

Process Design of Microalgae Slurry Pump

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Microalgae are a renewable source of dietary supplements, bioactive compounds, and potential energy. Once harvested, the microalgal medium is dewatered to form a slurry for downstream processing. This article outlines a process design for pumping the microalgae slurry. The pump requirements for delivering the *Chlorella* slurry with 5, 10 or 20 wt% solids at one tonne per hour (1,000 kg/h) and 10 bar were calculated. The 5 wt% microalgae slurry is a Newtonian fluid with a viscosity of 1.95 mPa·s. The 10 wt% and 20 wt% microalgae slurries are non-Newtonian fluids, whose viscosity depends on the shear rate (γ). The viscosity of 10 wt% and 20 wt% microalgae slurries is $1.504 (\gamma = 50 \text{ s}^{-1})/1.155 (\gamma = 100 \text{ s}^{-1})$ and $1.844 (\gamma = 50 \text{ s}^{-1})/1.219 (\gamma = 100 \text{ s}^{-1})$ mPa·s, respectively. The pump power requirements are mainly governed by the delivery pressure. The effect of the pipe length and the number of elbows is negligible. The effective power of the pump is calculated as 0.267-0.275 kW. To fulfill this duty, a ZGB type single-stage single-suction centrifugal slurry pump can be selected, which would provide enough shear rate to reduce the viscosity of the microalgae slurry and give required shaft power.

Keywords: Microalgae Slurry; Slurry Pump; Process Design; Viscosity; Pump Power

Introduction

Microalgae are a source of dietary supplements, bioactive compounds, and potential energy, which have been invested extensively [1, 2]. Generally, the microalgal culture has a very dilute concentration of 0.1-0.5 wt% dry solids [3]. Currently, the proposed harvesting process is using a series of mechanical unit operations to dewater the microalgae medium to a level of ~20 wt% dry solids [4], which is considered as a less energy intensive processing option than completely drying microalgae [5]. The slurry after dewatering is considerably more viscous, but it is still a flowable slurry. Thus, it only needs to be transported to downstream processing facility using a slurry pump. Downstream

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processing of microalgae may include drying [6], extraction to yield biochemicals [7], and hydrothermal liquefaction [8] or pyrolysis to produce bio-fuels [9, 10]. The slurry pump is the key equipment for transporting the feedstock.

This paper provides a simple process design for pumping microalgae slurry. The purpose is to provide a tutorial for calculating the power requirement for pumping of various microalgae slurries, and provide data support when selecting pumps. The effect of the pipe length and the number of elbows was also discussed.

Methodology

Process Description

A microalgae flow is pumped by a slurry pump from a storage tank to the downstream processing facility. The process is illustrated in Figure 1, in which the processing facility is assumed to be a drying unit. The calculation of the drying process is not within the scope of this article.

The flow rate of the microalgal slurry is 1,000 kg/h, and the solid content is 5 wt%, 10 wt% or 20 wt%. The temperature of the slurry is 25°C and the pressure is 1 bar. The duty of the slurry pump is to pressurize the flow to 10 bar, and the efficiency of the pump is 70%. The slurry is delivered through 100 meters of PVC pipe (diameter 0.1 m) and three 90° elbows to the top of the dryer.

