รายงานวิจัยฉบับสมบูรณ์

การประยุกต์ใช้อุปกรณ์ไฮโดรไซโคลนสำหรับการแยกยีสต์ในอุตสาหกรรมผลิตเบียร์

โดย ผศ.ดร.วรรณวิไล ไกรเพ็ชร์ เอวานส์ และคณะ

ธันวาคม 2551

สัญญาเลขที่ MRG5080035

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คณะผู้วิจัย   สังกัด

1. ผศ.ดร.วรรณวิไล ไกรเพ็ชร์ เอวานส์ ภาควิชาวิศวกรรมเคมี คณะวิศวกรรมศาสตร์ มหาวิทยาลัยศรีนครินทรวิโรฒ
2. ผศ.ดร. พิชัย อัษฎมงคล ภาควิชาวิศวกรรมเครื่องกล คณะวิศวกรรมศาสตร์ มหาวิทยาลัยศรีนครินทรวิโรฒ
3. พันเอก ผศ.ดร.อโณทัย สุขแสงพนมรุ้ง กองวิชาวิศวกรรมเครื่องกล โรงเรียนนายร้อยพระจุลจอมเกล้า

สนับสนุนโดยสำนักงานคณะกรรมการการอุดมศึกษา และสำนักงานกองทุนสนับสนุนการวิจัย

(ความเห็นในรายงานนี้เป็นของผู้วิจัย สกอ. และสกว. ไม่จำเป็นต้องเห็นด้วยเสมอไป)

ABSTRACT

This manuscript details the research work undertaken for the design and construction of hydrocyclones to recover yeast in the brewery industry. The hydrocyclone dimensions were defined using data obtained from the Computational Fluid Dynamics (CFD) simulation of the flow within hydrocyclones. The Finite Volume Method (FVM) and Reynolds Stresses Model (RSM) were used to model the turbulence characteristic of the flow. The particle motions were modeled by using the Lagrangian method with turbulent dispersion. It was found that the SWU10-2.6-2 and SWU 10-3.2-2 hydrocyclones had the better performance curves amongst the hydrocyclones studied. These two hydrocyclones were constructed, and their separation performance was investigated by treating the suspension obtained from the Pathumthani Brewery Co. Ltd., Thailand. The experimental results followed the same trend as the simulated results. It was found that the SWU10-2.6-2 produced better classification efficiency due to the smaller cut size, while the SWU10-3.2-2 produced better separation efficiency according to the higher solid recovery in the underflow. The effects of pressure drop on the solid classification and on the solid recovery were also studied. High turbulence in the flow caused by the high pressure drop and the flow rate had a major effect on the solid classification. A higher pressure drop also led to higher solid recovery performance.

Key words: Hydrocyclone, Finite Volume Method, Computational Fluid Dynamics, Yeast separation.

<u>บทคัดย่อ</u>

งานวิจัยเป็นการออกแบบไฮโดรไซโคลน เพื่อใช้ในการนำยีสต์กลับมาใช้ใหม่ในกระบวนการผลิตเบียร์ โดยใช้ข้อมูลที่ได้จากการจำลองการไหลในไฮโดรไซโคลน การจำลองการไหลในไฮโดรไซโคลนนั้นทำโดยใช้เทคนิคการคำนวณพลศาสตร์ของไหลด้วยวิธีการคำนวณระเบียบวิธีเชิงตัวเลขแบบ Finite Volume Method ด้วยกริดสามมิติเรียงตัวแบบไม่เป็นระเบียบ การคำนวณการไหลแบบปั่นป่วนโดยใช้สมการ Reynolds Averaged Nervier Stokes และแบบจำลอง Reynolds stresses model ส่วนการจำลองการเคลื่อนที่ของอนุภาคยีสต์ใช้เทคนิค Lagrangian ร่วมกับแบบจำลองการกระจายตัวแบบปั่นป่วนของอนุภาค จากผลการจำลองพบว่าไฮโดรไซโคลนแบบ SWU10-2.6-2 และ SWU 10-3.2-2 สามารถทำการคัดขนาดของอนุภาคยีสต์ได้ดีกว่าไฮโดรไซโคลนตัวอื่นที่ศึกษา ดังนั้นจึงทำการสร้างและทดสอสมรรถนะในการคัดขนาดของไฮโดรไซโคลนทั้งสองตัวนี้ โดยใช้น้ำเบียร์จากถังหมักในโรงงานผลิตเบียร์ พบว่ากราฟแสดงสมรรถนะในการคัดขนาดที่ได้จากการจำลองให้ผลสอดคล้องกับผลที่ได้จากการทดลอง SWU10-2.6-2สามารถให้สมรรถนะในการคัดขนาดได้ดีกว่า แต่SWU10-3.2-2สามารถให้เปอร์เซ็นต์ในการนำยีสต์กลับมาใช้ใหม่ได้ดีกว่า และพบว่าความดันลดมีต่อการคัดขนาดของไฮโดรไซโคลนมาก ค่าความดันลดสูงทำให้ได้เปอร์เซ็นต์การนำยีสต์กลับมาใช้ใหม่สูง

<u>คำสำคัญ</u> : ไฮโดรไซโคลน การคำนวณทางพลศาสตร์ของไหล ระเบียบวิธีเชิงปริมาตร กระบวนการแยกยีสต์

Content

Executive Summary

1. Background and problem statement (ความสำคัญและที่มาของปัญหา)

The biotechnology industry has been rapidly grown world wide due to the demand for the products of microbe's metabolites which are of enormous benefit because of their food and medical use. There are a number of fundamental challenges and difficulties which bio-processes present to engineer and many of these impinge directly upon separation process requirement, which affect directly the quality of products and the costs of production. Yeast is widely used in the biotechnology industry such as beverage industries, pharmaceutical industries, citric acid industries, etc. The bio-separation in these industries is mainly involved in the separation of yeast to clarify products, to recover yeast or to clean process water. Conventionally, centrifugation and filtration are used but both of these techniques have significant limitations. Centrifuges are high in cost for both manufacture and maintenance. In filtration, filter aids are needed. This would unavoidably lead an increase in production costs. Hydrocyclones do not need any separation aids. They are absolutely environmental friendly. Moreover, hydrocyclones have advantages of low cost, small space requirement, easy cleaning and installations are modular.

Hydrocyclone geometry and operational parameters can be calculated by applying empirical models, which consist of a set of design equations. Most of the design equations are based on the correlations obtained experimentally, using dimensionless similarity numbers. These equations have their limitations due to the specific systems used for the model development. The application of the empirical model to different systems is still limited and unreliable. Therefore, in many cases, they cannot be used with confidence to predict the design of an individual separator, or the overall plant configuration that is required to meet different user requirements. This is a main problem, which has always been found in industry. Additionally, they do not offer an insight into the underlying physical mechanisms of fluid flow in the hydrocyclone.

Alternatively, an attempt to model the flow in a hydrocyclone has been made by using the theoretical models, which is based on solving a set of conservation equations, resulting from mass and momentum principles by using the Computational Fluid Dynamics (CFD) techniques. This technique provides a physical insight into the fundamental causes of the observed phenomena. This approach is a better choice for a design tool since this method is unlimited, reliable and flexible in the change of hydrocyclone geometry. It can be apply to all hydrocyclone systems.

The aim of this work is to find the suitable hydrocyclone designs for the separation of yeast in brewing industry by using the CFD technique as a design tool. Furthermore, the effect of operating condition, such as, pressure drop, feed flow rate and temperature on the separation performance will be investigated.

2. Aims and objectives of the research programme (วัตถุประสงค์)

The ultimate goal of undertaken research is to take advantage of computational simulations more effectively in the overall design process and consequently optimise separation and classification process.

The main objectives of the project are:

1. to introduce the numerical method "Computational Fluid Dynamics (CFD) techniques", to the simulation of flow problem in chemical engineering field.
2. to simulate the flow within hydrocyclone. The results will allow an assessment of the effect of hydrocyclone geometry on the separation flow zone.
3. to use the methodology to design hydrocyclone for yeast separation in brewing industry, and to test the prediction by fabricating the novel hydrocyclone design and testing its performance.

3. <u>Methodology and task explanations</u> (ระเบียบวิธีวิจัย)

Methodology

The intelligent procedure based on a computer model for hydrocyclone design developed by the author and colleagues will be used to study the flow within a hydrocyclone. This procedure will enable a specific type of hydrocyclone to be designed to meet the requirements of yeast separation processes in brewing industry. The character of the separation flow as a function of its geometrical parameters will be simulated. The simulation of 3D flow within a hydrocyclone will be carried out by using the Finite Volume Method (FVM) with an unstructured grid. A particle tracking method will be applied to predict particle distribution. This method is based on the calculation of a particle trajectory in a Lagrangian co-ordinate system. The turbulence flow character will be modelled by use a proper turbulence model.

From the simulation results, the novel hydrocyclone for yeast separation will be designed and constructed. Its separation performance will be investigated. Then the validation of the simulated result will be carried out by concerned with the comparison of simulation data with the flow characteristic such as a pressure drop or split ratio versus throughput.

A work schedule is presented in Table 1

Task 1

The arrangement and setting of the computational facilities and instruments used in numerical simulation, which will be placed at Department of Chemical Engineering, Faculty of Engineering, SWU. The facilities and instruments include the PC computer work station, CFD code and AVS/express Visualization edition.

Task 2

The computational mesh will be created using the 3D unstructured grid system. The suitable grid type will be determined.

Task 3

This task is concerned with solving a set of mass and momentum conservation equations. The partial differential equations will be solved in 3D numerically by using the FVM method. The Reynolds Averaged Navier-Stokes equations (RANS) and the Large Eddies Simulation (LES) modelling approach will be implemented to investigate the turbulent flow in this work.

Task 4

Visualise the obtained results from Task 3. The AVS/express visualisation edition may be used as the post-processor of the obtained results due to the unstructured system of the data. The flow simulation results will be shown in forms of flow velocity (contour, velocity vectors, isoline and so on), flow pressure, and fluid and particle pathlines.

Task 5

The study of the effect of hydrocyclone geometries on the separation flow zone in the separator will be carried out, by using the developed simulation technique.

Task 6

In this task, a specific type of hydrocyclone to be designed to meet the requirements of yeast separation processes in beer-brewing industry.

Task 7

The construction of the experimental rig and the made of hydrocyclone will be done in this task.

Task 8

Investigate the separation performance of the design hydrocyclone or yeast separation by treating with the sample slurry form beer-brewing plant. Moreover, the effect of operating condition, such as, pressure drop, feed flow rate and temperature on the separation performance will be studied.

Task 9

Validate the numerical simulations by comparing the flow characteristic obtained form the numerical simulations with the data from experiments.

Table 1

Tasks	Six-month period			
	1th	2nd	3rd	4th
1. Arrangement and setting of the computational facilities and instruments.	■			
2. Constructing the 3D-unstructured computational mesh.	■			
3. Solving the flow problem		■		
4. Visualisation the obtained data from Task 3.		■		
5. Study of the effect of hydrocyclone geometries on the separation flow zone.		■		
6. Design hydrocyclone for yeast separation using CFD code as a design tool.			■	
7. Construction of the experimental rig and the made of hydrocyclone.		■	■	
8. Investigate the separation performance of the design hydrocyclone.				■
9. Validate the numerical simulations.				■

4. <u>Project plan & Management</u> (แผนการดำเนินงานวิจัยตลอดโครงการในแต่ละช่วง 6 เดือน)

The project will be managed following the project schedule (Table 1), which describes list of tasks and time scale for each six months. The detail explanations of each task are described in Section 3

(Methodology and task explanations). The tasks will be executed by the author at Department of Chemical Engineering, Srinakarinwirote University and supervised by the mentor from Department of Mechanical Engineering, Srinakarinwirote University. Six monthly summary research reports will be held to monitor progress against the planned programme in Table 1. Monthly review meeting between the researches may be held if necessary.

5. <u>Exploitation</u> (ผลงาน/หัวข้อเรื่องที่คาดว่าจะตีพิมพ์ในวารสารวิชาการระดับนานาชาติ)

The deliverables from the research are expected to include; an advanced fluids dynamics modelling approach for design of particle separators, an improved fundamental knowledge of the mechanism of separation based on three-dimensional simulation and the special type of hydrocyclone for yeast separation process in brewing industry.

The results of the project will be disseminated international publicity via refereed publications submitted to the established journals:

1) Title: The simulation of the flow within a hydrocyclone.

2) Title: Computational Fluid Dynamics approach for design the small hydrocyclone for biological-solid separation.

An application of small hydrocyclones for separating yeast in the brewing industry

1. Abstract

The separation performance of the dewatering (MZ) and the deoiling (HY1) hydrocyclones for separating yeast in the brewing industry were investigated. Their applications in the liquid clarification and yeast recovery processes were studied. The feed suspensions used in these experiments were taken from the fermentation tank in the brewing plant. For the liquid clarification application, both hydrocyclones demonstrated their ability to clarify liquid with up to 50% clarification efficiency. The clarification efficiency was found to increase with an increase in pressure drop. Only the dewatering hydrocyclone could provide solid classification for both suspensions studied. Additionally, a high operating pressure drop did not provide any benefit to the classification because yeasts have low time constant, which are turbulence sensitive.

Keywords: Hydrocyclone, Yeast, Solid-Liquid Separation.

2. Introduction

2.1 Background

The biotechnology industry has been rapidly grown worldwide due to the demand for the products of microbe's metabolites which are of enormous benefit because of their food and medical use, etc. There are a number of fundamental challenges and difficulties which bio-processes present to the engineer and many of these impinge directly upon separation process requirements, which affect directly the quality of products and the costs of production. Yeast is widely used in the biotechnology industry such as beverage industries, pharmaceutical industries, citric acid industries, etc. The bio-separation in these industries is mostly concerned with the separation of yeast to clarify the product, to recovery yeast or to clean process water. An example of the biotechnology process using yeast is a brewery plant as shown in Figure 1. Conventionally, centrifugation and filtration are used, but both of these techniques have significant limitations. Centrifuges are high cost in terms of both operation and maintenance. In filtration, filter aids such as Kieselguhr are needed. This would unavoidable lead to an increase in production costs, and moreover, the environmental problem caused by the disposal of used filter aids. Hydrocyclones do not need any separation aids. So they are absolutely environmentally friendly. Moreover, hydrocyclones have the advantage of being low cost in terms of purchasing, installation, operation and maintenance, small space requirement, ease of cleaning and also because installations are modular.

