Telemark University College

Faculty of Technology

Bachelor of Engineering

REPORT FOR 6TH SEMESTER PROJECT SPRING 2015

PRH612 Bacheloroppgave

K6-4-15

Bachelor Student's Project

Evaluating and Designing Systems for Mixing Water in Oil

Faculty of Technology

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Høgskolen i Telemark
Fakultet for teknologiske fag
Bachelor i ingeniørfag

RAPPORT FRA 6. SEMESTERS PROSJEKT VÅREN 2015

Emne: *PRH612 Bacheloroppgave*
Tittel: *Evaluating and Designing Systems for Mixing Water in Oil*
Rapporten utgjør en del av vurderingsgrunnlaget i emnet.

Prosjektgruppe: *K6-4-15* **Tilgjengelighet:** *Åpen*

Gruppedeltakere:

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Hovedveileder:	*Lars E. Øi*	**Sensor:**	*Kjell-Arne Solli*
Biveileder:	*Kjell-Arne Solli*	**Prosjektpartner:**	*Steve Watson Gabriel*

Godkjent for arkivering:____

Sammendrag:
Olje- og gassindustrien består av utforsking, uthenting, oppgradering, separering, raffinering, transportering og markedsføring av oljeprodukter. Etter separeringsprosessen er vann fjernet i stor grad, og kun en liten andel gjenstår i råoljen. Når produktene markedsføres, er verdien essensiel, og på grunn av dette må det tas en representativ prøve for å fastslå kvaliteten. Dette krever at vanndråpene er uniformt fordelt i oljen når den evalueres.

FMC Technologies forespurte et miksesystem som kunne oppnå en homogen strømning i et rør, for en rekkevidde av parametere. Ettersom en laminær strømning er mest utfordrende å blande, blir parameterene som gir det laveste Reynolds tallet valgt til videre evaluering.

Litteraturstudier viser at det finnes flere metoder å oppnå en uniform blanding på. Blandetank, statisk miksing, og power miksing ble analysert. Statiske miksere ble evaluert basert på dagens teknologi, og et power miksing system ble designet for lavest mulig Reynolds tall. For å kunne evaluere metodene ble det utført beregninger, og det ble oppdaget at blandetanken ikke er egnet for miksing i rør. Den ble derfor ikke evaluert videre.

Trykktap er økonomisk ugunstig, og dette blir tatt hensyn til når konklusjonen diskuteres. Statisk miksing er anbefalt når Reynolds tallet er under 2000, og diameteren i hovedrøret er mindre enn 0,4 m. Ingen miksing er nødvendig når Reynolds tallet når et visst punkt, da strømningen vil bli såpass turbulent at den vil mikses naturlig. Power miksing er anbefalt for alle andre definerte tilfeller.

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REPORT FOR 6TH SEMESTER PROJECT SPRING 2015

Course: *PRH612 Bacheloroppgave*

Title: *Evaluating and Designing Systems for Mixing Water in Oil*

This report is a part of the evaluation result for the course.

Project group: *K6-4-15* **Accessibility:** *Open*

Group participants:
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June Kanton
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Principal supervisor: *Lars E. Øi* **Examiner:** *Kjell-Arne Solli*
Co-supervisor: *Kjell-Arne Solli* **Project partner:** *Steve Watson Gabriel*

Approved for archiving:____

Summary:

The oil and gas industry includes the processes of exploration, extraction, upgrading, separation, refining, transporting and marketing oil products. After the separation process, water is removed to a great extent, and only a small percentage is left in the crude oil. When marketing the products, the value is essential, and therefore a representative sample has to be extracted to determine the quality. This requires that the water is uniformly distributed throughout the batch when it is evaluated.

FMC Technologies requested a mixing system that would be able to achieve a homogeneous flow in a pipeline, for a range of parameters. Because a laminar flow is the most challenging to mix, the parameters which gives the lowest Reynolds number are chosen as a worst case scenario.

By literature studies, it is stated that a uniform mixture can be provided by multiple processes. Mechanically agitated vessels, static- and power mixing have been analyzed. The static mixer is evaluated based on the state of the art, and a power mixing system is designed for the worst case parameters. Calculations are performed to be able to evaluate. It is found that mechanically agitated vessels are not recommended for in-line mixing and therefore not evaluated further.

Pressure drop is expensive, and this is taken into account when discussing a conclusion. A static mixer is recommended for Reynolds numbers below 2000 and a main pipe diameter below 0.4 m. No mixing is required when the Reynolds number reaches a certain peak where the turbulence in the flow is of a large extent and mixing will happened naturally. Otherwise, power mixing is the suggested method to provide a homogeneous flow.

Telemark University College

Facultad de tecnología

Grado en ingeniería

TRABAJO DEL 6TO SEMESTRE PROYECTO PRIMAVERA 2015

Curso: *PRH612 Bacheloroppgave*

Titulo: *Evaluating and Designing Systems for Mixing Water in Oil*

Este trabajo es una parte del resultado de la evaluación del curso.

Grupo del proyecto: *K6-4-15* **Disponibilidad:** *Abierta*

Miembros del grupo:

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Aprobado para su archivo____

Resumen:

En la industria del petróleo y el gas natural se incluyen los procesos de explotación, extracción, mejora, refinamiento, transporte y comercialización de los productos derivados del petróleo. Después del proceso del proceso de separación, el agua es eliminada en su mayor parte, sólo un pequeño porcentaje permanece en el crudo. En la comercialización de los productos derivados, conocer las características del crudo es esencial, y por tanto la muestra extraída para determinar su calidad tiene que ser representativa. Esto requiere que el agua este distribuida uniformemente en toda la sección en el momento de su valoración.

FMC Technologies encomendó un sistema de mezcla en interior de la tubería que fuera capaz de proporcionar un flujo homogéneo para un rango de parámetros. Los parámetros que proporcionan un menor número de Reynolds son los escogidos como peor caso, debido a que el flujo laminar es más difícil de mezclar.

Como afirman diferentes estudios de la literatura, una mezcla uniforme puede ser proporcionada por múltiples procesos. Los métodos de mezclado analizados son el tanque agitado, mezclador estático y mezclador JetMix. El mezclador estático es evaluado en base al estado del arte, y el sistema JetMix es diseñado para los parámetros del peor escenario posible. Para su evaluación diversos cálculos han sido realizados. El tanque agitado no está evaluado en profundidad porque no es el más recomendado para mezclar en interior de una tubería.

La pérdida de carga es cara, por lo que es esencial en la discusión de las conclusiones. Se recomienda un mezclador estático para números de Reynolds por debajo de 2.000 y un diámetro tubería principal por debajo de 0.4 m. No se requiere de mezclador cuando el número Reynolds alcanza un cierto valor donde la turbulencia en el flujo es muy elevada y la mezcla sucede de manera natural. En cualquier otro caso, mezclador JetMix es el método sugerido para proporcionar un flujo homogéneo.

PREFACE

This project was performed by four students at Telemark University College, during the 6th and final semester of an undergraduate degree. Three of the students are studying Gas- and Energy Technology and are accompanied by an exchange student from Polytechnic University of Catalonia, studying Chemical Engineering. The report is written in collaboration with FMC Technologies, a market leader in design, manufacture and supply of measurement products and systems for the oil and gas industry worldwide.

The team is grateful for the guidance provided by Steve Watson Gabriel, our contact person from FMC. The team would also like to thank Arve Langeland and Nils Petter Aaastad for their guidance and feedback.

The front page picture is an illustration of the designed power mixing system made in SolidWorks.

This report was made using standard Microsoft Office programs and SolidWorks.

It is expected of the reader to have basic knowledge of fluid mechanics.

Porsgrunn, 26.05.2015:

Ana Vicente

Anders Galland Andersen

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GLOSSARY

Symbol	Term	Unit
Q	Flow rate in main pipe	m^3/s
A	Area of main pipe	m^2
D	Diameter of main pipe	m
D_i	Inner diameter of main pipe	m
V	Main pipe velocity	m/s
ρ	Density of mixture	kg/m^3
μ	Viscosity	Pa*s
P	Pressure in main pipe	Pa, bar
T	Temperature	°C
g	Gravitational acceleration	kg/s^2
L_m	Mixing length	m
K_L, K_T	Pressure drop ratios for motionless mixers	Dimensionless
K_iL, K_iT	Mixing rate coefficient for blending	Dimensionless
CoV	Coefficient of variation	Dimensionless
ΔP_p	Pressure drop empty pipe	Pa
ΔP_{sm}	Pressure drop static mixer	Pa
Re	Reynolds number	Dimensionless
f	Friction factor	Dimensionless
$\Delta\rho$	Density difference in oil and water	kg/m^3
Fr’	Froude’s number	Dimensionless
h_A	Head needed from the pump	m
h_L	Head loss	m
v_1	Velocity of the fluid before the pump	m/s
v_2	Velocity of the fluid after the pump	m/s

K	Minor loss coefficient factor	Dimensionless
U	Saybolt Universal viscosity at a given temperature	SSU
C_v	Flow coefficient	Dimensionless
q	Flow rate in the power mixing loop	m^3/h
L_v	Length of vertical pipe in the power mixer	m
L_H	Length of horizontal pipe in the power mixer	m
L_{pm}	Length of total pipe in the power mixer	m
N_{RE}	Reynolds number of the worst case parameters	Dimensionless
v	Velocity in recycle pipe	m/s
A_{pm}	Area of recycle pipe	m^2
d	Diameter recycle pipe	m
d_0	Outside diameter of probe	m
d_i	Inside diameter of probe	m
d_{re}	Diameter of the nozzle outlet	m
A_{re}	Area of the nozzle outlet	m^2
St	Strouhal Number	Dimensionless
f_m	Factor	Dimensionless
L	Allowable length	m
z_1	Elevation in main pipeline	m
z_2	Elevation in nozzle	m
ΔZ	Elevation difference of probe and nozzle	m
C_1	Concentration of water on the top of main pipe	%
C_2	Concentration of water in the bottom of the main pipe	%
v_{re}	Velocity of re-injection	m/s
ϑ	Kinematic viscosity	mm^2/s
$\frac{\varepsilon}{D}$	Turbulence characteristics	m/s

G	Parameter dependent on degree of mixing	Dimensionless
W	Settling rate of water droplets	m/s
ρ_w	Water density	kg/m^3
ρ_o	Crude oil density	kg/m^3
E_r	Required energy dissipation	W/kg
ΔP	Pressure drop	Bar
E	Young’s Modulus of Elasticity	Pa
P_n	Pressure in nozzle	Pa
ΔX	Distance of homogeneous flow	m
t	Temperature	°F
x_w	Water concentration	%
x_o	Crude oil concentration	%

TABLE OF CONTENT

1 INTRODUCTION

After refining oil from the welds, the oil will contain some percentage of unwanted components. These components will be removed in separation processes, and the final product will contain a small percentage of water. To determine the quality of the oil, a representative sample has to be provided. This can be done by mixing the product before sampling.

FMC Technologies requested a design of a power mixing system, or an alternative economical solution which meets the requirements. The scope of the project is changed to evaluation and design of systems for mixing water in oil. The goal of the project is to recommend a mixing system for a defined case, as well as comparing methods for a range of parameters. The task from FMC can be found in Enclosure A.

The design and evaluation are based on literature studies and calculations performed in the report. No simulations will be performed during this project, therefore all results will be strictly theoretical.

The project limits are set by FMC, as a range of parameters. Values outside this range will not be taken into consideration. In addition to this, the focus is directed towards the mixing- and sampling station. The data from FMC can be found in Enclosure B.

Chapter 2 consists of a thorough description of the background for the problem.

In chapter 3, different mixing methods for solving this problem are presented.

The scope of the project is further explained in chapter 4.

The process of how to provide a representative sample is evaluated in chapter 5.

In chapter 6, static mixing is evaluated.

In chapter 7, a power mixing system is designed and later evaluated in chapter 8.

The results, uncertainties and suggestions for further work are discussed in chapter 9, before the final conclusions are presented in chapter 10.

2 BACKGROUND FOR THE PROJECT

Many operations depend to a great extent on effective mixing of fluids. Mixing refers to any operation used to change a non-uniform system into a uniform one. Mixing is an integral part of chemical or physical processes such as blending, dissolving, dispersion, suspension, emulsification, heat transfer, and chemical reactions.

The oil and gas industry includes the processes of exploration, extraction, upgrading, separating, refining, transporting and marketing oil products. When the liquid is extracted from an oil field, it consists primarily of hydrocarbons and other organic compounds. It may also contain various gases, solids, trace materials and water. The liquid is refined and separated to consumer products. In this separation process, it is impossible to remove all the unwanted components. [1][2]

When refined oil is to be purchased or sold, the value varies with the quality. When determining a price, the water content is an essential factor. The higher the water cut, the lower percentage of oil per volume, and the lower the value.

Oil and water are immiscible liquids. This is because hydrogen bonds can’t be formed when water molecules are polar and oil molecules are non-polar. To circumvent this fact, the water needs to be mixed into the oil so that it is equally distributed throughout the batch. Only then the true amount of water can be determined. [3]

Consequently, the purpose of mixing is to determine the amount of water and other components in the oil, and thereby the quality. Mixing plays an important role for product sampling in the pipeline transport, and has to be installed upstream of the sampler. Adequate mixing should create a good dispersion but still allow water to easily settle in downstream storage tanks.

After mixing water and oil, a sample that is representative for the whole batch is required to prove the quality of the product. This can only be accomplished by extraction of samples from a homogeneous mixture of the batch. This is achieved when the water droplets are of equal size, with equal distances to each other so they don’t coagulate, and uniformly distributed throughout the area of the container.

To ensure that the samples are representative is important for all the companies that are involved. Therefore, it is absolutely important to make sure that the sampling process is of a high standard. Several parameters are critical to ensure this, including placement, extraction point, treatment of the sample and time intervals between sampling. [1]

3 MIXING METHODS

Most of the general information about mixing methods is from reference [4].

Mixing is a unit operation where a heterogeneous fluid is made homogeneous. To achieve a homogeneous mixture the heterogeneous fluid will be stirred to the point where it has the same composition throughout the batch. There are not only liquids that can be mixed; solids and gasses are also fluids that can be blended if the right equipment is used. Different types of materials that can be mixed are:

- Liquid-liquid mixing
- Gas-gas mixing
- Solid-solid mixing
- Liquid-solid mixing
- Liquid-gas mixing
- Gas-solid mixing
- Solid, liquid, and gas mixing

For this project the only relevant mixing type is liquid-liquid mixing, because both water and oil are liquids. Single-phase and multiphase mixing are the two different types of liquid-liquid mixing.

Single-phase blending is when the liquids are miscible or at least soluble in each other. The liquids will dissolve easily in one another when both of them are water based. When both liquids have a low viscosity, the momentum of the liquid being added is sufficient to cause enough turbulence to mix the two. When the liquids have a higher viscosity it is necessary to use a stirring device to complete the mixing process.

Multiphase mixing is when the liquids are not soluble or miscible in each other. Water and oil is an example of multiphase mixing. When blending water and oil, it’s necessary to use a mixing device to achieve a homogenous mixture, which will start to separate if it’s not continually mixed.

There are different ways to mix a multiphase fluid. The fluid can either be mixed in a vessel or while it is flowing through a pipeline. In this chapter three different methods for mixing the oil and water will be described. The three mixing methods that will be evaluated are mechanically agitated vessels, static- and power mixing. The two most suited methods for the worst case parameters will be studied in depth before a final conclusion will be made.

3.1 Static Mixing

Information about this subject has been collected from source [5].

