CUT-SIZE DIAMETER CALCULATION OF SALT CRYSTALS FROM A HYDROCYCLONE

Derina Paramitasari[1], Dhani Avianto Sugeng [2]

[1]Starch Technology Center, National Research and Innovation Agency
[2]Center of Technology for Energy Resources and Chemical Industry, National Research and Innovation Agency
email: deri003@brin.go.id

ABSTRACT

A hydrocyclone is physical separation equipment employed in solid-liquid processing. An important parameter in hydrocyclone design is the so-called cut-size diameter (D50), which determines the minimum size of the separated solids when the equipment performs at 50% separation efficiency. This paper discusses the calculation of the cut-size diameter (D_{50}) of a hydrocyclone operating in a salt purification pilot plant in Manyar, East Java, Indonesia. The cut-size D_{50} is calculated based on the residence time approach and compared with the collection efficiency from the mass balance. D_{50} was found to be 69.73 microns. Moreover, by using Zanker's nomograph, it was found that at the solid separation efficiency of 80.48%, the minimum diameter of salt crystal (D_{min}) is 85 microns. Because the D_{50} of HC-1 is smaller than Zanker's design, it can be concluded that the hydrocyclone will work efficiently in separating the expected products.

Keywords: hydrocyclone; cut-size diameter; salt purification; efficiency
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INTRODUCTION

The salt processing technology is intended to purify salt into various grades, from consumption, industrial to pharmaceutical salt. The grades of salt are determined by the NaCl content and other bonded impurities such as Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Sulphate (SO_4^{2-}), water (H_2O), and other organic materials. Through the decree number 88/M-IND/PER/10/2014, the Indonesian Ministry of Industries requires consumption grade salt to have minimum NaCl content of 95 w/w%. Industries require generally higher purities; leather tanning industries require a minimum NaCl content of 97.5 w/w%, whereas the Chlor Alkali Plant (CAP) expects 98.5%. The pharmaceutical industry even demands more than 99.5% NaCl content with near-zero impurities [1] [2].

Solar salt production is the most basic salt processing. In solar salt production, solar energy is used to evaporate seawater. This method requires extensive labour and a large area for the multiple stages of evaporation. However, the NaCl content can only reach 85-95% w/w [3]. Some commercially advanced technology upgrades the purity of the solar salt by several steps of washing, separation, and drying before the salt qualifies as industrial grade.

The Indonesian Ministry of Research and Technology reported that 2.9 million tonnes of industrial- salt was imported in 2020. The chloralkali plant (CAP) consumed the largest share of the industrial salt at 2.3 million tonnes [4]. This huge import is a burden for the state finance if there are no policies and actions to compensate it. Therefore, BRIN (National Research and Innovation Agency), formerly BPPT, in cooperation with PT. Garam (Persero) built a pilot plant of 40,000 tons per year industrial salt of 99.2% NaCl in Manyar, East Java. The pilot plant will process solar salt from the surrounding salt farmers.

The plant utilizes several stages of purification using concentrated brine of 23 – 24 Be (Baume degree) to reduce the Mg^{2+}, Ca^{2+}, SO_4^{2-} and organic impurities. The Baume degree is defined as NaCl content in kilograms per litre solution, and hence, a litre brine of 24 Be contains 1.196 kg NaCl. The Baume degree is linear with salinity between 0 and 29 [5].

The purification process involves a screw classifier, a mixer washer, a hydrocyclone, and an elutriator (absorber). Hydrocyclone is static equipment with a conical shape with no moving parts. Hydrocyclone works to separate solid from its liquid, known as slurries [6], [7]. The principal process of hydrocyclone can be schematized in **Figure 1.** In the Manyar plant, salt is mixed with 24 Be brine in a mixer-washer before the hydrocyclone (HC-1). The bottom product of HC-1 is a slurry of fine salt, whereas its overflow is 25 Be brine. The overflow is recycled to the mixer-washer, while the underflow goes to the Elutriator to remove the impurities further. The involved streams of HC-1 are described in **Figure 2**, while **Table 1** contains the expected composition of the finished product.

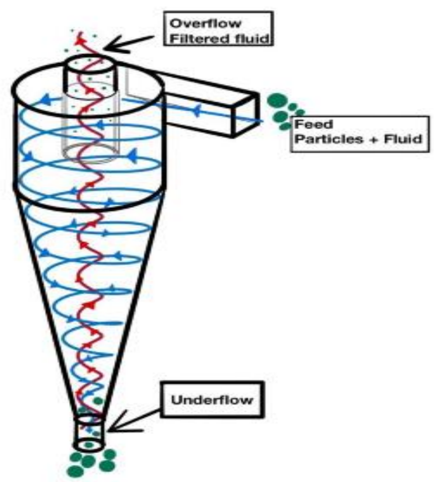

Figure 1. Hydrocyclone Schematic Process Flow. [8]

Table 1. Salt Product Specification of Industrial Grade Pilot Plant Capacities 40.000 TPY in Manyar, Gresik, East Java.

