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โดยกระบวนการโคอะเลสเซอร์

นาย ณัฐวิญญ์ ชวเลิศพรศิยา

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ENHANCEMENT OF CUTTING OIL WASTEWATER TREATMENT
AND SEPARATION BY COALESCER PROCESS

Mr. Nattawin Chawaloesphonsiya

ศูนย์วิทยทรัพยากร
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ณัฐวิญญ์ ชวเลิศพรศิยา : การเพิ่มประสิทธิภาพการบำบัดและแยกอนุภาคน้ำมันจากน้ำเสียปนเปื้อนน้ำมันตัดโดยกระบวนการโคอะเลสเซอร์ (ENHANCEMENT OF CUTTING OIL WASTEWATER TREATMENT AND SEPARATION BY COALESCER PROCESS)
อ. ที่ปรึกษาวิทยานิพนธ์หลัก: อาจารย์.ดร.พิสุทธิ์ เพียรมนกุล, 142 หน้า

งานวิจัยนี้ได้ทำการศึกษาการบำบัดน้ำเสียปนเปื้อนน้ำมันสังเคราะห์ โดยใช้น้ำเสียปนเปื้อนน้ำมันตัดความเข้มข้น 1 กรัมต่อลิตร ด้วยกระบวนการร่วมระหว่างอุปกรณ์โคอะเลสเซอร์และถังตกตะกอน โดยมีวัตถุประสงค์เพื่อศึกษากลไกการทำงาน ประสิทธิภาพและปัจจัยต่าง ๆ ที่มีผลต่อประสิทธิภาพการบำบัดน้ำเสียปนเปื้อนน้ำมันด้วยอุปกรณ์โคอะเลสเซอร์ โดยประยุกต์ใช้ตัวกลางโพลีโพรพีลีนรูปร่างที่มีรูปร่างแตกต่างกันได้แก่ ชนิดเม็ดกลม ชนิดเส้นใย และชนิดหลอดกลวง รวมถึงการพัฒนาเพื่อเพิ่มประสิทธิภาพด้วยการวางตัวกลางแบบขั้นตอน การหมุนเวียนน้ำเสีย และการเพิ่มประสิทธิภาพของถังตกตะกอน

จากผลการทดลองพบว่า วัสดุโพลีโพรพีลีนมีความเหมาะสมในการใช้เป็นตัวกลางโคอะเลสเซอร์เนื่องจากมีความไม่ชอบน้ำ โดยมีค่ามุมสัมผัสกับน้ำมันในน้ำโดยเฉลี่ยเท่ากับ 68 องศา สำหรับตัวกลางทั้ง 3 รูปแบบ นอกจากนี้ยังพบว่า ความสูงของชั้นตัวกลางและความเร็วการไหลของน้ำเสียมีผลต่อประสิทธิภาพการบำบัด เช่นเดียวกับรูปร่างและความพรุนของชั้นตัวกลาง โดยประสิทธิภาพการบำบัดที่สูงที่สุดได้จากการใช้ตัวกลางชนิดหลอดกลวงหนา 10 เซนติเมตร ที่ความเร็วการไหล 2 เซนติเมตรต่อวินาที เท่ากับร้อยละ 43.64 ขนาดของอนุภาคน้ำมันในรูปเส้นผ่านศูนย์กลางเฉลี่ย และเส้นผ่านศูนย์กลางเฉลี่ยแบบซอร์เทอร์ของน้ำเสียที่ผ่านตัวกลางโคอะเลสเซอร์มีขนาดใหญ่กว่าในน้ำเสียที่เข้าระบบ ซึ่งส่งผลให้อนุภาคน้ำมันสามารถแยกตัวออกจากน้ำได้เร็วขึ้น จากการศึกษาเพื่อเพิ่มประสิทธิภาพของโคอะเลสเซอร์ด้วยการวางตัวกลางแบบขั้นตอน (Step-bed configuration) และการหมุนเวียนน้ำเสีย พบว่ามีผลกระทบต่อประสิทธิภาพที่แตกต่างกันในตัวกลางแต่ละชนิด โดยพบว่าประสิทธิภาพของตัวกลางแบบเส้นใยเมื่อประยุกต์ใช้แนวทางเพิ่มประสิทธิภาพทั้งสองวิธีเพิ่มสูงขึ้น ในขณะที่ประสิทธิภาพการบำบัดไม่มีการเปลี่ยนแปลงสำหรับตัวกลางแบบเม็ดกลม แต่สำหรับตัวกลางชนิดหลอดประสิทธิภาพกลับมีค่าลดลง ซึ่งเป็นการยืนยันผลกระทบจากรูปร่างของตัวกลางต่อประสิทธิภาพการบำบัด จากการศึกษาการเพิ่มประสิทธิภาพโดยการวางตัวกลางหลายชนิดแบบขั้นตอนให้ประสิทธิภาพสูงที่สุดที่ร้อยละ 59.12 นอกจากนี้ จากผลการทดลองสามารถสร้างความสัมพันธ์ของการตกตะกอนแบบโคต เพื่อช่วยในออกแบบถังตกตะกอนที่มีประสิทธิภาพ การประยุกต์ใช้สมการของ Ergun เพื่อคำนวณขนาดเส้นผ่านศูนย์กลางแท้จริงของตัวกลางพบว่าค่าที่ได้มีค่าใกล้เคียงกับขนาดจริงสำหรับตัวกลางชนิดเม็ดกลม นอกจากนี้ การใช้โมเดลซึ่งประยุกต์จากสมการประสิทธิภาพการกรองและการตกตะกอนเพื่ออธิบายผลกระทบของสภาวะการเดินระบบ พบว่าผลกระทบจากความเร็วการไหล และความสูงของชั้นตัวกลางต่อประสิทธิภาพสอดคล้องกับผลจากการทดลอง โดยจากการประยุกต์ใช้โมเดลนี้กับผลการทดลองการบำบัดน้ำเสียปนเปื้อนน้ำมันตัดด้วยเส้นใยสแตนเลส พบว่าความสัมพันธ์ที่สร้างขึ้นจากโมเดลเป็นเส้นตรง ประสิทธิภาพจากการตกตะกอนมีค่าสูงกว่าประสิทธิภาพของโคอะเลสเซอร์พิจารณาในรูปของ $\alpha\eta_T$ ดังนั้น สามารถสรุปได้ว่าการเดินระบบที่สภาวะเหมาะสมสำหรับถังตกตะกอนจะเพิ่มประสิทธิภาพการแยกน้ำเสียปนเปื้อนน้ำมันตัดโดยรวมออกจากน้ำได้มากกว่าการปรับปรุงประสิทธิภาพที่ตัวกลางโคอะเลสเซอร์

สาขาวิชา การจัดการสิ่งแวดล้อม	ลายมือชื่อนิสิต ณัฐวิญญ์ ชวเลิศพรศิยา
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5187529620 : MAJOR ENVIRONMENTAL MANAGEMANT
KEYWORDS: CUTTING OIL EMULSION/ COALESCER

NATTAWIN CHAWALOESPHONSIYA: ENHANCEMENT OF CUTTING OIL WASTEWATER TREATMENT AND SEPARATION BY COALESCER PROCESS. THESIS ADVISOR: PISUT PAINMANAKUL, Ph.D., 142 pp.

The objective of this work is to study the treatment and separation of synthetic oily wastewater with 1 g/l cutting oil in water by combined process of coalescer and decantation. Three shapes of polypropylene (PP) materials were applied as coalescing medium including granular, fibrous, and tubular PP at different operating conditions. Moreover, the concept of stage coalescer (step bed configuration), liquid recirculation, and improvement of decantation performance were applied for increasing the overall treatment efficiency. Finally, the simple model will be proposed and applied for providing a better understanding on the cutting oily-wastewater treatment efficiency obtained with the combined coalescer and decantation processes.

The results shown that different shapes of polypropylene (PP) was hydrophobic material and can be used as coalescing medium with contact angle of 68 degrees in average. It can be noticed that the flow velocity and bed height can affect the overall treatment efficiency of the process: the highest treatment efficiency (43.64%) was obtained from 2.0 cm/s flow velocity and 10 cm bed height with tubular PP medium. It also found that the size of oil droplets was increased after passing coalescing medium, which caused the increasing of rising velocity of droplet, thus the separation was enhanced. Furthermore, by applying several methods with the conventional process, it was found that the effects of stage coalescer and wastewater recirculation application were different due to the medium types. The treatment performance of fibrous medium was enhanced, while unchanged and negative effect can be observed in case of granular and tubular PP, respectively. The concept of mixed bed by varying porosity for each bed was applied and found that the mixed step bed provided highest treatment efficiency at 59.12%. From the experimental results, the discrete settling relationship can be created and used for designing effective decanter. In addition, the simple model was applied for defining occurred treatment mechanisms. Ergun's equation was applied to determine the actual diameter (D_{actual}) of coalescing medium. The simple model combining filtration efficiency equation with decantation was used to investigate the effects of operating condition, which provided the similar trend with the experimental results. Moreover, by validating this model with the treatment of cutting oil emulsion with fibrous stainless steel medium, it was found that the efficiency obtained from decantation was comparatively much higher than the efficiency in term of $\alpha\eta_T$. The treatment efficiency of process might be improved by adjusting the optimal operating condition for decantation. However, this model was not considered the effect of turbulence in the process.

Field of Study: Environmental Management Student's Signature..Nattawin Chawaloesphonsiya

Academic Year: 2009 Advisor's Signature....Pisut P.

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LIST OF SYMBOLS

v_T	=	Terminal settling or rising velocity of particles (m/s)
$\Delta\rho$	=	Density difference between disperse and continuous phase (kg/m^3)
g	=	Gravitational acceleration (m/s^2)
D_E	=	Diameter of disperse phase particle (m)
μ	=	Continuous phase viscosity (Pa.s)
η_S	=	Sedimentation efficiency
v_0	=	Flow velocity of wastewater (m/s)
η_I	=	Interception efficiency
D_P	=	Collector diameter (m)
η_D	=	Diffusion efficiency
K	=	Boltzmann's constant (kg·m2/K·s)
T	=	Absolute temperature of continuous phase (K)
η_T	=	Single collector efficiency
C_0	=	Initial concentration of wastewater (mg/l)
A_0	=	Cross-sectional area of bed (m^2)
ε	=	Porosity of bed
α	=	Attachment efficiency of oil droplets on collector
C	=	Final concentration of wastewater (mg/l)
H	=	Height of medium bed (m)
a_v	=	Specific surface area (m^{-1})
ψ	=	Sphericity of collector
D_{eq}	=	Equivalent diameter of flow channel (m)
r_H	=	Hydraulic radius (m)
ρ	=	Continuous phase density (kg/m^3)
ΔP	=	Pressure loss from flow through bed (Pa)
γ_{CG}	=	Critical surface tension of material (mN/m)
γ_{WC}	=	Interfacial tension between water and medium (mN/m)
γ_{CO}	=	Interfacial tension between oil and medium (mN/m)
θ	=	Contact angle between oil and medium in water (degrees)
γ_{OG}	=	Surface tension of oil (mN/m)

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γ_{WG} = Surface tension of water (mN/m)

t = Retention time of wastewater in decanter (min)

H = Height of decanter (m)

P = Penetration

D_{actual} = Actual diameter of collector (m)

η_{Decant} = Efficiency of decanter

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CHAPTER I
INTRODUCTION

1.1 State of problems

Nowadays, wastewater is the most concerned environmental problems, since it causes various severe effects on environment and human being. Wastewater can be generated from many sources, but typically are from community and industry. The characteristics of wastewater depend on types of contaminant, which resulting in difference of property and toxicity.

"Oil" is one of the important contaminant in water, which usually called as oily wastewater. Oily wastewater can be generated from many sources; for example, household (i.e. palm oil), transportation (i.e. gasoline and lubricants), and also industry (i.e. cutting oil). Oily wastewater is normally considered as hazardous waste, since it can contain toxic substances; such as Poly Aromatic Hydrocarbon (PAHs), which was categorized as mutagenic and carcinogenic substances (Tri, 2002). Furthermore, it should be noted that oily wastewater is rarely degraded by biological process. Oil usually contaminate in water in four forms, including (1) Oil film on water surface; (2) soluble oil in water; (3) oily emulsion with surfactants; and (4) oily emulsion without surfactant (Aurelle, 1985). From these types, oily emulsion with surfactant is the most difficult to handle due to its stability, resulting in the inefficient oil separation.

In order to treat oily wastewater, physical processes are selected as the primary treatment for separating oil content from wastewater before transferred to biological treatment. The advantages of physical process are its effectiveness, less time consumption, and economize on investment. Moreover, separated oil from physical process can be either recovered or applied as fuels. Many techniques have been proposed for treating oily wastewater; for example, chemical processes (i.e. coagulation-flocculation and sorption), and physical process, such as decantation, flotation, and coalescence.

The contaminated oil in water is usually detected in form of oily emulsion with surfactant (called as “oily emulsion” or “stabilized emulsion” in this study), since surfactants are generally used for oil cleaning. This type of emulsion has high stability and contains very small oil droplets that are difficult to physically separate according to Stoke’s law (Aurelle, 1985). For that reason, the high efficient equipment is required.

Cutting oil is one of the broad used oil in industry, since it can be applied in every machining work (i.e. cutting, drilling, and boring). The components of cutting oil are mineral oils, surfactants, biocides, and specific purpose additives (i.e. extreme pressure additives (EP) or biocides). Hence, rejected cutting oil is typically detected in form of stabilized emulsion with contaminant, such as particles, heavy metals, and hydrocarbon substances. The general treatment method of rejected cutting oil is physical or chemical separation from water and then purified or direct disposal. The purified oil can be recovered to used in manufacturing process again; therefore, the effective separation process is required in order to remove the contaminated oil in water and efficient cutting oil recovery.

“Coalescer” is one of the widely used equipment for separating oil from water due to its simplicity and less time required. This process has been studied in many aspects, for example, the mechanisms in coalescer, coalescence of dispersed phase with in the media bed, the effects of bed type and various operating conditions on the treatment efficiency. The results have shown that the treatment performances of coalescer for stabilized oily emulsion separation were still low, and also an imprecise treatment mechanism based on interaction between oil and coalescer media has been existed. Moreover, clogging in coalescer bed as well as costly media was the problems in application of coalescer process for treating oily wastewater. To fill this gap, the objective of this study is to analyze the locally coalescer system in terms of media characteristics and operating conditions. Moreover, different techniques will be applied in order to enhance the oil separation efficiency: chemical coagulation, liquid recirculation in coalescer column and step media bed configuration concepts. Finally, a mathematical model will be applied for providing the better understanding on treatment mechanism and the process efficiency.

1.2 Objectives

The main objective of this study is to enhance the treatment and separation of oil from emulsified cutting oil wastewater by coalescer process. The specific objectives can be expressed as following:

1. To determine the separation/treatment efficiency of oil from wastewater by conventional coalescer process.
2. To improve the separation of convention coalescer process via several methods, including step-bed coalescer media, liquid recirculation, and chemical addition.
3. To describe the treatment mechanism and effect of operating conditions on the treatment efficiency by application of simple model adapting from filtration efficiency equation.
4. To propose the pilot scale of hybrid process concept.

1.3 Hypotheses

1. Stabilized emulsion of cutting oil in wastewater is difficultly treated and separated by conventional separation process (i.e. sedimentation tank, oil and grease trap, etc.)
2. Emulsified cutting oil can be separated by coalescer process.
3. The performance of coalescer process can be improved by combining with the decantation and chemical coagulation-flocculation processes as hybrid process.

1.4 Scopes of the study

This study was conducted as a pilot scale set up at Department of Environmental Engineering, Faculty of Engineering, Chulalongkorn University. A cutting oil emulsion used in this study was synthesized at concentration of cutting oil in water at 1 g/l. The coalescer column is 8 cm in diameter with 80 cm height cylindrical clear acrylic tank. Batch process operation was applied in this study.

This research is divided into 4 steps including:

1. ***Determination of coalescer media characteristics***

   The aim of this step is to understand the physical properties and conditions; for instance, contact angle, density, and porosity, of the different types of media applied as a coalescer media, including stainless, granular and fibrous polypropylene.

2. ***Evaluation of cutting oil emulsion separation by the coalescer process***

   The purpose of this part is to determine the operating coalescer condition for well separating oil droplet from wastewater, and the separation efficiency by analyzing COD, oil and grease, and oil droplet size distribution as the analytical parameters.

3. ***Enhancement of oil droplet separation by hybrid process between coalescer and decantation***

   The objective of this step is to improve the treatment efficiency of coalescer and enhance separated oil from wastewater by applying various methods. The probability of collision and attachment between each oil droplets and between oil droplets and coalescing media will be increase by stage coalescer (step-bed configuration) and liquid recirculation. Moreover, efficiency of decantation process will be improved.

4. ***Application of coalescer-decantation process efficiency prediction model***

   In this step, the model equation by modifying the filtration efficiency equation was applied with the experimental results in order to comprehend the obtained treatment mechanism based on interaction between oil droplets and coalescer medium.

CHAPTER II
BACKGROUND AND LETERATURE REVIEW

2.1 Oily wastewater

Oily wastewater is usually binary mixture systems between oil and water that can be in major four forms (Aurelle, 1985); for example, soluble oil in water, oily emulsion with or without surfactant, and floating film oil. However, in order to select the appropriate treatment or separation processes, the properties of these wastewaters have to be realized. The physical property is one among the several categorized criteria that must be considered; especially, for separation process. Hence, there are 3 main classified criteria based on physical properties, including, the characteristics of continuous phase, stabilization of emulsions, and the degree of dispersion.

Classification by the characteristic of continuous phase

The mixture between oil and water is usually in the emulsion form, which imply to the non-miscible mixture. In the mixture systems, the particles or suspended solid containing liquid is called “disperse phase”, while the other is known as “continuous phase”. For example, the oily emulsion consists of oil as dispersed phase, and the continuous phase is water. Hence, the emulsions are divided into 2 major groups as classified by their components: -

1. ***Direct emulsion*** (or O/W emulsion) is the emulsion which the continuous phase that of is water.
2. ***Inverse emulsion*** (or W/O emulsion), on the other hand, is the emulsion, which contain oil as continuous phase.

Classification by the stability of oily wastewater

According to these criteria, oily wastewater can be divided into 2 groups:

1. ***Non-stabilized emulsion***: this kind of oily wastewater mainly contains only two components, including, oil and water, without surfactants. Hence, there is no effect of surfactant to enhance the stability of emulsion. The stability of this emulsion depends on "degree of dispersion" or the oil droplets size in the wastewater. If oil droplet is small, it will take long time to rise to the surface and agglomerate with other droplet, so it stays in the water phase for a long time. For this emulsion, the stability of emulsion is referred from the droplets staying time in water. The degree of dispersion relies on the energy used in mixing or dispersing the oil phase, such as, the supplied from agitation or pump.
2. ***Stabilized emulsion***: the components of this type are usually oil, water, and surfactant. Presence of surfactant in the system causes the decrease of interfacial tension between oil and water, so the oil can disperse into very small droplets. Moreover, surfactants also cause the barrier (electrical and mechanical) due to their localization and orientation that prevent collision and coalescence between droplets. Therefore, the oil droplet remains small, and obtains very small rising velocity compared to Brownian motion. Thus, this emulsion is stable and not tends to naturally separate.

Classification by the degree of dispersion

This classification is based on the rising velocity of oil droplets, which relate on properties of oil and water, and the oil droplet size. For common separation process, the droplet's velocity is acquired from Stokes's law. Hence, oily wastewater can be divided into 5 groups:

1. ***Film or layer of oil on water surface***: the density of oil is generally less than water, so film or layer of oil are usually formed at the surface of water. This type of oily water is relatively easy to treat, since the oil and water are readily separated.

2. ***Primary emulsion***: this type of oily water contains oil droplets that have greater 100 microns in size.
3. ***Secondary emulsion***: oily wastewater will be classified into this group if the oil droplets are smaller than 20 microns.
4. ***Macroemulsion***: this type of oily wastewater usually contains surfactant, so size of oil droplets in water is very small, between 0.06 to 1.0 microns. The macroemulsion usually has a milky appearance; for example, cutting oil emulsion.
5. ***Microemulsion:*** this type of oily wastewater contains a large amount of surfactant. The droplet size in emulsion is between 10 to 60 nanometers. This emulsion is usually transparent or translucent.

Figure 2.1 displays the classification summary of primary and secondary emulsion and relation between oil droplets size and their rising velocity.

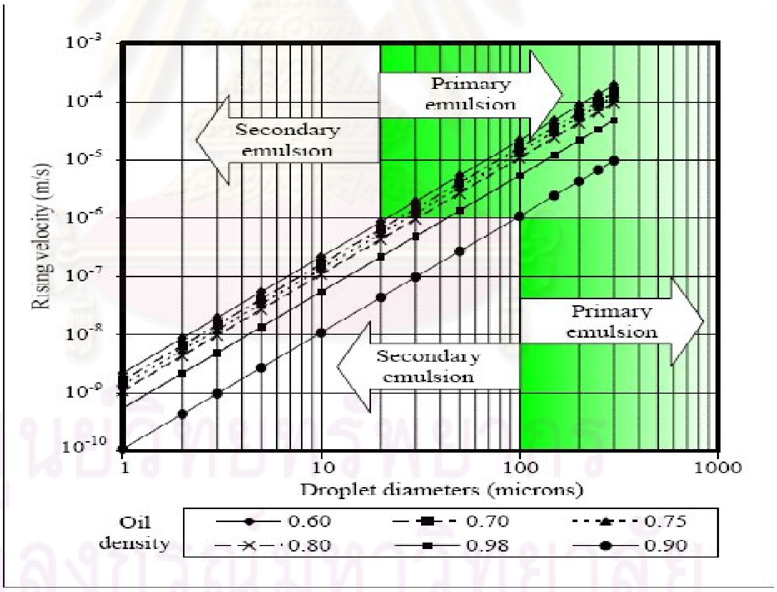

Figure 2.1 Relations between droplets size and rising velocity of primary and secondary emulsion (Wanichkul, 2000)

From three criteria mentioned above, there are some overlaps from different criteria. Therefore, in order to avoid any confusion, categorization of oily wastewater can be categorized as demonstrated in Figure 2.2.

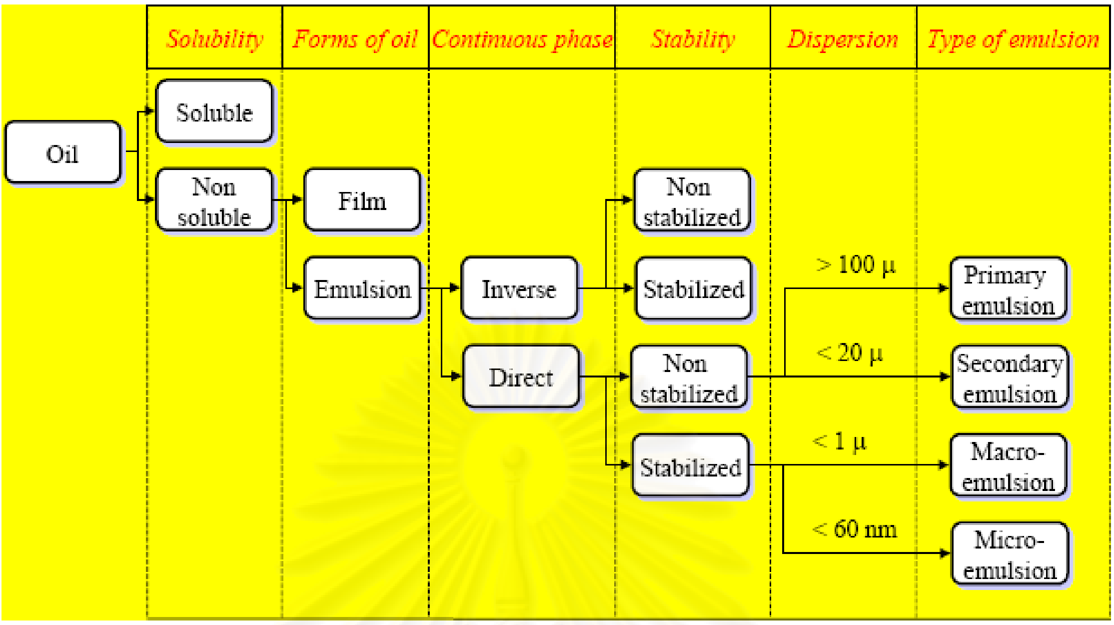

Figure 2.2 Classification of oily wastewater by physical properties (Rachu, 2005)

As mentioned above, it can be concluded that the characteristics of oily wastewater are greatly variety depended on oils and oily wastewater compositions, and also the degree of dispersion. Therefore, the best method to classify the oily wastewater is to analyze its properties by standard method in order to obtain the necessary data for appropriate treatment method selection.

2.2 Cutting oil

Cutting fluids or metalworking fluids are various fluids that used in machining work. Large ranges of cutting fluid types depend on their application and using purpose. Cutting fluids play an important role in every kind of machining e.g. boring, drilling, and grinding (El Baradie, 1996). The three basic actions obtained from cutting fluid which can affect in cutting process are:

1) Cooling
2) Friction reduction (or lubricating), and
3) Reduction of shear strength of the work material

Different types of cutting fluid can be classified according to several criteria; however, the fluids generally group by the constituents that form either solution or emulsion. There are four basic categories of cutting fluids (Boothroyd, 2006):

1) Straight or neat oils which are usually undiluted mineral oils, but often include other lubricants. These fluids provide very good lubricity but are relatively poor coolants.
2) Mineral-soluble oils (emulsion) which consist of oil with emulsifiers. These oils are used in diluted form, and widely used in industry.
3) Semi-synthetic fluids (or micro-emulsion) are essentially a combination of synthetic and soluble oil fluids; therefore, they offer good corrosion resistance, lubrication and contamination tolerance.
4) Synthetic fluids which formulated from organic and inorganic compounds. These oil-free solutions are used by diluting with water. They present a very good cooling performance in industrial practice.

Moreover, some additives are added in the cutting oils in order to increase its efficiency and specific intention. For instance, extreme pressure (EP) additives are employed for severe machining operations, which demand high pressure tolerance property and high active temperature regions. Biocides, or bacteria killing agents, must be added when cleaning of pollutants or contaminants are required.

The lifecycle of cutting fluids in a machining facility involves four stages (Grzesik, 2008): storage and handling, mixing with water, process using and disposal. After the using stage, cutting oils in emulsion form will consist of different contaminants, for example, particles, heavy metals, and organic matters. These used oils are typically handled by two methods. The first process is recycling, which the contaminants are separated from rejected oil and purification before returning to the oil system for process using. The separation process can be operated by variety of physical processes, such as, separation by magnetic or centrifugal force, filtration, and settlement. Afterwards, the oils are purified to adjust their properties. For example, the oils are heated to reduce viscosity. Sterilization is also significant process for infection protection in order to eliminate the bacteria that are the constituents of emulsion. Another process used with rejected oil is disposal, which applied when oil recovering is unable or difficult, for instance, high water containing emulsion that has little recovery value, or inadequate quality recovered oil. The disposal process normally consists of two processes. Firstly, the oil emulsions are destabilized into oil and water normally by chemical processes. According to Rios *et al.* (1998), inorganic salts, which are employed as coagulants, can demulsify the emulsion, and the number of oil droplets in water are removed by settling. These separated oils will enter the disposal process. The conventional disposal process of oils in industry is combustion, which using oil as alternative fuel. Moreover, biodegradation is another interesting alternative as Cheng *et al.* (2005) has reviewed that the biological degradation, such aerobic and anaerobic, can effectively remove COD and turbidity, which represent the cutting oils in water. Electro-coagulation was another process that applied for treatment of metalworking fluid in water (Bensadok *et al.*, 2008; Kobya *et al.*, 2008).

The toxicity of cutting fluid commonly occurs from the contaminants in emulsion through skin contact and inhalation exposure pathways. Skin disorders, respiratory diseases, and cancer are the adverse health effects involve in cutting fluids exposure (OSHA, 1999). The severity of effects depend on several factors, such as, kind of fluid, concentration and type of contamination, and also the level and duration of exposure. The symptoms of skin disorders from cutting fluids are acne and contact dermatitis, which can be divided into two kinds: irritant and allergic contact dermatitis (El Baradie, 1996). The exposure through skin contact results from working or accident with inadequate protecting equipments. Whereas, cutting fluid aerosol or mist inhalation can cause the respiratory diseases and also aggravate the effects of existing diseases. The symptoms of the diseases are such acute (e.g. airway irritation, asthma, and lung inflammation) and chronic effects, such as, chronic bronchitis and lung function damage (OSHA, 1999). It should be noted that a number of studies have found an association between cutting fluids exposure and variety of cancers causing by the fluids composition, which the effects of cancer are signified after the long period exposure.

2.3 Stokes's law

The settling or rising velocity of the spherical particles having Reynolds's number less than 1 (Laminar regime) can be defined by Stokes's law as shown in Equation 2.1 (Aurelle, 1985):

$$v_T = \frac{\Delta\rho g D_E^2}{18\mu} \tag{2.1}$$

Where v_T is the terminal settling or rising velocity of particles;
$\Delta\rho$ is the density difference between disperse and continuous phase
d_E is the diameter of disperse phase particle
μ is the continuous phase viscosity

In case of oily water, the disperse phase is oil droplet, while continuous phase is water. The most widely used process to separate oil and water is decantation, since it is relatively simple. As can be seen in equation, rising velocity of oil particles can be increased by 4 methods; including:

1. Reduction of continuous phase viscosity (μ) by raising its temperature;
2. Increase of density difference (Δρ) between dispersed and continuous phase (oil and water), for instance, flotation process;
3. Increase the gravimetric acceleration (g); such as, hydrocyclone process;
4. Increase the oil droplet size (D_E); for example, coalescence.

In practice, these separation methods are used to develop variety of techniques for oily water separation.

2.4 Treatment of oily wastewater

The treatment processes of oily wastewater can be concluded from Aurelle (1985) as shown in Table 2.1

Table 2.1 The treatment processes of oil-containing wastewater

Process	Advantages	Disadvantages
Gravity separation	- Can remove suspended solid - Can remove both free and dispersed oil in water - Simple and economical process	- Large volume of separation tank - Low flow velocity required - Unable to treat emulsion and water-soluble oil
Air flotation	- Can removed suspended solid - Can removed dispersed oil and emulsion by combining with chemical addition - Capable for shock loading of oil or solid	- Chemical sludge produced and needed to be treated
Chemical flocculation	- Competent for high suspended solid containing water	- Chemical sludge produced
Filtration	- Can remove suspended solid - Capable for emulsion, free and dispersed oil treatment	- Treatment of backwash water is required
Coalescence	- Can remove all types of oil except the soluble oil	- Preliminary treatment is required - Sensitive to suspended matter resulting in media clogging
Membrane process	- Capable for water-soluble oil removed	- Limitation from clogging and useful life - Preliminary treatment is required - Low treatment rate
Biological process	- Efficiently remove soluble oil in water	- Require preliminary treatment
Carbon adsorption	- Competent for treat all types of oil	- Require preliminary treatment - Costly - Carbon changing or regeneration are required

2.5 Decantation

Decantation or floating is the basic separation process based on the property of oil and water. This process is suitable for treating primary emulsion or large oil drop from water. The working principle of decantation base upon Stoke's law (1); where the separating velocity of oil droplet depends on the gravity force (g) and the density difference between two phases and a droplet size of oil (Δρ). The performance of decantation is mainly controlled by the retention time of oily water in the tank, since oil droplets require a sufficient time for rising to the water surface as applied in oil/grease trap as displayed in Figure 2.3. However, the separation efficiency of decantation is limited by size of oil droplet in water that incapable to separate by itself in restricted time, which normally implied to droplet smaller than 10 μm (Wanichkul, 2000). The smallest droplet size that can float to the surface is called the "cutting size"; where the droplet with smaller size than the cutting size cannot be separated from water by the conventional decantation. The removal of oil droplets occurred in conventional decantation tank is displayed in Figure 2.4.

