Study on design and performance evaluation of hydrocyclone separators for micro-irrigation systems

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ABSTRACT

Hydrocyclone is a simple mechanical device, with no moving parts, where solid particles or immiscible liquids are separated from liquid. It is used as a primary filter for micro irrigation systems to remove floating particles as well as to remove high density particles from the irrigated water. In this study, the six hydrocyclone models were designed, fabricated and tested for its performance evaluation. The models were designed for the removal of particulate matter of size 48 microns and larger sizes from irrigation water. The models were designed with combination of 20° and 26° cone angles and 0.04, 0.05 and 0.065 m underflow cylinder diameters. These hydrocyclones were fabricated with 3 mm thick mild steel sheet. The clean water pressure drop and the percentage of sand trapped in hydrocyclone were recorded. It was found that, the hydrocyclone model M3 with 26° cone angle and 0.065 m underflow cylinder diameter was the best model with the removal efficiency of 95.68% among all the six models.

ORIGINALLY in the later part of the 19th century hydrocyclone was used as a solid/liquid separator to remove sand from well water. A typical hydrocyclone consists of a cylindrical section, a conical section, an underflow cylinder section and a sand collection basket as shown in Fig. 1. The separation is based on density difference between the liquid and the matter to be separated. The principle of centrifugal separation is used to remove or classify solid particles from a fluid, based on particle size, shape and density. Hydrocyclones are used as a primary filter for separation of larger sized particulate matter in irrigation water before it is passed through the screen filters or sand filters. These primary filters are basically meant to reduce the workload on the secondary filters. The hydrocyclones that are presently used in drip irrigation are those that have been designed and used in other industrial applications and there is a good scope for improving their efficiency. For this purpose, there is a need to design hydrocyclones that are meant to be specifically used in drip irrigation systems, taking into account the needs of the system.

METHODOLOGY

The present study on study on design and performance evaluation of hydrocyclone separators for micro-irrigation systems was conducted at Jain Irrigation systems Limited, Jalgaon, Maharashtra. A standard cyclone is defined as, a cyclone which has the proper geometrical relationship between the cyclone diameter, inlet area, vortex finder and apex orifice and has sufficient length to provide retention time in order to properly classify the particles. There are various design parameters of hydrocyclone which are as follows:

Cone angle:

For design purpose, 20° and 26° cone angles were chosen. Arterburn (1976) reported that the larger the hydrocyclone diameter, the coarser the separation. The included angle of the cone section is normally between 10° and 20°.

Cone section length:

The length of cone depends upon the underflow cylinder diameter and cone angle.

Length of the underflow cylinder section:

The length of underflow cylinder section varies with the cone length and cone angle. The underflow cylinder section starts at the point where it joins the cone section at one end and ends where the apex of the imaginary cut
off portion of the cone is located namely at the entrance of the sand collection basket. This cone was cut at the selected underflow cylinder section diameter values i.e. 0.04 m, 0.05 m and 0.065 m.

**Underflow cylinder diameter:**

To know the effect of change of underflow cylinder diameter on the performance efficiency of hydrocyclone, the three diameters of underflow cylinder section were chosen i.e. 0.04, 0.05 and 0.065 m.

**Inlet and overflow section diameters:**

The inlet and overflow pipe diameter values were fixed at 0.05 and 0.05 m, respectively for a flow rate of 25 m$^3$/h. Svarovsky (1984) reported that to increase the intake capacity of a hydrocyclone, its inlet diameter has to be increased.

**Cylinder section diameter:**

In the present study, all the six models including the control model had a diameter of 0.198 m (I.D.) which was 3.73 times the overflow pipe diameter. Zhao and Abrahamson (1999) reported on the dimensions of cyclone, wherein they suggested that the diameter of cylinder section of the cyclone should be 2 times the overflow pipe diameter.

**Cylinder section length:**

Typically hydrocyclones have a cylinder section length equal to or greater than the hydrocyclone diameter. Zhao and Abrahamson (1999) reported on the dimensions of cyclone, wherein they suggested that the length of cylinder section should be 3 times the overflow pipe diameter. In the present study, the cylinder section length was chosen as 3 times the overflow pipe diameter for models $M_1$, $M_2$, $M_3$, $M_4$, $M_5$ and $M_6$ and the length of the cylinder section for the control model was 4.01 times the overflow pipe diameter.

