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Scaling Up Manufacturing of Edible Coatings for Food

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Abstract

One of the most important methods for prolonging the shelf life of fruits and vegetables is edible coatings. The manufacture of the edible coating was tested in the laboratory before being scaled up to the industrial scale which is a procedure for applying, which applies the same process to different output volumes. One of the most crucial processes in the manufacturing of edible coatings is mixing. The equipment needed to scale up the production of edible solutions for food coating was also assessed. The results of the measurements revealed that scaling up mixing is based upon constant power/volume, equal blend duration, and adjusting the impeller/tank (D/T) diameter ratio was possible. A four-blade impeller was utilized to homogenize 1% carrageenan solutions at 70°C. Also, mixing parameters (Power number, Blend number, and Pumping number) were determined at different D/T ratios. Cost-effective pipe diameter and optimum pipe diameter per unit length were also determined.

Keywords: Scale-up; Mixing process; Economic pipe diameter; Rheology; Edible coating.

1. Introduction

Edible films and coatings are one of the emerging strategies for food-quality optimization. Their utility is determined by their ability to retain quality, extend shelf life, and contribute to the economic efficiency of packaging materials [1]**.** Furthermore, people want high-quality products made entirely of natural ingredients. Over the past years, many techniques have been used for preserving, being edible coatings for a composite of the method to greater results [2]. Edible coatings and edible films are not the same; edible coatings can be applied directly on the surface of fruits, vegetables, and other food products, whilst edible film is utilized as a wrapping and packaging material [3].

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Carrageenans are water-soluble polymers that contain a linear chain of partly sulphated galactans and have a strong film-forming potential. These sulphated polysaccharides come from the cell walls of a wide range of red seaweeds (Rhodophyceae). Carrageenans are produced in various ways by different seaweeds. The placements and quantities of sulfate ester groups are significant since they are, collectively, responsible for the creation of sulfate esters. [4]. There are several methods for making edible coatings, the most prevalent of which involves removing the solvent that was used to generate the coating solution. To develop and stabilize a continuous structure, this process relies on the physical or chemical intermolecular interactions. The coating solution's macromolecules are diluted in solvents such as water, ethanol, or acetic acid, and then mixed [5]. The mixing of liquids, solids, and gases is one of the most frequent unit operations in the food processing industry. Mixing enhances a system's homogeneity by removing non-uniformity or gradients in composition, features, or temperature. Pressure difference in various sections of the stirred tank functions as a driving force in mixing, which is generated by impeller rotation. The goal of mixing is to diminish the tank's heterogeneous qualities and create a homogenous mixture [6]. Non-Newtonian fluids are commonly found in industrial settings, such as coal-fired power plants, the food industry, and the petroleum industry. The most used method of transporting these fluids is to pump them through pipes, in which – notably due to skin friction - pressure drop is observed. This pressure loss in Newtonian fluids is usually determined by the Reynolds number and the pipe roughness (in the turbulent regime). However, in the case of non-Newtonian fluids, even establishing the Reynolds number is difficult, and other parameters must be included [7]. The primary goal of this research was to investigate the experimental pilot plant's scale-up qualities and issues in relation to the laboratory process for edible coating manufacture.

2. Methods

2.1. Material

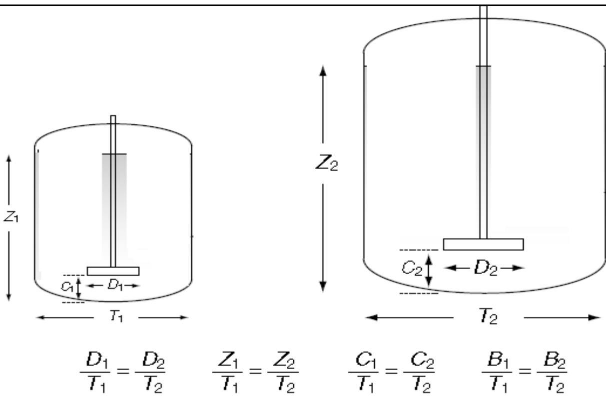
Glycerol was acquired from a Middle East company in Egypt, and carrageenan from Mefad.