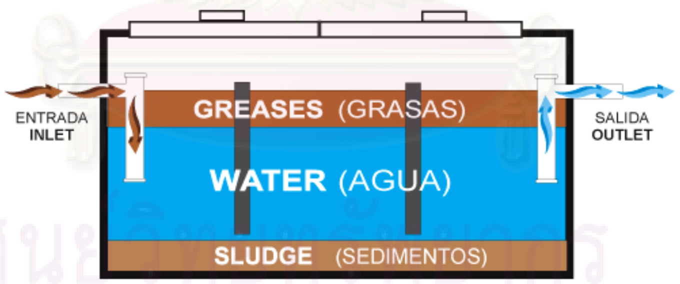

Figure 2.3 Typical grease traps (WARCO Group Corporation: http://warcopr.com/illustrations.html)

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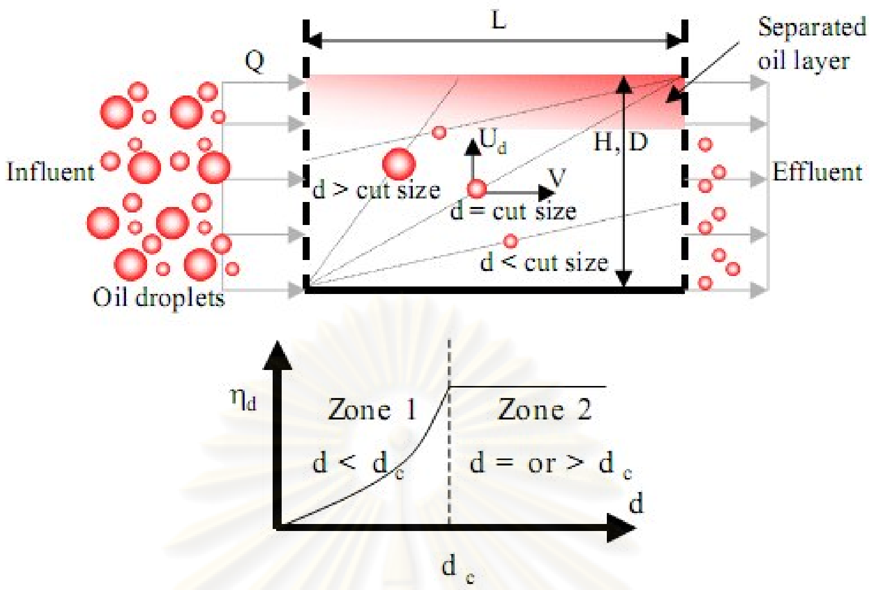


Figure 2.4 Schematic and typical removal efficiency of simple decantation tank by floating of oil droplets (Rachu, 2005)

Decantation or floating can be classified into 4 types depended on concentration and interaction of particles as following (Carlsson, 1998):

1. *Discrete particle settling*: The particles settle without interactions. Settling velocity of particle is constant as can be determined from Stoke's law (Equation 2.1). This phenomenon usually occurs at low particles concentration.
2. *Flocculent settling*: Particles initially settle initially, but then flocculate after moving through the distance in the settling tank. The velocities of settling particles are usually increasing as the aggregation of particles.
3. *Hindered settling*: The inter-particle forces obstruct and decrease the settling velocity of the neighbor particles, thus the particles tend to be in steady position. This settling type occurred at the certain high concentration level.
4. *Compression settling*: For very high concentration of particles, the particles at one level are mechanically influenced by particles at lower level, which resulting in reducing of settling velocity.

2.6 Coalescer

Coalescer is an equipment that is suitable for liquid-liquid dispersion, or emulsion separation. The process is usually implied as the emulsion upflow through a layer of coalescer media (Wanichkul, 2000). As a result, the micro oil droplets will attach to the media and then increasing their size. The mechanisms of coalescer apparatus can be seen in Figure 2.5. Since the rising velocity is a square function of droplets diameter, increasing in droplets size will enhance the separation of oil from emulsions (Equation 1). An important component of coalescer is the media bed, which is typically hydrophobic medium, since it has higher ability to attach with oil droplets (Hydrophobic media), and thus coalesce to produce larger oil particles. Hence, media selection is an essential point in order to achieve the efficient coalescer performance. The type of coalescer can be divided by different kinds of media into two types, i.e. granular bed coalescer and fibrous bed coalescer.

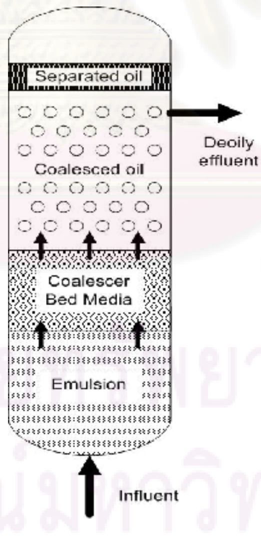


Figure 2.5 The mechanisms of coalescer apparatus

The mechanisms occur in coalescence process can be divided in to three steps as follows (Rachu, 2005):

1. Interception: The mechanisms in this step are similar to the filtration mechanisms, which consist of 3 transport phenomena that will be subsequently

defined in the next topic. The phenomena in this step is the adherence of oil to the collector

2. Adhesion and coalescence of oil droplets, where droplets within the bed will coalesce to media and then creating the oily film, which can coalesce with other droplets to form the large oil droplets. This step is important for coalescer process, since the coalescing media should be well chosen in order to encourage the attachment probability between oil and media. For that reason, the hydrophobic (oleophilic) materials are usually applied because it contains high wettability with oil, which results in high attachment probability with oil droplets.
3. Salting out or enlargement of coalesced liquid, which defined as the leaving of coalesced oil droplet from bed to the water surface. The mechanism in this step is critical for oil separating from water. The mechanism is governed by 4 major properties, including:
   - The wettability of the salting out surface;
   - The interfacial oil/water tension and the diameter of the drip point;
   - The velocity of emulsion through media bed; and
   - Oil in water ratio.

The phenomena of these three steps are shown in Figure 2.6 and 2.7.

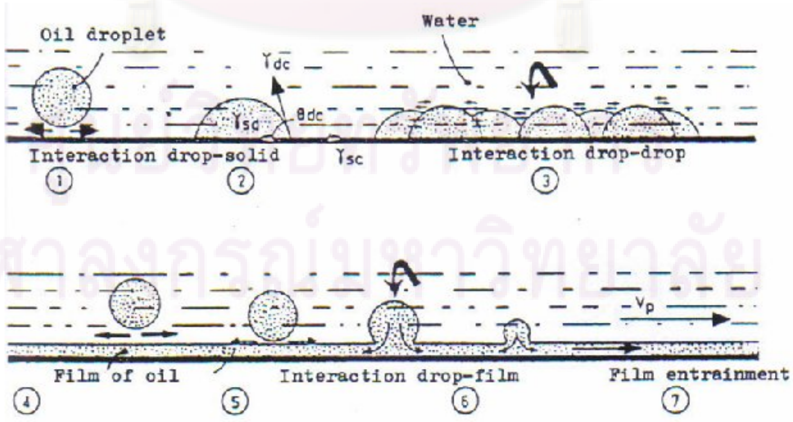


Figure 2.6 Schematic diagram of phenomena occurred in interception, adhesion, and coalescence steps (Aurelle, 1985)

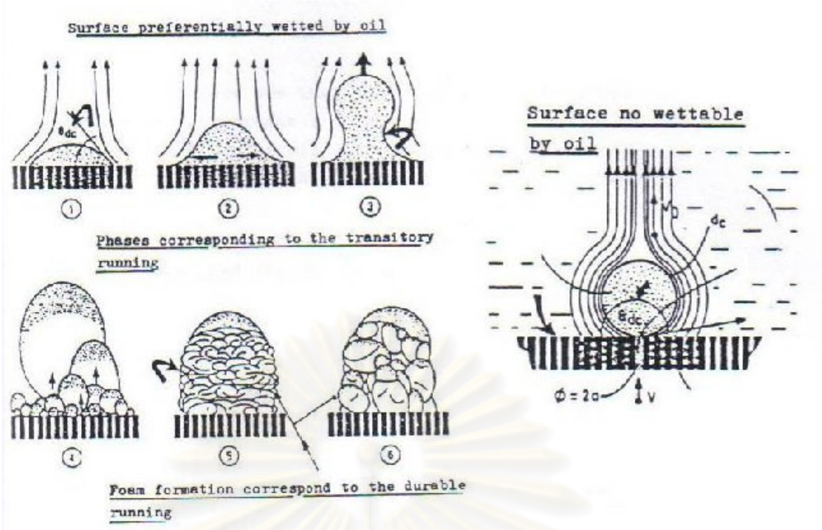


Figure 2.7 Schematic diagram of salting out phenomena of coalesced oil droplets (Aurelle, 1985)

The efficiency of coalescer process is suggested to be controlled by many factors, which can be classified into 3 major parts (Wanichkul, 2000); for example,

1. Oily emulsion characteristics: The effects of emulsion characteristics are summarized in Table 2.2.

Table 2.2 Impact of oily emulsion characteristics

Variables	Effects
Oil droplet size	Larger droplet size can easier coalesce to each other.
Emulsion viscosity	Efficiency is exponentially decreased in function of viscosity.
Surfactants	Efficiency is reduced in presence of surfactants.
Molecular weight	Greater molecular weight results in higher coalescence efficiency.
Suspended solid	Presence of suspended solid cause the decrease in coalescence efficiency.

2. Characteristics of coalescing media: The effects of media properties are concluded in Table 2.3.

Table 2.3 Influences of media properties

Variables	Effects
Roughness	The separation efficiency will not alter by changing media materials, which contain the same roughness.
Media bed height	Increment of bed height results in higher coalescence of oil droplets, however, the pressure drop, which also increase, can cause the breaking of large coalesced droplets.
Fiber diameter	Higher coalescence of oil droplets is theoretically defined by applying the small and long fiber media.
Surface force	The efficiency is direct varied with separation efficiency. The coalescence efficiency is related to zeta-potential and hydrophobicity of media.

3. Operating conditions: The influences of operating conditions are summarized in Table 2.4.

Table 2.4 Impacts of operating conditions

Variables	Effects
Flow velocity	Decreasing in flow velocity of emulsion results in the increase of efficiency, and also coalescence of oil.
Temperature	Altering of operating temperature cause the complicated change in the diffusion transport of oil droplets.

The advantages of coalescer process are the simplicity and reliability for treating oily wastewater as well as its low construction and operation cost. However, media clogging by some contaminants in water (i.e. suspended solid) and also the low efficiency for using in stabilized oily emulsion treatment are its major disadvantages.

2.7 Transport of oil droplets to contact with collector

In order to understand the treatment mechanism obtained with coalescer processes, the transport phenomena of oil droplets to contact with media should be considered. Normally, it can be described by 3 mechanisms, including transportation by 1) Sedimentation, 2) Direct interception, and 3) Diffusion (Aurelle, 1985). These concepts are normally applied from the filtration model, since the interception of oil droplets by collector is relatively close to that of filtration through the media (Rachu, 2005). The schematic diagrams of the transport phenomena are illustrated in Figure 2.8.

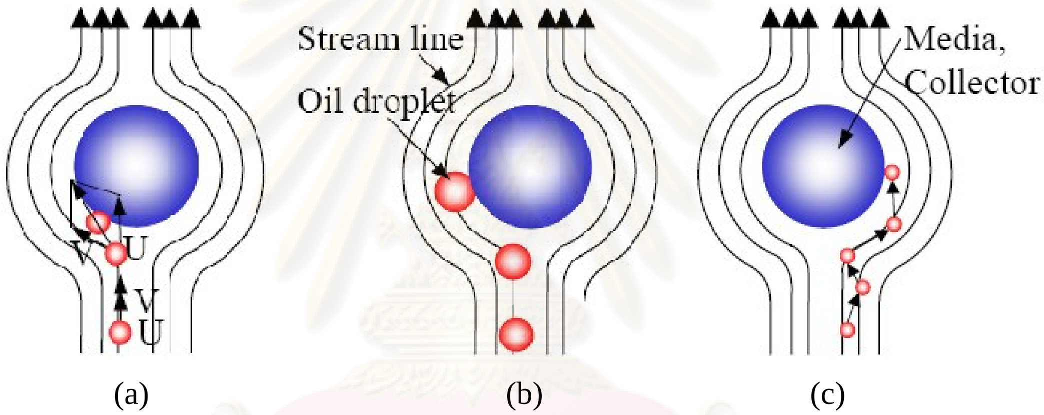


Figure 2.8 Schematic diagrams of the transport phenomena

(a) Sedimentation; (b) Direct interception; and (c) Diffusion (Rachu, 2005)

1. Transportation by sedimentation

The oil droplet of diameter “d” is subjected to two velocity vectors, including “U” which is the rising velocity governed by Stokes’s law, and the flow velocity, “V”, of the water through the collector as displayed in Figure 2.8 (a). At a far distance from the collector, the two vectors have the same direction, and the oil droplet will follow the streamline. When the oil drop approach to the collector, the rising velocity, “U” still conserve its direction, but the “V” flow velocity vector will follow the streamline direction; therefore, the resultant vector causes the oil droplet to leave the streamline. For that reason, the oil drop likely to collide with the collector, thus, sediment on the collector. The efficiency factor of this phenomenon (η_s) can be calculated by Equation 2.2, where D_E is the diameter of oil droplet.

$$\eta_S = \frac{\Delta\rho g D_E^2}{18\mu v_0} \qquad (2.2)$$

2. <u>Transportation by direct interception</u>

This phenomenon will occur when the density difference of oil droplet and water is the same. Therefore the Δρ is equal to zero, and transportation by sedimentation cannot occur. However, the oil drop can still contact to the collector by the mechanism of direct interception. Consider oil droplets of diameter "d" carried by the streamline, the oil drops that flow within the distance "d/2" far from the collector will contact, and will be intercepted by the collector as shown in Figure 2.8 (b). The direct interception efficiency (η_I) can be calculated from Equation 2.3, where D_P represents the diameter of collector.

$$\eta_I = \frac{3}{2}\left(\frac{D_E}{D_P}\right)^2 \qquad (2.3)$$

3. <u>Transportation by diffusion</u>

This transport model is used in order to describe the interception of oil droplet of diameter less than 5 microns. These micro-droplets prone to have Brownian movement, resulting in random direction movements that likely encourage the oil droplets interception in the collector. Figure 2.8 (c) demonstrates the mechanisms of transportation by diffusion. The efficiency factor of this transport phenomenon (η_D) can be calculated from Equation 2.4.

$$\eta_D = 0.9\left(\frac{KT}{\mu D_E D_P v_0}\right)^{\frac{2}{3}} \qquad (2.4)$$

Where, K and T are Boltzmann's constant (1.38×10^{-23} kg·m^2/K·s) and liquid temperature in Kelvin, respectively.

As mentioned above, the efficiency factor of each transport phenomenon can be calculated for single collector. The total efficiency of interception step of coalescer for single collector is the summation of the efficiency factor of those phenomena; hence, the single collector total efficiency (η_T) can be calculated from Equation 2.5.

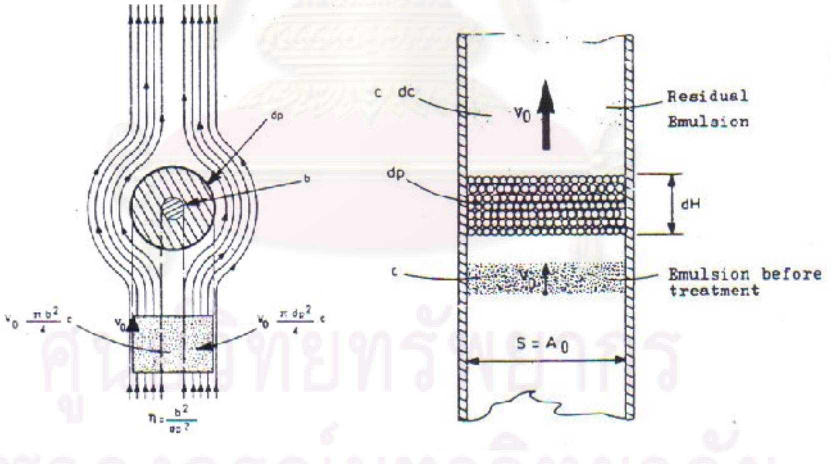
$$\eta_T = \eta_S + \eta_I + \eta_D \qquad (2.5)$$

Note that the efficiency of coalescer directly depends on the oil droplet size as described in Equation 2.6.

$$\eta_T = \frac{\Delta\rho g D_E^2}{18\mu V_0} + \frac{3}{2}\left(\frac{D_E}{D_P}\right)^2 + 0.9\left(\frac{KT}{\mu D_E D_P V_0}\right)^{\frac{2}{3}} \qquad (2.6)$$

2.8 Filtration (Coalescer) efficiency equation

The equation of coalescer was proposed by Aurelle (1985) based on the filtration efficiency equation due to the fact that emulsion was flowed through medium bed in coalescer process likewise in filtration, despite oil droplets in emulsion in case of coalescer were not supposed to trap in the coalescing bed. Since the efficiency of coalescer mainly depends on the interception, the efficiency equation has to consider in that mechanism. The efficiency equation was proposed by considering the wastewater flow through single spherical collector in laminar flow regime as illustrated in Figure 2.9 (a), and then adapt for entire volume of medium bed.



(a) (b)

Figure 2.9 Schematic diagrams of single collector (a) and entire media bed volume (b) (Aurelle, 1985)

First, the fraction of wastewater flowing passes the collector can be defined as the flow through the projected area of the collector (q) as in Equation 2.7. Afterwards, some oil droplets would be transported to the collector (media) due to the single collector total efficiency (η_T), which quantity of dC_1 as in Equation 2.8.

$$q = \frac{\pi}{4} D_P^2 \cdot v_0 \tag{2.7}$$

$$dC_1 = \eta_T q C_0 \tag{2.8}$$

Where, v_0 and C_0 are the flow velocity and initial concentration of wastewater, respectively. Then, the equation was accommodated for applying with entire bed volume with slight bed height (dH) as displayed in Figure 2.9 (b). The number of collector in this bed can be calculated from the cross sectional area of bed (A_0), collector size (D_P), and porosity of the bed (ε). Total concentration of intercepted oil in this slice bed, dC_2, is equal to the product of concentration intercepted by single collector and number of collector. The attachment efficiency (α), which defined as the probability of oil droplets to adhere with collector, has to be considered as the actual quantity of intercepted oil droplet. Hence, the total concentration of intercepted oil in bed can be defined as in Equation 2.9.

The number of collector in slice bed height dL $= \dfrac{dL(1-\varepsilon)A_0}{\frac{\pi}{6}D_P^3}$

$$dC_2 = \alpha \frac{dL(1-\varepsilon)A_0}{\frac{\pi}{6}D_P^3} dC_1 \tag{2.9}$$

The concentration of oil reduced after passing through the bed dL is equal to $-V_0 A_0 dC$; therefore, the efficiency equation can be defined as in Equation 2.10 and 2.11.

$$-V_0 A_0 dC = \alpha \eta_T \frac{\pi}{4} D_P^2 V_0 C \frac{dL(1-\varepsilon)A_0}{\frac{\pi}{6}D_P^3} \tag{2.10}$$

$$\frac{dC}{C} = -\frac{3}{2}\alpha \eta_T (1-\varepsilon)\frac{dL}{D_P} \tag{2.11}$$

By integrating Equation 2.11, the final equation of filtration (coalescer) efficiency can be obtained as expressed in Equation 2.12.

$$\ln \frac{C}{C_0} = -\frac{3}{2}\alpha \eta_T (1-\varepsilon)\frac{L}{D_P} \tag{2.12}$$

This equation could be used to explain the impact of mechanisms occurred in the coalescence process, since the effects of medium properties and operating conditions (i.e. flow velocity and bed height) were considered.

2.9 Fluid flow past immersed objects

Packed bed is the media materials filled in hollow column or vessel. Types of packing materials are dependent upon the purpose of application, such as granular or fibrous material. Typically, the material used as media contains high specific surface area in order to improve contact between two phases; for example, packed bed column used in adsorption or filtration processes. Figure 2.10 displays the appearance of packed bed column. The behavior of fluid flow through packed bed column can be described as flowing past tortuous pipeline with different area surface and length. Therefore, the pipeline flow model can be applied to define the behavior of packed bed flow by comparing the surface area and diameter of pipeline to the actual characteristics of packing materials.

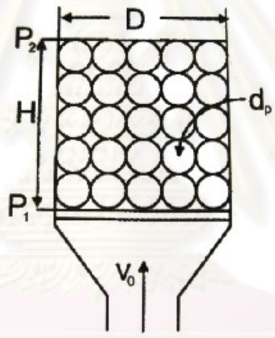


Figure 2.10 Packed bed column (Hunsom, 2008)

The packing media in column cause the flowing resistance that depends on several factors, for instance, flow regime, turbulence in column, shape of packing material, etc. This can be calculated in term of head (pressure loss) by means of flowing resistance along the bed length. However, the calculation is based on the assumption that the medium material is uniformly packed throughout the column bed, which consequently result in the uniform distribution of pore in medium bed. Moreover, the packing materials have to be relatively small compare to the diameter or size of column.

The specific surface area (a_v) of packing material, defined as the surface of medium per unit volume can be calculated by Equation 2.13 (McCabe, 2000).

$$a_v = \frac{A_p}{V_p} \tag{2.13}$$

Where A_p and V_p are the surface area and volume of medium material, respectively. In case of spherical material, the specific surface area can be calculated from Equation 2.14 (McCabe, 2000).

$$a_{v,sphere} = \frac{A_{p,sphere}}{V_{p,sphere}} = \frac{\pi D_p^2}{\frac{1}{6}\pi D_p^3} = \frac{6}{D_p} \tag{2.14}$$

However, such packing material is practically not actually in sphere shape; for example, cylindrical rod or fibrous material. The sphericity factor has to be determined. The sphericity (ψ) is measure of how spherical shape a material is, which defined as the ration of surface area of sphere, which has the same volume as the particle, to the surface area of the packing particle as expressed in Equation 2.15 (Wadell, 1935).

$$\psi = \frac{\pi^{\frac{1}{3}}(6V_p)^{\frac{2}{3}}}{A_p} = \frac{6/D_p}{a_v} \tag{2.15}$$

For spherical particle, the sphericity value is equal to 1. From Equation 2.14 and 2.15, the specific surface area (a_v) can be rewrite as in Equation 2.16.

$$a_v = \frac{6}{\psi D_p} \tag{2.16}$$

In the uniform packing material, the porosity of medium bed (ε), defined as ration of void volume (V_v) to the entire volume or bulk volume (V_{bulk}) of the medium bed as can be calculated in Equation 2.17.

$$\varepsilon = \frac{V_{void}}{V_{bulk}} \tag{2.17}$$

Nevertheless, void within medium bed is usually a non-circular channel like the pipeline flow. The equivalent diameter (D_{eq}) has to be determined as a represent of pipe diameter. The total head loss along packing bed considers the overall surface area throughout the bed by assuming that pores or voids in bed are the paralleled straight pipeline with the same length with bed height as shown in Equation 2.18 (McCabe, 2000).

$$n\pi D_{eq} L = A_0 L(1-\varepsilon)\frac{6}{\psi D_p} \tag{2.18}$$

The flow velocity fluid that used to calculate pressure loss in the system is the superficial velocity (v_0), which can be defined as flow velocity of fluid in the empty column, not the interstitial velocity (v_{av}) or flow velocity in packing bed. The relationship between superficial and interstitial velocity is expressed in Equation 2.19.

$$v_0 = v_{av}\varepsilon \tag{2.19}$$

From D_{eq} and v_0, Reynold's number of flow in packing bed ($N_{Re,p}$) can be determined via Equation 2.20. Note that the D_{eq} for a channel is $D_{eq} = 4r_H$, where r_H is hydraulic radius defined as ration of cross-sectional flow area to the wetted perimeter (Geankoplis, 2003).

$$N_{\mathrm{Re},p} = \frac{(4r_H)v_o\rho}{\mu} = \frac{D_p v_o \rho}{(1-\varepsilon)\mu} \tag{2.20}$$

In laminar flow regime ($N_{Re,p} < 10$), pressure loss occur in the circular straight pipeline is function of flow velocity and medium pore size according to Hagen-Poiseuille equation (Geankoplis, 2003). However, the flow channel in bed is practically tortuous. The correction factor (λ_1) is proposed and applied in the equation as shown in Equation 2.21.

$$\frac{\Delta P}{L} = \frac{32 v_{av}\mu}{D_{eq}^2} = \frac{72\lambda_1 v_0 \mu (1-\varepsilon)^2}{\psi^2 D_p^2 \varepsilon^3} \tag{2.21}$$

Where ΔP is pressure loss. From the experimental results, it was found values of constant or λ_1 that of 150 and 2.1, respectively. By replace these values in Equation 2.21, the final equation was obtained as expressed in Equation 2.22. This equation is called "Blake-Kozeny equation" (Geankoplis, 2003).

$$\frac{\Delta P}{L} = \frac{150 v_0 \mu (1-\varepsilon)^2}{\psi^2 D_p^2 \varepsilon^3} \tag{2.22}$$

For turbulent flow regime ($N_{Re,p} > 1000$), the Hagen-Poiseuille equation can be rewrite by applied the other correction factor (λ_2) as shown in Equation 2.23.

$$\frac{\Delta P}{L} = \frac{2 f \rho v_{av}^2}{D_{eq}} = \frac{3 f \lambda_2 \rho v_0^2 (1-\varepsilon)}{\psi D_p \varepsilon^3} \tag{2.23}$$

The λ_2 was found in experiment as 1.75. Then, Equation 2.23 can be rewrite as shown in Equation 2.24. This equation is called “Burke-Plummer equation” (Geankoplis, 2003).

$$\frac{\Delta P}{L} = \frac{1.75\rho v_0^2 (1-\varepsilon)}{\psi D_p \varepsilon^3} \tag{2.24}$$

By summation of Equation 2.22 and 2.24, Equation 2.25, which is widely known as “Ergun’s equation”, was obtained (McCabe, 2000). This equation can be applied to evaluate pressure loss both in laminar and turbulent flow regime, since the loss from liquid viscosity and kinetic energy loss of fluid were considered.

$$\frac{\Delta P}{L} = \frac{150 v_0 \mu (1-\varepsilon)^2}{\psi^2 D_p^2 \varepsilon^3} + \frac{1.75\rho v_0^2 (1-\varepsilon)}{\psi D_p \varepsilon^3} \tag{2.25}$$

2.10 Literature review

Kulowiec (1979) concluded the concentration in various types of industrial wastewater as displayed in Table 2.5

Table 2.5 Typical range of oil and grease concentration in industrial wastewaters

Wastewater types	**Concentration range (mg/l)**
Sewage	10 – 100
Food processing	100 – 1000
Textile (Wool processing)	10 – 50
Petroleum refining	100 – 1000
Primary metals	
Rinse waters	10 – 1000
Concentrate	10000 – 15000
Metal fabrication	10000 – 150000
Metal cleaning	
Rinse waters	10 – 1000
Concentrate	100 – 5000
Commercial laundries	100 – 2000

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Li and Gu (2005) have studied the coalescence mechanisms of oil particles in emulsion in fibrous and granular bed coalescer. The apparatus was a 73 mm diameter with 70 cm length stainless steel pipe. Figure 2.11 shows the diagram of coalescer system in this experiment. Emulsion effluent was horizontally flowed through coalescer media beds, which were polypropylene fiber, nylon fiber, and granular polypropylene. The studied parameters in this research were the influent flowrate, emulsion concentration, media bed length, and size of fiber media. The results were shown by system efficiencies that evaluated from the coalescer efficiency equation, and oil droplet size distribution.

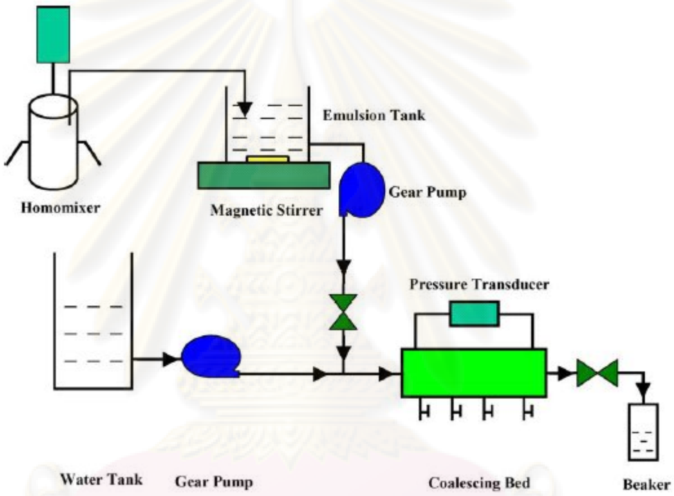


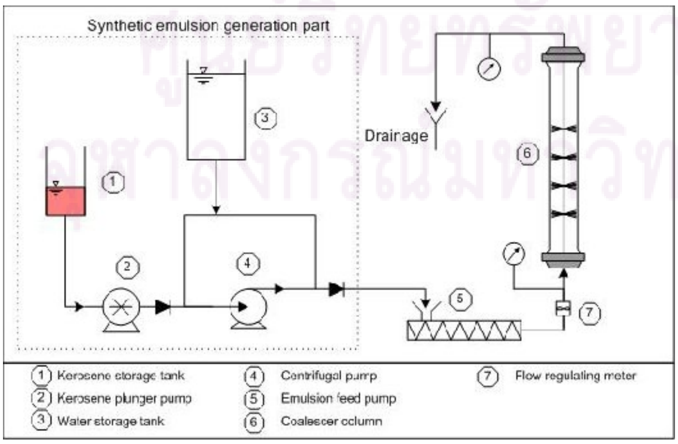
Figure 2.11 Diagram of coalescer system set-up (Li and Gu, 2005)

The study founded that the efficiencies of coalescer were influenced by the inlet oil concentration and type of media. An effective coalescence can be achieved by using small fiber media, or low oil inlet concentration. The high efficiency coalescer can be obtained for appropriate flowrate range, which can be investigated in an experiment. However, the effect of media bed length can be neglected for horizontal flow coalescer.

Rebelein and Blass (1990) conducted the separation of micro-dispersions in fiber beds in order to improve the separation efficiency. The media used in this research is 5 - 50 microns size range fibrous media; including stainless, glass, and PTFE (Polytetrefluoroethylene) fiber, with 5 - 60 millimeters bed length. The concentration of operated emulsions is less than two percent by volume, and 1 – 100 microns in size. It was reported that small size and high velocity effluent caused low separation efficiency. Moreover, the emulsion separation efficiency is dependent on the wettability and size of media fiber, whereas the coalescer bed length caused slightly effect on the efficiency.

Madia *et al.* (1979) studied the effect of packed granular bed wettability on coalescence. Four different types of granular media used in this study consisted of anthracite, Ottawa sand, polypropylene, and XAD-2 polymeric adsorbent packed with 2 inch bed height in 1 inch-in-diameter. The emulsion flow velocity was in the range of 0.1 – 0.5 l/min. Wettability of coalescing media was determined by GC measuring required time for water and hexane vapor move through packed bed. The oil-wetted surface provided high time ration of hexane to water vapor. The experimental results showed that higher coalescence efficiency was obtained from oil-wetted materials and higher emulsion wettability resulted in greater oil droplet separation efficiency of the media.

Wanichkul (2000) studied the effects of bed heights, liquid flow velocity, and multi-stage bed configuration on the coalescer performance for treating oil in water emulsion. The processes, as displayed in Figure 2.12 (a), consist of 2 major parts, for example, emulsion generation part and coalescer unit, which contain cylindrical coalescer column and coalescer media.



(a)

(b)

Figure 2.12 (a) Schematic diagram of the process; (b) Stainless fibrous media (Wanichkul, 2000)

The media used in this study is shown in Figure 2.12 (b), which was brush type in a ring configuration made from stainless steel (SS 304) with 60 micrometers diameter. Emulsions used in this experiment were kerosene in water emulsion at concentration around 1% with 10 micrometers mean oil droplet size.

The study found that the efficiency of coalescer process was impacted by both media bed height and liquid velocities. The increment of bed height convinced an increase in treatment efficiency until it reached 7 cm height, and then the efficiency was slightly dependent to the bed height, while the increase of liquid velocity resulted in low treatment performance. Moreover, multi-stage coalescer configuration can reduce the coalescer media clogging problem and provided approximately 25 % higher treatment efficiency than those obtained from the classical one.

Meyssami and Kasaeian (2005) have reported the study of olive oil-water emulsion treatment by using coagulants in induced air flotation process (IAF). The model emulsions were prepared by olive oil with various types of surfactant and chemical stabilizer including, sodium dodecyl sulfate, aniline, butanol, di-sodium and tri-sodium phosphates, and texapone. This study was consisting of 2 major parts: first, the jar test experiments for determining type and concentration of surfactant, which can provide highest emulsion stability. Moreover, jar tests were also used for determining the appropriate pH value and concentration of various coagulants (i.e. chitosan, starch, ferric chloride, and alum) for using in destabilization of oily emulsion. Afterwards, induced air flotation (IAF) was applied for oily emulsion treatment by combining with chemical coagulation. The apparatus used in this experiment is shown in Figure 2.13. The effects of various parameters were considered in this study including, liquid temperature, concentration of surfactants, air flowrate, and the aeration time.

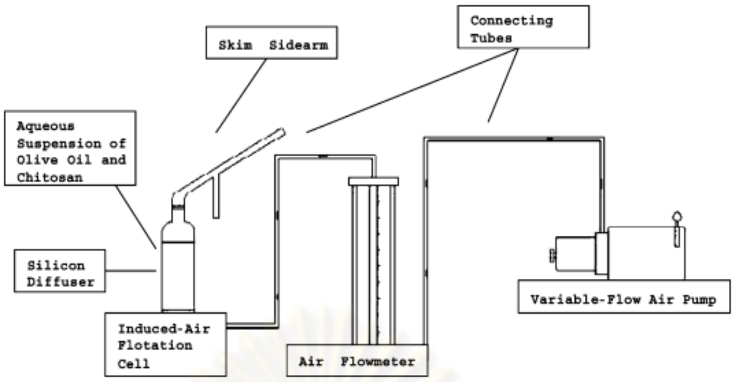


Figure 2.13 Laboratory scale induced air flotation (IAF) system used in this study (Meyssami and Kasaeian, 2005)

The results of this study showed that using of chitosan with alum as coagulants at pH 6 with concentration of 15 and 25 mg/l, respectively, provided the 90% reduction the emulsion turbidity. Furthermore, the application of chitosan with 100 ppm concentration in IAF (3 l/min air flowrate for 45 seconds) at pH 6 produced the highest olive oil emulsion treatment efficiency of 95% in term of COD removal.

