INVESTIGATION OF THE EFFECT OF LIQUID HEIGHT AND BAFFLE GEOMETRY ON DRAWDOWN OF FLOATING SOLIDS IN STIRRED TANKS

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ABSTRACT

INVESTIGATION OF THE EFFECT OF LIQUID HEIGHT AND BAFFLE GEOMETRY ON DRAWDOWN OF FLOATING SOLIDS IN STIRRED TANKS

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In solid-liquid mixing operations, stirred tanks are commonly used in industries. The geometry of the stirred tanks significantly affect the flow characteristics of these operations. Baffle configuration and aspect ratio which is ratio of liquid height (H) to tank diameter (T) are some of the main geometric factors. Especially in a fermentor (bioreactor) where it needs adeaquate volume for an efficient aeration, aspect ratio is one the substantial parameters. Moreover, baffles promote mixing so, it increases reaction rates and heat transfer in chemical reactions.

Solids drawdown, which is immersion of floating particles from the liquid surface, is one of the main study field in solid-liquid mixing operations in stirred tanks. Solids drawdown is used for avoiding particle clumping on liquid surface and maximizing solid-liquid contact area for mass transfer and reaction. Thus, in this thesis, distribution of particles is taken into account together with drawdown. There are significant studies in solids drawdown and distribution of drawn down particles focusing on baffle geometry but none of these studies has taken the liquid height into account. The solo and synergistic analysis of these factors needs to be done. Hence, objective of this study is investigation of the effect of the liquid height and baffle geometry on drawdown of floating solids in stirred tanks.

The key design parameters of the system were just drawdown speed (N_{jd}) which indicates that no floating particles remain on liquid surface more than 1-2 seconds, Cloud Depth (CD), which indicates the distance between liquid surface and the lowest point of the clustered particle region in the liquid. A new parameter was defined as fully distributed speed (N_{fd}), which is the impeller speed at which all particles are distributed throughout the tank at which cloud depth of the particles equals to liquid height. Furthermore, power consumption at N_{jd} (P_{jd}) and power consumption at N_{fd} (P_{fd}) were measured.

A flat-bottomed plexiglass mixing tank with diameter of 24 cm was used. The experiments were conducted with tap water and at ambient pressure. Polypropylene granule particles (PP) whose dimensions are approximately 3 mm x 4 mm x 5 mm were used. In the beginning of the experiments where the liquid height is equal to tank diameter, solid concentration of particles is adjusted to 1% by weight w/w. Then, the mass of solid particles was kept constant while the liquid height varied. Submergence (S) which is the distance from liquid surface to bottom of the impeller blades was fixed to 8 cm (S= T/3).

Three types of impellers were used; four bladed 45° up pumping and down pumping pitched blade turbine (PTBU and PBTD) and Rushton turbine (RT). Two different diameters (D) of each of the three impellers were used: 8 cm (D=T/3) and 12 cm (D= T/2). Surface baffles (B=5T/24) and full baffles (B=H) configurations were used. In addition, liquid height was increased by 4 cm from 20 cm to 40 cm (H=0.83T to H=1.67T).

In general, increasing the liquid height from H=0.83T to H=1.67T resulted in a slight increase in $N_{jd,}$ P_{jd} and CD for all baffle and impeller configurations. Morever, for all impellers at varying liquid heights, combining an impeller with the full baffles gave more CD than combination of same impeller with surface baffles.

T/2 impellers gave lower N_{jd} and P_{jd} than T/3 impellers for all baffle configurations and liquid heights. Moreover, for all baffle configurations and impellers, for all liquid heights, RT-T/2-surface baffles combination gave minimum N_{jd} among all configurations whereas PBTD-T/3-full baffles combination had the highest N_{jd} values.

In the overall, at H≥1.17T, for all impellers except for PBTD-T/3 at H=1.17T, it is not recommended to use surface baffles because it is impossible to reach N_{fd} due to swirling movement below the baffles which blocks axial flow at some speed around 100 rpm larger than N_{jd}.

Finally, from comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd}, for all combinations, it can be concluded that baffle type was more effective than impeller diameter in terms of full distribution of particles.

Keywords: Drawdown of solids, just drawdown speed (N_{jd}), power consumption at N_{jd} (P_{jd}) Cloud Depth (CD), fully distributed speed (N_{fd}), power consumption at N_{fd} (P_{fd})

ÖZ

KARIŞTIRMA TANKLARINDA, SIVI YÜKSEKLİĞİNİN VE ENGEL GEOMETRİSİNİN YÜZEN KATI PARÇACIKLARIN SIVI İÇERİSİNE DAHİL ETMEYE ETKİSİNİN İNCELENMESİ

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Katı-sıvı karıştırma operasonlarında, karıştırma tankları endüstrilerde yaygın olarak kullanılmaktadır. Karıştırılan tankların geometrisi bu operasyonların akış özelliklerini önemli ölçüde etkiler. Engel konfigürasyonu ve sıvı yüksekliğinin (H) tank çapına (T) oranı olan en-boy oranı ana geometrik faktörlerdendir. Özellikle etkili bir havalandırma için yeterli hacme ihtiyaç duyulan bir fermentörde (biyoreaktörde) en-boy oranı önemli parametrelerden biridir. Ayrıca engeller karıştırmaya destek olur, böylece kimyasal reaksiyonlarda reaksiyon hızlarını ve ısı transferini artırır.

Yüzen parçacıkların sıvı yüzeyinden sıvı içerisine batırılması ile gerçekleşen katı parçacıkların sıvı içerisine dahil edilmesi, karıştırma tanklarında, katı-sıvı karıştırma operasyonlarının ana çalışma alanlarından biridir. Katı parçacıkların sıvı içerisine dahil edilmesi, parçacıkların sıvı yüzeyinde birikmesini önlemek ve kütle transferi ve reaksiyon için katı-sıvı temas alanını maksimuma çıkarmak için kullanılır. Bu tezde, katı parçacıkların dağılımı, katı parçacıkların sıvı içerisine dahil edilmesi ile beraber hesaba katılmaktadır. Katı parçacıkların sıvı içerisine dahil edilmesi ve parçacıkların dağılımı konusunda, engel geometrisine odaklanan önemli çalışmalar vardır, ancak bu çalışmaların hiçbiri sıvı yüksekliğini hesaba katmamıştır. Bu faktörlerin tekil ve beraber olarak analizinin yapılması gerekmektedir. Bu nedenle,

bu çalışmanın amacı, karıştırma tanklarında yüzen katı maddelerin sıvı içerisine dahil edilmesinde, sıvı yüksekliğinin ve engel geometrisinin etkisinin araştırılmasıdır.

Sistemin temel tasarım parametreleri, sıvı yüzeyinde 1-2 saniyeden fazla yüzen parçacık kalmadığını gösteren sıvı içerisine dahil edilme hızı (N_{jd}) ve sıvı yüzeyi ile sıvının içerisinde kümelenmiş parçacık bölgesinin en alçak noktası arasındaki mesafeyi belirten bulut derinliğidir (CD). Bulut derinliğinin sıvı yüksekliğine eşit olduğu durumda, tüm parçacıkların tank boyunca dağıldığı karıştırıcı bıçak hızı tam dağılım hızı (N_{fd}), yeni bir parametre olarak tanımlanmıştır. Ayrıca N_{jd}'deki güç tüketimi (P_{jd}) ve N_{fd}'deki (P_{fd}) güç tüketimleri ölçülmüştür.

Çapı (T) 24 cm olan düz tabanlı pleksi cam karıştırma tankı kullanılmıştır. Deneyler musluk suyunda ve ortam basıncında gerçekleştirilmiştir. Polipropilen granül parçacıklar (PP) kullanılmıştır. Bu parçacıkların boyutları yaklaşık olarak 3 mm x 4 mm x 5 mm kadardır. Deneylerin başlangıcında, sıvı yüksekliğinin tank çapına eşit olduğu (H=T) durumda, parçacıkların katı konsantrasyonu %1 w/w olarak ayarlanmıştır. Daha sonra, sıvı yüksekliği değişirken katı parçacıkların kütlesi sabit tutulmuştur. Batma derinliği (S), sıvı yüzeyinden karıştırıcı bıçağının alt tarafına kadar olan mesafedir ve 8 cm'ye sabitlenmiştir.

Tek karıştırıcılı sistem kullanılmıştır. Dört kanatlı 45° yukarı ve aşağı pompalayan eğimli bıçaklı karıştırıcı (PTBU ve PBTD) ve Rushton türbini (RT) 8 cm (D=T/3) ve 12 cm (D= T/2) olmak üzere iki farklı çapta (D) kullanılmıştır. Yüzey engeli (B=5T/24) ve tam engel (B=H) kullanılmıştır. Ayrıca sıvı yüksekliği (H) 4’er cm artırılarak 20 cm'den 40 cm'ye çıkarılmıştır (H=0.83T ila 1.67T).

Genel olarak, sıvı yüksekliğinin H=0.83T'den H=1.67T'ye arttırılması, tüm engel tiplerinde ve karıştırıcı bıçak konfigürasyonları için N_{jd}, P_{jd} ve CD'de hafif bir artışla sonuçlanmıştır. Ayrıca, değişen sıvı yüksekliklerindeki tüm karıştırıcı bıçakları için, karıştırıcı bıçaklarının tam engel ile beraber kullanımı, aynı karıştırcı bıçağının yüzey engeliyle beraber kullanımından daha fazla CD vermiştir.

T/2 çaplı karıştırıcılar, tüm engeller ve sıvı yükseklikleri için, T/3 çaplı karıştırıcılara göre daha düşük N_{jd} ve P_{jd} değeri vermiştir. Ayrıca, tüm engel ve karıştırcı kombinasyonlarında, tüm sıvı yükseklikleri için, RT-T/2-yüzey tam engel kombinasyonu minimum N_{jd}'ye sahipken, PBTD-T/3 tam engel kombinasyonu en yüksek N_{jd} değerine sahiptir.

Tüm engel konfigürasyonları ve T/2 cinsinden karıştırıcı bıçak çapı için, tüm sıvı yükseklikleri için RT-T/2-yüzey engeli kombinasyonu, tüm konfigürasyonlar arasında minimum Njd'leri verirken, PBTD-T/2-tam engelli kombinasyon en yüksek N_{jd} değerlerine sahiptir.

Sonuç olarak, H≥1,17T'de, H=1,17T'de PBTD-T/3 hariç bütün karıştıştırıcılarla yüzey engelinin kullanıldığı tüm kombinasyonlarda, karıştırcı hızının, N_{jd}'den 100 rpm'den fazla olacak şekilde artırıldığında, engel altındaki dönme hareketi eksenel hareketi kısmi olarak engellemesi nedeniyle, bu sıvı yüksekliği aralığında N_{fd}'ye ulaşmak imkansız hale gelir. Bu nedenle, yüzey engeli kullanımı tavsiye edilmemektedir.

Anahtar kelimeler: katı parçacıkları sıvı yüzeyinden sıvı içerisine dahil etme, sıvı içerisine dahil etme hızı (N_{jd}), bulut derinliği (CD), tam dağılım hızı (N_{fd}), N_{jd} hızındaki güç tüketimi (P_{jd}), N_{fd} hızındaki güç tüketimi (P_{fd})

To my mother Şeyma, my father Hanifi and my wife Bengisu

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ABBREVATIONS

BSA	burst spectrum analysis
CD	cloud depth (cm)
CFD	computational fluid dynamics
ERT	electric resistance tomography
LDA	laser doppler anemometry
PBT	pitched blade turbine
PBTU	up-pumping pitched blade turbine
PBTD	down-pumping pitched blade turbine
PBPU	up-pumping pitched blade paddle
RT	rushton turbine

SYMBOLS

Roman Characters

B_H	Baffle height (cm)
C	off-bottom clearance of the impeller (m)
c	off-bottom clearance of the impeller (m)
D	diameter of the impeller (m)
d_p	particle diameter (mm)
F_{jd}	froude number at N_{jd}
G	dimensionless number relating to impeller type
g	gravity ($kg.m/s^2$)

H	height of the liquid (m)
k	dimensionless number relating to impeller type
N	impeller speed (rps)
N_{js}	just suspended speed (rpm)
N_p	power number
N_{jd}	just drawdown speed (rpm)
N_{fd}	fully distributed speed (rpm)
P	power consumption (W)
P_{jd}	power consumption at N_{jd} (W)
P_{fd}	power comsumption at N_{fd} (W)
S	submergence (cm)
T	diameter of the tank (m)
T_q	torque (N.m)
w	width of the baffles (mm)
X	solid concentration (w/w)

Greek Characters

ρ_L	density of the liquid (kg/m^3)
$\Delta\rho$	density difference between solid and liquid phases
π	pi number

CHAPTER 1

INTRODUCTION

1.1 Solid-Liquid Mixing; Suspending of Sinked and Buoyant Particles

In industry, there are solid-liquid mixing operations in stirred tanks in many applications such as mineral processing, polymerization, pharmaceutical production, and sewage treatment. Understanding of hydrodnamics of these systems is crucial to accomplish sustainable operations. There are two types of operation; drawdown of buoyant particles into the liquid phase, which is examined in this thesis and suspension of sinking particles. Solids drawdown is immersing of floating particles from the liquid surface and dispersing the particles throughout the liquid whereas solid suspension is suspending of settled particles from tank bottom and dispersing the particles throughout the tank.

1.2 Brief History of the Beginning of Drawdown of Floating Solids

In solid suspension operations in stirred tanks, the objective is mainly to lift settled particles off the bottom of the tank, providing maximum contact area between the solid and liquid. From an engineering perspective, it is significant to perform these operations at minimum impeller rotational speed and power consumption. Zwietering (1958) defined this minimum impeller speed and proposed a model for the first time to predict this speed. He defined this speed as 'just suspended' speed (N_{js}), where no particle stays still on the tank bottom for more than 1 or 2 seconds. The prediction of N_{js} was based on system geometry and properties of materials used. Most of the subsequent studies took the definition and model of this study as basis and cited it as an origin. For instance, starting with a critical analysis of the Zwietering's correlation, Ayranci & Kresta (2014) developed a new correlation for N_{js} for higher solid concentrations and made it applicable for scale-up conditions.

Analogous to solids suspension, for drawdown of floating solids operations in stirred tanks, the aim is to submerge the floating particles from the surface of the liquid and disperse them. Solids drawdown plays a crucial role on preventing the particles from clumping on the surface which may result in deformation of encapsulated particles and lowering contact area between solid and liquid phase which is important for reaction rate and heat transfer. In this field, for the first time, referenced to Zwietering (1958), Joosten et al.(1977) adapted N_{jd} for solids drawdown and called it as 'just drawdown' speed, N_{jd}. Authors defined the N_{jd} where stagnant zones created by floating particles on liquid surface was just disappeared.At the same time, they proposed a model for Froude number at N_{jd} (F_{jd}) given below.

$$F_{jd} = k(D/T)^{-3.65}(\Delta\rho/\rho_L)^{\,0.42} \tag{1}$$

where,

$$F_{jd} = \frac{(N_{js})^2 D}{g} \tag{2}$$

The Equation 1 was applicable in specific ranges based on correlated parameters. k value changes according to impeller types. The tested impellers were a 2-bladed inclined paddle, a 4-bladed inclined paddle, a 6-bladed inclined paddle and a 3-bladed marine propeller and the corresponding k values were found as 7.4×10^{-2}, 3.6×10^{-2}, 3.3×10^{-2} and 19.6×10^{-2}, respectively. Furthermore, they measured torque exerted on impeller shaft which enabled them to determine power consumption and calculate the power number (N_p) of impellers by equation 3 and 4 given below.

$$P = N_p\, \rho_L\, N^3\, D^5 \tag{3}$$

$$P = 2\,\pi\, N\, T_q \tag{4}$$

where;

N: impeller speed (rps)

ρ_L: liquid density (g/ cm^3)

D: impeller diameter (m)

Tq: torque (N.m)

After Joosten et al (1977), Edwards&Ellis (1984), worked on the effect of impeller type, baffle number, off-bottom clearance and solid concentration on solids drawdown. They defined N_{jd} at which only a few particles on the surface remained and then completely drawdowned for less than 3-5 seconds, which is different than Joosten et al.. Also, they found that solid loading in a specific range do not have impact on N_{jd}. On the other hand,increasing the submergence of an impeller by increasing the number of baffles made N_{jd} and P_{jd} raised.

Hemrajani et al. (1988) and Bakker & Frijlink (1989) conducted studies in the field also. Hemrajani and his co-workers investigated the effect of baffle arrangement on N_{jd} and found that a controlled central vortex was powerful enough to drawdown the floating solids homogeneosly. Bakker & Frijlink (1989) focused on influence of different types of commonly used impellers in industries on N_{jd} and P_{jd}, which is power consumption at N_{jd}. They also related N_{jd} with Zwietering's N_{js} and modified the definition of N_{jd} as the impeller speed at which there are no particles remaining on the liquid surface more than 1 second. They stated that, the drawdown consists of two steps; first drawdown and second dispersion of floating solids and they only aimed at the drawdown step. Lastly, they also integrated gas to their systems and did operations in solid-liquid-gas systems for the first time. In this case, vortex was not created easily compared to solid-liquid system so, N_{jd} increased.

Consideration of the studies in literature on solid suspension and solids drawdown, it is clear that creating hydrodynamic design of these sytems is based on similar considerations and requirements. As seen, the initial studies in solids drawdown was benefited from solids suspension. Solid suspension studies still lead solid-liquid mixing literature by having more content diversity and the number of studies than solids drawdown. For this reason, studies on solids drawdown need to be branched more by content and also, unclear concepts need to be clarified. Due to this fact, solids drawdown was investigated in thesis.

Solids drawdown studies mentioned above are core studies in its field in literature. Considering the core solids drawdown studies, it can be seen that first, they focus on the drawdown of floating particles with minimum speed and power while dispersion of particles was a second concern. Also, they mentioned drawdown mechanism with a limited knowledge and did experiments to find effective parameters and system geometry on solids drawdown. Due to lack of knowledge and proof on findings, it becames essential to do improvements. They were given in the next section.

1.3 Pioneer Study Investigating in Solids Distribution and Radical Change in Modelling Drawdown Based on N_{jd}

Takahashi and Sasaki (1999) investigated solids $_{drawdown}$ and dispersion with 4-bladed 45° pitched blade turbine for up and down pumping modes (PBTU and PBTD) as a mixed flow impeller and Rushton turbine (RT) as a radial flow impeller. They used full four-baffles configuration.The liquid height (H) was equal to tank diameter (H=T). They varied impeller diameter and immersion depth of the impeller and examined the influnce of these geometric paramters on solids drawdown. N_{jd} was determined with respect to Joosten et al.'s measurement specifying the speed that stagnant zones on the surface just disappeared. For measurement of local solid concentrations, they took samples through the axial direction from different points near the wall, and determined the axial concentration profiles. This technique was referenced by Barresi and Baldi (1987) studying solid suspension. Finally, they improved Joosten et al.'s model given in Equation 1. They added solids concentration(X), particle diameter(d_p) and off-bottom clearance (c) to the model and proposed a new model given below in Equations 5, 6 and 7.

$$F_{jd} = G(d_p/D)^{0.31}\,(\Delta\rho/\rho_L)^{0,85}\,X^{0.17} \qquad (5)$$

For RT, $$G = 0.265\ (D/T\ )^{-2.52}\ (c/T)^{-0.91} \quad (6)$$

For PBT, $$G = 0.1(D/T\ )^{-3.95}\ (c/T)^{-1.94} \quad (7)$$

In their study, it was also given an axial solid concentration distributions at N_{jd} and lower impeller speeds. According to samples from 5 data points, they dispersed the particles throughout tank. It was also pointed out that this study achieved more uniform dispersion compared to Barresi and Baldi's study. In the end, this study gave a significant information for solid dispersion throughout tank at N_{jd}. It was one of the comprehensive study for solid distribution in this subject to this date. Developing the model contributed the literature in a significant extent.