2.2. Preparation of carrageenan solution

One gram Carrageenan powder was reconstituted in 100 mL distilled water as 1% (w/v) and 1% glycerol added. The solution was subsequently heated using a hot plate until it reached 70°C [8], for blend time (0.5h.). A 4-blade impeller laboratory mixer was used to mix the solution at various rotational speeds (500, 1050, 1650, and 2000 rpm).

2.3. Mixing process

The term "scale up" means the process of raising the batch size. It can also be thought of as a method of will be applied the same procedure to several output volumes. Scaling up is concerned with raising the linear dimensions from the laboratory to the plant size in mixing applications [9]. The exact geometrical similarity, which is particularly crucial in developing systems for scaling up, is satisfied in the design of mixing tanks on both a lab and commercial scale as shown in Fig. 1.



PM = P / 0.85

Figure 1: Geometrical parameters (Lab scale and industrial scale)

The mixing process was carried out in a laboratory at various rotational speeds (500, 1050, 1650, 2000 rpm) and 70°C for carrageenan solution (1%). The Reynolds number for shear-thinning fluids at different speeds can be computed as following Eq. (1): [10]

$$\mathrm{Re} = \frac{\rho\ N^{2-n} D^2}{k} \qquad (1)$$

Where, N is impeller speed, D is impeller diameter, ρ is density, and μ is viscosity The parameter of N_p which is used to predict the power of the mixer, may be calculated by the following Eq.(2): [11]

$$N_p = \frac{P}{\rho\ N^3 D^5} \qquad (2)$$

Where, P is mixing power, ρ is density, N is impeller speed

The impeller blend number, NB, is used to predict the blend time, θ, in a mixed system. Blend number, NB, attempts to predict the effect of impeller D/T on the results Eq. (3):

$$N_B = N\theta(D/T)^{2.3} \qquad (3)$$

Where, N_B is the blend number, Θ is the blend time, s.

The impeller pumping number, N_Q, is used to predict the impeller pumping rate, q, Eq.(4)

$$N_Q = \frac{q}{N\ D^3} \qquad (4)$$

2.4. Rheological properties of carrageenan solution

The flow behavior of manufactured edible coatings was investigated using rheological characteristics, which is a significant element for food coating materials. Brookfield Engineering (labs DV-III Ultra Rheometer) was used to evaluate the rheological parameters (Shear stress, Shear rate, and viscosity) of carrageenan (1%) by the addition of glycerol (1%). The sample has been placed in a small sample adapter, the viscometer was set at10 to 100 revolutions per minute, and the results were retrieved immediately from the instrument. The measurement was carried out using a SC4-21 spindle [12]**.**

2.5. Cost Estimation

2.6. Energy Cost

The annual energy cost for pumping apricot jam puree per unit pipe length is calculated by the following Eq. (5): [13-14]

$$Cost = C_{II} \times \frac{\Delta PQ}{\eta} \times annual\ operating\ hours \qquad (5)$$

Where, CII is the price per kilowatt electricity, L.E/kW.hr.

2.7. Fixed Cost of pipe

The annual cost of pipe per unit pipe length can be written as Eq. (6):

Cost of pipe = Purchased cost × (1+0.6) × 0.15 (6)

Where, (1+0.6) is the cost of installation and maintenance, 15% is the depreciation cost

2.8. Total annual cost

The total cost of pipeline is simply the sum of the annual costs of pipes and energy per unit pipe length as shown in Eq. (7):

Total cost = Energy cost + Pipe Fixed cost (7)

3. Results and Discussion

The primary idea is to collect data from scale equipment and then explain it by building a commercial scale process setup.