Sokolović *et al.* (2006) studied the coalescence of oil droplets in diluted emulsion by coalescer process. The impacts on efficiency of various operating conditions, for instance, coalescing media bed height (3 – 15 cm), flow pattern (horizontal, upflow and down flow vertical), media properties, and flow velocity (16 – 50 m/h) as well as oil concentration (500 – 10,000 mg/l with mean diameter 20 μm). The applied medium is Polyurethane (PU) fiber. The results were compared by using critical velocity (defined as the flow velocity that produced the effluent concentration of 15 mg/l) and oil concentration in effluents.

It was founded that horizontal flow pattern provided the highest critical velocity in every experiment. The critical velocity is higher when water permeability and length of media bed were increase. Moreover, the influent oil concentration impacted the critical flow velocity as well as the effluent concentration. However, the impacts of oil concentration can be ignored in case of long bed height.

Zhou *et al.* (2009) studied the effects of medium types and also operating parameters on oil separation efficiency of modified resin coalescer. Diesel oil #0 and anionic surfactant (SDBS) were used for preparing synthetic wastewater at 1000 mg/l concentration with 10 μm mean droplet diameter. Coalescing media used in the study were organic medium (i.e. PP and polystyrene resin) and inorganic (granular activated carbon: GAC and ceramic filter: CF), while various considered operating parameters were flow velocity, bed height, influent oil concentration, pH, and temperature. In this study, polystyrene resin was modified by grafting cetyltrimethyl-ammonium bromide for demulsification of oily emulsion purpose. The results indicated that modified resin provided higher efficiency than that of PP, ceramin, can GAC media. Moreover, highest treatment efficiency of resin medium was achieved at more than 80% under optimal operating conditions; for example, flow velocity of 60 – 180 ml/h, bed height 20 – 40 cm, temperature 20 – 60 °C, and pH value 2 – 10. This high efficiency might be the integration of both chemical demulsification and coalescence occurred in the process, which was the major disadvantage of this medium.

Sokolović *et al.* (2009) studied treatment of heavily polluted oil wastewater by fiber-bed coalescer. The experimental set-up was carried out in real industrial plant in Serbia. Oily wastewater used in this study was the real one from Oil Company at constant concentration of 500 mg/l with mean droplet diameter as 20 μm. The applied coalescing media were two different types: granular expanded polystyrene (EPS) and polyurethane fiber (PU) with vertical flow pattern. The schematic diagram of coalescer in this study is shown in Figure 2.14. In all experiments, the steady-state was established from the beginning of the experiment by pre-oiling of the coalescing fiber. Fluid velocity applied in this study was 7 m/h in every experiment with constant temperature of 35 °C. Oil concentration in water was investigated by IR spectrometry. It was found that the designed bed coalescer provided effective oil removal from heavily polluted wastewater where effluent oil concentration was less than 15 g/l in whole experiment. The oil separation efficiency was dependent on inlet oil concentration and droplet size. Moreover, higher performance of coalescer was obtained from the special design and application of two medium materials. The design flow orientation provided inertia force, which was one of dominant separation mechanisms. The oil removal mainly occurred by two different mechanisms: coalescence of oil droplets at water surface and capture in the coalescing bed.

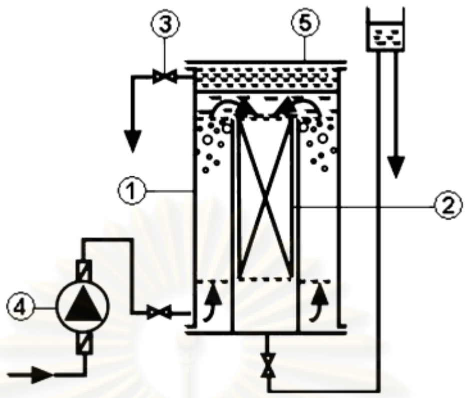


Figure 2.14 Schematic diagram of the coalescer

According to many researches, study of cutting oil emulsion treatment by coalescer process was still rarely conducted. The applied flow velocity was in the range of 0.2 – 6.8 cm/s and 0.5 – 40 cm bed height. Moreover, the coalescer reactor in each research was different in shape, flow orientation, and dimension. Polypropylene (PP) polymer was employed as medium in various studies. Therefore, PP plastic was selected as applied coalescing media in this study. Flow velocity at relatively high range (2.0 – 6.8 cm/s) and bed height of 2 – 10 cm were applied in this study. Note that the selected operating conditions were in the same range of other reviewed study.

As mentioned above, the coalescer processes have been studied in many aspects, for example, the mechanisms in coalescer, coalescence of dispersed phase with in the media bed, the effects of bed type and various operating conditions on the treatment efficiency. The results have shown that the treatment performances of coalescer for oily emulsion separation were still low, and also an imprecise treatment mechanism based on interaction between oil and coalescer media has been existed. Moreover, clogging in coalescer bed as well as costly media was the problems in application of coalescer process for treating oily wastewater. To fill this gap, the objective of this study is to analyze locally the coalescer system in terms of media characteristics and operating conditions. Moreover, different techniques will be applied in order to enhance the oil separation efficiency: liquid recirculation in coalescer column and step media bed configuration concepts as well as improvement of decantation tank. Finally, a mathematical model will be applied for providing the better understanding on treatment mechanism and also the effect on efficiencies of the process.

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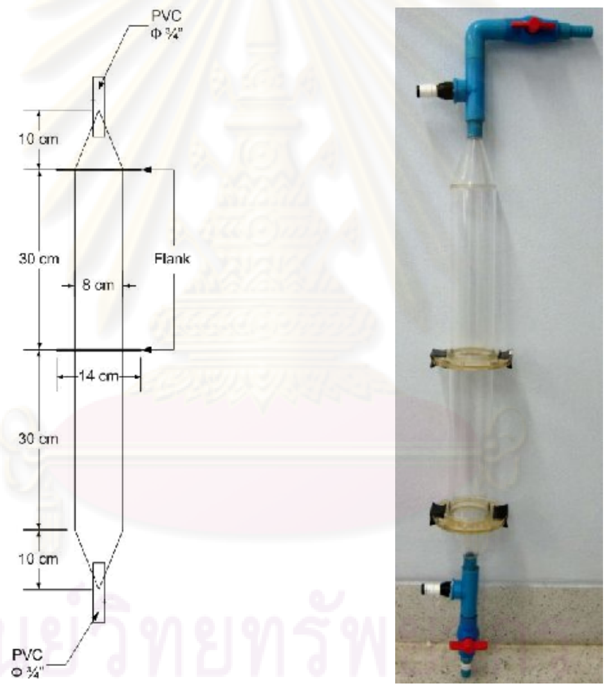
CHAPTER III
METHODOLOGY

3.1 Materials

3.1.1 Equipments

1. Coalescer apparatus was cylindrical column made from clear acrylic with 8 cm-in-diameter and 80 cm-in-height as displayed in Figure 3.1.



(a) (b)

Figure 3.1 Coalescer column used in this experiment

2. Coalescing bed used in this study was polypropylene (PP) plastic in 3 different types including granular, fibrous, and tubular shape as illustrated in Figure 3.2.

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(a) (b) (c)

Figure 3.2 Coalescing media used in this study: (a) granular PP; (b) fibrous PP; and (c) Tubular PP

3. Decantation tank was clear cylindrical acrylic column with 8 cm in diameter and 40 cm-in-height as displayed in Figure 3.3.

Figure 3.3 Decantation column employed in this study

4. Salting out device was stainless steel mesh with 8 cm diameter as displayed in Figure 3.4.

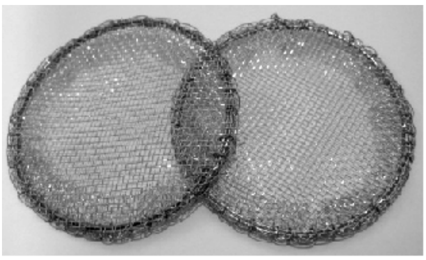

Figure 3.4 Salting out device

5. Settling column was made from clear acrylic with 5 cm-in-diameter of cylindrical shape. The height of column was 200 cm with every 10 cm interval sampling point.
6. Submersible pump, Jun, with maximum flowrate and head of 200 LPH and 2 m, respectively.
7. Agitator
8. Optical microscope: Nikon YS2-H
9. Stage and ocular microscope
10. Liquid rotameter: New-Flow Technologies, Inc.
11. Compact digital camera: Canon IXY 920is
12. Emulsion storage 8 gallon tank
13. Equipment set of COD test
    - Tube size 16 x 150 mm with tetrafluoroethylene (TFE) cap
    - Hot air oven 600, Memmert, Germany
    - Volumetric flask
    - Cylinder
    - Pipet
14. Turbidimeter: Lovibond PCcheckit

3.1.2 Chemical agents used in this study

1. Cutting oil, Castrol Cooledge BI, was purchased from Castrol Co., Ltd. The characteristics of Castrol Cooledge BI are exhibited in Table 3.1. Note that the presented anionic surfactant in cutting oil was sulfonate group surfactant.

Table 3.1 Physical characteristics of cutting oil used in this study

Relative density (at 21ºC)	0.898
Kinetic viscosity (at 25 ºC) (cps)	9.13
Appearance	White, milky emulsion
pH (at 5% concentration)	9.5
Surface tension (mN/m)	30.963

2. Destabilization agents:
   - Calcium chloride ($CaCl_2$) was purchased from Ajax Finechem Ptl Ltd.
3. Potassium dichromate digestion ($K_2Cr_2O_7$) was purchased from Ajax Finechem Ptl Ltd.
4. Concentrate sulfuric acid (Conc. H_2SO_4) was purchased from J.T. Baker
5. Silver sulfate (Ag_2SO_4) was purchased from Merck Chemical co.
6. 1-10 Phenantroline was purchased from Ajax Finechem Ptl Ltd.
7. Ferrous Ammonium Sulfate ($Fe(NH_4)_2(SO_4)_2 6H_2O$) was purchased from Ajax Finechem Ptl Ltd.
8. Sodium dodecyl sulfate (SDS) was purchased from Carlo Erba Co.,Ltd. The characteristics of SDS are shown in Table 3.2.

Table 3.2 Characteristics of SDS

IUPAC name	Sodium dodecyl sulfate
Other names	Sodium monododecyl sulfate; Sodium lauryl sulfate; Sodium monolauryl sulfate; Sodium dodecanesulfate; dodecyl alcohol, hydrogen sulfate, sodium salt; n-dodecyl sulfate sodium; Sulfuric acid monododecyl ester sodium salt;
Molecular formula	$C_{12}H_{25}SO_4Na$ ()
Molar mass	288.38 g mol^{-1}
Density	1.01 g/cm^3
Melting point	206 °C
CMC	The critical micelle concentration in pure water at 25°C is 0.0082 M

9. DI water

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3.1.3 Experimental apparatus set-up

The configuration of process including lab scale coalescer and decantation tank is displayed in Figure 3.5.

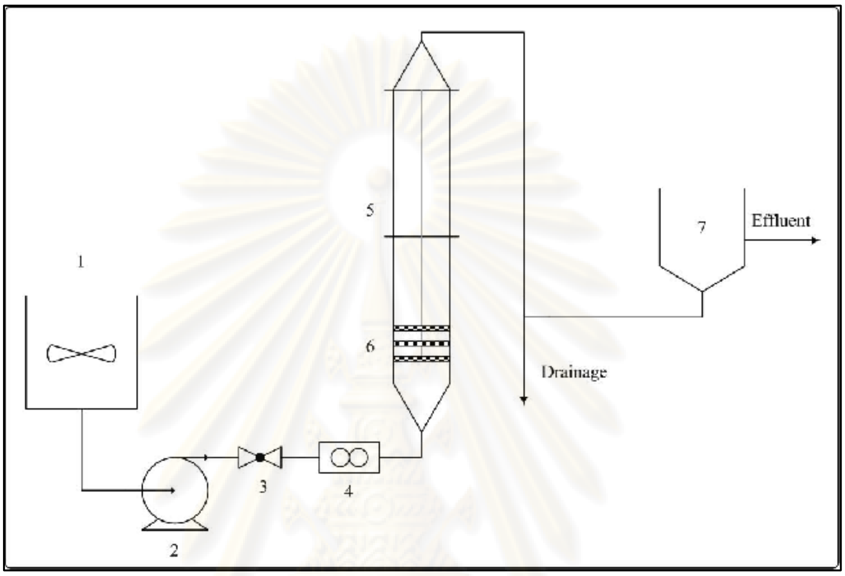

Figure 3.5 Experimental set-up

The processes can be divided into 3 parts: 1) emulsion generation part, 2) coalescer unit, and 3) decantation tank. Oil and water in storage tank (1) was mixed by the turbine for generating the oily emulsion and then pumped by to the coalescer unit (5), which comprise 10 cm diameter circular column with 80 cm height and coalescer media (6) by the centrifugal pump (2). The flowrate through the coalescer was controlled by globe valve (3) and measuring by flow regulating meter (4). The effluent from coalescer will be separated and then entered to the decantation tank (7).

3.2 Experimental procedures

This research was divided into 5 steps as illustrated in Figure 3.6.

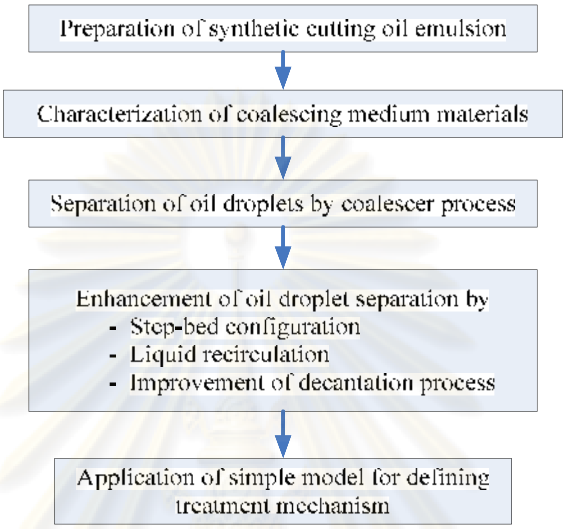

Figure 3.6 Overall experimental procedures in this research

3.2.4.1 **Preparation of synthetic cutting oil emulsion**

The oily emulsion used in this study was synthesized at the oil concentration of 1 g/l in water by mixing cutting oil and water in the emulsion storage tank with stirring agitator. The characteristics of prepared cutting oily-emulsion (viscosity, density, surface tension, turbidity, and COD) were determined by standard method (APHA, AWWA, and WEF, 1998) in order to well define and control the obtained liquid phases under test. The preparation process and measured variables are shown in Figure 3.7 and Table 3.3, respectively. The prepared emulsion was verified for required concentration by analyzing turbidity of wastewater.

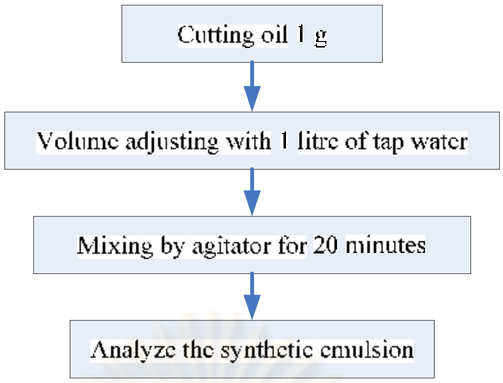

Figure 3.7 Preparation process of synthetic cutting oil emulsion

Table 3.3 Measured variables for the synthetic cutting oil emulsion

Fixed Variables	**Parameters**
Type of oil	Cutting oil
Concentration of emulsion	1 g/l
Temperature	Room temperature
Type of water	Tap water
Dependent Variables	**Parameters**
Surface tension	Surface tension
Interfacial tension between oil and water	Interfacial tension
Oil concentration	COD Turbidity
Emulsion viscosity	Viscosity
Oil droplet size	Droplet mean diameter

3.2.2 Characterization of coalescing medium materials

Consider the attachment of oil on the coalescing medium material in water displays in Figure 3.8.

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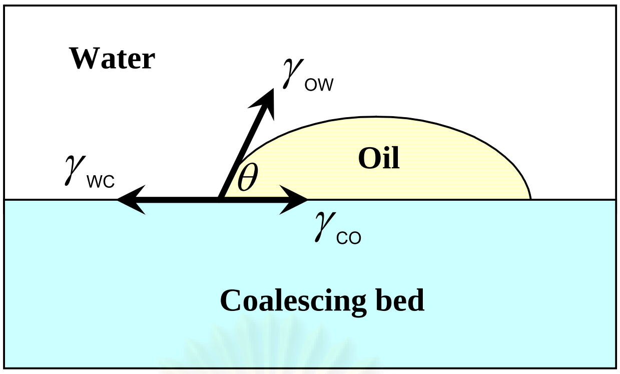


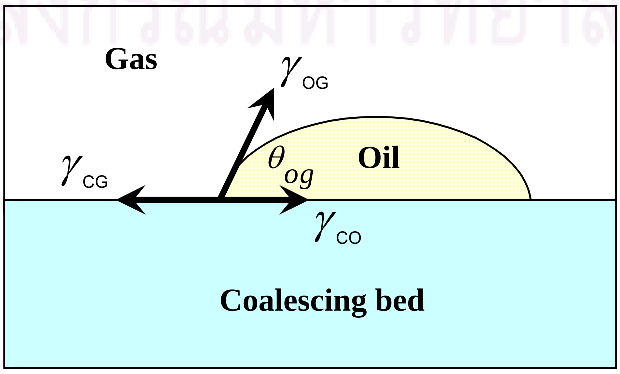
Figure 3.8 Free body diagram of interfacial tension of oil droplet on coalescing medium in water

According to Young's equation (Aurelle, 1985) as in Equation 3.1

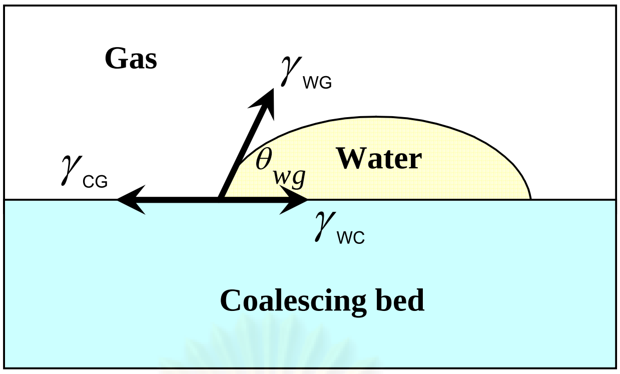
$$\gamma_{wc} = \gamma_{co} + \gamma_{ow} \cos\theta \quad (3.1)$$

Where γ_{wc} is interfacial tension between water and medium;
γ_{co} is interfacial tension between medium and oil droplet;
γ_{ow} is interfacial tension between oil and water; and
θ is contact angle of oil droplet on medium

From Equation 3.1, it was found that every interfacial tension values have to be known in order to determine the contact angle (θ). However, interfacial tension values between water and oil to the medium within water phase are difficultly determined. Therefore, interfacial tension between oil and water to medium within air atmosphere were determined as displayed in Figure 3.9.



(a)



(b)

Figure 3.9 Surface tension of (a) oil droplet; and (b) water droplet on coalescing medium in air atmosphere

From Figure 3.10, Equation 3.2 and 3.3 were obtained through applying Young's equation.

$$\gamma_{cg} = \gamma_{co} + \gamma_{og} \cos \theta_{og} \quad (3.2)$$

$$\gamma_{cg} = \gamma_{cw} + \gamma_{wg} \cos \theta_{wg} \quad (3.3)$$

Nevertheless, γ_{cg} was unknown variable Equation 3.2 and 3.3. This value is the specific property of material, which is called "critical surface tension" of material. This γ_{cg} can be determined by several methods. Zisman method is one of widely used method to evaluate the critical surface tension via dropping liquid with known different surface tension on material surface and evaluate the contact angle of each drop (Zisman, 1964). By linearly plotting between the cosines of obtained contact angles with surface tension as illustrated in Figure 3.10, the γ_{cg} can be achieved as the surface tension where cosθ equals to 1.

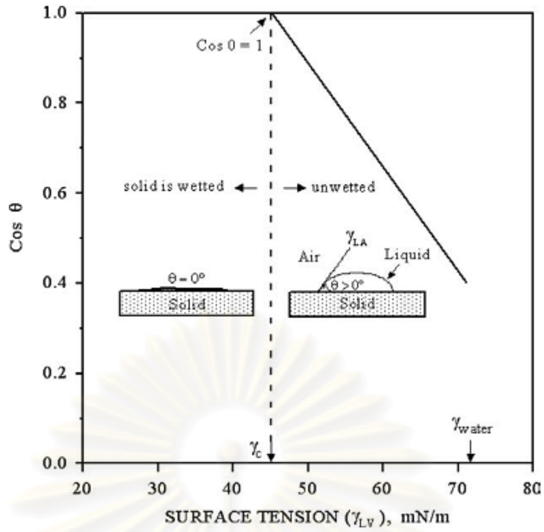


Figure 3.10 Schematic representation for critical surface tension (γ_{cg}) determination by Zisman plot (Ozkan, 2004)

As replace γ_{cg} in Equation 3.2 and 3.3, γ_{co} and γ_{cw} can be evaluated. Finally, the contact angle (θ) was obtained.

According to Equation 3.1, it can be noted that hydrophobicity of medium material can be evaluated via calculated contact angle (θ) where more hydrophilic surface provides smaller contact angle. The hydrophobicity is the essential factor for selecting material as coalescing medium. Hence, the hydrophobicity of medium material used in this study (i.e. polypropylene) was determined for selecting appropriate coalescing medium types applied in the research. The characterization of coalescing media was divided into 2 parts as following:

3.2.2.1 Determination of medium's critical surface tension (γ_{CG})

The critical surface tension (γ_{cg}) of PP was determined by Zisman method as illustrated in Figure 3.11. The measured variables are shown in Table 3.4.

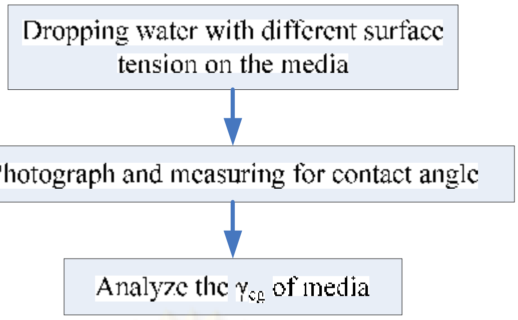


Figure 3.11 Critical surface tension determinations by Zisman method

Table 3.4 Measured variables for the determination of γ_{CG} by Zisman method

Fixed Variables	**Parameters**
Type of water	Tap water
Type of surfactant	SDS
Independent Variables	**Parameters**
Concentration of surfactant	0 – 0.008 M
Media type	Polypropylene
Dependent Variables	**Parameters**
Critical surface tension of medium material	Critical surface tension of medium material

3.2.2.2 Measurement of contact angle of oil and water droplet on medium

The contact angle of oil and water droplets on coalescing medium were measured for evaluating the hydrophobicity of polypropylene (PP) with 3 different forms; for example, granular, fibrous, and tubular shape. The measurement method is displayed in Figure 3.12, and the measured variables are shown in Table 3.5.

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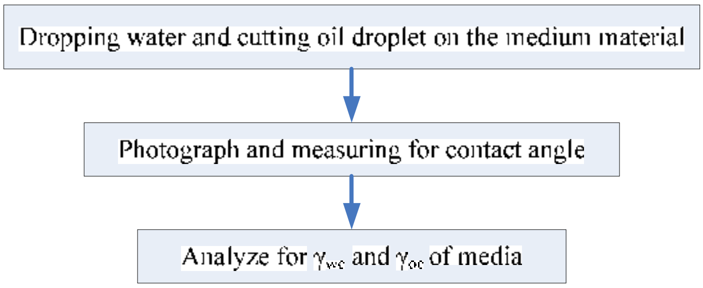

Figure 3.12 Measurement of contact angle

Table 3.5 Measured variables for contact angle measurement

Fixed Variables	**Parameters**
Type of water	Tap water
Type of surfactant	SDS
Independent Variables	**Parameters**
Concentration of surfactant	0 – 0.008 M
Media type	Polypropylene
Dependent Variables	**Parameters**
Critical surface tension of medium material	Critical surface tension of medium material

3.2.3 Separation of oil droplets by coalescer process

The objective of this section is to determine the optimum operating conditions, for instance, coalescing medium types, medium bed height, and wastewater velocities, for treating cutting oil emulsion by conventional coalescer process. The batch process was applied in this section with 3 different medium types including granular, fibrous, and tubular-shaped polypropylene (PP). The treatment efficiencies were evaluated via the reduction of COD and turbidity of the wastewater. Moreover, the droplet volume distribution of oil in water was also determined. The results obtained in this section were proper type and height of the coalescing medium as well as the optimal wastewater velocity that provided highest treatment efficiency of coalescer process. These operating will be further applied in the later studies. However, it should be noted that temperature of emulsion in this study was varied in the range of 25$\pm$2 °C due to the limitation of instruments. The study in this section can be divided into 2 parts including:

3.2.3.1 Kinetic study of oily emulsion treatment by conventional coalescer process

The kinetic study is aim to determine the saturation time of emulsion treatment by coalescer and decantation process. The experimental procedure and measured variables are shown in Figure 3.13 and Table 3.6, respectively. This saturation time will be applied in the sequential study.

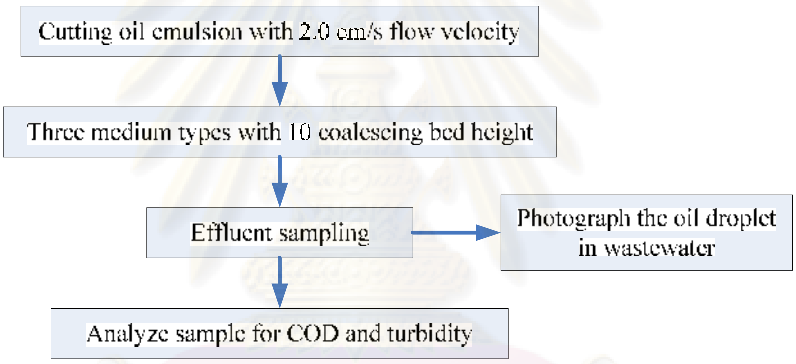

Figure 3.13 Determination the kinetic time of treatment process

Table 3.6 Measured variables for kinetic study

Fixed Variables	**Parameters**
Wastewater velocity	2.0 cm/s
Medium bed height	10 cm
Concentration of emulsion	1 g/L
Independent Variables	**Parameters**
Coalescing medium types	Granular, fibrous, and tubular PP
Sampling time	Every 30 minutes until reach 240 minutes
Dependent Variables	**Parameters**
Treatment efficiency	COD and turbidity

3.2.3.2 Investigation of appropriate operating condition for oil separation by coalescer process

The objective of this study is to determine the optimal operating condition of oily emulsion treatment by hybrid process between coalescer and decantation. The conditions varied in this study included 3 medium types (i.e. granular, fibrous, and tubular polypropylene), 4 wastewater velocities (i.e. 2.0, 3.4, 4.8, and 6.8 cm/s), and 5 coalescing medium heights (i.e. 2, 3, 5, 7, and 10 cm). The study procedure is illustrated in Figure 3.14 and the measured variables are shown in Table 3.6.

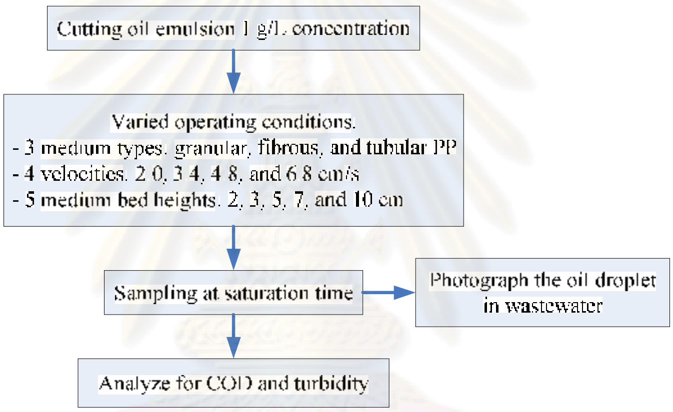

Figure 3.14 Investigation of appropriate operating condition

Table 3.7 Measured variables for appropriate operating condition

Fixed Variables	**Parameters**
Concentration of emulsion	1 g/L
Sampling time	Obtained from Experiment 3.2.3.1
Independent Variables	**Parameters**
Coalescing medium types	Granular, fibrous, and tubular-shaped polypropylene
Wastewater velocities	2.0, 3.4, 4.8, and 6.8 cm/s
Coalescing medium height	2, 3, 5, 7, and 10 cm
Dependent Variables	**Parameters**
Treatment efficiency	COD and turbidity
Oil droplet size distribution	Oil droplet size distribution

3.2.4 Enhancement of oil droplets separation

In order to enhance oil separation from oily emulsion by the hybrid process, several methods were applied in batch process operation, for instance, step-bed configuration, chemical coagulation, and liquid recirculation. The treatment efficiencies in term of COD and turbidity reduction were determined as well as oil droplets size distribution. The operating conditions used in this study were determined from Experiment 3.2.3.2. This study section can be divided into 3 parts as following:

3.2.4.1 Enhancement of treatment efficiency by step-bed configuration

The stage coalescer (step-bed configuration) was applied for improving oily emulsion treatment efficiency. The step-bed configuration can be illustrated in Figure 3.15, where the numbers of steps were varied as 1, 2, 4, and 5 steps.

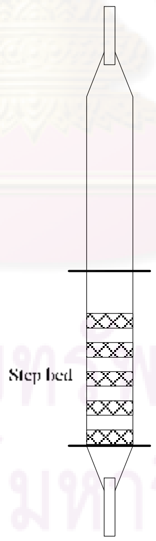

Figure 3.15 Stage coalescer (step-bed configuration)

The medium height used in this study was obtained as the proper height from Experiment 3.2.2.2 and divided into 2, 4, and 5 beds, then sampling at the saturation time. The study method and measured variables are shown in Figure 3.16 and Table 3.7, respectively.

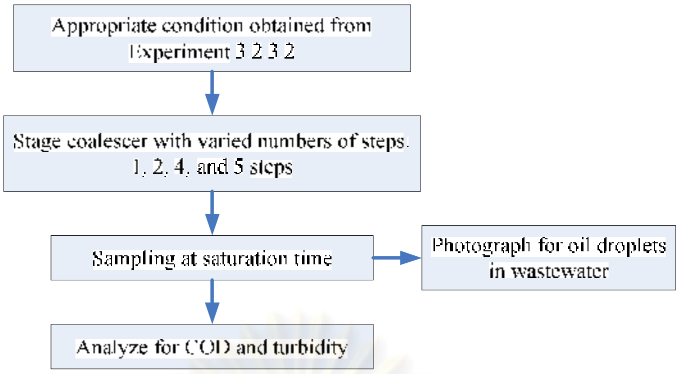

Figure 3.16 Step bed configuration study

Table 3.8 Measured variables for stage coalescer study

Fixed Variables	**Parameters**
Concentration of emulsion	1 g/L
Sampling time	Obtained from Experiment 3.2.3.1
Wastewater velocity	Obtained from Experiment 3.2.3.1
Coalescing medium height	Obtained from Experiment 3.2.3.1
Coalescing medium types	Obtained from Experiment 3.2.3.2
Independent Variables	**Parameters**
Number of step bed	1, 2, 4, and 5 steps
Dependent Variables	**Parameters**
Treatment efficiency	COD and turbidity
Oil droplet size distribution	Oil droplet size distribution

3.2.4.2 Enhancement of treatment efficiency by liquid recirculation

The objective of this section was to study the effect of wastewater recirculation on the treatment efficiency of coalescer process. The ration of recirculation was varied as 20, 50, 80, and 100 percent, where the operating condition was obtained from Experiment 3.2.3.2. The experiment procedure and measured variables are displayed in Figure 3.17 and Table 3.8, respectively.

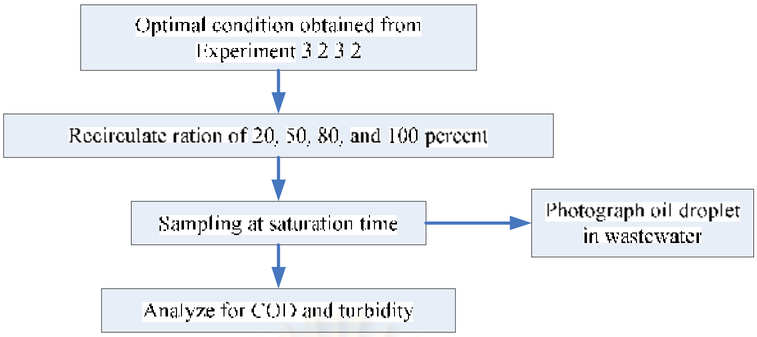

Figure 3.17 Study the effect of liquid recirculation

Table 3.9 Measured variables for effect of liquid recirculation

Fixed Variables	**Parameters**
Concentration of emulsion	1 g/L
Sampling time	Obtained from Experiment 3.2.3.1
Wastewater velocity	Obtained from Experiment 3.2.3.1
Coalescing medium height	Obtained from Experiment 3.2.3.1
Coalescing medium types	Obtained from Experiment 3.2.3.2
Independent Variables	**Parameters**
Recirculate ration	20, 50, 80, and 100%
Dependent Variables	**Parameters**
Treatment efficiency	COD and turbidity
Oil droplet size distribution	Oil droplet size distribution

3.2.4.3 Improvement of decantation process efficiency

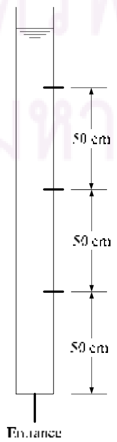

Figure 3.18 Schematic diagram of settling column

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In order to improve the efficiency of decanter, the discrete settling study was determined. This experiment was aim to study the characteristic of oil droplets settling in the decantation tank, which the results can be applied for effective oil decanter design. The settling column is illustrated in Figure 3.18. The experiment procedure and measured variables in this study are displayed in Figure 3.19 and Table 3.9, respectively.