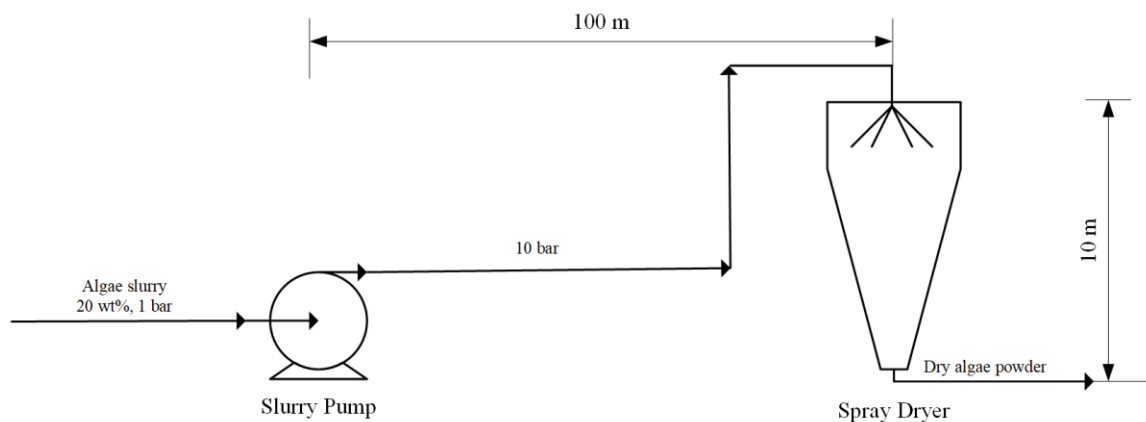


Figure 1. Process for microalgae pumping and drying

Microalgae

Green microalga *Chlorella sp.* is assumed to be grown autotrophically, harvested, and concentrated to a solid content of up to 20 wt% via a series of dewatering processes. The detailed design of the dewatering process can be found in the literature [3]. The elemental composition and biochemical components of *Chlorella sp.* have been summarized in our previous study [11].

Results and Discussion

Viscosity of 5, 10, and 20 wt% Microalgal Slurry

The *Chlorella* slurry with a solid content of 5 wt% is a Newtonian fluid. The viscosity can be calculated by the following formula [12]:

$$\mu_{eff} = 1.9 \times 10^{-5} \times C + 1.0 \times 10^{-3} \quad (1)$$

where μ_{eff} (Pa·s) is the effective viscosity, and C is the microalgae concentration and its unit is (kg/m³). Assuming the 5 wt% concentration is the percent weight/volume (% w/v), Equation 1 becomes:

$$\mu_{eff} = 1.9 \times 10^{-5} \times 50 + 1.0 \times 10^{-3} = 1.95 \text{ mPa} \cdot \text{s} \quad (2)$$

The *Chlorella* slurry with a solid content higher than 6 wt% is considered as non-Newtonian fluid. Its viscosity depends on the shear rate and follows the Herschel-Bulkley model:

$$\eta = K|\dot{\gamma}|^{n-1} + \tau_y|\dot{\gamma}|^{-1} \quad (3)$$

where η is the viscosity, τ_y is the yield stress, K is the consistency, n is the flow index, and $\dot{\gamma}$ is the shear rate [s⁻¹]. The Herschel-Bulkley parameters for the *Chlorella* slurry can be found in the literature as follows [13]:

Table 1. Herschel-Bulkley parameters for the *Chlorella* slurry

Solid content	10%	20%
τ_y (mPa)	50.56	80.1
K (MPa·S ⁿ)	0.103	0.011
n	1.4	1.79

For the 10 wt% microalgal slurry, when $\dot{\gamma}$ is 50 s⁻¹,

$$\eta = 0.103 \times 50^{1.4-1} + 50.56 \times 50^{-1} = 1.504 \text{ mPa} \cdot \text{s} \quad (4)$$

When $\dot{\gamma}$ is 100 s⁻¹,

$$\eta = 0.103 \times 100^{1.4-1} + 50.56 \times 100^{-1} = 1.155 \text{ mPa} \cdot \text{s} \quad (5)$$

For the 20 wt% microalgal slurry, when $\dot{\gamma}$ is 50 s⁻¹,

$$\eta = 0.011 \times 50^{1.79-1} + 80.1 \times 50^{-1} = 1.844 \text{ mPa} \cdot \text{s} \quad (6)$$

When $\dot{\gamma}$ is 100 s⁻¹,

$$\eta = 0.011 \times 100^{1.79-1} + 80.1 \times 100^{-1} = 1.219 \text{ mPa} \cdot \text{s} \quad (7)$$

Therefore, the viscosity of 5, 10, and 20 wt% *Chlorella* slurries was 1.95 mPa·s, 1.155 mPa·s (at $\dot{\gamma}$ = 100 s⁻¹), and 1.219 mPa·s (at $\dot{\gamma}$ = 100 s⁻¹), respectively. The viscosity of the microalgae slurry mainly depends on the fluid type.