There are some other research works on the application of small hydrocyclones for micro-organism separation, which are [1], [2], [3] and [4]. Cillier and Harison [1] studied the effect of viscosity on the recovery and concentration of Bakers' yeast from glucose' water solution using a 10-mm dewatering hydrocyclone. They found the solid recovery decreasing for higher feed concentrations. Yuan et al. [2] did the experimental works to explore the yeast separation with various types of hydrocyclone. The suspensions used in their experiments were Nylon powder, Baking yeast, and Brewing yeast in sucrose's water solution. They reported that their deoiling type hydrocyclone, which was developed for the separation of dispersed oil in water, gave better liquid separation results than other types of hydrocyclone. Rickwood et al. [3] investigated the possible used of a 10-mm dewatering hydrocylcone and a 35mm deoiling hydrocyclone for the recycling of used Kieselguhr by removing yeast into the overflow, while the bulk of the Kieselguhr is in the underflow. The suspension used was dry Kieselguhr in distilled water. Their results showed that the de-watering hydrocyclone design gave an efficient separation of Kieselguhr and yeast suspension.

2.2 Objectives

The main aim of the work presented here was to investigate the performance of small hydrocyclones for separating yeast in the brewing industry utilising the actual suspension from the Pathumthani Brewery Co. Ltd., Thailand. Two different hydrocyclones, 11-mm deoiling hydrocyclone developed by [2] (HY1), and 10-mm dewatering hydrocyclone from Richard Mozley Ltd. (MZ) were used. There were two separation applications considered, which were the liquid clarification for the pre-filter unit and the yeast recovery for the fermentation unit. The feed suspensions used in these experiments were taken from the middle and bottom parts of the fermentation tank in the brewing plant.

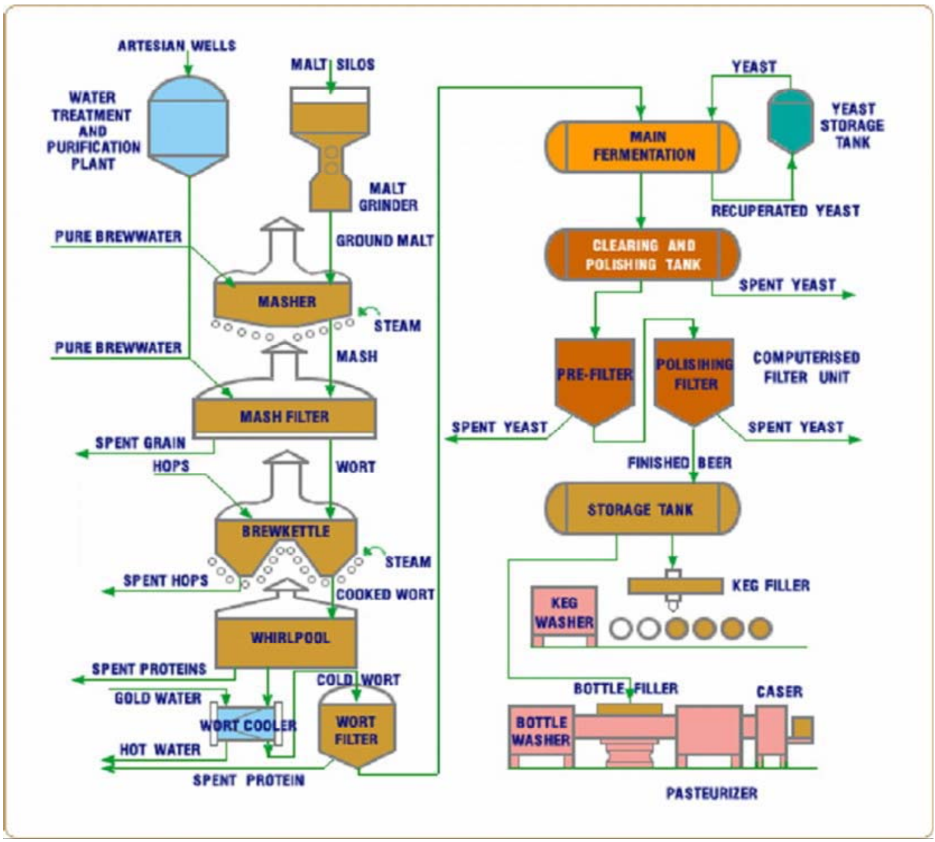


Figure 1. Schematic diagram of a brewery plant.

3. Separation performance

3.1 Selectivity curve

The selectivity function is defined as the fraction of each particle size in the feed flow reporting to the underflow product. It represents the separation efficiency of particles with a particular (particle) size. This function is usually plotted as a monotonic curve on a log-linear scale, and is known as the selectivity curve, partition curve, performance curve, tromp curve or grade efficiency curve. This curve will not pass though the origin because a portion of the flow bypasses the classification region as a result of flow division. For any particle size d the selectivity function, *S (d),* is defined as:

$$S(d) = \frac{\dot{U}\dot{u}(d)}{\dot{F}\dot{f}(d)} \quad (1)$$

where $\dot{F}$ and $\dot{U}$ are the mass flow rates of solids and $\dot{f}$ (d) and $\dot{u}$ (d) are the weight fractions of particle size d in the feed and underflow stream, respectively. The above equation evaluates the performance of a hydrocyclone based on experimental data.

The cut size, d_{50}, is one of the methods used to determine the hydrocyclone separation efficiency. It is defined as the particle diameter, which has an equal probability of reporting to both the underflow and overflow. The cut size can be obtained from the selectivity curve. Plitt [5] commented that the corrected cut size is a more fundamental parameter because it is a measure of the separation forces operating on the particles in the hydrocyclone.

The other important parameter is the throughput ratio, R_f, which is the ratio between the volumetric flow rate of the underflow and that of the feed, yields the recovery of the suspension to the underflow.

3.2 Clarification Efficiency

The separation efficiency also can be evaluated with the clarification efficiency defined as follows [2]:

$$E_c = 1 - (C_o/C_i)$$

where C_o and C_i are volumetric concentration of solid particles in overflow and feed streams, respectively.

4. Experimental method

4.1 Equipment

The hydrocyclones were equipped and set up with a feed pump and pressure gauge to measure the feed inlet pressure (see Figure 2). The geometrical hydrocyclone parameters are shown in Figure 3 and Table 1. Hydrocyclone overflows and underflows were directed back to the sump for recirculation. The operating pressure drop was varied from 20 kPa to 200 kPa by varying the inlet feed flow rate. Hydrocyclone tests were performed at 25°C. The feed suspensions used in the experiments were taken from the fermentation tank in the brewing plant of Pathumthani Brewery Co. Ltd., Thailand. For the liquid clarification application, the feed suspension was taken from the middle part of the fermentation tank, and was called Suspension type A. For the yeast recovery application, the feed suspension was taken from the bottom part of the fermentation tank, and was called Suspension type B. The density of brewing yeast is 1,204 kg/m^3. Yeast cells show a narrow size distribution with the dominant diameter measured as 8.9960 μm by laser diffraction technique, as shown in Figure 4. The properties of the suspensions are summarised in Table 2.

Table 2. Properties of the feed slurry.

Suspension type	Particle size (μm)	Viscosity (cSt) at 25 °C	Density (kg/m^3) at 25 °C
A	0.0582 – 301.6802	1.800	1000.0
B	0.0582 – 301.6802	2.934	1000.3

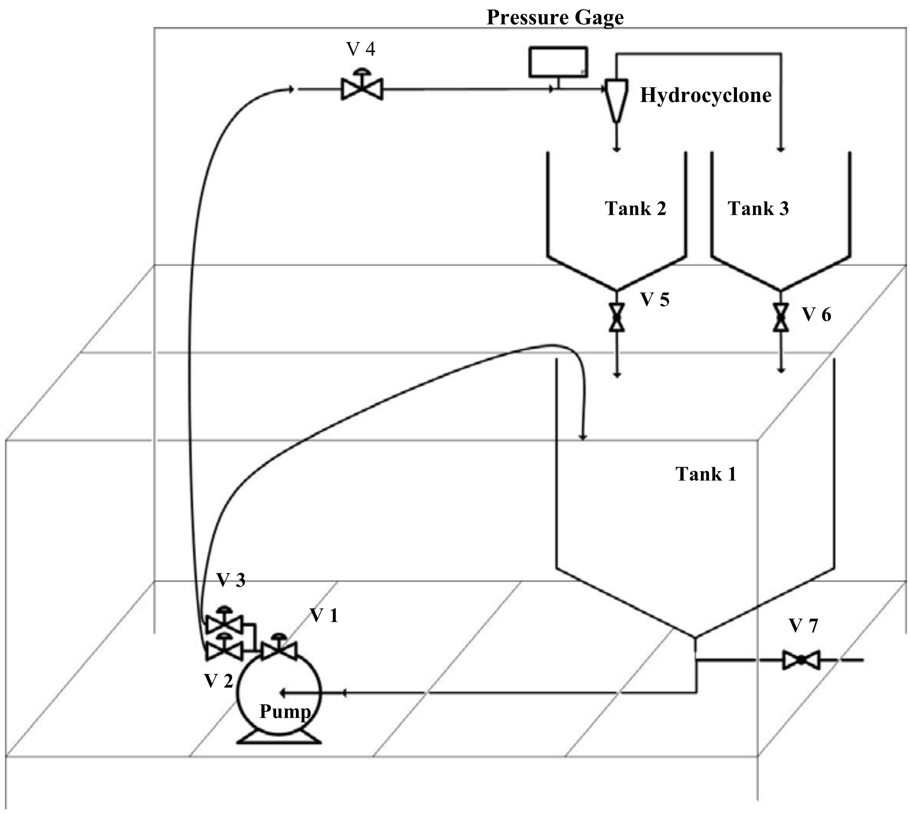
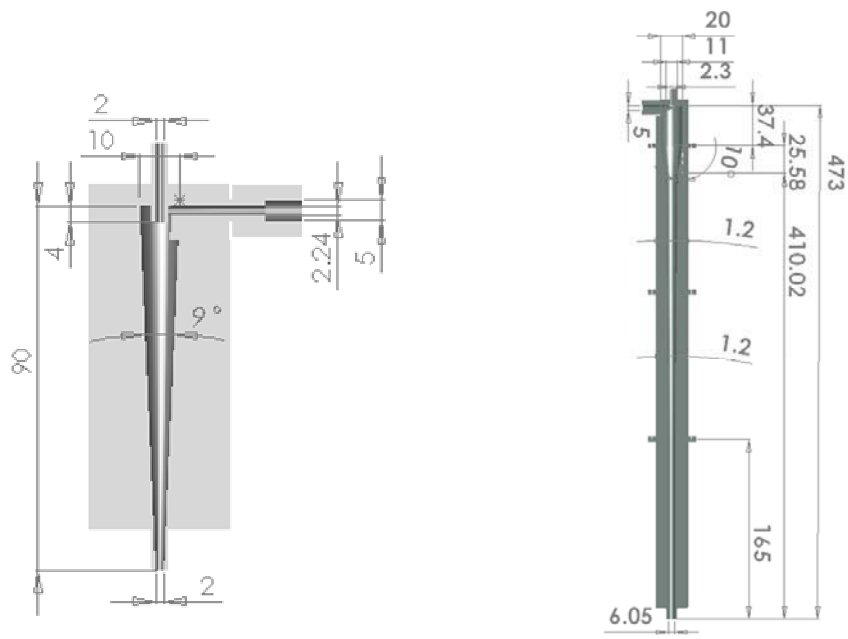


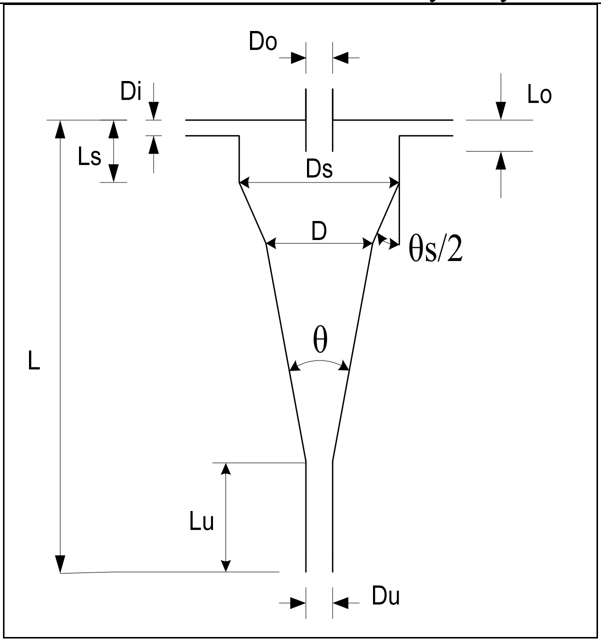
Figure 2. Hydrocyclone apparatus.



(a) **(b)**

Figure 3. Schematic diagram of (a) dewatering MZ and (b) deoiling HY1 (not to scale).

Table 1. Hydrocyclone dimension.



Size (mm)	HY1	MZ
D	11.0	10.0
D_S	20.0	10.0
D_I	5.0	2.2
D_O	2.3	2.0
D_U	6.0	2.0
L	473.0	90.0
L_S	37.4	0.0
L_O	0.0	4.0
L_U	165.0	0.0
$\theta(^o)$	1.2	9.0
$\theta_S(^o)$	20.0	0.0

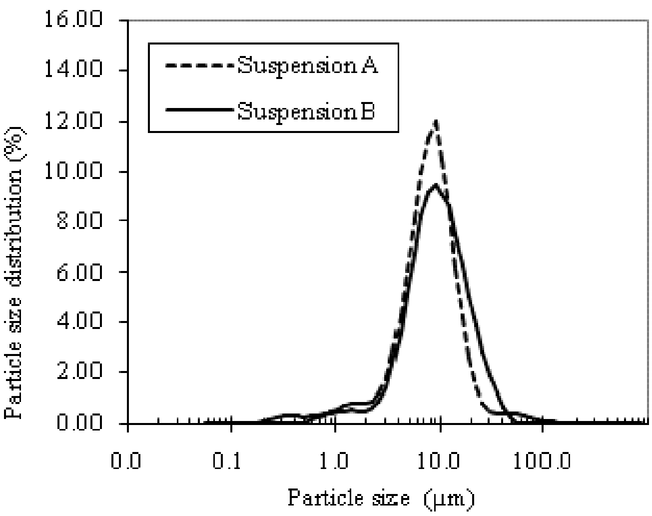


Figure 4. Particle size distribution in the feed suspension A and B.