3.1. Flow behavior of carrageenan solution

The rheological data and curve fit of the shear rate-shear stress relationship for carrageenan edible solution (1%) at 70°C mixed at different rotational speeds (500, 1050, 1650, 2000 rpm) by the addition of (1 ml glycerol/100ml solution) are presented in Fig. 2. At all rotational speeds studied, the apparent viscosity decreased, and shear stress increased as the shear rate rose. The results indicated that at all rotational speeds investigated, carrageenan edible solution displayed shear thinning behavior, which fit well with the following Eq.(8):

$$\tau = k\gamma^{n} \qquad (8)$$

Where, τ is the shear stress, Pa, k is consistency index, γ is the shear rate, s^{-1}, n is flow behavior index.

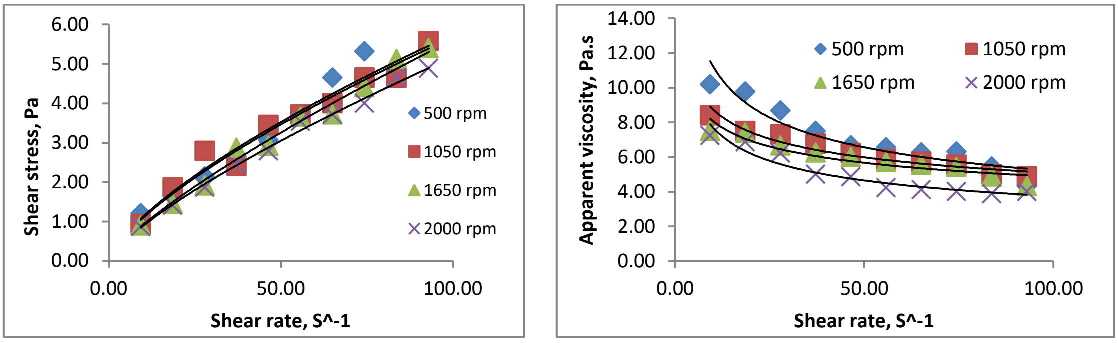


Figure 2: Flow behavior for carrageenan edible coating solution (1%)

The rheological properties of carrageenan solution (1%) at various rotational speeds (500, 1050, 1650, 2000 rpm) are summarized in Table 1. Results indicated that increasing agitation rotational speed lowered the consistency index (k), while increasing rotational speed raised the flow behavior index (n)

Table 1: Rheological parameter for carrageenan solution

Agitation speed	k (consistency index)	n (flow behavior index)
500	24.369	0.665
1050	15.117	0.763
1650	13.468	0.78
2000	13.456	0.782

3.2. Mixing process of edible solution

The value of a mixing-based product will be determined by the state of mixing on a commercial scale. The product is tested in a lab setting before the mixing process is examined. Tank geometry, impeller geometry and speed, baffles, density, and rheological qualities of liquid are all elements that might affect mixing quality.

Those elements must be considered when developing a stirred tank [6].

3.3. Power number of mixing process

The Power number is equal to the friction factor; it's proportional to the ratio of the drag force acting on a unit region of the impeller to inertial stress, where intern refers to the movement of momentum associated with the fluid's bulk motion [15]. The relation between Reynolds number and power number was fairly fitted to the following Eq. (9).

$$\text{Log NP} = \log A + B \log Re \qquad (9)$$

Where, P_0 is the power number, Re is Reynolds number, A and B are constants. Figures (3) show the relation between Power number and Reynolds number at various impeller to column diameter (D/T) ratios. The viscous dispersion is more pronounced as the impeller rotational speed increases, resulting in reduced power consumption. This could be attributed to the fact that as the impeller diameter increased, so does the blade size, resulting in a larger tank. Figure 3 shows experimental data on power consumption as a function of Reynolds number at various impeller-to-tank diameter ratios. It should be noted that when the Reynolds number rises, the power number for laminar flow drops. It is also worth noting that all data sets are organized in a series of parallel lines, making the power number reliant on the impeller's speed, implying that the impeller's speed is the most important factor [16].

