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Hydrocyclone design and energy requirement for treating storm water runoff from bridge

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ABSTRACT

A design methodology was proposed for the hydrocyclone used for solids separation from runoff. The design approach was validated by performing experiments on an *in situ* hydrocyclone with a diameter of 7.5 cm. The performance of the hydrocyclone was evaluated based on monitoring work, with the results indicating that the observed average pressure inside the collection pipe was proportional to the rainfall intensity. When the respective average observed pressure was 1.5 and 5.0 m water head, the volume fraction of underflow was estimated as 16 and 12%, respectively. The solids separation efficiency was proportional to the pressure, and it was in the range of 20–90% ,while the pressure ranged from 0.5 to 9 m water head. For the hydrocyclone in the test bed, the operation energy was directly provided by the pressure generated inside the collection pipe. In the case of the potential energy being unavailable, a pump can be applied to support the required energy. While the respective flow rates were 0.8, 2.4, and 3.6 m^3/h, the total required energy was 1.7, 6.7, and 10.7 m water head, respectively.

Keywords: Hydrocyclone design; Bridge runoff; Energy requirement

1. Introduction

Many studies indicate that the pollution in runoff, especially in urban areas, is not negligible. This pollution is in the form of suspended solids and may consist of pesticides, heavy metals, and hydrocarbons [1]. Normally, in order to separate the suspended solids in runoff water, a classical sedimentation process, such as a settling tank, has been applied. However, due to lack of space, the process undertaken in urban areas must be compact and produces high sludge concentrations. Thus, the hydrocyclone process, which is compact, reliable, and highly efficient, would be more suitable. The development and use of hydrocyclone has provided alternative cost-effective storm water management systems for the control of both water quantity (alleviating flooding) and water quality (preventing pollution). A number of academics and industrialists have been advocating the application of a hydrodynamic separator in the management of runoff [2–4].

Hydrocyclones are an important device for the separation of solid–liquid suspensions; they have been

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used extensively in many industries since their original design [5,6]. Besides a large amount of applications in mineral processing, this separation technique has recently been applied in environmental engineering, food engineering, electrochemical engineering, bioengineering, and pulping process [7,8]. Due to their wide practical applications, much attention has been paid toward hydrocyclones, with previous investigations having mainly concentrated on geometric modification by means of carrying out experiments and computational fluid dynamics.

The separation performance of a hydrocyclone can be influenced by many factors, such as geometrical relationship, operational conditions (including pressure and flow rate), and particle size distribution of the targeted water [9,10]. As an important affecting parameter, operational pressure plays a key factor in the determination of hydrocyclone performance [11], the required pressure is normally provided by a pump in industrial applications. Very few researchers have carried out studies aiming at the application of natural water head, and few studies have focused on the calculation of required energy in the treatment of runoff using hydrocyclone. In terms of low impact and green development, it is especially important to seek a way of using natural energy for the separation of solids from runoff.

In terms of geometrical size, its effect on the performance of hydrocyclone has been documented in many studies [12,13], while some geometry changes will have a significant effect on solids separation within a hydrocyclone [14]. It has been documented that the smaller nominal diameter results in the high separation of fine particles [13]. Although the nominal diameter is the most important parameter in hydrocyclone separation efficiency, the other parameters such as feed diameter, overflow diameter, and underflow diameter still influence the separation efficiency. These three parameters are usually optimized and calculated based on semiempirical equations and dimensionless numbers proposed in previous studies [15]. Thus, an effective hydrocyclone should have the proper geometrical relationship among the cyclone diameter, inlet and outlet areas, vortex finder, and sufficient length that provides adequate retention time to properly separate solids.

The objectives of this study were (1) to propose an effective design methodology for hydrocyclone used for solids separation from runoff, (2) to verify the operation feasibility of the hydrocyclone *in situ*, and (3) to calculate the energy required for the hydrocyclone operation based on the monitored results.

2. Hydrocyclone design and performance

2.1. Hydrocyclone design

In this study, the schematic diagram and the picture of the modified hydrocyclone *in situ* are shown in Fig. 1, which was designed according to the Rietema criteria [16]. The hydrocyclone diameter is the first parameter to be determined and is related to the operation pressure and inflow flow rate. The flow rate is proportional to the hydrocyclone diameter with a given operational pressure [17].

