Experimental testing of the effectiveness of novel hydrocyclones for separation of impurities in biofuels

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Abstract. This paper investigates the potential sources of renewable energy, in particular biofuels. Biofuels tend to contain multiple harmful impurities that need to be separated if the biofuel is to have good energy performance, and the systems that run on it to produce electricity or heat are to operate more reliably. The paper discusses use of hydrocyclones as the most productive and reliable biofuel purification method. It dwells upon the factors that negatively affect separation of mixtures in a hydrocyclone, which are attributable to the complex hydrodynamics of the flow in such a unit. In order to eliminate these factors, the authors hereof have developed two hydrocyclone designs. An experimental test bench was designed and made to test these designs. Parts of the units were 3D printed from an environmentally friendly material. For testing, we used a biodiesel made from waste cooking oil with an impurity content of 23%. Experiments showed a maximum separation rate of 94.2%. The proposed solutions did improve the effectiveness of biodiesel mixture separation. These designs can be effectively used to separate non-homogeneous mixtures.

1. Introduction

Energy can be produced from a variety of biomasses including agricultural waste, livestock waste, municipal solid waste, and other types of organic waste. Several processes exist that can directly convert such waste into electricity or heat, or produce gaseous, liquid, or solid fuels from such waste, with biodiesel, bioethanol, and biogas considered to have the best potential. Thus, pure biofuels or, more commonly, biofuels mixed with a petroleum-based fuel can be used in liquid fuel-fired systems in transport or heating. Bioenergy technologies are diverse, and their advancement in the current state of the art varies significantly [1-2].

Biodiesel is environmentally friendly, biodegradable, and easy to use. It is produced by chemical transesterification of vegetable oils. The resulting biodiesel contains impurities such as glycerin or particulate matter that needs to be separated, as the degree of purity affects the performance of the fuel and the reliability of systems running on it. There are electrostatic, centrifugal, and other technologies for separation of impurities. Units that perform such separation are rather bulky, difficult to operate, not particularly productive or efficient. Hydrocyclones are void of these weaknesses [3-5].
Hydrocyclones are common in mechanical engineering, where they are used in particular to separate impurities and particulate matter. They are common in oil production, mining, chemical and other industries.

Petrochemical industry uses hydrocyclones to mechanically separate polydisperse heterogeneous systems. They also make part of oil / oil sludge / water refining and treatment plants, in particular to remove mechanical impurities from formation waters and oil, to clean drilling mud and process fluids used in machinery. Hydrocyclones are simply and sturdily designed to be low-maintenance, cheap-to-operate units, which is what makes them a popular choice.

Although used on a large scale, efforts to further improve hydrocyclone design never stop. Their core weaknesses are [6-8]: (i) continuous stirring of the mixture in the working zone, which causes turbulent diffusion to significantly affect the effectiveness of separation; (ii) the circular vortex under the lid affects the separation capacity as particulate matter that escapes the vortex goes into the outflow pipe.

Thus, the behavior of the flow in a hydrocyclones is complicated by vortical turbulence. The presence of vortices necessitates longer separation and negatively affects its quality, as impurities regularly end up in the outflow pipe. This hinders the separation capacity.

Circular vortices emerge due to the presence of two major unidirectionally rotating flows: the outer flow that moves forward down the spiral, and the inner flow that moves up the spiral towards the outflow pipe. Beside those, a hydrocyclone contains multiple local circulations and flow mixing [9-10].

All of this complicates the hydrodynamic processes and negatively affects the effectiveness of separating dispersed systems, which is why it is relevant to investigate vortex movements of the flow and to design a hydrocyclone that will have none.

2. Methods and materials

The Biofuel Composition Laboratory of Siberian Federal University has designed hydrocyclones intended to have none of the above problems.

Figure 1 shows the diagram of the first design to be tested [11].

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**Figure 1.** Diagram of Design 1: 1 is the cylinder body (the cylinder), 2 is the cover, 3 is the conical body (the cone), 4 is the inlet pipe, 5 is the outflow pipe, 6 is the sand nozzle, 7 is the disk reflector, 8 is the conical protrusion.
This new design prominently features the cascaded disk reflector 7 with the conical protrusion 8. When the hydrocyclone is running, part of the circular vortex under the cover, which is rich in impurities and particulate matter, will not enter the outflow pipe 5; rather, it converts into the radial flow A2, which boosts centrifugal forces. At the same time, part of the inner vertical flow changes its direction to the radial direction A1 towards the cyclone walls, which further boosts centrifugal forces.

This novel design has the following strengths: better separation capacity thanks to lower risk of impurities and particulate matter going from the outer upstream to the outflow pipe plus an enlarged centrifugal field; an ability to control the flow productivity by moving the disc reflector vertically along the outflow pipe.