4.2 Method of sampling and analysis

The feed pressure was recorded with both of the outlets open to the atmosphere. The volume flow rates of feed, overflow and underflow were measured. From each experiment, samples were collected from the feed, overflow and underflow streams. The collected samples were weighed and mass flow rates determined. The concentration of each stream was determined by their dry weight. The samples were filtered through Cellulose Acetate 0.45 μm filters and dried in an oven at 50°C. The particle size distribution of each stream was measured by using the laser-diffraction size-analysis technique. To achieve repeatability, multiple samples were taken and averaged values used. The results for particles below approximately one micron were generally unreliable according to the limitation induced by the sensitivity of the laser diffraction instrument.

5. Discussion of results

5.1 Liquid clarification

The clarification efficiency of both hydrocyclones treating suspension A was examined. The operational data (pressure drop), the concentration and flow rate of each stream, the cut size and throughput ratio (R_f) of each run are shown in Table 3 and 4. The clarification efficiency of HY1 and MZ hydrocyclones treating Suspension A are shown in Figure 10.

Table 3. Experimental results of Suspension A separation.

Run	Hydro-cyclone	Pressure drop (kPa)	Feed		Overflow		Underflow	
			Flow rate (l/min)	Concen-tration (% wt.)	Flow rate (l/min)	Concen-tration (% wt.)	Flow rate (l/min)	Concen-tration (% wt.)
1	HY1	20.0	4.65	0.16	0.30	0.14	4.35	0.16
2	HY1	40.0	11.89	0.16	0.35	0.11	11.54	0.16
3	HY1	50.0	14.33	0.16	0.37	0.10	13.96	0.16
4	HY1	60.0	15.93	0.16	0.39	0.09	15.54	0.16
5	MZ	50.0	3.28	0.16	1.08	0.12	2.20	0.19
6	MZ	100.0	4.94	0.16	1.88	0.1	3.06	0.21
7	MZ	200.0	6.68	0.16	2.62	0.08	4.06	0.21

Table 4. Experimental results of Suspension A separation.

Run	Hydrocyclone	Pressure drop (kPa)	%Ec	d_{50} (μm)	R_f
1	HY1	20.0	15.38	-	0.94
2	HY1	40.0	31.25	-	0.97
3	HY1	50.0	38.46	-	0.97
4	HY1	60.0	50.00	-	0.98
5	MZ	50.0	23.08	0.6707	0.67
6	MZ	100.0	38.46	0.7000	0.62
7	MZ	200.0	50.00	0.5757	0.61

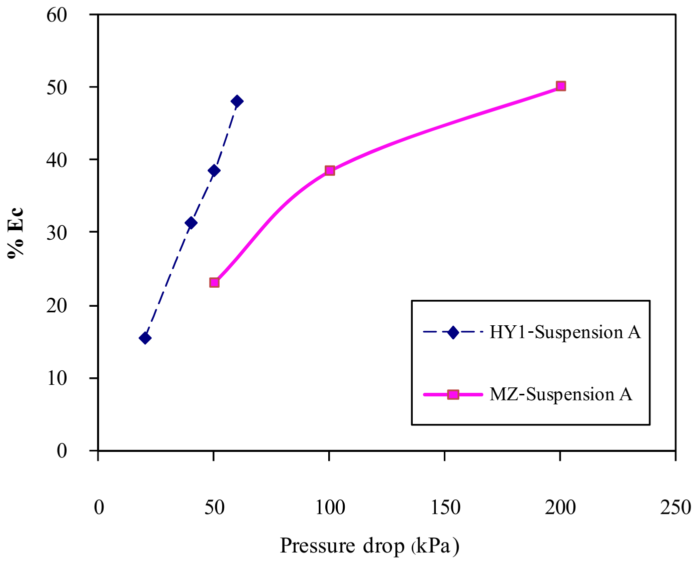


Figure 10. Clarification efficiency of HY1 and MZ hydrocyclones treating Suspension A.

It can be seen that an increase in operating pressure drop leads to an increased flow rate in all flow streams but also results in a decreased concentration of solid particles in the overflow stream. The pressure drop has less affect on the concentration of solid particles in the underflow. HY1 produced a very high throughput ratio that increased with an increase in pressure drop. However, the throughout ratio of the MZ hydrocyclone was found to decrease where the pressure drop was increased due to the reversed flow caused by higher velocity flow and the small diameter of the underflow outlet.

It was also found that the operating pressure drop range of the two hydrocyclones were around five times different, although they were operating with the same pumping power. The range of the operating pressure drop of HY1 and MZ hydrocyclones were 20-60 kPa and 50-250 kPa respectively. HY1 produced a higher feed flow rate than MZ however, as a result of its relatively low throughput ratio the MZ hydrocyclone can generate greater overflow production. The tests demonstrated that both hydrocyclones can provide a clarification efficiency of up to 50%. An increase in operating pressure drop leads to an increase the clarification efficiency. The clarification efficiency of HY1 is very responsive to the change in pressure drop and from the obtained efficiency curve it can be predicted that further increases of the pressure drop could provide significantly better separation performance. In contrary, the MZ efficiency curve indicates that any further pressure drop increase is unlikely to significantly improve the clarification efficiency of the MZ hydrocyclone.

The classification performance of the two hydrocyclones was also examined and the obtained selectivity curves are presented in Figures 6 and 7. HY1 could not provide any classification for all operating pressure drop values and therefore the cut size could not be obtained, which is due to its high throughput ratio. The MZ hydrocyclone gave poor classification and the cut size obtained was between 0.5757-0.6707 microns. Furthermore, the selectivity curve for the 50 and 100 kPa operating cases did not correspond to the theoretical relationship due to the effect of high turbulent dispersion and the fluid-particle interaction [7].

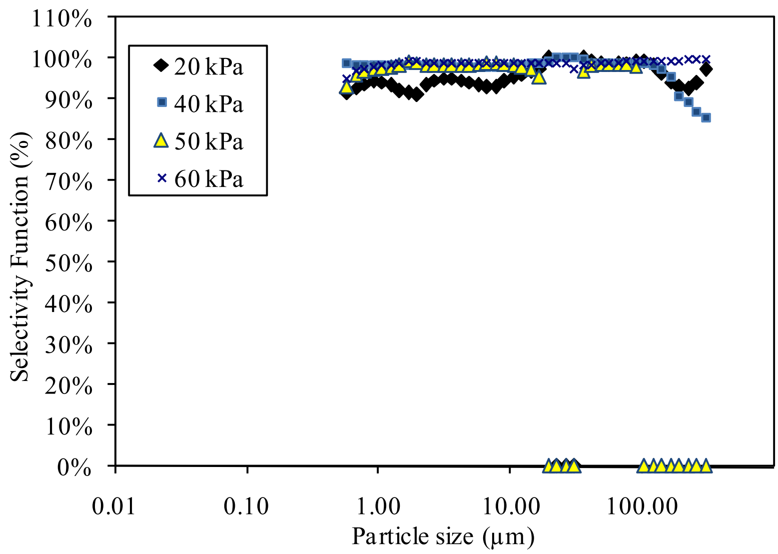


Figure 6. Selectivity curves of HY1 hydrocyclone treating Suspension A.

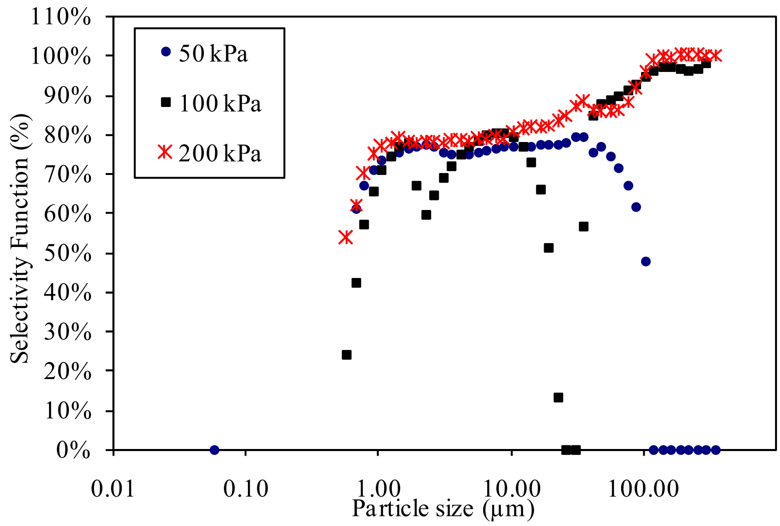


Figure 7. Selectivity curves of MZ hydrocyclone treating Suspension A.

5.2 Yeast recovery

Suspension B was used in the yeast recovery experiments and because it was taken from the bottom part of the fermentation tank, its viscosity was very high. The performance of the HY1 and MZ hydrocyclones operating with Suspension B was measured. The operational data, the concentration and flow rate of each stream, the cut size and throughput ratio (R_f) of each run are shown in Table 5 and 6.

As a result of the high viscosity of Suspension B, the highest operating pressure drop obtained from the HY1 runs was 50 kPa. Also, as can be seen from Table 5, the effect of the pressure drop on the flow rate in all flow streams, on the solid concentration of the overflow stream, and on the throughput ratio, are consistent with the results obtained in the liquid clarification experiments. For HY1, the solid concentration of the underflow stream increased with an increase in operating pressure drop, whilst an increase in the operating pressure drop of MZ resulted in a decrease in the solid concentration of the underflow stream.

Table 5. Experimental results of Suspension B separation.

Run	Hydro-cyclone	Pressure drop (kPa)	Feed		Overflow		Underflow	
			Flow rate (l/min)	Concen-tration (% wt.)	Flow rate (l/min)	Concen-tration (% wt.)	Flow rate (l/min)	Concen-tration (% wt.)
8	HY1	20.0	3.72	1.02	0.24	0.86	3.48	1.08
9	HY1	50.0	11.47	1.02	0.30	0.80	11.17	1.14
10	MZ	50.0	2.62	1.65	0.86	0.84	1.76	1.51
11	MZ	100.0	3.92	1.65	1.50	0.64	2.45	1.49
12	MZ	200.0	6.10	1.65	2.40	0.59	3.70	1.17

Table 6. Experimental results of Suspension B separation.

Run	Hydrocyclone	Pressure drop (kPa)	%Ec	d_{50} (μm)	R_f
8	HY1	20.0	15.29	-	0.94
9	HY1	50.0	21.18	-	0.97
10	MZ	50.0	49.28	0.2443	0.67
11	MZ	100.0	61.50	0.2443	0.63
12	MZ	200.0	64.50	2.2757	0.61

The classification performance of these hydrocyclones is illustrated by their respective selectivity curves. Figure 8 shows that there was no solid classification observed for HY1 operating at 50 kPa and when operating HY1 at 20 kPa only a very poor classification was measured. The classification efficiency for MZ operating at 50, 100 and 200 kPa can be compared in Figure 9. The selectivity curves for 50 and 100 kPa are similar and provide better classification than the 200 kPa curve due to the considerably smaller cut size and the higher sharpness or gradient of the curve. The higher pressure drop causes highly turbulent flow, which has an adverse effect on the separation of particles with a low time constant, such as yeasts, because they are turbulence sensitive and as a result they are more likely to be re-mixed or re-entrained by the flow reversal. However, it is important to note that both types of hydrocyclone produce a low solid recovery percentage, which perhaps is due to the suspension concentration or viscosity being too high to begin with.

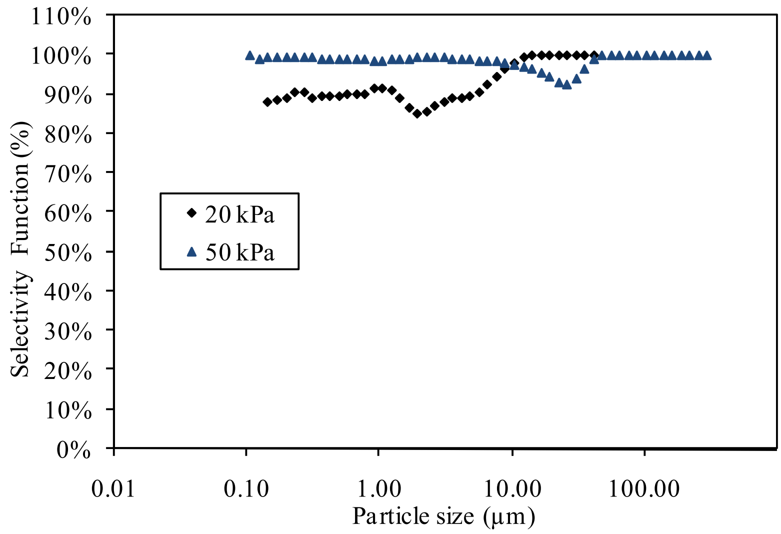


Figure 8. Selectivity curves of HY1 hydrocyclone treating Suspension B.

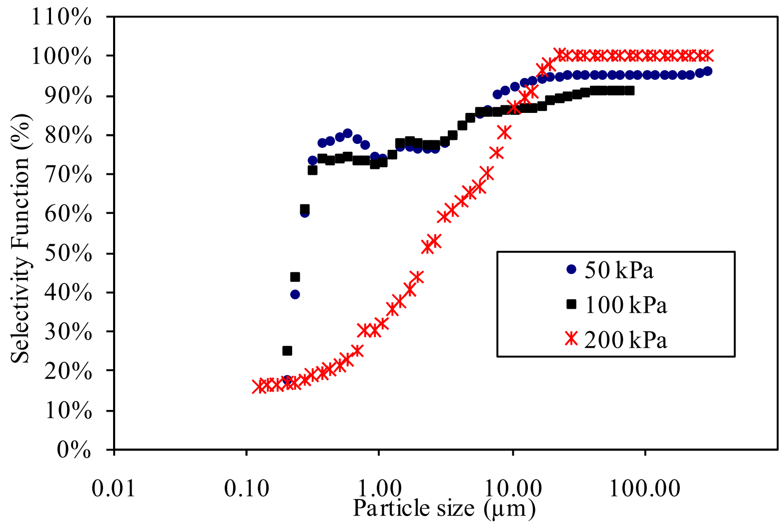


Figure 9. Selectivity curves of MZ hydrocyclone treating Suspension B.