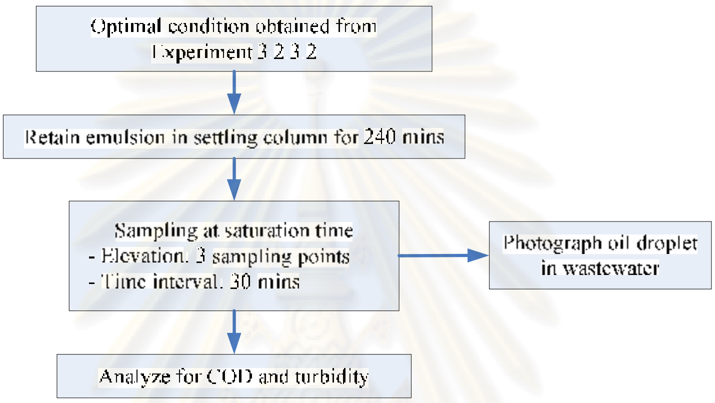


Figure 3.19 The discrete settling study

Table 3.10 Measured variables for effect of discrete settling study

Fixed Variables	**Parameters**
Concentration of emulsion	1 g/L
Sampling point	50, 100, and 150 cm from entrance
Wastewater velocity	Obtained from Experiment 3.2.3.1
Coalescing medium height	Obtained from Experiment 3.2.3.1
Coalescing medium types	Obtained from Experiment 3.2.3.2
Independent Variables	**Parameters**
Sampling time	30 mins time interval until 240 mins
Dependent Variables	**Parameters**
Treatment efficiency	COD and turbidity
Oil droplet size distribution	Oil droplet size distribution

3.2.5 Application of simple model for defining the treatment mechanism

In this part, the simple model regarding the treatment efficiency was applied for describing the occurred treatment mechanism. The single collision efficiency (η_T) and attachment efficiency (α) were determined and considered as main treatment mechanisms of coalescer process as well as the efficiency of decantation process. Finally, the effects of operating condition on the overall treatment efficiencies were defined by the model.

3.3 Analytical methods

The analytical methods in this study are summarized in Table 3.10.

Table 3.11 Analytical parameters in this study

Parameters		Instrument/Method
Oil Concentration	COD	Closed reflux, titrimetric method [5220 C] (APHA, AWWA, and WEF 1998)
	Turbidity	Turbidimeter
Surface tension		Tensio meter
Liquid flowrate		Liquid rotameter
Coalescing medium height		Measured tape
Emulsion viscosity		Viscosimeter
Removal efficiency		$\%Eff = \frac{COD_{in} - COD_{out}}{COD_{in}}$
Oil droplet volume distribution		Microscopic method

The microscopic method for determining oil droplet size and volume distribution can be described by applying microscope. Ocular and stage microscope, which contained length scale, were used for calibrating oil droplet size. The photograph was taken under 400-time magnification and then measured for diameter comparing with the scale. The obtained data were manually sorted, analyzed, and constructed the distribution of droplet size and volume.

CHAPTER IV
RESULTS AND DISCUSSION

The results presented in this chapter were based on the series of experiments conducted during the course of this study and can be divided into five parts. The first and second parts present the properties of synthetic cutting oily emulsion wastewater and the characterization of coalescing medium material, respectively. Moreover, the two consecutive parts describe the treatment of oily emulsion wastewater by hybrid process comprised of coalescer and decantation reactor, and then the separation efficiencies of oil droplets will be enhanced by several techniques including stage coalescer, liquid recirculation, and improvement of decantation efficiency. Finally, the simple model will be proposed and applied for providing a better understanding on the cutting oily-wastewater treatment efficiency obtained with the combined coalescer and decantation processes.

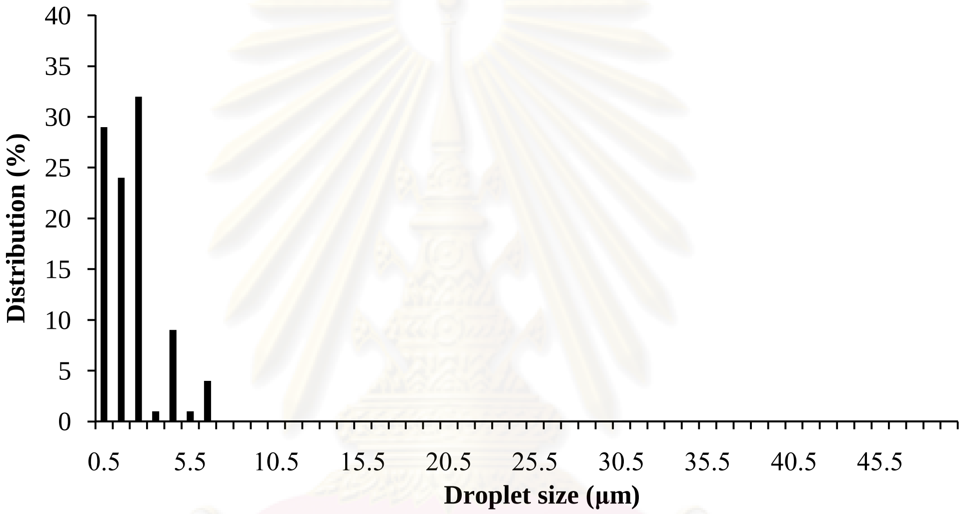
4.1 Properties of synthetic cutting oil emulsion wastewater

The synthetic emulsion prepared at 1 g/l concentration was determined in terms of several characteristic parameters; for example, COD, turbidity, oil droplet size distribution, viscosity, and surface tension. The appearance of cutting oily wastewater was milky emulsion. The droplet size of emulsion was determined by two different method such as mean diameter (D_{mean}) and Sauter mean diameter (D_{32}) as expressed in Equation 4.1 and 4.2, respectively.

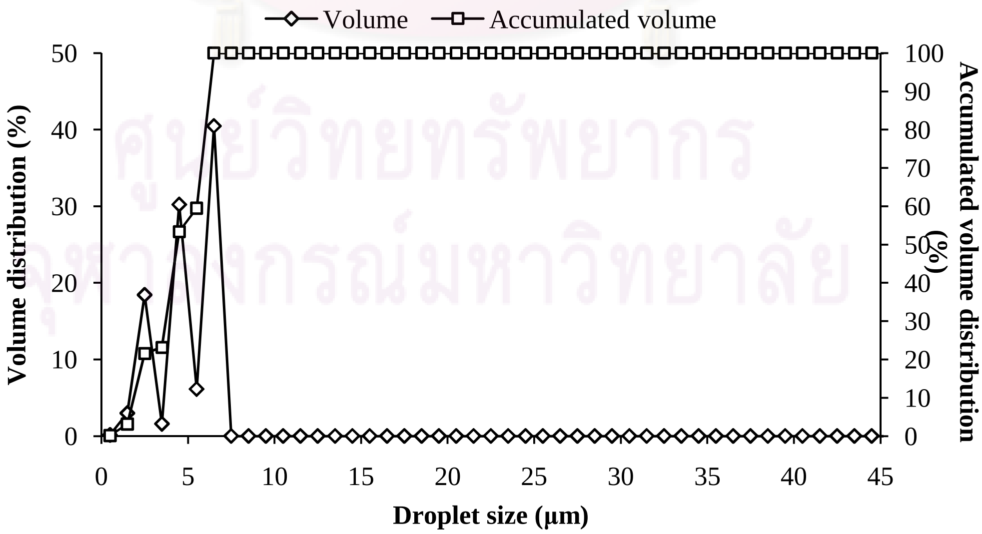
$$D_{mean} = \frac{\sum_{i=1}^{n} D_i}{n} \qquad (4.1)$$

$$D_{32} = \frac{\sum_{i=1}^{n} D_i^3}{\sum_{i=1}^{n} D_i^2} \qquad (4.2)$$

These obtained oil droplet diameters are different as seen in Equation 4.1 and 4.2. The mean diameter (D_{mean}) is calculated based on number of droplets, whereas, Sauter mean diameter (D_{32}) is mainly calculated dependent on spherical shape, which contains equal volume-to-surface area ratio. This Sauter mean diameter is frequently applied where the active surface or surface area is important (e.g. catalysis or combustion) (Gibbs, 1999). The droplet sizes in sample were analyzed by optical microscope with ocular and stage microscope. The sample emulsions were magnified for 400 times and photograph. The droplet sizes were measured for diameters and then calibrating for actual size by the scale on ocular and stage microscope. The size distributions were plotted as percentage size distribution and accumulated volume distribution (Chooklin, 2004).



(a)



(b)

Figure 4.1 (a) Oil droplet size distributions; and (b) accumulated volume distributions of synthetic cutting oil emulsion

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Table 4.1 Characteristics of synthetic cutting oil emulsion

Parameters	Values
Turbidity (NTU)	≈ 1,200
COD (mg/l)	≈ 1,600
viscosity (cps)	9.16
Zeta potential (mV)	- 52
Oil droplet mean diameter (μm)	1.95
Oil droplet Sauter mean diameter (μm)	4.12

The characteristics of synthetic emulsion are summarized in Table 4.1. Moreover, the size and accumulated volume distribution of oil droplets in synthetic emulsion are displayed in Figure 4.1, where the mean and Sauter mean diameters were 1.95 μm and 4.12 μm, respectively. The accumulated volume distribution of oil droplets in emulsion can be defined as the calculated oil volume for each droplet size and plotted with the droplets' diameters. This distribution represented the composition of oil quantity presented in water in terms of volume of each droplet's size. Photograph of oil droplets in wastewater with 40-times magnification is illustrated in Figure 4.2.

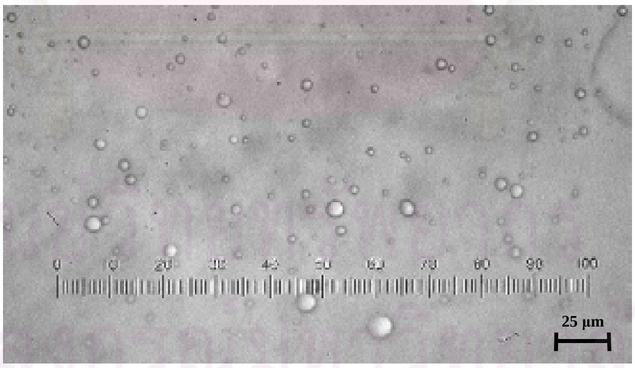


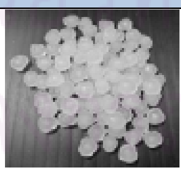
Figure 4.2 Photograph of oil droplet in synthetic emulsion

As can be seen in Figure 4.1, the droplet size in range of 2.5 μm was dominant in the overall size distribution as 32% presented in wastewater. Therefore, this emulsion can be classified as the secondary emulsion types due to the droplets diameter (< 20 μm). According to Stoke's law (Equation 2.1), the calculated rising velocity of the 4.12 μm is 1.06 x 10^{-6} m/s, in other words, the droplet required approximately 11 days for 1 m rising. Note that viscosity of cutting oil was relatively much lower than other oil types, for instance, 88.6 cps for palm oil (Kongkangwarn, 2009), 145 cps for lubricating oil SAE30, and 172.5 cps for diesel (Ji *et al.*, 2009). Moreover, it can be stated that turbidity and COD of the wastewater were varied with the quantity of cutting oil presented of water. The zeta potential of synthetic wastewater indicated that the oil droplets in the emulsion contained high negatively charges (Ríos *et al.*, 1997). Hence, from the zeta potential and oil droplet size results, it can be stated that this synthetic cutting oil wastewater had a very high stabilization, which required the effective process for treatment.

4.2 Characterization of coalescing medium materials

The objective of this part was to determine the characteristics of coalescing medium in different shapes (granular, fiber and tubular) of polypropylene-based materials. The characteristics of the media are shown in Table 4.2. The hydrophobicity, which is the important property of material used as coalescing medium, was also determined in terms of contact angle between oil droplet and medium in water phase and critical surface tension of the medium materials.

Table 4.2 Characteristics of coalescing medium polypropylene (PP) in this study

Characteristics	**Polypropylene**		
	Granular	**Fiber**	**Tubular**
Appearance			
Porosity (%)	0.5512	90.34	81.77
Density of PP (kg/m^3)	855	855	855
Dimension (mm)	4 – 5 (Diameter)	10 x 280 x 0.5 (Width x Length x Thickness)	5 x 8 (Diameter x Height) 4 mm of inner diameter

The porosities of medium bed used in this study were determined by water saturation method, which defined as replacement of void volume with water (Gleabey *et al.*, 1991). The replaced water was measured for mass that indicated the pore volume in the packed bed. It can be noted that the media porosities of both fibrous and tubular PP used in this study were slightly lower than those obtained by other researches; for example, media porosities of 0.90 to 0.95 and 0.966 were obtained by Vasudevan and Chase (2004) and Speth *et al*. (2002), respectively. Except for the granular shape, the porosity was roughly closed to that of a sand medium, which is used in the conventional filtration process (typically 0.40-0.45) (AWWA and ASCE, 1990). The sizes of different PP types applied in this study were quite larger than that used in other study, for instance, Li and Gu (2005), Vasudevan and Chase (2004), and Ji (2008). Therefore, the difference in size, porosity, and shape of coalescing medium might impact to the overall treatment efficiency of coalescer process and also the mechanisms occurred within the medium bed, which was studied in the consequent section.

4.2.1 Critical surface tension (γ_{CG}) of coalescing medium determination

The critical surface tension (γ_{CG}) of the coalescing medium was determined by using Zisman method, which defined as dropping of water with different surface tension adjusted by SDS on the material and then measure for contact angle (Zisman, 1964). Note that the coalescing medium applied in this study was the same material type – polypropylene. The results for critical surface tension (γ_{CG}) are shown in Table 4.3 and Figure 4.3.

Table 4.3 The results of critical surface tension of PP by Zisman method

SDS concentration (M)	Surface tension (mN/m)	Contact angle (degree)	cos θ
0	72	79.8	0.18
0.001	67	65.8	0.41
0.002	59	52.1	0.61
0.004	48	24.2	0.91
0.006	42	18.9	0.95
0.008	40	13.3	0.97

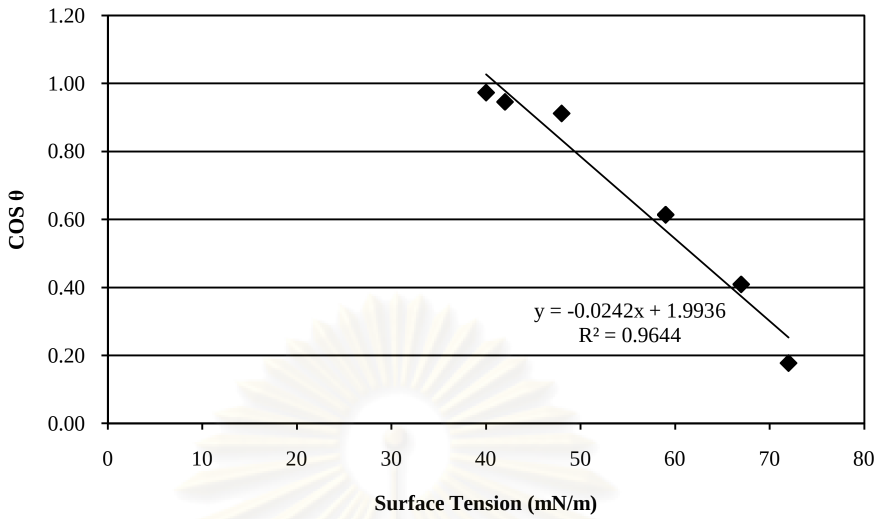


Figure 4.3 Zisman plot for determination of critical surface tension of coalescing medium

From Figure 4.3, critical surface tension (γ_{CG}) of PP, which is tension where cos θ equals to 1, was 41.10 mN/m obtained from calculation. This value was greater than that report by Sabreen (Sabreen, 1991), which in range of 29 – 31 dynes/cm (29 – 31 mN/m). The critical surface tension of polypropylene implied to the low surface energy of material that related to the contact angle of liquid on its surface. The critical surface tension of PP was lower than other materials; for example, polyester (41 – 44 dynes/cm) and nylon (33 – 46 dynes/cm). The low energy surface can be classified as hydrophobic material since water, which is high energy liquid, will not spread on the low energy surface those results in hydrophobicity of material (Zisman, 1964). Therefore, the hydrophobic polypropylene was suitable for using as coalescing medium.

4.2.2 Measurement of contact angle between oil droplet and medium in water

From Young's equation (Equation 3.1) (Aurelle, 1985), contact angle between oil droplet and coalescing medium in water can be calculated from interfacial tension of water and oil droplet on medium material in air, since the measurement of contact angle of oil droplet on medium's surface in water was difficult to provide the accurate experimental values.

$$\gamma_{WC} = \gamma_{CO} + \gamma_{OW} \cos\theta \qquad (3.1)$$

Where, γ_{WC} is interfacial tension between water and medium. The γ_{CO} and γ_{OW} are interfacial tension between medium and oil droplet and between oil and water, respectively. θ is contact angle of oil droplet on medium in water. The results are shown as following:

4.2.2.1 Determination of interfacial tension between oil droplet and medium (γ_{OC})

The interfacial tension between oil droplet and medium and the contact angle between oil droplets on three different coalescing medium types obtained from this study are exhibited in Table 4.4. Photographs of oil droplets on the coalescing media are displayed in Figure 4.4.

Table 4.4 Interfacial tension between oil and different medium types

Parameters	**Polypropylene**		
	Granular	**Fiber**	**Tubular**
Contact angle (degrees)	11.8	12.7	13.7
cos θ	0.9790	0.9755	0.9715
γ_{CG} (mN/m)	41.10	41.10	41.10
γ_{OG} (mN/m)	30.96	30.96	30.96
γ_{CO} (mN/m)	10.79	10.89	11.02

(a) (b) (c)

Figure 4.4 Cutting oil droplet on coalescing medium: (a) granular PP; (b) fibrous PP; and (c) tubular PP

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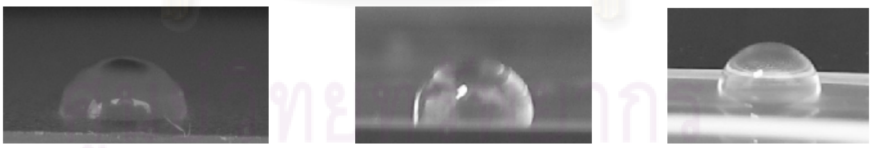
4.2.2.2 Determination of interfacial tension between water droplet and medium (γ_{WC})

The interfacial tension between water droplet and medium and the contact angle between water droplets on three different coalescing medium types obtained from this study are exhibited in Table 4.5. Photographs of oil droplets on the coalescing media are displayed in Figure 4.5. It can be noticed that the contact angles of water on three media were not different since they were all polypropylene-based materials that provided the same surface energy; thus, the same contact angles were obtained.

Table 4.5 Interfacial tension between water and different medium types

Parameters	**Polypropylene**		
	Granular	**Fiber**	**Tubular**
Contact angle (degrees)	79.8	79.6	79.8
cos θ	0.1765	0.1805	0.1771
γ_{CG} (mN/m)	41.10	41.10	41.10
γ_{OG} (mN/m)	72.00	72.00	72.00
γ_{CW} (mN/m)	28.39	28.10	28.35



(a) (b) (c)

Figure 4.5 Water droplets on coalescing medium: (a) granular PP; (b) fibrous PP; and (c) tubular PP

From interfacial tension between oil and water droplet to coalescing medium, the contact angle of oil droplet on media in water can be calculated by Young's equation (Equation 3.1). The interfacial tension between cutting oil and water was 47.02 mN/m measured by tensiometer. Then the calculated contact angles (θ) as displayed in Figure 4.6 were obtained. The contact angles of oil droplet on granular, fibrous, and tubular PP in water were 68.01, 68.53 and 68.37 degrees, respectively. These angles exhibited that these medium materials contain hydrophobic surface, since the contact angles of oil droplets were less than 90 degrees (Aurelle, 1985). Note that these contact angles were smaller than reported in other research, for instance, 87.88 and 90.97 degrees for polyester base and stainless steel SS304 fibrous materials (Kongkangwarn, 2009), respectively. The hydrophobicity of these materials indicated that they could be applied as a coalescing medium as the oil droplets can attach on the surface of medium. Hence, the separation of oil from water will be studied in the next experiment by applying all three PP types as the coalescing medium.

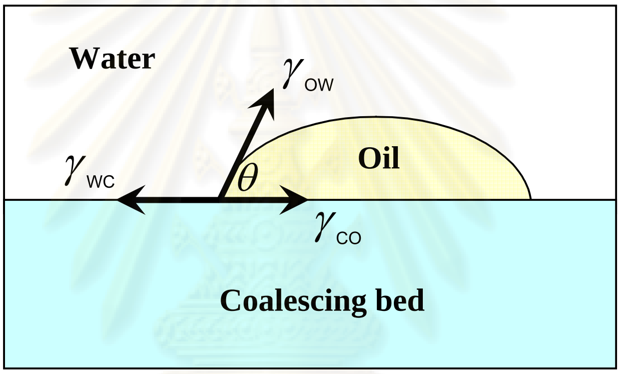


Figure 4.6 Contact angle (θ) of oil droplet on coalescing medium in water

4.3 Separation of oil droplets by hybrid process between coalescer and decantation

In this part, the influences of different operating conditions on the oily emulsion treatment of conventional coalescer process were determined by applying the granular, fibrous and tubular polypropylene as the coalescing media. The parameters studied in this study were coalescing medium types, medium bed height, and flow velocity of oily wastewater. Moreover, the separation efficiencies of decantation were also determined. The overall efficiency of the hybrid process between coalescer and decantation were the summation of efficiency of each process. This section was consisted of kinetic study results and determination of optimal condition for oil separation by hybrid process.

4.3.1 Kinetic study of oil droplets separation by hybrid process

In order to evaluate firstly the saturated time of the treatment process, the kinetic study of the system were determined. The operating condition used for determining the kinetic study was 2.0 cm/s flow velocity and medium bed height of 10 cm, since the saturated time of this condition might be longest due to the applied slowest flow velocity. The result is shown in Figure 4.7 as the highest efficiencies were achieved at 120 minutes for 25.64, 26.62, and 42.28% for granular, fibrous, and tubular PP, respectively. After that, the treatment efficiencies tend to be stable conditions. Therefore, it can be concluded that the saturated time of the hybrid process between coalescer and decantation was 120 minutes, which will be applied in the subsequent experiments.

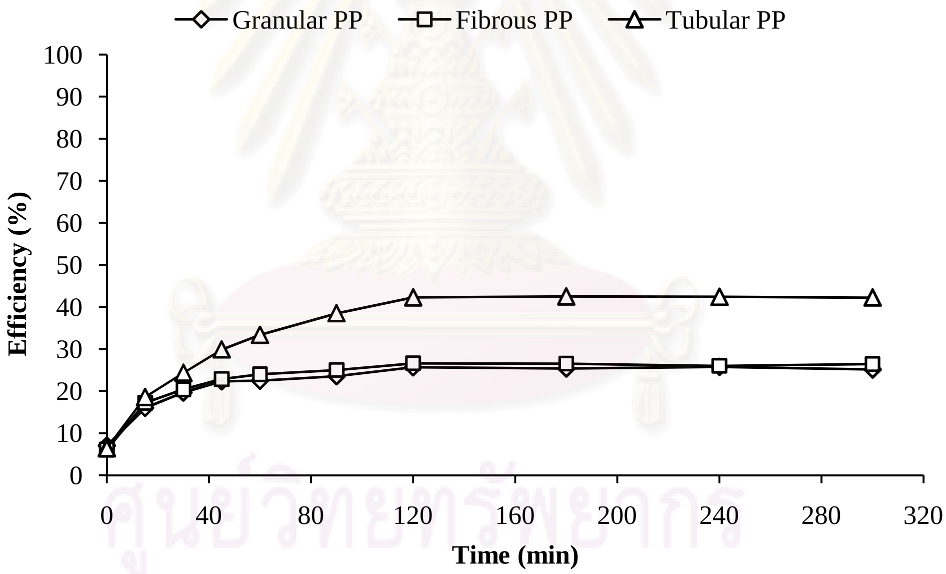


Figure 4.7 Kinetic results of the hybrid process for different coalescing media with 2.0 cm/s flow velocity and 10 cm bed height

4.3.2 Optimal condition for oil droplets separation by hybrid process

In this part, three different medium types (i.e. granule, fiber, and tube) were applied as coalescing medium and determined for optimal operating condition. The results were shown as following:

4.3.2.1 Granular polypropylene (PP) medium

Figure 4.8 presents the treatment efficiencies of cutting oil emulsion by the hybrid process between coalescer and decantation as a function of medium bed height for different flow velocity of oily emulsion by applying granular polypropylene as a coalescing medium.

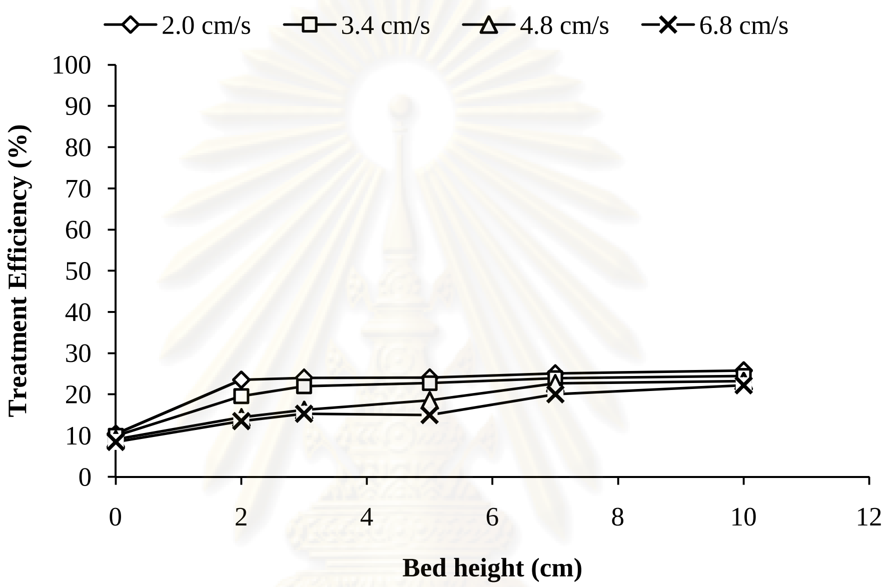


Figure 4.8 Treatment efficiencies of hybrid process as a function of bed height for granular PP coalescing medium

From Figure 4.8, it can be seen that the treatment efficiencies were slightly influenced by the operating conditions for both medium bed height and flow velocity of oily emulsion. However, it should be noticed that the effects of bed height were greater for high flow velocity, since the filtration mechanism played a key role in this case as the collision probability between oil droplets and media was increased from the turbulence occurred throughout the medium bed height. This oil filtration effect might be the result of short operating time since steady state of medium bed was not achieved: oil removal by filtration still can be obviously noticed. The highest efficiency of 25.76% was obtained from 2.0 cm/s flow velocity and 10 cm bed height. These results conformed to the oil droplet size presented in water. Figure 4.9 displays the volume distribution of cutting oil droplets in synthetic wastewater. It was found that the mean diameters (D_{mean} = 3.84 μm and D_{32} = 7.91 μm) of droplet size after passing the coalescing bed were slightly larger than the oil droplets in influent emulsion.

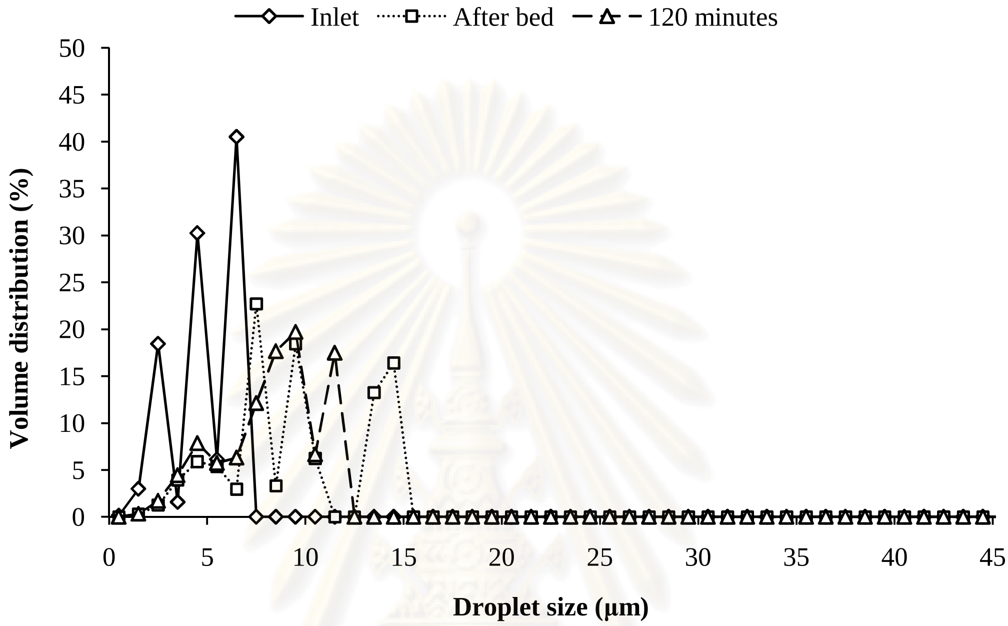


Figure 4.9 Volume distribution of cutting oil droplets presented in synthetic cutting oil emulsion for granular medium (10 cm bed height and 2.0 cm/s flow velocity)

Figure 4.9 also illustrates the volume distributions of oil droplets in synthetic oily wastewater after 120 minutes decantation. It could be noticed that the mean diameters of oil droplets were relatively close to that presented after passing coalescing bed (D_{mean} 4.12 μm and D_{32} 7.27 μm). The results indicated that the oil droplets after passing the granular bed were barely separated in decantation by themselves due to their small size. According to the medium characteristics, the granular bed contained low porosity of 55.12%, which was in the range to that of sand filter as mentioned above, and the result of droplet size distribution. Filtration should be considered as the dominated mechanism in this process. However, the filtration is different to coalescence mechanism, since the purpose of coalescer is to aggregate oil droplets and produced larger coalesced droplets but not to trap oil in the medium bed. In case of filtration, the oil droplets will be trapped in the dense or low porosity (0.3 – 0.5), and small medium. Due to the mechanisms occurred in filtration, the filtered medium will be clogged and require the backwash or maintenance process (AWWA and ASCE, 1990). Moreover, the size of granular PP used in this study (4 – 5 mm) was relatively larger than conventional filtered medium. Thus, the turbulence (N_{Re} = 6932 for 4.8 cm/s flow velocity) could occur when the wastewater entered to the medium bed, especially in case of long bed height. The higher energy in term of head loss took place inside the medium bed, which resulted in break-up of oil droplets: the droplet sizes were not thus increased significantly. In conclusion, the benefit from applying hydrophobic surface as a coalescing medium to attach with oil droplet was not clearly pronounced. The droplets that passing the medium bed were not increase in size and still ineffectively separated by decantation.

4.3.2.2 Fibrous polypropylene (PP) medium

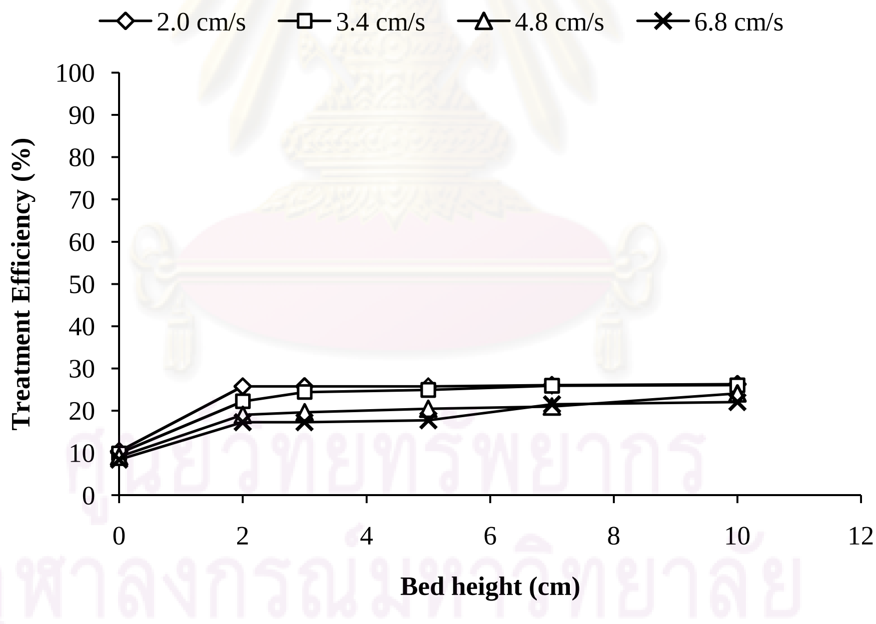


Figure 4.10 Treatment efficiencies of hybrid process as a function of bed height for fibrous PP coalescing medium

Figure 4.10 exhibits the treatment efficiencies of hybrid process in function of bed height with fibrous PP coalescing medium for different flow velocity of synthetic emulsion. It can be seen in Figure 4.10 that the efficiencies provided the similar tendency to those obtained from granular PP medium. The highest efficiency was obtained from flow velocity of 2.0 cm/s and 10 cm bed height as 26.31%. The operating conditions for both flow velocities of emulsion and coalescing medium height did not obviously impact the efficiencies of the process, except in case of high flow velocity range of emulsion. The increment of coalescing medium bed height at high flow velocity range resulted in higher efficiency since the filtration mechanism was dominated as described in case of granular medium. However, it was found that mean diameters in the emulsion after passing coalescing bed were increased to 4.83 μm and 17.41 μm for mean diameter (D_{mean}) and sauter mean diameter (D_{32}), respectively. The volume distribution of cutting oil droplets in this case were illustrated in Figure 4.11. These diameters were greater than that contained in the inlet emulsion, which indicated that the cutting oil droplets in water were coalesced or aggregated together, and then from the larger oil droplets: this was difference compared in the case of granular media. The presence of few large oil droplets resulted in existing of high oil volume distribution peak comparing to the small size since the oil volume was calculated from the droplet size. The larger the diameter was, the higher the volume obtained.