Slurry Pump Design

This section calculates the power and equipment selection of the slurry pump. The calculation considers three kinds of algal slurry concentration, 100 meters of pipeline length, 10 meters of tower height, and three 90° right angle elbows. The density of *Chlorella* slurry is not available in the literature. Therefore, it is assumed that the density

of *Chlorella* slurry is similar to that of *Nannochloropsis salina* [14]. Therefore, the density of 5, 10, and 20 wt% microalgae slurries are 1,009, 1,020, and 1,042 kg/m³, respectively.

5 wt% Microalgae Slurry

The volumetric flow rate is calculated as:

$$q_v = \frac{q_m}{\rho} = \frac{1000}{1009} = 0.99 \text{ m}^3 / \text{h} \quad (8)$$

Flow velocity in the pipe is:

$$u = \frac{q_v}{\frac{\pi d^2}{4}} = \frac{0.991}{\frac{\pi}{4} \times 0.1^2} = 126.188 \text{ m/h} = 0.035 \text{ m/s} \quad (9)$$

Because the 5 wt% microalgal slurry belongs to Newtonian fluid, the viscosity is constant. So, Reynolds number (Re) is calculated as

$$\text{Re} = \frac{du\rho}{\mu} = \frac{0.1 \times 0.0351 \times 1009}{0.00195} = 1813.728 < 2000 \quad (10)$$

Reynolds number is less than 2000, so the fluid is a laminar flow. Friction coefficient is

$$\lambda = \frac{64}{\text{Re}} = \frac{64}{1813.728} = 0.0353 \quad (11)$$

According to the Chemical Engineering handbook [15], for the 90° elbow, the coefficient of local resistance and the equivalent length ratio are:

$$\zeta = 0.75 \quad (12)$$

$$\frac{l_e}{d} = 35 \quad (13)$$

The total resistance of the pipeline is:

$$\sum h_f = \left(\lambda \frac{\sum l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2} = \left[0.0353 \times \left(\frac{100}{0.1} \right) + 3 \times 0.75 \right] \times \frac{0.0351^2}{2} = 0.0231 \text{ J/kg} \quad (14)$$

$$\sum H_f = \frac{\sum h_f}{g} = \frac{0.0231}{9.81} = 0.00236 \text{ m} \quad (15)$$

Assuming the horizontal pipe is the datum, Bernoulli equation is listed as:

$$z_1 + \frac{u_1^2}{2g} + \frac{p_1}{\rho g} + H_e = z_2 + \frac{u_2^2}{2g} + \frac{p_2}{\rho g} + \sum H_f \quad (16)$$

where, $z_2 - z_1 = 10 \text{ m}$, $u_1 = 0$, $u_2 = 0.0351 \text{ m/s}$, $P_1 = 1 \text{ bar}$, $P_2 = 10 \text{ bar}$

Pump head is calculated as

$$H_e = 10 + \frac{0.0351^2}{2 \times 9.81} + \frac{9 \times 10^5}{1009 \times 9.81} + 0.00236 = 100.927 \text{ m} \quad (17)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.991}{3600} \times 1009 \times 9.81 \times 100.927 = 0.275 \text{ kW} \quad (18)$$

The pump shaft power is

$$P = \frac{P_e}{\eta} = \frac{0.275}{0.7} = 0.393kW \quad (19)$$

10 wt% Microalgae Slurry

The volumetric flow rate is

$$q_v = \frac{q_m}{\rho} = \frac{1000}{1020} = 0.98m^3/h \quad (20)$$

Flow velocity in the pipe:

$$u = \frac{q_v}{\frac{\pi}{4}d^2} = \frac{0.98}{\frac{\pi}{4} \times 0.1^2} = 124.891m/h = 0.0347m/s \quad (21)$$