1.4 The Mechanism of Solids Drawdown

There was still inadequate explanations for functional principles of solids drawdown until Khazam & Kresta (2008)'s study. They gave explanations on mechanisms of solids drawdown by observing movements of particles throughout tank. They specified forces acting on a single particle floating on the surface of the denser and/or non-wetting liquid. They then created a force balance to show that whether the particle is sinked or not. A representative demonstration of acting forces on a particle floating on liquid surface is given below in Figure 1.

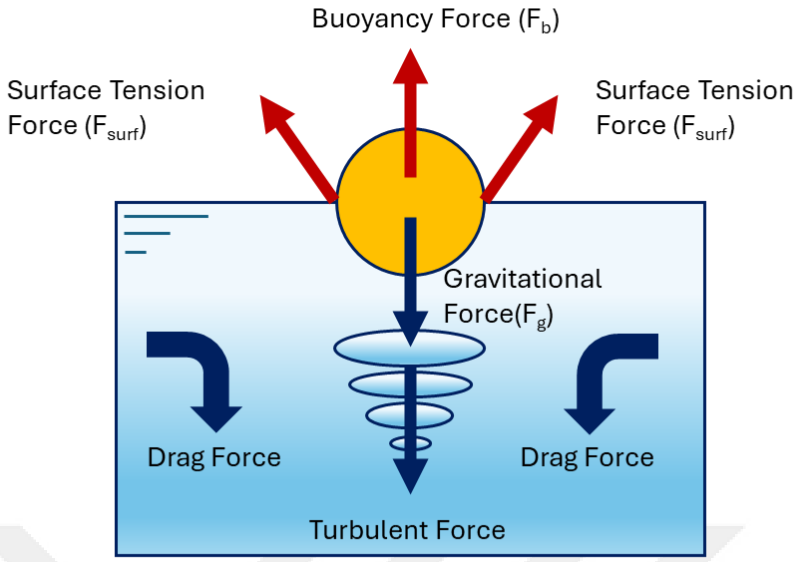


Figure 1 Force balance on a single particle (Khazam,2008)

They declared that solids drawdown occurred with 3 different mechanisms.

a) **Single vortex formation:** in only unbaffles systems, a large stable vortex is formed at the center of the tank. It breaks the stagnant zones on the surface which is comparable to the condition at N_{jd} with baffles configuration. However, solids are not distributed to entire regions of the tank in the presence of vortex. Due to vortex, particles spin, and then gathered around the center of tank. They are drawdowned by centrifugal forces. It is noted that mean velocity is mainly in the tangential direction so, it does not have considerable effect on solids drawdown. Besides, vortex size depends on the type and immesion depth of impeller. (Khazam,2008)

Representative solids drawdown by a single vortex formation in unbaffles tank was given below in Figure 2.

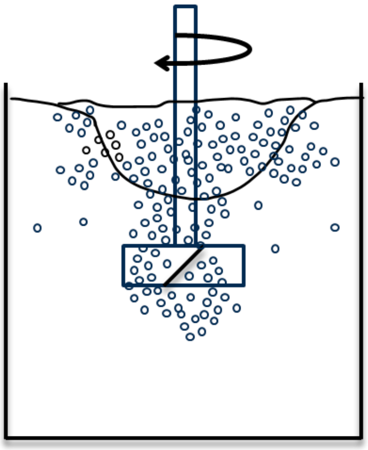


Figure 2 Solids drawdown by a single vortex formation in unbaffles tank

b) **Turbulent fluctuations:** a wavy and splashy surface with energetic surface eddies generates the turbulent fluctuations especially seen by using small submergence of impellers. Eddies appear and disappear quickly. They immerse particles in small packets. The eddies smaller than particles do not have an adequate energy to drawdown the particles. Also, very large eddies are controlled by mean circulation loops. Actually, turbulent fluctuations are corresponding with the meso-scale eddies. Their size 3-10 times the size the particle or approximately 2-4% of the size of the particle diameter. (Khazam,2008)

Solids drawdown performed by turbulent engulfment due to eddy formation in full baffles tank was shown in Figure 3.

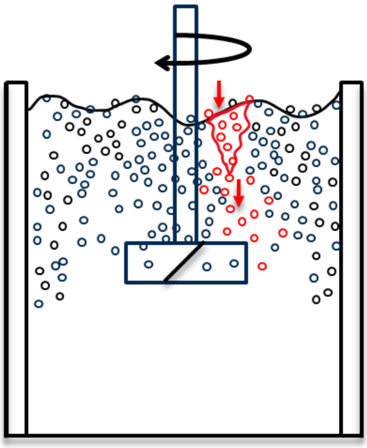


Figure 3 Solids drawdown by eddy formation in full baffles tank

c) **Mean drag:** large swirls and waves growing on the surface disrupt the stagnant zones discontinuosly and drawdown more solids. Macro-instabilities in the mean flow are useful to scatter solid clumps and draw down of the particles. Powerful mean circulations give opportunities for a better solid distribution than a strong central vortex. The axial component of mean velocity which determines the drag force must be larger than the particle slip velocity, defined as difference between the particle velocity and the surrounding fluid velocity, at some point close to the liquid surface to function the drawdown mechanism efficiently. (Khazam,2008)

Solids drawdown due to mean drag in full baffles tank was indicated in Figure 4.

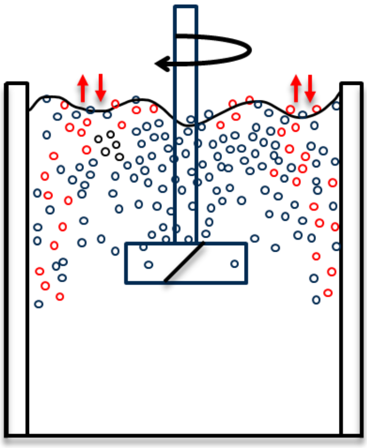


Figure 4 Solids drawdown due to mean drag in full baffles tank

1.5 Definition and Measurement of the Cloud Depth(CD)

Khazam & Kresta (2008) declared that these mechanisms function together for most of the tank configurations, but usually, one dominates.

In order to interpret particle distribution based on observation, they defined a parameter called Cloud Depth (CD). Cloud depth is the distance from the lowest point the liquid surface to the point where particle concentration declines sharply. Measurement of CD at N_{jd} gives vital information to evaluate hydrodnamic characteristic of configured systems. To understand their definition, representative drawing is given in Figure 5.

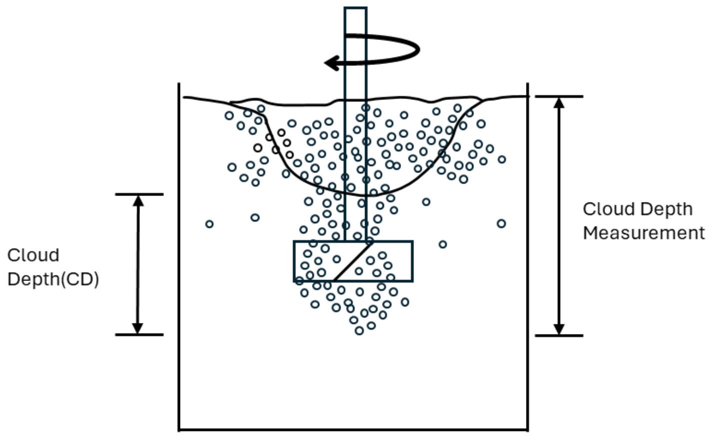


Figure 5 Cloud depth measurement for unbaffles tank with deformed surface (Khazam,2008)

In this study, they also investigated the effect of baffle configuration, submergence level of impeller, particle density and concentration on N_{jd}. They used unbaffles,one-full baffles and four-full baffles configuration in experiments. Baffles configurations provided considerably more Cloud depth(CD) than unbaffles ones.They defined that at N_{jd}, no particles remain on the surface more than 1-2 seconds. The liquid height (H) was equal to tank diameter (H=T). The other details and the results are given in literature review section of this thesis.

There was no studies that aim complete drawdown with full dispersion of particles. However, Wojtowicz (2014) did a study while modeling the drawdown based on this. He defined N_{min} speed where all particles are drawdowned and full dispersed and P_{min}, power consumption at N_{min}. He used conventional impellers which are PBTU, PBTD and RT for single and dual impeller systems and single vibromixer. For all experiments, liquid height was fixed and equal to tank diameter. They modeled solids drawdown using parameters depending on geometry and chemical properties. The details of this study is given literature review part.

1.6 Flow Patterns of Impellers

Each types of impeller has specific flow patterns. RT is a radial impeller whereas PBT is a mixed flow impeller. In Figure 6, the flow patterns of PBTU, PBTD and RT were given together.

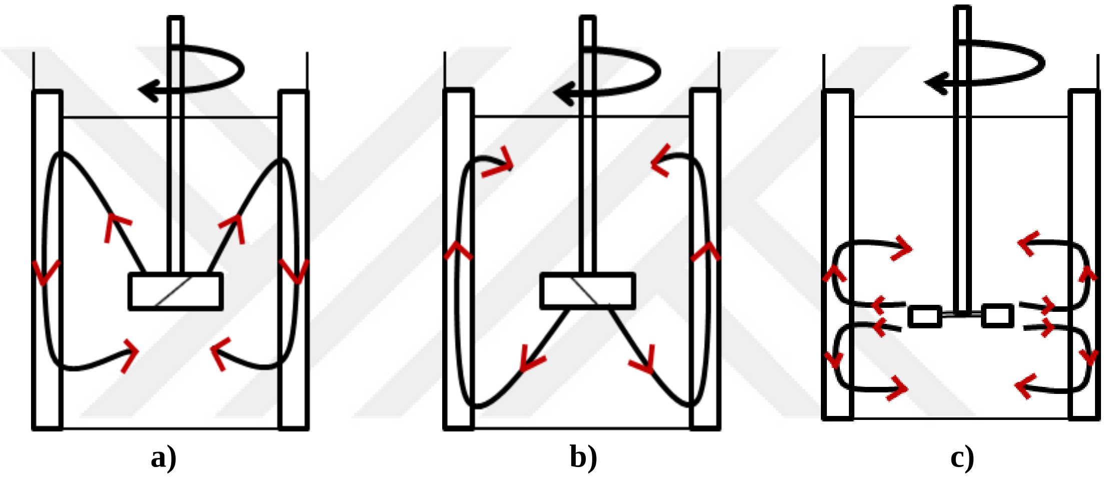


Figure 6 Flow Patterns of Impellers; **a)** PBTU **b)** PBTD **c)** RT

1.7 The Motivation of the Thesis

In literature, most of the studies focused on only drawdown and did not give systematic information for distribution of drawn down particles. Only, Khazam&Kresta (2008) defined cloud depth (CD) to interpret the distribution of particles, but this was only for N_{jd}. This study did not aim obtaining distribution of particles throughout tank and record the speed (N) for that condition. Wojtowicz (2014) was only concerned in full dispersion of particles at drawdown conditions and recorded the impeller speed named N_{min} for its specific condition. However, they did not record N_{jd} and an information for solid distribution at N_{jd}. In operations, however, the particles need to be drawn down and distrubuted at the same time with minimum power consumption. This shows the need for a study involving cloud depth at N_{jd} and the impeller speed that provides full distribution of particles throughout the tank. In this thesis the latter is defined as the fully distributed speed N_{fd}. The difference between the N_{jd} and N_{fd} is shown below in Figure 7.

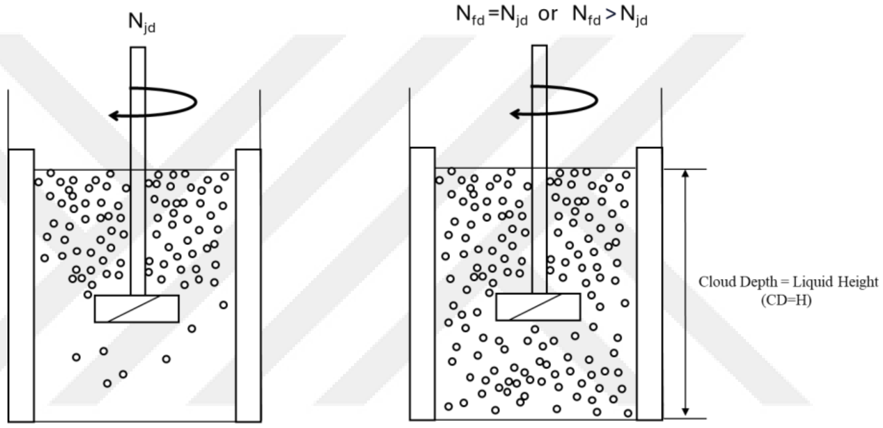


Figure 7 Illustration of N_{jd} and N_{fd}

Furhermore, most of the studies fixed the liquid height equal to the tank diameter. There was no systematic information on higher liquid heights than tank diameter for solids drawdown and distributions especially for single impeller systems.

The analysis of drawdown mechanism,available in the literature clearly demonstrated importance of baffle configuration.

This study aims to meet the needs given above in the field of dradown of floating solids. Hence, the objective of this study is to investigate of the effect of liquid height and baffle geometry on drawdown of floating solids in stirred tanks, considering N_{jd}, P_{jd}, N_{fd}, P_{fd} and CD simultaneously.

CHAPTER 2

LITERATURE REVIEW

2.1 The Effect of Baffle Configuration on Solids Drawdown and Distribution

Thring & Edwards (1990) studied the effect on baffle configuration,impeller type,solid concentration and impeller clearence from the tank on solids drawdown. Especially, they focused on influence on the baffle configuration on solids drawdown in detailed. They 22 different baffle configurations to find the best minimum suspension speed (N_{min}) and power consumption (P_{min}) at N_{min}. The N_{min} was defined as the just drawdown speed (N_{jd}) where no particles remain on liquid surface for longer than 3 seconds.

They used used the flat-bottomed cylindrical tank with a diameter (T) 1.22 m. The liquid height was equal to tank diameter. They used also,6-bladed turbine (RT),3-bladed propeller and 2-bladed paddle. The impeller clearances from the bottom were T/3 and T/2. The solid concentration varied between 0.75% w/w to 3% w/w invervals of 0.75% w/w. They specified two terms for baffle position, lowered and raised baffle. Lowered baffle was fully immersed whereas the raised baffle was rised from the bottom and created clearance of 0.305 m (T/4) from the bottom. They used no baffles,one,two,three and four baffles combinations. All possible lowered and raised baffle configuration were used within these combinations.

Finally, they found that the baffle configuration did not have impact on solids drawdown by N_{min},but it affected the power consumption.Increasig number of baflles resulted in the power number of impellers. Furtherly, it was recommended that two configurations; first:one baffle,3-bladed-propeller,clearence(C=H/3),second:four-baffles, 6-bladed turbine,clearence (C=2H/3).

Özcan-Taşkın& McGrarth (2001) studied the effect of impeller type,impeller sumergence and the number of baffles. The evaluation of experiments was based on N_{jd} and P_{jd}. N_{jd} was defined as remaning no particles on liquid surface more 1-2 seconds whereas P_{jd} was power consumption at N_{jd}. Experiments were carried out a 0.31 m diameter tank(T) in perspex vessel. The liquid height was equal to tank diameter. They used 6-bladed disk turbine(RT), 4-bladed 45° down pumping pitch turbine (PBTD) and LE-20 impellers. The impeller diameter (D) was T/3. Besides, the impeller submergence(S) was varied from the T/8 to 2T/3. They used oval shaped nearly uniform dimensions of 5x3x2. The density of particle 905 kg/m^3 and solid concentration was 1% w/w.

In addition, they used the number of one ,two and four baffles configurations. Increasing number of baffles decreasing the N_{jd} and P_{jd}. Solids drawdown occurred due to recirculation loops than vortices because of impeller characteristics.That's why, drawdown needs less power. Lastly, they added, if the axial or radial impeller was mounted close to base(S ≤ T/4), 4-baffles vessel was suggested.

Khazam & Kresta (2008) studied the effect of impeller type,solids concentration,particle size and shape,impeller submergence and baffle configuration on N_{jd} defined as remaining no particles on liquid surface more than 1-2 seconds. They also utilized the CFD simulations to analyze the circulation patterns of impellers. Furthermore,to determine how particles distributed throughout the tank, they defined Cloud Depth (CD) which is a distance from the liquid surface to a point where concentration of particles drops in a large extent. It was measured at N_{jd}.

They conducted out the experiment with the tank diameter in 0.24 m. The liquid height was equal to tank diameter.The submergence was between 0.01 m < S < 0.12. They used PBTU and PBTD with diameters T/2 and T/3, and A340 in up-pumping with diameter 4T/9. They also used four different particles which were EPS 1, EPS 2, EPS 3 and PE grids. Their densities were 0.9,0.4,0.3 and 1 g/cm^3 respectively whereas their particle diameters (d_p) were 1 mm, 1.5 mm, 2 mm and 8 mm x 8 mm x 1 mm respectively. The liquids were tap water (998 kg/m^3) and Bayol (794 kg/m^3).

Moreover, the performances of unbaffles, one fully baffles and four fully baffles configurations were compared with respective to N_{jd} and CD.The solid concentration was 2% v/v.

For CD values, for all impellers, by inreasing the submergence, for one baffle and four baffles were better by far compared to unbaffles tank. For all submergences, for PBTU and PBTD, four baffles system gave the best resulst for CD whereas for A340, one baffle was superior a little bit than four baffles.

For N_{jd} values,for all submergences, for PBTD, baffle configuration did not influence the N_{jd} considerably.For PBTU, for S/T < 0.375, four baffles system nearly gave the minimum N_{jd} values. For A340, for all submergences, one baffle and four baffles system was better than unbaffles system especially S/T >0.15 and for S/T< 0.15, there were almost no difference between baffles to have minimum N_{jd} value.

In the end, for S/T < 0.375, PBTU with four baffles system was more efficient while S/T >0.375, using PBTD impellers were recommended.

Khazam & Kresta (2009), they pursued their study given above in 2008 and they studied the effect of baffle with different geometry on N_{jd} and P_{jd}, power consumption at N_{jd}. They used surface,half and full four baffles configuration. Surface baffle length from the surface to liquid bottom was 5 cm (5T/24) whereas half baffle length was T/2. The full baffle length was equal to the liquid height. Other than these, the whole system and other specialties were same with their studies at 2008 except for submergence range which was upgraded to 0.01 m < S < 0.16.

Like the Khazam & Kresta(2008),the performances of surface,half and full four baffles configurations were compared with respective to N_{jd} and CD. The solid concentration was 2% v/v.

For N_{jd}, for all submergences, for PBTU and PBTD, surface baffle have better result than half baffle and full baffle confirugarions at which they have nearly same results. For A340, for all submergences, their results were close.

For CD, for all submergences,for PBTU and PBTD, full baffles was better than surface and half baffles. For A340, for S/T< 0.25, the results were so close. For S/T >0.25, surface baffles better than other ones.

For P_{jd}, the comparison was made only for surface and full baffles. For PBTU and PBTD in diameter T/2, for S/T< 0.33, PBTD with 4 baffles combination had highest value where the other three had nearly same value. For S/T >0.33, power consumption of PBTU and PBTD with full baffles was higher than PBTU and PBTD with surface baffles at which their values are the same. Furthermore, For PBTU and PBTD in diameter T/3, for S/T< 0.25, PBTU with surface baflles and PBTU with full baffles had almost the same results and better than PBTD with baffles. For S/T >0.25, PBTU with full baffles most energy efficient confirguration among them.