Figure 10 and 11 present a comparison between the clarification efficiency obtained from both hydrocyclones treating the two types of suspension. It can be seen that HY1 provides better clarification efficiency when dealing with lower concentration or viscosity, whereas MZ provides greater clarification efficiency when dealing with higher concentration or viscosity. However, MZ can produce as much solid recovery percentage as HY1 and MZ can also provide solid classification; an increase in the pressure drop leads to an increase in the clarification efficiency, but a decrease in the classification efficiency.

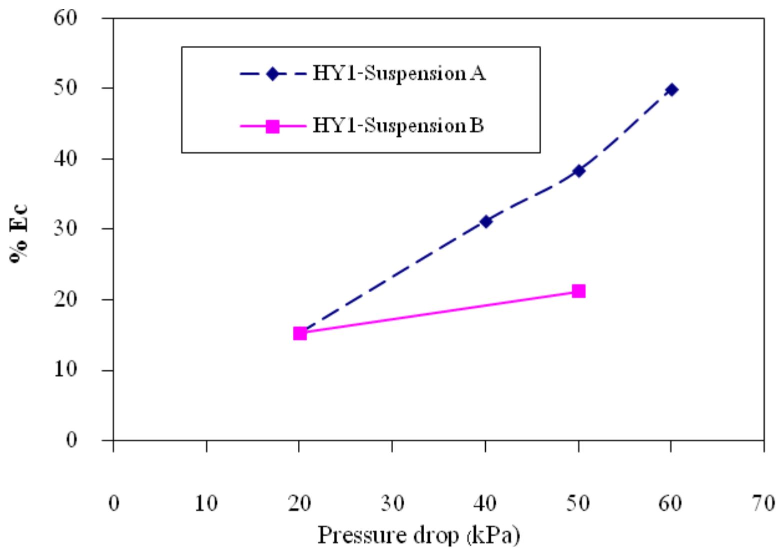


Figure 10. Clarification efficiency of HY1 hydrocyclone.

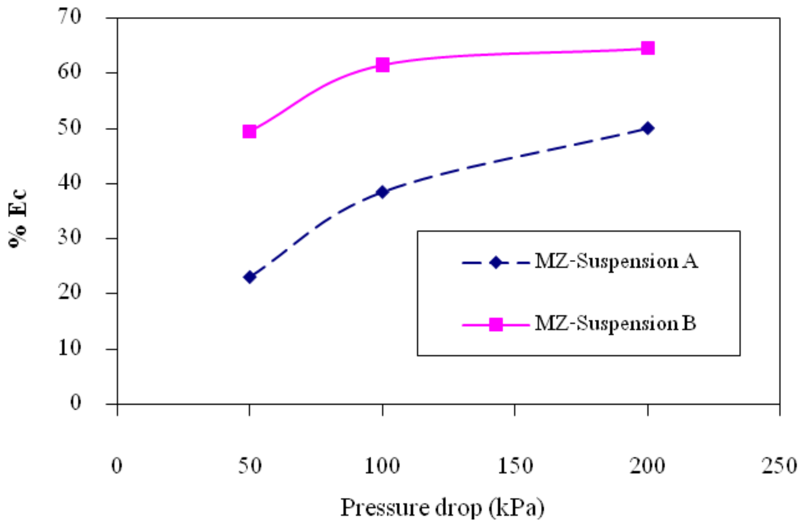


Figure 11. Clarification efficiency of MZ hydrocyclone.

6. Conclusion

Both deoiling (HY1) and dewatering (MZ) hydrocyclones demonstrated their ability to produce up to 50% liquid clarification in the pumping power range of this study. However, the clarification efficiency of HY1 was found to be very responsive to the pressure drop and it can be predicted that further increases of the pressure drop could provide significantly better separation performance.

Only the dewatering hydrocyclone could provide solid classification for both suspensions studied. Additionally, a high operating pressure drop did not provide any benefit to the classification because yeasts have low time constant, which are turbulence sensitive. However, both types of hydrocyclone produce a low solid recovery percentage, which perhaps is due to the suspension concentration or viscosity being too high to begin with.

7. Nomenclature

C_i	volumetric concentration of solid particles in feed streams
C_o	volumetric concentration of solid particles in overflow
d	particle size
d_{50}	cut size
E_c	clarification efficiency
$\dot{f}\ (d)$	weight fractions of particle size *d* in the feed stream
$\dot{F}$	mass flow rates of solids in the feed stream
R_f	throughput ratio
$S(d)$	selectivity function
$\dot{u}\ (d)$	weight fractions of particle size *d* in the underflow stream
$\dot{U}$	mass flow rates of solids in the underflow stream

8. Acknowledgement

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Computational Fluid Dynamics approach for design the small hydrocyclone for biological-solid separation.

1. ABSTRACT

This manuscript details the research work undertaken for the design and construction of hydrocyclones to recover yeast in the brewery industry. The hydrocyclone dimensions were defined using data obtained from the Computational Fluid Dynamics (CFD) simulation of the flow within hydrocyclones. The Finite Volume Method (FVM) and Reynolds Stresses Model (RSM) were used to model the turbulence characteristic of the flow. The particle motions were modeled by using the Lagrangian method with turbulent dispersion. It was found that the SWU10-2.6-2 and SWU 10-3.2-2 hydrocyclones had the better performance curves amongst the hydrocyclones studied. These two hydrocyclones were constructed, and their separation performance was investigated by treating the suspension obtained from the Pathumthani Brewery Co. Ltd., Thailand. The experimental results followed the same trend as the simulated results. It was found that the SWU10-2.6-2 produced better classification efficiency due to the smaller cut size, while the SWU10-3.2-2 produced better separation efficiency according to the higher solid recovery in the underflow. The effects of pressure drop on the solid classification and on the solid recovery were also studied. High turbulence in the flow caused by the high pressure drop and the flow rate had a major effect on the solid classification. A higher pressure drop also led to higher solid recovery performance.

Keywords: Hydrocyclone, Computational Fluid Dynamics, Yeast recovery.

2. INTRODUCTION

A hydrocyclone is a piece of separation equipment for solid-liquid and liquid-liquid systems. Recently hydrocyclones have been introduced in the biotechnology industry as a result of their simplicity of design and operation, high throughput, low maintenance, low operating cost and small physical size of the unit. Yeast is widely used in the biotechnology industry in fields such as the beverage industry, pharmaceutical industry, citric acid industry, etc. The bio-separation in these industries is mostly concerned with the separation of yeast to clarify the product, to recovery yeast or to clean process water. Conventionally, centrifugation and filtration are used, but both of these techniques have significant limitations. Centrifuges are high cost in terms of both operation and maintenance. In filtration, filter aids such as Kieselguhr are needed. This would unavoidably lead to an increase in production costs, and moreover, the environmental problem caused by the disposal of used filter aids. Hydrocyclones do not need any separation aids, so they are absolutely environmentally friendly.

There are some other research works on the application of small hydrocyclones for micro-organism separation, which are [1], [2], [3] and [4]. Cillier and Harison [1] studied the effect of viscosity on the recovery and concentration of Bakers' yeast from glucose water solution using a 10-mm dewatering hydrocyclone. They found the solid recovery decreasing for higher feed concentrations. However, the separation was achieved only up to 38% solid recovery. Rickwood et al. [3] investigated the possible used of a 10-mm dewatering hydrocylcone and a 35mm deoiling hydrocyclone for the recycling of used Kieselguhr by removing yeast into the overflow, while the bulk of the Kieselguhr is in the underflow. The suspension used was dry Kieselguhr in distilled water. Their results showed that the de-watering hydrocyclone design gave an efficient separation of Kieselguhr and yeast suspension. The previous part of the author's research work also found that the dewatering hydrocyclone can provide better classification efficiency than the deoiling hydrocyclone. From all these studies, the dewatering hydrocyclone would appear to be a suitable alternative to the yeast recovery equipment currently used. Therefore, this research work seeks to develop a new approach and improvement in the design and operation of hydrocyclones for the yeast recovery process in brewing plants.

The most popular approach to study the characteristics of hydrocylones, and consequently to optimize their performance, consists of varying operational parameters, such as pressure drop, cut size, and volumetric throughput and examining the effects of the changes. Other attempts to model the flow in a hydrocyclone have been made by using the theoretical models, which are based on the analytical solution of a set of simplified conservation equations, resulting from mass and momentum conservation principles. Such an approach provides a physical insight into the fundamental causes of the observed phenomena. The earlier theoretical models are steady state and 2D-axisymmetrical models, which are limited to dilute flow only. In addition, it is difficult to describe the behaviour of highly turbulent swirling flow caused by the 3D-flow entry. Therefore, more advanced modelling is needed that allows, for example, the study of such phenomena as an adjustment of three-dimensional flow to axisymmetrical, particle-fluid, particle-particle and particle-wall interactions. Such models, which are probably only possible by using computational fluid dynamics, should allow the description of particle effects on suppressing or generating turbulence and non-Newtonian slurry flows. Additionally, in the context of modelling turbulence, a comprehensive physical model is needed to show how a fluid turbulent deformation characterises swirl flows. Of course, improvements not only in physical modelling but in computational power will need to happen in order for computational modelling to become a viable option, [5]. However even with current limitations, computational methods of design have significant advantages over the empirical data, such as freedom of changing the geometry quickly for verification of possible changes in separation efficiency. Furthermore investigation of the embedded turbulence modelling aspects provides a fruitful avenue for understanding a number of open issues regarding internal swirling flow and their implications on separation efficiency of hydrocyclone.

The main aim of the present work is to design and construct hydrocyclones for yeast recovery in the brewery industry by introducing Computational Fluid Dynamics (CFD) techniques to the simulation of 3D flow within small hydrocyclones. This procedure is employed to predict pressure and velocity fields in the hydrocyclones with different geometries. A method for predicting particle trajectories with turbulent dispersion in a hydrocyclone and its separation efficiency is demonstrated. The numerical results are compared with the experimental data, showing good agreement.

3. PROBLEM FORMULATION

3.1 Model Description and Governing Equations

The governing partial differential equations are the continuity equation and the Navier-Stokes equations.

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial (\rho \overline{u}_i)}{\partial t} + \frac{\partial (\rho \overline{u}_i \overline{u}_j)}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u}_i}{\partial x_j} \right) + \frac{\partial}{\partial x_j}\left(-\rho \overline{u_i' u_j'} \right) + \rho g_i \tag{2}$$

The variables ρ, p and μ represent density, pressure and molecular viscosity respectively. The velocity u_i is decomposed into its mean and flactuating components.

$$u_i = \overline{u}_i + u_i' \tag{3}$$

The Reynolds stress term $-\rho \overline{u_i u_j}$ includes the turbulence closure, which is modelled in order to close equations (1) and (2). The recent paper of Delgadillo and Rajamani [6] presents a comparative study of three turbulence-closure models for the hydrocylone problems. They conclude that Large Eddy Simulation (LES) allows the accurate prediction of the velocity profile at different locations. Their simulations demonstrated the dynamics which leads to the formation of the air-core. These results were further confirmed by Narasimha et al. [7] in their LES simulations which allowed prediction of air-core diameter and shape. Although LES simulations show considerable potential they are enormously computationally expansive. The subgrid-scale model accounting for the effects of particles has not yet been used in LES simulations. Consequently, the Reynolds Stress Model (RSM) has been applied as turbulence closure in this study. The simulations using the RSM model and supporting validation studies in the context of hydrocyclones were also presented in recent papers of Bhaskar et al. [8] and Wang and Yu [9]. The RSM model was found to produce an acceptable prediction of anisotropic turbulence.

The equation describing the components of the Reynolds stress tensor, in a tensor notation, has the following form:

$$\frac{\partial\left(\rho \overline{u_i' u_j'}_i\right)}{\partial t} + \frac{\partial\left(\rho \bar{u}_k \overline{u_i' u_j'}\right)}{\partial x_k} = P_{ij} - \varepsilon_{ij} + \varphi_{ij} + \phi_{ij} \tag{4}$$

The right hand side terms are:

the stress production term:

$$P_{ij} = -\left(\overline{u_j' u_m'}\frac{\partial \bar{u}_i}{\partial x_m} + \overline{u_i' u_m'}\frac{\partial \bar{u}_j}{\partial x_m}\right) \tag{5}$$

the pressure strain term:

$$\varphi_{ij} = \overline{\frac{p'}{\rho}\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)} \tag{6}$$

the dissipation term:

$$\varepsilon_{ij} = 2\nu\overline{\left(\frac{\partial u_i'}{\partial x_m}\frac{\partial u_j'}{\partial x_m}\right)} \tag{7}$$

and the turbulent diffusion term:

$$\phi_{ij} = \frac{\partial}{\partial x_m}\left[\nu\frac{\partial \overline{u_i' u_j'}}{\partial x_m} - \overline{u_i' u_j' u_m'} - \overline{\frac{p'}{\rho}\left(u_i'\delta_{jm} + u_j'\delta_{im}\right)}\right] \tag{8}$$

where δ is the Kronecker delta.

