was varied from 100 to 450. The mixture introduced into the cyclone separator through the inlet was discharged through two outlets. The mixtures discharged through the overflow and underflow were collected in different beakers and dried using a dryer. The weight of the dried powder was measured to evaluate the separation efficiency, as depicted in Fig. 6. The performance was evaluated under the same conditions as the flow analysis.

Table 3 Property data of Alumina

Maker	D50	Al_2O_3[%]	g/cm3	Color
Sumitomo	60	99.9	3.9	Brown

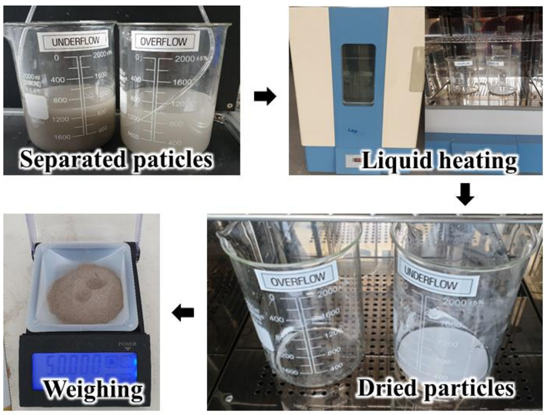

Fig. 6 Test circuit – Hydro cyclone

4. Results and Discussion

4.1 Results of analysis

To compare the changes in the mass flow rate of the hydro cyclone separator based on the inlet velocity, a numerical analysis was conducted for the velocities of 2, 4, and 6 m/s. Table 4 presents the results of the numerical analysis based on the change in velocity. When the velocity was increased from 2 to 4 and 6 m/s, a cyclone was formed from the inlet through the vortex finder. A descending primary vortex was also formed through the application of swirl motion.

Fig. 7 depicts the variations in the flow based on the velocity. Owing to the occurrence of the descending primary vortex, particles were collected through the underflow as water collided with the inner wall of the main body. As the inner wall became narrower toward the bottom of the cylinder, the velocity of the swirl flow increased, resulting in sufficient centrifugal force. In addition, as the downward swirl flow increased as it approached the apex at the lower part of the conical portion through the end of the cylindrical section, it finally led to upward swirl motion owing to the generation of an ascending secondary vortex, thereby causing water to be discharged through the overflow.[9]

Table 5 presents the results of the analysis of the mass flow rate. For the inlet velocities of 2, 4, and 6 m/s, the maximum velocity was observed when water passed through the inlet and reached the vortex finder, as illustrated in Fig. 8.

When the inlet velocity was increased from 2 to 4 and 6 m/s to compare changes in the mass flow rate of the hydro cyclone separator according to the inlet velocity, it was found that the flow rate also increased. As the inlet velocity increased, the pressure increment increased, causing an increase in the mass flow rate through the underflow and overflow. The maximum value of the underflow was -0.0248 at an input velocity of 2 m/s, but it increased to -0.0495 at 4 m/s and -0.0743 at 6 m/s. Therefore, when the mass flow rates of the hydro cyclone separator were compared through numerical analysis based on the inlet velocity, it was confirmed that the mass flow rate at the inlet and outlets increased along with the pressure rise when the inlet velocity increased.[10–13] In the analysis of mass flow rate for each model, both the underflow and overflow exhibited similar mass flow rate values. This similarity can be attributed to the fact that the water discharged after the primary vortex performed an upward swirl motion owing to the secondary vortex, as depicted in Fig. 9.

Table 4 Results of Inlet and Outlet velocity

		2 m/s	4m/s	6m/s
Inlet max. velocity (m/s)	max	12.286	24.214	36.388
	ave	12.251	24.177	36.311
	min	12.206	24.137	36.245
Over-flow velocity (m/s)	max	1.172	2.621	3.789
	ave	1.124	2.426	3.662
	min	1.107	2.195	3.508
Under-flow velocity (m/s)	max	1.963	3.884	5.926
	ave	1.837	3.809	5.850
	min	1.758	3.754	5.803

Table 5 Results of mass flow rate

		2 m/s	4m/s	6m/s
Over-flow (Kg/s)	max	-0.0095	-0.0192	-0.0278
	min	-0.0097	-0.0186	-0.0278
Under-flow (Kg/s)	max	-0.0248	-0.0495	-0.0743
	min	-0.0248	-0.0495	-0.0743