Finally, for P_{jd}, for PBTD by T/2, for %10 v/v solid concentration,surface,half and full baffles performances were compared. for S/T< 0.15, half and full baffles had same results and better than surface baffles. S/T >0.15, surface baffles was better than them.

At the end, It was found that PBTU and PBTD with large diameters had smaller power consumption at N_{jd} compared to smaller ones. It was also added that PBTU was influenced by baffle configuration more than PBTD. This meant PBTD provided more stable operations than operations with PBTU.

Karcz & Mackiewicz(2009) studied the effects of vessel baffling on solid drawdown.The purpose was using different baffle combinations to obtain minimum N_{jd}. They utilized, one,two,three or four baffles. Two kinds of baffle type; full length and short baffles where baffle height is half of the liquid height. They combine these baffle types and created 12 combinations to be used in experiments.

The tank diameter was 0.295 m. Also, they used RT,PBTU by 45°and PBTD by 45° and propeller. The liquid height(H) was equal to tank diameter. Impeller diameter was T/3 and Clearances(C) were C=2H/3 and C=H/3. The solid concentration was betweeen 1% w/w to 4% w/w. The N_{jd} was defined as nod particles stayed on surface of liquid longer than 1-2 seconds.

They declared that effect of baffles on N_{jd} depends on clearance (C). Also, PBTU with clearance C=0.67H/T with four- full lentgh baffles was more energy efficient than other configuurations.

Furukawa et al. (2024) investigated the effect of inside surface baffle on N_{jd}. Surface baffle was placed a specific location where there are clearance (C) between the surface baffle and tank wall. They compared to unbaffles, full baffles, surface baffle on the wall and inside suface baffles performances.

They utilized flat-bottomed vessel with diameter 0.15 m. The liquid height(H) was equal to tank diameter(T). The surface baffle lentgh(B) was equal to 0.2 times of liquid height. (B= 0.2H). They used up-pumping pitched blade paddle (PBPU) and down-pumping pitched blade paddle (PBPD). The impeller diameter was 0.070 m and the impeller angle was 60°. The clearance between the wall and the surface baffle varied 0.1T, 0.2T and 0.3T. They also changed baffle angles for surface and inside surface baffle. They defined 0° as tangential to flow direction whereas 90° was defined as perpendicular to tank wall. Clearence was between 0.2H to 0.7H. The solid concentrations were 3% v/v ,5% v/v and 7% v/v. The Njd was defined as no particles stayed on surface of liquid longer than 1-2 seconds.

At the end, they found that the N_{jd} for each impeller increased, decreased and stabled for C=0.7,C=0.2 and C=0.5 respectively. P_{jd} value was the smallest for all impellers at the angle 0° and largest at 90°. Furthermore, it was pointed out that the baffle placed at 0° is also efective as a baffle when placed parallel to the primary tangential flow.

2.2 Alternative Tecniques Used In Analysis of Solids Drawdown and Distribution

Özcan-Taşkin & Wei (2003) studied the effect of impeller-to-tank diameter ratio on drawdown of floating solids by using three tecqniques; doing experiments based on visual observation, LDA (Laser Doppler Anemomety) measurements, CFD (computational fluid dynamics) protocol. LDA and CFD gives information on axial and radial fluid velocity distribution on tank. At the end, the found the flow pattern and kinetic energy profile of impellers.Doing experiments based on viusal observation, they used a tank which its diameteris equal to 0.61 m. For all experiments, liquid height equals to tank diameter. They used PBTU, PBTD and LE-20 (mainly axial flow impeller). They used 2 impeller sizes (D), D=T/2 and D=T/3. They used four different submergences for these impellers. Also, particle concentration was fixed to 1% w/w.

For the LDA measurement setup, they used smaller tank where its diameter (T) equals to 0.292 m. For CFD study took this tank diamater (T) for modelling. For LDA modelling and CFD study was only used PBTU sized in T/2 and T/3. For LDA measurement, they used two submergences whereas for CFD study, there was only one surmergence. It means that for these 3 techniques, there was only 2 sets of experiments to compare in detail.

Futhermore, for all tecniques, they changed the time period of particles staiyng on surface at N_{jd} by raising time from 1-2 seconds to 2-4 seconds due to diffuculty on repeatable determination of N_{jd}.

The LDA which is a technique of using Dopplershift in a laser beam, has three beam (two-component) laser,consists of an argon laser gun and burst spectrum analysis (BSA) as a signal processor. Also, the operation was conducted out in backscatter mode. Using the LDA, axial and radial velocity profiles generated by impeller’s discharges were measured using the traverse placed to two points; near the surface and just above the blade. CFD simulations utilized the k-epsilon turbulence model.

Thanks to sliding-mesh tecnique, it provided to do explicit modelling of interaction between impellers and baffles. Moreover, two different models, slip wall function and free surface models.

In the end, they found that for the experiments depend on visual observation, although using the large impeller provided lower N_{jd} compared to small ones, they consumed more energy and had higher P_{jd}. From the CFD simulations and LDA measurements, It was found that Impeller by T/2 gives more radial flow and less axial flow compared to impeller by T/3. Hence, small one disturb surface more than larger one.

Finally, all three techniques showed that using the impeller by T/3 instead of T/2 has advantageous by energy consumption in solids drawdown.

Paglianti et al. (2017) investigated the distribution of solid particles and liquid mixing dynamics in solid-liquid stirred tanks.. They measured the local solids concentration distribution at steady-state conditions, based on liquid homogenisation in the presence of dispersed particles in order to evaluate the mixing level labelling the well-mixed or poorly-mixed.

Electric Resistance Tomography (ERT) was chosen as an experimental technique for data acqusition which is the process of sampling signals, conductivies for ERT, to convert measured values from real-world phsical into digital numeric numbers for the first time to analyze the distribution of floating particles throughout the tank.

They used PBTU and PBTD impellers and equally spaced four baffles. The liquid height was equal to tank diameter and varied up to nearly 7T/6. In addition,they implemented 4 horizontal planes which divides sysyem into 4 parts and they put 16 electrodes for each plane in order to gather conduvities. The conductiviy map was created based on these electrodes.

In the end, thanks to the conductivity maps, particle distribution throughout tank with local characteristics was accomplished.Important axial concentration gradient was obtained by PBTU and PBTD. PBTU was more effective than PBTD.

CHAPTER 3

EXPERIMENTAL PROCEDURE

There are two stirred tank setups used in experiments. Both experimental setups consist of flat bottom transparent cylindrical plexiglass tank which have 0.24 m diameter (T). Both have same featured baffles and impellers which allowed performing experiments in two setups. In Figure 7, the pictures of the setups are given.

a) **b)**

Figure 8 Experimental setups; **a)** Setup on the bench **b)** Setup on lifting mechanism

In Table 1, functional properties of the setups are specified. Most of the experiments were conducted with the setup on bench, but, some were run on the setup with the lifting mechanism since impeller speeds lower than 200 rpm were required and the bench top system could not provide that. Furthermore, in order to obtain power comsumption, torque measurements were done with setup on lifting mechanism.

While technically it was possible to run all the experiments on the setup with lifting mechanism, this setup was not available for the entire duration of the experiments of this thesis; therefore, an alteration of the two setups based on availability was required.

Table 1 Functional properties of the two setups

No	Functionality	Setup on the bench	Setup on lifting mechanism
1	**Motor speed range (rpm)**	200-1500	0-2000
2	**Motor rotational direction**	Clockwise	Clockwise and Counter Clockwise
3	**Axial Moving part**	Motor	Plexiglass Tank
4	**Torque measurement with torquemeter**	No	Yes
5	**PLC remote control system and recording data**	No	Yes

a) **b)**

Figure 9 Polypropylene particles; **a)** close up **b)** on surface

All the experiments were done under atmospheric pressure and room temperature. Tap water was used as the liquid phase and hydrophobic polypropylene (PP) granule particles were used in the experiments. Images of the particles are shown in Figure 8. The density of the particles is 910 kg/m^3. The amount of solid particles by mass was kept constant at all liquid heights (H). It equals to the mass of 1% w/w solid loading when the liquid height (H) is equal to the tank diameter (T). In all experiments, solid particles cover the surface of liquid creating thin layer on the surface. The dimensions of the particles approximately were 3 mm **x** 4 mm **x** 5 mm.

Experiments were performed using a single impeller. Tank geometry with symbols are given in Figure 10, and definitions of these symbols are given in Table 2.

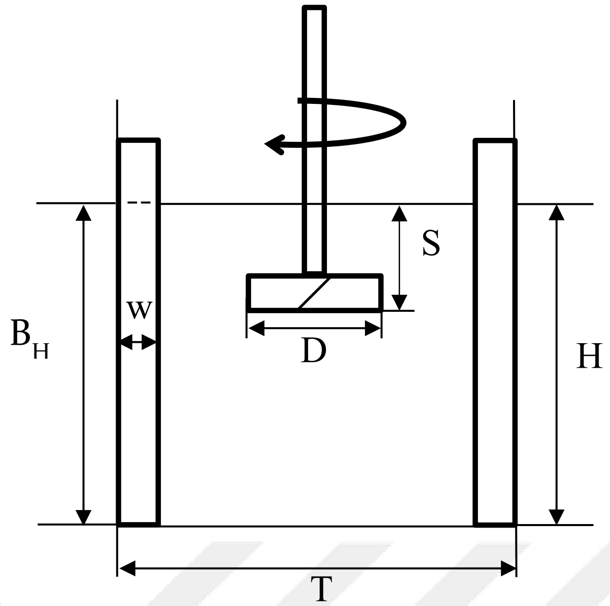


Figure 10 Tank Geometry with symbols

Table 2 Definitions and symbols corresponding tank geomerty

Definition	**Symbol**
Liquid Height	H
Tank Diameter	T
Impeller Diameter	D
Submergence	S
Baffle Width	w
Baffle Height	B_H

A radial flow impeller - Rushton turbine (RT), mixed flow impellers - 45° four-bladed up-pumping pitched blade turbine (PBTU) and 45° four-bladed down-pumping pitched blade turbine (PBTD) were used in experiments. They are 3D printed from polyamide material. To attach the impellers on shaft, a stainless steel ring is located in the hub of the impellers. Using 4 mm stainless steel screw, they are pinned on the shaft.

Each impeller was manufactured in two impeller diameters: 0.08 m (T/3) and 0.12m (T/2), to be able to test the effect of impeller diameter on the investigated parameters. In Figure 11, images of the impellers are shown. In Table 3, the geometric specifications of these impellers and stainless steel impeller shafts are given.

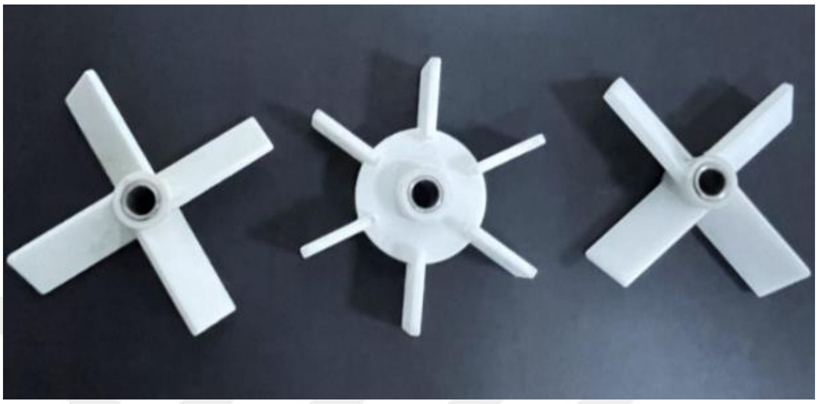


Figure 11 From left to right, PBTD, RT and PBTU respectively.

Table 3 Geometric specifications of the impellers.

	PBTD	RT	PBTU
Diameters (mm)	80 & 120	80 & 120	80 & 120
Hub diameter (mm)	16	16	16
Hub height (mm)	15	15	15
Hub internal diameter (mm)	11	11	11
Blade length (mm)	64 & 104	24 & 44	64 & 104
Blade thickness (mm)	3	3	3
Disk diameter (mm)	-	40	-

	Shaft 1	Shaft 2
Total Length (mm)	485	400
Diameter entering the motor(mm)	7	7
Length pass through into motor (mm)	35	adjustible
Diameter entering impeller hub (mm)	7	7
Length pass through impeller hub (mm)	7	adjustible

Four baffles surface and full baffle configurations were used. The baffles have the same dimensions in terms of baffle width (24 mm, W=T/10) and baffle thickness (2 mm, B_T=T/120) but they are different in height (B_H). Baffle height is the distance from liquid level to an ultimate point where the baffle is immersed in liquid. For all experimental conditions, surface baffle is positioned and fixed to extend 5 cm below from liquid surface (B_H= 5 cm). Full baffle length is fixed as equal to the liquid height. The representative drawing of baffles is given below in Figure 12.

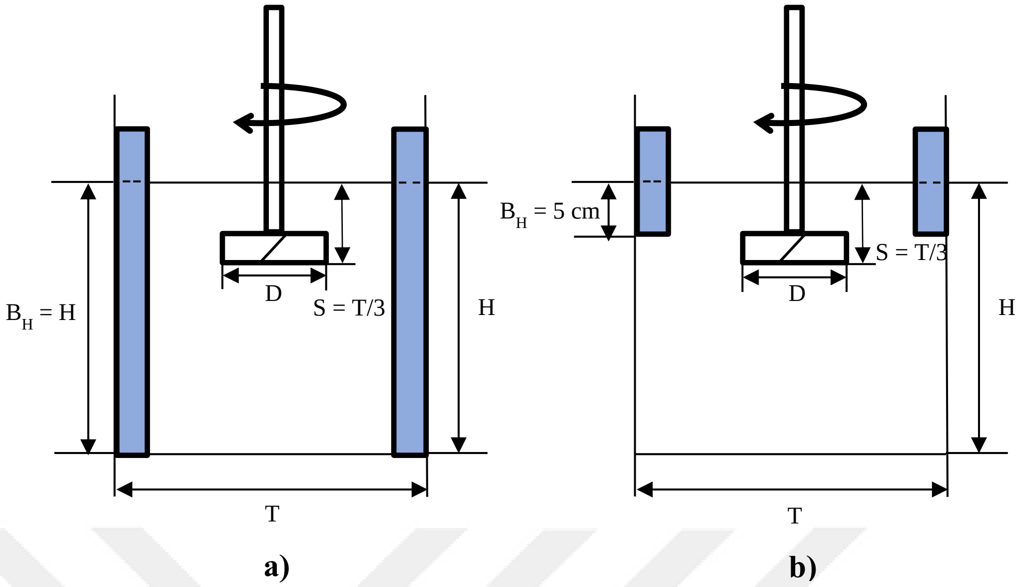


Figure 12 Baffle Configurations; **a)** Full Baffles **b)** Surface Baffles

Submergence of the impeller is defined as the distance between liquid surface and lowest point of impeller blade. As shown in Figure 12, submergence is fixed to 8 cm (T/3). Another fixed parameter was the mass of the particle. It is equalized to the mass of the particles resulting in a particle concentration of 1% by mass when the liquid height is equal to the diameter of the tank (H=T) for all experimental conditions. The mass covers the surface and creates a thin layer. This mass was 109.62 g.

In experiments, the main changing variable is liquid height (H). It varies from 20 cm (5T/6) to 40 cm (10T/6) at 4 cm (T/6) intervals.

The aim of the experiments is investigation of the effect of liquid height and baffle geometry on drawdown of floating solids in stirred tanks The design criterion is chosen as just drawdown speed (N_{jd}) power consumption at N_{jd} (P_{jd}), cloud depth (CD) , fully distributed speed (N_{fd}) and power consumption at N_{fd} (P_{fd}).

Just drawdown speed (N_{jd}) is the impeller speed at which no particles remain on the surface of the liquid more than 1-2 seconds. N_{jd} is determined visually. In the experiments, impeller speed was increased gradually. In the beginning, impeller speed was raised by 30 rpm and waited for 5-10 seconds to observe the system. Later on, as speed increases, increment in the speed was reduced to 10 rpm and the time for observation was 30-60 seconds. As the impeller speed approached N_{jd}, the reappearance of the solid particles on the surface takes more time compared to previous speeds. When this condition is reached, increments in the impeller speed was reduced to 5 rpm. For each rotational speed, the system was let run for 2 minutes enabling it reach steady-state conditions. The system was then observed for 5 to 10 minutes to ensure that the conditions required for N_{jd} was met.

For torque (T_q) measurements, the measurement was taken once N_{jd} was met. The torque meter had a range of up to 5 N.m with 0.1% sensitivity. Data rate was one data per second. For three minutes, data were collected and averaged. Then, P_{jd} was calculated by Equation 4 in section 1.2.

As defined in the introduction section, a new term called fully distributed speed (N_{fd}) was defined and measured. This is the required impeller speed to distribute the particles throughout the tank, this means all the way to the bottom of the tank. By definition, at fully distributed condition, CD must be equal to H and N_{fd} must be equal to or higher than N_{jd}. Firstly, N_{jd} and CD were recorded for solids drawdown condition. If CD <H at N_{jd}, the impeller speed was raised gradually until CD was equal to H. When CD equals H, impeller speed was recorded as N_{fd}. It is important to note that by increasing the impeller speed, there are situations that CD cannot reach H due to geometric configuration of the system. In that case, N_{fd} cannot be recorded. The details of these conditions are given in Chapter 4. Then, evaluation of the system was performed with respect to this fact.Furtherly, by following the same procedure in the calculation of P_{jd}, P_{fd} was also calculated.

A representative figure for cloud depth (CD) is shown below in Figure 13. CD is the distance from liquid surface to point where buoyant particle concentration changes in a dramatic manner. It was determined by visual observation so it can present a perspective how the particles are dispersed throughout the tank. To determine CD, at N_{jd}, a long side of the 50 cm ruler was put on lateral side of the tank. Then the system was observed to determine whether the concentration of particles drop sharply. CD line was marked with a pencil. In the end, CD was determined measuring the distance from the liquid level to the CD line with a ruler. If just a few particles , numbering up to a dozen, determined by visual observations, pass through down the marked pencil line and below the line, these particles are not seen constantly, and they disapper for more than 2 seconds, the distance traveled down was not taken into account as part of CD.

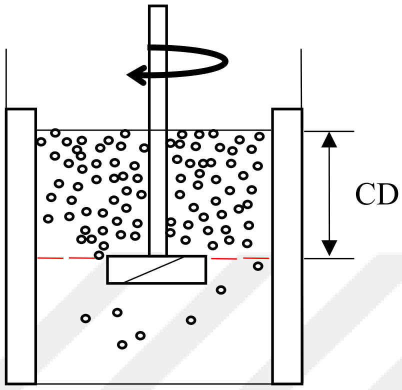
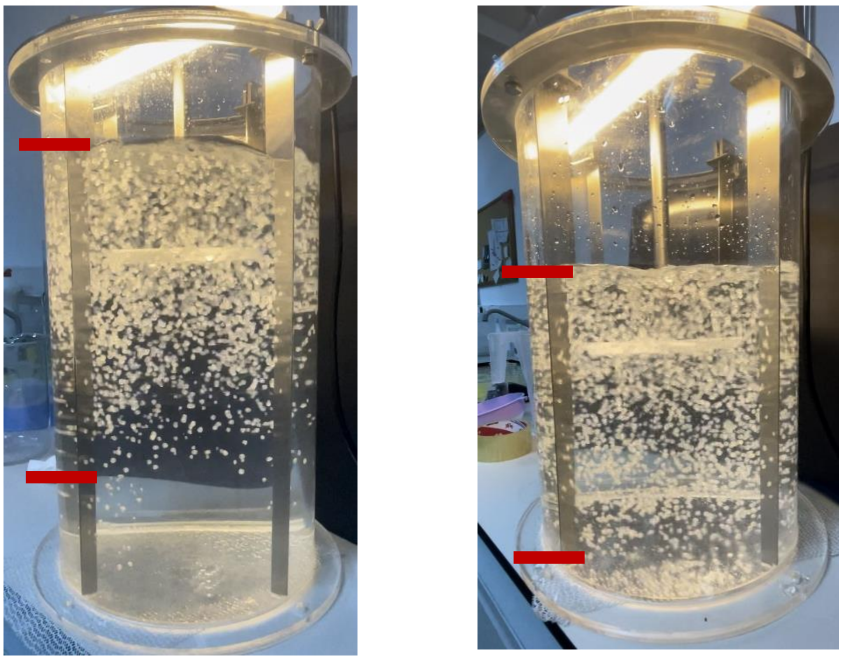


Figure 13 Demonstration of Cloud Depth(CD)

In order to visualize better, photographs from experiments during CD measurement was shown below in **Figure 14**. CD was shown in between red lines.



a) **b)**

Figure 14 CD measurents from experiments; **a)** partial CD **b)** full CD

All of the N_{jd}, N_{fd}, and CD by experiments were repeated twice and the arithmetic mean of the two measurements were reported. The percent error between the two measurements was 5% for N_{jd} and N_{fd} and also, 10% for CD. P_{jd} and P_{fd} values was calculated by average torque data which was collected once and thus, it was not possible to give errors for them.