Static mixers, also known as motionless mixers, are mixing devices which consist of elements inserted into a pipe. In that way a process fluid flows through a pipe and is redirected multiple times by various mixing elements placed inside the pipe. An example of how this affects the flow is shown in Figure 3-1 below. There are many different types of mixing elements, but all of them are stationary in use. This is an advantage as the result is practically no need for maintenance, in addition to having very low operating costs. This method of mixing is very flexible, as it is possible to include multiple mixing elements, based on the difficulty of the mixing task.

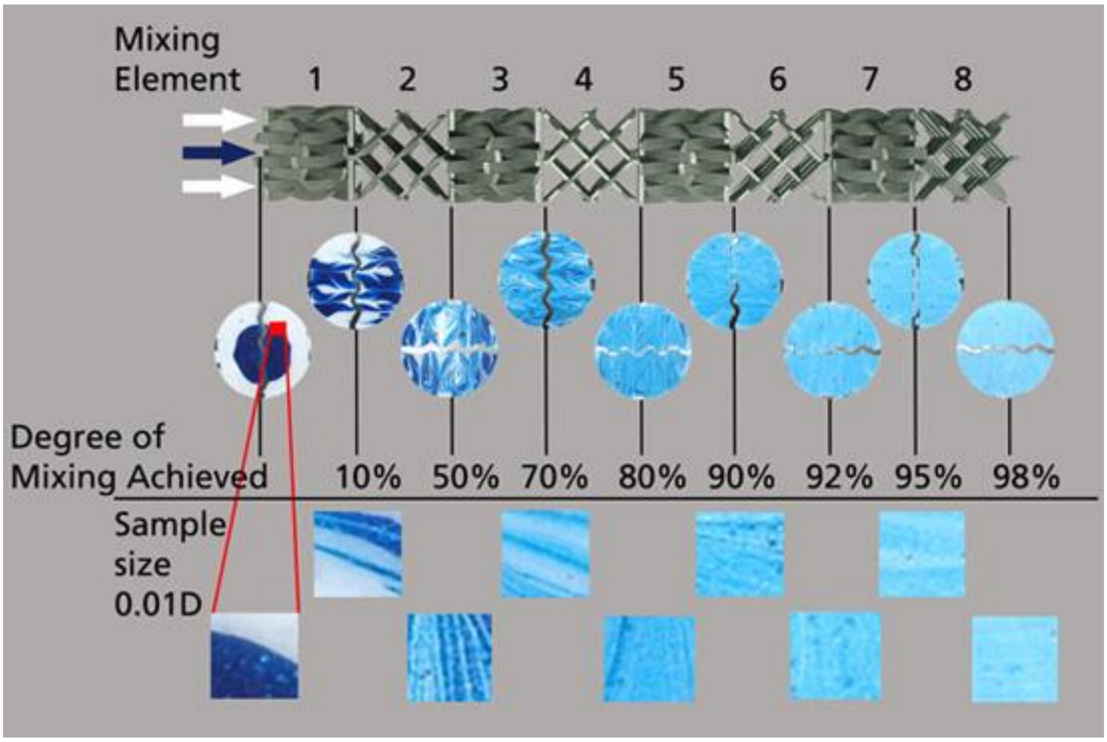


Figure 3-1: Mixing efficiency using GXM mixing elements [6]

Static mixers are used in both laminar and turbulent processes. Laminar flow mixing consists of a combination of flow division and re-orientation. In turbulent flow mixing, the mixing elements create a higher level of turbulence than in an otherwise empty pipe.

A common type of static mixing is the packed column used in distillation processes. In this column, water and gas is being mixed by directing the flows through small openings inside a tube, of which an example is shown in Figure 3-2. As with any other static mixers, the type of packing inside the tube varies from column to column, and is easily replaced. A thing to note about the packed column is that the flows are countercurrent, whereas the static mixer usually handles co-current mixing problems.

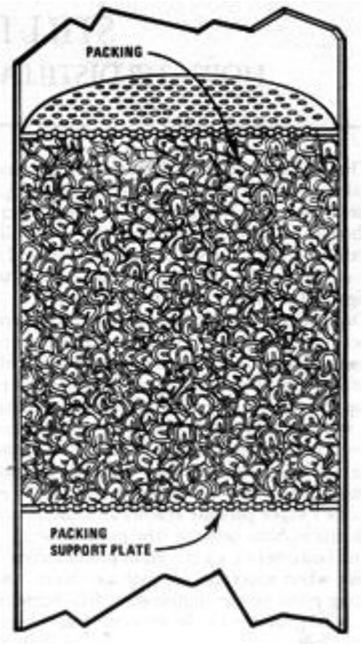


Figure 3-2: Example of a packed column used in distillation. [7]

One of the problem-areas of the static mixers is the pressure drop they create. The only driving force in this mixing process is the pressure inside the pipe, and as the fluid flows through the mixing elements, the pressure will drop. Therefore it is important to make sure that the operating pressure never drops below the vapor pressure for the specific fluid.

3.2 Power Mixing

For this chapter reference [9], [10] and [11] are used.

Power mixing is when an external power device is used to achieve a satisfying mixture. The power mixer system removes a portion of the liquid from the main pipe and re-injects it under pressure. A probe is used to remove a small portion of the fluid from the main pipe and into the mixing loop. Inside the mixing loop a pump will provide the necessary pressure for the fluid to get re-injected back into the main pipe, and to prevent back flow. The re-injection is done through a nozzle, which is designed to create as much turbulence as possible in the main pipe. Figure 3-3 is an illustration of how a power mixing system is constructed.

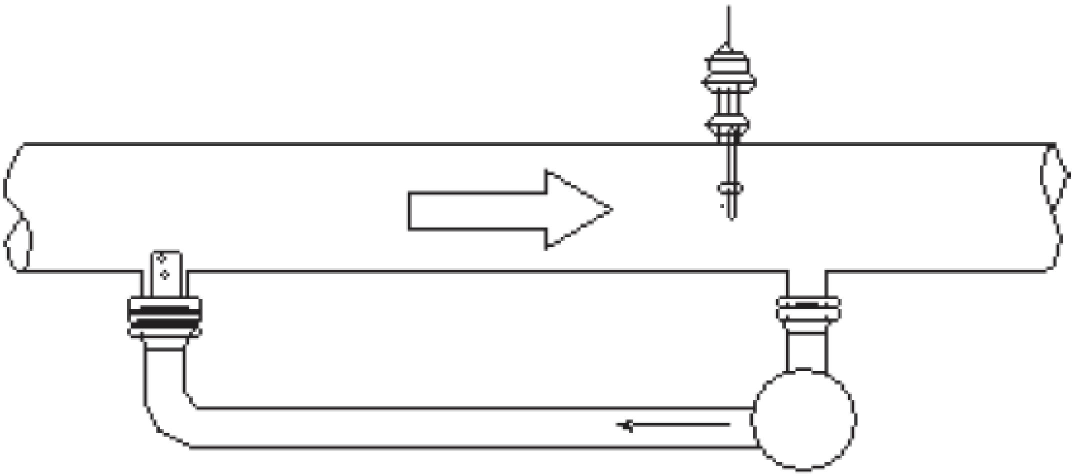


Figure 3-3: Illustration of Power Mixing. [8]

Because of the difference in densities for water and oil, they will start separating after the mixing process. The gravitational force will cause the water to appear as slugs inside the pipe and sink to the bottom of a horizontal pipe. When the fluid is flowing upstream in a vertical pipe the velocity of the oil will be slightly higher than the velocity of the water. This is because the density of water is higher and the gravitational force will make it harder for the water to move upwards. In a vertical pipe where the fluid is flowing downstream it will be the opposite; the water will be transported faster downwards than the oil. The gravitational force will affect the separation between the water and oil less in the vertical pipe than in the horizontal pipe.

Because the gravity has an effect on the separation of the water and oil it is important that the quality of the oil is measured when the flow is still homogeneous.

When deciding the type of mixer that should be used for a certain process the pros and cons for each type of mixing system should be evaluated.

When constructing the power mixer, the capital cost will be large compared to the static mixer. The reason for the high expenses when purchasing a power mix system is the equipment needed such as the different utilities and piping.

Another disadvantage for the power mix system is that the operating cost will be higher than in the static mixer. The operating cost in the power mixing system is caused by the power consumption from the pump.

An advantage of the power mixer is that it will work for all different ranges in parameters. At some point the flow inside the pipeline will have a turbulent flow where the water and oil naturally mixes by itself. A benefit for the power mixer is that it can be shut off and save the operational expenses.

The power mix system will be less secure than a static mixer because the system depends on a pump. If there is any damage to the pump that requires maintenance, the system has to be shut down until the pump is functional again.

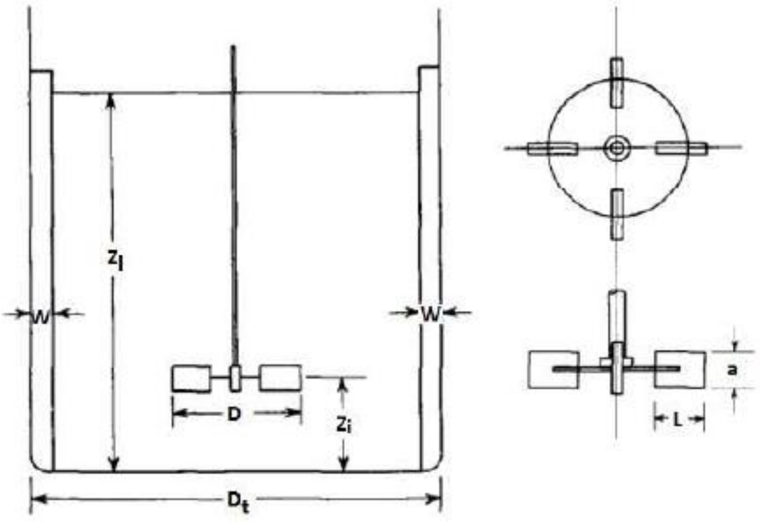
The pressure drop of the fluid inside the power mix system will be small compared to the static mixer. Elements that will cause the pressure to decrease through the mixing loop are valves, elbows, probe, filter and pipe surface. The pressure drop caused by these utilities will be significantly lower than drop caused by the obstructions in the static mixer.

3.3 Mechanically Agitated Vessels

Most of the information in this chapter is from the references [12] and [13].

Mixing refers to any operation used to change a non-uniform system into a uniform one. Particularly agitation implies forcing a fluid by mechanical means to flow in a circulatory or other pattern inside a vessel.

The basic components to take into account in a design of a mechanically agitated vessel are the tank, the impeller and the baffles. Figure 3-4 illustrates a basic design with the size relationships that the different elements should meet.



Geometric portions for standard agitation system:

· $D = \frac{Dt}{3}$

· $Zl = Dt$

· $Zi = \frac{Dt}{3}$

· $a = \frac{Dt}{5}$

· $L = \frac{Dt}{12}$

· $W = \frac{Dt}{10}$

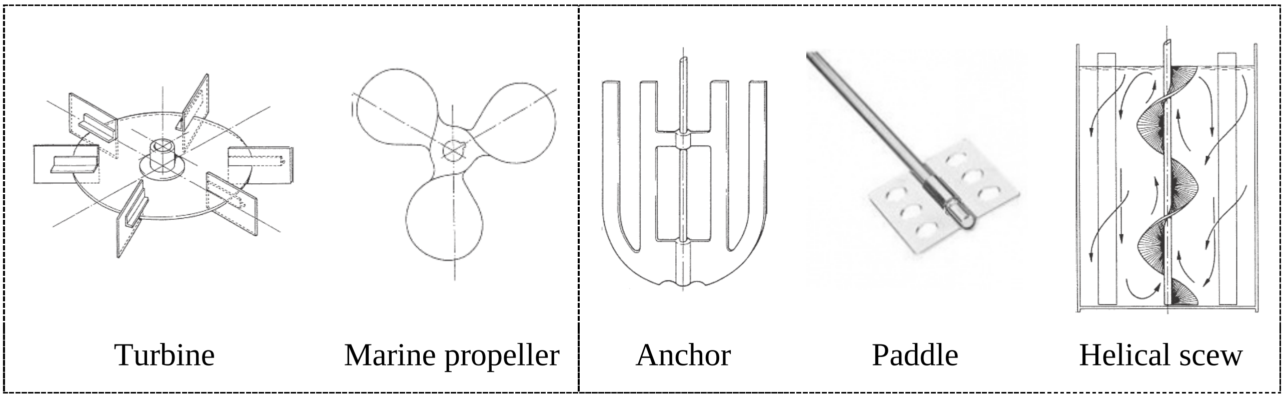
Figure 3-4: Standard tank configuration (6 blade turbine with 4 symmetrical baffles).

The top of the vessel may be open or sealed, the vessel bottom is normally not flat but rounded to eliminate sharp corners or regions into which the fluid currents would not penetrate. Dished ends are most common, because they require less power than flat ends. Baffles are needed to prevent vortexing and rotation of the liquid mass as a whole, except at high Reynold numbers.

Impellers are the most important components to change when designing for different applications. In general, they can be classified in two main groups:

- Impellers with a small blade area, which rotate at high speeds, are used to mix low to medium viscosity liquids. These include turbines and marine propellers.
- Impellers with a large blade area, which rotate at low speeds, are effective for high-viscosity liquids. These include anchors, paddles, and helical screws.

In Figure 3-5, the most common types of impellers used today are illustrated.



Turbine Marine propeller Anchor Paddle Helical scew

Figure 3-5: Different kinds of impellers. [14]

The properties of the liquid and the dimensions and arrangement of impellers, baffles and other internals are factors that influence the amount of energy required for achieving a required amount and quality of agitation. For that reason, the power consumed by a stirred tank depends on: Type of impeller and its size and geometry, characteristics of the fluid and rotation speed of the stirrer.

Process requirements vary widely. Some applications require homogenization at near molecular level, while other objectives can be met as long as large scale convective flows sweep through the whole vessel volume. Performance is crucially affected both by: the nature of the fluids concerned and on how quickly the mixing or dispersion operation must be completed.

In the studied case, oil and water are two immiscible liquids which are not easily blended. For this case turbine impellers is the most suitable stirrer to provide the desired mixing conditions for immiscible liquids.

3.3.1 Evaluation of the Method

Mechanically agitated vessel is a well-known method because it has been used for a long time. Moreover it can be used for a wide range of applications by only changing the main design (for example the kind of impeller or the dimensions of the tank), that is why it is a flexible method.

On the other hand, it also has some disadvantages: The power consumption is high because it is necessary to make an impeller rotate with a constant speed. Moreover, as it is not wished to create a stable emulsion, the design of this mixing system should be very accurate. If the two liquids are not blended enough, after the stirring the crude oil and water, the small drops of water will join again and the two liquids will split up. However, if the two liquids are blended too much a stable emulsion could be obtained.

This method is usually performed in a tank, but in-line mixing is possible. A version of this is stirring the mixture inside the pipe by simply adding an impeller like it is shown in Figure 3-6.

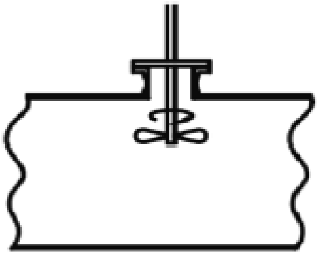


Figure 3-6: Impeller stirring the liquids driven inside a pipe. [15]

This option is not an effective one: When blending easy miscible liquids of similar viscosities, an agitator will produce satisfactory results. On the other hand, when there is a significant difference in viscosity between the two liquids, an agitator tends to move them around without actually blending them together and it can take a long time to achieve a uniform mixture.

These devices could give short blend times or high local energy dissipations. To overcome this problem, horizontal baffles are added and the liquids are blended in two steps. This type of in-line mechanical mixer is called rotatory in-line blenders as illustrated in Figure 3-7.