Figure 2 shows the diagram of the second design to be tested [12].

![Diagram of Design 2](image)

Figure 2. Diagram of Design 2: 1 is the cylinder, 2 is the cover, 3 is the cone, 4 is the inlet pipe, 5 is the outflow pipe, 6 is the sand nozzle, 7 is a large-diameter embossed socket, 8 is a small-diameter embossed socket.

This unit prominently features a flow damper that has embossed (tapered) surface on the concentric sockets 7 and 8. The sockets 7 and 8 form an annular channel that connects to the tangential inlet 4 and to the cavity in the lower cone 3. Biofuel to be separated is fed through the inlet pipe 4 that connects tangentially to the cylinder 1. Then the flow is centrifugally accelerated and spirals down the channel 9 created by the sockets 7 and 8; the flow is damped in the process to become less turbulent. Then it spirals down along the walls of the cone 3 to the lower outlet pipe 6. Most of the extracted fine matter spirals up in the opposite direction towards the outflow pipe 5. Larger particles are pressed against the walls of the cone 3 and exist through the lower outlet pipe 6.

Thus, by damping the flow in the cylinder, this unit can prevent or minimize circular vortices to have better separation capacity as a result.

Both designs were 3D printed from polylactide for experimental testing. PLA plastic is one of the environmentally friendliest materials used in 3D printing; its biodegradability makes it a perfect candidate for the experiments described herein. Figure 3 shows one of the printed parts — the disk reflector used in Design 1.
For better accuracy and comparability of the experimental results, both designs had identical linear dimensions, see figure 4 and table 1.

An experimental test bench was designed to test the effectiveness of biofuel separation, see figure 5. Both designs (shown in figures 1 and 2) were tested experimentally for hydrodynamics and separation capacity.
Biodiesel mixture premade by transesterification of cooking oil and and poured into the feed tank 2 would be pumped into the hydrocyclone 1 by a Sterwins 1000 WP CE 41-3 submersible high-pressure pump (nominal pressure: 80 kPa, peak flow: 5.5 m³/h), see figure 5. Special sampling tanks were mounted on the hydrocyclone pipes. 10 tests were run on one of the units, then it was replaced with its counterpart for 10 more tests.

To distribute the dispersed phase uniformly in the feed, it was mixed in the tank by a SKAT KPP-230-24 compressor with a maximum operating pressure of 0.8 MPa. An inlet manometer was used to monitor the pressure in order to prevent the operating parameters of the feed from affecting the experiments.

The mixture initially contained 23% of glycerin and particulate matter. We premade enough of the mixture for all the 20 tests; its temperature was kept constant at 24°C. Concentration of impurities was measured before and after purification by sedimentation analysis on a centrifuge. Particle counter returned an average particle size of ~ 25 µm.

3. Results
The graph in figure 6 shows the post-centrifugation readings for both designs; test numbers are on the X-axis, % purification of the initial mixture (PIM) is on the Y-axis.

Figure 5. Experimental test bench: 1 is the hydrocyclone; 2 is the feed tank.

Figure 6. Experimental results.
Experiments showed both designs (figures 1 and 2) to be well-capable of removing glycerin and particulate matter from biodiesel. However, Design 1 performed somewhat better. In particular, its maximum purification percentage reached 94.0%, cf. 93.2% for Design 2. Design 1 performed at 93.67% on average across 10 tests, whereas Design 2 performed at 93.09%.

4. Conclusion
The authors hereof analyzed the factors hindering the effectiveness of biofuel separation, came up with and tested two hydrocyclone designs. Design 1 featured a disk reflector. Design 2 featured a flow damper consisting of two sockets, each with a tapered surface.

For testing, we designed and made an experiment test bench; hydrocyclone parts were 3D printed from an environmentally friendly material. Biodiesel with a 23% concentration of impurities was made from cooking oil and used in tests as the biofuel.

The experiments and further sedimentation analysis showed Design 1 to reach a maximum purification of 94.0%, Design 2 to reach 93.2%. Design 1 performed at 93.67%, and Design 2 performed at 93.09% on average. Thus, both designs were shown to be well-capable of removing impurities from biodiesel and to have better separation capacity thanks to the lower risk of particulate matter going from the outer upstream to the outflow pipe. However, the disk reflector design performed somewhat better. This might be due to the fact that the disk reflector intensified the biodiesel purification process to a greater degree, as it facilitated the enlargement of fine glycerin droplets.

It is safe to say that the proposed designs could be effectively used in chemical and oil-and-gas mechanical engineering to separate impurities.

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