CHAPTER 4

RESULTS & DISCUSSION

4.1 The Effect of Liquid Height on N_{jd}, P_{jd} and CD

In literature, there was no study focusing directly on the effect of liquid height on solids drawdown. This subject was issued with measuring the N_{jd}, P_{jd} and CD while changing the liquid height, using different baffle geometry, impeller type and impeller diameter which are known tools capable of changing the drawdown mechanism Although multiple impellers are used for high liquid heights (H>>T) in literature and industry, the onset of employing a second impeller in terms of liquid height in case of solids drawdown was unclear.That is, there was no systematic approach to address this problem.

This topic was covered and discussed in next steps according to two basic aspects; the effect of baffle geometry and impeller sizes while varying liquid height on N_{jd}, P_{jd} and CD.

4.1.1 The Effect of Baffle Geomety with Varying Liquid Height on N_{jd}, P_{jd} and CD

The analysis in this section is first done for the T/2 impellers and then for the T/3 impellers.

- As seen in Figure 15, for all baffle geometries and impellers with a diameter of D=T/2, increasing liquid height resulted in slight increase in N_{jd}. There is only once exception that is explained later. In stirred tanks, energy is transferred to the fluid by rotational movement of the impeller. Increasing the liquid height makes the total volume of the fluid increase. The impeller's position is fixed from the liquid surface at S=T/3. This means that as the liquid height increases there is a larger volume of liquid that needs to be put in motion by the same impeller compared to a lower liquid height. Some of the energy provided by the rotation of the impeller is now consumed by the larger volume of the liquid, and therefore, N_{jd} increases. Since radial flow impellers generates more turbulence with lower speed than axial flow impellers (Paul et al., 2004) and PBT are mixed flow impeller providing both radial and axial flow, RT impellers had minimum N_{jd} values.

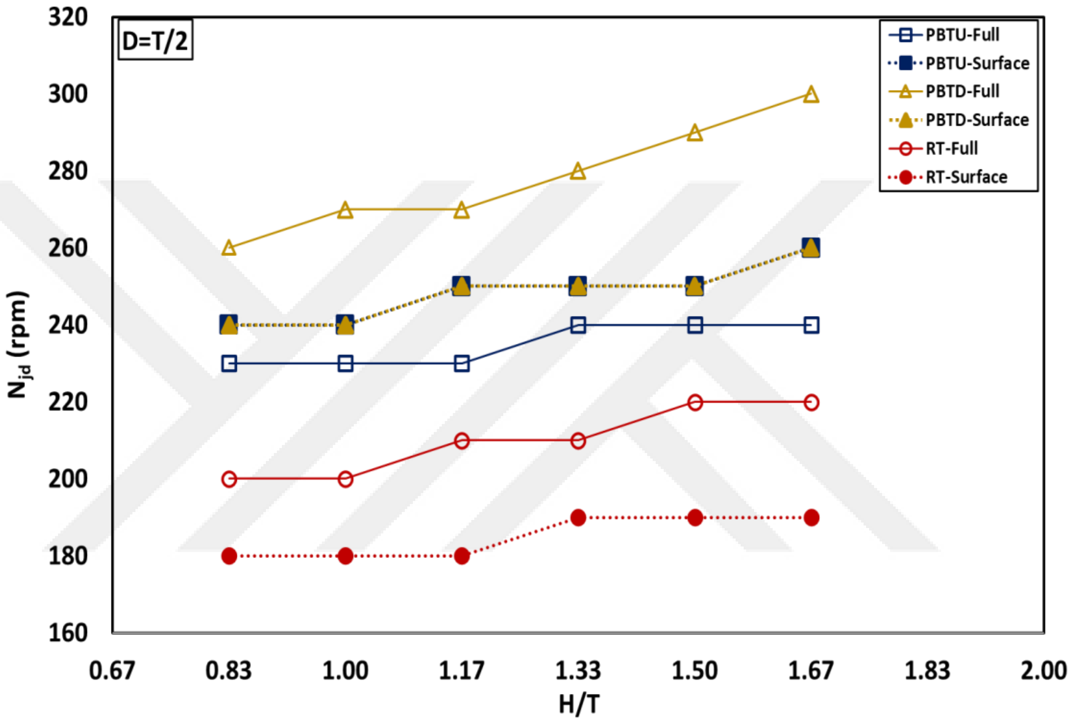


Figure 15 The effect of baffle geometry on N_{jd} with respect to liquid height for impeller diameter by T/2. Submergence of the impeller is T/3

Only with PBTD-T/2 full-baffles configuration N_{jd} was considerably influenced by the increase in liquid height compared to other configurations which were only slightly affected by change in liquid height. This is related to a combination of the flow pattern of the impeller and the geometry (length) of the baffles. PBTD impeller discharges liquid downwards with a 45 degree angle. The liquid turns towards the walls and when towards the surface only after it reaches the lowest position it can with its momentum. The baffles allow for the liquid to be directed toward the liquid surface. Once the liquid reaches the surface, it comes back to the shaft region to go back to the impeller, while drawing down some particles. Because the fluid first needs to go down and as will be explained later the flow is allowed to go lower with the use of full baffles, it requires more energy, and therefore, more impeller speed to be able to come back to the surface and draw down solids. With a PBTU, the discharge of the impeller is directed towards the surface, which dominates the draw down mechanism. With RT, the discharge is directed toward the walls which is then divided into two loops, one upper one lower loop, and the upper loop is mainly responsible for the drawdown of solids. The flow patterns provided by the PBTU and RT are not as strongly related to the larger volume of liquid below the impeller; therefore, N_{jd} with these two impellers is not strongly affected by the increase in liquid height.

Considering all impellers and baffle configurations, RT-T/2 with surface and full baffle configurations had the lowest N_{jd} values with varying liquid heights. The lowest N_{jd} was obtained with RT with surface baffle geometry at all liquid heights whereas PBTD with full baffle configuration resulted in highest N_{jd} at all liquid heights.

It is also noted that although flow generated by the PBTU and PBTD discharge the liquid with the same angle, but in opposite directions, one up and the other down, when a surface baffle was used, N_{jd} values overlapped. This shows the importance of baffle geometry on the flow pattern. The discharge of the impeller is not as strongly connected to the bottom of the tank with surface baffles compared to full baffles. When the down pumping impeller is combined with surface baffles, the liquid comes back to the surface without being as strictly directed towards the bottom compared to the full baffles. This allows for easier drawdown, almost similar to the up pumping impeller.

In addition, for same impeller-baffle combinations, power consumption at N_{jd} (P_{jd}) with varying liquid heights was shown in Figure 16. Similar to N_{jd}, generally, P_{jd} slightly increases with increasing the liquid height. However, it should be noted that for long term usage, these small differences in power consumption can turn into large costs. Hence, evaluation of power consumption data requires different approaches.

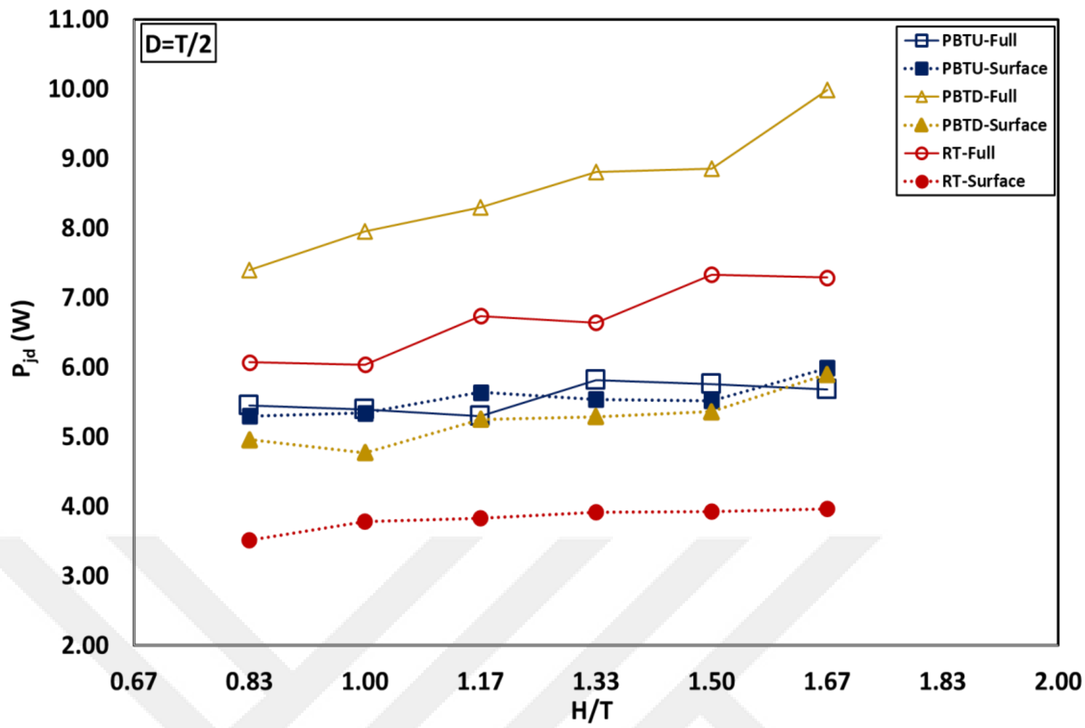


Figure 16 The effect of baffle geometry on P_{jd} with respect to liquid height for impeller diameter by T/2. Submergence of the impeller is T/3

Parallel to N_{jd} value, RT with surface baffles has lowest P_{jd} value while the PBTD with full baffles has highest P_{jd}. But,comparing N_{jd} and P_{jd} values with varying liquid heights, these two graphs did not match directly. In general, for T/2 impellers, it can be said that surface baffles are superior to the full baffles in terms of power consumption. Although, for RT and PBTD, using surface baffles resulted in lower P_{jd} than using full ones, for PBTU, the results are the same with the two baffle geometries. This was due to flow pattern of PBTU T/2. It pumps flow up and its axial velocity is towards surface, so, it disturbs the surface. Because the flow is directed upwards, the interaction of the discharge of the impeller with surface and full baffles is very similar. As a result, for PBTU by T/2, using surface or full baffles is indifferent.

The particle distribution performance of these impellers and baffle configurations are given in Figure 17 in terms of CD. All the data is for T/2 impellers. At all liquid heights, for all the impellers, the full baffles configuration produced larger CD values which show the particles are better distributed throughout the tank compared to surface baffles.

Moreover, it can be inferred from Figure 17 that for H=0.83T which is the only liquid height smaller than tank diameter, use of surface or full baffles showed no difference. Only a slight difference is seen at H=T. For H=1.17T and higher liquid heights (up to H= 1.67T) there is a significant difference between the cloud heights depending on the baffle geometry. Using PBTD and RT, as liquid height increases the difference in CD using full or surface baffles increase. With PBTU, the difference between CD values using the two baffle geometries is similar at all liquid heights.

RT-T/2 with full baffle combination was the best combination in terms of CD. At all liquid heights, CD values equal to the liquid height which was the indication of distibution of solids throughout tank. Keeping the impeller the same, but changing the baffle geometry flips the outcome. RT with surface baffle combination gave the lowest CD values for all liquid height levels.

Lastly, it can be added that for both baffle configurations, trends show that generally, increasing liquid height caused a raise in CD values.

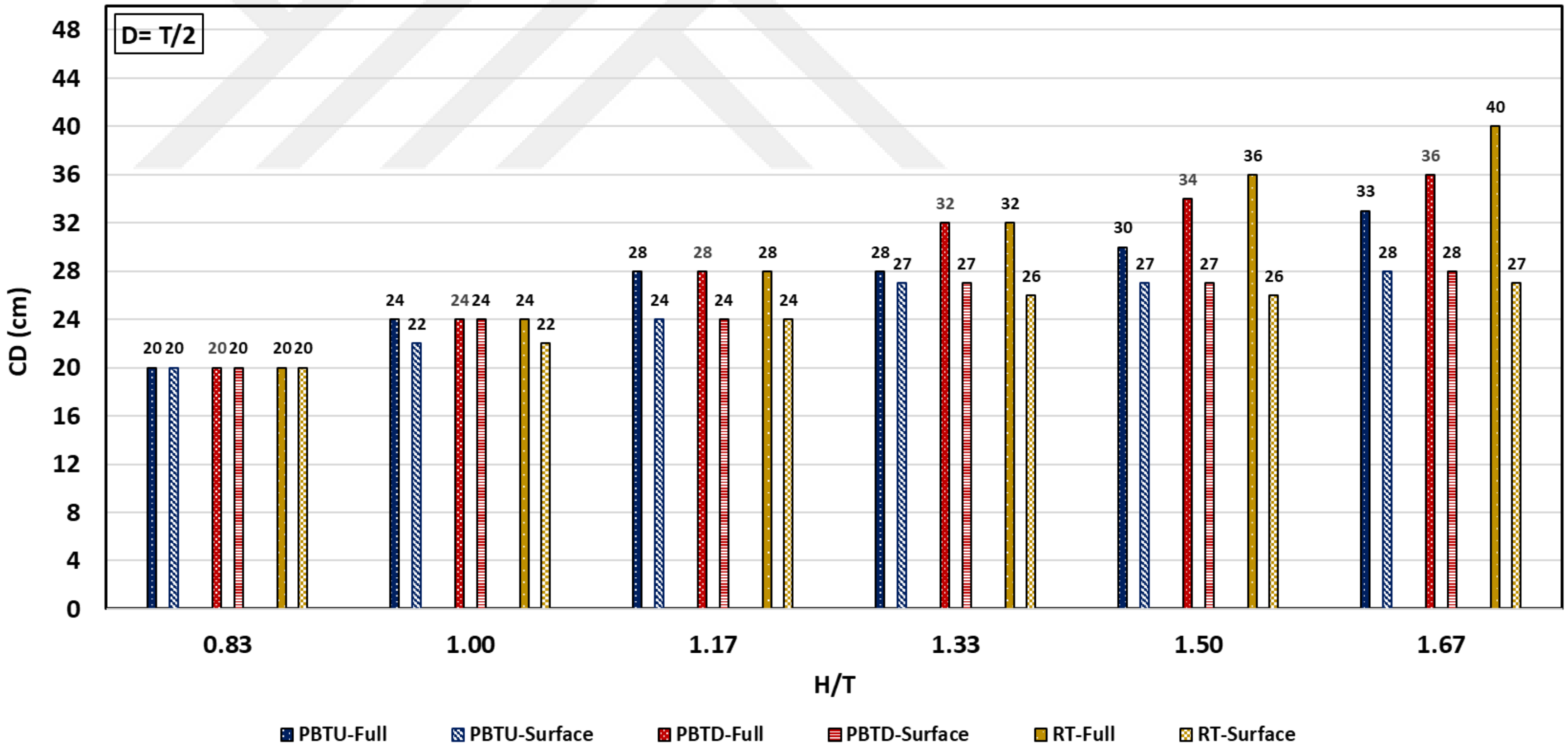


Figure 17 The effect of baffle geomety on baffle geomerty CD with respect to liquid height for impeller diameter by T/2 where T=24 cm

Figure 18 shows N_{jd} data for T/3 impellers. Similar to data in Figure 15, increasing liquid height resulted in slight increase in N_{jd}. At H=0.83T and H=T, PBTU T/3 with full baffles and RT T/3 with surface baffles gave the lowest and the same N_{jd} values. For H=1.17T and at liquid heights above them (up to H= 1.67T), PBTU T/3 with full baffles provided the lowest N_{jd} value, even lower than PBTU T/3 with full baffles.

According to Özcan-Taskin&Wei (2003), PBTU T/3 discharges the flow strongly axially. Hence, it directly disturbs the surface by primary circulation loop. The flow on the surface is from center to the wall. The flow hits the wall and particles are drawdown near the baffles. Longer than surface baffles, full baffles break the flow better. It creates more drag force near the baffles, so particles tend to go downward more and deeper.This is why using full baffles is better than surface baffles for PBTU T/3.

Because of its radial flow pattern, RT T/3 draws the solids by secondary circulation loop. It pumps the liquid towards the wall, creates two secondary loops going upwards and downwards. Using surface baffles considerably decrease the drag force due to absence of baffles in the lower part of the tank and makes upper secondary loop stronger. The turbulence on the surface becomes more effective. In the end, it gives better performance.

According to the Khazam&Kresta (2009), for some cases it was impossible to drawdown particles by using surface baffles with PBTD T/3 because it produces less circulation and less mean drag, which manipulates the drawdown mechanism for this impeller flow pattern. They declared, for S/T > 0.25, it is impossible to perform drawdown. However, for the experiments in this thesis, for S/T=0.33T, using surface baffles with PBTD T/3 was possible and was better than using full baffles. Since particle concentration and particle wettability influence the drawdown of floating (Gentile et al.,2003), difference in results maybe explained by this.

The N_{jd} for PBTU-T/3 with full baffle configuration did not change with respect to change in liquid heights. Because it discharges the flow strongly axially towards liquid surface, it was not influenced by liquid volume change in tank. Similar to

PBTU-T/2 trend, highest N_{jd} value obtained by PBTD-T/3-full baffle configuration because it discharges the flow axially downward and so, using with the full baffles, it was consumed more energy result in raise up the dradown speed.