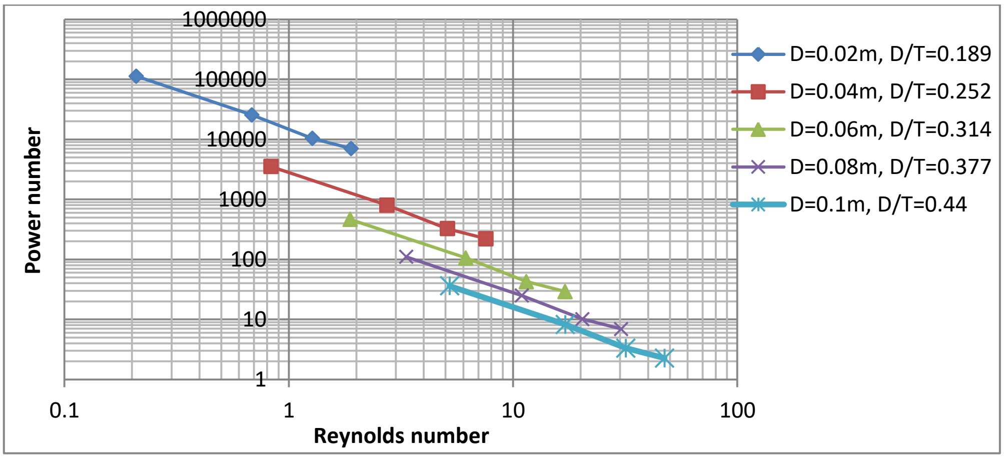


Figure 3: Effect of Reynolds number on power number for the different impeller diameter

The industrial-scale geometry of this research was 2000 L., the tank dimensions are listed in Table 2.

Table 2: Geometry similarity between lab scale and industrial scale

Geometry	Lab scale	Industrial scale
Tank diameter	0.159 m	1.6 m
Impeller diameter	0.07 m	0.7 m
Height of liquid	0.16m	1.6 m
Impeller clearance	0.26m	1.4 m

3.4. Simulation of P/V parameter

The target of scale up is most commonly to build production scale equipment; nevertheless, mixing experiments must be designed before scale-up, so that the pilot scale equipment may imitate production scale performance. The amount of power required in the mixing operation is the most significant consideration when designing and operating an impeller. This factor can also assist an engineer in estimating mixing performance. As a result, it's important to remember that the power in both lab and industrial scales is proportional to volume. Before calculating the power per volume ratio with the following equation, the mixing tank's unit volume must be known as illustrated in Table 3, [15].

$$V = \frac{\pi T^3}{4} \qquad (10)$$

Where, V is the volume of mixing tank m^3, T mixing tank diameter, m.

Table 3: Summary of Scale-up analysis

Run	N, rpm	Re	P/V	PM, watt
Lab scale	500	3	28125	105.88
Industrial scale	107.7	60.005	28116.24	82.694
N Lab scale	1050	7.65	28906.25	108.82
Industrial scale	226.22	151.804	29263.3	86.06
Lab scale	1650	13.47	29687.5	111.76
Industrial scale	355.48	267.21	29984.9	88.19
Lab scale	2000	16.94	30468.75	114.706
Industrial scale	430.89	339.91	30297.4	89.11

The scale-up of the mixing procedure for edible coating solution on an industrial scale is illustrated in Table 3. The volume of the lab-scale tank was 0.002 m^3, depending on the Eq. (8). As stated in table, the P/V value was calculated. In this scenario, the value will be a parameter. When the P/V values are as close as possible on both scales, the impeller speed will be specified, as a result, the impeller rotational speed was 107.7 rpm. The unit volume in industrial scale is 0.1 m^3, the simulation's power was 105.88 watts on an industrial scale, resulting in a P/V value of 28116.4. In lab-scale, the value is close to the P/V. As a result, the tank and impeller designs on an industrial scale are fulfilled.