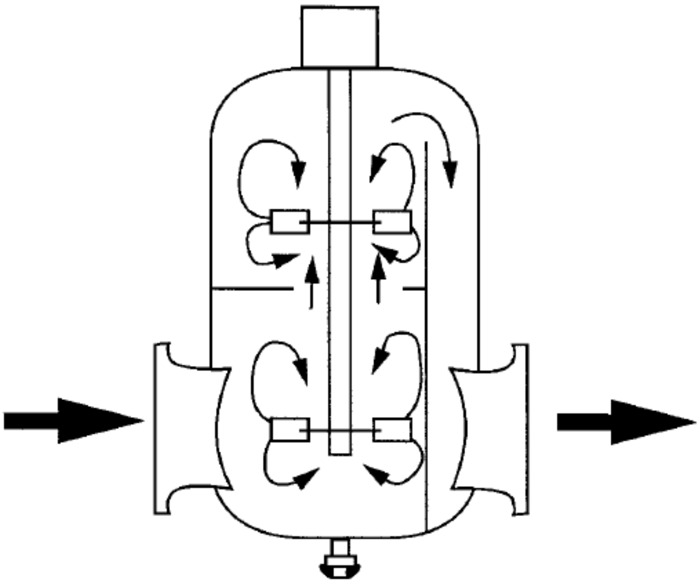


Figure 3-7: Rotatory in-line blender. [12]

This blender is installed in an oversized section of the pipe in order to increase residence time and reduce superficial velocity. More than two stages can be used to provide more accurate residence time. The design consists of at least two stages, each with an impeller, and internal baffles. The incoming flow is forced to pass through each stage with strategically designed baffles before exiting.

This mixer works most efficiently at low flow rates when mixing is most needed. When the flow rate is high, the mixer can be turned off to prevent formation of a stable emulsion.

4 PROBLEM DESCRIPTION

The main goal of this project is to provide FMC Technologies with a suggestion of the most reasonable mixing method and sampling method for their process. A range of parameters from previous projects was provided, and the range is listed in Table 4-1.

Table 4-1: Historical data from FMC Technologies. [16]

Parameter	**Value**		**Unit**
	Minimum	**Maximum**	
Header Velocity	0.15	15.43	m/s
Density	600	1000	kg/m^3
Viscosity	0.4	100	Cp
	0.0004	0.1	Pa·s
Pressure	0	100	Barg
Temperature	-	150	^{o}C
Water Cut	0.5	5	%
Header Size Range	6	30	"
	0.1536	0.768	m

Reynolds number is a dimensionless value used to describe the flow characteristics of a fluid and the tendency to experience a considerable amount of viscous drag. The importance of the Reynolds number is that it determines what flow regimes will exists for fluids of known density and absolute viscosity traveling at a given velocity. The lower the value, the more laminar the flow, and it is calculated by Equation (4.1).

$$Re = \frac{\rho * V * D}{\mu} \tag{4.1}$$

In a laminar flow the fluid particles move in a straight parallel line in such a way that individual particles do not cross the path of neighboring particles. When the turbulence in the flow increases, this is no longer the case. The movement of the particles will be in a more random manner resulting in a natural mixing of the fluid. Because of this, a laminar flow is the most difficult to mix properly, and the parameters that gives the lowest value of Reynolds number are chosen when evaluating the mixing systems. According to Equation (4.1), this corresponds to the lowest density, pipe diameter and velocity and the highest viscosity, as highlighted in Table 4-1.

FMC requested in-line mixing, which makes the mechanically agitated vessel less applicable. Because of this, coupled with the high power consumption, the mechanically agitated vessel was deemed unfit for this problem and will not be evaluated further. [16]

5 SAMPLING

Most of the information in this chapter is based on international standard 3171. [1]

Hydraulic laws are important regarding the behavior of the heterogeneous liquids, which will mix in the pipe. It is proved that if the stream conditions that results in a sufficiently high energy dissipation rate are met, the drops of water will be kept suspended in the crude oil. This energy dissipation can be provided by mixing, in this case, static- or power mixing.

A representative sample is defined as a sample having its physical and chemical characteristics identical to the average characteristics of the total volume being sampled. In other words, when the mixture is homogeneous, as defined in chapter 2. There are four conditions that must be met:

1. The samples should have the same composition as the average composition of the crude oil over the whole cross-section of the pipeline at the location and time of sampling.
2. The rate of sampling should be in proportion to the flow rate in the pipe.
3. The sample should be maintained in the same condition as in the point of extraction.
4. When dividing the sample into sub-samples, it must be done in such a way that ensures each of the sub-samples to have the same composition of the original sample.

There are two main types of sampling systems. One of which is in-line sampling, where a probe is placed and samples are grabbed directly. This method is the simplest system available, but offers the lowest accuracy and highest uncertainty. Fast-loop sampling is the other main system on the market, where the sample is taken inside the pipeline in a bypass loop. This is a more expensive and complicated system, but will thereby provide a higher accuracy. These two systems including CoJetix- sampling represents the state of the art in sampling technology. A CoJetix system is a sampler combined with a power mixing system, and this system provides the lowest uncertainty of all sampling systems available. [17]

Within the systems, either manual- or automatic sampling is installed. If the homogeneous liquids composition and quality do not vary with time, manual sampling would be adequate. Otherwise automatic pipeline sampling is recommended.

In this case, no variations with time cannot be guaranteed because an undispersed phase can occur. A peak with relatively high concentration of water can travel down the pipeline at some time depending on the uploading procedure. To ensure that the sampling system designed is suitable for multiple processes, automatic pipeline sampling will be recommended instead of manual sampling. By choosing this sampling method, continuous or repetitive extraction of small samples ensures that any changes in the bulk, including peaks, are reflected in the samples. [19]

5.1 Automatic Pipeline Sampling

In this chapter, the design of a sampling station that will ensure a representative sample will be presented. Automatic pipeline sampling is the method suggested to be used in the sampling process, and the sample location, probe, and ratio are important parameters that will be evaluated.

5.1.1 Profile Testing

By performing profile testing, a test of the uniformity of water dispersion across the pipeline at a possible sampling location is determined. It is recommended to perform five of these tests to ensure uniformity.

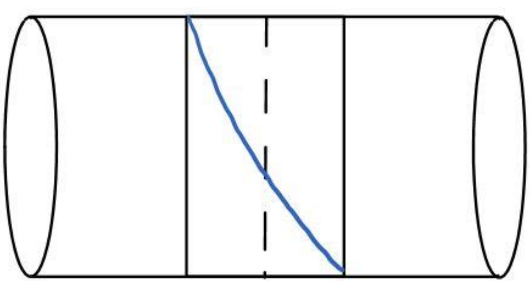


Figure 5-1: Concentration profile case 1

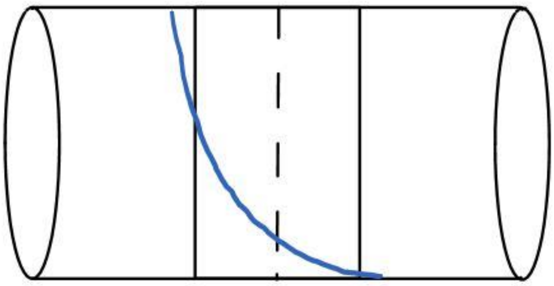


Figure 5-2: Concentration profile case 2

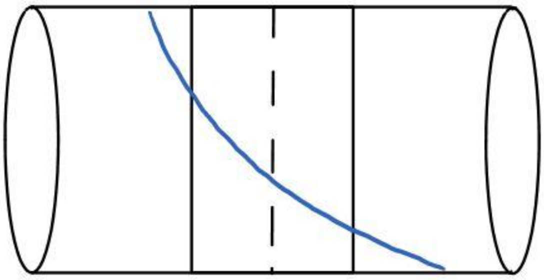


Figure 5-3: Concentration profile case 3

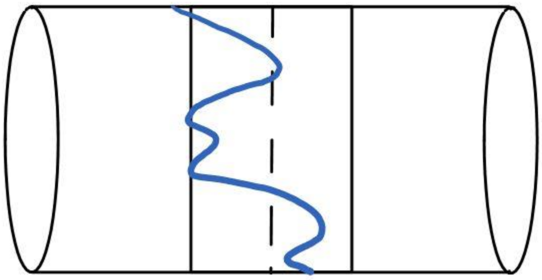


Figure 5-4: Concentration profile case 4

The figures above illustrates different profiles that can be found by profile testing. In case 3 and 4, illustrated in Figure 5-3 and Figure 5-4, the concentration across the cross-section is non-linear, and a range of different concentrations of water exists throughout the pipeline. Therefore, with this profile, it is not possible to extract a representative sample at any location.

For case 2, as in Figure 5-2, there is a uniform gradient but yet the concentration varies from one point to another across the cross-section area. There is at least one point where a representative sample could be extracted, but sampling will only be representative within limits.

The purpose of mixing is to achieve the concentration profile 1 as illustrated in Figure 5-1. In this case, the concentration is the same within the acceptable limits across the entire cross-section of the pipeline. In other words, small water droplets are equally distributed the conditions are acceptable for sampling.

5.1.2 Design and Position of Sampling Probe

The linear velocity and direction of the liquid flowing into the opening of the probe has to be equal to the linear velocity and direction of the main pipeline. This is because, if the sampling velocity is less than the fluid velocity, particles will typically not enter the sampling tube. If the sampling velocity is higher, suction will occur and more particles will enter the probe compared to the amount that are continuing with the main flow. In this case, the particles are the water droplets and maybe some trace components. This is termed isokinetic sampling, and the probe has to be designed in such a way that this is taken into account.

The length the probe can be inserted into the main pipe without failure due to the effects of resonant vibrations has to be considered. Resonant vibrations occur when the fluid flows past obstructions, like a probe, by formation of vortex shedding which creates a pressure drop on that side of the obstruction. Thereby the probe will tend to bend towards this lower-pressure side which can lead to crack formation and ultimately failure. The length allowable without the possibility for cracks can be calculated according to Equation (5.1). [19]

$$L^2 = \frac{0.14 * f_m * d_0}{St * V} * \sqrt{\frac{E}{\rho} * (d_0^2 + d_i^2)} \tag{5.1}$$

The factor f_m equals 0.9 for liquids, and the Strouhal Number St is dependent on the shape of the probe and the Reynolds number of the process flow. With a Reynolds number of the value up to 10^5 and a circular probe, the Strouhal Number is roughly constant at 0.2, which is the case in the major part of the given range in chapter 4. These values are substituted into Equation (5.2). [19]

$$L = \sqrt{\frac{0.51 * d_0}{V} * \sqrt{\frac{E}{\rho} * (d_0^2 + d_i^2)}} \tag{5.2}$$

Recommended diameter of the sampling probe is larger than 6 mm, somewhat dependent on the main pipe diameter. By assuming a thickness of 1 mm, the allowable length can be calculated, and the parameters and results for the design of the probe are listed in Table 5-1. [1]

Table 5-1: Parameters and values for the calculations of probe length.

Symbol	**Value**	**Unit**
d_0	0.007	m
d_i	0.006	m
V	0.15	m/s
E	$1.8822*10^{11}$	Pa
ρ	600	kg/m^3
L	2	m

The allowable length is larger than the main pipe diameter, and the probe can be placed at any point in the main pipe without any chance for failure. The most suited position of the sampling probe is within the area where the two liquids are most likely to be well mixed at all times, which depends on the mixing orientation. This area is illustrated as the grey zone in Figure 5-5 for a vertical pipe and Figure 5-6 for a horizontal pipe. [1]

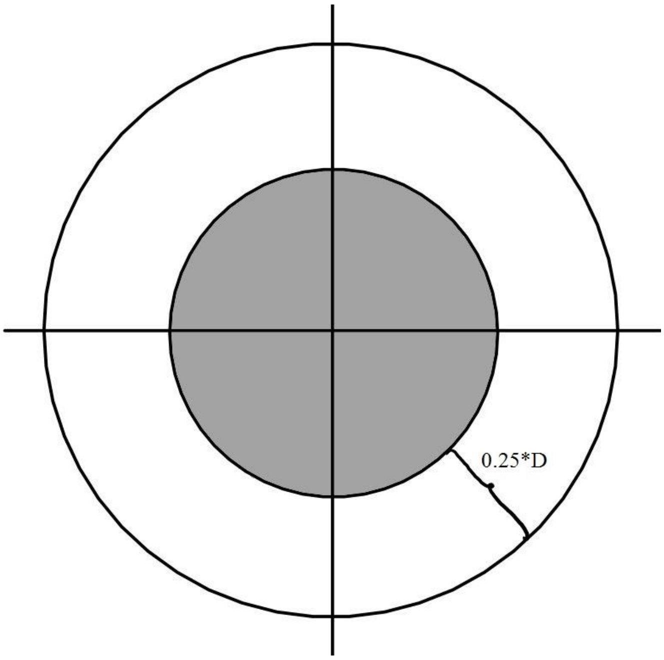


Figure 5-5: Well-mixed zone of the main pipe, vertical orientation.

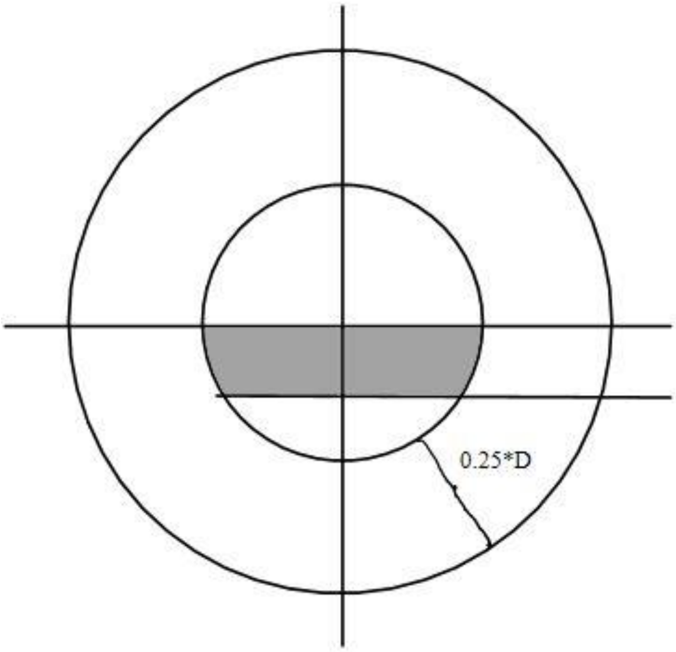


Figure 5-6: Well-mixed zone of the main pipe, horizontal orientation.

For main pipe diameters above 300 mm, five or more sampling points should be constructed. For pipe diameters below 300 mm, as in this case 153.6 mm, three sampling points are recommended. To be able to perform profile testing, a probe is needed at the bottom and top of the pipe. The conclusion is to place three probes, two for profile testing and one for sampling.

Recommended distances from the mixing device and the probes are at least three- and preferably greater than five pipe diameters, depending on mixing method, which determines the settling rate of the average-sized water droplets. It is important that the probe is placed within the distance where separation has not yet occurred, as when water droplets are settling. It should also be taken into account that swirl and asymmetry is generated by the mixing device, unrepresentative sampling can be avoided by not placing the probe too close to the device. On these grounds, it is suggested to place the sampling probe on a distance of eight pipe diameters from the mixing nozzle.

5.1.3 Sampling Loop

A sample loop is a by-pass to the main pipeline. A representative portion of the total flow is circulated through the sampling loop and by this way transported back to the main pipeline.

