A 3D-printed mini-hydrocyclone for high throughput particle separation: Application to primary harvesting of microalgae

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Supplementary Information

Reynold Stress Model

The continuity equation and the time smoothed momentum equation for the incompressible flow are given as follows:

$$\frac{\partial\rho}{\partial t}+\frac{\partial\rho}{\partial x_j}(\rho U_i)=0 \tag{E1}$$

$$\rho\frac{D\,U_i}{Dt}=-\frac{\partial}{\partial x_i}p+\frac{\partial}{\partial x_j}[\mu\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)+\frac{\partial}{\partial x_j}(-\rho\overline{u_i\,u_j})+\rho g_i \tag{E2}$$

where ρ and μ are the density and viscosity of the liquid, U_i and u_i are the x_i components of the mean fluid velocity and the fluctuating fluid velocity, p is pressure, g is gravitational acceleration, and $\rho\overline{u_i\,u_j}$ are the components of the turbulent moment flux, known as "Reynolds stresses". The RSM solve the NS-equation by computing the Reynolds stresses, abandoning the isotropic eddy-viscosity hypothesis as used in the $k-\varepsilon$ models.

$$\frac{\partial}{\partial t}(\bar{\rho}ui^{\top}uj^{'})+C_{ij}=D_{ij}^{T}+D_{ij}^{L}+P_{ij}+G_{ij}+\emptyset_{ij}+\varepsilon_{ij}+F_{ij} \tag{E3}$$

Where, Cij is the Convection-Term, D_{ij}^{T} equals the Turbulent Diffusion, D_{ij}^{L} stands for the Molecular Diffusion, P_{ij} is the term for stress production, G_{ij} equals Buoyancy Production, $\emptyset_{ij}$ is for the Pressure Strain, ε_{ij} stands for the Dissipation and F_{ij} is the Production by System Rotation.

Particle Tracking

The following equation of motion for a single particle is used for calculating the trajectories of the discrete phase:

$$\frac{dv_i}{dt} = F_D(U_i - v_i) + \frac{g}{\rho_p}(\rho_p - \rho) + F_i \tag{E4}$$

where v is the particle velocity, $F_D(U_i - v_i)$ is the drag force per unit particle mass (F_D is given by Eqn. 5), and F_i are other forces acting on the particle, such as lift and Brownian forces (F_i is assumed to be negligible in the present work).

$$F_D = \frac{3\mu}{4\rho_p\, d^2}\, C_D\left(\frac{d|U - v|\rho}{\mu}\right) \tag{E5}$$

where C_D is the drag coefficient, and the term between brackets is the Reynolds number for the particle.

Effect of Particle Size On Net Force Balance:

As given in the manuscript, the forces acting on a particle due to the flow inside the hydrocyclone are the following:

$$F_c = m\frac{v_t^2}{r} = \frac{\pi D_p^3 v_t^2}{6\ r}\rho_p \tag{E6}$$

$$F_b = -\frac{\pi D_p^3 v_t^2}{6\ r}\rho_f \tag{E7}$$

$$F_d = -\, 3\pi D_p \mu v_r \tag{E8}$$

At a given density difference between liquid and the particles, the magnitude of the forces as given in equation (E6-E8), depend on the particle diameter D_p and the tangential velocity v_t, such that larger particles and higher flow rates can give better separation efficiency. Ignoring the drag force F_D and the constant terms in equations E6 & E7, the net force balance can be described as $(D_p^3\rho_f)-(D_p^3\rho_p)$,

with: D_p*: Particle diameter,* ρ_f*: Fluid density = 1 g/cm*^{3}*,* ρ_p *:Particle density= 1.15 g/cm*^{3}

The fractional relative difference in the net force balance by the variation of particle size has been demonstrated in the table S1

Table S1 Description of relative difference of the net force balance as function of particle size

D_p (μm)	$D_p^3\rho_p$	$D_p^3\rho_f$	Force balance ($D_p^3\rho_f$)-($D_p^3\rho_p$)	Relative difference
5	143.75	125	18.75	-
10	1150	1000	150	0.875
15	3881.25	3375	506.25	0.703
20	9200	8000	1200	0.578
25	17968.75	15625	2343.75	0.488

In the table S1, the relative difference is the fractional difference between the force balances of two consecutive particle sizes.

$$Relative\ difference = \frac{(force\ balance\ of\ current\ particle\ size - force\ balance\ of\ previos\ particle\ size)}{force\ balance\ of\ current\ particle\ size}$$

So, we conclude from Table S1 that the fractional relative difference of the net force balances between 5 and 10um particles is 0.87 whereas it decreases to 0.48 for 20 and 25µm particles. This confirms that the effect of buoyant forces becomes more significant for larger particle sizes as found in the figure 4(B) in the manuscript.

Algae Dewatering Results:

The concentrations and volumes of algae before and after the experiments in the feed tank as well as in overflow tank have been given in the table S2.

Table S2 Volume and concentrations of algae feed tank and overflow tank

	Volume (ml)		**Concentration (x10^4 cells/ml)**	
	Initial	**Final**	**Initial**	**Final**
Feed Tank (with underflow recirculation)	1300	110	45	321
Overflow Tank	-	1190	23	42.25

Comparison between conventional techniques and current work

Brief comparison has been made between the conventional techniques for primary harvesting of microalgae based on the concentration factor and power consumption in the table S3.

Technique	Concentration factor	Power consumption (kWh/m^3)	Continuous	Ref
Macro-hydrocyclone	4	0.3	Yes	(1)
Decanter bowl centrifuge	11	8	No	(2)
Vacuum filter	2-18.5	-	Yes	(3)
Nozzle discharge centrifuge	20-100	0.9-8	No	(1)
Hydrodynamic separation	6	-	Yes	(4)
Mini-hydrocyclone (Current work)	**7.13**	**0.83**	**Yes**	**-**

References:

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