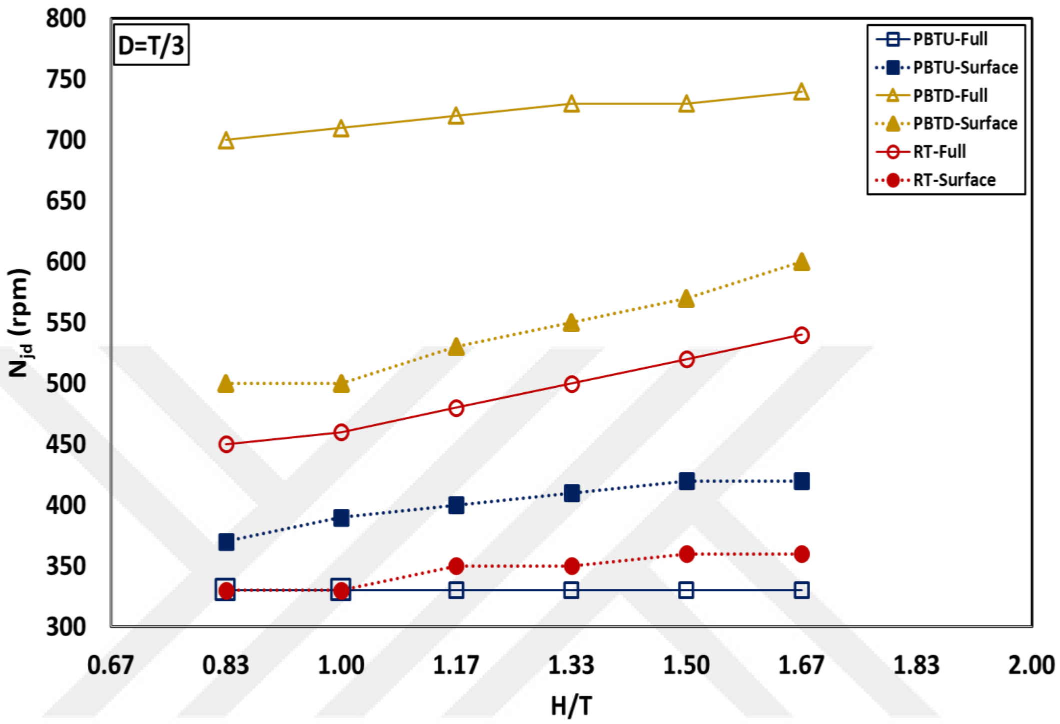


Figure 18 The effect of baffle geometry on N_{jd} with respect to liquid height for impeller diameter by T/3. Submergence of the impeller is T/3

In Figure 19, P_{jd} values with varying liquid height for T/3 impellers with surface or full baffle are shown. Firstly, looking at the graph, it can be said that similar to N_{jd} values, in general, P_{jd} slightly increased by increasing liquid height. Secondly, the order in P_{jd} and N_{jd} results was same except for the order in between RT-full and PBTD-full combinations. N_{jd} value for RT-full was lower than N_{jd} value for PBTD-full whereas for P_{jd}, the situation was visa-versa. According to Paul et al. (2004), power number (N_p) of PBT was smaller than rushton turbine. Thus, it may be related to power consumption of the types of the impellers. Thirdly, for all liquid heights, impellers with surface baffle configurations had smaller P_{jd} values except for PBTU full baffle combination had lowest P_{jd} values due to having lowest N_{jd}. Finally, PBTU-surface, PBTU-full and RT-surface combination seem to form a group of lower Pjd values compared to the rest of the impeller-baffle combinations. It was inferred that for PBTU-T/3 impeller, although using baffles had an impact on P_{jd}, flow pattern of the impeller was determinant. Moreoever, as seen in Figure 16, RT-T/2 with surface combination, also had nearly lowest values for P_{jd}. It can be explained with that using surface baffles, discharged flow by RT did not hit the baffles directly and thus it declines power consumption significantly.

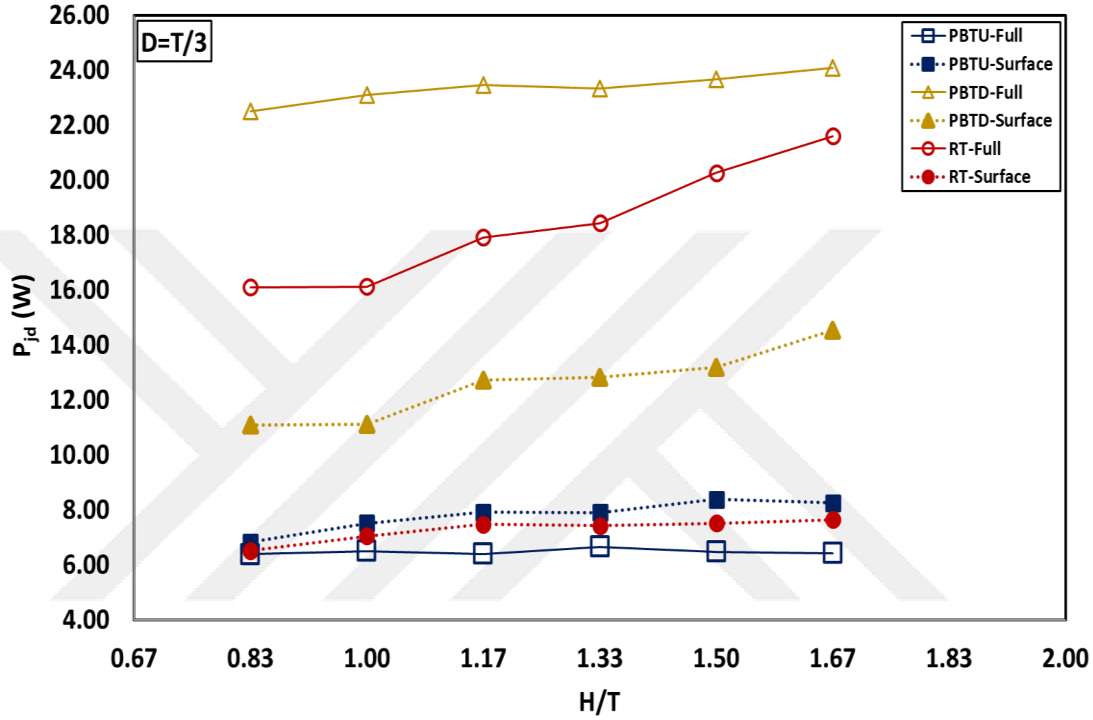


Figure 19 The effect of baffle geometry on P_{jd} with respect to liquid height for impeller diameter by T/3. Submergence of the impeller is T/3

Figure 20 shows the solids distribution performance of T/3 impellers at N_{jd}. At all liquid heights, for any chosen impeller, full baffles provided larger CD values which shows solids distribution is much better with full baffles.

PBTU-T/3-Surface baffle combination gave the lowest CD values for all liquid heights whereas PBTD-T/3-full baffle and RT-T/3-baffle gave the highest CD values. Khazam & Kresta (2008) showed that using one baffles or/and four full baffles systems resulted in much more CD compared to unbaffles tank for PBTU, PBTD and A340 which is radial impeller. Using full-four baffles system was most effective in distribution of particles for all given flow patterns. Furthermore, the purpose of using baffles in mixing is to reduce swirling in the bulk fluid and generate circulation on top and bottom of the tank. From here, it can be inferred that full baffle usage is directly related particle distribution throughout the tank. Whereas, surface baffle is designed for disturbing the surface to decrease N_{jd}. It is very short by length and therefore, it cannot prevent swirling movement and it cannot distributed particles well. Hence, using surface baffle configuration gave lower results in this study.

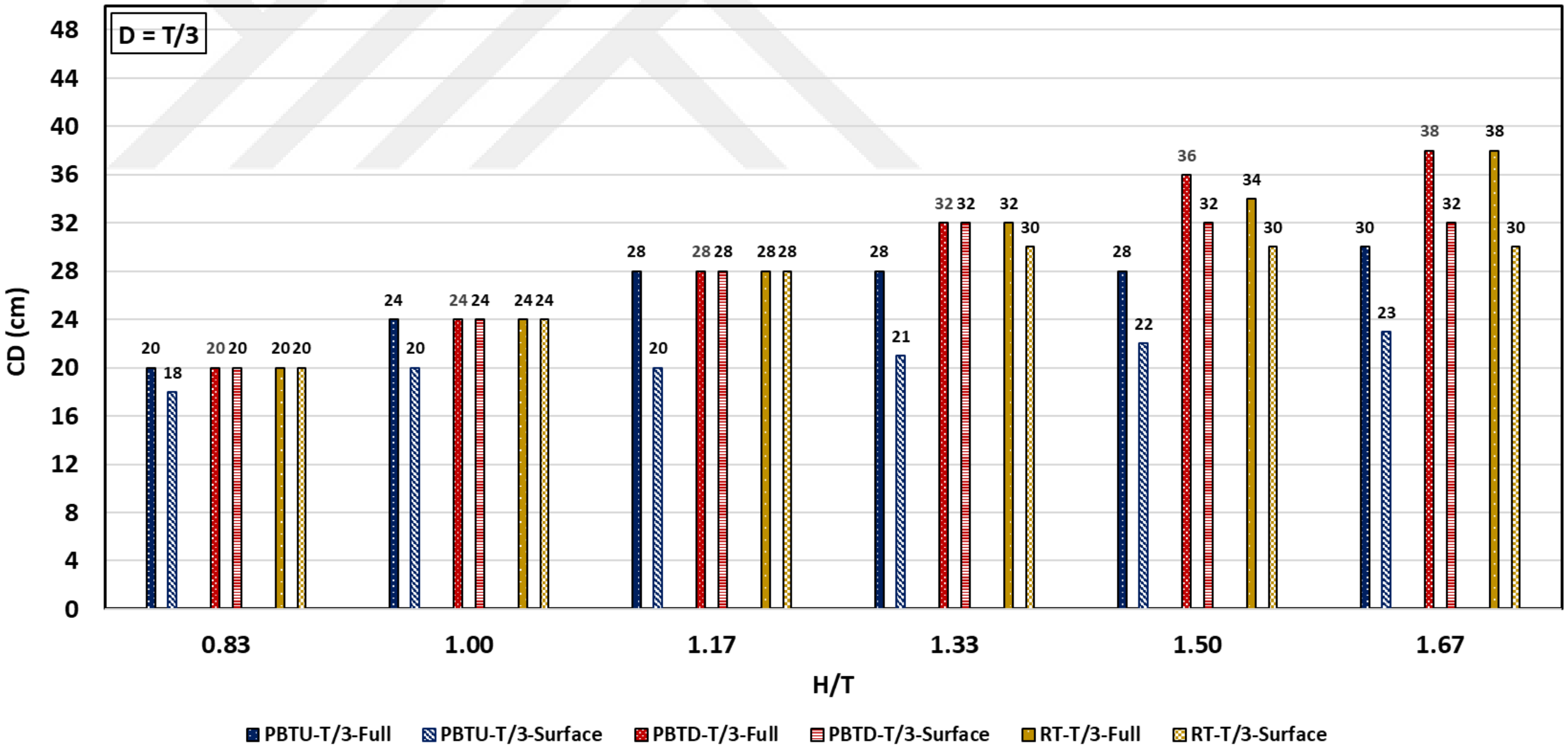


Figure 20 The effect of baffle geomety on CD with respect to liquid height for impeller diameter by T/3 where T= 24 cm

In summary, for all baffle geometries and both impellers increasing liquid height resulted in a slight increase in N_{jd} and for both impeller sizes, full baffles provided larger CD values which shows better distribution of particles throughout the tank compared to surface baffles.

4.1.2 The Effect of Impeller Diameter with Varying Liquid Height on N_{jd}, P_{jd} and CD

As mentioned above, Özcan-Taskin &Wei (2003) declared that PBT T/3 impellers discharge axial flow dominantly while PBT T/2 impellers discharge more radial flow. For this reason, PBT T/3 disturbs surface more. Furthermore, Khazam & Kresta (2008) declared that drawdown mechanism depends on submergence. From 0.25 < S/T < 0.4, mean drag and turbulent engulfment are both active for drawdown. In this study, S/T was fixed to 0.33 which means that both mechanism is active. Thus, the impeller diameter was determinant and it can be said that using the full baffle, large impellers made drawdown of solids governed by turbulence engulment while small impellers is drawdowned by mean drag dominantly.

Figure 21 shows the effect of impeller diameter on N_{jd} at varying liquid heights for full baffles configuration. Large impellers (T/2) provide lower N_{jd} values than small impellers (T/3) because T/2 impellers more power number (N_p) (Paul et al. 2004) which means that they created more turbulence than T/3 with same speed (N). The N_{jd} values of the large impellers were close to each other which means that size of the impeller is effective than impeller type; however, for small impellers, the N_{jd} values were far away from each other depend strongly on the type of the impeller.

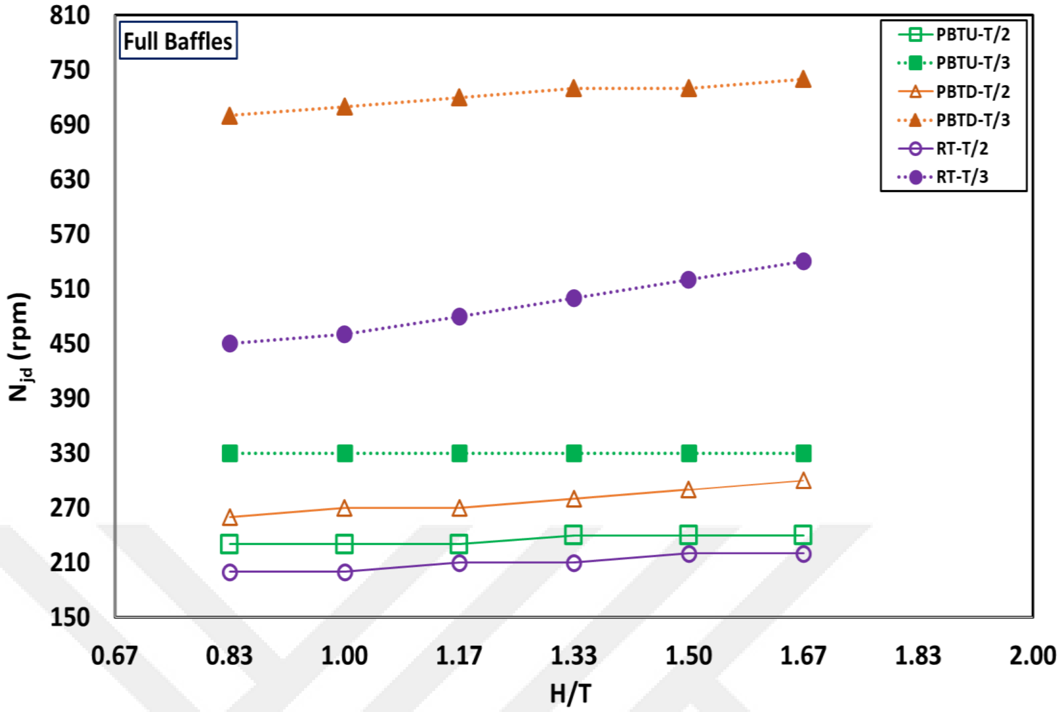


Figure 21 The effect of impeller diameter on N_{jd} with respect to liquid height for full baffles configuration

Figure 22 shows that for all combinations of impellers-full baffles at varying liquid height, P_{jd} trends were parallel to N_{jd} trends. In general, large impellers consumes less energy than small ones based on P_{jd} values. In contrast, P_{jd} of PBTU-T/3 impellers was almost equal to P_{jd} of RT-T/2 for all liquid heights and close to the P_{jd} of PBTU-T/2 which was lowest value. In the end, it can be inferred that PBTU impellers with surface baffles were superior to other types in terms of P_{jd}.

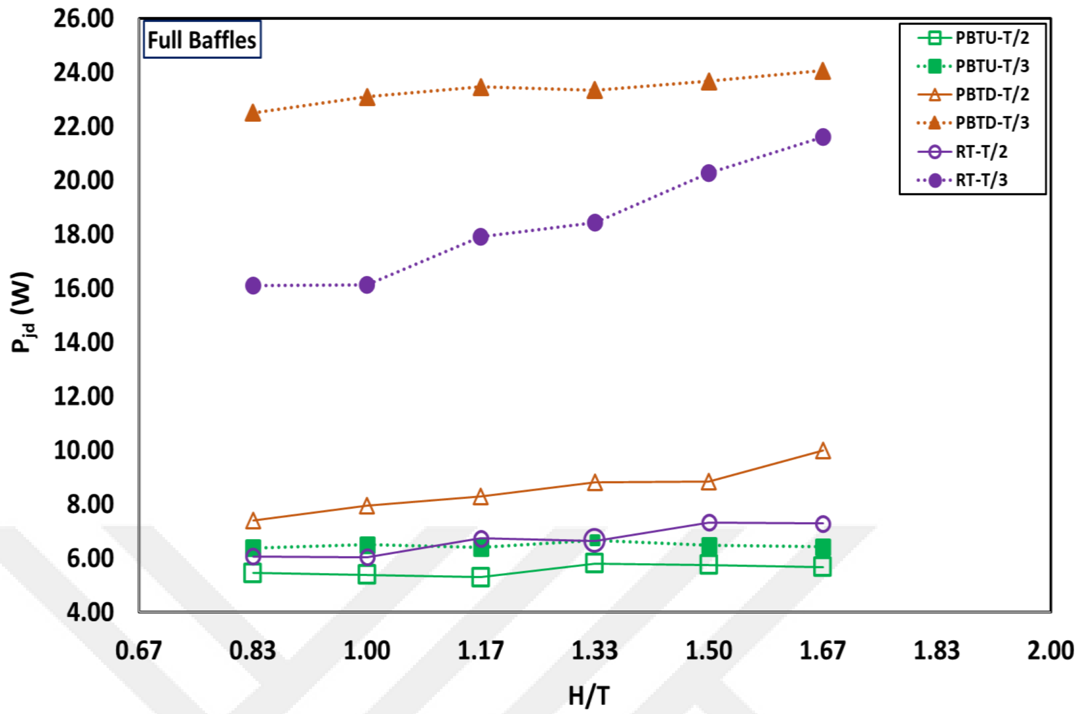


Figure 22 The effect of impeller diameter on P_{jd} with respect to liquid height for full baffles configuration

In Figure 23, at H=0.83T, H=T and H=1.17T for both sizes of the three types of impellers, CD values were the same as the liquid height and particles were fully distributed throughout the tank. Above these liquid heights, CD values for PBTU impellers increased only slightly whereas those for PBTD and RT increased considerably, even reaching the total liquid height in some cases.

In between H=1.33T to H=1.67T, using T/2 impellers resulted in the same or larger CD for PBTU and RT, but for PBTD, using T/3 impellers resulted in larger CD. As mentioned in section 4.1.2, since PBT T/2 discharges more radial while PBT T/3 discharges more axial flow, PBTD T/3 with full baffles pumped the flow downward more which contributed to CD considerably, but resulted in highest N_{jd} among all configurations and that's why PBTD T/3 gave higher CD values than PBTD-T/2.