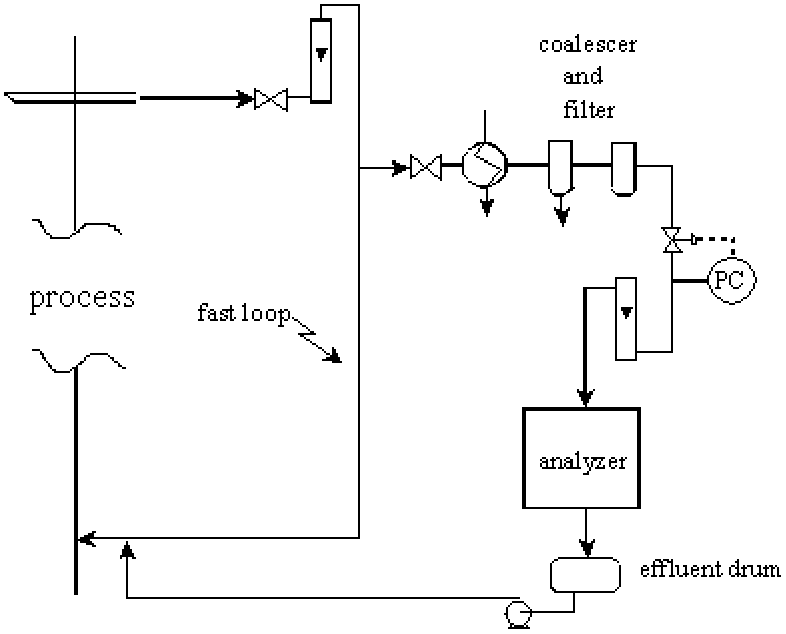


Figure 5-7: Horizontal fast loop sampling. [18]

With fast loop transport of the sample, as illustrated in Figure 5-7, rapid response to process changes are achieved and valuable liquid waste are avoided. It requires less differential pressure than the alternative; single line transport, and is appropriate for liquid samples when the tap-to-analyzer line is of a certain length. The time-delay associated with sample systems will also be kept to a minimum with this kind of sampling system. A fast loop system can also run at higher flow rate than a single-line configuration. [19][20]

When the mixing occurs in a vertical pipe, the sampling loop should be of a horizontal orientation, and vice versa.

An intermittent sampler, which contains a system for extraction of liquid from the flowing stream in the pipeline, should be installed in the loop. There is a sample received and the sampling frequency and grab volume are regulated in relation to the flow rate. The sum of the grabs represents one sample. Strictly speaking, the grab volume and sampling frequency are dependent on the flow rate. [1]

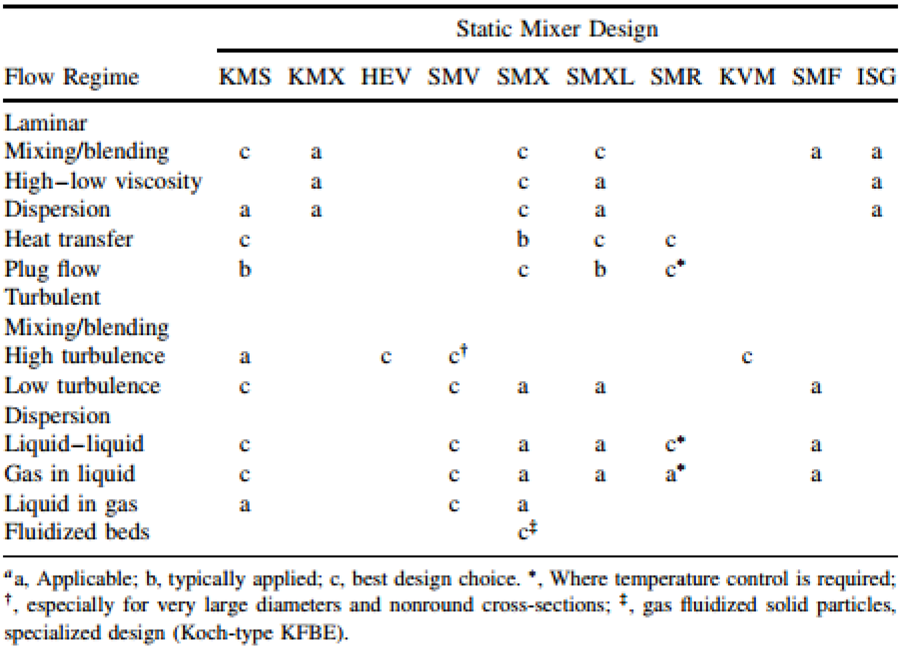
6 EVALUATING STATIC MIXING

In this chapter, static mixing will be evaluated for the worst-case scenario as well as for the entire range of parameters given by FMC. Two prominent types of static mixers will be compared, and a suggestion will be made as to which of the types are recommended for the worst-case scenario, as well as for the entire range of parameters.

6.1 Worst-Case Scenario

A static mixer, as explained in chapter 3.1, is a very simple mixing method that does not require any additional piping or equipment, other than the mixing elements themselves. As a result of this, the process looks similar to that of a fluid flowing through an empty pipe, with the only difference being the obstructions inside the pipe.

Different types of static mixers use different types of mixing elements to blend the fluid either radially, or by use of flow reorientation. Both of these methods have proven to be effective, when applied correctly. Because there are so many different types of static mixers, it can be difficult to select the optimal one for a given process. Figure 6-1 provides a rough guideline for this selection. The figure shows that for this process, which is mixing/blending of two fluids, the best design choices are KMS, SMX and SMXL for laminar flow and KMS for turbulent flow with low turbulence. For turbulent flows with high turbulence, only KMS is applicable among these three.



	Static Mixer Design									
Flow Regime	KMS	KMX	HEV	SMV	SMX	SMXL	SMR	KVM	SMF	ISG
Laminar										
Mixing/blending	c	a			c	c			a	a
High–low viscosity		a			c	a				a
Dispersion	a	a			c	a				a
Heat transfer	c				b	c	c			
Plug flow	b				c	b	c*			
Turbulent										
Mixing/blending										
High turbulence	a		c	c†				c		
Low turbulence	c			c	a	a			a	
Dispersion										
Liquid–liquid	c			c	a	a	c*		a	
Gas in liquid	c			c	a	a	a*		a	
Liquid in gas	a			c	a					
Fluidized beds					c‡					

[a] a, Applicable; b, typically applied; c, best design choice. *, Where temperature control is required; †, especially for very large diameters and nonround cross-sections; ‡, gas fluidized solid particles, specialized design (Koch-type KFBE).

Figure 6-1 – Guidelines for applications in the laminar and turbulent flow regimes. [12]

The most fitting types of static mixers for the scope of this project, are the twisted ribbon-type mixer (KMS, see Figure 6-2), and the structured packing-type mixer (SMX, see Figure 6-3). The SMXL mixer is not included due to it being used mostly for heat exchanging processes. [21]

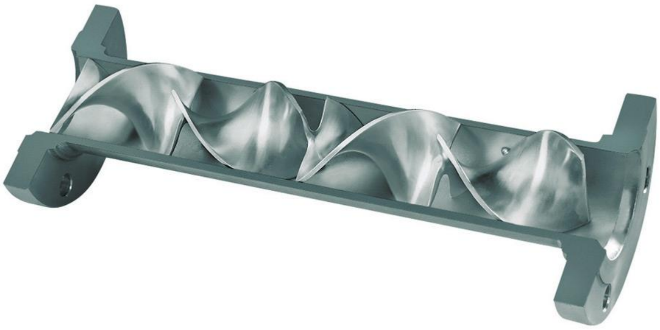


Figure 6-2: Twisted-ribbon mixer (KMS) [22]

Figure 6-3: Structured packing mixer (SMX) [23]

In order to decide which type of static mixer to use for a process, it is important to look at how they perform with the given process parameters. A fairly well used way of measuring performance of static mixers is comparing the pressure drop created by them, assuming that they both achieve the same level of mixing, as well as the length required to achieve this criteria. [24]

Calculating pressure drop and required mixing length for static mixers requires various parameters; most importantly, the degree of mixing must be determined. This parameter is known as the coefficient of variation CoV, and the smaller this value is, the better the quality of the mixture. A CoV value of 0.05 means that 95 % of the concentration measurements taken from the pipe will be within ±10 % of the mean concentration. [25]

For the calculations preformed for the static mixers, a CoV value of 0.03 is selected. This is to ensure that a good mixture quality is achieved.

6.1.1 Mixer Orientation

When mixing in a horizontal pipe, a density difference in the two fluids could increase the mixing length drastically. The reason behind this is that the fluids will separate quicker, as the heavier of the fluids will sink to the bottom of the pipe. [12]

It is therefore important to look at the Froude number for this process, and determine whether the mixing should take place in a vertical pipe. For laminar flow, Equation (6.1) provides a criteria for orientation. For turbulent flow, Equation (6.2) is used.

$$\frac{\mathrm{Fr}'}{\mathrm{Re}} = \frac{\mu V}{\Delta \rho g D^2} < 1.0 \tag{6.1}$$

$$\mathrm{Fr}' = \frac{\rho V^2}{\Delta \rho g D} < 20 \tag{6.2}$$

For the worst-case scenario, which is in the laminar flow regime, it is clear that the mixer orientation should be vertical, due to the relation between Froude and Reynolds number being as low as 0.000154. These calculations do not take into consideration what kind of mixer is being used, and therefore it does not matter what solution is chosen. The suggested orientation will always be vertical for these process parameters.

6.1.2 Calculating Mixing Length and Pressure Drop

Equation (6.3) is used to the coefficient of variance, and uses a K_i-factor called mixing rate coefficient for blending. This coefficient is different for each type of static mixer, and flow regime, so that K_iL is for laminar flow and K_iT is for turbulent. Table 6-1 provides an overview of the different K_i-factors that will be used for the following calculations.

$$CoV = K_i^{\frac{L_m}{D}} \tag{6.3}$$

Table 6-1: List of K_i-values used in length-calculations

Device	**K_iL**	**K_iT**
KMS	0.87	0.50
SMX	0.63	0.46

Equation (6.3) is used to formulate Equation (6.4), which is used to calculate the mixing length.

$$L_m = \frac{D * \ln CoV}{\ln K_i} \tag{6.4}$$

With this information, it is possible to calculate the required mixing length for both types of static mixers, using the worst-case parameters. The results of these calculations are found in Table 6-2 below.

Table 6-2: Required mixing length for both types of static mixer.

Device	**Length**	**Unit**
KMS	3.868	m
SMX	1.166	m

With the mixing length calculated, it is possible to calculate the pressure drop created by these two static mixers. There are many different ways to do this, but it is very common to use the pressure drop in an equivalent empty pipe and multiply that by a K-factor, known as the pressure drop ratio for motionless mixers, as in Equation (6.5). This K-factor, similarly to the K_i-factor, is also dependent on the flow regime as well as the mixing device. Table 6-3 provides an overview of the different K-factors used for the KMS and SMX mixers.

Table 6-3: List of K-values used in pressure drop calculations.

Device	**K_L**	**K_T**
Empty pipe	1	1
KMS	6.9	150
SMX	37.5	500

By looking at these values in accordance to Equation (6.5), it is obvious that the SMX mixer will create the biggest pressure drop. The equation used for calculating pressure drop, as presented in Equation (6.6), is as mentioned a combination of the K-factor and the equation for pressure drop in an empty pipe.

$$\Delta P_{sm} = K * \Delta P_{pipe} \tag{6.5}$$

$$\Delta P_{pipe} = 4f\frac{L_m}{D}\rho\frac{V^2}{2} \tag{6.6}$$

The friction factor f used in Equation (6.6) is calculated using Equation (6.7) if the flow is laminar, and Equation (6.8) if the flow is turbulent.

$$f = \frac{16}{Re} \tag{6.7}$$

$$f = \frac{0{,}079}{Re^{0{,}25}} \tag{6.8}$$

By using these equations, along with the calculated mixing length and the parameters for the worst-case scenario, it is possible to calculate the pressure drops from each of the static mixers. Table 6-4 below shows the results from these calculations.

Table 6-4: Pressure drop created by both types of static mixer.

Device	**Pressure drop**	**Unit**
KMS	542.93	Pa
SMX	889.38	Pa

As predicted, the SMX mixer provides the highest pressure drop, despite using almost one third of the length. As such, the suggestion would be to use a structured packing-type mixer for this process, due to its short mixing length. The pressure difference between the two mixing methods

(~345 Pa) is negligible. However, it is important to note that if space is no issue when choosing a static mixer, the twisted ribbon-type might be more suited due to the smaller pressure drop.

6.1.3 Slight Variations in Process Parameters for the Worst-Case Scenario

When the process is ongoing, it is to be expected that some of the parameters can vary slightly. To ensure that such small variations will not cause any problems, it is important to take these variations in consideration when preforming calculations.

For this process, only two parameters will have any effect on the performance of the mixer, these being the velocity and viscosity of the mixture. The diameter of the pipe is not included for obvious reasons, and the density and water cut does not affect the calculations of mixing length or pressure drop for a laminar flow. This can be shown by combining Equation (6.5), (6.6) and (6.7). The resulting Equation (6.9) shows that only the viscosity and velocity will affect the pressure drop, when the diameter and resulting mixing length are constant.

$$\Delta \mathrm{P_{sm}} = K_L * \frac{32\mu L V}{D^2} \tag{6.9}$$

It is assumed that the viscosity of the fluid will not increase above the range provided by FMC, so the only possible variation of this parameter is a decrease, which would result in a reduced pressure drop. The velocity, on the other hand, could easily decrease to values below the expected range for various reasons. This is not important due to the resulting decrease in pressure drop. The only issue that might occur as a result of these variations, is an increase in velocity because of the increasing pressure drop. Looking at a maximum 20 % increase in velocity, this would not cause any other issues besides a 20 % increase in pressure drop. This increase in velocity does not have an effect on the flow regime, as the resulting Reynolds number would be approximately 166, well below the laminar limit of 2000.

The results of these considerations are that the slight variations in process parameters will not cause any issues other than a slight increase in pressure drop.

6.2 Varying Parameters

In addition to providing a suggested mixing method for the worst-case scenario, it is also important to research if the suggested method can work for different parameters within the range provided by FMC. By varying different parameters and looking at how they affect the performance of the static mixer, it is possible to fin if there are any limitations regarding the use of these mixers.

All the parameters listed in the problem description will be varied, starting from the worst case-value and increasing/decreasing until the entire range is covered. This will first be done individually parameter by parameter, before all the parameters will be varied simultaneously, from lowest to highest possible Reynolds number.

6.2.1 Pipe Diameter

From equations used in chapter 6.1, it is clear that an increase in the pipe diameter will result in a longer mixing length. Figure 6-4 is made using Equation (6.4) with 20 different diameters, increasing from 0.536 m to 0.768 m.

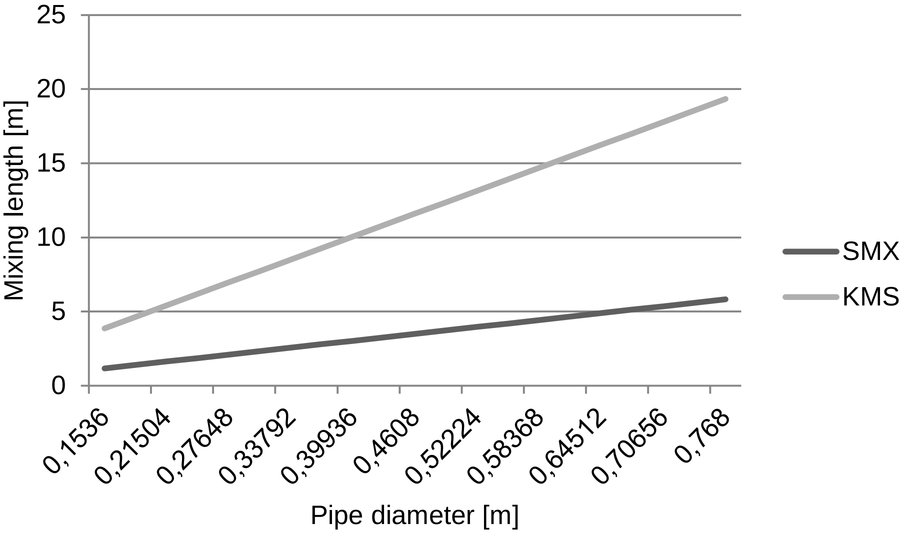


Figure 6-4: Mixing length as a function of pipe diameter.