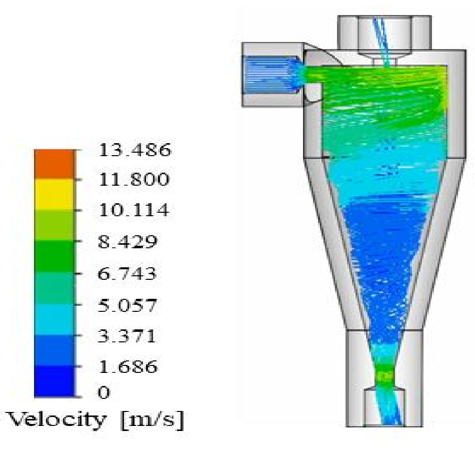

Fig. 7 Flow trajectory of flow simulation

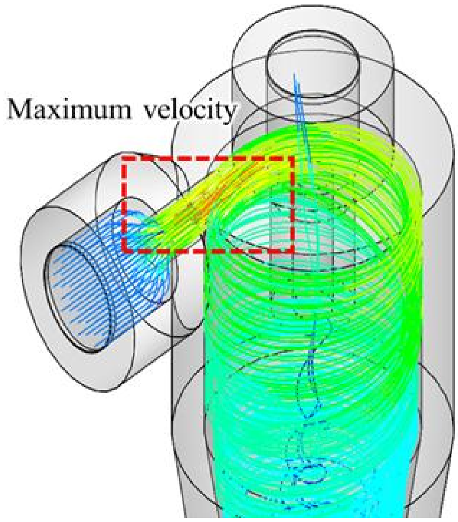

Fig. 8 Maximum velocity of flow simulation

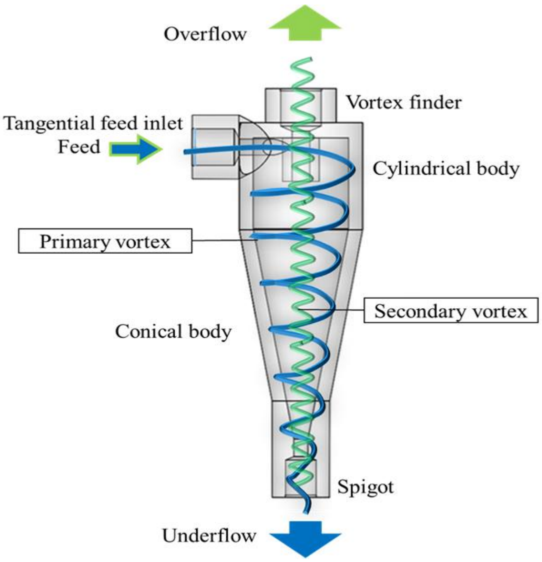

Fig. 9 Schematic diagram of the secondary vortex

Table 6 Results of separation efficiency

Velocity(m/s)	Separation efficiency(%)	Mass flow ratio
2	87.8	5.3:4.7
4	92.6	5.1:4.9
6	83.5	5.5:4.5

4.2 Performance evaluation of hydro cyclone separator

In the performance evaluation, the particle separation efficiency was evaluated by measuring the amount of water discharged through the underflow and overflow of the fabricated hydro cyclone separator and evaporating the water. Table 6 presents the results of measurement of the proportion of water discharged to the outlets. The separation efficiency exceeded 80% at 2, 4, and 6 m/s, and the resulting mass flow rate ratio was found to be 5.3:4.7 at 2 m/s, 5.1:4.9 at 4 m/s, and 5.5:4.5 at 6 m/s.

When these results were compared with the results of analysis of the mass flow rate because the secondary vortex could not be confirmed in the performance evaluation, it appears that the amount of water discharged to the overflow was increased by the secondary vortex. The highest separation efficiency could be obtained at 4 m/s; the mass flow rate ratio was approximately 5:5.

The lowest separation efficiency was measured at 6 m/s, which indicates that this flow rate condition is not appropriate for the size of the cyclone separator.[9] It was found that the hydro cyclone separator operating at an inlet flow rate of 0.03 kg/s demonstrates excellent separation efficiency at 4 m/s because a large amount of water is not required as the sample water for the power plant and the water discharged through the underflow is not subjected to water quality analysis sampling.

5. Conclusion

In this study, a numerical analysis was conducted to improve the applicability and separation efficiency of a designed hydro cyclone separator. The separator was fabricated using a 3D printer, and the mass flow rate and separation efficiency were evaluated based on the inlet velocity. The main results obtained in this study are as follows.

1. For the hydro cyclone separator fabricated through 3D printing, the separation efficiency increased from 87.8% to 92.6% as the inlet velocity increased from 2 to 4 m/s. This is because the internal pressure and centrifugal force acting on the particles increased as the inlet velocity increased.
2. The separation efficiency decreased to 83.5% at 6 m/s. This indicates that the excessive flow rate considering the size of the cyclone separator had a negative effect on the separation efficiency.
3. Based on a comparison of the experimental results obtained for the fabricated cyclone separator with the results of the numerical analysis, we conclude that the mass flow rate and separation efficiency of the mini-hydro cyclone separator can be predicted through conventional numerical analysis.

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