Because the 10 wt% microalgal slurry is non-Newtonian fluid, when $\gamma = 50 \text{ s}^{-1}$, the viscosity η is 1.504 mPa·s. Reynolds number is

$$Re_t = \frac{du\rho}{\eta} = \frac{0.1 \times 0.0347 \times 1020}{1.504 \times 10^{-3}} = 2353.32 > 2000, \quad (22)$$

Reynolds number is higher than 2000, so the fluid is a turbulent flow. Then, the modified Blasius equation can be applied:

$$\lambda = \frac{a}{Re_t^b} \quad (23)$$

where turbulent constants a and b are the function of the flow behavior index (n) with $a = 0.3104n^{0.105}$, $b = 0.2495n^{-0.217}$, and $n=1.4$. Substitute these values into the equation to obtain $a=0.3216$, $b=0.232$, and $\lambda=0.0531$.

The total resistance of the pipeline is:

$$\sum H_f = \left(\lambda \sum \frac{l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2g} = \left[0.0531 \times \left(\frac{100}{0.1} \right) + 3 \times 0.75 \right] \times \frac{0.0347^2}{2 \times 9.81} = 0.00339m \quad (24)$$

Bernoulli equation gives the pump head as:

$$H_e = 10 + \frac{0.0347^2}{2 \times 9.81} + \frac{9 \times 10^5}{1020 \times 9.81} + 0.00339 = 99.948m \quad (25)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.98}{3600} \times 1020 \times 9.81 \times 99.948 = 0.272kW \quad (26)$$

The pump shaft power is

$$P = \frac{P_e}{\eta} = \frac{0.272}{0.7} = 0.389kW \quad (27)$$

When $\gamma = 100 \text{ s}^{-1}$, the viscosity η is 1.155 mPa·s. Reynolds number is

$$Re_t = \frac{du\rho}{\eta} = \frac{0.1 \times 0.0347 \times 1020}{1.155 \times 10^{-3}} = 3064.42 > 2000 \quad (28)$$

The fluid is a turbulent flow. The modified Blasius equation gives

$\lambda = \frac{a}{\text{Re}_l^b}$, $a = 0.3104n^{0.105}$, $b = 0.2495n^{-0.217}$, $n=1.4$. Substitute these values into

the equation to obtain:

$$a=0.3216, b=0.232, \lambda=0.0499 \quad (29)$$

The total resistance of the pipeline is:

$$\sum H_f = \left(\lambda \frac{\sum l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2g} = \left[0.0499 \times \left(\frac{100}{0.1} \right) + 3 \times 0.75 \right] \times \frac{0.0347^2}{2 \times 9.81} = 0.00321m \quad (30)$$

Bernoulli equation gives:

$$H_e = 10 + \frac{0.0347^2}{2 \times 9.81} + \frac{9 \times 10^5}{1020 \times 9.81} + 0.00321 = 99.948m \quad (31)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.98}{3600} \times 1020 \times 9.81 \times 99.948 = 0.272kW \quad (32)$$

The pump shaft power is

$$P = \frac{P_e}{\eta} = \frac{0.272}{0.7} = 0.389kW \quad (33)$$

20 wt% Microalgae Slurry

The volumetric flow rate is

$$q_v = \frac{q_m}{\rho} = \frac{1000}{1042} = 0.96m^3/h \quad (34)$$

Flow velocity in the pipe is

$$u = \frac{q_v}{\frac{\pi d^2}{4}} = \frac{0.96}{\frac{\pi}{4} \times 0.1^2} = 122.254m/h = 0.034m/s \quad (35)$$