**Vortex finder design:**

Vortex finder takes the clean water and delivers it to the outlet. If the length of vortex finder increases, it is likely to disturb the vortex and result in coarser separation of particles. So the length of the vortex finder should be optimum and is found by a trial and error method. In the study, the length of the vortex finder was kept at 0.398 m for control model and 0.335 m for the other six models. Arterburn (1976) reported that the diameter of the vortex finder was equal to 0.35 times the hydrocyclone diameter.

**Height of hydrocyclone:**

The height from the top of the outflow pipe to the end of the underflow cylinder section is referred to as total height of hydrocyclone.

**Cut size:**

The cut size is defined as the diameter ($d_p$) of a particle, which has a probability of $n\%$ to end up in the underflow section (Svarovsky, 1984). The design probability ($n$) of trapping of particles in the collection basket was taken as 95%. Particle separation is based on the density difference between the liquid and the matter to be separated. A higher density difference results in a finer separation. For this investigation, silica sand with a specific gravity of 2.65 g/cc was selected. The hydrocyclones were designed by using the mathematical expression given by Anonymous, (2005a).

$$dp = \sqrt{\frac{n \times 0.01 \times 0.5(D - D_0) \times 18n}{(p_s - p_l) \lambda a}}$$  \hspace{1cm} (1)

where,

- $D$: Hydrocyclone diameter
- $D_0$: Overflow pipe diameter
- $p_s$: Specific gravity of sand
- $p_l$: Specific gravity of liquid
- $\lambda$: Viscosity
- $a$: Axial acceleration
- $n$: Design trapping probability

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\[ d_p = \text{diameter of removed particles, m} \]
\[ n = \text{probability, per cent.} \]
\[ D = \text{diameter of the cylinder section, m.} \]
\[ D_o = \text{diameter of the overflow pipe, m} \]
\[ \eta = \text{dynamic viscosity of the liquid at room temperature, Pa-s} \]
\[ \rho_s = \text{density of the solids, kg/m}^3 \]
\[ \rho_l = \text{density of liquid, kg/m}^3 \]
\[ a = \text{acceleration, m/s}^2 \]

\[ a = \frac{u_i^2}{D/2} \]

where,
\[ u_i = \text{inlet velocity of fluid, m/s} \]
\[ u_i = \frac{Q}{A_c} \quad \text{and} \quad A_c = \frac{\pi}{4} x D_1^2 \]

where,
\[ A_c = \text{cross-sectional area of inlet pipe, m}^2 \]
\[ Q = \text{inlet flow rate, m}^3/\text{s} \]
\[ \lambda = \text{residence time, s} \]

\[ \lambda = \frac{L}{Q} \frac{1}{\pi \left( \frac{D_2 - D_3}{4} \right)} \]  

where,
\[ L = \text{length of the cyclone from the top of inlet pipe up to the end of cone section, m} \]

**Fabrication of hydrocyclone:**

The cylinder section and cone section of the hydrocyclones were fabricated by using M.S. (mild steel) sheet of 3mm thickness. Commercially available 0.05m diameter, class-B mild steel pipe was used to fabricate the inlet and outlet sections of the hydrocyclone. To fabricate the underflow cylinder section, the commercially available 0.04, 0.05 and 0.065m diameter, class-B mild steel pipes were used as needed. All the hydrocyclones were coated with pure polyster powder.

**Experimental procedure:**

The clean water pressure drops for each model of hydrocyclone was recorded at discharge rates of 20, 25 and 30m³/h. The pressure drop values in the hydrocyclones were tested according to IS: 14743:1999. The experimental set–up for testing the hydrocyclone performance is illustrated in the Fig. 2. The trapped silica sand material in collection baskets of respective hydrocyclone models were collected and analyzed for their particle size distribution by using motorized sieve shaker. These values were then compared with the particle size distribution of the sand sample that was fed into the system. Based on this, the hydrocyclone with the maximum trapping efficiency was selected as the best model and the dimensions of that model of the hydrocyclone were selected as the best combination of dimensions.

The overall trapping efficiency of the hydrocyclone was calculated by using the following formula given by Anonymous, (2005a):

\[ E = \frac{w_U}{w_F} \times 100 \]  

where,
\[ E = \text{trapping efficiency of hydrocyclone, dimensionless} \]
\[ w_F = \text{mass fraction in the feed flow, dimensionless} \]
\[ w_U = \text{mass fraction in the underflow, dimensionless} \]

**RESULTS AND DISCUSSION**

The results obtained from the experiment on design, fabrication and testing of hydrocyclones are discussed in this section.