Considering the rainfall patents and the monitored watershed area (500 m^2), a 7.5-cm-diameter hydrocyclone was selected. The relationship between the dimensions is listed in Table 1. The vortex finder is important to control the solids separation and flow leaving the hydrocyclone; the height of vortex finder (H_1) equals 0.33 times the hydrocyclone diameter. The function of cylinder section and conical section is to provide the retention time [17]. The solids separation performance of the hydrocyclone was documented in detail using artificial highway runoff in a previous study [18].

2.2. Hydrocyclone performance

The 7.5-cm-diameter hydrocyclone *in situ* was monitored during the period from March to November, 2010. A total of 35 rainfall events were conducted.

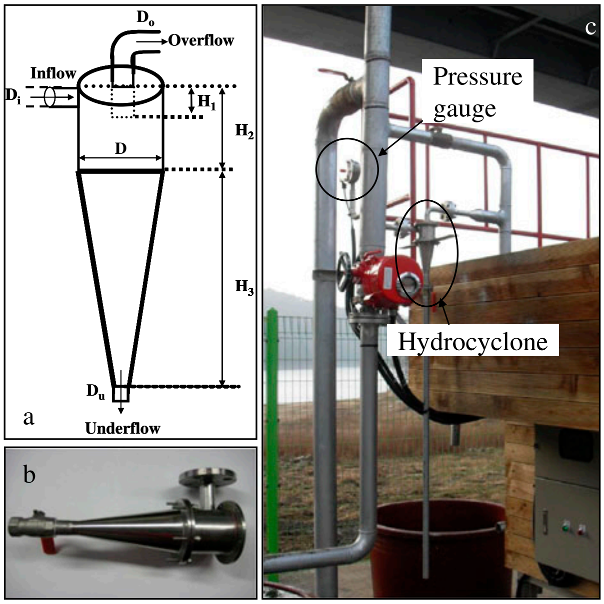

Fig. 1. Hydrocyclone used in this study: (a) schematic diagram, (b) photo, and (c) picture *in situ*.

Table 1
Relationship among configuration dimensions of the hydrocyclone

Configuration section	Symbol	Size
Hydrocyclone diameter	D_0	–
Vortex finder height	H_1	$0.4D_0$
Cylinder section height	H_2	D_0
Conical section height	H_3	$2D_0$
Inlet diameter	D_i	$0.33D_0$
Underflow outlet diameter	D_u	$0.0–0.33D_0$
Overflow outlet diameter	D_o	$0.35D_0$

These events were divided into three categories according to the rainfall intensity (RI): $1 \leq \mathrm{RI} < 5$ mm/h, $5 \leq \mathrm{RI} < 10$ mm/h, and $\mathrm{RI} \geq 10$ mm/h. The observed average pressure reads from the pressure gauge (see Fig. 1(c)) were 1.5, 5.0, and 6.7-m water head, respectively, for the rainfall events in the above three groups, and the corresponding values of average flow rate were 0.8, 2.4, and 3.6 m^3/h (see Table 2).

The performance of the hydrocyclone *in situ* was evaluated and discussed in our previous study [4], with the main points summarized in Fig. 2. It can be seen that the average pressure inside the separator was proportional to the rainfall intensity, and the pressure increase became weaker alongside the rainfall intensity increasing due to the existence of spilled flow at a certain rainfall intensity (Fig. 2(a)). Similarly, the pressure was proportional to the runoff flow rate generated in the studied bridge area (Fig. 2(b)). The solids separation efficiency was positively affected by the pressure (Fig. 2(c)), and it was ranged from 20 to 90%, while the obtained pressure was in the range of 0.5–9.0 m. And the pressure also showed significant effect on runoff volume distribution. The percentage of underflow decreased as a function of increasing pressure, while the percentage of overflow increased (Fig. 2(d)).

3. Energy requirement

The total energy required for hydrocyclone operation includes three parts (see Fig. 3): the hydrostatic pressure (read from the pressure gauge), the head loss during the transportation process inside the collection pipe, which includes the friction loss, and the partial loss (pipe junction).

The friction loss (h_f) along the collection pipe can be calculated using the Darcy–Weisbach equation [19]:

$$h_f = f_f \frac{LV^2}{2gD} \tag{1}$$

where f_f is the friction coefficient along the collection pipe; L is the pipe length, m; V is the flow velocity, m/s; D is the diameter of the collection pipe, m; and g is the acceleration due to gravity, 9.8 $\mathrm{m/s^2}$.