3.2. Modelling particle motion with turbulent dispersion of particles

The motion of particles due to turbulent dispersion in the fluid phase was predicted by using the particle trajectory method with a stochastic discrete-particle approach. The method provides a direct description of the particulate flow by tracking the motion of individual particles. Newton's second law, with semi-empirical forms for the hydrodynamic forces, governs particle motion, [10]. The trajectory of the discrete phase particle is obtained by integrating the force balance for individual particles, using the instantaneous fluid velocity along the particle path during the integration. The fluctuating velocity components are discrete piecewise constant functions of time. Their random values is kept constant over an interval of time given by the characteristic lifetime of the eddies. The mathematical model of this approach can be found in [11]. The particles do not perturb the flow field and the fluid satisfies the continuum equations that are solved on a fixed field. The reduced momentum equations describing a balance between the drag and centrifugal or gravity forces are:

for the radial direction:

$$\left(\rho_p - \rho_m\right)\frac{w^2}{r}\pi\frac{d^3}{6} = \frac{1}{2}\rho\left|\mathbf{V}_{rel}\right|\left(v_p - v\right)\frac{\pi d^2}{4}C_D \tag{9}$$

for the axial direction:

$$\left(\rho_p - \rho_m\right)g\pi\frac{d^3}{6} = \frac{1}{2}\rho\left|\mathbf{V}_{rel}\right|\left(u_p - u\right)\frac{\pi d^2}{4}C_D \tag{10}$$

where $\left|\mathbf{V}_{rel}\right|$ is the absolute relative velocity between fluid and particle, equal to $\sqrt{\left(u_p - u\right)^2 + \left(v_p - v\right)^2 + \left(w_P - w\right)^2}$, *d* is particle size, *u*, *v* and *w* are velocity components ,

C_D is drag coefficient, ρ_p is particle density, ρ_m is density of slurry and g is gravitational acceleration.

3.3. Boundary conditions and numerical technique

Since partial differential equations are incorporated in the model, it is necessary to define boundary conditions for all boundaries of the flow domain. Uniform velocity boundary condition was applied at the inlet. Pressure boundary condition, with outlet gauge pressure equal to zero, was applied to the two outlets. This kind of outlet boundary condition was used to simulate the occurrence of the region of negative gauge pressure in the centre of hydrocyclone, where we considered as the air-core zone. No-slip boundary condition is assumed at the solid wall. As a result, all velocity components are zero at the wall.

3.4. Air-core modelling

The interface tracking algorithm based on the volume of fluid method (VOF) of Hirt and Nichols [12] was applied for calculating the position of the air-core. The equation of motion (1) and (2) are solved for the mixture to obtain the velocity field which is shared between the two phases. The volume fraction averaged density ρ is given by

$$\rho = \sum_k \alpha_k \rho_k \tag{11}$$

The fraction of fluid in each cell is defined as α_k which varies between 0 and 1. An additional transport equation for the volume fraction is solved in order to track the air-core. It has the following form:

$$\frac{\partial \alpha}{\partial t} + u_j \frac{\partial \alpha}{\partial x_i} = 0 \quad (12)$$

3.5. Numerical scheme

The physical problem was numerically discretized using finite-volume approximation in three-dimensional Cartesian coordinate system. The decoupled solver was chosen for the governing Navier-Stokes equations, which are solved iteratively in sequential manner until the defined values of convergence are met. The solution method used in this study is the SIMPLEC algorithm developed by Patankar [13]. The continuity and the Navier-Stokes equations are discretized by using the QUICK spatial discretization scheme. This is the higher-order scheme allowing for interpolation of field variables from cell centres to faces of the control volumes.

3.6. Numerical simulation

The investigation of the flow within 10-mm hydrocyclones was carried out. The simulations were done with different hydrocyclone dimensions under a range of inlet Reynolds number between 1250 and 3000. The liquid density and viscosity are 1000.3 kg/m^3 and 0.0198 kg/m-s, respectively. The density of solid (brewing yeast) is 1,204 kg/m^3. The hydrocyclone schematic diagram and the dimensions are shown in Figure 1 and Table 1. The hydrocyclones were named in a series with the following form: D-D_o-D_u.

Table 1. Hydrocyclone dimension.

Hydrocyclone	Hydrocyclone dimension (mm)					
	D	D_I	D_O	D_U	L	L_O
SWU10-2-2	10	2.24	2	2	41	4
SWU10-2-3	10	2.24	2	3	41	4
SWU10-2.6-2	10	2.24	2.6	2	41	4
SWU10-3.2-2	10	2.24	3.2	2	41	4
SWU10-3.2-3	10	2.24	3.2	3	41	4

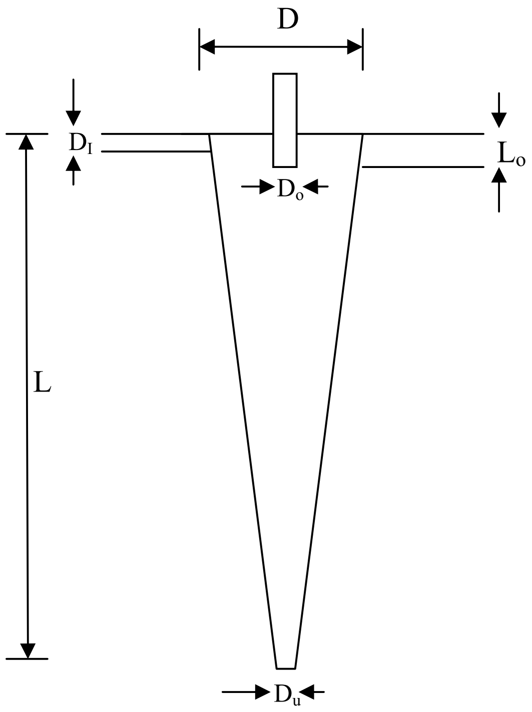


Figure 1. Schematic diagram of hydrocyclone.

The linear systems associated with the solution of the pressure and momentum equations have been solved with a tolerance on the residual to 10^{-6}. The iterative procedure is declared converged when all residuals have been reduced below 10^{-6}. The computations were carried out on a PC computer work station, with FLUENT 6.2 Code and the typical CPU time was 2 days on average for the case with 250,000 computational grids. The generated unstructured grid consisted of tetrahedral elements.

4. RESULTS AND DISCUSSIONS

4.1. Numerical results

4.1.1. Selectivity curve

In this study, it is assumed that the particle phase is the particle of yeast within the range of 0.0582 – 301.6802 microns. The performance curve, which depicts the percentages of each particle size of feed reporting to the underflow discharge, is also called the selectivity curve. The selectivity curves obtained from the simulation data for each hydrocyclone demonstrated that for every inlet Re the SWU 10-3.2-2 and SWU 10-2.6-2 hydrocyclones generated the better separation performance. These selectivity curves together with the selectivity curve for a 10-mm dewatering hydrocyclone obtained by Richard Mozley Ltd are presented in Figure 2. Only SWU 10-3.2-2 and SWU 10-2.6-2 provided a sharp classification. Consequently, these two hydrocyclones were constructed and tested with the suspension from the brewing plant. The experimental results for the classification and solid recovery efficiencies of these hydrocyclones are discussed in the next section.

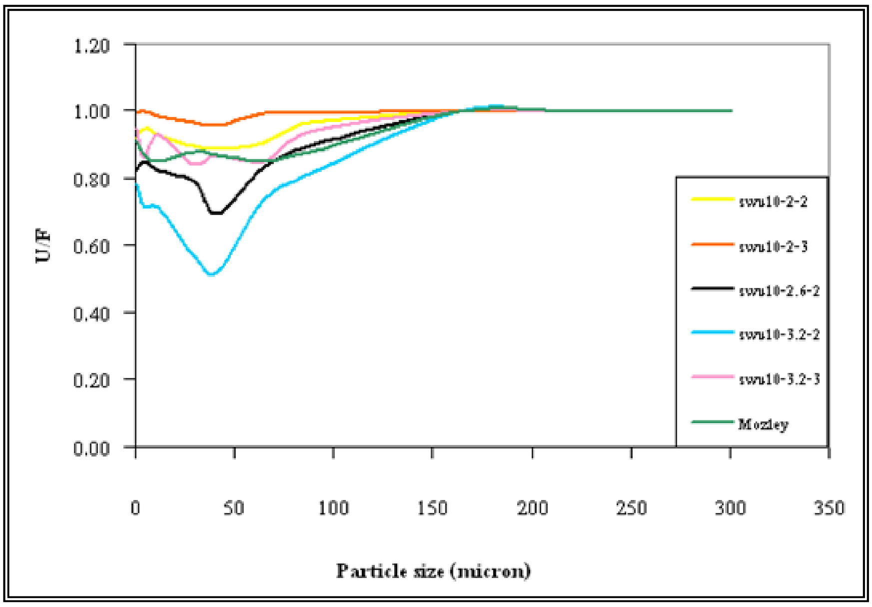


Figure 2. The selectivity curves obtained form the simulated data at Re = 1731.43.

The experimental results shown in Figure 2 demonstrate that the fish-hook phenomenon was observed. It is a dip or fish-hook in the fine end of the curve, which is caused by the effects of the particle-particle interaction and the turbulent dispersion on fine particles. The fine particles are largely unaffected by the classification forces and can be considered to be quasi-homogeneously dispersed. They are also dragged by the wakes generated behind larger particles and flow to the underflow.

4.1.2. Velocity profiles

The characteristics of the flow within the hydrocyclone are obtained from the post-processing procedure of the predicted data for the flow pressure and velocity components. The schematic diagram shows the plane positions of the 10-mm hydrocyclone in Figure 3.

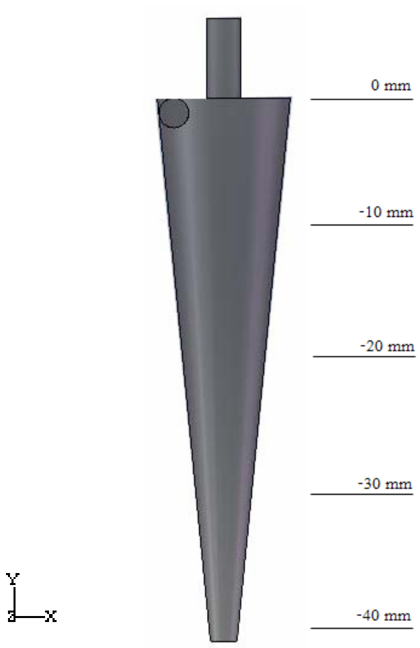


Figure 3. Schematic diagram shows the plane positions of 10-mm hydrocyclone.

The axial and tangential velocity profiles projected on a horizontal plane of the hydrocyclones at inlet velocity of 15.30 m s^{-1}, are shown in Figure 4 and 5. The axial velocity profiles prove the existence of the LZVV (the location where the zero axial velocity exists), where the separated flow occurs in hydrocyclone.

(●) SWU 10-3.2-3 (●) SWU 10-2-3 (●) SWU 10-3.2-2(●) SWU 10-2-2 (●) SWU 10-2.6-2

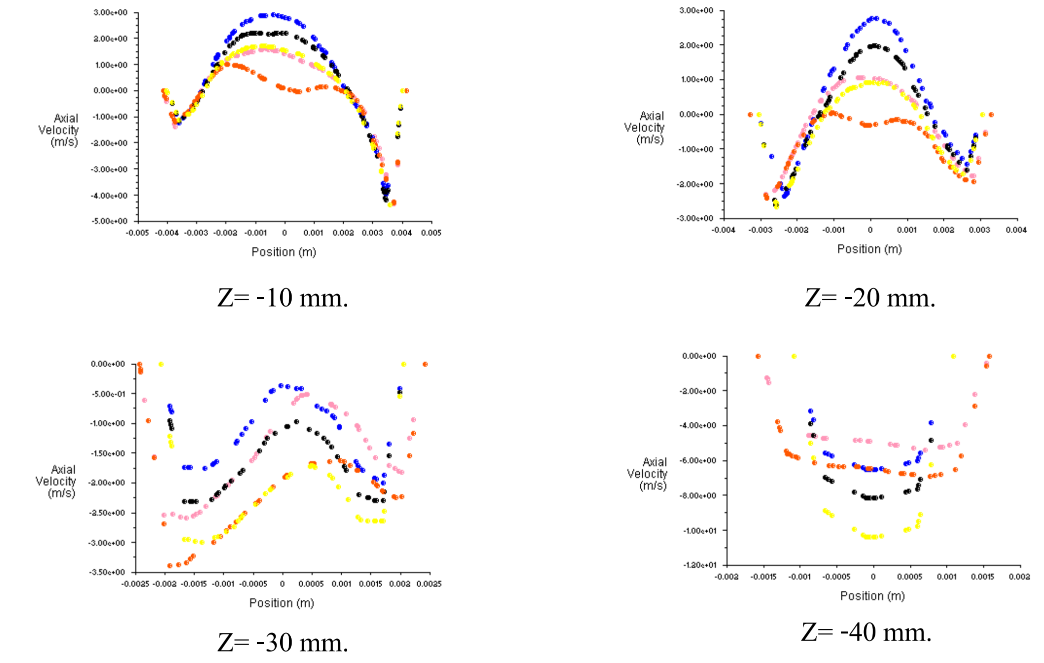


Figure 4. The axial velocity profiles at the inlet Re = 1731.43.

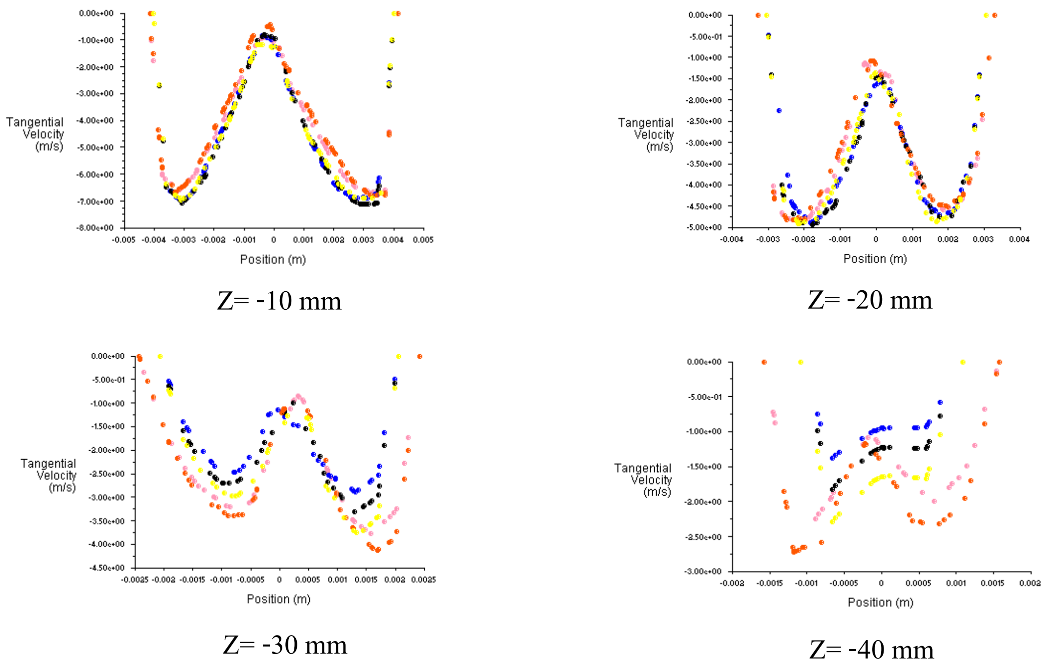


Figure 5. The tangential velocity profiles at the inlet Re = 1731.43.