Figure 6-4 gives a clear representation of a problem that arises when the pipe diameter becomes too large. Due to the mixer orientation being vertical, a very long mixing length can become problematic because of the space required.

In addition to having an effect on the mixing length, varying the pipe diameter will also affect the pressure drop created by each static mixer. To plot this in a graph, the same method was used as with the mixing length, only using Equation (6.9) instead.

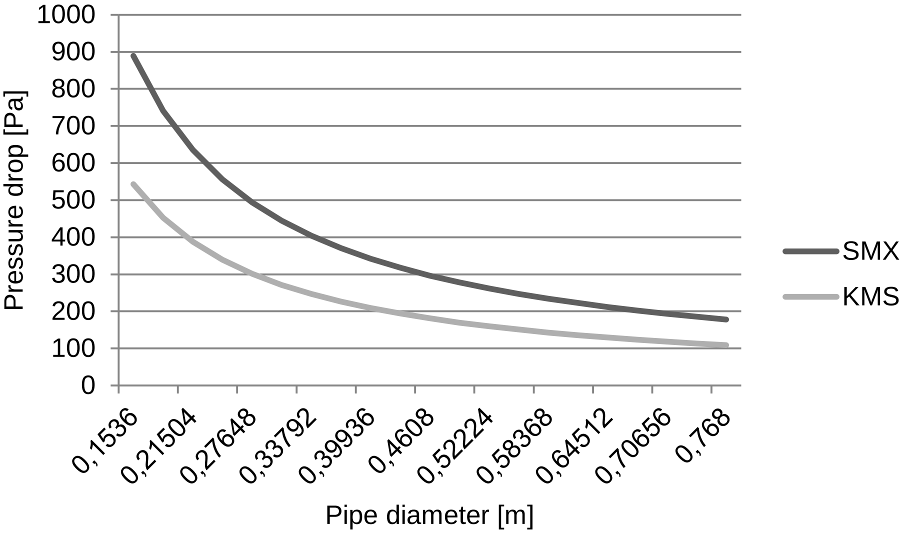


Figure 6-5: Pressure drop as a function of pipe diameter.

As Figure 6-5 shows, the pressure drop will decrease with increasing pipe diameter. Despite the increase in length, the increasing diameter will still result in a smaller pressure drop created for both types of mixers.

The only problem that occurs when looking at increasing diameter is the length of the mixer. If there is limited space, these static mixers might become unsuitable if the pipe diameter is too large.

6.2.2 Density and Water Cut

Looking at Equation (6.9), it is clear that density has no effect on the pressure drop. Nor does it have any effect on the length of the mixer. When looking at varying water cut, it is assumed that the oil density remains constant, and therefore the only change would be the total density of the mixture. Therefore, neither the water cut nor the density will affect the pressure drop or mixing length.

However, it is necessary to look at the effect a change in density will have on the criteria for mixer orientation. This is done by calculating the oil density based on a constant water density and the varying density of the mixture using Equation (6.10).

$$\rho_o = \frac{\rho - \rho_w x_w}{x_o} \tag{6.10}$$

By using Equation (6.10), for 20 different oil densities, a graph is made, as illustrated in Figure 6-6. This graph shows that unless the density difference is approaching 0, it is suggested to use a vertical mixer. This is due to the low Reynolds number from the other parameters. If the velocity was higher, it would probably reach a point where a horizontal mixer is suggested.

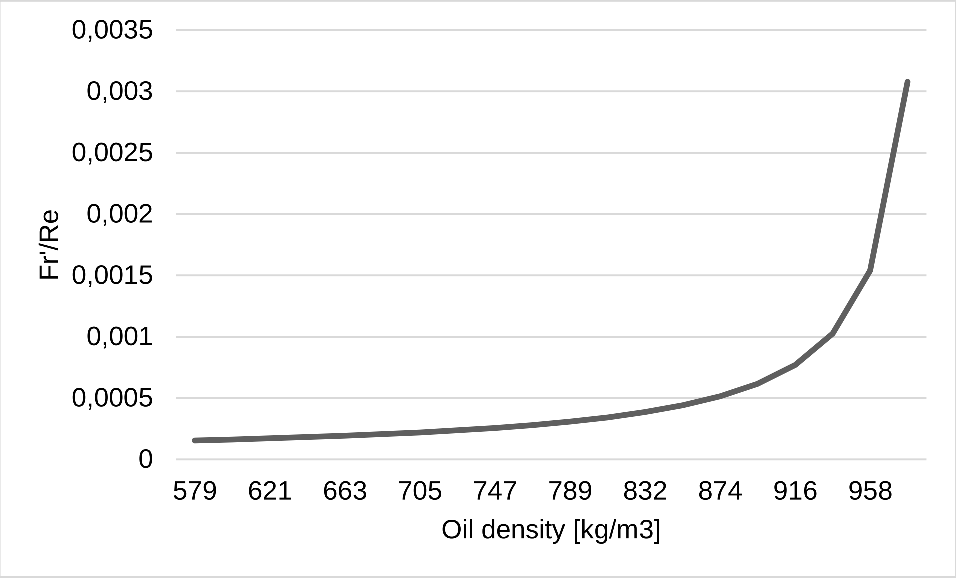


Figure 6-6: Fr'/Re as a function of the density.

6.2.3 Viscosity

When decreasing the viscosity from 0.1 Pa*s to 0.0004 Pa*s, it is important to note that the Reynolds number will become increasingly large, and the flow will at some point no longer be laminar. At that point, equations and K-factors for turbulent flows are used.

Any effect on the Fr'/Re relation can be neglected, as the decrease in viscosity only serves to decrease the relation. As a result of this, a vertical orientation is favored even more.

The only effect of a change in viscosity is a decrease in pressure drop, as Equation (6.9) suggests. However, as previously stated, it is important to note that when the flow leaves the laminar regime, it could have large effects on the calculations. This is shown in Figure 6-7, where the pressure drop is decreasing with decreasing viscosity, until the flow becomes turbulent and different equations are used. Due to the very high K_T factor of the SMX-type mixer, the pressure drop will increase in a much larger rate than for the KMS in the turbulent regime.

The pressure drops for the turbulent flow still remain below those of the values in the worst-case scenario, so mixing fluids with a viscosity as low as 0.0004 Pa*s should not be problematic.

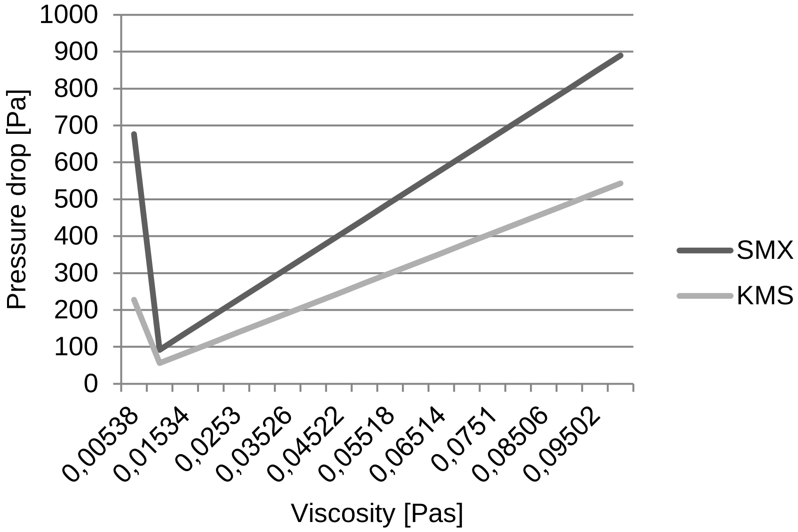


Figure 6-7: Pressure drop as a function of viscosity

6.2.4 Velocity

Looking at the ranges of parameters from FMC, it is clear that apart from the viscosity, none of the parameters see such a large percentage increase from minimum to maximum as the velocity. Seeing also that the values are so much higher than those of the viscosity, it is possible to assume that a change in velocity will result in large effects on the pressure drop, and the Reynolds number.

When increasing the velocity from 0.15 to 15.43 m/s, the Reynolds number increases from 138.24 to 12812, and the flow becomes turbulent early on. As Figure 6-8 shows, this has a large effect on the pressure drops, as they increase to up to ~39 bar for the SMX-type, and ~13 bar for the KMS-type.

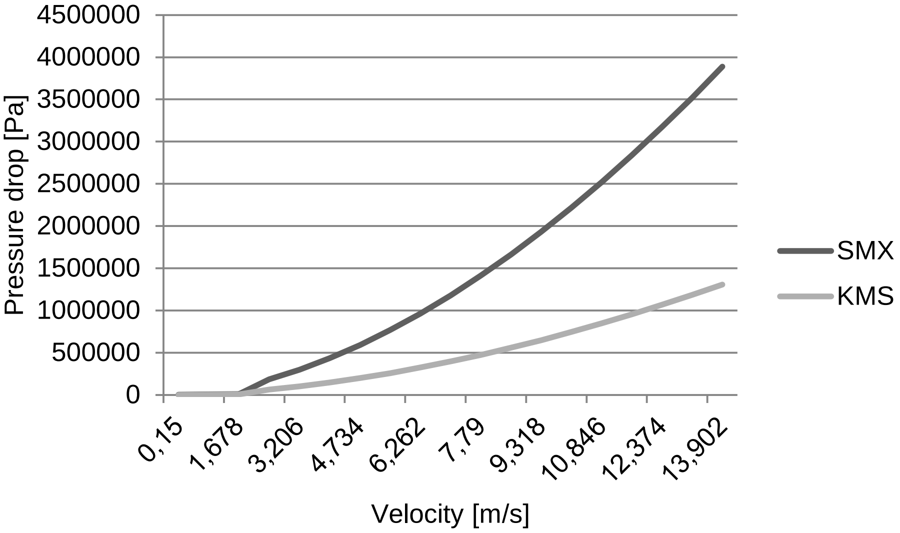


Figure 6-8: Pressure drop as a function of the velocity

As mentioned in chapter 6.2.3, an increase in velocity could also affect the mixer orientation. Using the criteria mentioned in chapter 6.1.1 with increasing velocities, it is possible to make two graphs. One for each flow regime that shows at what point a horizontal mixer orientation can be considered.

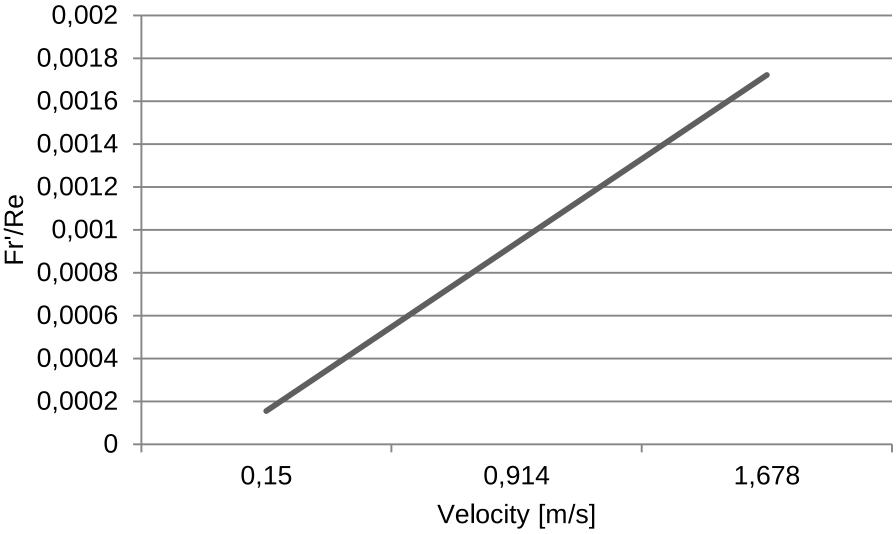


Figure 6-9: Mixer orientation criteria for laminar flow with increasing velocity.

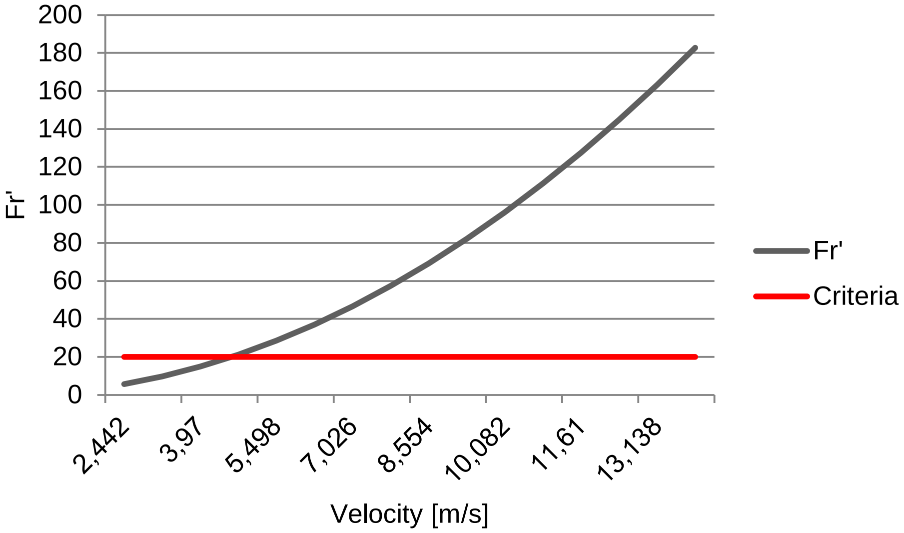


Figure 6-10: Mixer orientation for laminar flow with increasing velocity

For laminar flow velocities, it is clear from Figure 6-9 that the mixing orientation should remain vertical. Looking at Figure 6-10, it clearly shows that when the velocities become larger than ~4.5 m/s, a horizontal mixer is suggested.

6.2.5 All Parameters

By looking at all parameters individually, observations have been made as to which parameter has the greatest impact on the pressure drop and mixing length parameters. The diameter and velocity have both shown to create problems for the static mixers, in terms of long mixing length and high pressure drops respectively. In order to see how all these parameters work together, 20 calculations were performed by increasing velocity, density and diameter and decreasing viscosity with a constant water cut of 5 %. This results in a range from the lowest possible to the highest possible Reynolds number. The results of these calculations is illustrated in Figure 6-11 below.

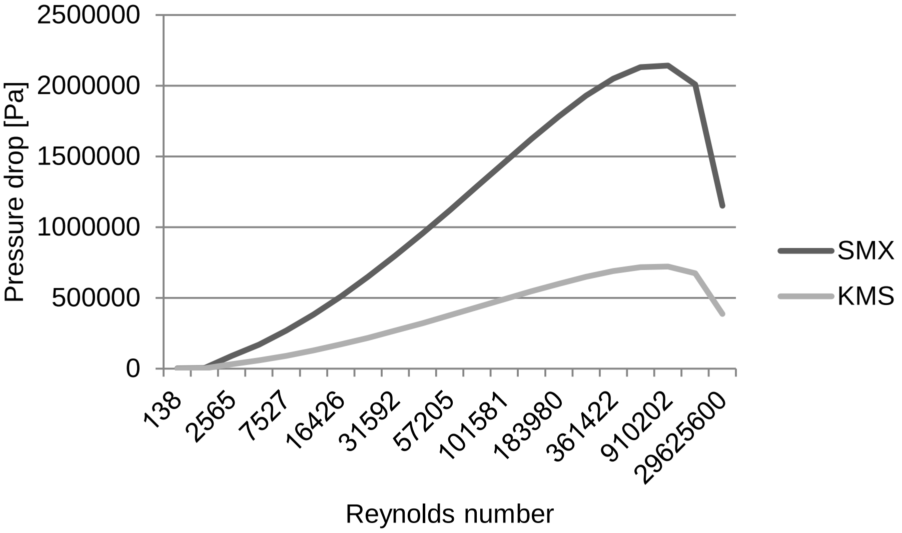


Figure 6-11: Pressure drop affected by increasing the Reynolds number.