Salt Components	% wt.
NaCl	99.10
Ca^{2+}	0.10
Mg^{2+}	0.05
SO_4^{2-}	0.20
Organic impurities	0.03
Water (H_2O)	0.50
Anti-Caking	0.02
Total	100.00

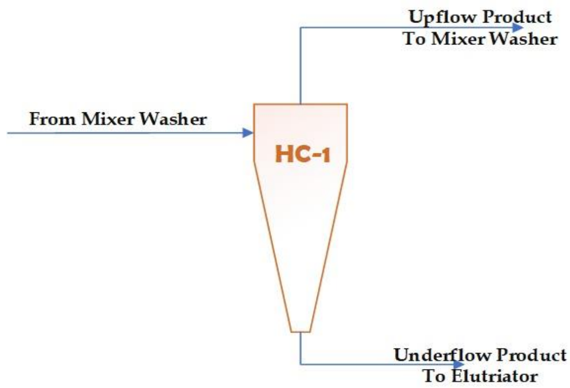

Figure 2. Block Diagram of Hydrocyclone in Industrial Grade Salt Pilot Plant Capacities 40,000 TPY in Manyar, Gresik, East Java.

This paper focuses on determining the cut-size diameter of solid salt (D_{50}) of HC-1. D_{50} defines the smallest particle diameter that will go with the underflow at 50% solid separation efficiency [9] [10]. The calculation of the hydrocyclone will be based on a capacity of 40 kilotonnes per annum (kTPA). All assumptions were made using an existing mass balance of the 40 kTPA pilot plant in Manyar, East Java, Indonesia.

METHODS

The hydrocyclone design will first be evaluated. After that, the D_{50} calculation will be based on the process' mass balance and compared with a plot of Zanker's nomograph [12].

1. Hydrocyclone Dimensions

Hydrocyclone design is based on its geometric ratio (**Figure 3**).

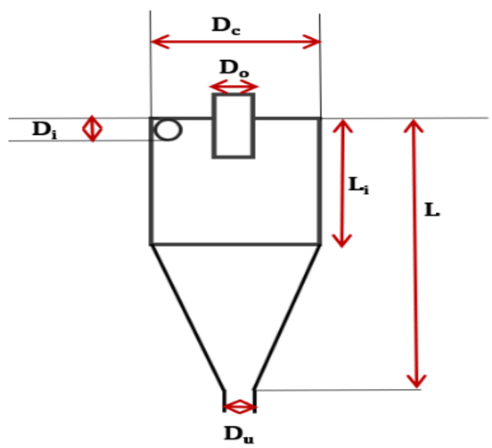

Figure 3. Hydrocyclone Geometric Dimensions.

Generally, the geometric ratios are determined by either Rietema or Bradley design standards. Those standards are used widely for manufacturing conventional cyclones and hydrocyclones. **Table 2** shows the existing hydrocyclone (HC-1) geometries, and **Table 3** compares the geometrics of the conventional standards to HC-1.

Table 2. Geometric Dimensions of the Hydrocyclone (HC-1).

Geometric Names (HC-1)	Dimensions (mm)
Cylindrical Inside Diameter (D_c)	280
Upflow Outlet Inside Diameter (D_o)	89
Inlet Inside Diameter (D_i)	57
Total Height (L)	1059

Table 3. Geometric Ratios of Hydrocyclone Types. [8]

Types vs Geometric	Rietema	Bradley	HC-1
D_o/D_c	0.34	0.20	0.32
D_i/D_c	0.28	0.14	0.20
L/D_c	5.00	6.80	3.78

2. Mass Balance of Hydrocyclone (HC-1)

The mass balance for HC-1 was also obtained from the engineering design documents. The balances of each stream of HC-1, which indicates the solid separation, are detailed in **Tables 4**, **5,** and **6**. In addition, the total mass balance can be obtained in **Table 7**.

Table 4. Feed Compositions of the Hydrocyclone (HC-1).