The negative value of the tangential velocity represents flow in the clockwise direction. The tangential velocity tends to increase with decreasing radius until it reaches a maximum at some point. At radial distances less than this point, the velocity decreases proportionally with the radius. This demonstrates two different zones of forced vortex flow. The tangential velocity profile at the underflow outlet (z= - 40) shows the two zones of the swirling flow, while the axial velocity profile demonstrates the reduction of the velocity in the centre caused by the external pressure force. The values of axial velocity in the upper part of the equipment (z = -10 and -20) obtained from SWU 10-3.2-2 and SWU 10-2.6-2 are higher than obtained from the other hydrocyclones. At the lower part (z = -30), the axial velocity profiles obtained from SWU 10-3.2-2 and SWU 10-2.6-2 are more symmetrical, which indicates more stable flow.

4.1.3. Contour of static pressure

The obtained pressure of fluid projected on a vertical plane of SWU 10-2.6-2 and SWU 10-3.2-2 hydrocyclones are shown in Figure 6 and 7, respectively. The numerical results depict the air-core region, where the pressure is low, in the centre of the hydrocyclone. The air-core was found to be instable and its size, shape and position are unfixed because of the instability of the gas-liquid interface. It can be seen that the flow in SWU 10-3.2-2 has less pressure drop due to the larger diameter of the overflow channel; the higher inlet flow velocity causes a higher pressure drop.

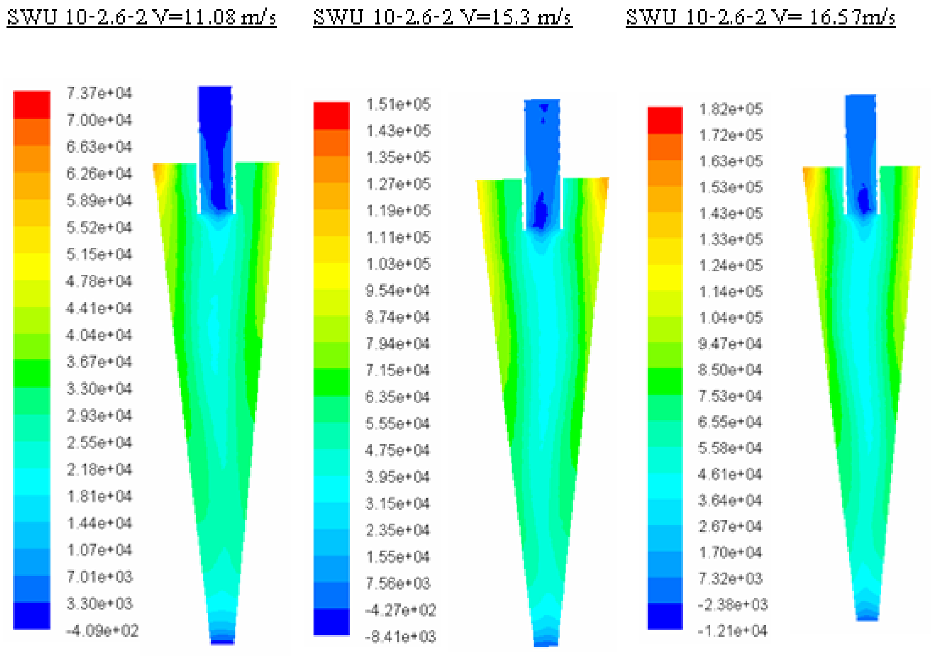


Figure 6. Contour of static pressure of SWU 10-2.6-2 of inlet velocity at a)11.08 m s^{-1}, b) 15.30 m s^{-1}, and c) 16.57 m s^{-1}.

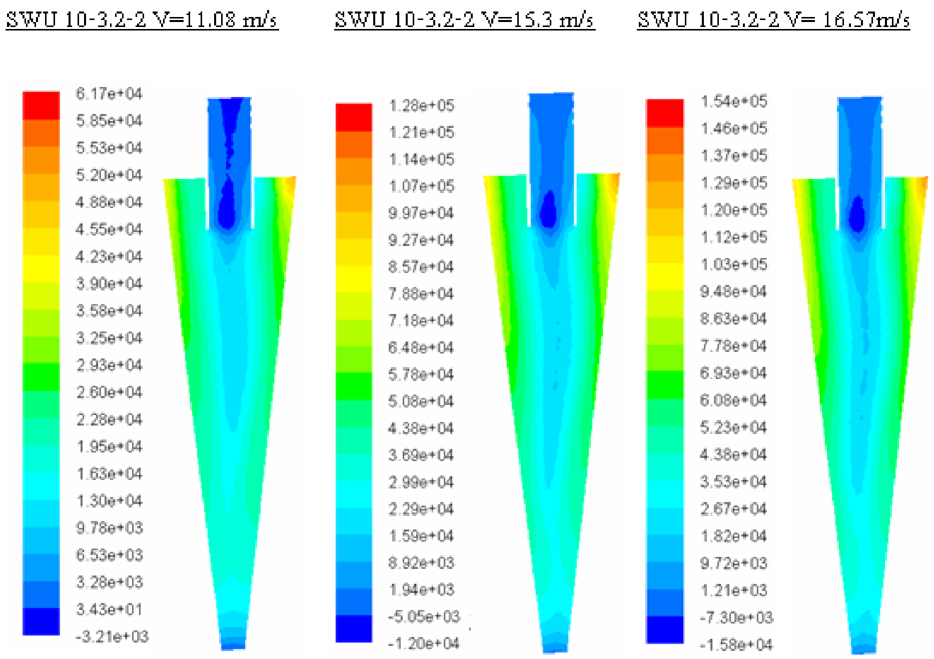


Figure 7. Contour of static pressure of SWU 10-3.2-2 of inlet velocity at a) 11.08 m s^{-1}, b) 15.30 m s^{-1}, and c) 16.57 m s^{-1}.

4.1.4. Velocity contour

The separation flow is successfully simulated and can be demonstrated by the axial velocity component as shown in Figure 8 for every hydrocyclones. The positive and negative values of the axial velocity indicate the upward flow and downward flow, respectively. The typical high axial velocity at the overflow area is observed. The axial velocity at the overflow area obtained form SWU 10-2.6-2 is higher than that of SWU 10-3.2-2 due to the smaller diameter of the overflow outlet. This increases the particle resident time in the hydrocyclone and therefore yields better classification.

The tangential velocity is an important velocity component as it creates the high swirling field in hydrocyclone as can be seen in Figure 9. The fluid enters through the tangential inlet with high inlet velocity and its initially linear motion is converted to angular motion by the hydrocyclone. The numerical result demonstrates a double vortex pattern or two swirling flows, which are the outer downward and the inner upward flows. It can be seen that the flow within the hydrocyclone is not symmetric. The magnitude of axial and tangential velocity components increases with an increase in the inlet velocity. Figure 9 and 10 shows that flow in SWU 10-3.2-2 is higher swirling than the flow in SWU10-2.6-2, according to the higher magnitude of tangential velocity components. This may produce the better separation.

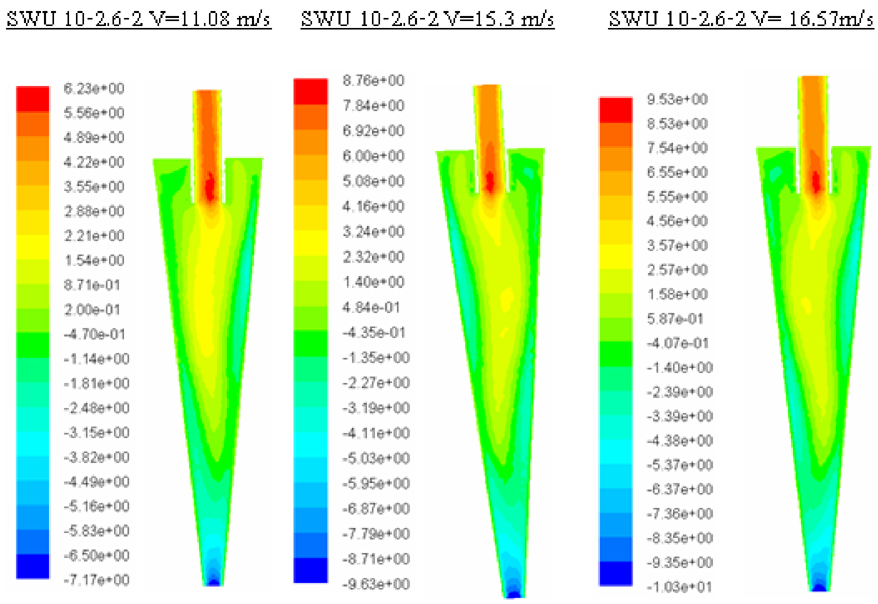


Figure 8. Contour of axial velocity of SWU 10-2.6-2 of inlet velocity at a) 11.08 m s^{-1}, b) 15.30 m s^{-1}, and c) 16.57 m s^{-1}.

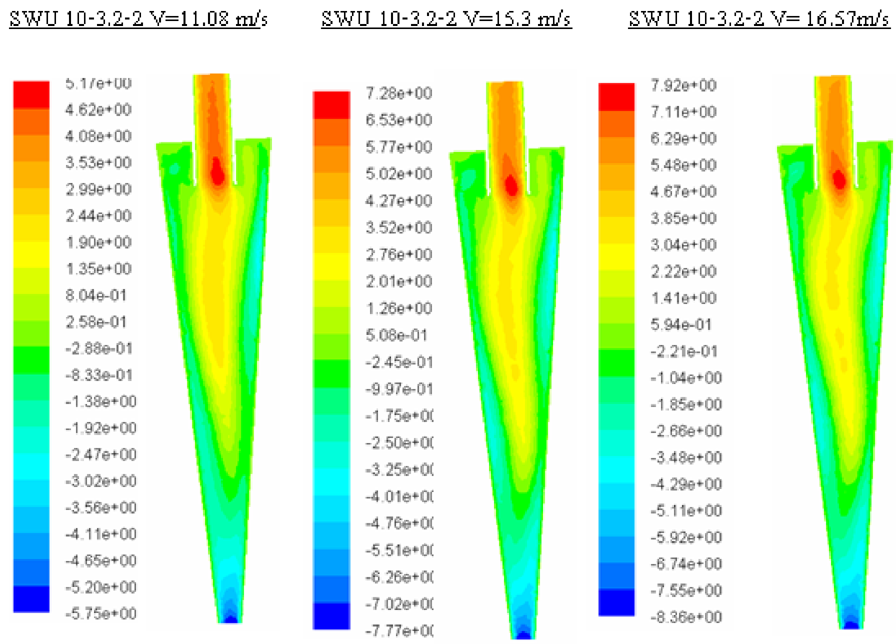


Figure 9. Contour of axial velocity of SWU 10-3.2-2 of inlet velocity at a) 11.08 m s^{-1}, b) 15.30 m s^{-1}, and c) 16.57 m s^{-1}.

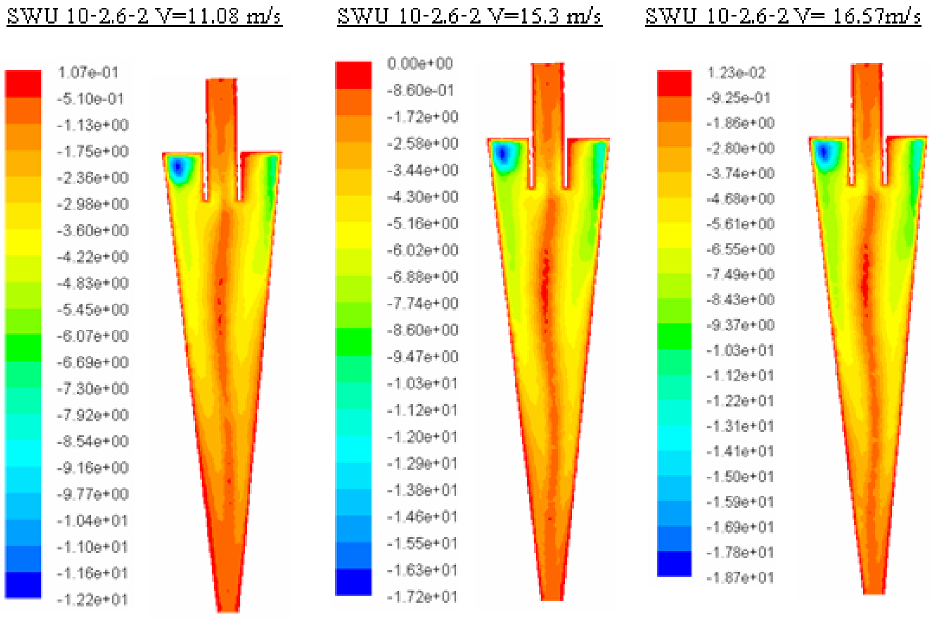


Figure 10. Contour of tangential velocity of SWU 10-2.6-2 of inlet velocity at a) 11.08 m s^{-1}, b) 15.30 m s^{-1}, and c) 16.57 m s^{-1}.