When comparing these numbers with the ones from the varying velocity, the pressure drop is lower. This is due to the diameter and viscosity decreasing the pressure drop as they increase and decrease respectively. The sudden and large decrease in pressure drop at the end is caused by the viscosity reaching values close to 0, resulting in a large increase in Reynolds number. In Equation (6.8), the friction factor will become very small when the Reynolds number reaches high values, resulting in a low pressure drop as shown in the graph above.

The graph presents a problem that gives an explanation for why SMX is not considered applicable for high turbulence flows. The KMS is applicable, but not usually used as shown in Figure 6-1. The pressure drops becomes high when the flow becomes turbulent. It is clear that the KMS is the better choice for turbulent flows, as Figure 6-1 suggests. On the other hand, the length of the mixer would still be a problem that would need to be considered.

7 DESIGN OF A POWER MIXING SYSTEM

In this chapter, a power mixing system will be designed based on the worst-case scenario parameters presented in chapter 4. All utilities are evaluated to provide a homogeneous flow of the heterogeneous mixture uploaded to the mixing station. It is taken into account that the mixture needs to stay homogeneous for a required distance after the mixing station. A high pressure drop is expensive, and therefore the utilities are evaluated based on the amount of pressure drop they will add to the process.

7.1 Process Description

The pump needs to compensate for the pressure drop caused by all equipment in the mixing loop. The size of the pump is measured in head, which is how many meters the pump has to push the fluid for it to get re-injected and to prevent backflow. Total head needed for the power mixing can be calculated from Equation (7.1) below.

$$h_A = \frac{\Delta P}{\rho * g} + \frac{v_2^2 - v_1^2}{2 * g} + z_2 - z_1 + h_L \tag{7.1}$$

The size of the pump depends on the pressure, velocity and elevation difference between the probe and nozzle, as well as the head loss in the mixing loop.

For a power mixing system it is necessary that the pressure out of the mixing nozzle is higher than in the main pipe. That is why the pump size has to be chosen carefully. The power mix process is shown in Figure 7-1, where point one and two are marked. Point one is the inlet of the mixing loop and point two is the outlet.

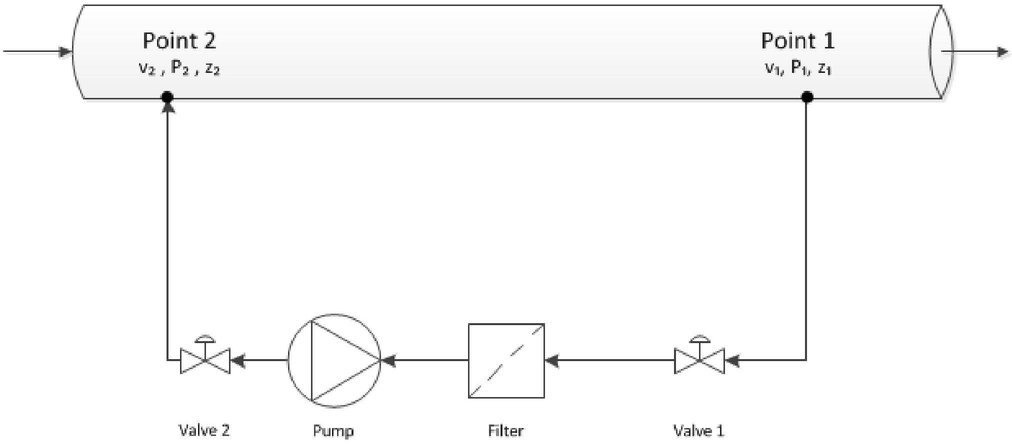


Figure 7-1: Power-mixing system

The pressure difference is how much pressure that is required in the mixing nozzle to achieve a homogeneous flow in the main line. Since the pressure in the take-of probe is the same as the pressure in the main pipe the difference will be the required energy in the mixing nozzle.

The velocity in the mixing loop will be constant because the areal in the pipeline will stay unchanged throughout the whole power mixer. This can be proven by Equation (7.2) below. When the difference in velocity is 0, the velocity link in Equation (7.1) can be removed from the equation. It means that it can be simplified to Equation (7.3).

$$\rho_1 * v_1 * A_1 = \rho_2 * v_2 * A_2 \tag{7.2}$$

$$v_1 = v_2 \tag{7.3}$$

When deciding the elevation difference, the distance between the mixing nozzle and sample probe is evaluated. The mixing system is recommended to be placed in a vertical pipe because it is easier to achieve good mixing, for reasons explained in chapter 3.2.

Because the mixing system will be placed in a vertical pipe, the elevation difference of the probe and nozzle will cause a pressure drop. As described in chapter 5, the distance between the mixing nozzle and sample probe has to be eight pipe diameters. The distance between the mixing nozzle and the take-off probe to the power mixing loop is suggested to be six times the inner pipe diameter of the main pipe. This is because it has to be shorter than the distance between the mixing nozzle and sample probe. The elevation difference can be calculated from Equation (7.4).

$$\Delta Z = 6 * D \tag{7.4}$$

Table 7-1: Elevation difference between nozzle and probe

Parameter	**Value**	**Unit**
ΔZ	0.9216	m

The last parameter that needs to be decided before the head of the pump can be calculated is the head loss through the power-mixing loop. The head loss of the loop is created by elements such as probe, valves, elbows, filter and tubing. Each different element has its own minor loss coefficient, which affects the pressure drop through it.

7.2 Utilities

In this chapter, recommendations will be made as to which elements should be used in the power mixing loop.

7.2.1 Probe

The probe's function is to extract a portion of the flow in the main pipe that is going to be re-injected. It is formed as a tube with a bend which will be inserted into the pipeline. To achieve good mixing, the re-injected flow should be a homogeneous mixture, and therefore the probe has to be placed within the range where water droplets are uniformly distributed. [20]

The design of the probe is based on the volume flow in the main pipeline. By recycling 10 % of this flow, a volume flow in the recycle loop can be calculated. For design reasons, the velocity in the recycle loop is chosen. The area and diameter of the probe, and thereby the recycle pipe, can be calculated according to Equation (7.5) and (7.6).

$$A_{pm} = \frac{Q}{v} \tag{7.5}$$

$$d_i = \sqrt{\frac{4 * A_{pm}}{\pi}} \tag{7.6}$$

The parameters are listed in Table 7-2, and the results in Table 7-3.

Table 7-2: Dimensions of probe and recycle pipe

Symbol	Value	Unit
Q	0.00027	m^3/s
v	0.5	m/s

Table 7-3: Resulting dimensions of the probe.

Symbol	Value	Unit
A_{pm}	0.00055	m^2
d_i	0.026	m

Regarding the length of the mixing probe into the main pipe, the same limitations due to vibrations as mentioned in chapter 5.1.2 apply. By assuming a thickness of the probe to be 10 mm, to calculate outside diameter of the probe, the allowable length can now be calculated by using Equation (5.2). The parameters are listed in Table 7-4 and the result in Table 7-5.

Table 7-4: Parameters and values for the calculations of probe length.

Symbol	Value	Unit
d_0	0.0366	m
d_i	0.0266	m
V	0.15	m/s
E	$1.8822*10^{11}$	Pa
ρ	600	kg/m^3

Table 7-5: Allowable length for the probe.

Symbol	Value	Unit
L	10	m

Because vortex shedding is increasing proportionally to velocity, and the worst case scenario is based on a low velocity, there will be no limit of the length in this case. The only restriction is thereby to avoid placement close to the walls because of the wall effects. The probe should be placed so that the recycled stream is homogeneous, which is most likely to occur within the area illustrated in Figure 5-5.

7.2.2 Nozzle

Most of the information and equations are from the international standard 3171. [1]

A nozzle is a device that can be used to modify the flow of a fluid. In this case, the nozzle is designed to mix the water into the oil in the flow of the main pipe, by increasing the kinetic energy at the expense of its pressure. Therefore, the nozzle is one of the most important elements in the power mixing system. It is formed as a circular tube, of equal diameter as the probe, and its length having the same limitations as the probe. In the power mixing system, the nozzle's main function is to re-inject the recycled portion of the fluid into the main flow, and thereby achieve a mixed fluid and a homogeneous flow. [26]

To what degree the water droplets are mixed into the crude oil depends on the rate of energy dissipation. As a result, the nozzle can be designed based on the required energy dissipation. [1][20]

A good dispersion is defined as when the ratio of C_1/C_2 is between 0.9 and 1. A ratio below 0.4 gives a poor distribution of water droplets, and results in a high potential for water stratification.

$$\frac{C_1}{C_2} = e^{\left(\frac{-W}{\varepsilon/D}\right)} \tag{7.7}$$

The rate of energy dissipation is calculated by the turbulence characteristics according to Equation (7.8). The parameters are chosen based on a worst case scenario.

$$\frac{\varepsilon}{D} = 6.313 * 10^{-3} * \vartheta^{0.125} * V^{0.875} * D^{-0.125} \tag{7.8}$$

The settling rate of water droplets are thereby calculated by Equation (7.9).

$$W = \frac{\varepsilon/D}{\mathrm{G}} \tag{7.9}$$

Where G is a parameter dependent on the required ratio of C_1/C_2. With this, the required energy for an acceptable concentration profile is determined by Equation (7.10).

$$E_r = 4630 * \left(\frac{\rho_w - \rho_o}{\vartheta * W}\right)^{1.25} * \rho_o{}^{-2.75} \tag{7.10}$$

When the required energy for representative sampling is known, the required pressure drop can be calculated from Equation (7.11).

$$E_r = \frac{\Delta P * V}{\Delta X * \rho} \rightarrow \Delta P = \frac{E_r * \Delta X * \rho}{V} \tag{7.11}$$

Bernoulli's equation, Equation (7.12), can be rearranged to calculate the required velocity of the re-injection from the nozzle.

$$\frac{P}{\rho g} + \frac{V^2}{2g} + z_1 = \frac{P_n}{\rho g} + \frac{{v_{re}}^2}{2g} + z_2 \tag{7.12}$$

The density is not changing, and can be neglected from the equation. The velocity in the main pipeline will be of such small proportion compared to the re-injection velocity, therefore this too can be neglected. By rearranging Equation (7.13), the velocity can be calculated as in Equation (7.14).

$$\frac{v_{re}^2}{2g} = \frac{P}{\rho g} - \frac{P_n}{\rho g} + z_1 - z_2 \tag{7.13}$$

$$v_{re} = \sqrt{\frac{2 * \Delta P}{\rho} + \Delta Z} \tag{7.14}$$

When the velocity is known, the re-injection area and diameter can be calculated by Equation (7.15) and (7.16) respectively, derived from and the continuity Equation (7.2). The parameters for the calculations are listed in Table 7-6, and the results in Table 7-7.

$$A_{re} = \frac{A_{pm} * v}{v_{re}} \tag{7.15}$$

$$d = \sqrt{\frac{4 * A_{re}}{\pi}} \tag{7.16}$$

Table 7-6: Parameters for the nozzle design

Symbol	**Value**	**Unit**
ϑ	166.667	mm^2/s
$\frac{\varepsilon}{D}$	0.00287	m/s
G	10	Dimensionless
W	0.000287	m/s
ρ_w	1000	kg/m^3
ρ_o	578.947	kg/m^3
E_r	9.95	W/kg
ΔX	10*D	m

Table 7-7: Results for the nozzle design

Symbol	Value	Unit
ΔP	0.59	bar
v_{re}	14.025	m/s
d_{re}	0.005	m

The re-injection is happening through an outlet of the nozzle, and the degree of mixing is dependent of the diameter, the amount and the positions of the outlets, as well as the velocity and angle of re-injections.

In order to determine the most efficient design of the nozzle, simulations needs to be performed. Some suggestions are as follows:

- Re-inject countercurrent to the main flow to provide the most disturbance to the flow.

- Divide the total outlet area into multiple outlets to provide disturbance to a large as possible portion of the main flow.
- Study the effect of varying angles of the outlets.

7.2.3 Pump

In this chapter, the information is found in reference [28].

A pump is a device used to transport fluids through a pipeline. Pumps can be used to move fluids from a low pressure- to high pressure area, or from a low elevation to a higher elevation. The types of pumps are divided by how they move the fluid through the pipeline. The four major types of pumps are: centrifugal-, displacement-, rotary displacement- and Eductor-jet pumps. Almost every type of pump can be used for gasses and liquids but they will be specially designed for what type of fluid they are transporting.

When selecting the right pump for the power mixer, it is important to be aware of the ranges in parameters for this process. There are a lot of different pump types within the four major groups.

The Eductor-jet pump was excluded immediately because the main purpose of this pump was to mix the process fluid with water, air or steam.

There are many different types of rotary displacement pumps, some of them are only suited for liquids with high viscosities. Because the ranges in viscosity for the crude oil contains both high and low values, this type of pump is excluded. The other types of rotary displacement pumps that were suited for all viscosities had limits for pressure and volume flow. These types can only be used for processes with pressure between 10 and 40 barg and a volume flow below 60 m^3/h, and as a result of this they are not suited for this process either.

Another option is displacement pumps, but these are more suited for acids and bases.

For petrochemical and oil refinery plants, centrifugal pumps are recommended. This is also the only type of pump that meets all the criteria for the worst case scenario and the ranges of parameters.

7.2.4 Valves

The type of valves used for a specific process depends on the pump choice. For this process the centrifugal pump was recommended, and therefore it is necessary to install two gate valves. One gate valve has to be placed on the suction side of the pump and the other one is placed on the discharge side to provide a tight shut off if necessary.

A gate valve gives a low pressure drop, as they offer no resistance to the fluid passing through. The minor loss coefficient for gate valves is listed in table Table 7-8.

Table 7-8: Minor loss coefficient K for a gate valve. [27]

Type of valve	**K**
Gate Valve, fully open	0.15

To calculate the head loss through a gate valve, Equation (7.17) is used. This mixing loop contains two gate valves, therefore the head loss has to be multiplied by two.

$$h_L = K * \frac{v^2}{2 * g} \tag{7.17}$$

To calculate the total pressure drop through these two valves Equation (7.18) is used.

$$\Delta P = \rho * g * h_L \tag{7.18}$$

The head loss and pressure drop through the two gate valves for the power mixing are listed in Table 7-9.

Table 7-9: Results of the head loss and pressure drop for two gate valves in the power mixer system.

Parameter	**Value**	**Unit**
h_L	0.0038	m
ΔP	0.0021	bar

7.2.5 Elbows

When selecting the type of elbows for the power mixer the value for the pressure drop is essential. To keep the pressure drop as low as possible, a 90° long radius elbow is suggested instead of the 90° regular radius elbow. The difference between these two types, in addition to the significantly larger pressure drop in the regular radius, is the length and curvature. In a long radius elbow the radius of curvature is 1.5 times the nominal diameter, while it is one times the nominal diameter for the regular elbow. Long radius elbows are the most common type of elbow and are used when the space is available and when the flow is more critical. [29][30]

Threaded and flanged fittings are the two types of fittings for the different sorts of elbows. The flanged types of elbows cause the least pressure drop. This is because the elbow is attached to the tubing with a plate outside the pipe. The threaded type is when the elbow is connected with a screw end inside the pipe. This type of fittings causes the inner diameter to decrease, which causes a higher pressure drop than the flanged type.