3.5. Blend number

Blend time is an empirical factor that specifies how long it takes for the contents of a vessel to be homogenized. Blend number is a prediction of blend time. The relation between the Reynolds number and blend number is shown in Fig. 4. The results reveal that blend number rose rabidly as Reynolds number and D/T ratio rose.

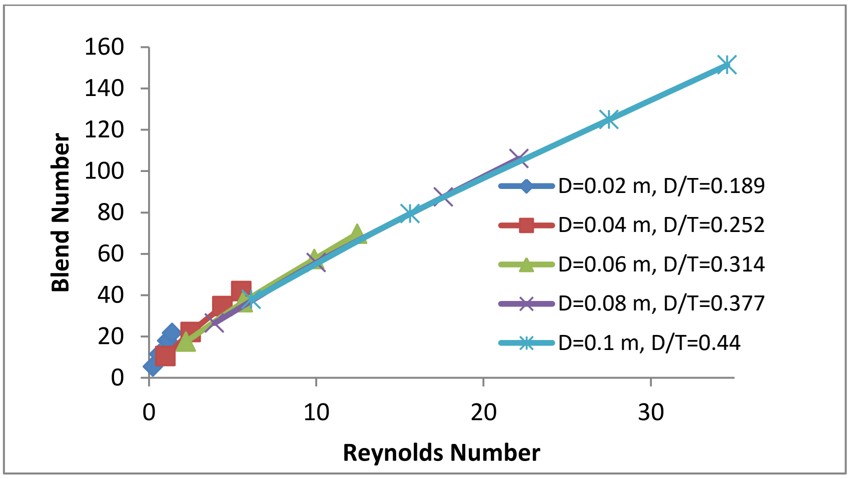


Figure 4: Relation between Reynolds number and Blend Number

3.6. Pumping number

The effect of the D/T ratio on pumping number is shown in Fig. 5. At the same Reynolds number, an increase in D/T ratio causes a decrease in pumping number. This may be the case that explains the fact that the volumetric flow rate of water is constant. The fluid leaving the impeller, q, necessitates a reduction in pumping power, as the impeller diameter increased.