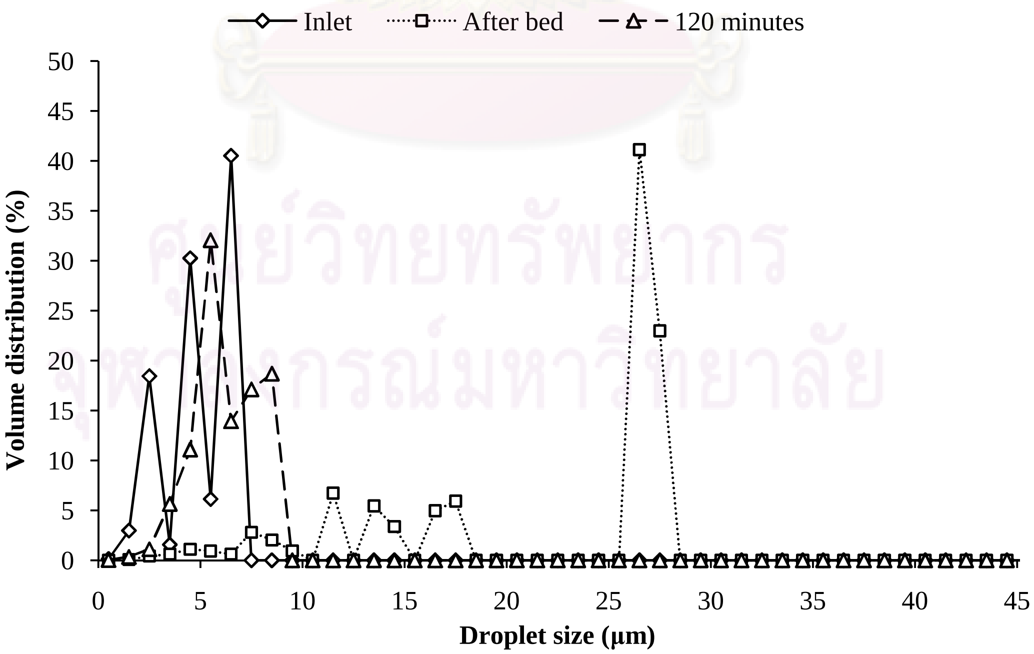


Figure 4.11 Volume distribution of cutting oil droplets presented in synthetic cutting oil emulsion for fibrous medium (10 cm bed height and 2.0 cm/s flow velocity)

Figure 4.11 shows the volume distribution of oil droplets in synthetic oily wastewater after 120 minutes decantation. The mean diameters of oil droplets were also close to that presented in inlet wastewater (D_{mean} 3.39 μm and D_{32} 5.76 μm). In this case, it could be concluded that the coalesced oil droplets can rapidly separated or floated to the water surface. Hence, the detected droplet sizes were very small as in the influent that consumed very long time to separate by itself. The mechanism occurred in this treatment process was different to the case of granular coalescing medium since the porosity of fibrous PP medium was very high (90.34%), which the filtration mechanism might barely happen. The coalescence of oil droplets would be the main mechanism in the treatment of oily emulsion by this hybrid process by fibrous medium. However, the efficiencies obtained from the granular and fibrous PP were not obviously different, which might be the outcome of various factors; for example, the very small size of oil droplet presented in wastewater. Moreover, the large and porous of medium materials resulted in low surface area for trapping oil droplets, thus, the collision efficiency between oil droplets and medium was low. Nevertheless, the oil droplets can be aggregated to form larger oil droplets when the droplets collided to the coalescing bed due to the hydrophobicity of medium material and lower turbulence (N_{Re} = 4229 for 4.8 cm/s flow velocity) in along the higher porosity bed height compared with granular one. Moreover, it could be noticed that small quantity of large coalesced oil droplets did not directly affect to the overall efficiency since the numbers of small oil droplets still presented in wastewater and cannot be separated in the 120 minutes period.

4.3.2.3 Tubular polypropylene (PP) medium

Figure 4.12 displays the treatment efficiencies of cutting oil emulsion by the process as a function of medium bed height for different flow velocity of oily emulsion by employing tubular polypropylene as a coalescing medium. As can be seen in Figure 4.12, the treatment efficiencies of hybrid process between coalescer and decantation by using tubular-shaped PP as a coalescing medium were affected by both flow velocity and medium bed height. The treatment efficiencies in this case were higher than the previous two cases. The highest efficiency was achieved in case of 2.0 cm/s flow velocity and 10 cm bed height as well at 43.64%. Due to the high porosity of tubular PP medium (81.77%), the coalescence mechanism could be considered as the main mechanism occurred in this process. Nevertheless, this medium bed was denser that the fibrous one, thus the oil droplets could have higher probability to be filtered within the bed. According to the efficiency results, it can be concluded that the tubular PP contained the proper porosity and dimension to be used as coalescing medium comparing the two previous medium types. The properties of this tubular PP provided the high collision and attachment efficiencies of oil and medium with low turbulent flow that resulted in largest coalescing oil droplet, which can be separated rapidly from water by decantation. Therefore, the overall treatment efficiency was increase due to the fact that oil content in water was decrease from trapping in the medium bed and separated from water.

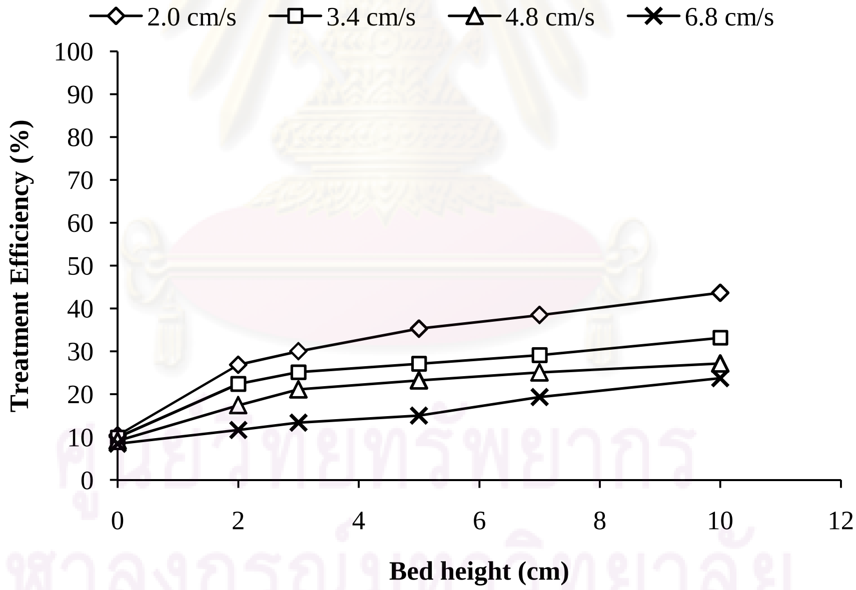


Figure 4.12 Treatment efficiencies of hybrid process as a function of bed height for tubular PP coalescing medium

Figure 4.13 displays the volume distribution of oil droplets in wastewater after passing tubular PP coalescing bed. Note that the mean and sauter mean diameters were 5.64 and 21.86 μm, respectively, which were greater than that in the influent emulsion and the granular and fibrous PP medium. These droplet sizes confirmed that there were the coalescences between oil droplets in this case.

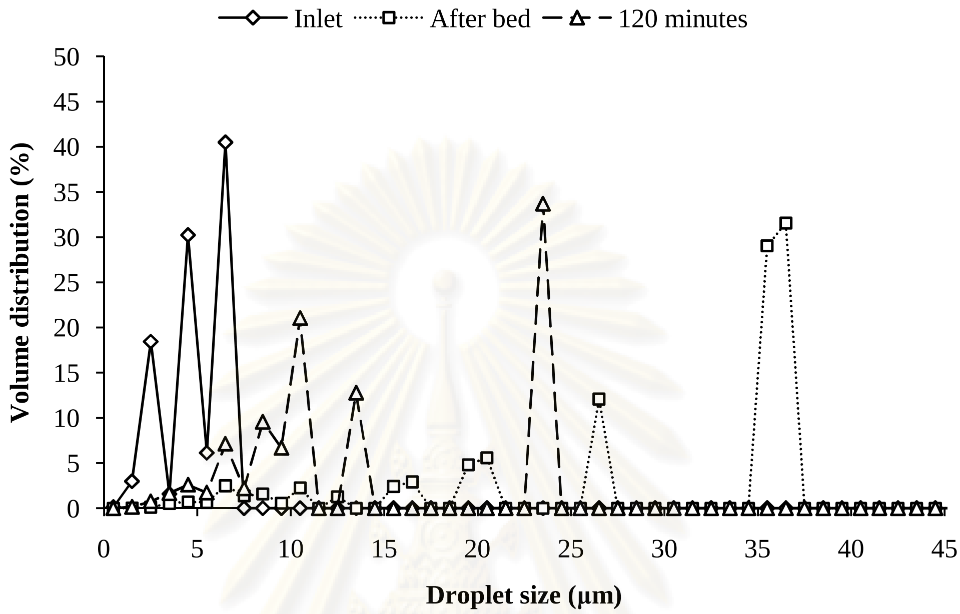


Figure 4.13 Volume distribution of cutting oil droplets presented in synthetic cutting oil emulsion for tubular medium (10 cm bed height and 2.0 cm/s flow velocity)

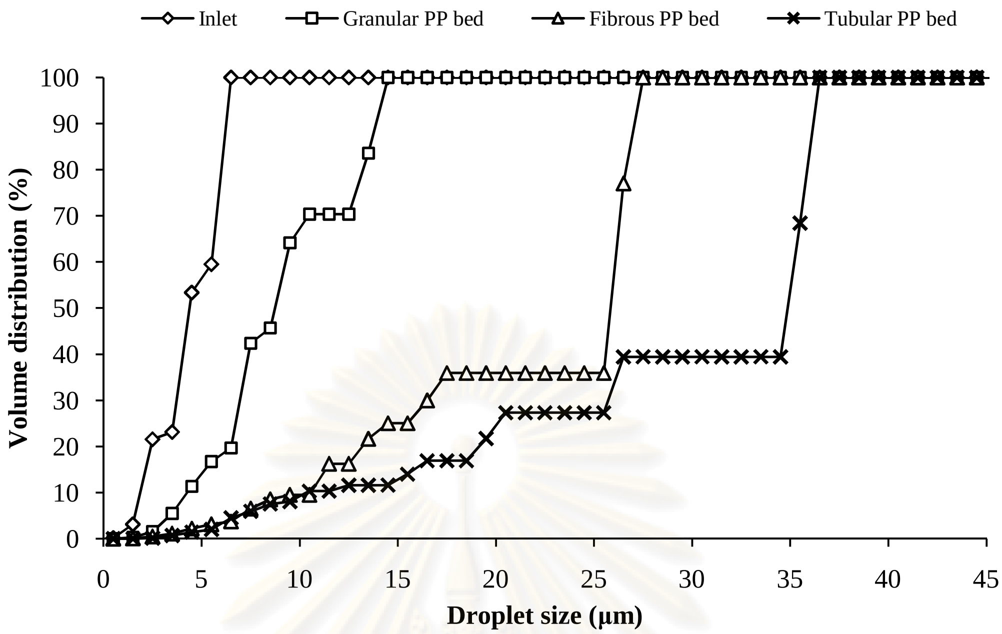
Figure 4.13 shows the volume distribution of oil droplet in oily emulsion after 120 minutes decantation for tubular PP medium types. It can be noticed that the mean and sauter mean diameters of remaining oil droplets in water (D_{mean} = 4.67 μm and D_{32} = 10.54 μm) were less than that presented in the wastewater after passing the bed. The large coalesced oil droplets can rapidly float to the water surface and separate from water, therefore, the remaining oil droplets were smaller. Moreover, there was possibility for oil droplets storage with in the medium bed according to the existence of hollow space within the tubular medium, which resulting in the increase of overall treatment efficiency.

From the results in this section, it can be concluded that polypropylene (PP) based-materials in different shapes can be used as a coalescing medium. The treatment efficiencies of the hybrid process were dependent on the operating conditions such as flow velocity, bed height, and coalescing medium shapes. The highest efficiencies for all three medium types were obtained in cases of lowest flow velocity (2.0 cm/s) and longest medium bed height (10 cm), which was considered as the optimal treatment condition in this study. The highest efficiency (43.64%) was obtained from the tubular shape PP medium bed, while granular and fibrous PP provided the equally lower efficiency (25.76 and 26.31%) since the obtained oil droplet size after passing bed was relatively larger than the other two medium types. Furthermore, storage of oil in the tubular medium can affect to the higher overall efficiency. The porosity and dimension of medium bed play an important role to govern the mechanisms (transport, attachment, coalescence and thus gravitational separation) occurred in the system, which impact to the oil droplet size in synthetic emulsion. The mean diameters in this study were summarized in Table 4.6.

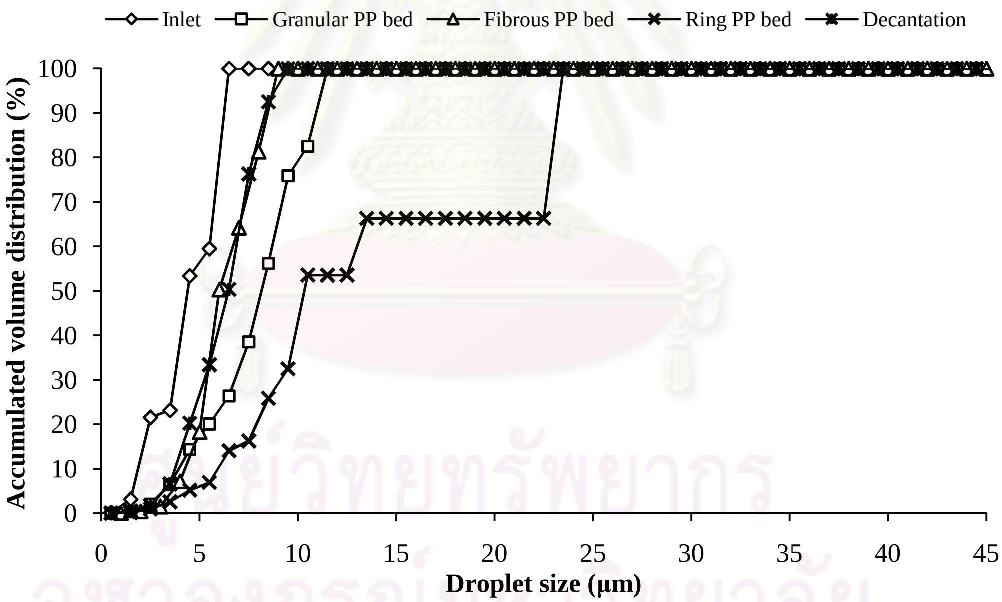
Moreover, the results indicated the obscure influence of stainless steel salting out device on the produced oil droplet size after passing bed and also the separation efficiency. Since the large coalesced oil droplets of 37 μm can be detected in case of tubular medium, the salting out mesh might not provoke the droplet break-up. However, application of more hydrophilic material as salting out device could result in larger coalesced droplet generated.

Table 4.6 Summary of oil droplet size at optimal condition (2.0 cm/s flow velocity and 10 cm bed height)

Coalescer	**After bed**		**120 minutes**		**Efficiency (%)**
	D_{mean}	**D_{32}**	**D_{mean}**	**D_{32}**	
No media bed	-	-	3.60	5.99	10.40
Granular PP	3.84	7.91	4.12	7.27	25.76
Fibrous PP	4.83	17.41	3.39	5.76	26.31
Tubular PP	5.64	21.86	4.67	10.54	43.64



(a)



(b)

Figure 4.14 Accumulated volume distributions of oil droplets in cutting oil emulsion for (a) after passing bed; and (b) after 120 minutes decantation at optimal condition

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From the changing of droplets' mean diameters, the volume distributions of different size of oil droplets were modified as shown in Figure 4.14. The accumulated volume distributions of droplet after passing medium bed shifted to the greater size range due to the presence of larger oil droplet in wastewater, especially for tubular PP medium that provided highest efficiency and largest droplet's mean diameter. After decantation, the remaining oil droplets had smaller diameter than before decantation due to the fact that the small droplets cannot separate from water in the restricted time period.

Note that the effects of flow velocity in this study contained the similar trend with the other research such as Li and Gu (2005) and Wanichkul (2000), which reported that the treatment efficiency of coalescer process will decrease when flow velocity was raised. Moreover, the slightly impacts of bed height on the efficiencies were correspond to Sokolović *et al.* (2007), which suggested that changing of bed height will not influence on the treatment efficiencies of coalescer process in case of vertical flow pattern.

Nevertheless, the optimal condition in this study only defined for flow velocity and medium bed height. The effects of other factors, for instance, liquid temperature, medium materials, flow orientation, were beyond the scope and not considered because of some limitation in the experiments.

The optimal conditions (i.e. bed height and flow velocity) of all three medium types were applied in the consequent section in order to enhance the treatment efficiency of the hybrid process between coalescer and decantation.

4.4 Enhancement of oil droplets separation by hybrid process

The objective of this part was to improve the separation efficiency of oil droplet from water by applying several methods. The conditions used in this part were the optimal operating conditions obtained from the previous section for each coalescing medium material.

4.4.1 Application of step-bed configuration (Stage coalescer)

The stage coalescer was applied for improving the process efficiency by providing more collision opportunity between oil droplets and collector from entering each bed. It was expected that the oil droplet within the bed height was barely transform to be film layer on the surface of collector due to its high stability with containing surfactant. Figure 4.15 displayed the treatment efficiencies of the stage coalescer for three different medium types. Note that the bed height used in this study was 10 cm divided into 2, 4, and 5 steps.

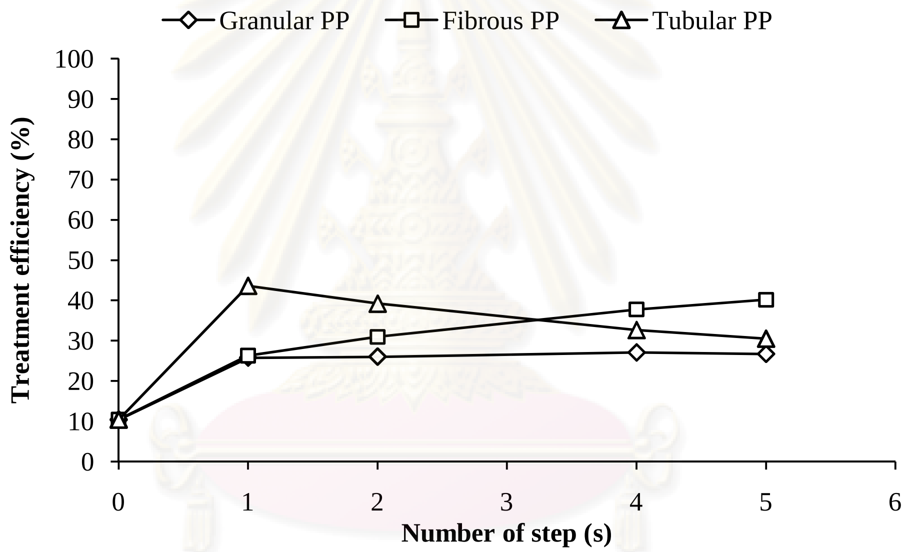

Figure 4.15 Treatment efficiencies of 5 step-beds coalescer at 120 minutes operation time in optimal operating condition for three PP medium

As presented in Figure 4.15, the application of stage coalescer concept provided different results from the various medium types. For granular PP medium, it can be noticed that the efficiencies were almost similar compared with conventional condition: this can be described by the mechanism occurred in this medium type that was filtration, which the efficiency was dependent on the bed height. As the total bed height was the same, the efficiency of this medium type would be remained the same treatment efficiencies. Figure 4.16 illustrates the volume distributions of cutting oil droplets for 5 steps bed configuration after passing coalescing bed of granular PP medium. It could be noticed that the mean diameters (D_{mean} = 4.09 μm; D_{32} = 9.18 μm) were slightly greater than the inlet wastewater, thus the coalescence of oil droplets would hardly occurred.

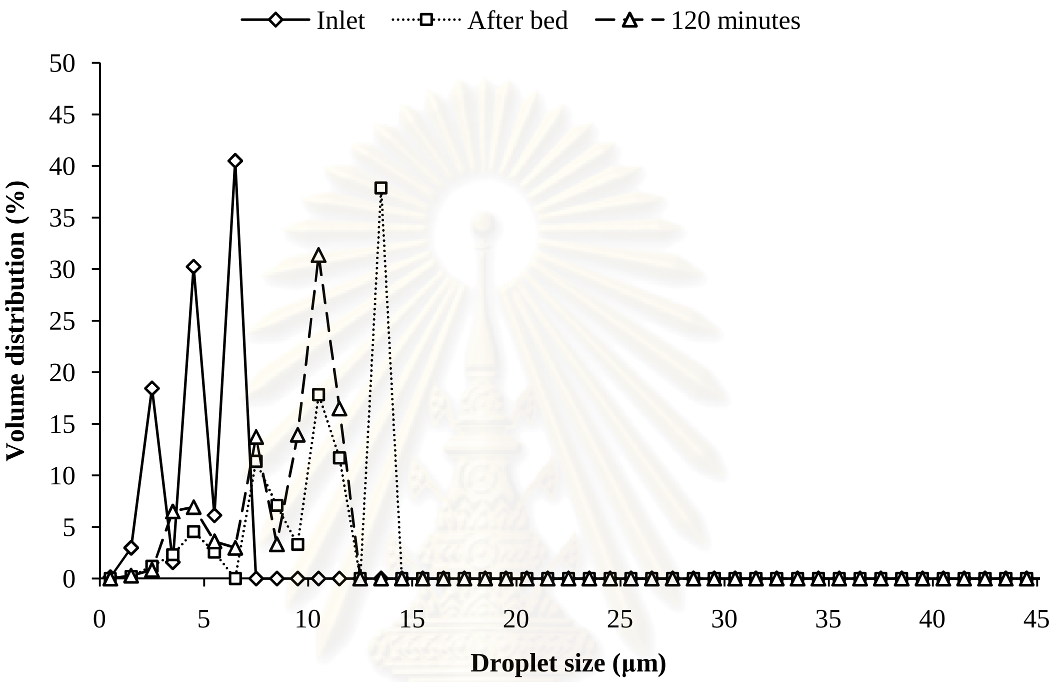

Figure 4.16 Volume distributions of cutting oil droplets in synthetic cutting oil emulsion in case of 5 steps coalescing bed in granular PP medium

Figure 4.16 displays the volume distribution of cutting oil droplets for 5 steps bed configuration of granular PP medium after 120 minutes decantation. The mean diameters in this case (D_{mean} = 4.00 μm; D_{32} = 7.51 μm) did not obviously change from that presented after passing the medium since the oil droplets were still tiny and require much more time to separate from water. Hence, it can be concluded that the application of step bed coalescer for granular PP or dense medium bed cannot enhance the overall treatment efficiency.

In case of fibrous PP, the increment of step number resulted in treatment efficiency raised as presented previously in Figure 4.15. Moreover, the mean diameters from 5 medium steps after passing bed were determined as 6.28 μm and 19.19 μm for D_{mean} and D_{32}, respectively. The droplet sizes in this case were higher than the only one step. The larger sizes resulted in higher emulsion treatment efficiency via separation. Figure 4.17 presents the volume distribution of cutting oil droplets for 5 steps bed configuration after passing coalescing bed of fibrous PP medium. In this case, the application of step-bed configuration resulted in the increase of collision and attachment efficiency (η_T and α) between oil droplets and coalescing medium (Wanichkul, 2000). Since the porosity of each step bed was the same as one step, the turbulence occurred from the entire medium bed was not increased and did not disturb the coalescence mechanism between oil droplets. Therefore, sizes of oil droplets after passing bed were larger than the one step coalescer. It can be concluded that stage coalescer should be applied for high porosity coalescing medium for enhancing the efficiency.

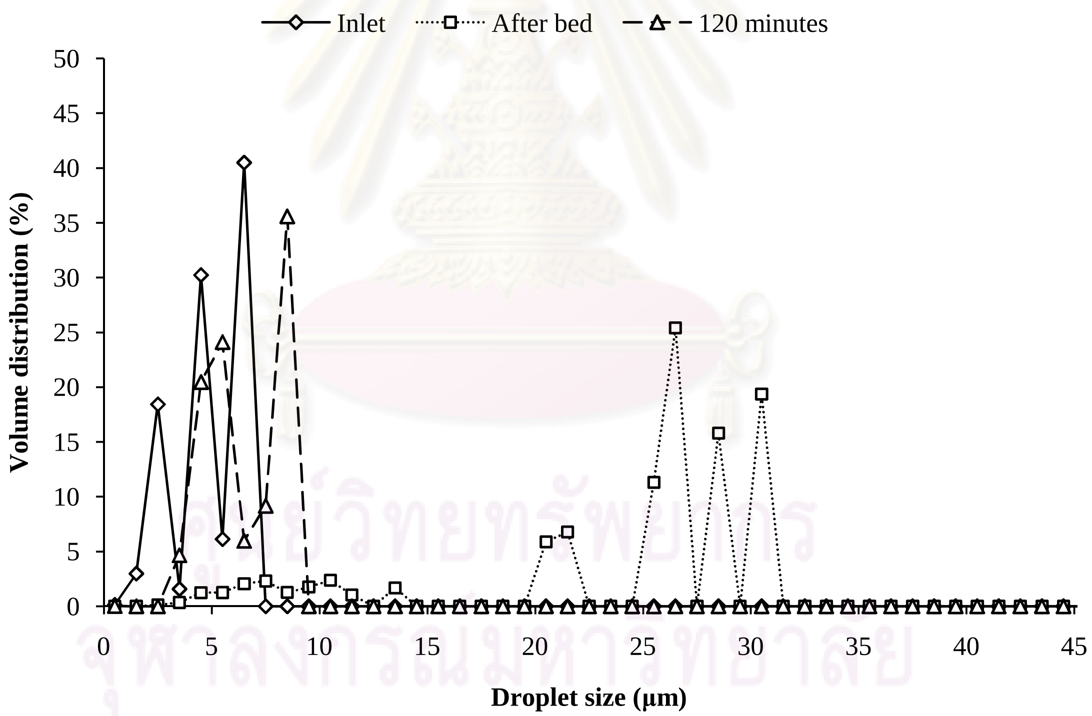

Figure 4.17 Volume distributions of cutting oil droplets in synthetic cutting oil emulsion in case of 5 steps coalescing bed in fibrous PP medium

The mean diameters of oil droplets after 120 minutes decantation in this case (D_{mean} 3.39 µm and D_{32} 5.76 µm) contained the similar trend with the other cases that were also close to in the inlet emulsion. The size distribution of cutting oil droplets for 5 steps bed configuration of fibrous PP medium after 120 minutes decantation were illustrated in Figure 4.17.

For tubular PP medium, the efficiencies were decreased when the numbers of step increased as can be seen in Figure 4.15. The volume distribution of cutting oil droplets for 5 steps bed configuration after passing coalescing bed of tubular PP medium were illustrated in Figure 4.18. The mean and sauter mean diameters in this case were 4.36 μm and 7.98 μm, respectively. These sizes were much less than the conventional 10 cm bed height. The break-up or splitting of larger coalesced oil droplets from first step in the consequent bed would occurred from effect of turbulent from changing of cross-sectional area in each step: lower media porosity compared with fibrous one should be responsible for these results. Moreover, the storage effect as aforementioned might affect the quantity of oil droplet presented in water after passing each bed, which resulting lower probability for coalescing and producing larger oil droplets. Therefore, the separation efficiency of oil droplets was low.

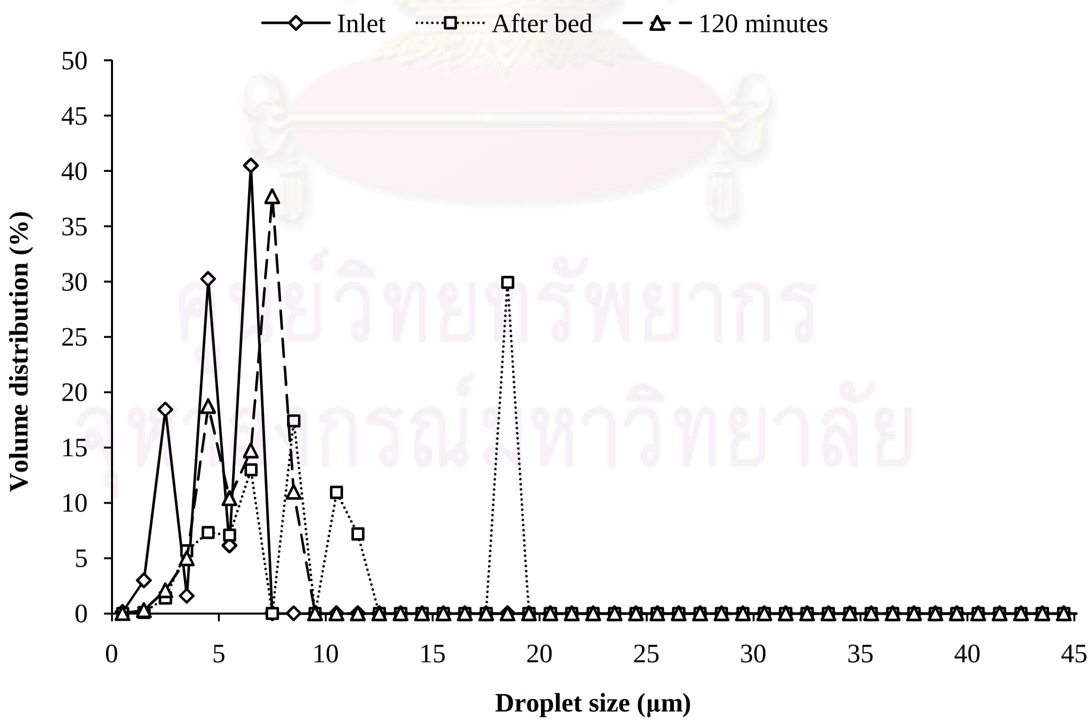

Figure 4.18 Volume distributions of cutting oil droplets in synthetic cutting oil emulsion in case of 5 steps coalescing bed in tubular PP medium

Figure 4.18 also presents the volume distribution of cutting oil droplets for 5 steps bed configuration of tubular PP medium after 120 minutes decantation. The distributions did not clearly change from after passing bed since the small droplets were incapable to separate in the 120 minutes period. The average sizes in this case were 4.37 μm and 7.70 μm for D_{mean} and D_{32}, respectively.

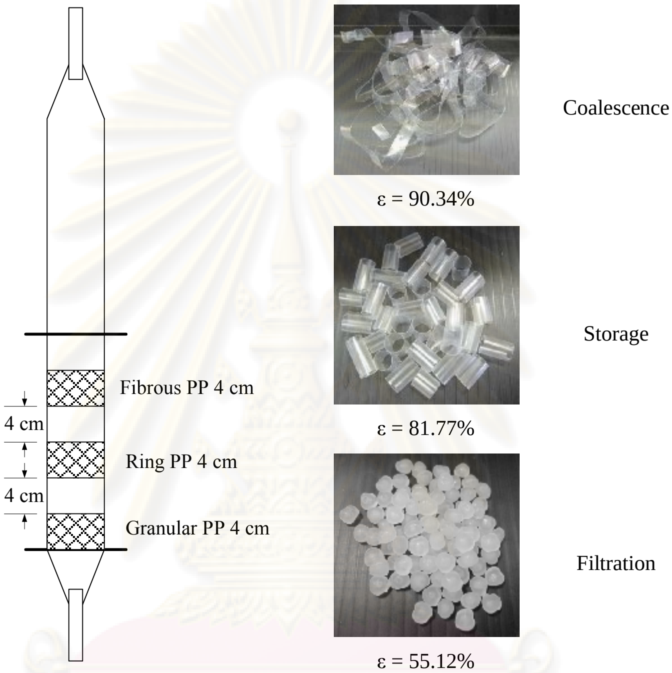

Figure 4.19 Configuration of mixed step bed coalescer

According to results of stage coalescer, it can be seen that the oil droplet sizes were involved with the porosity of medium bed, since the splitting or break-up of large droplets would occur in dense coalescing bed. Hence, application of step bed configuration with vary medium porosity could enhance the efficiency of coalescer process. For that reason, the mixed bed coalescer was studied to fulfill this assumption by using three different porosity PP media including granular, tubular, and fibrous PP, which contain 33.87, 81.77, and 90.34% porosity, respectively. The different treatment mechanism was expected for each bed. Filtration was anticipated in first granular bed due to its low porosity; next, coalescence and storage of oil droplets were expected in tubular medium, and finally coalescence for fibrous bed. The configuration of mixed step bed coalescer and expected mechanism for each bed is displayed in Figure 4.19. Note that the height of 4 cm for each medium type was applied in this study.