For the power mixer, the flanged long radius 90° elbow is suggested. The minor loss coefficient value for this type of elbow is listed in Table 7-10 below. Equations (7.17) and (7.18) can still be used for calculating the pressure drop and head loss through the elbows for this process. It is still necessary to multiply these equations by two because the loop contains two elbows.

Table 7-10: Minor loss coefficient for 90° long radius elbow. [27]

Type of valve	**K: Minor loss coefficient value**
Elbow, Threaded long radius elbow 90°	0.7

7.2.6 Filter

To prevent damage to the centrifugal pump, there is installed a filter in the power mix loop. The filter is used to prevent solids from entering the pump because most pumps are not designed to handle foreign material. A common problem is milling inside the pipes, which is when particles from the pipe surface detaches and get mixed with the oil. [31][32]

Mesh is the scale used to determine the opening size in the filter. A common mistake is to use a too small opening size for the process, which causes the pressure drop to increase dramatically. For oil, the size of the filter can be 40 mesh or lower depending on the viscosity of the oil. This means that there are 40 small squares across one inch of screen. 40 mesh has the smallest grids that is used as filters for oil, and it is guaranteed to remove all particles that might have been mixed in the oil. Because pressure drop increases with increasing mesh size, it will also cause the highest possible pressure drop.

To calculate the pressure drop for the necessary filter for this process, the flow coefficient $C_{v,}$ is required. The C_v factor can be found in tables when the viscosity of the fluid is known as the Saybolt Universal viscosity. When calculating the Saybolt Universal viscosity at a certain temperature, Equation (7.19) has been used. [33]

$$U_t = U_{100°F} * (1 + 0.000061 * (t - 100)) \tag{7.19}$$

The Saybolt Universal viscosity at 100° F is listed in Table 7-11.

Table 7-11: Saybolt Universal viscosity at 100°F

Parameter	**Value**	**Unit**
$U_{100°F}$	463	SSU

The result of the Saybolt Universal viscosity at a temperature of 150° C is listed in Table 7-12. The calculated viscosity is used to find the flow coefficient factor for the filter.

Table 7-12: Result of the Saybolt Universal viscosity at 302° F (150° C)

Parameter	**Value**	**Unit**
$U_{302°F}$	468	SSU

For a filter that have 40 mesh scale, the C_v value is listed in a table for fluids that have a viscosity at 30 SSU, 500 SSU and higher viscosities. Due to this, interpolation is required to find the flow coefficient for the oil that has a viscosity at 468 SSU. Using Equation (7.20) and the values in Table 7-13, interpolation can be performed.

Table 7-13: Parameters needed for interpolation when calculating the flow coefficient for oil with a viscosity of 468 SSU at 40 Mesh. [33]

Parameter	**Value**	**Unit**
U_1	30	SSU
U_2	500	SSU

C_{v1}	1.2	Dimensionless
C_{v2}	1.9	Dimensionless

$$C_v = C_{v1} + (C_{v2} - C_{v1}) * \frac{U_{302°\mathrm{F}} - U_1}{U_2 - U_1} \tag{7.20}$$

In Table 7-14, the flow coefficient factor for the oil in the power mixer is listed with a 40 mesh.

Table 7-14: Result of the flow coefficient, C_v, at 302° F (150° C)

Parameter	**Value**	**Unit**
C_v (150° C)	1.85	Dimensionless

To calculate the pressure drop through the filter, Equation (7.21) is used.[34]

$$\Delta P = \frac{\left(\frac{q}{C_v}\right)^2 * (133{,}6)}{10^2} \tag{7.21}$$

The pressure drop through the filter in the power mix loop is listed in Table 7-15, and is calculated from the worst-case scenario parameters given in chapter 4.

Table 7-15: Result of the pressure drop in the filter by using the worst-case scenario parameters.

Parameter	**Value**	**Unit**
ΔP	0.39	bar

7.2.7 Piping

When choosing the type of material for the mixing loop, reference [35] and [36] is mostly used.

When deciding the material for the piping in the power mixer, the corrosion resistance, pressure rating and operating temperature have been taken into consideration. For pipes in oil and gas production and processing, 22Cr duplex, 6Mo and 316 are different materials that are recommended.

For the power mixer the 316 stainless steel type of material is suggested. The 316 SS has a high corrosion resistance and a high strength at elevated temperatures. This material is common for oil, gas and chemical industries because of its cost and it being easy to fabricate.

The 316 stainless steel material has an L grade, which will reduce the tendency to crack after welding. For the power mix loop the 316 L is suggested to give an opportunity for welding if it is necessary.

The length of the tubing in the mixing loop is designed from the international standard 3171. The distance between the mixing nozzle and the sample probe is recommended to be between onehalf of the main pipe diameter and eight pipe diameters. Because the probe for the mixing system has to be before the sampling probe, it is suggested to be placed at six pipe diameters from the mixing nozzle. The length of vertical pipes is calculated from Equation (7.22). [1]

$$L_v = D * 6 \tag{7.22}$$

For design reasons, the length of horizontal piping is suggested to be the same length as the vertical piping. The length has to be multiplied by two because of the inlet- and outlet pipe. To calculate the total length of horizontal piping Equation (7.23) has been used.

$$L_H = 2 * D * 6 \tag{7.23}$$

For total length of tubing in the power mixer, Equation (7.24) has been used.

$$L_{pm} = L_v + L_H \tag{7.24}$$

The total length of tubing for the power mixing system is listed in Table 7-16.

Table 7-16: Results of vertical, horizontal and total tubing in the mixing loop.

Parameter	**Value**	**Unit**
L_V	0.9216	m
L_H	1.8432	m
L_{pm}	2.7648	m

The total pipe length is used to calculate the pressure drop caused by friction from the surface inside the pipe. Equation (7.25) is used to calculate the head loss caused by the tubing in the mixing loop.

$$H_L = \frac{64}{N_{Re}} * \frac{L_{pm}}{d_{re}} * \frac{v^2}{2 * g} \tag{7.25}$$

The total head loss caused by the inside surface of the pipe is listed in Table 7-17 below.

Table 7-17: Results of head loss caused by the inside surface of the pipe.

Parameter	**Value**	**Unit**
H_L	1.0618	m

To calculate the pressure drop caused by the tubing in the process, Equation (7.21) was used. The total pressure drop from the pipes in the mixing loop is listed in Table 7-18.

Table 7-18: Pressure drop in the mixing loop caused by the tubing.

Parameter	**Value**	**Unit**
ΔP	0.0625	Bar

7.2.8 Sizing the Pump

When the pressure difference and the elevation difference between the probe and nozzle, as well as the head loss through the whole mixing loop is known, the size of the pump can be calculated. The total head loss for the mixing system can be calculated from Equation (7.26) for the suggested equipment.

$$h_L = h_{L,probe} + h_{L,valves} + h_{L,elbows} + h_{L,filter} + h_{L,pipeline} \tag{7.26}$$

The total head loss through the power mixing system is listed in Table 7-19.

Table 7-19: Total head loss in the power mixer

Parameter	**Value**	**Unit**
h_L	7.706	m

The head loss value is further used to calculate the size of the pump. When calculating the head needed by the pump, Equation (7.27) is used.

$$h_A = \frac{\Delta P}{\rho * g} + \Delta Z + h_L \tag{7.27}$$

Total head needed from the pump in the power mixer is listed in Table 7-20.

Table 7-20: Total head needed from the pump in the power mixer

Parameter	**Value**	**Unit**
h_A	18.652	m

To calculate the size of the pump, Equation (7.28) can be used. The pump efficiency is usually 80%, and this is also used for the centrifugal pump for the power mixer.

$$P = \frac{\rho * Q * g * h_A}{\eta} \tag{7.28}$$

The size of the pump is listed in Table 7-21. To be sure that the pump will be able to provide the required energy when varying the velocity in the main pipe, it is also designed for a 20 % increase of the velocity.

Table 7-21: Pump size for worst case parameters and for a 20 percent increase of the velocity.

Parameter	**Value**	**Unit**
P	38.12	W
P_{design}	44.68	W

8 EVALUATING POWER MIXING

In this chapter the power mixing design will be evaluated, and how varying the parameters throughout the given range will affect the efficiency.

8.1 Worst Case Scenario

The power mixing system described in chapter 7 is based on the worst case scenario, which parameters are presented in chapter 4. Figure 8-1 below illustrates the designed power mixing system, including all utilities and dimensions of piping. The equipment labels in this figure are explained in Table 8-1.

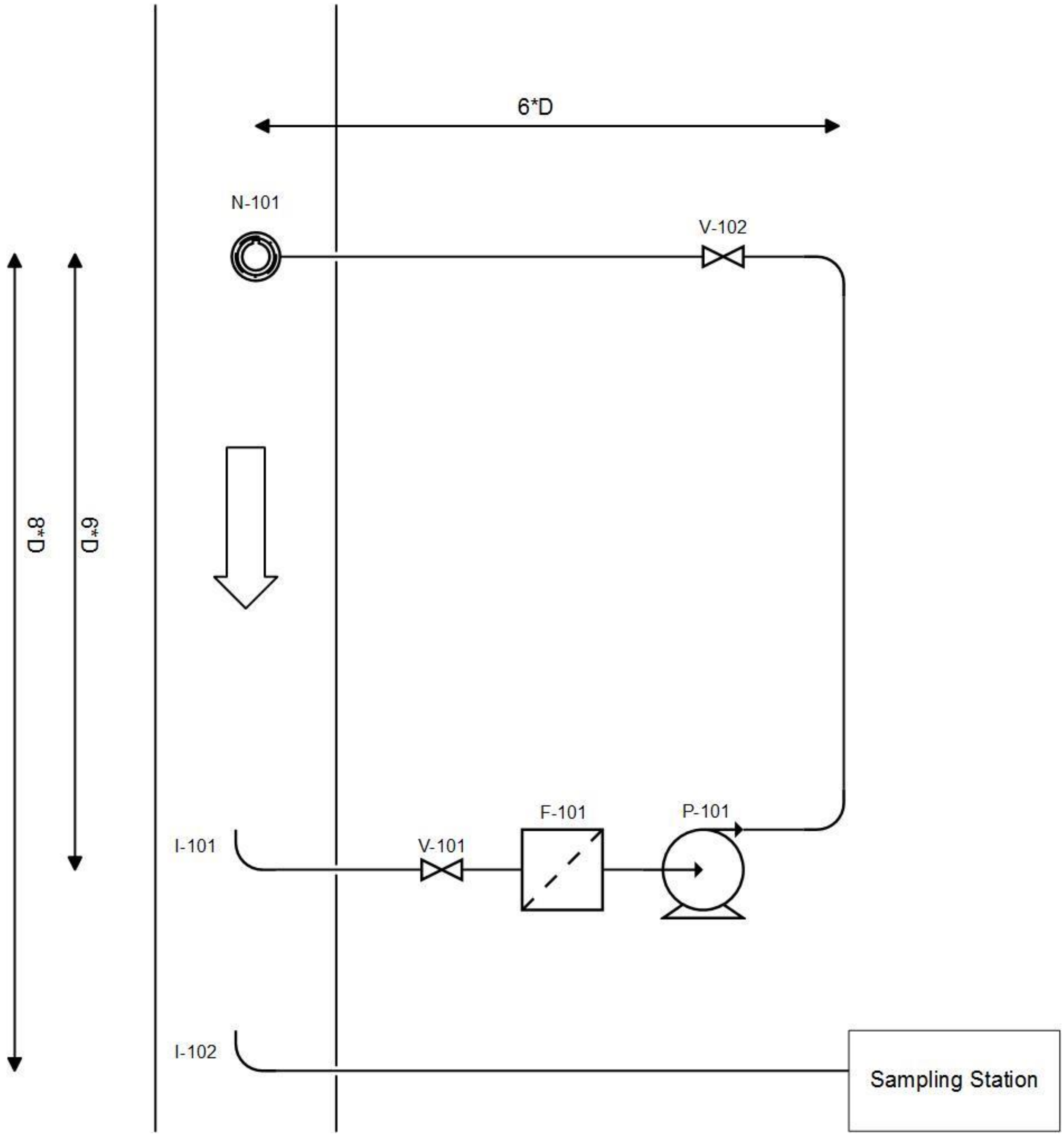


Figure 8-1: Illustration of the designed power mixing system

Table 8-1: Identifications of items in Figure 8-1.

Label	**Identification**
N-101	Nozzle
V-101	Gate valve
V-102	Gate valve
F-101	Filter
P-101	Pump
I-101	Mixing probe
I-102	Sampling probe

The three main utilities in the power mixing system are the pump, nozzle and probe. In designing the system, the parameters of the worst case scenario were central. Therefore, the system will work in its most efficient way when these parameters are the case.

The pump was designed based on the total head loss through the process, the probe design based on 10% recycle of the main flow, and the nozzle designed to provide the necessary rate of energy dissipation to the flow. The design will provide a good mix as a homogeneous flow with parameters varying of 20 %. In this way, it is taken into account that any sudden variations will not lead to unrepresentative sampling.

The limitations of the system are essential when evaluating if this mixing method will provide a homogeneous flow for a given process. When designing the nozzle based on the required energy dissipation, the density of oil and water are crucial, represented by Equation (7.10).

The distance of which the main flow is kept homogeneous after the nozzle, ΔX, has to be determined by simulation. This parameter was estimated to be maximum ten times the inner main pipe diameter, as stated in international standard 3171. [1]

8.2 Varying Parameters

8.2.1 Pipe Diameter

The power mixing system is designed for the diameter of the lowest value in the given range of parameters. Because of this, the designed power mixing system has limitations according to increasing diameter. The Figure 8-2 below illustrates the required pressure drop in the nozzle which increases with increasing diameter.

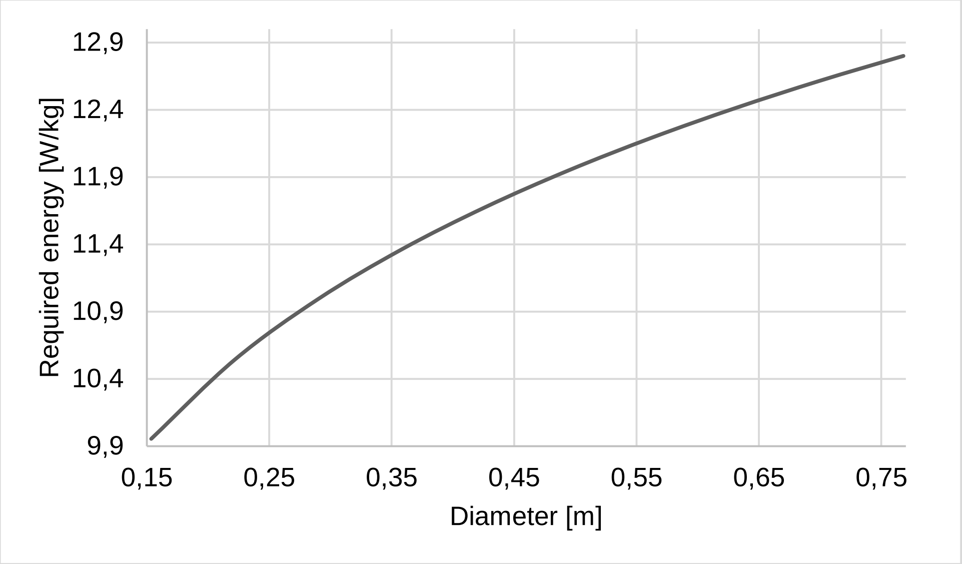


Figure 8-2: Diameter versus required energy

The mixture is well mixed if the ratio of concentration at the top and bottom are 0.9 or higher, which gives a G value of ten. If the requirement are lowered to a G value of eight, which is associated with a concentration ratio of 0.88, the flow will still be homogeneous but maybe not for as long of a distance as the previous case. On the other hand, when the recycle- and sampling- probe was placed, there was taken into account that some variations could occur, and therefore the design distance was less than the maximum allowed distance from the mixing station. On these grounds, the maximum allowed pressure drop for guaranteed well mixed flow is higher than the design pressure.