The friction coefficient can be read from the Moody diagram (see Fig. 4) with the values of Reynolds number (Re) and the pipe roughness ratio, ε/D. Here, ε is the pipe roughness height (4.57×10^{-5} m) and D is the pipe diameter (0.25 m). The value of Re can be calculated using the following formula:

$$\mathrm{Re} = DV\rho/\mu \tag{2}$$

Here, ρ is the water density, $\mathrm{m^3/kg}$, and μ is the viscosity coefficient, $\mathrm{N\,s/m^2}$.

The partial loss (h_b) at the junction part can be obtained by:

$$h_b = f_b \frac{V^2}{2g} \tag{3}$$

Here, f_b is the friction coefficient at the junction part (minor loss coefficient, see Fig. 3); the value of f_b is determined by the angle between the incoming flow direction and the outgoing flow direction at the pipe junction, while the value of f_b ranges from 0.05 to 1.32 depending on the incoming and outgoing flow directions (in this study, it was set as 0.99). Thus, the total energy required yields the below formula:

$$H = h + f_f \frac{LV^2}{2gD} + f_b \frac{V^2}{2g} = h + \frac{8(f_f \cdot L + f_b \cdot D)}{\pi^2 \cdot g \cdot D^5} Q^2 \tag{4}$$

Table 2
Rainfall intensity and observed pressure of the monitored rainfall events

Item	Total number of events	Rainfall intensity (mm/h)		Average flow rate ($\mathrm{m^3}$/h)	Average pressure (m)
		Average	SD		
$1 \leq \mathrm{RI} < 5$ mm/h	24	2.22	1.285	0.8	1.5
$5 \leq \mathrm{RI} < 10$ mm/h	7	6.35	0.871	2.4	5.0
$\mathrm{RI} \geq 10$ mm/h	4	12.14	1.130	3.6	6.7

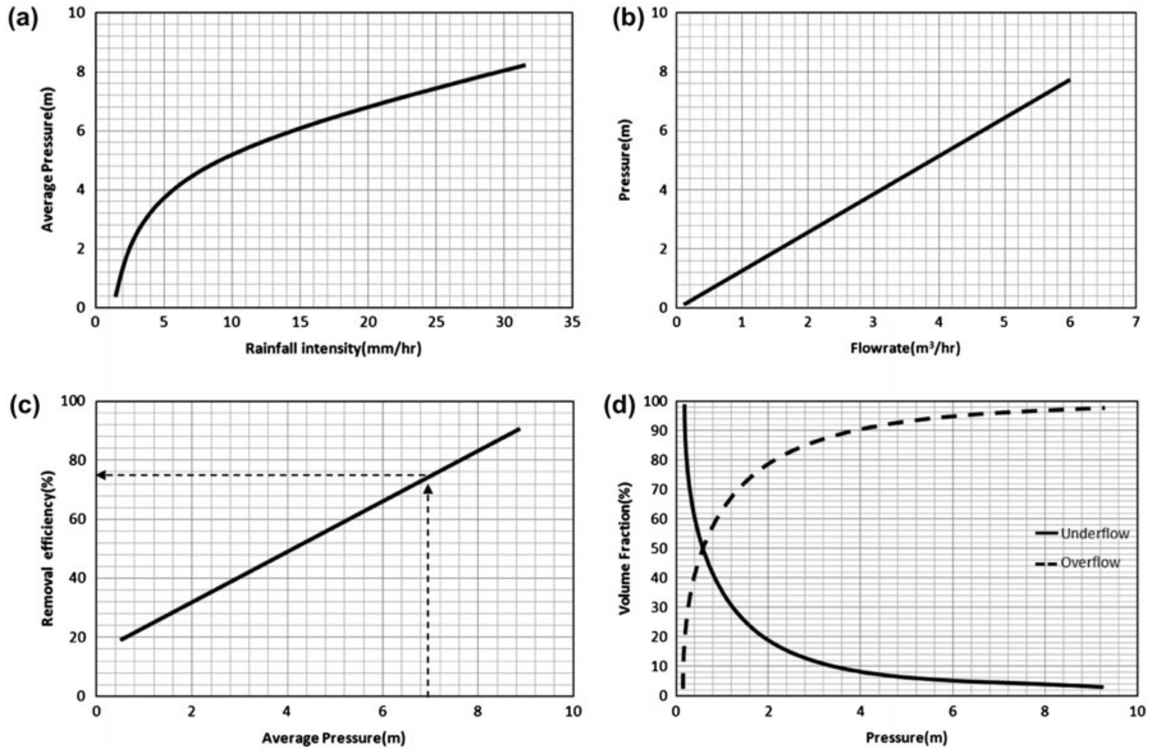

Fig. 2. Performance summarization of the hydrocyclone *in situ*: (a) relationship between rainfall intensity and pressure, (b) relationship between flow rate and pressure, (c) effect of pressure on solids removal, and (d) effects of pressure on runoff volume distribution.