This mixed step bed coalescer provided the highest treatment efficiency compared with different operating conditions: note that this is greater than that obtained with the conventional step coalescer for 59.12%. This enhanced efficiency would be the result of large coalesced oil droplet produced in this study, since the droplet might not be broke up after passing the series of coalescing medium, which were increased in porosity of bed for each step. The mechanism occurred in each step was different including, filtration in granular bed, oil storage in tubular medium, and coalescence of residual or break oil droplets from previous bed in fibrous medium, which resulted in higher efficiency. The droplets' mean (D_{mean}) and sauter mean (D_{32}) diameters were 7.62 and 26.24 μm and 4.37 and 7.70 μm in emulsion after passing medium bed and 120 minutes decantation, respectively. The volume distributions of oil droplets in oily emulsion for after passing bed and 120 minutes decantation are illustrated in Figure 4.20.

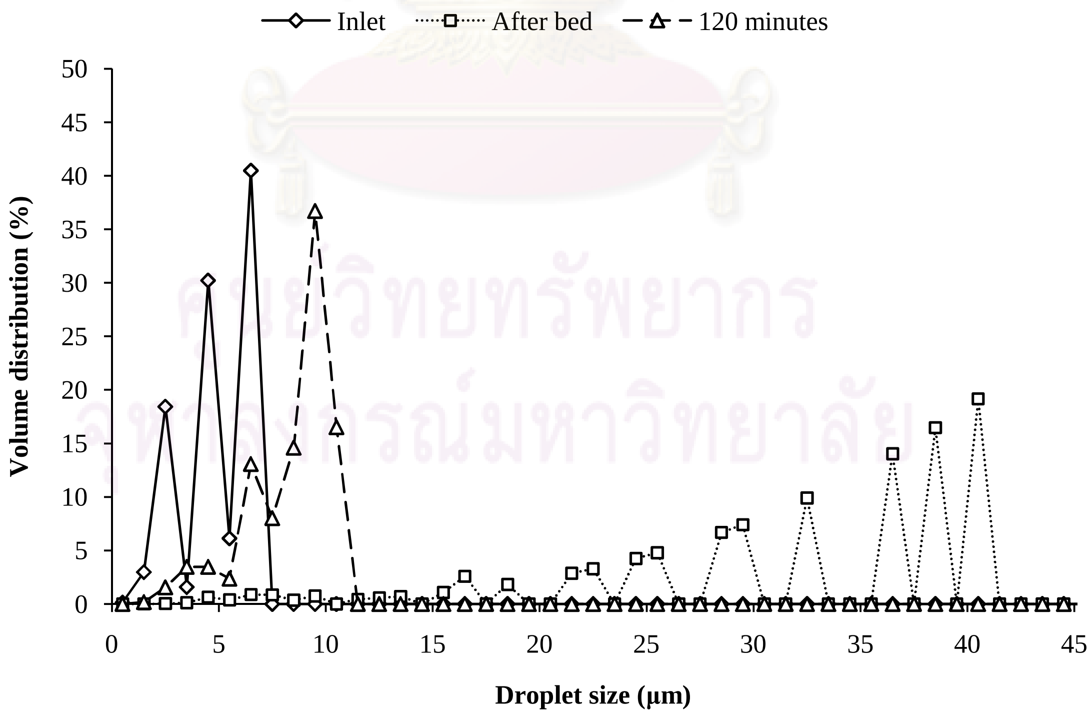

Figure 4.20 Volume distributions of oil droplets presented in wastewater for mixed medium step bed

The results of mean diameters in this section were summarized in Table 4.7.

Table 4.7 Summary of oil droplet sizes for 5 steps bed configuration at optimal condition

Step coalescer	After bed		120 minutes		Efficiency (%)
	D_{mean}	D_{32}	D_{mean}	D_{32}	
Granular PP	4.09	9.18	4.00	7.51	26.70
Fibrous PP	6.28	19.19	4.18	6.10	40.16
Tubular PP	4.36	7.98	3.75	5.90	30.48
Mixed bed PP	7.62	26.24	4.37	7.70	59.12

Due to the change of droplets' mean diameter in every case, the volume distributions of droplets in emulsion were also altered. The distributions of oil volume in terms of accumulated volume distribution by droplet size of wastewater after passing bed and 120 minutes decantation are presented in Figure 4.21.

It can be noticed that the volume distributions of oil droplets in wastewater after passing medium bed were shifted to the larger size range due to the coalescences of oil droplets occurred. Whereas, the volume distribution of oil droplets after 120 minutes decantation were relatively closed to the inlet emulsion since the large droplets were already separated by floating to the water surface. The remaining droplets, therefore, were small size and incapable to separate in the limited time period.

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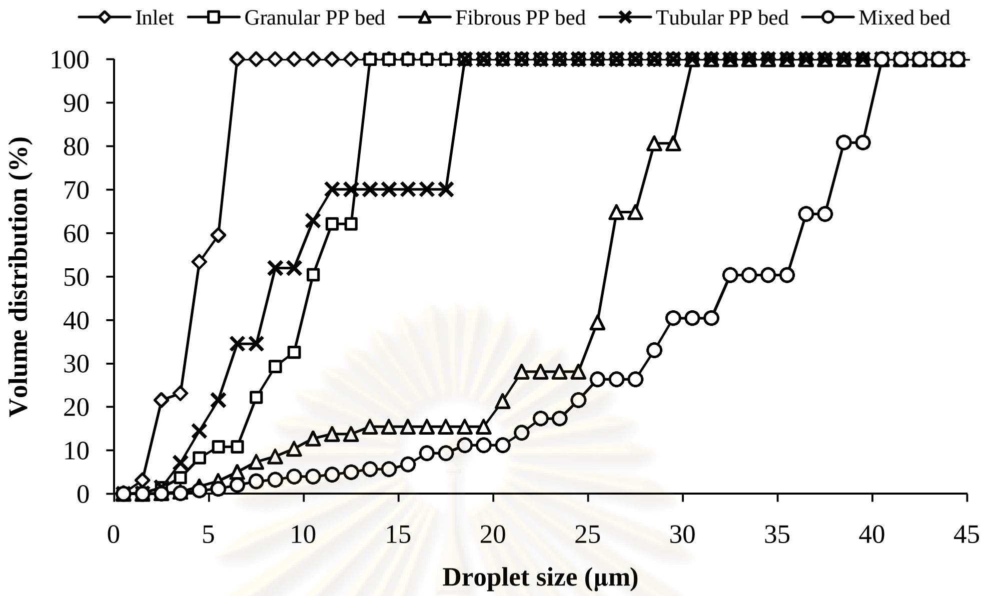

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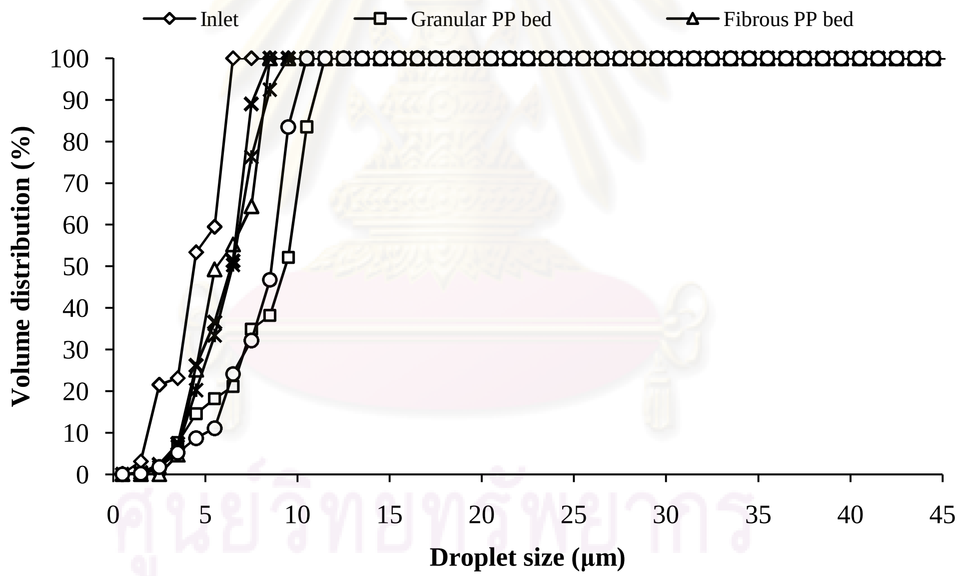

(b)

Figure 4.21 Accumulated volume distribution of (a) after passing bed; and (b) after 120 minutes decantation for step coalescer

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4.4.2 Oily wastewater recirculation in coalescer column

Figure 4.22 exhibits the treatment efficiencies of the hybrid process by varying the recirculation ration in optimal operating condition obtained with previous experiments.

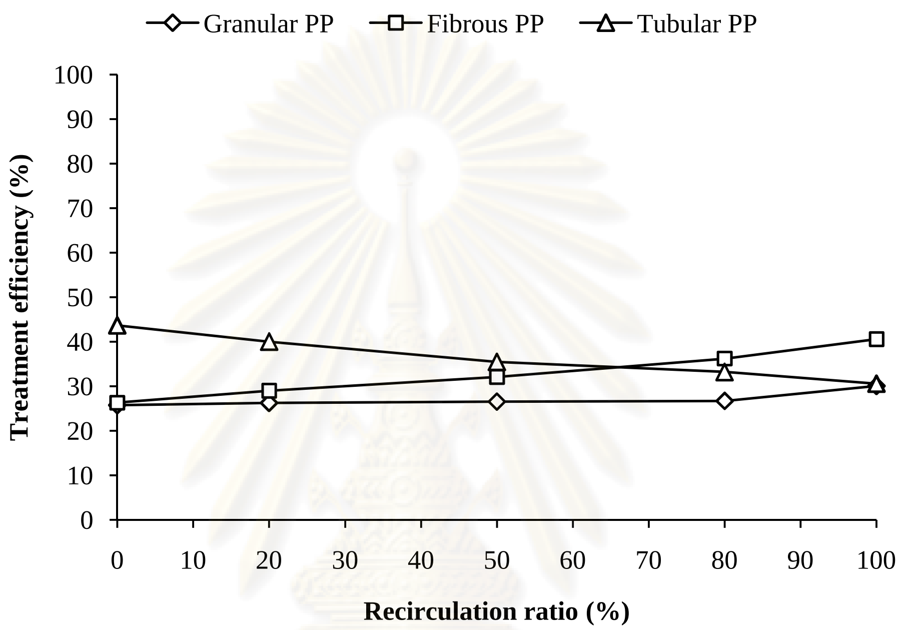


Figure 4.22 Treatment efficiencies of step-bed coalescer at 120 minutes operation time in optimal operating condition of three PP medium

From Figure 4.22, the ratio of wastewater recirculation had no distinct effect on the treatment efficiency provided from granular PP. As mentioned above, the main mechanism occurred in case of granular medium was filtration. If the filter bed was saturated, the oil droplets cannot be trapped in the medium bed anymore even more oil droplet entered the system. The slightly increase of removal efficiency for 100% recirculation observed from Figure 4.22 might be the result of dilution of inlet emulsion by recirculating of treated emulsion. Figure 4.23 illustrates the volume distributions of cutting oil droplets for complete wastewater recirculation (100% ratio) in coalescer column after passing granular PP medium bed and 120 minutes decantation. It can be seen that the oil droplet size presented in wastewater after passing bed was slightly increased (D_{mean} = 6.05 μm and D_{32} = 10.23 μm), and then reduced to 3.63 μm and 6.34 μm for mean diameter (D_{mean}) and sauter mean diameter (D_{32}), respectively, which were relatively similar size to the inlet. These changes of oil droplets repeatedly confirmed again that coalescence was not the main mechanism provided from granular medium, even with the oil-coalescer media enhancement.

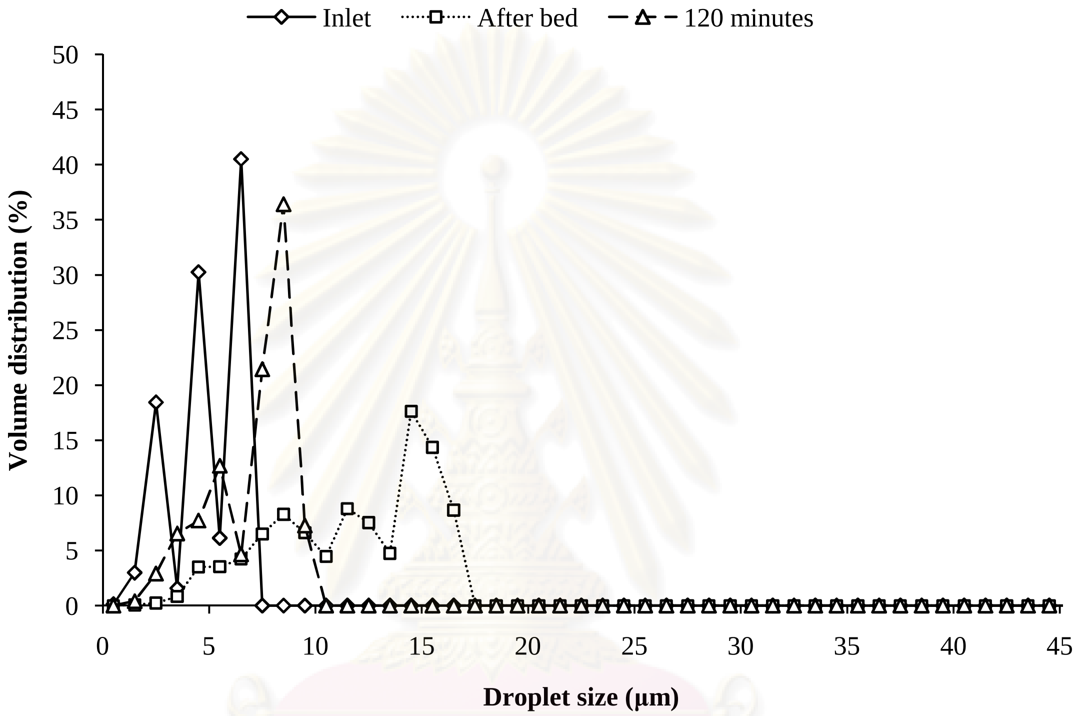


Figure 4.23 Size distributions of cutting oil droplets in synthetic oily emulsion for complete recirculation of granular PP coalescing medium

In case of fibrous PP medium, the efficiency was increase along the increment of recirculation ratios. The wastewater recirculation enhanced the probability of collision and attachment between oil droplets and coalescing medium. As mention above that the dominant mechanism of the fibrous PP was coalescence, the enhancement of both collision and attachment resulted in the increase of the treatment efficiency. Fibrous medium had an advantage with high surface area that oil droplet can attach on its surface. As emulsion was recirculated, the oil droplet would have more opportunity for coalescing to form larger oil droplets that can quickly float to the water surface. The treatment efficiency result conformed to the changing of size distribution in the system. Figure 4.24 exhibits the volume distribution of oil droplet presented in inlet emulsion, after passing bed, and after 120 minutes decantation for complete wastewater recirculation (100% ratio). It was found that the droplet size after passing bed was greater than that of inlet emulsion with D_{mean} and D_{32} were 7,17 μm and 22.95 μm, respectively. After that, the large droplets can separate by themselves under the limited time period 120 minutes. The remaining droplet size after decantation, therefore, was close to the inlet (D_{mean} 4.23 μm and D_{32} 5.92 μm).

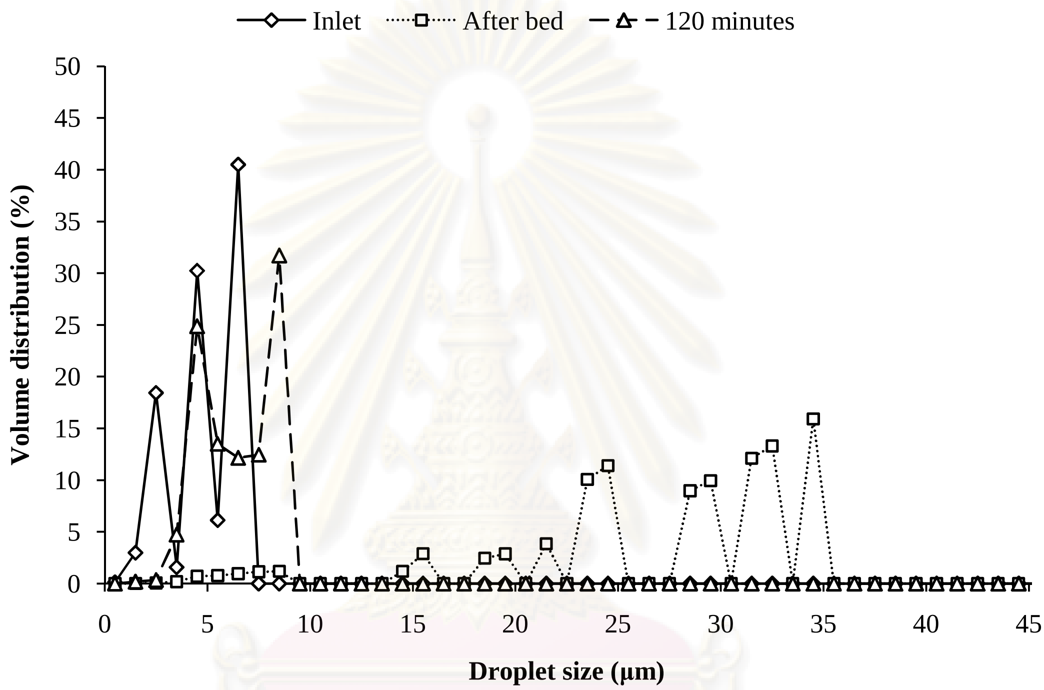


Figure 4.24 Volume distributions of cutting oil droplets in synthetic oily emulsion for complete recirculation after passing fibrous PP medium

For tubular PP, the treatment efficiencies were decrease as the ratios increased as in Figure 4.22. This can be described by the occurred mechanisms. The advantage from oil storage might not be enhanced by recirculation as the hollow space could be fully filled with emulsion after pass through the bed. Moreover, the break-up or splitting of the coalesced droplets might occur from changing of cross-sectional flow are that causing turbulence as well as step bed configuration. The changes of volume distribution in this case are shown in Figure 4.25. It can be seen that the droplet size after passing bed was slightly changed from the inlet emulsion. The mean diameter (D_{mean}) and sauter mean diameter (D_{32}) of this case were 4.35 μm and 8.34 μm, respectively. The mean diameters in this case were much smaller in case of coalescer process without recirculation of tubular PP medium, which corresponded to the discussion regarding to the droplet break-up above. After decantation, sizes of the droplets were not obviously change due to the fact that the small droplets were incapable to separate in the confined 120 minutes period (D_{mean} 3.84 μm and D_{32} 6.18 μm).

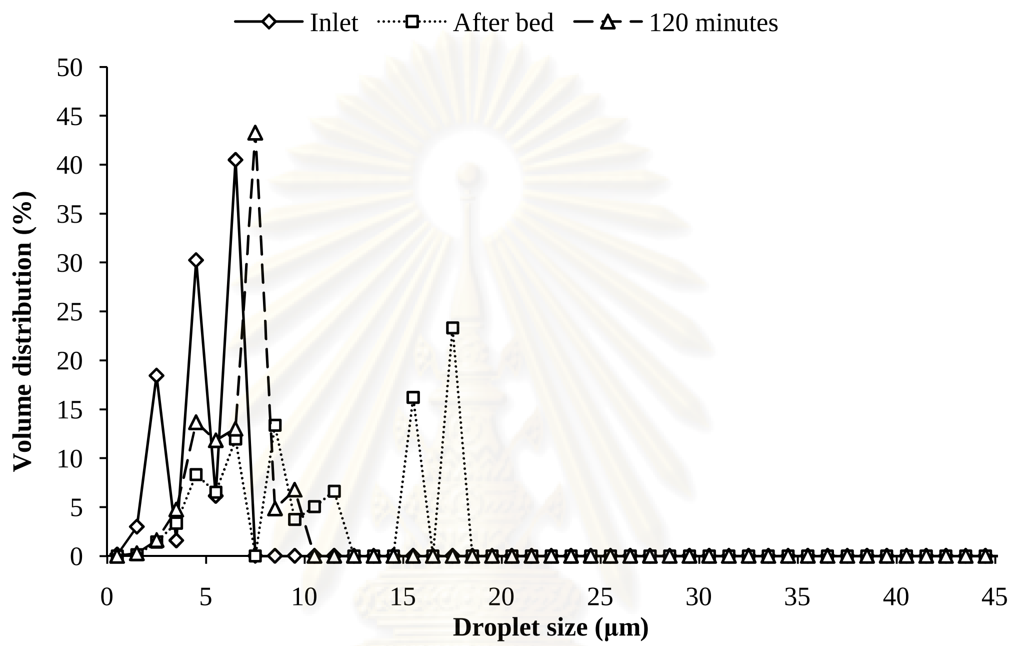
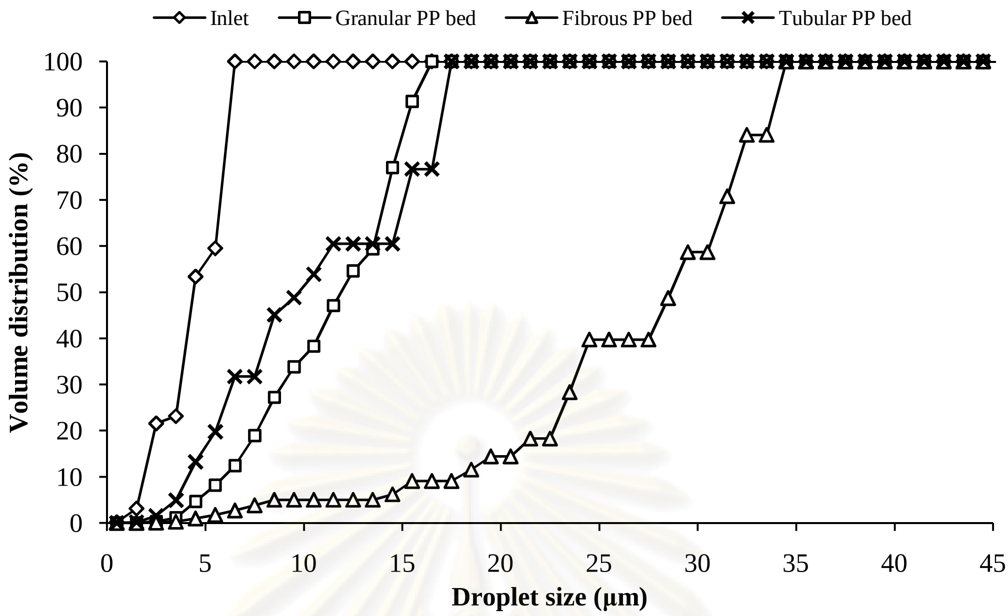


Figure 4.25 Volume distributions of cutting oil droplets in synthetic oily emulsion for complete recirculation after passing tubular PP medium

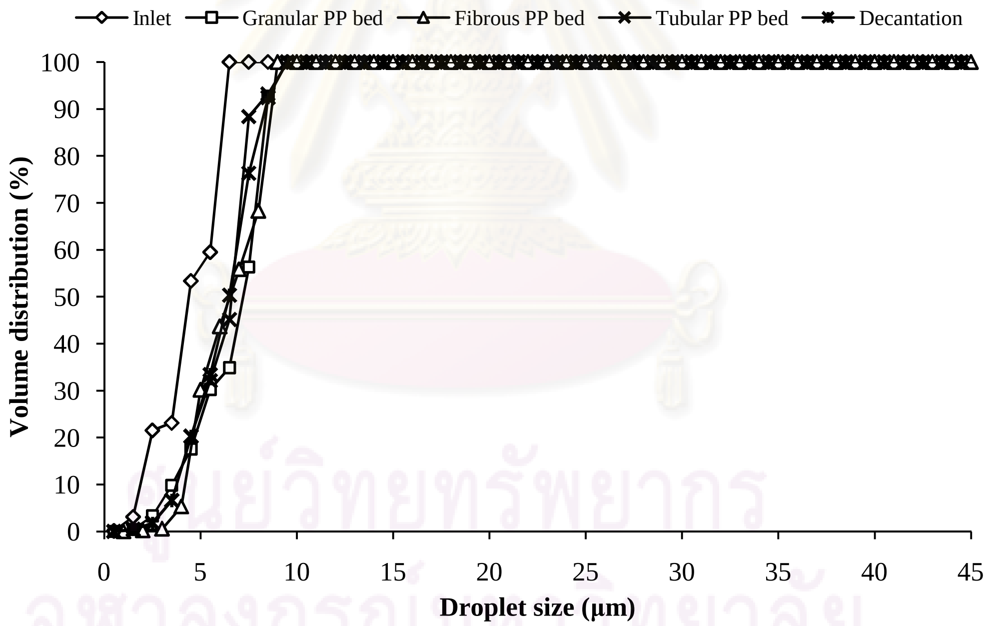
The mean diameters in this study were summarized in Table 4.8.

Table 4.8 Summary of oil droplet sizes for complete emulsion recirculation at optimal condition

Coalescer	After bed		120 minutes		Efficiency (%)
	D_{mean}	D_{32}	D_{mean}	D_{32}	
No media bed	-	-	3.80	5.99	10.40
Granular PP	6.05	10.23	3.63	6.34	30.10
Fibrous PP	7.17	22.95	4.23	5.92	40.57
Tubular PP	4.35	8.34	3.84	6.18	30.62



(a)



(b)

Figure 4.26 Accumulated volume distribution of (a) after passing bed; and (b) after 120 minutes decantation for complete recirculation

The accumulated volume distribution of oil droplets in complete wastewater recirculation in coalescer column are exhibited in Figure 4.26. The change of distributions had the similar trend to the discussion in two previous sections as the oil droplet sizes were increase after passing medium bed. After decantation, the oil droplet decreased to as small as inlet influent. Moreover, it can be concluded that recirculation technique should be applied in case of high porous bed in order to enhance the treatment efficiency and also for recovering of oil content from water.

4.4.3 Improvement of decantation process

In this section, the enhancement of overall treatment efficiency by improvement of decantation efficiency was studied since the application of stage coalescer and wastewater recirculation considered only on the coalescer process. It can be seen that the very small size of oil droplets might be the limitation for enhancement of the efficiency in the two methods above. In this part, the enhancement of treatment efficiency by designing the decanter that was appropriate to the droplet sizes obtained from the passing a coalescing medium. Since cutting oil emulsion was stabilized emulsion, the stabilized oil droplets in wastewater were anticipated to freely rising. The coalescence or aggregation between oil droplets after passing bed might rarely occur; hence, the discrete settling was assumed as the settling type for this decantation process (Carlsson, 1998). The assumption of the discrete settling was the oil droplets were not break up or coalesced with other droplets along the floated distance to the surface of water. By applying the result of oil droplets decantation, the discrete settling relationship was created in order to use as primary data for decanter design, and also for predicting the overall treatment efficiency. The decantation efficiency can be calculated from Equation 4.1 or 4.2.

$$1-\frac{C}{C_0}=\frac{v_t}{v_0}=\frac{v_t}{\frac{H}{t}}=\frac{t\cdot v_t}{H} \qquad (4.1)$$

$$P=1-\frac{t\cdot v_t}{H} \qquad (4.2)$$

Where, C and C_0 are the final and initial concentration, respectively. The ration between C and C_0 is denoted as penetration (P). The v_t and v_o are velocity of oil droplet and wastewater. From Equation 4.1, it can be seen that the efficiency of decantation was related to the flow velocity ($\frac{H}{t}$), where H and t are the height of

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decanter and retention time of wastewater in decanter, respectively. The $\frac{H}{t}$, which can be called as overflow rate, and the rising velocity of particles are important parameters for designing of effective decanter. Hence, the study for effect of overflow rate on the efficiency of decanter in term of penetration (P) was conducted.

Table 4.9 Oil droplet sizes obtained from coalescer in discrete settling study

Coalescing medium	Mean droplet size (µm)	
	D_{mean}	D_{32}
Inlet	1.95	4.12
Granular PP	3.84	7.91
Fibrous PP	4.83	17.41
Tubular PP	5.64	21.86

In this study, three different PP media were also applied as coalescing media in order to determine the decantation efficiencies of different oil droplet sizes. The oil droplet sizes obtained from coalescer with different media in terms of mean and sauter mean diameter were shown in Table 4.9. The outlets were sampled from three different height sampling point with time interval until reached 240 minutes. The experimented results in this study are shown in Table 4.10. By plotting between penetration and overflow rate ($\frac{H}{t}$) the discrete settling relationship was obtained as shown in Figure 4.27.

Table 4.10 Discrete settling results for different coalescing media

Medium types	Height (cm)		Time (min)									
			0	15	30	60	90	120	150	180	210	240
Granular PP	50	C	1257	1183	1152	1113	991	979	961	944	935	929
		C/C0	1	0.94	0.92	0.89	0.79	0.78	0.76	0.75	0.74	0.74
		H/t (cm/min)	-	3.33	1.67	0.83	0.56	0.42	0.33	0.28	0.24	0.21
	100	C	1257	1206	1184	1167	1045	1028	1009	991	980	968
		C/C0	1	0.96	0.94	0.93	0.83	0.82	0.8	0.79	0.78	0.77
		H/t (cm/min)	-	6.67	3.33	1.67	1.11	0.83	0.67	0.56	0.48	0.42
	150	C	1257	1229	1201	1192	1157	1133	1102	1077	1051	1033
		C/C0	1	0.98	0.96	0.95	0.92	0.9	0.88	0.86	0.84	0.82
		H/t (cm/min)	-	10.00	5.00	2.50	1.67	1.25	1.00	0.83	0.71	0.63

Medium types	Height (cm)		Time (min)									
			0	**15**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**
Fibrous PP	50	C	1209	1115	1087	1022	987	958	925	901	894	884
		C/C0	1	0.92	0.90	0.85	0.82	0.79	0.77	0.75	0.74	0.73
		H/t (cm/min)	-	3.33	1.67	0.83	0.56	0.42	0.33	0.28	0.24	0.21
	100	C	1209	1173	1113	1080	1061	1034	1002	978	953	924
		C/C0	1	0.97	0.92	0.89	0.88	0.86	0.83	0.81	0.79	0.76
		H/t (cm/min)	-	6.67	3.33	1.67	1.11	0.83	0.67	0.56	0.48	0.42
	150	C	1209	1191	1159	1123	1107	1082	1053	1027	994	978
		C/C0	1	0.99	0.96	0.93	0.92	0.89	0.87	0.85	0.82	0.81
		H/t (cm/min)	-	10.00	5.00	2.50	1.67	1.25	1.00	0.83	0.71	0.63
Tubular PP	50	C	1227	1009	976	904	803	784	771	758	741	724
		C/C0	1	0.82	0.80	0.74	0.65	0.64	0.63	0.62	0.6	0.59
		H/t (cm/min)	-	3.33	1.67	0.83	0.56	0.42	0.33	0.28	0.24	0.21
	100	C	1227	1074	996	975	934	901	863	832	801	779
		C/C0	1	0.88	0.81	0.79	0.76	0.73	0.7	0.68	0.65	0.63
		H/t (cm/min)	-	6.67	3.33	1.67	1.11	0.83	0.67	0.56	0.48	0.42
	150	C	1227	1121	1066	1009	976	942	899	851	825	814
		C/C0	1	0.91	0.87	0.82	0.80	0.77	0.73	0.69	0.67	0.66
		H/t (cm/min)	-	10.00	5.00	2.50	1.67	1.25	1.00	0.83	0.71	0.63

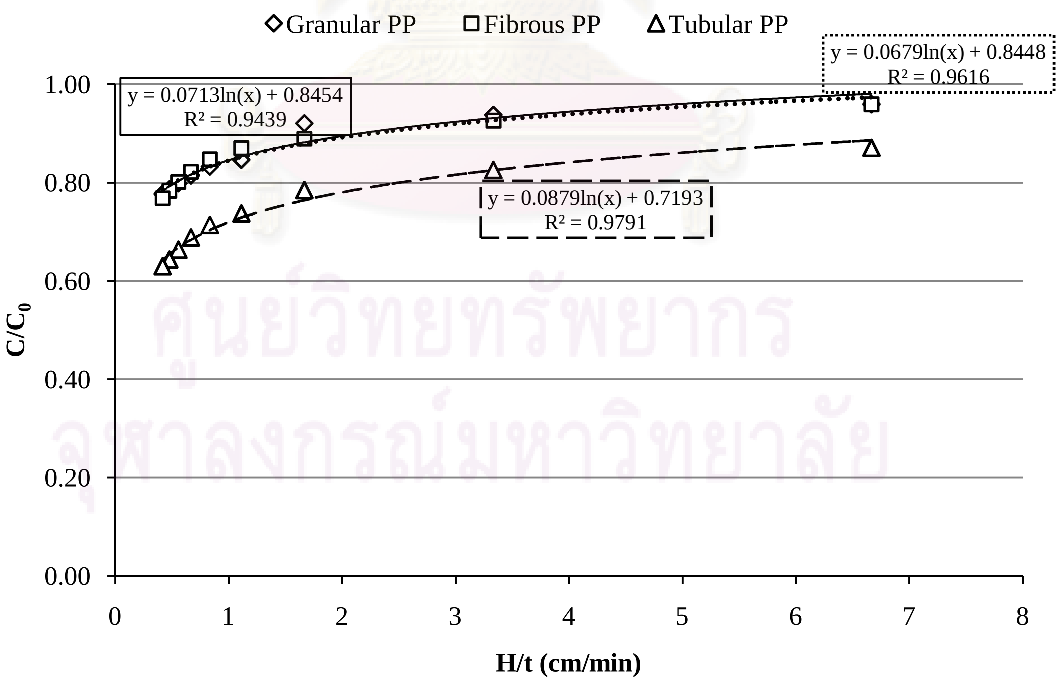

Figure 4.27 Discrete settling study results

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As can be seen in Figure 4.27, the tubular PP provided the lowest penetration, on the other words, highest efficiency comparing to the other two media. Moreover, the high decantation efficiency was achieved by very low flow velocity (overflow rate or surface loading rate) for all cases; for example, the 0.7 penetration of tubular PP was obtained from 0.803 cm/min of overflow rate. From the discrete settling relationship, the treatment efficiency of decanter can be calculated from Equation 4.2 (Tuntoolavest, 1999).

$$P = (1 - P_0) + \frac{1}{v_0}\int_0^{P_0} v_i dP_i \qquad (4.2)$$

Where P is the treatment efficiency of decanter

P_0 is the percentage of droplets with rising velocity less than v_0 ($= \frac{Q}{A}$)

P_i is the percentage of droplets that contained rising velocity less than v_i (which is less than v_0)

Therefore, the (1-P_0) term is the droplets that can be completely separated from water by the rising velocity of themselves, which are higher than v_0, and $\frac{1}{v_0}\int_0^{P_0} v_i dP_i$ is the droplets that can separate from water even their rising velocities are less than v_0. The model for determining the treatment efficiency of decanter is illustrated in Figure 4.27.