Compositions	Mass (kg/hour)	Density (kg/L)
NaCl	9,942.82	2.160
Ca^{2+}	20.36	1.540
Mg^{2+}	520.53	1.740
SO_4^{2-}	543.70	1.840
Organic Impurities	150.45	2.160
H_2O	11,769.77	1.000
Total	**22,947.63**	

Table 5. Upflow Compositions of the Hydrocyclone (HC-1).

Compositions	Mass (kg/hour)	Density (kg/L)
NaCl	1,941.14	2.160
Ca^{2+}	6.47	1.540
Mg^{2+}	227.23	1.740
SO_4^{2-}	233.70	1.840
Organic Impurities	24.20	2.160
H_2O	5,407.08	1.000
Total	**7,839.82**	

Table 6. Underflow Compositions of the Hydrocyclone (HC-1).

Compositions	Mass (kg/hour)	Density (kg/L)
NaCl	8,001.68	2.160
Ca^{2+}	13.88	1.540
Mg^{2+}	293.31	1.740
SO_4^{2-}	310.00	1.840
Organic Impurities	126.26	2.160
H_2O	6,362.69	1.000
Total	**15,107.82**	

Table 7. Mass Balance of the Hydrocyclone (HC-1).

Compositions	Feed (kg/hour)	Overflow (kg/hour)	Underflow (kg/hour)
NaCl	9,942.82	1,941.14	8,001.68
Ca^{2+}	20.36	6.47	13.88
Mg^{2+}	520.53	227.23	293.31
SO_4^{2-}	543.70	233.70	310.00
Organic Impurities	150.45	24.20	126.26
H_2O	11,769.77	5,407.08	6,362.69
Total	**22,947.63**	**7,839.82**	**15,107.82**

3. Cut Size Diameter (D_{50})

In HC-1, the solid salt particles go down as underflow with less water than overflow product. The cut-size diameter (D_{50}) of HC-1 can be estimated with Equation 1. This equation is based on the residence time approach; a particle with a certain size can be separated if it remains in HC-1 for longer than necessary to allow it to hit the HC-1 wall.

$$D_{50} = K \left[\frac{\mu \; x \; D_c}{Q \; x \; (\rho_s - \rho)}\right]^{0.5} x \; D_c \qquad (1)$$

With K as the design constant for a hydrocyclone (**Table 8**), μ as the liquid's viscosity (kg/ms), D_c as the cylindrical inside diameter (m), Q as the volumetric feed flow rate (m^3/s), ρ_s as the solid density (kg/m^3) and finally ρ as the liquid density (kg/m^3)

Table 8. Constant Parameter for Rietema's and Bradley Conventional Designs. [11]

Design	K	B	C	Euler Number
Rietema	0.039	145	4.75	1,200
Bradley	0.016	54.6	2.61	7,000

4. Solid Separation Efficiency

Solid separation efficiency is a percentage ratio between the solid flow rate in the underflow product and the solid flow rate in the feed that can be described in Equation 2 below.

$$\eta_s = \frac{m_u}{m_f} x\ 100\% \quad (2)$$

With :

m_u : NaCl flowrate in underflow product, kg/hour

m_f : NaCl flowrate in feed, kg/hour

η_s : Solid separation efficiency, %

5. Zanker Nomograph

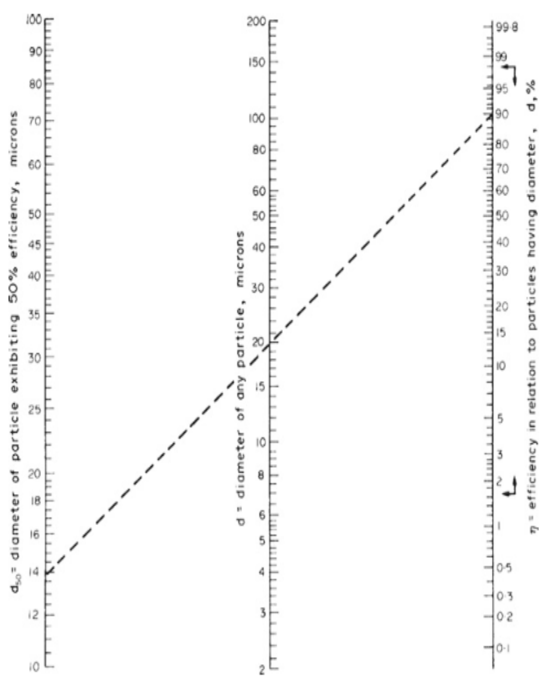

Figure 4. Zanker Nomograph. [12]

The Zanker nomograph is widely used in the preliminary calculation of cyclones and hydrocyclones. The nomograph correlates D_{50} and Dmin at a certain η_s.