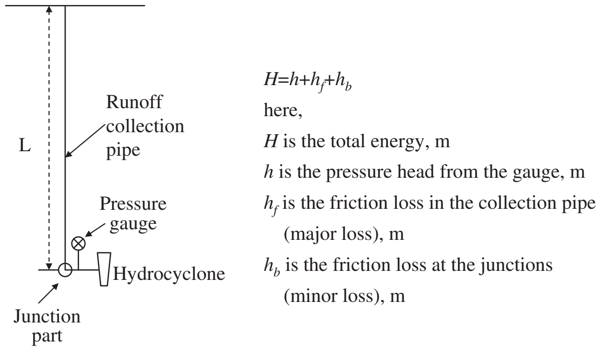

Fig. 3. Energy loss during the runoff transportation process.

It should be pointed out that there are some issues which could bring errors to the calculation were not included in Eq. (4). Such as the flow rate meter and pressure gauge installed on the collection pipe could result in some water head loss, and the pipe material also indicates effect on the amount of total required energy. Eq. (4) is only effective for forged steel pipe.

In this study, the water temperature was set as 20℃, the water density was $0.99823 \times 10^3\ \mathrm{kg/m^3}$, and the water viscosity was $1.002 \times 10^{-3}\ \mathrm{kg/m\,s}$. The values of f_f can be read from the Moody diagram as 0.03, 0.028, and 0.027, respectively, for the flow rates of 0.8, 2.4, and 3.6 $\mathrm{m^3/h}$ (see Table 3).

For the hydrocyclone *in situ*, the pipe length (*L*, see Fig. 3) was 15 m and the pipe diameter (*D*) was 0.025 m. The value of required total energy can be calculated using Eqs. (1) and (3). While the respective flow rate was 0.8, 2.4, and 3.6 $\mathrm{m^3/h}$, the total energy was 1.7, 6.7, and 10.7 m water head, respectively.

When the hydrocyclone was applied under a bridge (e.g. Fig. 5(a)), the required energy could be provided by the potential energy from the bridge to the hydrocyclone (see Fig. 5(a)). In the case of the potential energy not being available (see Fig. 5(b)), the required energy should be supported by a pump. The power of the pump can be determined using formula (5):