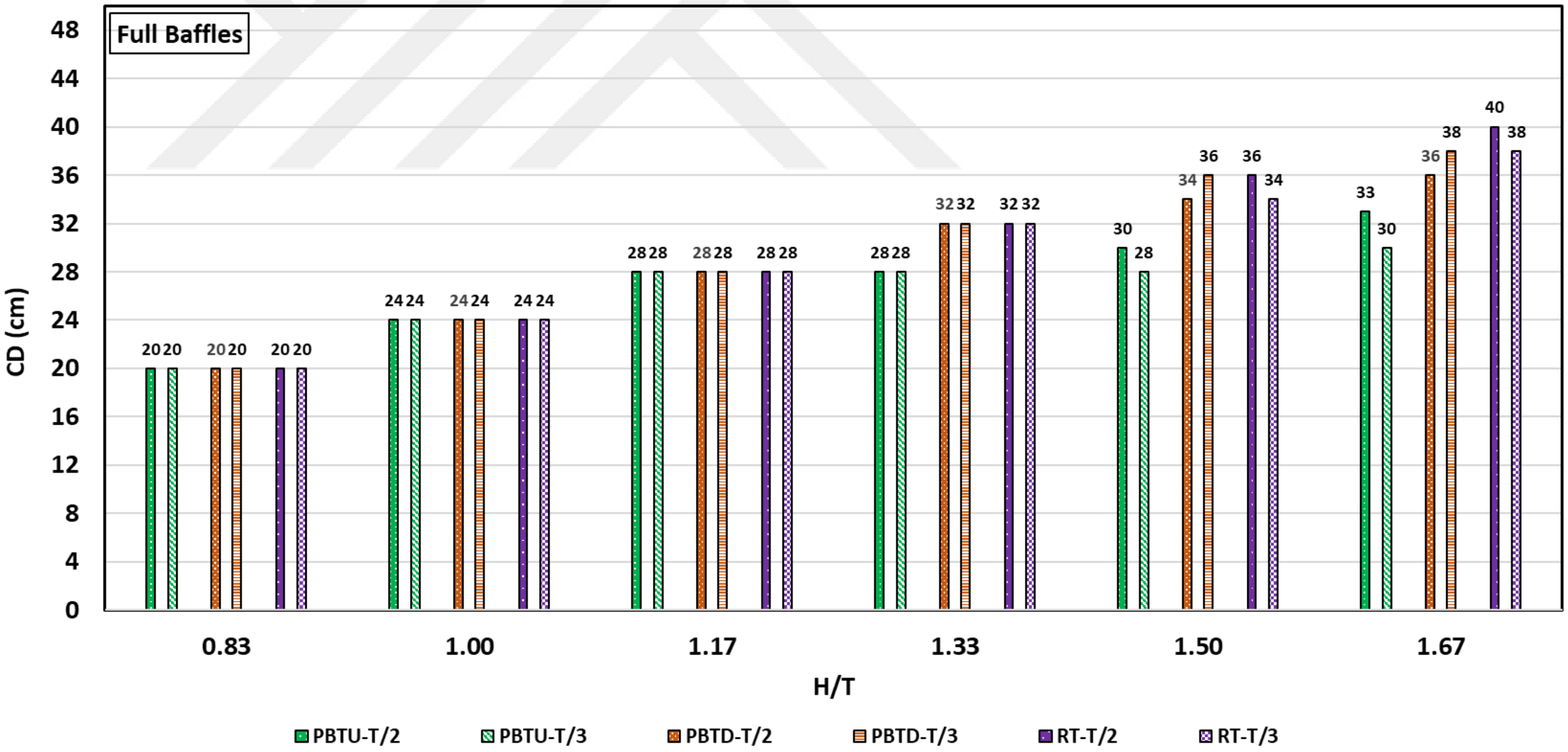


Figure 23 The effect of impeller diameter on CD with respect to liquid height for full baffles configuration where T= 24 cm

In Figure 24, like in Figure 21, at all liquid heights, using the surface baffles system, regardless of the type, impellers with large diameters (T/2) had lower N_{jd} values than impellers with small diameters (T/3). It is important to point out that RT-T/2 with surface baffles had the lowest N_{jd} among all combinations.

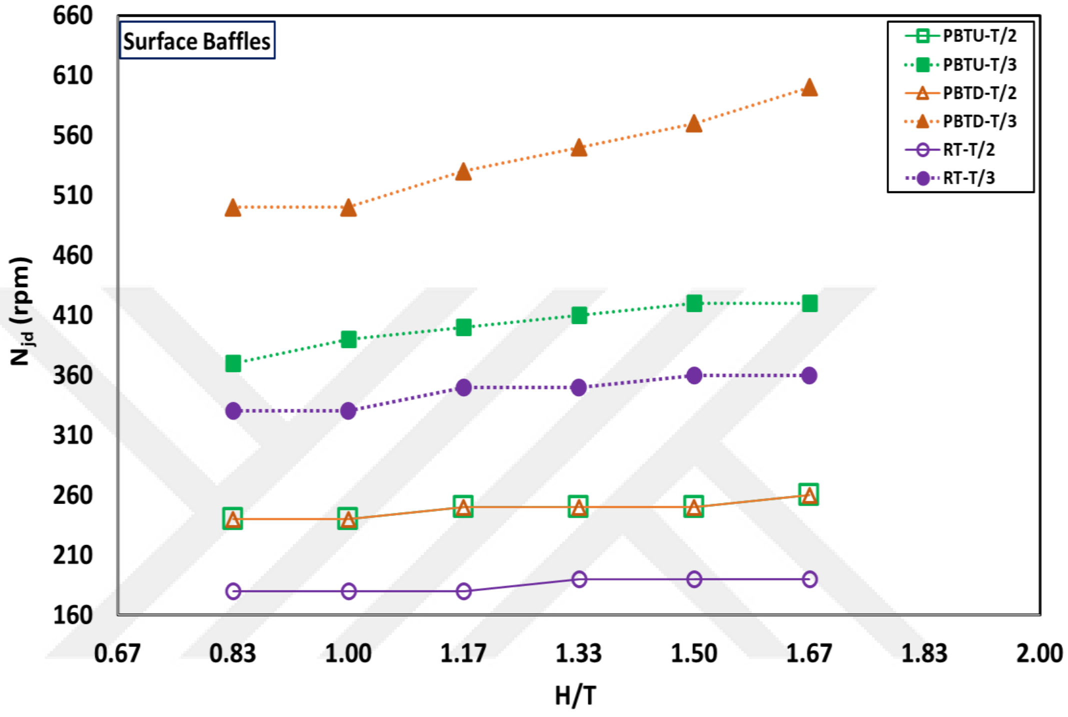


Figure 24 The effect of impeller diameter on N_{jd} with respect to liquid height for surface baffles configuration

In Figure 25, similar to Figure 22, for all liquid heights, impellers by T/2 had lower P_{jd} values than T/3 impellers. Besides, RT-T/2 with surface baffles had lowest P_{jd} among all combinations.

In the end, at varying liquid heights, a comparison of surface and full baffle perfomances in terms of P_{jd} showed that for all impellers except for PBTU-T/3, using surface baffles gave lower P_{jd} than full baffles.

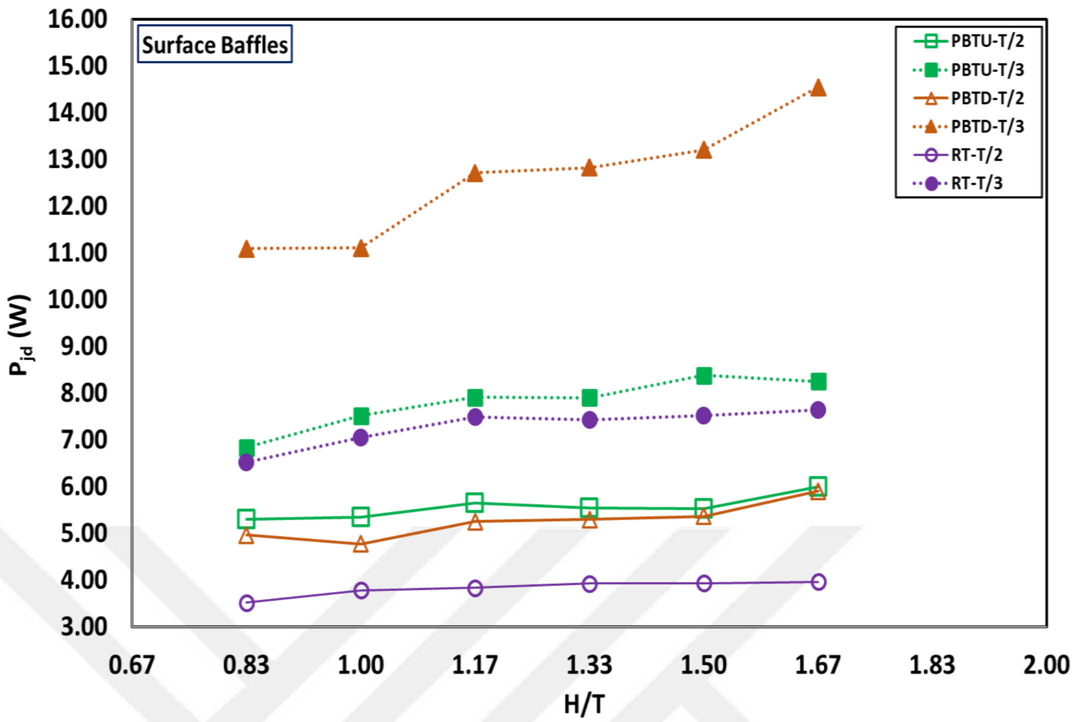


Figure 25 The effect of impeller diameter on P_{jd} with respect to liquid height for surface baffles configuration

In Figure 26, CD data for the two sizes of impellers with surface baffles is given. PBTU-T/3-surface baffles configuration showed lowest CD values among all configurations at all liquid heights while PBTD-T/3-surface baffles configuration showed highest CD values among all configurations at all liquid heights. Comparing this data with the data for the full baffles, Figure 23, it is clear that lower CD is obtained with surface baffles.

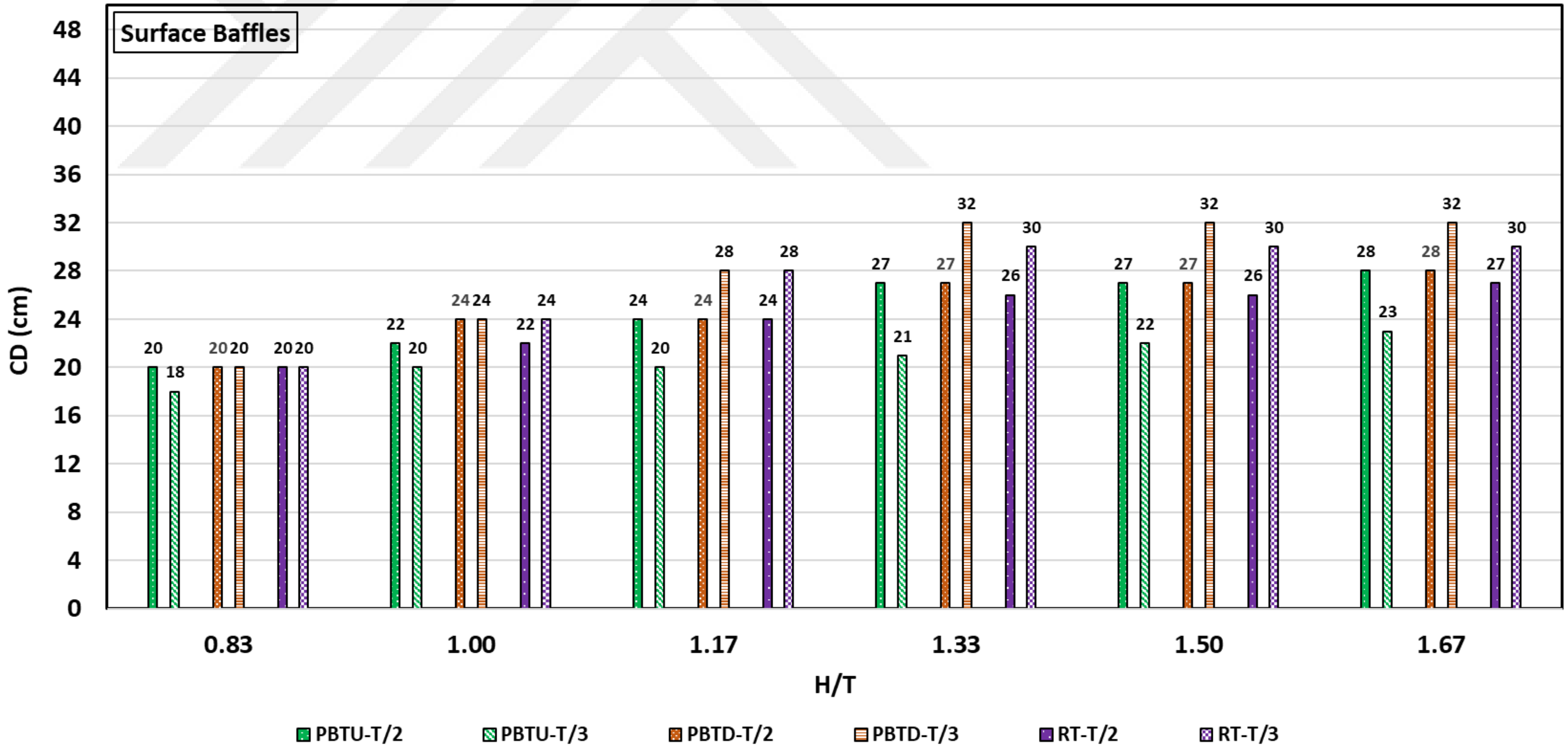


Figure 26 The effect of impeller diameter on CD with respect to liquid height for surface baffles configuration where T= 24 cm

4.2 Evaluation of N_{fd} and P_{fd} Measurements in Comparison with N_{jd} and P_{jd}

As defined in section 1.7, N_{jd} is the just drawdown speed and P_{jd} is power consumption at N_{jd}. Simirlarly, N_{fd} is the fully distributed speed where all particles are distributed throughout tank and P_{fd} is power consumption at N_{fd}. In some solid-liquid mixing operations, distribution of particles is the main objective. In drawdown operations, first, the aim is to immerse particles and then second, disperse them. For this reason, measuring N_{fd} and P_{fd} are a significant issue to observe the system capabilities and determine the needs. For example, in this system, measuring N_{fd} and P_{fd} may demonstrate the need for employing a second impeller at a given liquid height.

4.2.1 Performance of PBTU Impellers

In Figure 27 and Figure 28, for PBTU-T/2 impeller, using surface and full baffles with varying liquid heights, N_{jd}, P_{jd} , N_{fd} and Pf_d measurements were compared.

Looking at Figure 27, between H=0.83T to 1.17T, N_{jd} was equal to N_{fd} and P_{jd} was equal to P_{fd}, meaning the particles were distributed throughout the tank. But, between H=1,33 T to 1.67T, at N_{jd}, the CD was not full because N_{jd} remained nearly constant while the bottom volume of liquid was raised. Thus, the speed was insufficient and particles could not reach to the bottom. Then, the speed was increased to N_{fd} which was about 100 rpm larger than N_{jd} and the particles was distributed throughout the tank. Air entrainment from the surface to the liquid was increased at N_{fd} but, the extent of air did not affect the liquid medium and flow characteristics in the tank considerably.

In addition, at H=1.33T, H=1.5T and 1.67T, P_{fd} was found to be 64%, 100% and 128 % larger than P_{jd} respectively. For the two longest liquid heights, instead of raising the speed, implementing second impeller was suggested to be taken into consideration.

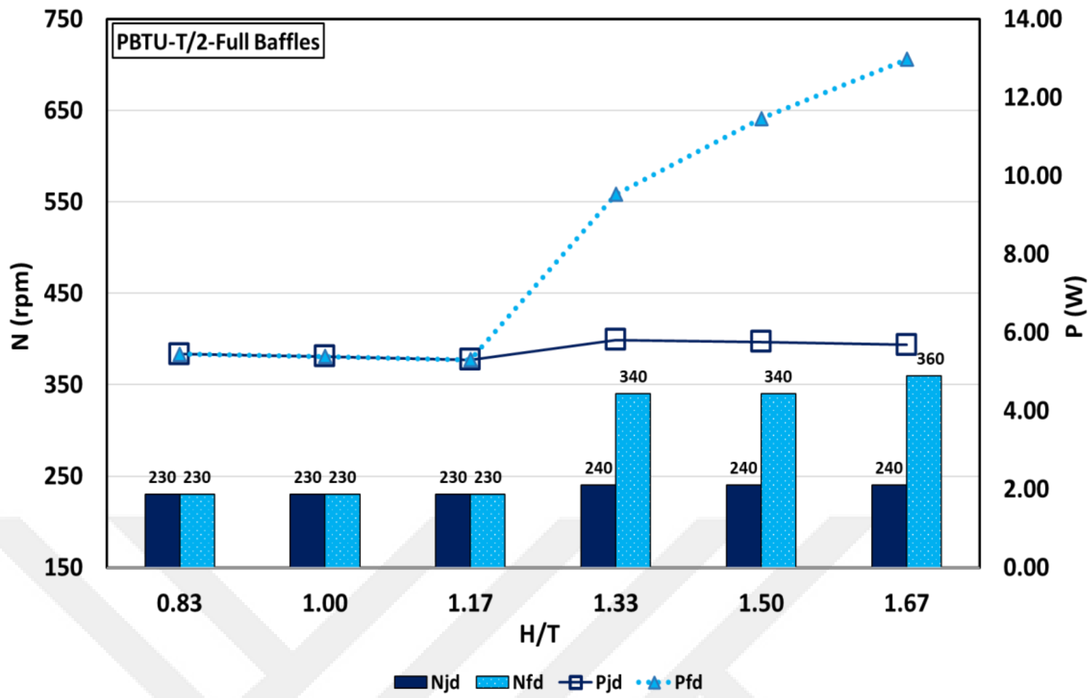


Figure 27 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTU-T/2-Full Baffles

In Figure 28, for T/2 impeller with surface baffles, N_{jd} was sufficent for full CD only for H= 0.83T. Above this, an increase in impeller speed was required to obtain full CD. At H=T and H= 1.17T, particles were distributed throughout the tank and CD becomes full at N_{fd}. But, there occurred too much air entrainment from surface which harmed the flow characteristic in tank. Hence, N_{fd} was not physically meaningful. It is, therefore, recommended to use a second impeller starting from H=T. For H ≥ 1.33T, raising the speed did not give full CD and no N_{fd} data was recorded.In the end, between H=T and H=1.67T, using second impeller was recommended.

Actually, in the beginning of raising the speed by up to 100 rpm, Cloud Depth (CD) of particles was in increasing trend, but the raising the speed more,CD of particles starts to decrease. This was maybe from the swirling movement of particles with liquid below the baffles throughout the tank. Then keeping increase in the speed, this swirling can block the axial flow to prevent complete ditribution of particles. Then, increasing the speed with great extent, in the end, enormous amount air entrained from the surface and because of the swirling movement, there occurs a whirlpool below the impeller. Thus, no N_{fd} could be recorded.

Considering the P_{jd} and P_{fd}, it can be said that at H= 0.83T, P_{jd} was equal to P_{fd} however, for H=T and H=1.17T, P_{fd} was found to be 90% and 145% larger than P_{jd} respectively. But, as declared above, since N_{fd} had no physical significance, there was no need to concern P_{fd} values between H=T and H=1.67T. Therefore, it was recommend to use a second impeller for these heights.

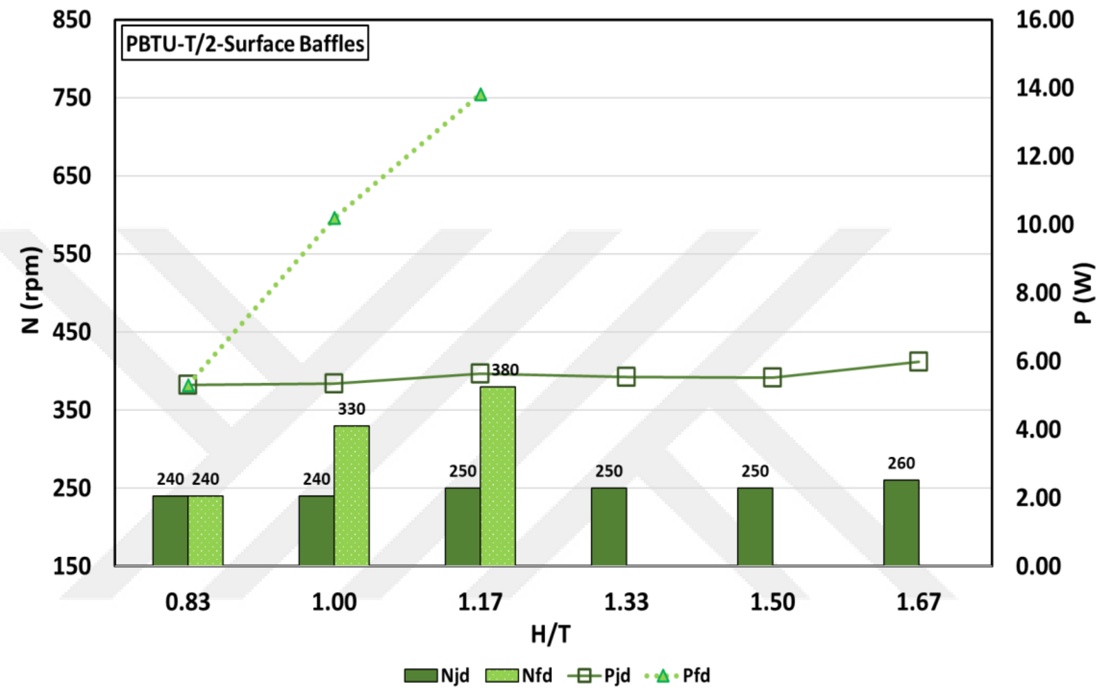


Figure 28 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTU-T/2-Surface Baffles

Figure 29 shows that a comparison of N_{jd} & P_{jd} with N_{fd} & P_{fd} at varying liquid height for PBTU-T/3 with full baffles. Similar to Figure 27, at N_{jd} between H= 0.83T and H=1.17T, CD was full. However, above this height between H= 1.33T and H=1.67T, N_{jd} did not generate required force to distribute the particles throughout the tank. Hence, at these liquid heights, N_{jd} was increased to N_{fd} successfully. However, it was logical only for N_{fd} at H= 1.33T where impeller speed was raised from 330 rpm to 400 rpm. At H=1.5T and H=1.67T, although N_{jd} remained constant, N_{fd} values were 510 rpm and 610 rpm respectively and thus, due to dramatical increase of impeller speed, too much air was entrained the system and disrupt system hydrodynamic. In the end, N_{fd} became useless.