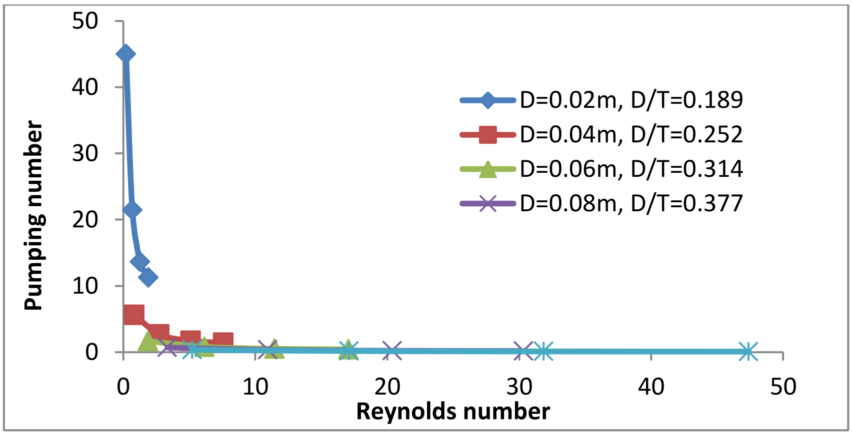


Figure 5: Generalized Relation between friction factor and Reynolds number

3.7. Pump sizing

Pump sizing is the method of matching a pump's flow and pressure rating to the flow rate and pressure required by the process [17]. Pumping can be simulated, based upon the principles of fluid flow and the Rheology of fluid. Small pipe can require a lower initial investment, but it has a higher head loss due to friction, which raises the energy cost. The added cost of a longer pipe would be offset by the savings in energy costs. Furthermore, the larger pipe can reduce the total pump head to the point that a higher and less expensive pump and power unit can be used. Hence, an optimum pipe diameter should exist; it may be determined by combining the principles of fluid dynamics with cost analysis [18-19]. In pipe flow problems, the friction coefficient is a function of Reynold's number and characterizes the nature of flow. For high Reynold's number; (Re < 2000), the flow is referred to as a laminar. The Reynolds number and friction factor is given as Eqs. (11-12):

$$\mathrm{Re} = \frac{\rho \; D^{n} v^{2-n}}{2^{n-3} k \; \left[(3n+1)/n\right]^{n}} \qquad (11)$$

$$f = \frac{2\tau}{\rho v^{2}} \qquad (12)$$

Where, ρ is the density, Kg/m^3, D is the pipe diameter, m, v is the fluid velocity, m/sec, n is the flow behavior index, k is the consistency index, τ shear stress, Pa. The frictional power required depends upon the flow rate, pipe size (diameter), overall pipe length, pipe description (surface roughness, material, etc.) and the properties of fluid being pumped. The following data were taken in consideration during this study:

Density of fluid = 960 kg/m^3

Pipe characterization, smooth stainless steel pipes

Annual operating hours = 7200 hr/year

Figure 6 represents the friction factor (f) in the case of the carrageenan solution (1%) as a function of generalized Reynolds number (Re)

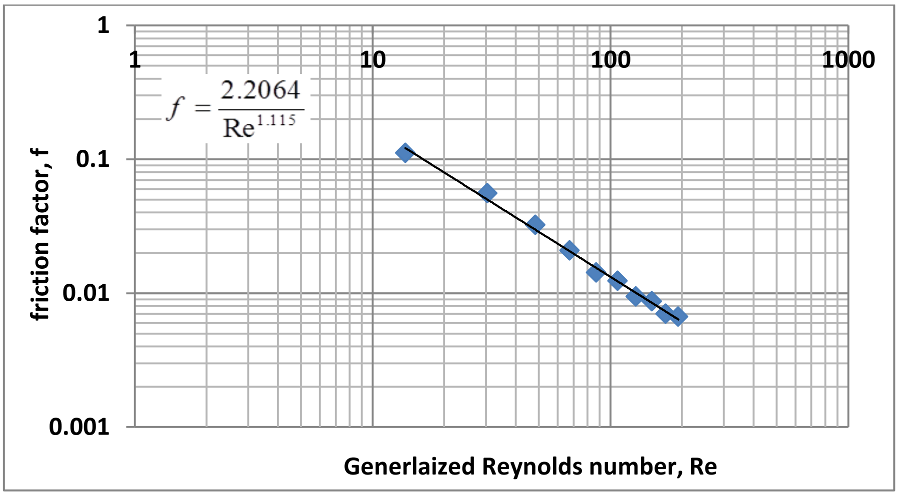


Figure 6: Experimental friction factor (f) vs. generalized Reynolds number (Re)

The Darcy –Weisbach equation specifies that for pipe of uniform diameter, the pressure loss due to viscous effects (ΔP) can be characterized by Eq. (13):

$$\frac{\Delta P}{L} = \frac{2 \ \rho \ v^2 f}{D} \qquad (13)$$

3.8. Optimum economic pipe diameter

The optimal economic diameter of pipe will be that diameter at which the present value of capital cost, operation and maintenance charges is minimum. Pipelines are normally designed to deliver fluid at the required head and flow rate in a cost effective manner. The selection of an optimum pipe size for pumping plants and pipelines should be based on careful economic analysis. Increase in conduit diameter leads to increase in annual capital costs, and decrease in operating costs [20]. The method accounts for pipe system cost accounts as a function of pipe diameter. The optimum diameter can be estimated given the rheological properties, fluid density, mass flow rate and economic parameters. Fig. 7 shows the relation between pipe diameters and fixed energy and total cost of pipe. Different pipes of varying sizes and their price per unit length are considered. The results observed that fixed cost of pipes increase with increasing pipe diameter, while energy cost decrease with increasing pipe diameter. The optimum economic pipe diameter was 0.032 m.