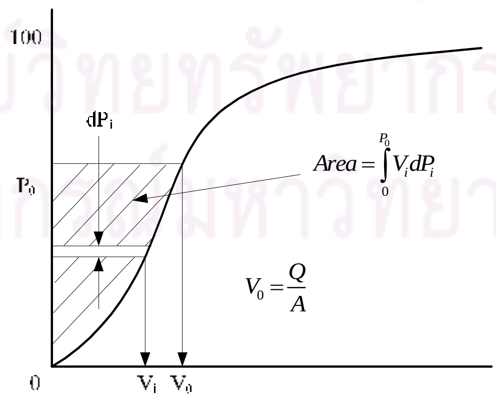

Figure 4.28 Model for determining treatment efficiency of decanter (Tuntoolavest, 1999)

According to the treatment efficiency determined from the method above, the efficiencies as a function of emulsion's flow velocity (overflow rate) connected to coalescer with three different coalescing medium were obtained as displayed in Figure 4.29

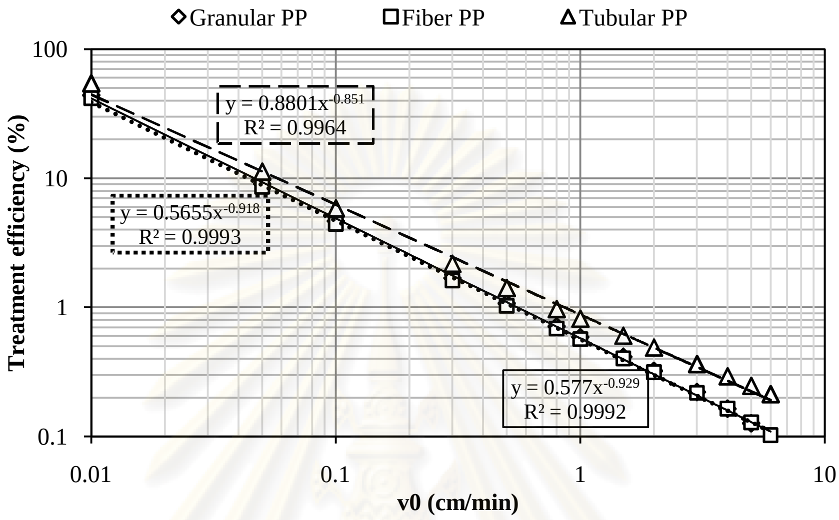

Figure 4.29 Treatment efficiencies as a function of flow velocity for various coalescing medium

As can be seen Figure 4.29, high treatment efficiency of decanter can be obtained from very low flow velocity. This relationship can be used for designing the certain efficient decanter with reasonable size and construction cost. For example, the estimated efficiency of 50% in case of tubular PP can be achieved at the inlet flow velocity of 0.01 cm/min, which required approximately 6 m^2 for sectional area with actual flow rate applied in this study (0.6 m^3/min or 2.0 cm/s inlet flow velocity). However, the efficiency of decanter can be also improved by plate or tube settler installation in order to reduce the flow velocity and handle higher wastewater flowrate. The application of plate and tube settler in case of parallel plates or tray result in changing of decanter's height (H) for each plate, which impacted to the flow velocity of wastewater as shown in Equation 4.3 (Aurelle, 1985).

$$v_0 = \frac{H}{(n+1)\cdot t} \tag{4.3}$$

Where, n is the number of plate or tube settler. Thus, the efficiency of decanter in Equation 4.1 can be rewritten as in Equation 4.4.

$$1-\frac{C}{C_0}=\frac{t\cdot v_t}{H}\cdot(n+1) \qquad (4.4)$$

It can be seen from Equation 4.4 that the overall efficiency will be raised by increasing the number of plate settler. However, the installation of the settlers has limitation from the dimension and size of decanter. Therefore, the improvement of decanter by addition of settler is still limited practically in real operating conditions.
According to the efficiency enhancement studies, the highest treatment efficiency was obtained from the mixed step bed where the porosity of each step was varied in order to provide the least disturbance to the coalesced oil droplets. Furthermore, the application of plate or tube settler in the decanter would result in higher decantation efficiency. Moreover, changing of medium bed height had no significant effect on the treatment efficiency, however, the low flow velocity provided higher efficiency than high velocity since the quiescent system was required in order to produce the large coalesced oil droplets. The enhancement of treatment efficiency by applying the liquid recirculation concept did not obviously improve the efficiency; however, this concept will be interesting for high concentration oily wastewater since it can be used for both treatment and recovery of oil in water. Moreover, it was found that the hybrid process of coalescer and decantation in this study still had limitation for separating very small droplets (1 – 3 μm), since the increment of coalescing bed height or expansion of decanter's area still be restricted by the construction cost and area. Therefore, this process should be considered as the pre-treatment process for decreasing or recovering oil quantity in water before entering to the finishing process, such as chemical, physico-chemical or biological treatment processes in further.

Hence, it can be concluded from the obtained experimented results that the overall efficiency of the hybrid process was dependent on both coalescer and decantation efficiency. Hence, in the next section, the simple models for comprehending the overall efficiency and the effect of operating conditions on the different treatment mechanism (filtration, coalescence, and decantation) occurred from both coalescer and decantation processes were proposed.

4.5 Application of simple model for defining treatment mechanisms

In this part, the simple model was used in order to determine the effects of operating conditions on the treatment efficiencies of the hybrid process. Firstly, the Ergun's equation, which defined as correlation of the friction factor in a spherical granular packed column as a function of Reynolds number, as in Equation 2.25 will be used for determining the diameter of media (D_P) used in this study. The equation is shown as following (McCabe, 2000).

$$\frac{\Delta P}{L} = \frac{150V_0\mu(1-\varepsilon)^2}{\psi^2 {D_p}^2 \varepsilon^3} + \frac{1.75\rho {V_0}^2(1-\varepsilon)}{\psi D_p \varepsilon^3}$$

Note that the sphericity factor (ψ) of medium can be calculated from Equation 2.15 shown as following.

$$\psi = \frac{\pi^{\frac{1}{3}}(6V_p)^{\frac{2}{3}}}{A_p} = \frac{6/D_p}{a_v}$$

The production of sphericity (ψ) and diameter of media (D_p), ψD_p, was calculated and denoted as the "actual diameter (D_{actual})" of different shapes of coalescing medium used in this study. In this work, this ψD_p term can be determined by applying Ergun's equation with pressure loss (Δp) of wastewater flow through the medium bed measured by manometer. However, the wetted surface in case of tubular PP was two-fold than the other two media since the inner surface of the tubular had to be taken into account, resulting in increasing of specific surface area (a_v) and also total surface area in medium bed (a) for 1.78 times as shown in Equation 4.5 (Geankoplis, 2003). Then, hydraulic radius was reduced and causing the decrease of equivalent flow channel (D_{eq}) as in Equation 4.6 (Geankoplis, 2003). Finally, the term of ration between occurred pressure loss and bed height was raised as in Equation 4.7 (McCabe, 2000), resulting in the decrease of D_{actual} term as expressed in Equaion 2.25 above.

$$a = a_v(1-\varepsilon) \tag{4.5}$$

$$r_H = \frac{\varepsilon}{a} = \frac{D_{eq}}{4} \tag{4.6}$$

$$\frac{\Delta p}{H} = \frac{32 v_{av}\mu}{D_{eq}^2} \tag{4.7}$$

The calculated ψD_p results were displayed in Table 4.11.

Table 4.11 The calculated D_{actual} from pressure loss by Ergun's equation

Medium types	v_0 (cm/s)	h_L (mmH2O)	Δp (Pa)	ψD_p (mm)	Average ψD_p (mm)
Granular PP (ε = 55.12%)	2.0	15.5	152.1	3.63	6.39
	4.0	47.5	466.0	3.92	
	6.0	69.0	676.9	5.51	
	8.0	92.5	907.4	7.02	
	10.0	145.0	1422.5	6.92	
	15.0	193.0	1893.3	11.37	
Fibrous PP (ε = 90.34%)	2.0	0.9	8.8	2.40	6.48
	4.0	1.9	18.1	4.22	
	6.0	3.0	29.4	5.73	
	8.0	4.2	41.2	7.21	
	10.0	5.8	56.4	8.20	
	15.0	9.5	93.2	11.12	
Tubular PP (ε = 81.77%)	2.0	1.4	13.7	2.23	5.66
	4.0	3.0	29.4	3.49	
	6.0	4.5	44.1	4.98	
	8.0	6.0	58.9	6.51	
	10.0	9.0	88.3	6.75	
	15.0	13.5	132.4	10.01	

From Table 4.11, it can be noticed that the D_{actual} from calculation of three different media were similar. Moreover, the calculated diameter in case of granular PP of 6.39 mm was close to the diameter from measurement at 5 mm. Therefore, it can be stated that determination of medium diameter by applying pressure loss occurred in the system with Ergun's equation can be possibly applied as the simple experimental method in real operating practice. In addition, the calculated diameter for fibrous medium was relatively close to the granular one; whereas, the calculated tubular medium size was smallest, which was suggested to have relation with the highest efficiency obtained.

The treatment efficiency of the coupling process can be examined by divide into two processes, firstly, the treatment efficiency of coalescer can be simply determined by the coalescence efficiency correlation (Equation 2.12) as shown below, where η_T and α are single collection and attachment efficiency, respectively (Aurelle, 1985). As aforementioned, this coalescence efficiency correlation was adapted from the filtration efficiency equation; therefore, the application of this equation for describing the coalescence phenomenon might cause some errors.

$$\ln\left(\frac{C_1}{C_0}\right) = -\frac{3}{2}\alpha\eta_T(1-\varepsilon)\frac{L}{D_p}$$

After that, the coalescer outlet entranced to the decantation tank; hence, the removal efficiency of decanter (η_{Decant}) can be determined as in Equation 4.8.

$$C_2 = C_1(1-\eta_{Decant}) \qquad (4.8)$$

Therefore, the overall efficiency was calculated by combining the efficiency of those two processes, and can be stated Equation 4.9.

$$\ln\left(\frac{C_0}{C_2}\right) = \frac{3}{2}\alpha\eta_T(1-\varepsilon)\frac{L}{D_p} - \ln(1-\eta_{Decant}) \qquad (4.9)$$

Note that the term $\alpha\eta_T$ represents the treatment efficiency occurred within the medium bed height, while the η_{Decant} is efficiency obtained from the mechanisms occurred between oil droplets after passing the medium bed.

According to Equation 4.6, the coalescer performance in term of $\alpha\eta_T$ and removal efficiency (η_{Decant}) were investigated by linearly plotting between $\ln\frac{C_0}{C_2}$ and $\frac{3}{2}(1-\varepsilon)\frac{L}{D_p}$. The values of $\alpha\eta_T$ and η_{Decant}, were obtained as the slope and Y axis-interception, respectively. However, the effect of oil storage as aforementioned was still not considered in this model, therefore, the storage effect had to be deducted from the efficiency. Figure 4.30 illustrates the storage of oil droplet stored in tubular medium.

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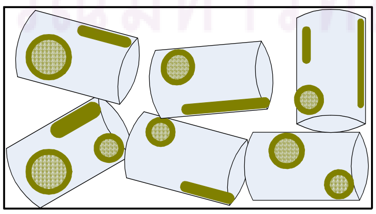

Figure 4.30 Oil droplets storage in the inner space of tubular medium

In this work, the effect of oil-droplet storage was confirmed by efficiency from each sampling point as shown in Figure 4.31. The difference of efficiency between tubular medium and the other two coalescing types was 17.33% at optimal operating condition, which could be defined as the impact of oil storage in the hollow space of PP tube.

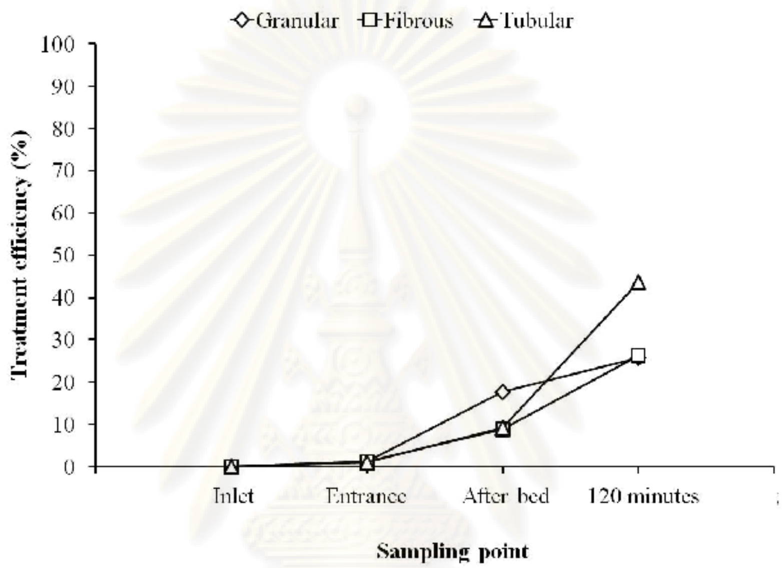

Figure 4.31 Changing of treatment efficiency for different sampling point at 2.0 cm/s flow velocity and 10 cm bed height

Therefore, the plotted results are illustrated in Figure 4.32. The overall efficiency of this hybrid process was the summation of $\alpha\eta_T$ and η_{Decant}. The obtained efficiencies from plotting are summarized in Table 4.12.

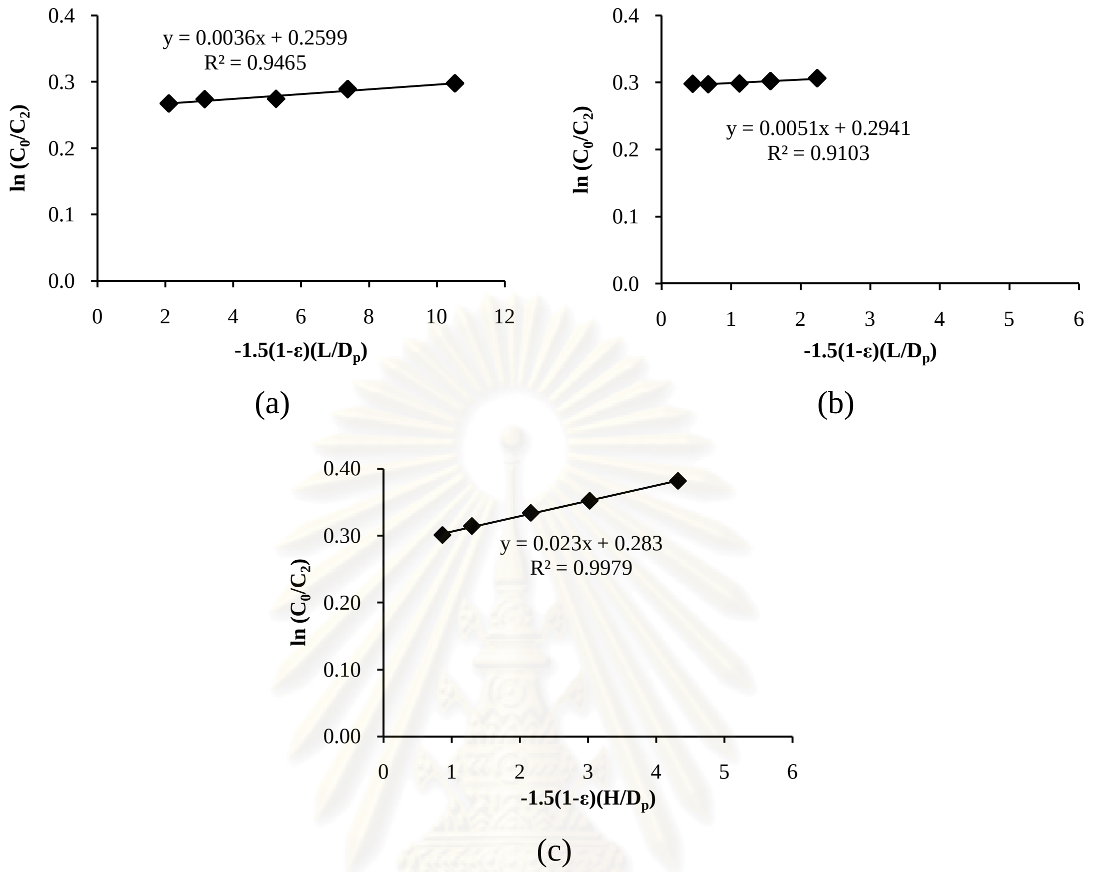

Figure 4.32 Plotting between $\ln\frac{C_0}{C_2}$ and $\frac{3}{2}(1-\varepsilon)\frac{L}{D_p}$ for different medium bed heights at 2.0 cm/s flow velocity for (a) granular PP; (b) fibrous PP; and (c) tubular PP

Table 4.12 The calculated efficiencies obtained from the plotting for different medium bed heights and flow velocities

Medium types	**v_0 (cm/s)**	**Slope (αηT)**	**Y axis intercept**	**η_{Decant}**	**Efficiency (%) [Calculated]**	**Efficiency (%) [Experimental]**
Granular PP	2.0	0.004	0.2599	0.229	23.25	25.76
	3.4	0.007	0.2170	0.195	20.18	24.43
	4.8	0.013	0.1356	0.127	14.02	23.25
	6.8	0.013	0.1247	0.117	13.02	22.19
Fibrous PP	2.0	0.005	0.2941	0.255	25.99	26.31
	3.4	0.024	0.2540	0.224	24.87	26.03
	4.8	0.033	0.1938	0.176	20.92	24.11
	6.8	0.038	0.1677	0.154	19.26	22.08
Tubular PP	2.0	0.023	0.2830	0.246	26.94	43.63
	3.4	0.020	0.2462	0.218	23.86	33.18
	4.8	0.021	0.1915	0.174	19.49	27.15
	6.8	0.024	0.1521	0.141	16.52	23.77

According to Table 4.12, it can be firstly seen that the calculated efficiencies were decreased when the flow velocities were raised that correspond to the experimental results. Moreover, the $\alpha\eta_T$ term, which was the efficiency of coalescence process, was relatively much lower than the removal efficiency (η_{Decant}). This indicated that the coalescer process provided very diminutive impacts on the removal of oil droplets from water. The oil droplets were expected to pass through the coalescing medium with larger size, but not trapped in the bed. The removal of oil from water occurred after the oil droplets passed through the coalescing bed. In addition, the efficiencies obtained from calculation in the model in case of granular and fibrous medium were such close to the experimental results; on the contrary, the calculated efficiency for tubular PP was quite lower than that of experimental one. As mentioned above, the storage effect was excluded from this model. Hence, by adding this 17.33% efficiency of storage to the calculated efficiency obtained from model, it was found that the obtained total efficiency was 44.27%, which was relatively precise comparing to the experimental results.

Furthermore, it can be noticed from Table 4.12 that the efficiencies obtained from calculations at high flow velocity range were incompatible with the experimental results. This could be explained by the effect of turbulence occurred at high flow velocity, which was not taken into account in the equation due to the limitation in laminar zone of above filtration equation. Note that the turbulence would result in more complex treatment mechanism occurred, like higher oil-droplet loading and collision probability of oil droplets on coalescing medium that caused the higher treatment efficiency by filtration, and thus provided the deviation between the experimental and calculated efficiencies.

In order to validate this model, the experimental results obtained from the treatment of cutting oil by coalescer process with other medium type were applied. These data were obtained from study of Wanichkul (2000) as the used coalescing medium was commercial fibrous stainless steel medium with diameter of 60 microns and 0.728 in porosity. The experimental set-up and applied coalescing medium are shown in Figure 2.12 (Wanichkul, 2000) as below.

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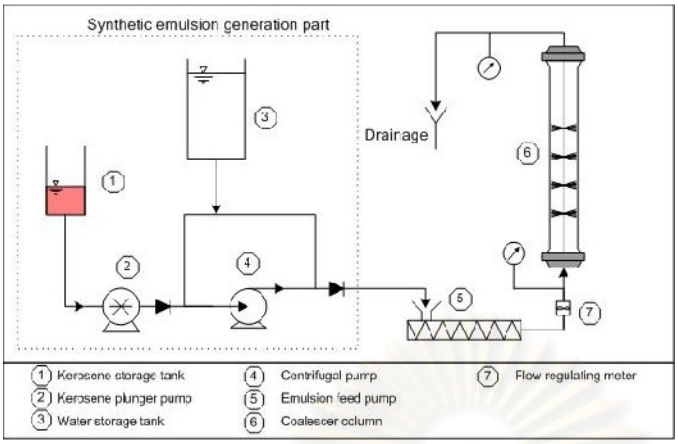

From the Wanichkul's study, the highest treatment efficiency of 45.65% was obtained from 2.0 flow velocity and 10 cm as well as the optimal operating condition in this study. Note that this commercial fibrous medium provided high efficiency, which might cause from its small diameter of fiber.

By applying Ergun's equation, the actual diameter (D_{actual}) was obtained as 1.80 mm, which was comparatively smaller than the polypropylene media in this study. Then, the plotting between $\ln\frac{C_0}{C_2}$ and $\frac{3}{2}(1-\varepsilon)\frac{L}{D_p}$ was conducted for 2.0 cm/s flow velocity as displayed in Figure 4.33.

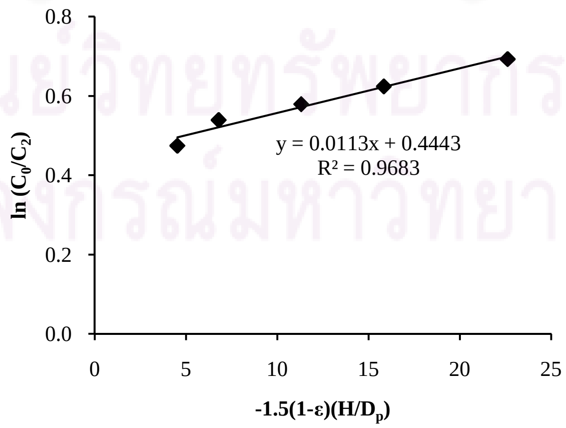

Figure 4.33 Plotting between $\ln\frac{C_0}{C_2}$ and $\frac{3}{2}(1-\varepsilon)\frac{L}{D_p}$ at 2.0 cm/s flow velocity for fibrous stainless steel coalescing medium

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From Figure 4.33, it was found that the plotting contained the linear relationship with high correlation coefficient of 0.9683. The $\alpha\eta_T$ and η_{Decant} obtained from plotting were 0.0113 and 0.359, respectively; therefore, the overall efficiency was 37.00% that was not differ from the experimental result. It can be noticed from the obtained values that η_{Decant} was dominate in the overall efficiency as well as the results of PP media. The coalescer efficiency in term of $\alpha\eta_T$ was very low. It was correspondent to Aurelle (1985) that the minimal $\alpha\eta_T$ was acquired from the application of coalescer for treatment of oily emulsion that contained size of oil droplets in range of 0.25 – 5 microns. Therefore, it should be suggested that in order to achieve the effective treatment of cutting oil by coalescer process, the operating would play an important role on the overall efficiency. Moreover, size of oil droplet was another important factor that provided impact to the efficiency of the process. In case of other oil type with larger droplet size (e.g. palm oil), the modification of coalescer process might result in higher impact to the overall efficiency.

In the future, more studies in the field of coalescer should be conducted in order to investigate for best operating condition and other factor affecting the treatment efficiency; for example, different oil types, coalescing medium, as well as the flow pattern or flow velocity of the oily wastewater in the process.

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CHAPTER V
CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The objective of this work was to evaluate the treatment and separation of 1 g/l emulsified cutting oil wastewater by applying different shapes of polypropylene (PP) in a conventional coalescer process. Moreover, several techniques were applied in order to improve the overall treatment efficiency of coupling process of coalescer and decantation; for example, step bed configuration, liquid recirculation, and improvement of decantation tank. Based on the obtained experimental results, the following conclusions can be presented.

5.1.1 Treatment of cutting oil emulsion by combined process between conventional coalescer and decantation

- The characteristics of three different polypropylene (PP) media (i.e. granular, fibrous, and tubular PP) can be applied as coalescing medium since they performed as hydrophobic material with contact angles of oil droplets on media surface in water were 68.01, 68.53, and 68.37 degrees for granular, fibrous, and tubular medium, respectively.
- The combined process between coalescer and decantation provided greater removal efficiency than that of only decantation. The flow velocity of emulsion had an effect on efficiency where the increase of velocity resulted in lower treatment efficiency, and the medium bed height caused a slightly effect on the efficiency.
- The shape and dimension of media as well as porosity of the packed bed played an important role on the treatment efficiency since the occurred treatment mechanisms were governed by these properties.
- The optimal operating conditions for cutting oily emulsion were 2.0 cm/s and 10 cm bed height for all three different medium types with

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treatment efficiencies of 25.76, 26.31, and 43.64% for granular, fibrous, and tubular PP, respectively.

- The oil droplet sizes presented in wastewater after passing coalescing media in terms of mean diameter (D_{mean}) and sauter mean diameter (D_{32}) were larger than droplet size in inlet emulsion for all three medium types. The larger droplets caused the increase in rising velocity according to Stoke's law that resulted in higher oil separation than decantation process, which can be confirmed by the treatment efficiency.

5.1.2 Enhancement of treatment efficiency by coalescer and decantation process

- Stage coalescer (step bed configuration) provided different effects on each medium type. In case of granular medium, the number of step increment did not clearly affect on the efficiency because of filtration mechanism occurred in this medium type mainly depended on the medium bed height. Whereas, increase of step number for fibrous medium resulted in efficiency raised since the droplets can re-coalesce after passing each step bed. For tubular PP, the application of stage coalescer concept caused the decreased of treatment efficiency due to the break up or splitting of large coalesced oil droplets was occurred.
- The application of step bed configuration with varied porosity of bed from low to high porosity produced the highest treatment efficiency of 59.12% since the filtration and coalescence can occurred with avoidance of droplets break-up. Whereas, liquid recirculation provided the same impacts to each bed but still cannot improved the overall efficiency of the process. However, the recirculation concept should be further studied to apply in purpose of oil recovery from oily wastewater.
- The discrete settling relationship was constructed by applying the experimental results. This relationship can be used for designing of

decanter with certain efficiency and evaluated for dimension of decantation tank.

5.1.3 Application of model for defining treatment mechanism

- Ergun’s equation can be applied for determining the actual diameter (D_{actual}) of medium by using pressure loss occurred from flowing through packed bed. The calculated diameter was relatively closed to the measured size in case of granular medium.
- It was found that coalescer process in term of $\alpha\eta_T$ provided slightly effects on the overall treatment efficiency comparing to the removal efficiency occurred after passing coalescing medium bed.
- The efficiencies obtained from model were decrease due to the increasing of flow velocity; however, the calculated efficiencies for high flow velocity range were deviate from the experimental one, which might be the effect of turbulent flow that was not considered in this model.
- The applied model still had the limitation since the effects of turbulence from the flow velocity and also oil storage in the medium bed were excluded.
- The simple model was validated with the results of cutting oil wastewater treatment by other coalescing medium type. The linear relationship of the model was obtained from the results, and emphasized the dominance of decanter efficiency, on the other words, optimal operating conditions on the overall efficiency for cutting oily emulsion.

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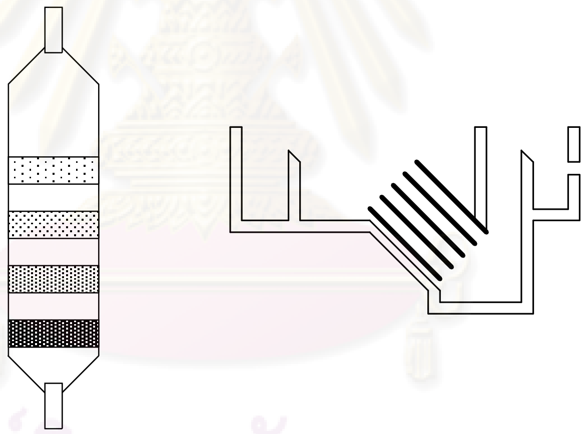
5.2 Recommendations

Coalescer should be applied as pre-treatment process for removing or recovering oil content from water before entrance the secondary treatment process. Therefore, the effective and extensive applying coalescer process has to be developed. In the future, it is interesting to study the different types of oily-emulsion wastewater produced from various types of oils and surfactants. It is essential to further study with different types of coalescing medium with various operating conditions (i.e. medium bed height, flow velocity, flow pattern, etc.) in order to obtain the optimal condition that provided high treatment efficiency. The enhancement of separation efficiency with novel techniques still has to be developed or explored. The effective decanter for using with coalescer process should be design for higher separation efficiency. Moreover, the model for describing occurred mechanisms in the process has to be developed for more accuracy and more intensive defining.

In order to enhance the overall treatment efficiency of this hybrid process, several techniques should be applied; for example, mixed step bed configuration with gradually increase in porosity for coalescer and plate or tube settler installation in decantation tank as shown in Figure 5.1.



(a) (b)

Figure 5.1 Proposed reactor concept of (a) coalescer column; and (b) decanter

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Furthermore, the improvement of coalescer efficiency by reducing flow velocity of emulsion and changing flow orientation should be also considered.