In addition, at H=1.33T, H= 1.5T and H=1.67T, P_{fd} was 18%, 75% and 136% larger than P_{jd} in orderly. But, P_{fd} was useful at H=1.33T based on N_{fd} and visual observations. As seen, for this height, power consumption was changed only 18% and it shows that there was no need to integrate the second impeller to system. Above this height, full distribution of particles is required, the second impeller was suggested to be implemented.

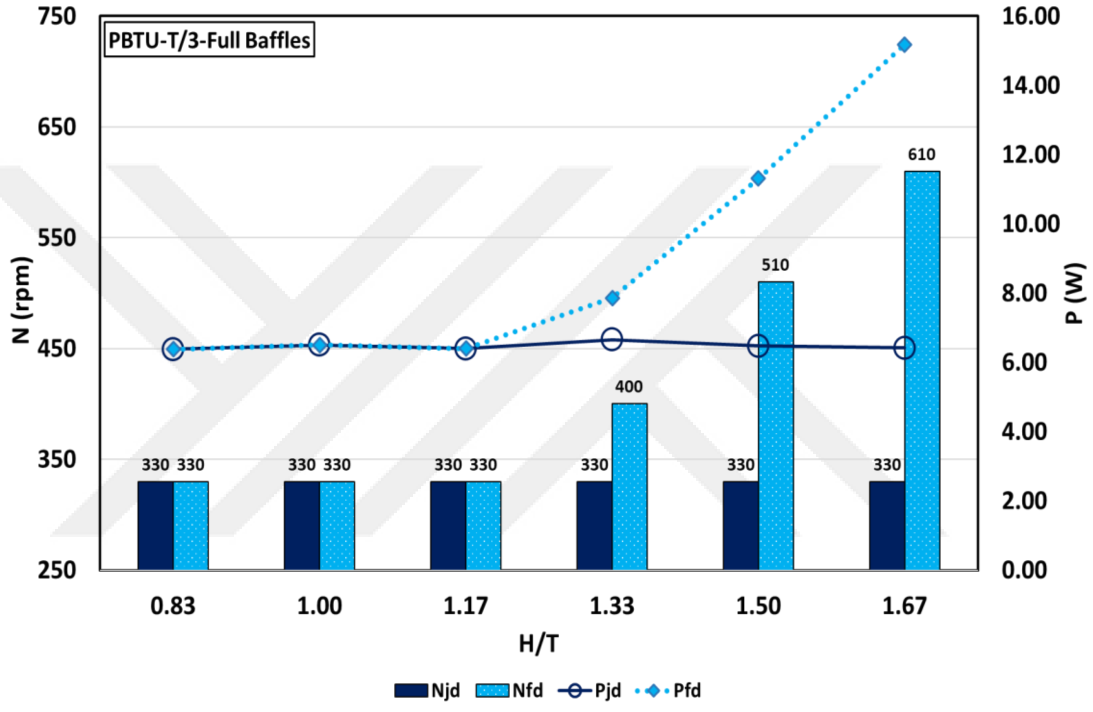


Figure 29 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTU-T/3-Full Baffles

In Figure 30, similar to in Figure 28, at H ≥ 1.33T, it was not possible to reach full CD by increasing the impeller speed. It meant that there was no N_{fd} at these heights. The reason behind this was clarified above in this subsection. Furtherly, at H ≤ 1.17T, N_{jd} was not enough to give full distribution of particles. Increasing the impeller speed ended up with N_{fd} at which CD is equal to H. For H=0.83T, N_{jd} was raised up to N_{fd} from 370 rpm 470 rpm. Although at N_{fd}, air entrained to the liquid to some extent, it was not strong enough to disrupt the flow characteristics in tank. In contrast, at H=T and H=1.17T, the differences between N_{jd} and N_{fd} were 240 rpm and 270 rpm in respectively and too much air was entrained to the liquid and it ruined the system hydrodynamics. For this reason, N_{fd} was not useful at all and in order to get full CD, second impeller should be used.

Furthermore, for H ≤ 1.17T, P_{fd} values were 44%, 125% and 159% larger than P_{jd} values from smallest H to highest H. For H=T and H=1.17T, due the difference in power consumption values, as inferred from the P_{fd} values above, it recommended to add the second impeller to obtain full CD.

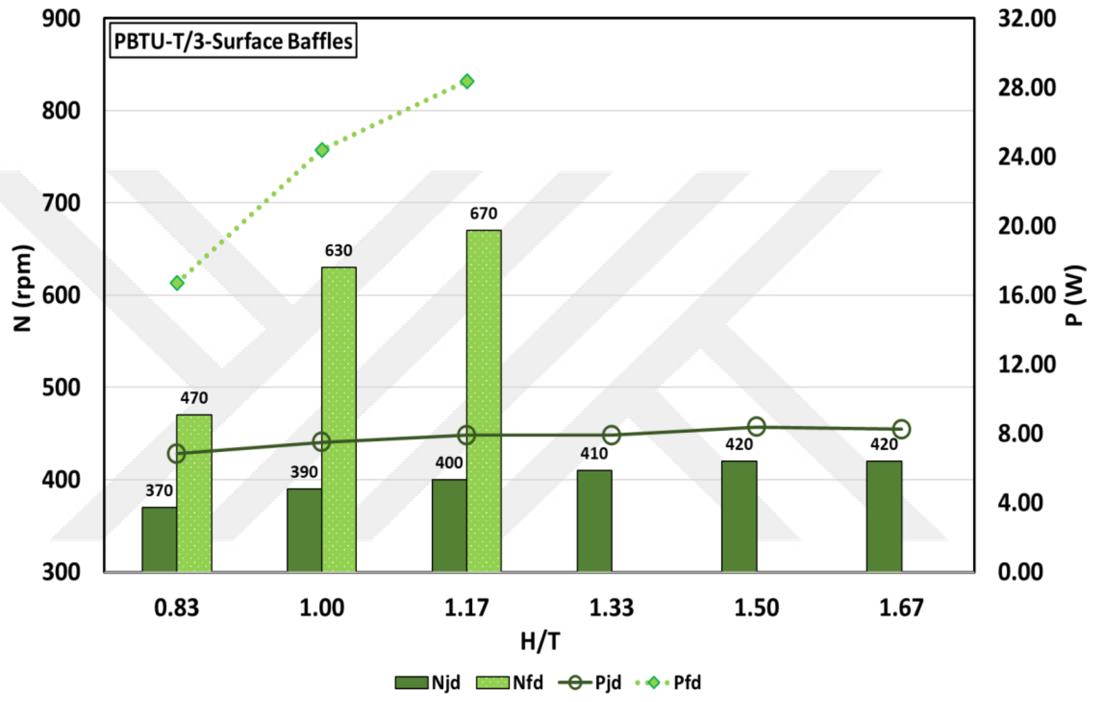


Figure 30 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTU-T/3-Surface Baffles

To sum up, PBTU-T/2 and PBTU-T/3, surface and full baffles charts have similar trends. Since the flow pumped by PBTU is towards liquid surface,at speeds above N_{jd}, it disturbs the liquid surface considerably,which results in disrupting system hydrodynamic by air entrance. Moreover, whether using surface baffles or full baffles influence the distribution of particles throughout the tank more directly. It can be inferred that baffle type was more effective than impeller diameter in terms of full distribution of particles

4.2.2 Performance of PBTD Impellers

In Figure 31 and Figure 32, for PBTD-T/2 impeller, using surface and full baffles with varying liquid heights, N_{jd}, P_{jd}, N_{fd} and P_{fd} measurements were compared.

In Figure 31, for H ≤ 1.33T, at N_{jd}, full CD was observed. For H = 1.5T and H= 1.67T, to obtain full CD, N_{jd} was increased to N_{fd} by changing with 30 rpm and 60 rpm respectively. The changes in N_{jd} were small because PBTD impeller pumped the flow towards bottom and it made particles tend to go down more which resulted in better CD and less air entrainment but higher the speed for solids drawdown.

Moreover, at H= 1.5T and H=1.67T, P_{fd} was 21% and 42% larger than P_{jd} in orderly. The difference between them was not much by power consumption and thus, raising N_{jd} to N_{fd} was more feasible than adding second impeller, which would double the power consumption.

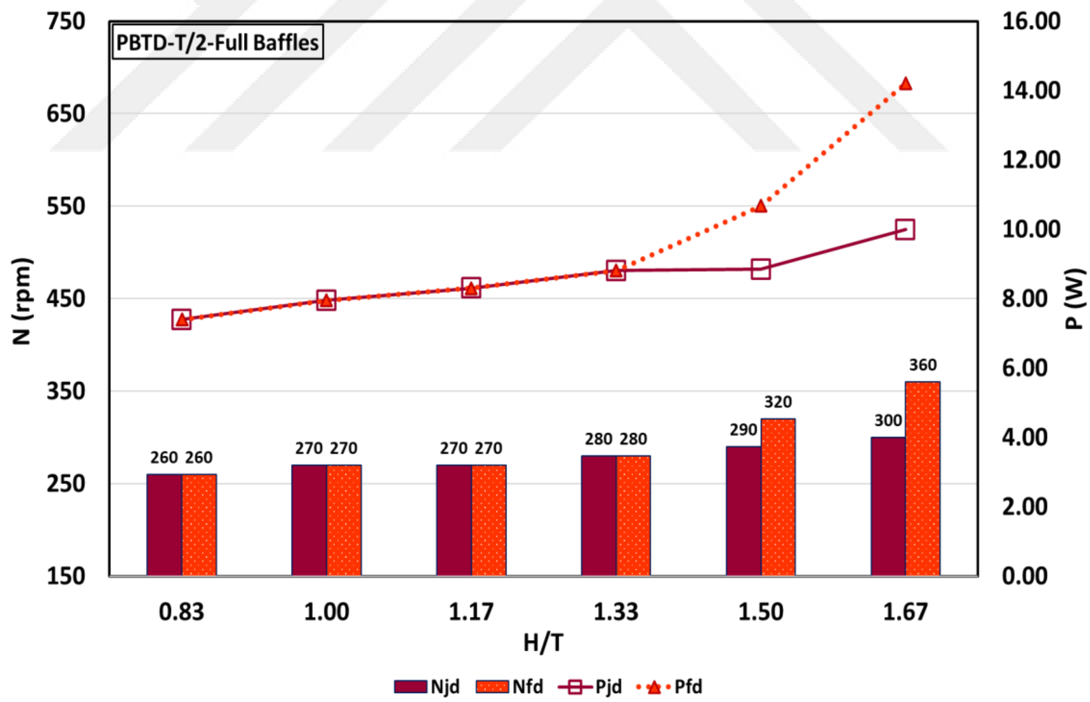


Figure 31 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTD-T/2-Full Baffles

In Figure 32, at H= 0,83 and H=T, at N_{jd}, full CD was observed. For H = 1.17T, to obtain full CD, N_{jd} was increased to N_{fd} by 90 rpm from 250 rpm to 340 rpm. It occurred air entrainment but its impact was too small to disrupt the fluid flow.

Besides, for H ≥ 1.33T, increasing the speed higher than N_{jd}, full CD was not obtained.

Moreover, at H= 1,17 T, P_{fd} was 86% larger than P_{jd} in orderly. The difference between them was considerable and thus, employing a second impeller could be tested.

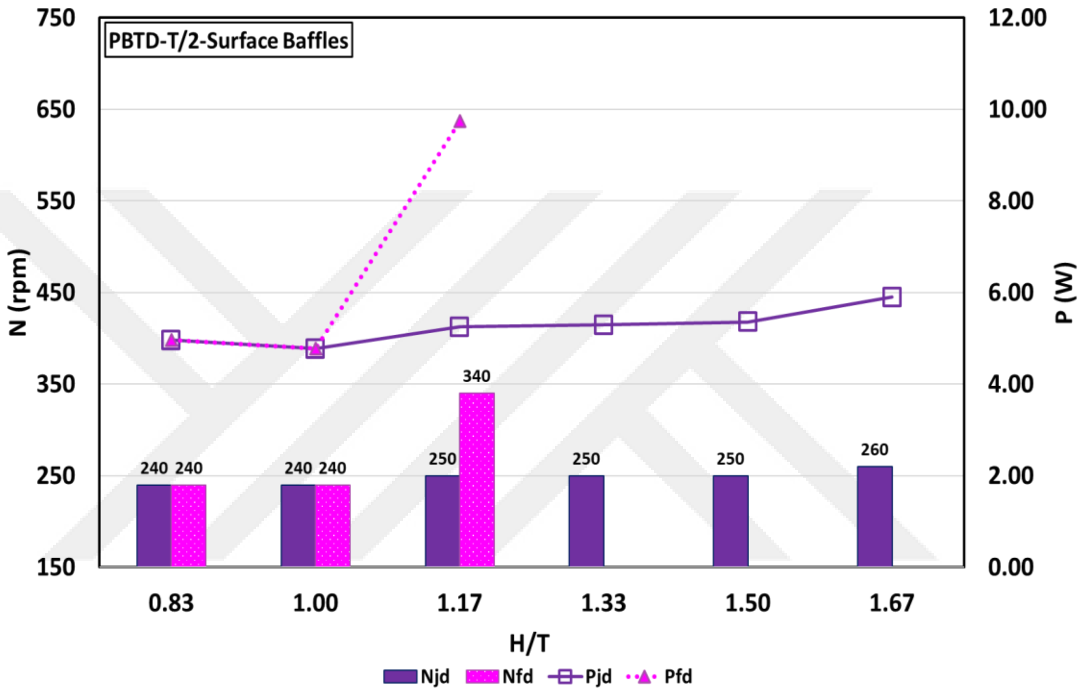


Figure 32 Ccomparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTD-T/2-Surface Baffles

In Figure 33, for all liquid heights except for H = 1.67T, full CD was achieved at N_{jd}. But, For H = 1.67T, to get full CD, N_{jd} was increased to N_{fd} by 100 rpm from 740 rpm to 840 rpm.

Moreover, at H=1.67T, P_{fd} was 22% larger than P_{jd}. Thus, the change in by power consumption was small and this impeller-baffle combination by power consumption at drawdown conditions was the highest ones among all combinations, it was not logical to use second impeller to obtain full CD.

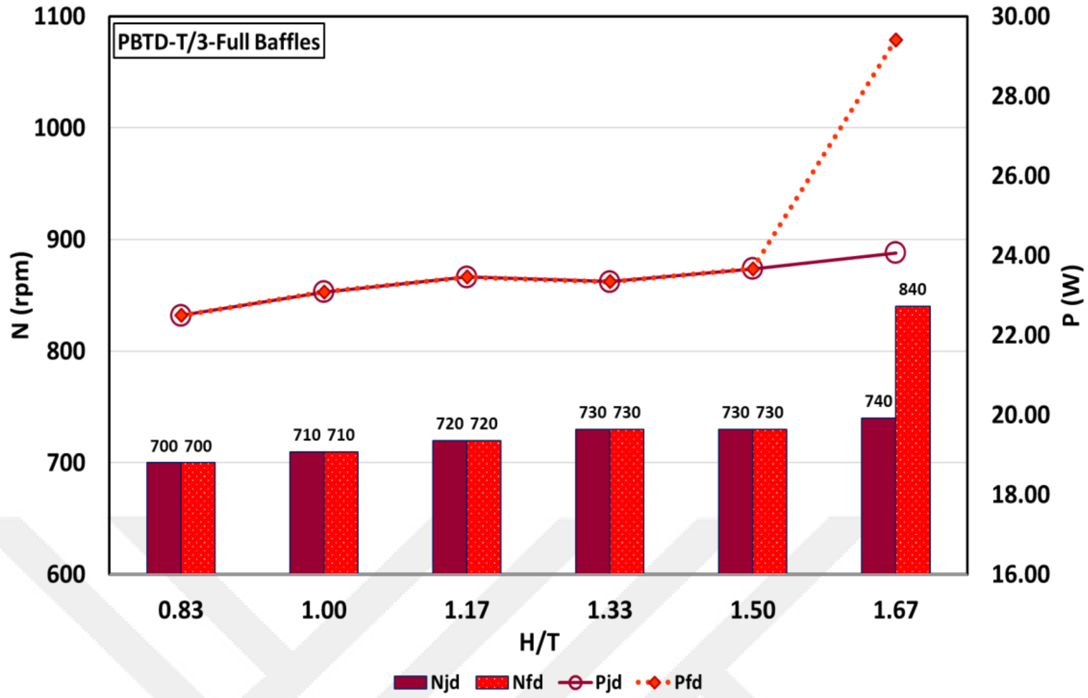


Figure 33 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTD-T3-Full Baffles

In Figure 34, at H ≤ 1.33T, N_{jd} was equal to N_{fd} while at H ≥ 1.5T, N_{fd} was not achieved because of extreme air entrainment. In order to accomplish full distribution of solid, at H ≥ 1.5T, using second impeller was a necessity. Besides, P_{jd} was equal to P_{fd} at H ≤ 1.33T. Although the power consumption of PBTD-T/3-surface baffles combination was much smaller than PBTD-T/3-full baffles, compared to other combinations, it was larger than most.