$$P = \frac{gHQ}{3,600\eta} \tag{5}$$

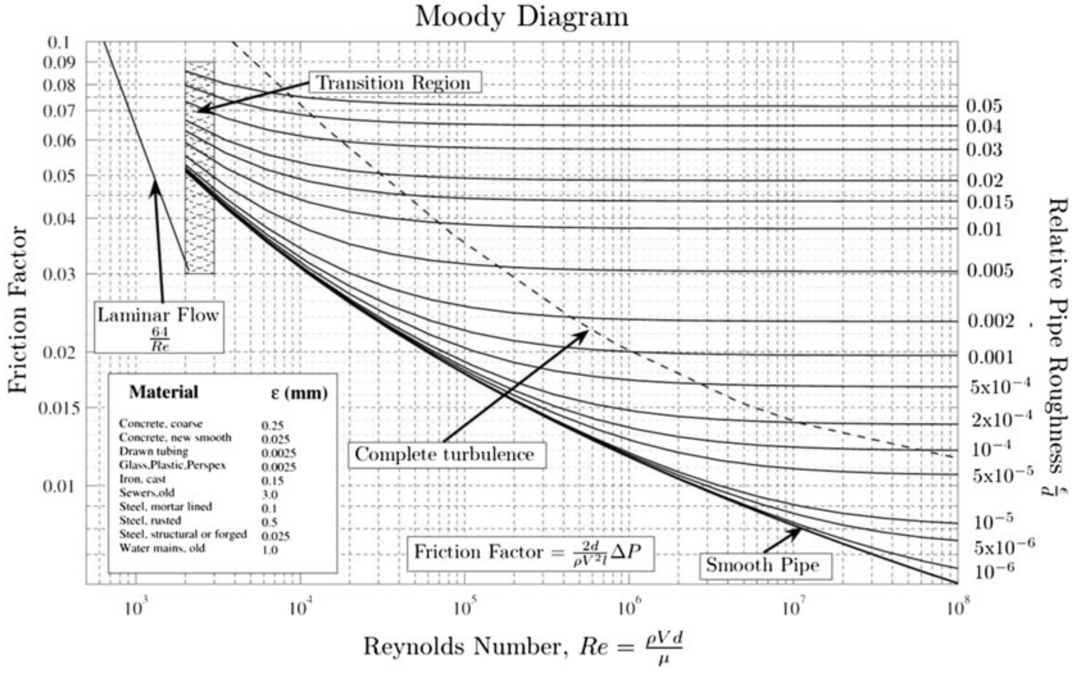

Fig. 4. The Moody diagram.

Table 3
Values of friction coefficients of the collection pipe

Flow rate (m^3/h)	ε/D	V (m/s)	Re	f_f (estimated)	f_b
0.8	0.001829	0.4529	1.13×10^4	0.03	0.99
2.4	0.001829	1.3588	3.39×10^4	0.028	0.99
3.6	0.001829	2.0382	5.08×10^4	0.027	0.99

Here, P is the pump power (KW), Q is the flow rate (m^3/h), H is the total required water head (m), and η is the pump efficiency (%), 50% in this study. When the flow rate was 0.8, 2.4, and 3.6 m^3/h, the calculated power was 0.0074, 0.0875, and 0.2097 kW, respectively.

4. Application examination

The energy calculation was processed based on one monitoring work while the potential energy was not available. The rainfall information and the hydrological conditions of the monitored event are shown in Table 4. Considering the effect of first flush, the runoff was captured and treated by the hydrocyclone only during the period of around 30 min. The average flow rate was approximately 3.33 m^3/h (0.0009 m/s) in the monitored period, and the average operational pressure (h) inside the collection pipe was around 7.34 m water head.

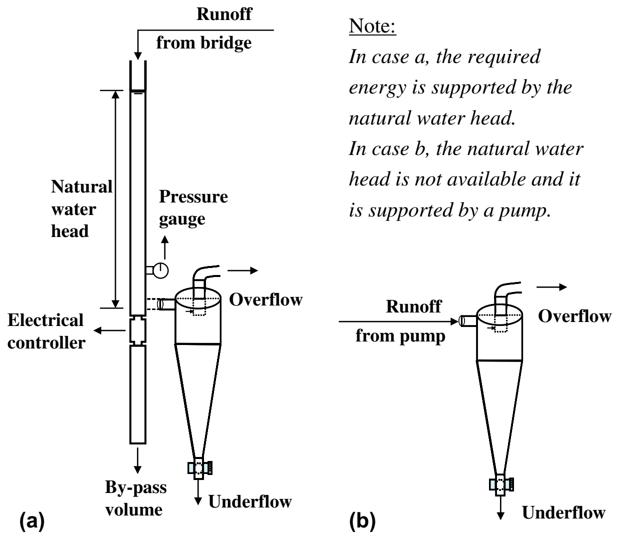

Fig. 5. Schematic diagram of hydrocyclone supported by (a) natural water head and (b) pump.

Table 4
Rainfall conditions and hydrological conditions

		Rainfall conditions			Runoff volume (m^3)		
Monitoring date	Time (min)	Rainfall depth (mm)	Rainfall intensity (mm/h)	Pressure head (m)	Underflow	Overflow	Runoff flow rate (m^3/h)
2011-04-30 5:05	0	6.2	–	3.0	0.21	0.03	–
2011-04-30 5:06	1	6.4	12.0	4.5	0.22	0.04	1.50
2011-04-30 5:07	2	6.6	12.0	6.5	0.23	0.05	0.90
2011-04-30 5:08	3	6.6	0.0	7.5	0.24	0.09	3.00
2011-04-30 5:09	4	6.8	12.0	8.3	0.25	0.16	4.80
2011-04-30 5:12	7	7.2	8.0	8.4	0.27	0.29	3.10
2011-04-30 5:16	11	8.0	12.0	8.4	0.33	0.50	3.98
2011-04-30 5:19	14	8.2	4.0	8.5	0.36	0.64	3.50
2011-04-30 5:24	19	8.8	7.2	8.5	0.43	0.91	4.08
2011-04-30 5:28	23	9.0	3.0	8.5	0.48	1.11	3.75
2011-04-30 5:31	26	9.2	4.0	8.0	0.53	1.29	4.60
2011-04-30 5:37	32	10.2	10.0	8.0	0.59	1.57	3.40