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APPENDICES

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APPENDIX A

1. Synthetic cutting oil emulsion wastewater

Table A-1 Size distribution of oil droplets in synthetic wastewater

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	29	29	0.13	0.13
1.5	24	53	2.99	3.12
2.5	32	85	18.43	21.55
3.5	1	86	1.58	23.13
4.5	9	95	3t540.24	53.37
5.5	1	96	6.13	59.50
6.5	4	100	40.50	100.00

Mean diameter (D_{mean}) = 1.95 μm
Sauter mean diameter (D_{32}) = 4.12 μm

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2. Kinetic results

Table A-2 Kinetic results at 2.0 cm/s flow velocity and 10 cm bed height

Time (min)	Granular PP		Fibrous PP		Tubular PP	
	Turbidity (NTU)	Removal (%)	Turbidity (NTU)	Removal (%)	Turbidity (NTU)	Removal (%)
Inlet	1374	-	1374	-	1374	-
0	1278	7.03	1291	6.06	1287	6.38
15	1154	16.01	1138	17.22	1119	18.60
30	1104	19.67	1094	20.40	1040	24.33
45	1067	22.34	1061	22.82	964	29.88
60	1066	22.46	1045	23.96	916	33.37
90	1051	23.55	1031	25.01	845	38.49
120	1022	25.64	1009	26.61	793	42.28
180	1026	25.37	1010	26.53	790	42.49
240	1021	25.73	1017	26.00	792	42.40
300	1029	25.13	1011	26.44	794	42.23

3. Effects of operating condition on oily emulsion treatment by coalescer

Table A-3.1 Effects of flow velocity and coalescing bed height for granular medium

Flow velocity (cm/s)	Bed height (cm)	Inlet Turbidity (NTU)	After bed		120 minutes	
			Turbidity (NTU)	Efficiency (%)	Turbidity (NTU)	Efficiency (%)
2.0	-	948	-	-	850	10.40
	2	1134	968	14.67	868	23.49
	3	1023	868	15.22	778	24.02
	5	1184	997	15.81	900	24.04
	7	1100	921	16.29	824	25.05
	10	1169	963	17.65	868	25.76
3.4	-	972	-	-	876	9.92
	2	962	859	10.75	774	19.58
	3	1019	881	13.62	796	21.93
	5	1106	950	14.11	855	22.72
	7	1072	922	13.97	816	23.81
	10	1155	973	15.72	873	24.43
4.8	-	1121	-	-	1019	9.10
	2	1123	1040	7.34	961	14.40
	3	1175	1078	8.25	985	16.22
	5	1089	969	11.04	884	18.80
	7	1148	996	13.24	888	22.68
	10	1181	1012	14.35	908	23.15
6.8	-	1237	-	-	1127	8.89
	2	1230	1152	6.35	1064	13.56
	3	1023	951	7.11	867	15.32
	5	1199	1084	9.55	985	17.85
	7	1249	1104	11.65	990	20.74
	10	1155	997	13.63	898	22.19

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Table A-3.2 Effects of flow velocity and coalescing bed height for fibrous medium

Flow velocity (cm/s)	Bed height (cm)	Inlet Turbidity (NTU)	After bed		120 minutes	
			Turbidity (NTU)	Efficiency (%)	Turbidity (NTU)	Efficiency (%)
2.0	-	948	-	-	850	10.40
	2	1087	1014	6.70	807	25.75
	3	1241	1149	7.36	921	25.77
	5	028	851	8.27	689	25.74
	7	1095	1001	8.57	810	26.07
	10	926	844	8.78	682	26.31
3.4	-	972	-	-	876	9.92
	2	1075	1007	6.28	836	22.24
	3	953	886	7.02	720	24.43
	5	1211	1121	7.43	910	24.92
	7	1236	1137	8.03	916	25.89
	10	1105	1013	8.36	818	26.03
4.8	-	1121	-	-	1019	9.10
	2	1148	1079	5.94	929	19.04
	3	1002	939	6.26	805	19.63
	5	1242	1160	6.62	988	20.46
	7	1241	1154	7.07	981	21.01
	10	1281	1189	7.23	972	24.11
6.8	-	1237	-	-	1127	8.89
	2	1091	1032	5.39	903	17.28
	3	1255	1182	5.79	1038	17.26
	5	1106	1032	6.72	910	17.74
	7	1189	106	6.95	933	21.55
	10	1114	1035	7.04	868	22.08

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Table A-3.3 Effects of flow velocity and coalescing bed height for tubular medium

Flow velocity (cm/s)	Bed height (cm)	Inlet Turbidity (NTU)	After bed		120 minutes	
			Turbidity (NTU)	Efficiency (%)	Turbidity (NTU)	Efficiency (%)
2.0	-	948	-	-	850	10.40
	2	1083	1021	5.78	792	26.86
	3	1269	1190	6.20	888	30.03
	5	1286	1186	7.74	832	35.28
	7	999	909	8.96	614	38.48
	10	1236	1123	9.16	697	43.64
3.4	-	972	-	-	876	9.92
	2	1082	1030	4.86	840	22.41
	3	1171	1112	5.03	877	25.14
	5	1213	1134	6.49	884	27.13
	7	1268	1178	7.11	899	29.12
	10	1076	987	8.24	719	33.18
4.8	-	1121	-	-	1019	9.10
	2	1107	1056	4.55	914	17.42
	3	1203	1141	5.10	949	21.12
	5	1161	1093	5.85	891	23.22
	7	1093	1026	6.11	819	25.08
	10	1083	1002	7.41	789	27.15
6.8	-	1237	-	-	1127	8.89
	2	1015	979	3.56	896	11.69
	3	1094	1055	3.54	948	13.38
	5	1119	1064	4.86	951	15.01
	7	1250	1197	4.20	1007	19.38
	10	1086	1033	4.83	828	23.77

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4. Optimal oily emulsion treatment condition by coalescer

Table A-4.1 Turbidity and COD removal for three medium at optimal condition (2.0 cm/s flow velocity and 10 cm bed height)

Medium types	COD (mg/l)			Turbidity (NTU)		
	Inlet	Outlet	Efficiency (%)	Inlet	Outlet	Efficiency (%)
Granular	1519	1138	25.08	1169	868	25.76
Fibrous	1361	993	27.04	926	682	26.31
Tubular	1538	881	42.72	1236	697	43.64

Table A-4.2 Size distribution after passing granular bed at optimal operating condition

Average size (µm)	**Size distribution (%)**	**Accumulative distribution (%)**	**Volume distribution (%)**	**Accumulative volume distribution (%)**
0.5	14	14	0.01	0.01
1.5	16	30	0.29	0.30
2.5	15	45	1.26	1.56
3.5	17	62	3.92	5.48
4.5	12	74	5.88	11.36
5.5	6	80	5.37	16.73
6.5	2	82	2.96	19.69
7.5	10	92	22.69	42.38
8.5	1	93	3.31	45.69
9.5	4	97	18.45	64.14
10.5	1	98	6.22	70.36
11.5	0	98	0.00	70.36
12.5	0	98	0.00	70.36
13.5	1	99	13.24	83.60
14.5	1	100	16.40	100.00

Table A-4.3 Size distribution after 120 minutes decantation for granular bed at optimal operating condition

Average size (µm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	4	4	0.00	0.00
1.5	17	21	0.33	0.33
2.5	19	40	1.71	2.04
3.5	18	58	4.43	6.47
4.5	15	73	7.86	14.33
5.5	6	79	5.74	20.07
6.5	4	83	6.31	26.38
7.5	5	88	12.13	38.51
8.5	5	93	17.64	56.15
9.5	4	97	19.71	75.86
10.5	1	98	6.66	82.52
11.5	2	100	17.48	100.00

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Table A-4.4 Size distribution after passing fibrous bed at optimal operating condition

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	5	5	0.00	0.00
1.5	18	23	0.07	0.07
2.5	24	47	0.41	0.48
3.5	13	60	0.62	1.10
4.5	11	71	1.10	2.20
5.5	5	76	0.92	3.12
6.5	2	78	0.61	3.73
7.5	6	84	2.80	6.53
8.5	3	87	2.03	8.56
9.5	1	88	0.95	9.51
10.5	0	88	0.00	9.51
11.5	4	92	6.72	16.23
12.5	0	92	0.00	16.23
13.5	2	94	5.43	21.66
14.5	1	95	3.37	25.03
15.5	0	95	0.00	25.03
16.5	1	96	4.96	29.99
17.5	1	97	5.92	35.91
18.5	0	97	0.00	35.91
19.5	0	97	0.00	35.91
20.5	0	97	0.00	35.91
21.5	0	97	0.00	35.91
22.5	0	97	0.00	35.91
23.5	0	97	0.00	35.91
24.5	0	97	0.00	35.91
25.5	0	97	0.00	35.91
26.5	2	99	41.12	77.03
27.5	1	100	22.97	100.00

Table A-4.5 Size distribution after 120 minutes decantation for fibrous bed at optimal operating condition

Average size (µm)	**Size distribution (%)**	**Accumulative distribution (%)**	**Volume distribution (%)**	**Accumulative volume distribution (%)**
0.5	27	27	0.03	0.03
1.5	10	37	0.35	0.38
2.5	7	44	1.11	1.49
3.5	13	57	5.65	7.14
4.5	12	69	11.09	18.23
5.5	19	88	32.05	50.28
6.5	5	93	13.93	64.21
7.5	4	97	17.11	81.32
8.5	3	100	18.68	100.00

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Table A-4.6 Size distribution after passing tubular bed at optimal operating condition

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	3	3	0.00	0.00
1.5	13	16	0.03	0.03
2.5	12	28	0.12	0.15
3.5	19	47	0.53	0.68
4.5	12	59	0.71	1.39
5.5	6	65	0.65	2.04
6.5	14	79	2.50	4.53
7.5	5	84	1.37	5.90
8.5	4	88	1.59	7.50
9.5	1	89	0.56	8.05
10.5	3	92	2.25	10.31
11.5	0	92	0.00	10.31
12.5	1	93	1.27	11.58
13.5	0	93	0.00	11.58
14.5	0	93	0.00	11.58
15.5	1	94	2.42	13.99
16.5	1	95	2.92	16.91
17.5	0	95	0.00	16.91
18.5	0	95	0.00	16.91
19.5	1	96	4.81	21.72
20.5	1	97	5.59	27.31
21.5	0	97	0.00	27.31
22.5	0	97	0.00	27.31
23.5	0	97	0.00	27.31
24.5	0	97	0.00	27.31
25.5	0	97	0.00	27.31
26.5	1	98	12.08	39.39
27.5	0	98	0.00	39.39
28.5	0	98	0.00	39.39
29.5	0	98	0.00	39.39
30.5	0	98	0.00	39.39
31.5	0	98	0.00	39.39
32.5	0	98	0.00	39.39
33.5	0	98	0.00	39.39
34.5	0	98	0.00	39.39
35.5	1	99	29.04	68.43
36.5	1	100	31.57	100.00

Table A-4.7 Size distribution after 120 minutes decantation for tubular bed at optimal operating condition

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	3	3	0.00	0.00
1.5	17	20	0.15	0.15
2.5	19	39	0.77	0.92
3.5	15	54	1.67	2.59
4.5	11	65	2.60	5.19
5.5	4	69	1.73	6.92
6.5	10	79	7.13	14.05
7.5	2	81	2.19	16.24
8.5	6	87	9.57	25.81
9.5	3	90	6.68	32.49
10.5	7	97	21.04	53.53
11.5	0	97	0.00	53.53
12.5	0	97	0.00	53.53
13.5	2	99	12.78	66.30
14.5	0	99	0.00	66.30
15.5	0	99	0.00	66.30
16.5	0	99	0.00	66.30
17.5	0	99	0.00	66.30
18.5	0	99	0.00	66.30
19.5	0	99	0.00	66.30
20.5	0	99	0.00	66.30
21.5	0	99	0.00	66.30
22.5	0	99	0.00	66.30
23.5	1	100	33.70	100.00

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5. Enhancement of coalescer efficiency by step bed configuration

Table A-5.1 Effects of number of step for three different medium types at 2.0 cm/s flow velocity and 10 cm height for each step

Medium types	Bed height (cm)	Inlet Turbidity (NTU)	After bed		120 minutes	
			Turbidity (NTU)	Efficiency (%)	Turbidity (NTU)	Efficiency (%)
Granular	1	1169	963	17.65	868	25.76
	2	1326	1097	17.27	981	26.01
	4	999	829	17.04	729	27.05
	5	1040	853	17.99	763	26.70
Fibrous	1	926	844	8.78	682	26.31
	2	1078	977	9.32	744	30.94
	4	1133	1020	9.99	705	37.76
	5	1236	1132	11.98	769	40.16
Tubular	1	1236	1123	9.16	697	43.64
	2	1256	1108	11.76	763	39.22
	4	1161	1021	12.01	782	32.63
	5	1292	1117	13.55	898	30.48
Mixed bed	-	1080	962	10.91	441	59.12

Table A-5.2 COD removal efficiency for 2.0 cm/s flow velocity with 5 bed steps

Medium types	COD (mg/l)			Turbidity (NTU)		
	Inlet	Outlet	Efficiency (%)	Inlet	Outlet	Efficiency (%)
Granular	1488	1087	26.95	1040	763	26.70
Fibrous	1613	944	41.48	1236	769	40.16
Tubular	1641	1132	31.02	1292	898	30.48
Mixed bed	1398	581	58.44	1080	441	59.12

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Table A-5.3 Size distribution of oil droplets after passing 5 steps granular bed at 2.0 cm/s flow velocity

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	12	12	0.01	0.01
1.5	16	28	0.21	0.21
2.5	20	48	1.20	1.42
3.5	14	62	2.31	3.73
4.5	13	75	4.56	8.29
5.5	4	79	2.56	10.85
6.5	0	79	0.00	10.85
7.5	7	86	11.36	22.21
8.5	3	89	7.09	29.30
9.5	1	90	3.30	32.60
10.5	4	94	17.82	50.42
11.5	2	96	11.71	62.13
12.5	0	96	0.00	62.13
13.5	4	100	37.87	100.00

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Table A-5.4 Size distribution of oil droplets after 120 minutes decantation for 5 steps granular bed at 2.0 cm/s flow velocity

Average size (µm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	9	9	0.01	0.01
1.5	16	25	0.29	0.30
2.5	10	35	0.85	1.15
3.5	28	63	6.51	7.65
4.5	14	77	6.91	14.57
5.5	4	81	3.61	18.17
6.5	2	83	2.98	21.15
7.5	6	89	13.72	34.87
8.5	1	90	3.33	38.20
9.5	3	93	13.94	52.14
10.5	5	98	31.37	83.51
11.5	2	100	16.49	100.00

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Table A-5.5 Size distribution of oil droplets after passing 5 steps fibrous bed at 2.0 cm/s flow velocity

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	0	0	0.00	0.00
1.5	9	9	0.02	0.02
2.5	11	20	0.12	0.14
3.5	12	32	0.35	0.49
4.5	20	52	1.24	1.73
5.5	11	63	1.25	2.98
6.5	11	74	2.06	5.04
7.5	8	82	2.30	7.35
8.5	3	85	1.26	8.61
9.5	3	88	1.76	10.36
10.5	3	91	2.37	12.73
11.5	1	92	1.04	13.77
12.5	0	92	0.00	13.77
13.5	1	93	1.68	15.45
14.5	0	93	0.00	15.45
15.5	0	93	0.00	15.45
16.5	0	93	0.00	15.45
17.5	0	93	0.00	15.45
18.5	0	93	0.00	15.45
19.5	0	93	0.00	15.45
20.5	1	94	5.88	21.33
21.5	1	95	6.78	28.11
22.5	0	95	0.00	28.11
23.5	0	95	0.00	28.11
24.5	0	95	0.00	28.11
25.5	1	96	11.32	39.43
26.5	2	98	25.40	64.83
27.5	0	98	0.00	64.83
28.5	1	99	15.80	80.63
29.5	0	99	0.00	80.63
30.5	1	100	19.37	100.00

Table A-5.6 Size distribution of oil droplets after 120 minutes decantation for 5 steps fibrous bed at 2.0 cm/s flow velocity

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	20	20	0.02	0.02
1.5	0	20	0.00	0.02
2.5	0	20	0.00	0.02
3.5	15	35	4.66	4.68
4.5	31	66	20.47	25.15
5.5	20	86	24.11	49.26
6.5	3	89	5.97	55.23
7.5	3	92	9.17	64.40
8.5	8	100	35.60	100.00

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Table A-5.7 Size distribution of oil droplets after passing 5 steps tubular bed at 2.0 cm/s flow velocity

Average size (µm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	1	1	0.00	0.00
1.5	6	7	0.10	0.10
2.5	19	26	1.40	1.50
3.5	28	54	5.67	7.17
4.5	17	71	7.32	14.49
5.5	9	80	7.08	21.57
6.5	10	90	12.98	34.54
7.5	0	90	0.00	34.54
8.5	6	96	17.41	51.96
9.5	0	96	0.00	51.96
10.5	2	98	10.94	62.90
11.5	1	99	7.19	70.08
12.5	0	99	0.00	70.08
13.5	0	99	0.00	70.08
14.5	0	99	0.00	70.08
15.5	0	99	0.00	70.08
16.5	0	99	0.00	70.08
17.5	0	99	0.00	70.08
18.5	1	100	29.92	100.00

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Table A-5.8 Size distribution of oil droplets after 120 minutes decantation for 5 steps tubular bed at 2.0 cm/s flow velocity

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	14	14	0.02	0.02
1.5	10	24	0.30	0.32
2.5	15	39	2.10	2.41
3.5	13	52	4.98	7.40
4.5	23	75	18.74	26.14
5.5	7	82	10.41	36.55
6.5	6	88	14.74	51.29
7.5	10	98	37.73	89.02
8.5	2	100	10.98	100.00

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Table A-5.9 Size distribution of oil droplets after passing mixed step bed at 2.0 cm/s flow velocity

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	2	2	0.00	0.00
1.5	8	10	0.01	0.01
2.5	9	19	0.04	0.05
3.5	9	28	0.11	0.16
4.5	24	52	0.63	0.79
5.5	8	60	0.38	1.17
6.5	11	71	0.87	2.05
7.5	7	78	0.85	2.90
8.5	2	80	0.35	3.25
9.5	3	83	0.74	3.99
10.5	0	83	0.00	3.99
11.5	1	84	0.44	4.43
12.5	1	85	0.56	5.00
13.5	1	86	0.71	5.71
14.5	0	86	0.00	5.71
15.5	1	87	1.07	6.78
16.5	2	89	2.59	9.37
18.5	1	90	1.83	11.20
20.5	0	90	0.00	11.20
21.5	1	91	2.87	14.06
22.5	1	92	3.29	17.35
23.5	0	92	0.00	17.35
24.5	1	93	4.24	21.59
25.5	1	94	4.78	26.37
26.5	0	94	0.00	26.37
27.5	0	94	0.00	26.37
28.5	1	95	6.68	33.05
29.5	1	96	7.40	40.45
30.5	0	96	0.00	40.45
31.5	0	96	0.00	40.45
32.5	1	97	9.90	50.36
33.5	0	97	0.00	50.36
34.5	0	97	0.00	50.36
35.5	0	97	0.00	50.36
36.5	1	98	14.03	64.38
37.5	0	98	0.00	64.38
38.5	1	99	16.46	80.84
39.5	0	99	0.00	80.84
40.5	1	100	19.16	100.00

Table A-5.10 Size distribution of oil droplets after 120 minutes decantation for mixed step bed at 2.0 cm/s flow velocity

Average size (μm)	**Size distribution (%)**	**Accumulative distribution (%)**	**Volume distribution (%)**	**Accumulative volume distribution (%)**
0.5	9	9	0.01	0.01
1.5	11	20	0.18	0.18
2.5	21	41	1.56	1.74
3.5	17	58	3.47	5.21
4.5	8	66	3.47	8.68
5.5	3	69	2.37	11.05
6.5	10	79	13.07	24.12
7.5	4	83	8.03	32.15
8.5	5	88	14.61	46.76
9.5	9	97	36.71	83.48
10.5	3	100	16.52	100.00

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6. Enhancement of coalescer efficiency by wastewater recirculation

Table A-6.1 Effects of recirculation ratio for three different medium types at 2.0 cm/s flow velocity and 10 cm bed height

Medium types	Bed height (cm)	Inlet Turbidity (NTU)	After bed		120 minutes	
			Turbidity (NTU)	Efficiency (%)	Turbidity (NTU)	Efficiency (%)
Granular	0	1169	963	17.65	868	25.76
	20	1180	972	17.63	870	26.28
	50	1069	879	17.83	185	26.55
	80	1143	937	17.98	837	26.72
	100	1236	992	19.73	864	30.10
Fibrous	0	926	844	8.78	682	26.31
	20	1219	1107	9.22	865	29.00
	50	1147	1033	9.92	779	32.09
	80	1243	1114	10.36	793	36.23
	100	1153	1019	11.65	685	40.57
Tubular	0	1236	1123	9.16	697	43.64
	20	811	706	13.01	487	40.03
	50	1132	933	17.57	730	35.51
	80	1099	901	18.04	734	33.23
	100	1171	923	21.13	812	30.62

Table A-6.2 COD removal efficiency for 2.0 cm/s flow velocity with complete recirculation

Medium types	COD (mg/l)			Turbidity (NTU)		
	Inlet	Outlet	Efficiency (%)	Inlet	Outlet	Efficiency (%)
Granular	1580	1091	30.95	1236	864	30.10
Fibrous	1573	927	41.07	1153	685	40.57
Tubular	1498	1053	29.71	1171	812	30.62

Table A-6.3 Size distribution of oil droplets after passing granular bed at 2.0 cm/s flow velocity with complete recirculation

Average size (μm)	**Size distribution (%)**	**Accumulative distribution (%)**	**Volume distribution (%)**	**Accumulative volume distribution (%)**
0.5	0	0	0.00	0.00
1.5	10	10	0.07	0.07
2.5	8	18	0.24	0.31
3.5	10	28	0.83	1.13
4.5	20	48	3.51	4.65
5.5	11	59	3.53	8.17
6.5	8	67	4.24	12.41
7.5	8	75	6.51	18.92
8.5	7	82	8.29	27.20
9.5	4	86	6.61	33.82
10.5	2	88	4.46	38.28
11.5	3	91	8.80	47.08
12.5	2	93	7.53	54.61
13.5	1	94	4.74	59.35
14.5	3	97	17.63	76.98
15.5	2	99	14.36	91.34
16.5	1	100	8.66	100.00

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Table A-6.4 Size distribution of oil droplets after 120 minutes decantation for granular bed at 2.0 cm/s flow velocity with complete recirculation

Average size (μm)	**Size distribution (%)**	**Accumulative distribution (%)**	**Volume distribution (%)**	**Accumulative volume distribution (%)**
0.5	11	11	0.01	0.01
1.5	14	25	0.40	0.41
2.5	22	47	2.91	3.32
3.5	18	65	6.53	9.86
4.5	10	75	7.72	17.57
5.5	9	84	12.68	30.25
6.5	2	86	4.65	34.90
7.5	6	92	21.43	56.34
8.5	7	99	36.40	92.74
9.5	1	100	7.26	100.00

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Table A-6.5 Size distribution of oil droplets after passing fibrous bed at 2.0 cm/s flow velocity with complete recirculation

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	3	3	0.00	0.00
1.5	8	11	0.01	0.01
2.5	10	21	0.06	0.07
3.5	11	32	0.18	0.25
4.5	20	52	0.71	0.96
5.5	12	64	0.77	1.73
6.5	9	73	0.96	2.69
7.5	7	80	1.14	3.84
8.5	5	85	1.19	5.03
9.5	0	85	0.00	5.03
10.5	0	85	0.00	5.03
11.5	0	85	0.00	5.03
12.5	0	85	0.00	5.03
13.5	0	85	0.00	5.03
14.5	1	86	1.18	6.21
15.5	2	88	2.89	9.10
16.5	0	88	0.00	9.10
17.5	0	88	0.00	9.10
18.5	1	89	2.45	11.55
19.5	1	90	2.87	14.42
20.5	0	90	0.00	14.42
21.5	1	91	3.85	18.28
22.5	0	91	0.00	18.28
23.5	2	93	10.06	28.34
24.5	2	95	11.40	39.74
25.5	0	95	0.00	39.74
26.5	0	95	0.00	39.74
27.5	0	95	0.00	39.74
28.5	1	96	8.97	48.71
29.5	1	97	9.95	58.66
30.5	0	97	0.00	58.66
31.5	1	98	12.12	70.78
32.5	1	99	13.31	84.08
33.5	0	99	0.00	84.08
34.5	1	100	15.92	100.00

Table A-6.6 Size distribution of oil droplets after 120 minutes decantation for fibrous bed at 2.0 cm/s flow velocity with complete recirculation

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	9	9	0.01	0.01
1.5	8	17	0.20	0.21
2.5	3	20	0.35	0.55
3.5	15	35	4.74	5.30
4.5	37	72	24.88	30.17
5.5	11	83	13.50	43.68
6.5	6	89	12.16	55.83
7.5	4	93	12.45	68.28
8.5	7	100	31.72	100.00

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Table A-6.7 Size distribution of oil droplets after passing tubular bed at 2.0 cm/s flow velocity with complete recirculation

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	2	2	0.00	0.00
1.5	9	11	0.13	0.13
2.5	21	32	1.43	1.56
3.5	18	50	3.36	4.92
4.5	21	71	8.33	13.25
5.5	9	80	6.52	19.76
6.5	10	90	11.95	31.72
7.5	0	90	0.00	31.72
8.5	5	95	13.36	45.08
9.5	1	96	3.73	48.81
10.5	1	97	5.04	53.85
11.5	1	98	6.62	60.47
12.5	0	98	0.00	60.47
13.5	0	98	0.00	60.47
14.5	0	98	0.00	60.47
15.5	1	99	16.21	76.68
16.5	0	99	0.00	76.68
17.5	1	100	23.32	100.00

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Table A-6.8 Size distribution of oil droplets after 120 minutes decantation for tubular bed at 2.0 cm/s flow velocity with complete recirculation

Average size (μm)	Size distribution (%)	Accumulative distribution (%)	Volume distribution (%)	Accumulative volume distribution (%)
0.5	14	14	0.01	0.01
1.5	10	24	0.27	0.28
2.5	13	37	1.60	1.88
3.5	14	51	4.74	6.62
4.5	19	70	13.66	20.28
5.5	9	79	11.82	32.10
6.5	6	85	13.00	45.11
7.5	13	98	43.28	88.39
8.5	1	99	4.85	93.23
9.5	1	100	6.77	100.00

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7. Discrete settling study

Table A-7.1 Discrete settling results

Medium types	Height (cm)		Time (min)									
			0	15	30	60	90	120	150	180	210	240
Granular	50	C	1257	1183	1152	1113	991	979	961	944	935	929
		C/C0	1	0.94	0.92	0.89	0.79	0.78	0.76	0.75	0.74	0.74
		H/t (cm/min)	-	3.33	1.67	0.83	0.56	0.42	0.33	0.28	0.24	0.21
	100	C	1257	1206	1184	1167	1045	1028	1009	991	980	968
		C/C0	1	0.96	0.94	0.93	0.83	0.82	0.8	0.79	0.78	0.77
		H/t (cm/min)	-	6.67	3.33	1.67	1.11	0.83	0.67	0.56	0.48	0.42
	150	C	1257	1229	1201	1192	1157	1133	1102	1077	1051	1033
		C/C0	1	0.98	0.96	0.95	0.92	0.9	0.88	0.86	0.84	0.82
		H/t (cm/min)	-	10.00	5.00	2.50	1.67	1.25	1.00	0.83	0.71	0.63
Fibrous	50	C	1209	1115	1087	1022	987	958	925	901	894	884
		C/C0	1	0.92	0.90	0.85	0.82	0.79	0.77	0.75	0.74	0.73
		H/t (cm/min)	-	3.33	1.67	0.83	0.56	0.42	0.33	0.28	0.24	0.21
	100	C	1209	1173	1113	1080	1061	1034	1002	978	953	924
		C/C0	1	0.97	0.92	0.89	0.88	0.86	0.83	0.81	0.79	0.76
		H/t (cm/min)	-	6.67	3.33	1.67	1.11	0.83	0.67	0.56	0.48	0.42
	150	C	1209	1191	1159	1123	1107	1082	1053	1027	994	978
		C/C0	1	0.99	0.96	0.93	0.92	0.89	0.87	0.85	0.82	0.81
		H/t (cm/min)	-	10.00	5.00	2.50	1.67	1.25	1.00	0.83	0.71	0.63
Tubular	50	C	1227	1009	976	904	803	784	771	758	741	724
		C/C0	1	0.82	0.80	0.74	0.65	0.64	0.63	0.62	0.6	0.59
		H/t (cm/min)	-	3.33	1.67	0.83	0.56	0.42	0.33	0.28	0.24	0.21
	100	C	1227	1074	996	975	934	901	863	832	801	779
		C/C0	1	0.88	0.81	0.79	0.76	0.73	0.7	0.68	0.65	0.63
		H/t (cm/min)	-	6.67	3.33	1.67	1.11	0.83	0.67	0.56	0.48	0.42
	150	C	1227	1121	1066	1009	976	942	899	851	825	814
		C/C0	1	0.91	0.87	0.82	0.80	0.77	0.73	0.69	0.67	0.66
		H/t (cm/min)	-	10.00	5.00	2.50	1.67	1.25	1.00	0.83	0.71	0.63

* C is inlet turbidity (NTU) or turbidity at 0 minutes

** C/C_0 is ratio of turbidity at time t to the inlet turbidity

Table A-7.2 Decanter efficiency obtained from discrete settling relationship in case of granular medium

v_0 (cm/min)	P_0	$1-P_0$	$1/v_0$ (min/cm)	$\int_0^{P_0} v_i dP_i$	P (%Efficiency)
0.001	0.353	0.647	1000.00		
0.01	0.517	0.483	100.00	0.00	43.84
0.05	0.632	0.368	20.00	0.00	9.04
0.1	0.681	0.319	10.00	0.00	4.65
0.3	0.760	0.240	3.33	0.02	1.69
0.5	0.796	0.204	2.00	0.01	1.07
0.8	0.829	0.171	1.25	0.02	0.71
1	0.845	0.155	1.00	0.01	0.59
1.5	0.874	0.126	0.67	0.04	0.41
2	0.895	0.105	0.50	0.04	0.32
3	0.924	0.076	0.33	0.07	0.22
4	0.944	0.056	0.25	0.07	0.16
5	0.960	0.040	0.20	0.07	0.13
6	0.973	0.027	0.17	0.07	0.10
			SUM	0.43	

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Table A-7.3 Decanter efficiency obtained from discrete settling relationship in case of fibrous medium

v_0 (cm/min)	P_0	$1-P_0$	$1/v_0$ (min/cm)	$\int_0^{P_0} v_i dP_i$	P (%Efficiency)
0.001	0.376	0.624	1000.00		
0.01	0.532	0.468	100.00	0.00	41.76
0.05	0.641	0.359	20.00	0.00	8.62
0.1	0.688	0.312	10.00	0.00	4.44
0.3	0.763	0.237	3.33	0.01	1.61
0.5	0.798	0.202	2.00	0.01	1.03
0.8	0.830	0.170	1.25	0.02	0.69
1	0.845	0.155	1.00	0.01	0.57
1.5	0.872	0.128	0.67	0.03	0.40
2	0.892	0.108	0.50	0.03	0.31
3	0.919	0.081	0.33	0.07	0.22
4	0.939	0.061	0.25	0.07	0.16
5	0.954	0.046	0.20	0.07	0.13
6	0.966	0.034	0.17	0.07	0.10
			SUM	0.41	

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Table A-7.4 Decanter efficiency obtained from discrete settling relationship in case of tubular medium

v_0 (cm/min)	P_0	$1-P_0$	$1/v_0$ (min/cm)	$\int_0^{P_0} v_i dP_i$	P (%Efficiency)
0.001	0.112	0.888	1000.00		
0.01	0.315	0.685	100.00	0.00	54.14
0.05	0.456	0.544	20.00	0.00	11.23
0.1	0.517	0.483	10.00	0.00	5.83
0.3	0.613	0.387	3.33	0.02	2.17
0.5	0.658	0.342	2.00	0.02	1.41
0.8	0.700	0.300	1.25	0.03	0.97
1	0.719	0.281	1.00	0.02	0.82
1.5	0.755	0.245	0.67	0.04	0.60
2	0.780	0.220	0.50	0.04	0.49
3	0.816	0.184	0.33	0.09	0.36
4	0.841	0.159	0.25	0.09	0.29
5	0.861	0.139	0.20	0.09	0.25
6	0.877	0.123	0.17	0.09	0.21
			SUM	0.53	

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APPENDIX B

1. Application of model

Table B-1 Determination of actual diameter (D_{actual}) of stainless steel medium from Ergun's equation

H_{Bed} (m)	v0 (m/s)	h_L (mH_2O)	ΔP (Pa)	D_{actual}
0.02	0.020	0.0011	10.79	0.0015
	0.034	0.0020	19.62	0.0019
	0.048	0.0029	28.45	0.0024
	0.068	0.0032	31.39	0.0039
0.03	0.020	0.0019	18.64	0.0012
	0.034	0.0027	26.49	0.0017
	0.048	0.0033	32.37	0.0023
	0.068	0.0038	37.28	0.0035
0.05	0.020	0.0044	43.16	0.0009
	0.034	0.0051	50.03	0.0013
	0.048	0.0057	55.92	0.0017
	0.068	0.0063	61.80	0.0024
0.07	0.020	0.0061	59.84	0.0009
	0.034	0.0069	67.69	0.0012
	0.048	0.0072	70.63	0.0016
	0.068	0.0075	73.58	0.0023
0.1	0.020	0.0083	81.42	0.0009
	0.034	0.0089	87.31	0.0012
	0.048	0.0094	92.21	0.0015
	0.068	0.0098	96.14	0.0021

Average D_{actual} = 1.80 mm

Table B-1.2 The calculated efficiencies obtained from the plotting between $\ln\frac{C_0}{C_2}$ and $\frac{3}{2}(1-\varepsilon)\frac{H}{D_p}$ for various flow velocities with stainless steel medium

v_0 (cm/s)	Slope (αηT)	Y axis intercept	η_{Remove}	Efficiency (%) [Calculated]
2.0	0.0113	0.444	0.359	37.00
3.4	0.0206	0.155	0.144	16.41
4.8	0.0184	0.122	0.115	13.31
6.8	0.0208	0.016	0.016	3.67

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BIOGRAPHY

Mr. Nattawin Chawaloespornsiya was born on March 25^{th}, 1986 in Bangkok. After graduated from Srinakharinwirot University: Prasarnmit Demonstration School (Secondary), he went to study in Faculty, Engineering at Chulalongkorn University. He graduated Bachelor's degree in Environmental Engineering in 2008. After that, he continued his study for a Master's Degree of Science in Environmental Management (International program) at Chulalongkorn University in May, 2008.

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