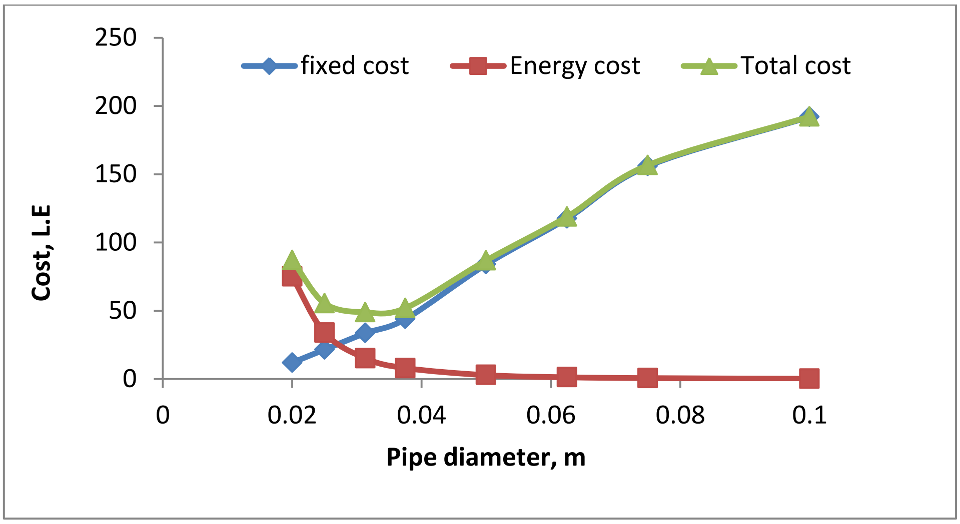


Figure 7: Optimum economic pipe diameter

The power consumption for pumping which depends on line size is substantial fraction of the total cost utilities; accordingly economic optimization of pipe size is a necessary aspect of plant design [21]. Power of the pump per unit length can be calculated from Eq. (14):

$$power = \frac{Q \Delta P}{\eta \ L} \text{ , } \eta \text{ (efficiency of the pump 70\%)} \qquad (14)$$

The volumetric flow rate (Q) was calculated from the following Eq. (15)

$$Q = \text{mass flow rate} / \rho \qquad (15)$$

The results indicated that power of the pump needed to transfer carrageenan solution (1%) to packaging tank was approximately 0.5 hp.

4. Conclusion

Power per volume parameter is recommended as a result for scale up of mixing process used in edible coating solutions. The plant rotational speed was found to be approximately 108 rpm and P/V was approximately constant for lab and industrial scale at 108 rpm. The optimum economic pipe diameter was determined 0.032 m and the pump power was 0.5 hp.

5. Abbreviations

A and B	Constants in equation (7), dimensionless Impeller diameter, m
D	Consistency index.
K	Flow behavior index
n	Impeller speed revolutions per second (rps)
N	Power number
N_P	Blend number
N_B	Pumping number
N_Q	Power of the mixer, watt
P	Motor power, hp
PM	Volumetric flow rate of fluid, m^3
Q	Tank diameter, m
T	Reynolds number
Re	Shear rate, s^{-1}
γ	Viscosity, Pa.s

μ	Density, kg/m^3
ρ	Shear stress, Pa
τ	Pressure drop, Pa
ΔP	Friction factor
f	Fluid velocity, m/s
υ	Pipe length, m
L	Price of electricity, L.E
CII	Blend number
N_B	Is the blend time, s.
Θ	

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