**Design of hydrocyclone:**

The design dimensions of the six hydrocyclone models (i.e. M₁, M₂, M₃, M₄, M₅ and M₆) calculated by using equation 1 (Anonymous 2005a) are presented in Table 1. It was observed that the cone angle and the underflow cylinder diameter were the main variables for the design of these hydrocyclones. The control model was the earlier model and the same is in use by the farmers in drip irrigation systems. The control model was

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**Fig. 2 : Typical hydrocyclone**

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**Table 1**

<table>
<thead>
<tr>
<th>Model</th>
<th>Diameter of Cylinder Section, mm</th>
<th>Diameter of Overflow Pipe, mm</th>
<th>Cone Angle, °</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₁</td>
<td>100</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>M₂</td>
<td>120</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>M₃</td>
<td>140</td>
<td>70</td>
<td>55</td>
</tr>
<tr>
<td>M₄</td>
<td>160</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>M₅</td>
<td>180</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td>M₆</td>
<td>200</td>
<td>100</td>
<td>70</td>
</tr>
</tbody>
</table>
designed to remove particles of size 51.67 microns and more. Likewise, the models $M_1$, $M_2$, $M_3$, $M_4$, $M_5$ and $M_6$ were designed to remove particles of 48.73, 50.03, 52.21, 54.24, 55.61 and 57.90 microns and larger size particles, respectively.

**Effect of change in cone angle on clean water pressure drop:**

The clean water pressure drops were recorded for all the seven hydrocyclones at three flow rates namely 20, 25 and 30 $m^3/h$ and the results are shown in Table 2. It was seen that at 25 $m^3/h$ flow rate, the models $M_1$, $M_2$ and $M_3$ which had a lower cone angle of $20^\circ$ had a lower pressure drop of 0.46, 0.47 and 0.43 kg/cm$^2$ and the models $M_4$, $M_5$ and $M_6$ which had a higher cone angle of $26^\circ$ had a higher pressure drop of 0.50, 0.51 and 0.52 kg/cm$^2$, respectively. Hence, as the cone angle increases the pressure difference between inlet and outlet increases and hence, lower the cone angle, lower the pressure drop.

| Table 2 : Clean water pressure drop for the seven hydrocyclone models |
|--------------------------|-----------------|-----------------|-----------------|
| Model No. | Flow, m$^3$/h | Pressure, kg/cm$^2$ | Inlet | Outlet | Drop |
| Control | 20 | 1.04 | 0.72 | 0.32 |
| 25 | 1.50 | 1.03 | 0.47 |
| 30 | 2.10 | 1.42 | 0.68 |
| $M_1$ | 20 | 0.99 | 0.69 | 0.30 |
| 25 | 1.50 | 1.04 | 0.46 |
| 30 | 2.18 | 1.51 | 0.67 |
| $M_2$ | 20 | 1.04 | 0.72 | 0.32 |
| 25 | 1.50 | 1.03 | 0.47 |
| 30 | 2.10 | 1.42 | 0.68 |
| $M_3$ | 20 | 1.02 | 0.74 | 0.28 |
| 25 | 1.50 | 1.07 | 0.43 |
| 30 | 2.31 | 1.64 | 0.77 |
| $M_4$ | 20 | 0.94 | 0.63 | 0.31 |
| 25 | 1.50 | 1.00 | 0.50 |
| 30 | 2.17 | 1.41 | 0.76 |
| $M_5$ | 20 | 0.98 | 0.65 | 0.33 |
| 25 | 1.50 | 0.99 | 0.51 |
| 30 | 2.15 | 1.40 | 0.75 |
| $M_6$ | 20 | 0.95 | 0.62 | 0.33 |
| 25 | 1.50 | 0.98 | 0.52 |
| 30 | 2.16 | 1.40 | 0.76 |

**Effect of change in cone angle on performance:**

The experiment results are presented in Table 3 which showed that the models $M_1$, $M_2$ and $M_3$ with a cone angle of $20^\circ$ had greater performance efficiency as compared with the models $M_4$, $M_5$ and $M_6$ which had
cone angle of $26^\circ$. The results of the hydrocyclone performance in terms of the cumulative sand trapping efficiency showed a decreasing trend with increasing cone angle. It was seen that the $M_3$ model with a cone angle of $20^\circ$ could remove sand of 56-106 microns range with the maximum efficiency of 62.78% among the models $M_1$, $M_2$, and $M_3$ with the same cone angle. The models $M_4$, $M_5$, and $M_6$ with the cone angle of $26^\circ$ could remove the same size range particles with efficiencies of 58.64, 60.63, and 60.26%, respectively. This can be attributed to the fact that a smaller cone angle ensures a more gradual increase in the swirling velocity of water as it passes through the hydrocyclone, which in turn leads to a more perfect separation of larger particles.