Table 5
Power fare required for the pump operation over 32 min

Country	USA	Korea	Australia	Canada	UK	Germany	France	South Africa	China
Electricity price (US cent/KW h)*	8–17	44.6	22–46	6–12	20	31.4	19.4	8–16	9.0
Power cost (US cent/kg SS)	2.5–5.3	13.9	6.9–14.4	1.9–3.9	6.3	9.8	6.1	2.5–5.0	2.8

*Data source: http://en.wikipedia.org/wiki/Electricity_pricing.

$$\begin{aligned} H &= h + \frac{8(f_f \cdot L + f_b \cdot D)}{\pi^2 \cdot g \cdot D^5} Q^2 \\ &= 7.34 + \frac{8(0.03 \times 15 + 0.99 \times 0.025)}{3.14^2 \times 9.8 \times 0.025^5} \times 0.0009^2 \\ &= 10.7 \text{ m} \end{aligned}$$

The pump power can be calculated with the efficiency of 50%:

$$\begin{aligned} P &= \frac{gHQ}{\eta} = \frac{9.8 \text{ m/s}^2 \times 10.7 \text{ m} \times 0.0009 \text{ m}^3\text{/s}}{0.5} \\ &= 0.188 \text{ kW} \end{aligned}$$

During the 32 min of the monitoring period, a total of 1.9 m^3 runoff was collected and piped into the hydrocyclone, and around 0.32-kg suspended solids was separated from the captured runoff. The required power cost per kilogram of separated solids was evaluated for different countries (Table 5). It can be seen that the cost was highest in Korea, where it was around 13.9 US cents per kilogram of separated solids. In other countries, it was normally lower than 10 US cents per kilogram of separated solids. Nevertheless, the cost level is feasible and would be considered acceptable in all the countries included in Table 5. The cost analyzed in this study is only for the energy support and does not include other costs caused by operational and maintenance activities. The cost analysis of the hydrocyclone operation is of key importance to the best management practices selection process.

5. Conclusions

A new design methodology was proposed for hydrocyclone used in the treatment of runoff. This methodology was applied to a case study. The results indicated that the designed hydrocyclone can work effectively in solids separation using natural water head. Solids removal efficiency was around 20–90%, while the operational pressure was from 0.5 to 9.0 m water head. The energy requirement of the hydrocyclone was also determined. Results indicated that the total energy needed was in the range of 1.7–10.7 m water head, while the runoff flow rate ranged from 0.8 to 3.6 m^3/h. This energy can be provided by a pump if the natural potential energy is not available; the required power was around 0.0074, 0.0875, and 0.2097 kW with the flow rates at 0.8, 2.4, and 3.6 m^3/h, respectively. Finally, the brief economic analysis conducted for the required energy showed that it would be feasible to run the hydrocyclone with a pump in cases where the natural water head is not available.

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Symbols

D — the diameter of the collection pipe (m)
D_0 — hydrocyclone diameter (cm)
D_i — inlet diameter (cm)
D_o — overflow outlet diameter (cm)
D_u — underflow outlet diameter(cm)
ε — the pipe roughness height (cm)
h_b — the friction loss at junctions (m)
h_f — the friction loss along pipe (m)
H — the total energy required (m)
H_1 — vortex finder height (m)
H_2 — cylinder section height (m)
H_3 — conical section height (m)
g — the acceleration due to gravity ($9.8\,\mathrm{m/s^2}$)
f_b — the fraction coefficient at the junction part
f_f — fraction coefficient along the collection pipe
L — the pipe length (m)
ρ — water density ($\mathrm{m^3/kg}$)
P — the pump power (KW)
Q — the flowrate ($\mathrm{m^3/h}$)
Re — Reynolds number
RI — rainfall intensity (mm/h)
μ — viscosity coefficient ($\mathrm{N\,s/m^2}$)
V — the flow velocity (m/s)
η — pump efficiency (%)

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