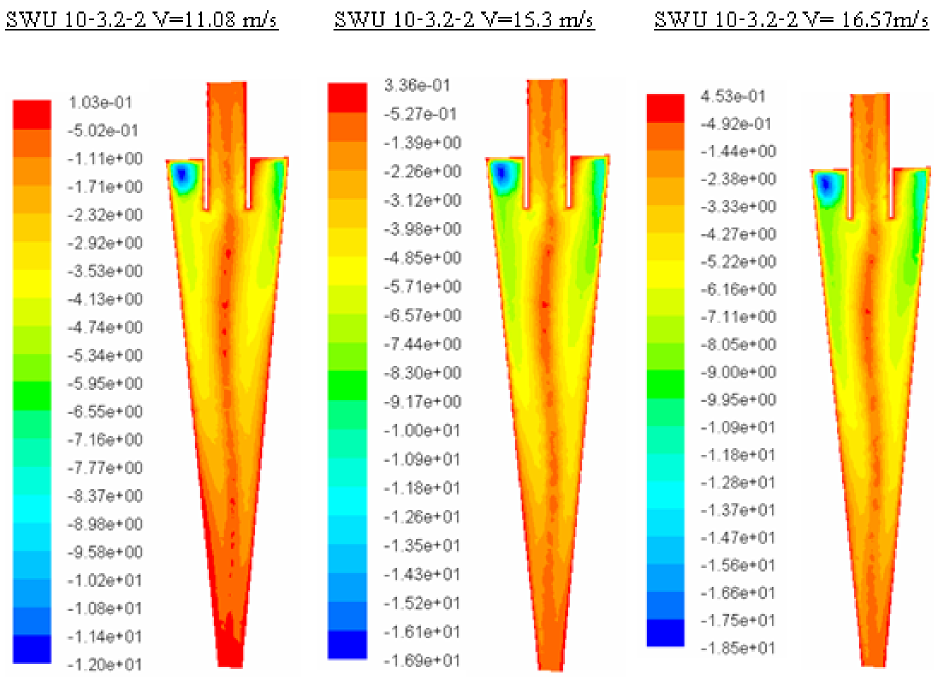


Figure 11. Contour of tangential velocity of SWU 10-3.2-2 of inlet velocity at a) 11.08 m s^{-1}, b) 15.30 m s^{-1}, and c) 16.57 m s^{-1}.

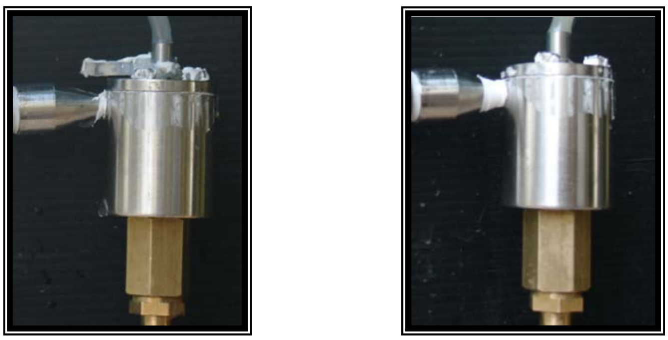
4.2. Experiment and validation of numerical result

The hydrocyclones were equipped and set up with a feed pump and pressure gauge to measure the feed inlet pressure (see Figure 12). The constructed SWU 10-2.6-2 and SWU 10-3.2-2 hydrocyclones are shown in Figure 13. Hydrocyclone overflows and underflows were directed back to the sump for recirculation. The operating pressure drop was varied from 50 kPa to 200 kPa by varying the inlet feed flow rate. Hydrocyclone tests were performed at 25°C. The feed suspensions used in the experiments were taken from the bottom fermentation tank in the brewing plant of Pathumthani Brewery Co. Ltd., Thailand. The density of brewing yeast is 1,204 kg/m^3. Yeast cells show a narrow size distribution with the dominant diameter measured as 8.9960 μm by laser diffraction technique. The experimental data are summarised in Table 2.

Figure 12. Hydrocyclone apparatus.

Table 2. Experimental results.

ΔP (kg/cm2)	F (L/min)	U (L/min)	O (L/min)	F %by wt.	U %by wt.	O %by wt.	% Recovery
SWU10-2.6-2 hydrocyclone							
50	2.19	0.8	1.33	3.46	4.13	2.80	19.64
100	3.60	1.20	2.460	3.46	4.65	2.59	34.67
150	4.50	1.50	3.00	3.46	4.80	2.53	39.08
200	5.75	2.00	3.75	3.46	4.81	2.39	39.56
SWU10-3.2-2 hydrocyclone							
50	2.46	0.46	2.00	3.17	4.53	2.93	43.20
100	4.17	0.57	3.60	3.17	4.87	2.82	54.29
150	5.55	0.75	4.80	3.17	4.98	2.79	57.64
200	6.00	1.00	5.00	3.17	5.04	2.61	59.62
Mozley hydrocyclone							
50	3.49	2.40	1.09	2.79	3.85	2.16	38.24
100	5.00	3.00	2.00	2.79	3.92	2.37	40.74
150	7.07	4.50	2.57	2.79	4.10	1.90	47.03
200	7.73	5.00	2.73	2.79	4.22	1.73	51.54

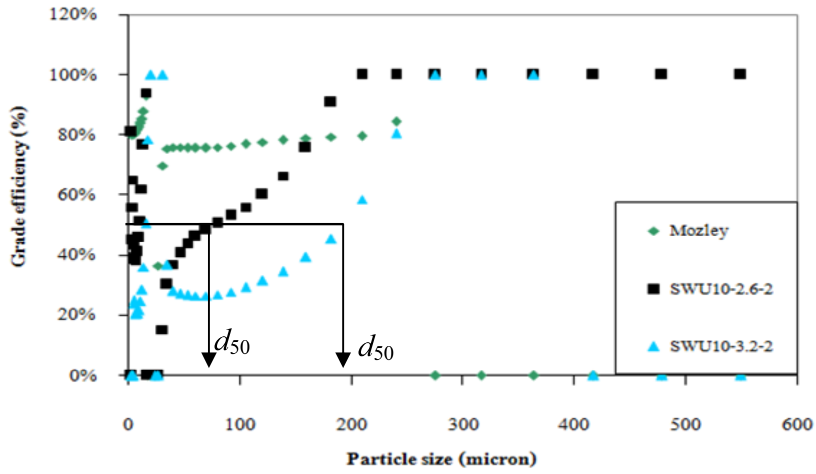


(a) (b)

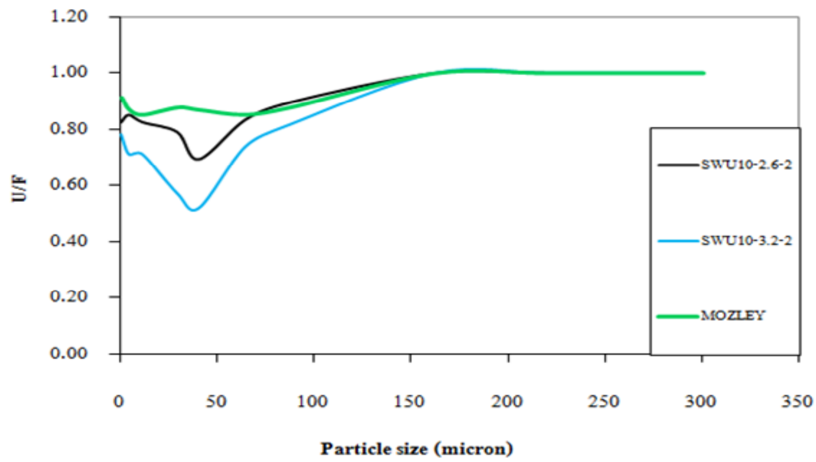
Figure 13. The constructed SWU 10-2.6-2 (a) and SWU 10-3.2-2 (b) hydrocyclones.

The classification performance of the two hydrocyclones and a 10-mm Mozley hydrocyclone was examined, and compared with the simulated results from last section, as presented in Figures 14. The simulation results were in agreement with the experimental data. Thus, the CFD technique can be applied as a tool to design hydrocyclone.

The SWU 10-2.6-2 provides better classification than the SWU 10-3.2-2 due to the considerably smaller cut size. The Mozley hydrocyclone gave poor classification and the cut size could not be obtained. It is also found that an increase in pressure drop cannot increase the classification efficiency. The higher pressure drop causes highly turbulent flow, which has an adverse effect on the separation of particles with a low time constant, such as yeasts, because they are turbulence sensitive and as a result they are more likely to be re-mixed or re-entrained by the flow reversal. The fish-hook phenomena at the fine end of the curve were observed. Due to the effects of the particle-particle interaction and the highly turbulent dispersion on fine particles, the fine particles are largely unaffected by the classification forces (see Figure 15) and can be considered to be quasi-homogeneously dispersed. Instead of following the liquid phase out of the overflow, it is dispersed in both overflow and underflow. Thus, fine particles are dominated in the suspension.



(a)



(b)

Figure 14. The selectivity curves obtained from the experiment at 50 kPa operating pressure drop (a) and the simulation (b).

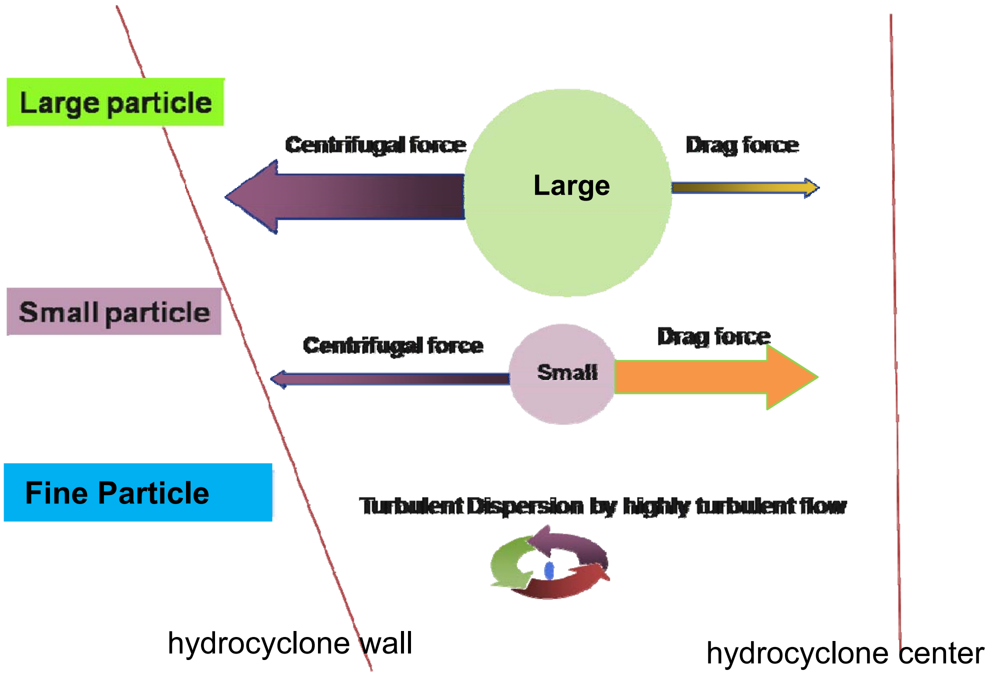


Figure 15. The classification forces versus the turbulent dispersion.

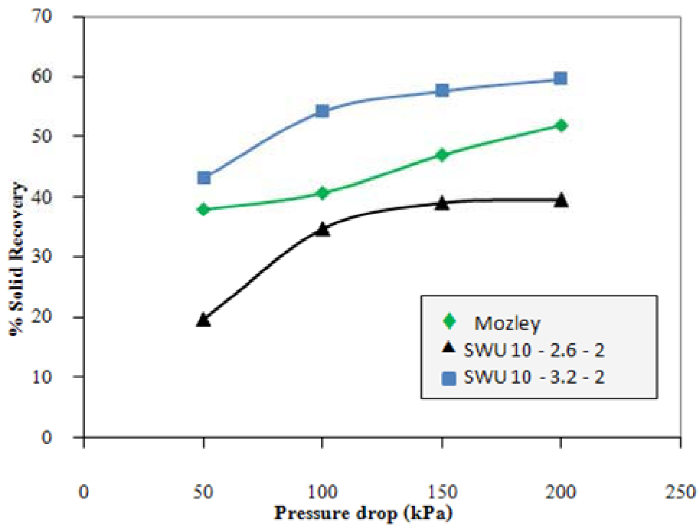


Figure 16. The yeast recovery (%) in underflow

Figure 16 presents a comparison between the percentage of yeast recovered from each of the three hydrocyclones. It can be seen that 10-3.2-2 provides better yeast recovery, although the SWU 10-2.6-2 provides better classification. This is caused by the dominating proportion of fine particles in the flow, which do not obey the theory of the classification forces but are controlled by turbulent dispersion. A higher pressure drop also leads to higher solid recovery performance. Yeast recovery obtained from the design hydrocyclone is up to 60% by weight. Hydrocyclone combination in series can increase the total separation efficiency of the system.

5. Conclusion

In conclusion, the application of Computational Fluid Dynamics (CFD) techniques to the simulation of 3D flow within 10-mm hydrocyclones using the Finite Volume Method (FVM) has been introduced. The particle motion was successfully predicted by using the particle trajectory method. The separation performance of the separator was determined by the relationship between percentages of each particle size of feed reporting to the underflow discharge. The experimental results followed the same trend as the simulated results. Thus, the CFD technique can be applied as a tool to design hydrocyclones. Separation of yeast cells from the brewing medium can be achieved by the 10-mm conventional hydrocyclone. Yeast recovery obtained from the designed hydrocyclone is up to 60% by weight.

6. Acknowledgement

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Exploitation (or Output) of the project

1. One Publications in International Journals		
1.1.	Title:	The simulation of the flow within a hydrocyclone operating with an air core and with an inserted metal-rod
	Authors:	Wanwilai Kraipech Evans, Anotai Suksangpanomrung and Andrew Nowakowski
	Journal:	Chemical Engineering Journal 143 (2008) 51-61
	Impact No.:	≅ 1.9
	Paper:	See Appendix A
2. Two Preparing Manuscripts for Future publications for International Journals		
2.1.	Title	An application of small hydrocyclones for separating yeast in the brewing industry
	Authors:	Wanwilai Kraipech Evans, Anotai Suksangpanomrung and Pichai Asadamongkol
	Journal:	Chemical Engineering Journal
	Impact No.:	≅ 1.9
2.2	Title	Computational Fluid Dynamics approach for design the small hydrocyclone for biological-solid separation.
	Authors:	Wanwilai Kraipech Evans, Anotai Suksangpanomrung and Pichai Asadamongkol
	Journal:	Chemical Engineering Journal
	Impact No.:	≅ 1.9

Appendix

Title: The simulation of the flow within a hydrocyclone operating with an air core and with an inserted metal-rod

Authors: Wanwilai Kraipech Evans, Anotai Suksangpanomrung and Andrew Nowakowski

Journal: Chemical Engineering Journal 143 (2008) 51- 61

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The simulation of the flow within a hydrocyclone operating with an air core and with an inserted metal rod

Wanwilai Kraipech Evans [a,*], Anotai Suksangpanomrung [b], Andrzej F. Nowakowski [c]

[a] *Department of Chemical Engineering, Srinakarinwirot University, 107 Rungsit-Nakorn-Nayok Road, Ongkharuk, Nakorn-Nayok 26120, Thailand*
[b] *Department of Mechanical Engineering, Academic Division, Chulachomklao Royal Military Academy, Nakorn-Nayok 26001, Thailand*
[c] *Department of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom*

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Dedicated to Professor Tomasz Dyakowski who passed away on the 15th of June 2006. He was our colleague, our friend and the driving force behind this research.