Because the 20 wt% microalgal slurry is non-Newtonian fluid, when $\gamma = 50 \text{ s}^{-1}$, the viscosity η is 1.844 mPa·s. Reynolds number is

$$\text{Re}_l = \frac{du\rho}{\eta} = \frac{0.1 \times 0.034 \times 1042}{1.844 \times 10^{-3}} = 1921.25 < 2000 \quad (36)$$

Reynolds number is less than 2000, so the fluid is a laminar flow. Friction coefficient is

$$\lambda = \frac{64}{\text{Re}} = \frac{64}{1921.25} = 0.0333 \quad (37)$$

The total resistance of the pipeline is:

$$\sum H_f = \left(\lambda \frac{\sum l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2g} = \left[0.0333 \times \left(\frac{100}{0.1} \right) + 3 \times 0.75 \right] \times \frac{0.034^2}{2 \times 9.81} = 0.00209m \quad (38)$$

According to the Bernoulli equation, the pump head is

$$H_e = 10 + \frac{0.034^2}{2 \times 9.81} + \frac{9 \times 10^5}{1042 \times 9.81} + 0.00209 = 98.048m \quad (39)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.96}{3600} \times 1042 \times 9.81 \times 98.048 = 0.267kW \quad (40)$$

The pump shaft power is

$$P = \frac{P_e}{\eta} = \frac{0.267}{0.7} = 0.382kW \quad (41)$$

When $\gamma = 100 \text{ s}^{-1}$, the viscosity η is 1.219 mPa·s. Reynolds number is

$$\text{Re}_l = \frac{du\rho}{\eta} = \frac{0.1 \times 0.034 \times 1042}{1.219 \times 10^{-3}} = 2906.32 > 2000 \quad (42)$$

Then, the modified Blasius equation is applied:

$$\lambda = \frac{a}{\text{Re}_l^b}, \quad a = 0.3104n^{0.105}, \quad b = 0.2495n^{-0.217}, \quad n = 1.79. \text{ Substitute these values into}$$

the equation to obtain $a=0.33$, $b=0.22$, and $\lambda=0.0571$.

The total resistance of the pipeline is

$$\sum H_f = \left(\lambda \frac{\sum l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2g} = \left[0.0571 \times \left(\frac{100}{0.1} \right) + 3 \times 0.75 \right] \times \frac{0.034^2}{2 \times 9.81} = 0.0035m \quad (43)$$

Bernoulli equation gives the pump head as:

$$H_e = 10 + \frac{0.034^2}{2 \times 9.81} + \frac{9 \times 10^5}{1042 \times 9.81} + 0.0035 = 98.05m \quad (44)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.96}{3600} \times 1042 \times 9.81 \times 98.05 = 0.267kW \quad (45)$$

The pump shaft power is

$$P = \frac{P_e}{\eta} = \frac{0.267}{0.7} = 0.382kW \quad (46)$$

Table 2. Power requirements for microalgae slurry pump

Parameters	5 wt%	10 wt%		20 wt%	
		$\gamma = 50 \text{ s}^{-1}$	$\gamma = 100 \text{ s}^{-1}$	$\gamma = 50 \text{ s}^{-1}$	$\gamma = 100 \text{ s}^{-1}$
Viscosity (mPa·s)	1.95	1.504	1.155	1.844	1.219
Effective power (kW)	0.275	0.272	0.272	0.267	0.267
Shaft power (kW)	0.393	0.389	0.389	0.382	0.382

Table 2 summarizes the calculation results. For the above-mentioned fluid that requires high-lift delivery, a ZGB type pump can be used, which is a single-stage single-suction centrifugal slag/slurry pump. The typical processing shear rates of centrifugal pumps are within a range of 5 to 300 s^{-1} [16], which will help reduce the viscosity [17]. Because the diameter of the pipeline is 100 mm, the 100ZGB type slurry pump can be selected.

Effect of Pipe Length on Pump Power

It is assumed that the 20 wt% microalgae slurry was pumped from the storage tank to the facility. This section discusses the effect of the pipe length on the power requirement of the pump, as the length of the pipe increases to 500 meters and 1,000 meters.