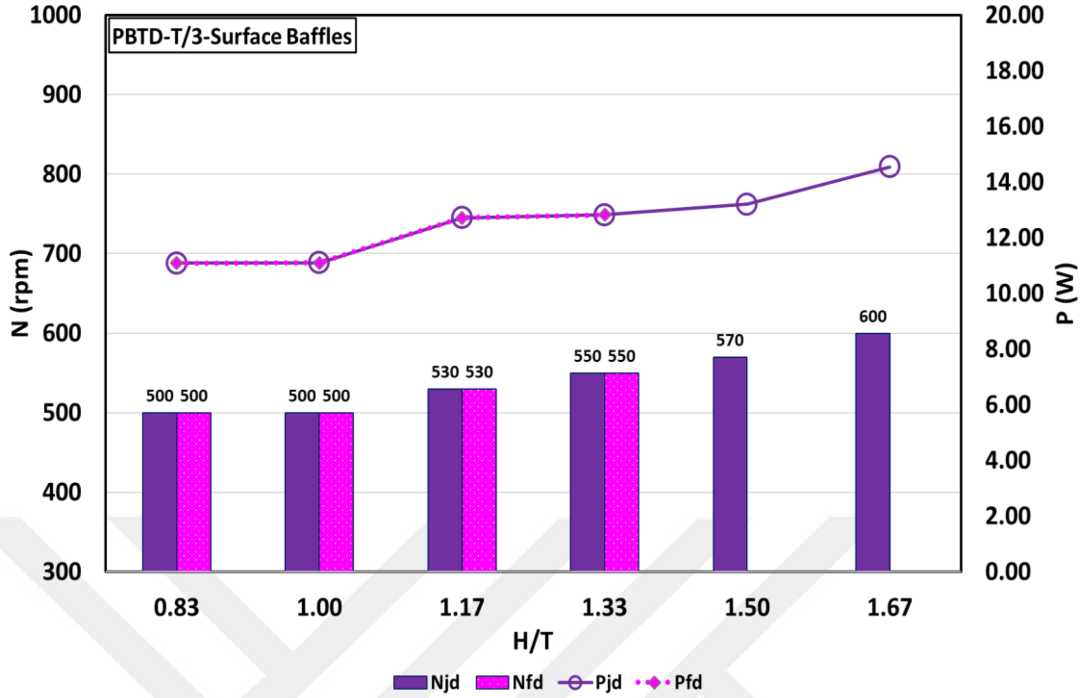


Figure 34 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for PBTD-T3-Surface Baffles

To sum up, similar to PBTU impellers, PBTU-T/2 and PBTU-T/3, surface and full baffles' charts have similar trends. Also, despite of higher power consumption, PBTD impellers were better than PBTU in terms of obtaining full CD. In contrast to PBTU, PBTD pumps the flow to downward and it provides particles distributed to tank more easily ended up with deeper particle clouds. In the end, same as PBTU impellers, it can be reached that baffle type was more effective than impeller diameter in terms of full distribution of particles.

4.2.3 Performance of RT Impellers

In Figure 35 and Figure 36, for RT-T/2 impeller, using surface and full baffles with varying liquid heights, N_{jd}, P_{jd} , N_{fd} and P_{fd} measurements were compared.

In Figure 35, it was clearly seen that for all liquid heights, N_{jd} was enough to reach full CD and it can also be named as N_{fd}. Besides, P_{jd} was equal to P_{fd}.

RT is a radial flow impeller and using with the full baffles, the secondary loops created by flow hitting the walls goes upward and downward. Thus, upward loops disturb the liquid surface and make solids drawdown while downward loop contribute to distribution of particles throughout the tank. These facts clarified the reason why N_{jd} was enough to get full CD for this combination.

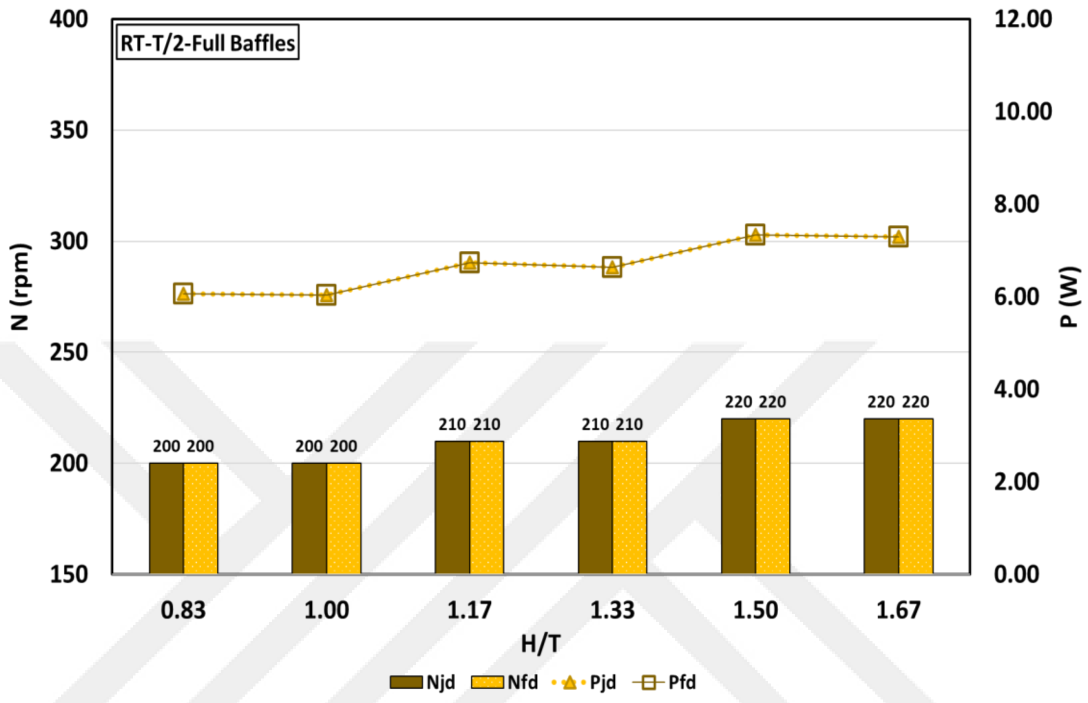


Figure 35 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for RT-T/2-Full Baffles

Figure 36 demonstrates that only at H= 0.83T, N_{jd} was enough to obtain full CD. For H= T and H=1.17T, N_{jd} values were raised to N_{fd} from 180 rpm to 220 rpm and 270 rpm respectively. For H ≥ 1.33T, full CD was not achieved which means that N_{fd} was not found because as mentioned in section 4.2.1, using surface baffles, increasing the speed with great extent made swirling movement below the baffles more strong result in blocking the axial flow to prevent complete distribution of particles.

In addition, at H=0,83, P_{fd} was equal to P_{jd} whereas at H= T and H=1.17T, P_{fd} was 54% and 133% larger than P_{jd} in orderly. H=1.17T, second impeller is suggested. For H=T, considering the change in impeller speed and power consumption, it can be said that there is no need to use second impeller. Moreover, H ≥ 1.33T, it was recommended to integrate second impeller to accomplish full CD.

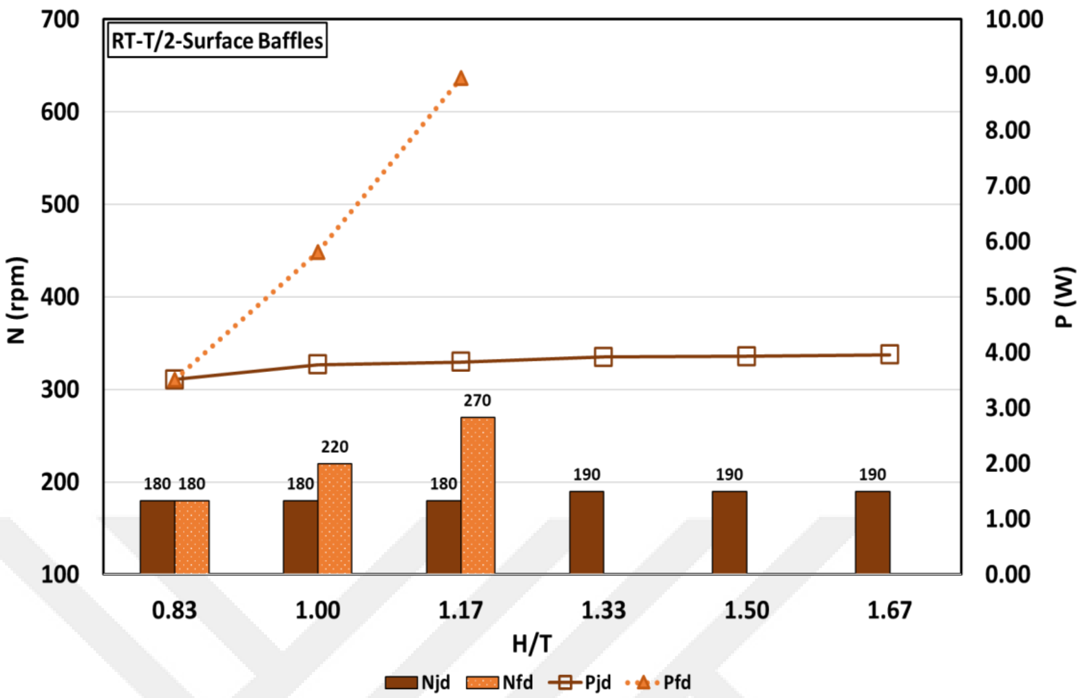


Figure 36 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for RT-T/2-Surface Baffles

In Figure 37, similar to RT-T/2- full baffles performance , RT-T/3 impeller with full baffles was good at solids drawdown and particle distribution. For H ≤ 1.33T, full CD was observed at N_{jd} whereas for H ≥ 1.5T, increasing N_{jd} for 40 rpm was enough to achieve full CD.

Furtherly, for H ≥ 1.5T, P_{fd} was 15% larger than P_{jd} for both H. Considering rhe change in speed and power consumption, full CD was easily obtained and so, using second impeller could not even come into question.

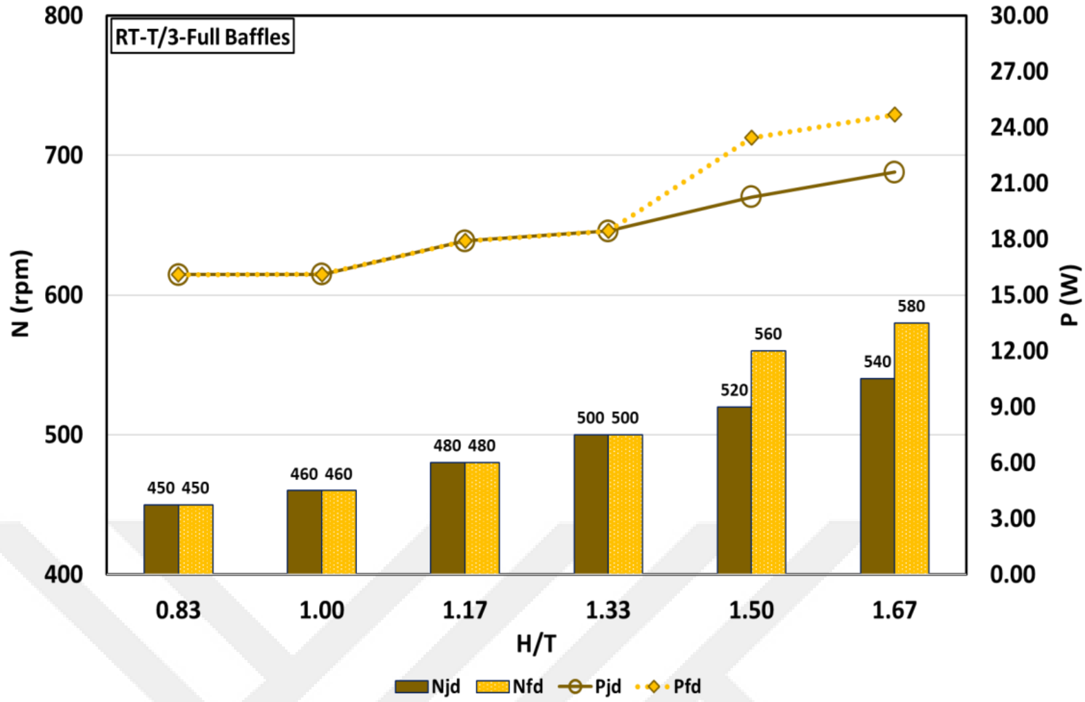


Figure 37 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for RT-T/3-Full Baffles

Figure 38 indicates that for $H \leq 1.17T$, at Njd, full CD was achieved however, for $H \geq 1.33T$, increasing the speed did not result in obtaining full CD and so, N_{fd} was not found due to consequences of using surface baffles as mentioned in this section above. In order to reach full CD, it was necessary to use second impeller at these liquid heights. Besides, at $H \leq 1.17T$, P_{fd} was equal to P_{jd} and above these heights, there was no P_{fd} due to inexistence of N_{fd}.

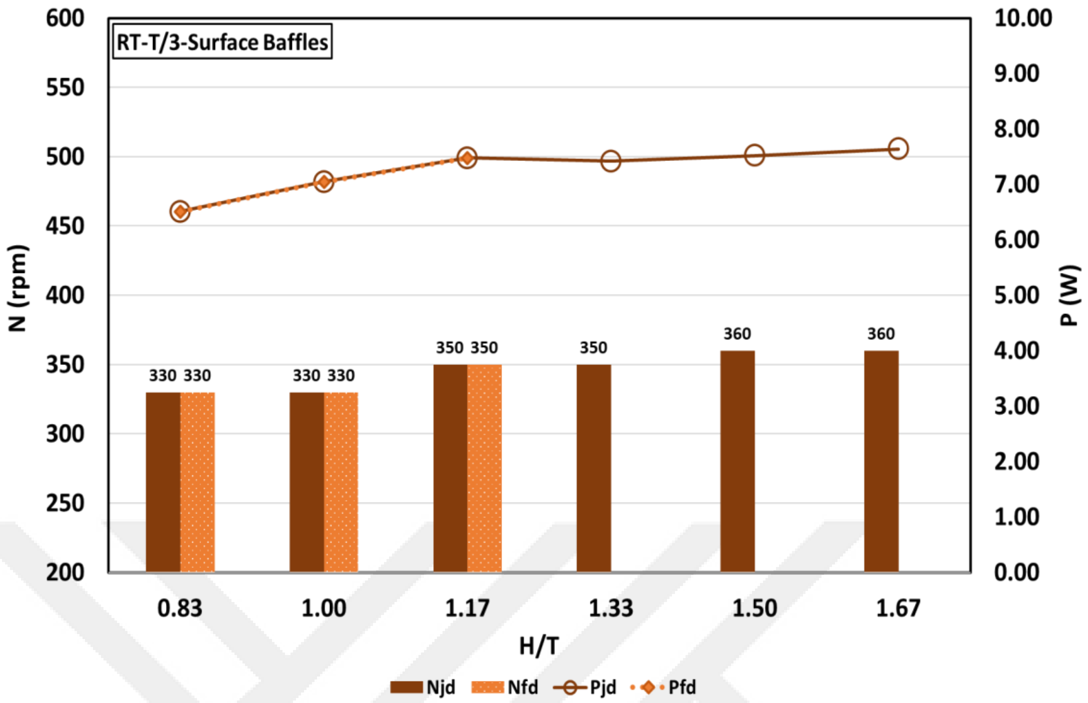


Figure 38 Comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd} for RT-T/3-Surface Baffles

In summary, similar to the PBTU and PBTD impellers, RT-T/2 and RT-T/3, surface and full baffles charts have similar trends. Especially, it can be said that at varying liquid heights,in general, RT with full baffles combinations gave best performances among all in terms of obtaining full CD. In the end, same as PBTU and PBTD impellers, it can be reached that baffle type was more effective than impeller diameter in terms of full distribution of particles.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Drawdown of floating solids is one of the significant study field in industrial solid-liquid mixing processes. It provides increasing solid-liquid contact area, which is crucial for mass transfer and reaction, with immersion of particles from liquid surface. Also, distribution of drawn down particles is an important issue due to its contribution to increase in solid-liquid contact area. Hence, understanding of solids distribution and drawdown has an important role to have an efficient system design. In addition to this, choosing an appropriate system geometry while determining design parameters are performed together to create an accurate approach on this subject. In literature, there is no study addressing the effect of liquid height on drawdown and distribution solids for single impeller system. Also, there is no certain criteria on examining the competence of the system for a single impeller on solids drawdown and solids distributions. To clarify this situation while considering the system geometry, the aim of this study was to investigate the effect of liquid height and baffle geometry on drawdown of floating solids in stirred tanks. The design parameters were N_{jd}, P_{jd}, CD, N_{fd} and P_{fd}. The liquid height was varied between 0.83T (20 cm) and 1.67T (40 cm) increased by 0,17T (4 cm). Also, to understand effect of system geometry on drawdown and distribution, surface and full four baffles, impellers in diameter T/3 (8 cm) and T/2 (12 cm), different types of conventional impellers, PBTU, PBTD and RT, were used in experiments.

Outcomes of this thesis are given in following:

- In general, Increasing the liquid height from H=0.83T to H=1.67T resulted in a slight increase in N_{jd} and P_{jd} for all baffle and impeller configurations. The reason behind this can be explained with the fact that when increasing liquid height by keeping other parameters constant, there is a larger volume of liquid that needs to be put in motion and thus, some of energy provided by the impeller are consumed by this volume and solids drawdown needs more energy.

- Increasing the liquid height from H=0.83T to H=1.67T generally resulted in an increase in CD for all baffle and impeller configurations. Maybe it is related to the extra volume created providing new movement space for the particles. Besides, the increasing rates of CD changes with respect to impeller-diameter-baffle combinations.
- For all impellers at varying liquid heights, combining an impeller with the full baffles gave more CD than combination of same impeller with surface baffles.
- Considering only CD while N_{jd} and P_{jd} were not taken into account, It was suggested to use RT and PBTD impellers.
- For all combinations, based on P_{jd}, using surface baffles were better than using full baffles.
- Using surface baffles provided lower N_{jd} for PBTD and RT impellers.
- Considering only P_{jd}, using full baffles, PBTU impellers were better than others due its flow pattern disturbing the liquid surface more directly thanks to its upward axial component. whereas using surface baffles, Impellers by T/2 were best.
- T/2 impellers gave lower N_{jd} and P_{jd} than T/3 impellers for all baffles and liquid heights.
- For all baffle configurations and impellers, for all liquid heights, RT-T/2-surface baffles combination gave minimum N_{jd} among all configurations whereas PBTD-T/3-full baffles combination had the highest N_{jd} values.
- RT-T/2 impellers had minimum values of N_{jd} because thanks to its larger size and its radial flow pump, they generated more turbulence on liquid surface.
- Considering full distribution of particles, targetting to obtain full CD for all liquid heights, using full baffles, RT impellers were best concerning P_{fd}.
- In the overall, at H≥1.17T, for all impellers except for PBTD-T/3 at H=1.17T, it is not recommended to use surface baffles, it is not recommended to use

surface baffles because it is impossible to reach N_{fd} due to swirling movement below the baffles which blocks axial flow at some speed larger than Njd around 100 rpm.

- In order to get full CD, in case of inexistence of N_{fd} and if too much air was entrained the system at N_{fd}, using a second impeller was suggested.
- Adding a second impeler doubles the power consumption; therefore, when P_{fd} is larger than P_{jd} by %100 and higher, use of a second impeller is recommended. If the difference was between %50 to %100, further tests are recommended to make the decision. If it was below the 50%, there is no need for implementing second impeller.
- From comparison of P_{jd} & N_{jd} with P_{fd} & N_{fd}, for all combinations, it can be concluded that baffle type was more effective than impeller diameter in terms of full distribution of particles.

5.2 Future Work

In this thesis, for a single impeller system, the effect of liquid height between 0.83T to 1.67T on solids drawdown by N_{jd},P_{jd},CD,N_{fd} and P_{fd} by using the surface and full four baffles was investigated and clarified. This study can be expanded in many respects. Works having potential to enlighten uncertain subjects are suggested and summarized as the following:

- The experiments should be performed at larger scales as this will contribute to applicability of this findings for industrial operations having large scales.
- Higher solid loadings and fine floating particles was recommended to use to widen the applicability area of this topic with same methods.
- Increasing the liquid height, the effect of impeller submergence (S) on N_{jd}, P_{jd}, CD, N_{fd} and P_{fd} was proposed to investigate to find optimum position for all impeller type and diameter.
- Using different baffle configurations is recommended in the next studies as an improvement because it has remarkable influence on N_{jd},P_{jd},CD, N_{fd} and P_{fd}.

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