RESULTS AND DISCUSSION

Table 3 shows that the geometric ratio of HC-1 is in a closer category to the Rietema design. This result is needed to determine the K value in **Table 8**. Moreover, the required parameters to calculate D_{50} and η_s are listed in Table 9.

Table 9. Data for Calculating Cut Size Diameter and Collection Efficiency of Hydrocyclone (HC-1).

Data	Value	Unit
K	0.039	
μ	0.0008	kg/m.s
D_c	0.28	Meter
Q	0.005	m^3/s
ρ_s	2,160	kg/m^3
ρ	1,000	kg/m^3
m_u	8,001.68	kg/hour
m_f	9,942.82	kg/hour

Equation 1 yielded D_{50} of 69.73 microns was obtained, and it means 50% of total salt crystals are smaller than 69.73 microns. The other 50% are larger than 69.73 microns and will go down as an underflow product of HC-1 at 50% solid separation efficiency (η_{50}).

Based on the mass balance in Table 4, Table 6, and Equation 2, the solid separation efficiency of HC-1 (η_s) is relatively high (80.48%). Higher η_s compared to η_{50} means that the minimum salt crystal size in the underflow of HC-1 (D_{min}) is larger than 69.73 microns (D_{50}).

D_{min} with a η_s of 80.48% can be estimated using D_{50} and η_s. When it is plotted in the Zanker nomograph in Figure 5, it can be observed that the blue line describes the estimation of D_{min} with a η_s of 80.48%.

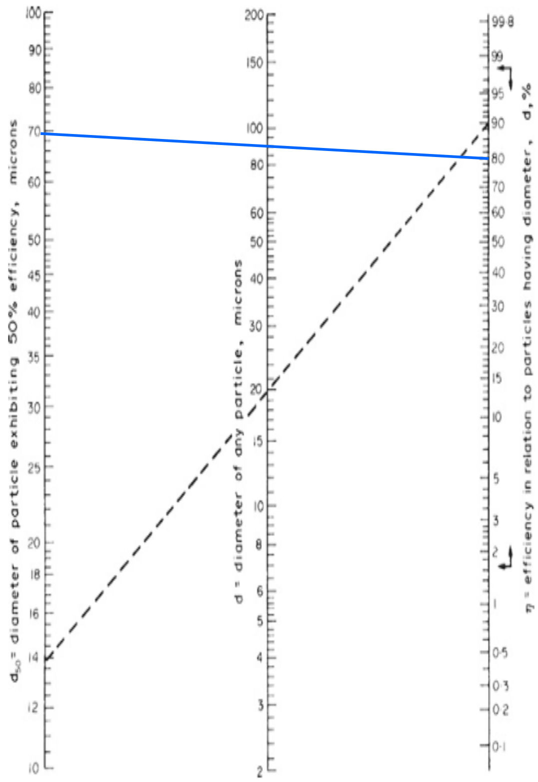

Figure 5. Zanker Nomograph for D_{min} Estimation.

From Figure 5, it was obtained that D_{min} on an η_s of 80.48% is 90 microns. The plot also shows that lesser η_s will obtain smaller D_{min}. The sensitivity of D_{min} against changes in η_s is tabulated in Table 10. It can be observed from the table that D_{min} declines as η_s goes lower.

Table 10. Sensitivity of Dmin vs. η_s.

η_s Value (%)	D_{min} (μm)
80.48	90
75	85
70	80
65	78
60	75
55	72.5
50	69.73

Based on the D_{50} and D_{min} results above, 50% salt crystals which are smaller than 69.73 microns will go up as overflow products. The other half is larger than 69.73 microns and will go with the underflow. In addition, at an η_s of 80.48%, 80.48% of total particles larger than 85 microns will be included in the underflow.

CONCLUSION

Hydrocyclone is one of the economical, effective, and simple equipment for solid-liquid separation. This equipment does not require extensive maintenance and can be found in wide-ranging applications, including salt purification. The dimensions of the hydrocyclone (HC-1) are found to be close to Rietema's design. The cut-size diameter of HC-1 effectively separates salt particles at a minimum of 69.73 microns as underflow with a separation efficiency of 50%.

Zanker's nomograph confirms a minimum diameter in the underflow of 90 microns at a solid separation of 80.48%. The smaller cut size of HC-1 demonstrates that the cyclone will work effectively.

AUTHOR INFORMATION

Corresponding Authors
Email: derina.paramitasari@bppt.go.id
Phone: +62 81807457175
Email: dhani.avianto@bppt.go.id

Author Contributions
First Author and Second Author have contributed equally to this work.

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