When γ is 50 s^{-1} and the pipe length is 500 m, the total resistance of the pipeline is:

$$\sum H_f = \left(\lambda \frac{\sum l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2g} = \left[0.0333 \times \left(\frac{500}{0.1} \right) + 3 \times 0.75 \right] \times \frac{0.034^2}{2 \times 9.81} = 0.00994m \quad (47)$$

Pump head is calculated as:

$$H_e = 10 + \frac{0.034^2}{2 \times 9.81} + \frac{9 \times 10^5}{1042 \times 9.81} + 0.00994 = 98.056m \quad (48)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.96}{3600} \times 1042 \times 9.81 \times 98.056 = 0.267kW \quad (49)$$

When the pipe length is 1000 m, the total resistance of the pipeline is:

$$\sum H_f = \left(\lambda \frac{\sum l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2g} = \left[0.0333 \times \left(\frac{1000}{0.1} \right) + 3 \times 0.75 \right] \times \frac{0.034^2}{2 \times 9.81} = 0.0198m \quad (50)$$

Head developed is

$$H_e = 10 + \frac{0.034^2}{2 \times 9.81} + \frac{9 \times 10^5}{1042 \times 9.81} + 0.0198 = 98.066m \quad (51)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.96}{3600} \times 1042 \times 9.81 \times 98.066 = 0.267kW \quad (52)$$

When the pipeline length is increased to 500 meters or 1000 meters, it does not have much impact on the pump power.

Effect of Number of Elbows on Pump Power

This section discusses the effect of the numbers of elbows on the power requirement of the pump, as the numbers of elbows increases from 3 to 10. It is assumed that the 20 wt% microalgae slurry was pumped from the storage tank to the facility through 100 m pipe and elbows.

When γ is 50 s^{-1} and the number of 90° right angle elbows is 10, the total resistance of the pipeline is:

$$\sum H_f = \left(\lambda \frac{\sum l_i}{d} + \sum \zeta_i \right) \frac{u^2}{2g} = \left[0.0333 \times \left(\frac{100}{0.1} \right) + 10 \times 0.75 \right] \times \frac{0.034^2}{2 \times 9.81} = 0.0024m \quad (53)$$

Pump head is

$$H_e = 10 + \frac{0.034^2}{2 \times 9.81} + \frac{9 \times 10^5}{1042 \times 9.81} + 0.0024 = 98.049m \quad (54)$$

The effective power of the pump is

$$P_e = q_v \rho g H_e = \frac{0.96}{3600} \times 1042 \times 9.81 \times 98.049 = 0.267 \text{ kW} \quad (55)$$

When the number of 90-degree elbows is increased from 3 to 10, it does not have much impact on the pump power requirements.

CONCLUSIONS

The pump requirements for delivering the *Chlorella* slurry with 5, 10, and 20 wt% solids at 1,000 kg/h and 10 bar were calculated. The 5 wt% microalgae slurry is a Newtonian fluid with a viscosity of 1.95 mPa·s. The 10 wt% and 20 wt% microalgae slurries are non-Newtonian fluid, whose viscosity depends on the shear rate (γ). The viscosity of 10 wt% and 20 wt% microalgae slurries are 1.504 ($\gamma = 50 \text{ s}^{-1}$)/1.155 ($\gamma = 100 \text{ s}^{-1}$) and 1.844 ($\gamma = 50 \text{ s}^{-1}$)/1.219 ($\gamma = 100 \text{ s}^{-1}$) mPa·s, respectively. The pump power requirements are mainly governed by the delivery pressure. The effect of the pipe length and the number of elbows is negligible. The effective power of the pump is calculated as 0.267-0.275 kW, and the shaft power at 70% efficiency is 0.382-0.393 kW. To fulfill this duty, a ZGB type single-stage single-suction centrifugal slurry pump can be used.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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