### Effect of change in underflow cylinder section on performance:

In the present experiment, the three different diameters ($i.e.$ 0.04, 0.05 and 0.065m) were chosen to see the effect of change in underflow diameter on the performance of hydrocyclone. The results obtained are tabulated in Table 3. It was observed that the models with 0.04m underflow cylinder diameter ($i.e.$ model $M_1$ and $M_4$) were less efficient (sand trapping efficiencies 93.32 and 90.43%, respectively) than the models with 0.05m underflow cylinder diameter ($i.e.$ models $M_2$ and $M_5$ having sand trapping efficiencies 93.73 and 93.18%, respectively) followed by the models with 0.065m underflow cylinder diameter ($i.e.$ models $M_3$ and $M_6$ having 95.68 and 93.33%, respectively). A larger diameter of underflow cylinder section increases the fluid flow out through the underflow cylinder section, carrying more of particulate matter to the collection basket. If the underflow cylinder diameter is larger than the vortex finder diameter, the cyclone will often drain itself through the underflow cylinder section and perform no separation function. However, if the underflow cylinder diameter is too small, much of the heavier particulate matter may discharge with the light particulate matter through the underflow cylinder section.

The percentage of trapped sand for the models $M_1$ and $M_4$ were recorded as 60.76 and 58.64%, respectively in the 56-106 microns range particles. Similarly, it was for the models $M_2$ and $M_5$ were recorded as 61.68 and 60.63%, respectively and for the models $M_3$ and $M_6$ were recorded as 62.78 and 60.26% (Table 3), respectively in the 56-106 microns range particles.

### Conclusion:

As the cone angle increases, the pressure difference between inlet and outlet increases and hence lower the cone angle, lower the pressure drop. The cone angle in the $20^\circ$ to $26^\circ$ range can be used to design a hydrocyclone used for micro-irrigation system.

Thus from the study, the following dimensions for a good hydrocyclone for the purpose of removal of solid particles from the water to be used for micro-irrigation:

- **Inlet and outlet diameter** = 0.05 m ($2"$)
- **Cylinder section diameter** = 0.198 m (I.D.)
- **Cylinder section height** = 0.213 m
- **Vortex finder length** = 0.335 m
- **Cone angle** = $20^\circ$
- **Cone section length** = 0.3771 m
- **Underflow cylinder diameter** = 0.065 m, if significant damage due to abrasion is expected (higher load of particulate matter in irrigation water). = 0.05 m, if the excepted damage is insignificant.
- **Underflow cylinder length** = 0.184 m (if underflow diameter is 0.065 m).

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**Table 3: Cumulative average percentage of sand trapped in all hydrocyclone models**

<table>
<thead>
<tr>
<th>Mesh size</th>
<th>Particle size (micron)</th>
<th>Cumulative initial percentage of sand taken (%)</th>
<th>Average cumulative percentage of trapped sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control</td>
</tr>
<tr>
<td>400-250</td>
<td>38-56</td>
<td>8</td>
<td>8.85</td>
</tr>
<tr>
<td>250-150</td>
<td>56-106</td>
<td>66</td>
<td>58.62</td>
</tr>
<tr>
<td>150-100</td>
<td>106-150</td>
<td>74</td>
<td>68.48</td>
</tr>
<tr>
<td>100-85</td>
<td>150-180</td>
<td>81</td>
<td>75.48</td>
</tr>
<tr>
<td>85-60</td>
<td>180-250</td>
<td>87</td>
<td>81.12</td>
</tr>
<tr>
<td>60-30</td>
<td>250-500</td>
<td>92</td>
<td>85.46</td>
</tr>
<tr>
<td>30-16</td>
<td>500-1000</td>
<td>96</td>
<td>89.38</td>
</tr>
<tr>
<td>16-8</td>
<td>1000-2000</td>
<td>100</td>
<td>93.22</td>
</tr>
</tbody>
</table>

Table 3 : Cumulative average percentage of sand trapped in all hydrocyclone models

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