Abstract

The simulations of the flow within the solid–liquid hydrocyclone operating with an air core and with an inserted metal rod were performed. Finite-volume method and Reynolds stresses model (RSM) were used to model the turbulence characteristic of the flow. The computational results demonstrate the double-vortex flow, which depict the two separation flows. The low-pressure zone or the air core in the centre core was simulated. The redesign hydrocyclone for reducing the energy loss due to this low-pressure core was done by inserting the metal rod in the middle of hydrocyclone. The effect of the inserted-rod on the velocity distributions and the separation performance was investigated. It was found that the separation performance can only be improved with the proper size of the inserted-rod.
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Keywords: Hydrocyclone; Computational fluid dynamics; Solid–liquid separation

1. Introduction

A hydrocyclone is a piece of separation equipment for solid–liquid and liquid–liquid systems. Recently hydrocyclones have been introduced in the food, oil and textile industries as a result of their simplicity of design and operation, high throughput, low maintenance, low operating cost and small physical size of the unit. Though the consistent use of hydrocyclones has been occuring since the 1950s, the full comprehension of the operation is still ambiguous. As they have many advantages and have been used in many industries, this research work seeks to develop a new approach and improvement in the design and operation of hydrocyclones.

The most popular approach to study the characteristics of hydrocyclones, and consequently to optimize their performance, consists of varying operational parameters, such as pressure drop, cut size, and volumetric throughput and examining the effects of the changes.

Other attempts to model the flow in a hydrocyclone have been made by using the theoretical models, which are based on analytical solution of a set of simplified conservation equations, resulting from mass and momentum conservation principles. Such approach provides a physical insight into the fundamental causes of the observed phenomena. The earlier theoretical models are steady state and 2D-axisymmetrical models, which are limited to dilute flow only. In addition, it is difficult to describe the behaviour of highly turbulent swirling flow caused by the 3D-flow entry. Therefore, more advanced modelling is needed that allows, for example, the study of such phenomena as an adjustment of three-dimensional flow to axisymmetrical, particle–fluid, particle–particle and particle–wall interactions. Such models, which are probably only possible by using computational fluid dynamics, should allow the description of particle effects on suppressing or generating turbulence and non-Newtonian slurry flows. Additionally, in the context of modelling turbulence, a comprehensive physical model is needed to show how a fluid turbulent deformation characterises

* Corresponding author. Tel.: +66 86 999 8908; fax: +66 37 322 608.
E-mail address: wanwilai@swu.ac.th (W.K. Evans).

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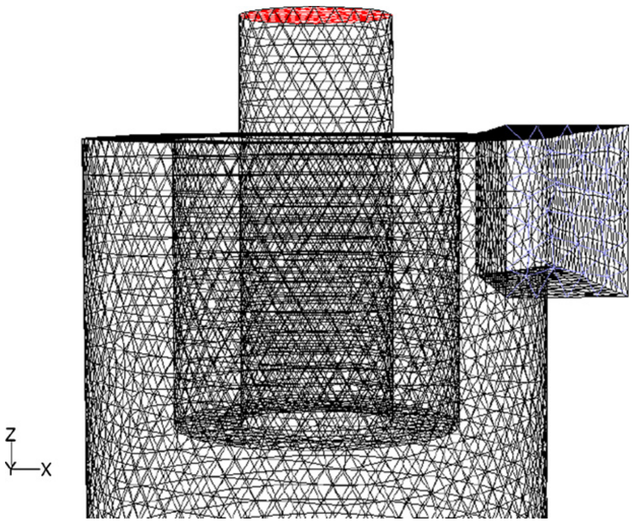

Fig. 1. Unstructured grid consisting of tetrahedral elements within a hydrocyclone for the finite-volume approximation.

swirl flows. Of course, improvements not only in physical modelling but in computational power will need to happen in order for computational modelling to become a viable option [1]. However even with current limitations, computational methods of design have significant advantages over the empirical data, such as freedom of changing the geometry quickly for verification of possible changes in separational efficiency. Furthermore investigation of the embedded turbulence modelling aspects provides a fruitful avenue for understanding a number of open issues regarding internal swirling flow and their implications on separation efficiency of hydrocyclone.

On the other hand, experimentation with changing the internal geometries of a hydrocyclone has been done to try and improve the separational efficiency. Yoshida et al. [2] innovative idea to improve the separational performance was to include a movable guide plate over the inlet.

Other researchers studied the performance of the hydrocyclone operating without an air core. Luo et al. [3] studied the velocity profiles of hydrocyclones by using the laser Doppler anemometry (LDA) technique. They removed the air core by sealing the apex with water and compared the velocity profiles of the ordinary and water-sealed hydrocyclones. They concluded that the water sealed hydrocyclone was superior, but that the capacity was reduced and the seal had to be carefully maintained. Xu et al. [4,5] also measured the velocity components of the hydrocyclone without an air core by using LDA. They replaced the air core with a solid rod and claimed that the air core contributes to the energy loss, and the separation efficiency should increase by removing it. However, they did not validate their statement. In order to test this postulation, Lee and Williams [6] carried out an extensive series of experiments whereby they measured the classification and separation efficiency of the conventional hydrocyclones compared with modified hydrocyclones, in which the air core was replaced by a steel rod insert. They reported that the insertion of a rod into the hydrocyclones does not appear to improve the separation efficiency. In the later, Chu et al. [7] carried out the experiment on the hydrocyclone with an inserted-rod, and they found that the inserted-rod could improve the separation performance of hydrocyclone. They reported that negative effect on the separation found in the experimental study of Lee and Williams [6] might be mainly due to their body supports designed for fixing the solid rod as the main flow field inside the hydrocyclone might be disturbed by the body supports, and the negative effect of this on separation performance might be more remarkable than the positive effect of eliminating the air core. As the result, the hydrocyclone separation performance was not improved, but deteriorated.

The main aim of the present work is to extend this research by introduction of computational fluid dynamics (CFD) techniques to the simulation of 3D flow within a hydrocyclone. This procedure is employed to predict velocity fields in the hydrocyclone with different geometries operating under a wide range

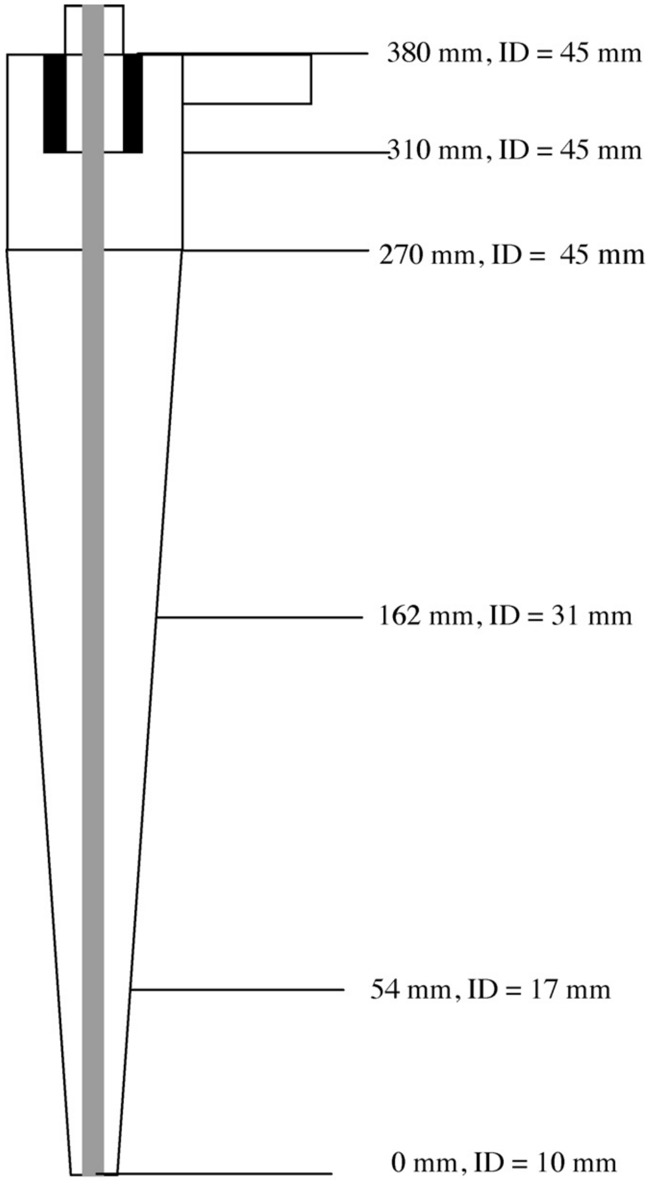

Fig. 2. Schematic diagram shows the plane positions of 50-mm hydrocyclone with inserted-rod. For each plane height the value of the section internal diameter ID is also given.

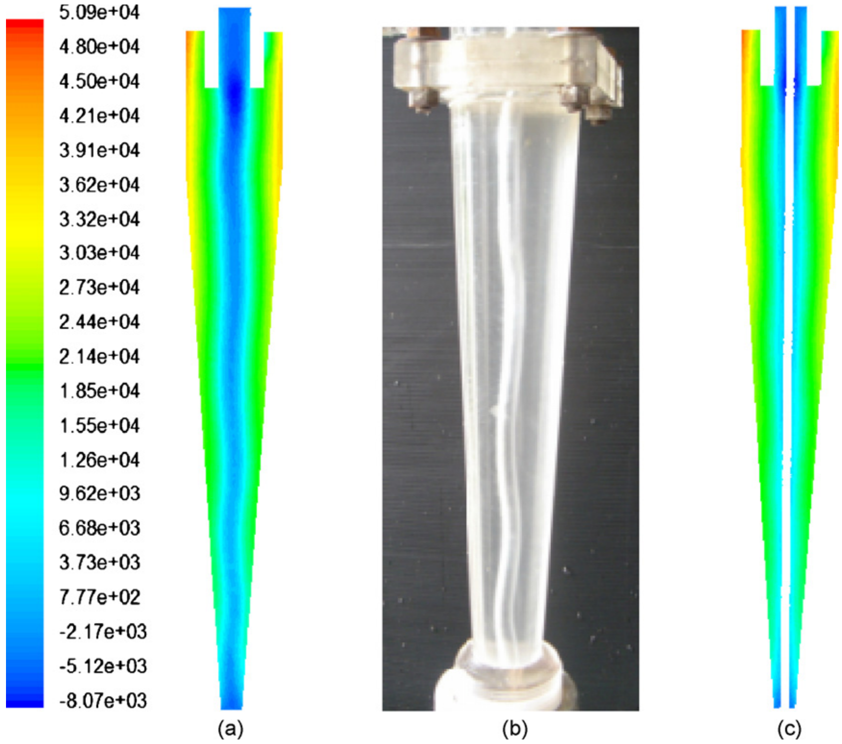

Fig. 3. The obtained pressure (Pa) of fluid projected on a vertical plane of the hydrocyclone: (a) operating with an air core, (b) experimental observation and (c) with 4-mm inserted-rod.

of conditions. A method for predicting particle trajectories in hydrocyclone and its separation efficiency is demonstrated. The numerical results are compared with available experimental data showing good agreement. The flow behaviour and the separation performance of a hydrocyclone operating with an inserted-rod are comparatively studied.

2. Problem formulation

2.1. Model description and governing equations

The governing partial differential equations are the continuity equation and the Navier–Stokes equations:

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho \bar{u}_i)}{\partial t} + \frac{\partial(\rho \bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j}\right) + \frac{\partial}{\partial x_j}(-\rho \overline{u_i' u_j'}) + \rho g_i \tag{2}$$

The variables ρ, p and μ represent density, pressure and molecular viscosity, respectively. The velocity u_i is decomposed into its mean and fluctuating components:

$$u_i = \bar{u}_i + u_i' \tag{3}$$

The Reynolds stress term—$\rho\overline{u_i u_j}$ includes the turbulence closure, which is modelled in order to close Eqs. (1) and (2). The recent paper of Delgadillo and Rajamani [8] presents a comparative study of three turbulence-closure models for the hydrocyclone problems. They conclude that Large Eddy simulation (LES) allows the accurate prediction of the velocity profile at different locations. Their simulations demonstrated the dynamics which leads to the formation of the air core. These results were further confirmed by Narasimha et al. [9] in their LES simulations which allowed prediction of air-core diameter and shape. Although LES simulations show considerable potential they are enormously computationally expansive. The subgrid-scale model accounting for the effects of particles has not yet been used in LES simulations. Consequently Reynolds stress model (RSM) has been applied as turbulence closure in this study. The simulations using RSM model and supporting validation studies in the context of hydrocyclones were also presented in recent papers of Bhaskar et al. [10] and Wang and Yu [11]. The RSM model was found to predict well anisotropic turbulence. The RSM provides information of all the stress components and contains exact terms for swirling effects in its stress transport equations. The description of the model is presented in Appendix A.

2.2. Modelling particle motion

The motion of particles due to turbulence in the fluid phase was predicted by using the particle trajectory method. The method provides a direct description of the particulate flow by tracking the motion of individual particles. Newton's second law, with semi-empirical forms for the hydrodynamic forces, governs particle motion [12]. The trajectory of the discrete phase particle is obtained by integrating the force balance on the particle. The volume occupied by the particles in a computational cell is