Calculations show that for an increasing diameter, the required pressure drop in the nozzle is increasing, the pressure drop associated with the piping decreases, and the remaining utilities are unaffected. The maximum pressure drop that the designed mixing system can handle is calculated to be 0.87 bar, which correspond to a main pipe diameter of 0.2 m.

If the total pressure drop is considered, the main limiting factor is the pressure drop caused by the filter. Although there is a maximum allowed pressure drop that the pump can maintain, simple modifications can be made so that the power mixing system will provide a homogeneous flow. Figure 8-3 illustrates how the total pressure drop is affected by variations in diameter.

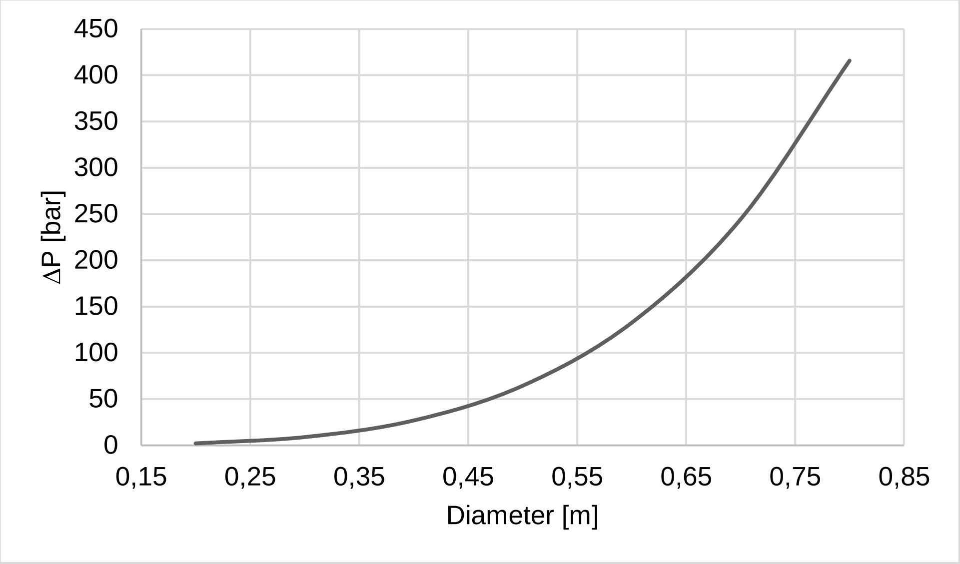


Figure 8-3: Diameter versus total pressure drop

When the limit of maximum pressure drop is reached, the filter can be changed to one that does not cause as much pressure drop as the filter chosen for this design, so that the pump can provide the required effect. Another option is to install a new pump, as the head needed from the pump increases with increasing diameter. Figure 8-4 shows the required effect versus the pressure drop.

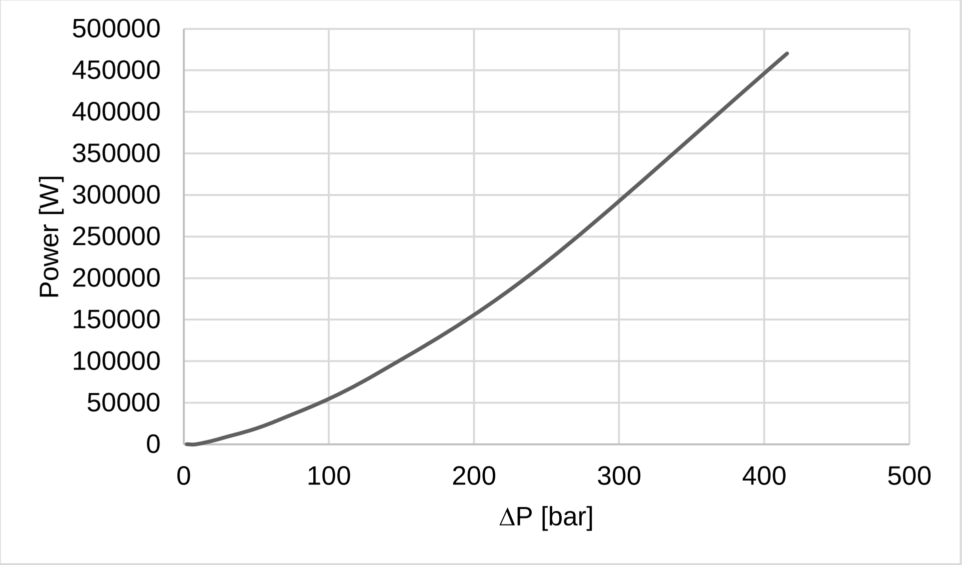


Figure 8-4: Total pressure drop versus required power from pump

By these grounds, it could be possible to evaluate what option would be the most economical; changing the filter and keep the pump, or install a new pump which can account for the total pressure drop as illustrated in the figure above.

8.2.2 Velocity

When the velocity increases and all the other parameters remain constant, the volume flow increases stated by Equation (8.1).

$$Q = v * A \tag{8.1}$$

To ensure that the power mixing system will provide a homogeneous flow for realistic velocity variations, the pump is designed to maintain the pressure drop at ± 20 % variations. The limiting factor in this case is the pressure drop caused by the filter, which increases with increasing velocity. Consequently, the head needed from the pump is determined for a flow of velocity of 20 % more than the design velocity.

The required energy and pressure drop in the nozzle decreases with increasing velocity and volume flow, according to Equation (7.10) and (7.11). Theoretically, the power mixing system will be functional at velocities from the worst case of a minimum value of 0.15 m/s to 1 m/s. After this point, the required diameter of the probe and nozzle will increase to a value that is unrealistic compared to the pipe diameter of 0.1536 m. A velocity of 1 m/s accounts for a velocity that is six times the design velocity, and an escalation of this extent are unlikely to occur under normal conditions.

For the case where the velocity is less than the worst case scenario, which can happen if there is an irregularity to the uploading process, the flow will not be well mixed. It has to be taken into account that representative sampling cannot be performed under these circumstances.

8.2.3 Density

As the total density increases, the density of oil will increase accordingly because the density of water is constant. As Figure 8-5 illustrates, the required energy dissipation decreases with increasing density.

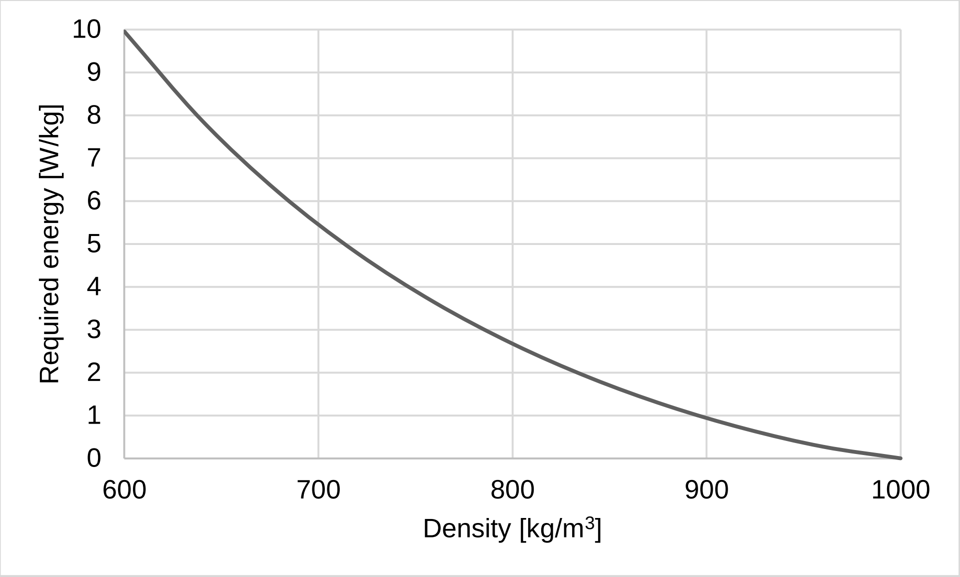


Figure 8-5: Density versus required energy

This can be explained by the fact that if the density of oil increases, the difference in density would decrease. When this occurs, the force of gravity, that has a higher impact the heavier fluid, will decrease accordingly. Thereby, it can be concluded that the lower the density difference of oil and water, the mixing becomes less energy consuming. This is illustrated in Figure 8-6.

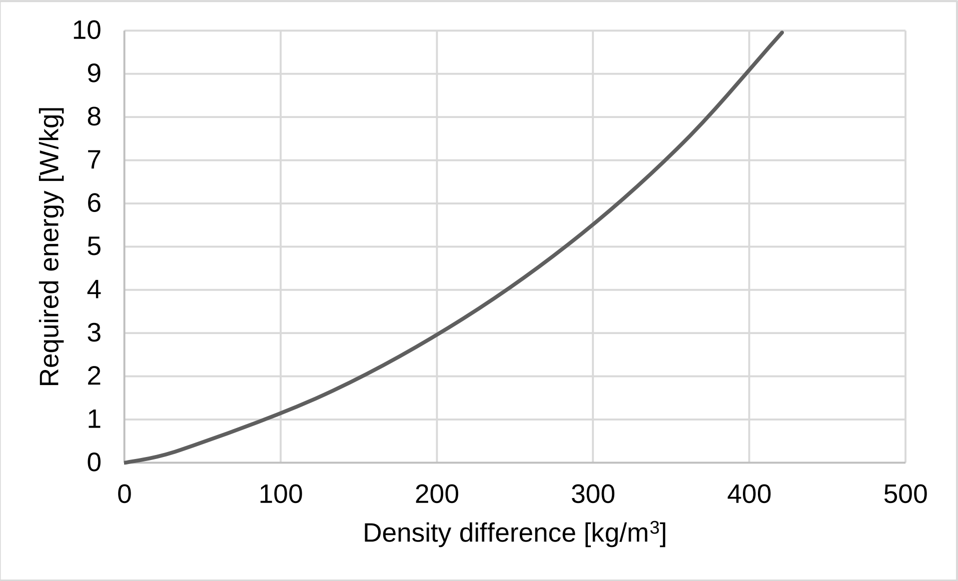


Figure 8-6: Density difference versus required energy

The graph shows that for no difference in density between water and oil, no energy dissipation is required. This is according to the calculations, but could be a case where the equations are not accurate.

In the worst case scenario, the water cut is set to be the highest value in the given range. Because the density of oil and water are constant for a given flow, a variation on water cut would affect the total density of the homogeneous mix. Water has the highest density, and therefore, when the amount of water in the mix increases, the easier the stratification will occur. In Figure 8-7 an increase of the water cut through the whole given range is illustrated. Because of the force of gravity, the required energy dissipation increases proportionally with an increasing water cut.

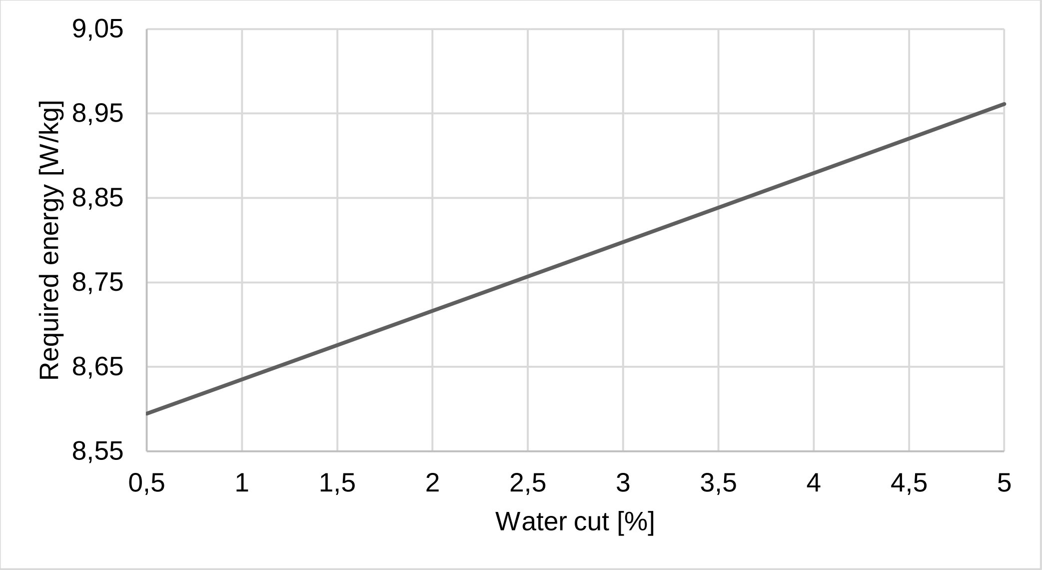


Figure 8-7: Water cut versus required energy.

8.2.4 Viscosity

When the viscosity decreases, the Reynolds number will increase. The graph in Figure 8-8 shows that the required energy dissipation is reduced, as stated in Equation (7.10). The value decreases as the kinematic viscosity increases, which occurs when the dynamic viscosity increases, according to Equation (8.2).

$$\vartheta = \frac{\mu}{\rho} \tag{8.2}$$

This case states the opposite as all the other cases in this chapter; an increase in required energy when the turbulence in the flow increases.

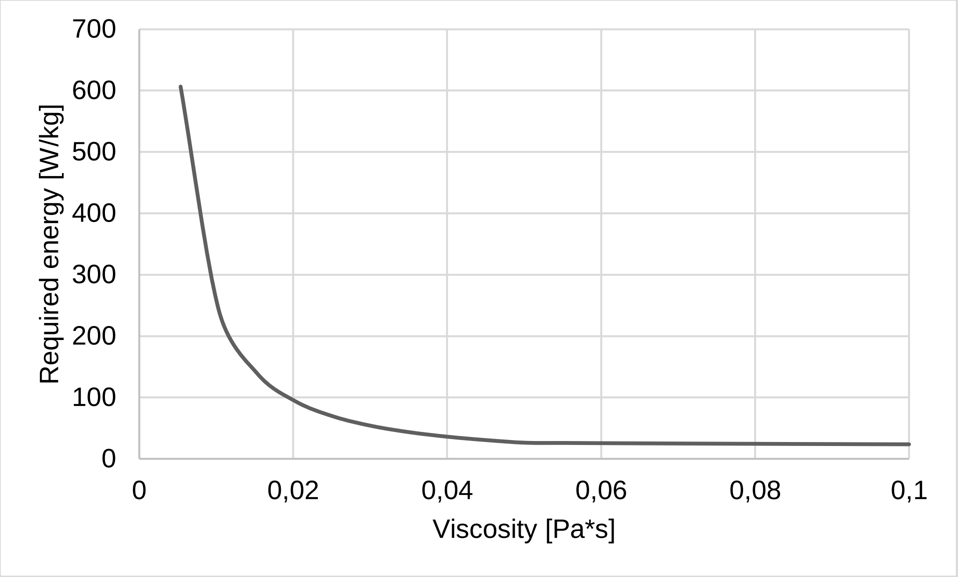


Figure 8-8: Viscosity versus required energy

8.2.5 All Parameters

As explained in chapter 4, the worst case scenario is set to be when we have the minimum Reynolds number. According to Equation (4.1), this number will increase when the density, velocity and diameter increases, and the viscosity decreases.

When evaluating an increasing Reynolds number, which is equivalent to an increasing turbulence in the flow, the parameters are varied through the given range.

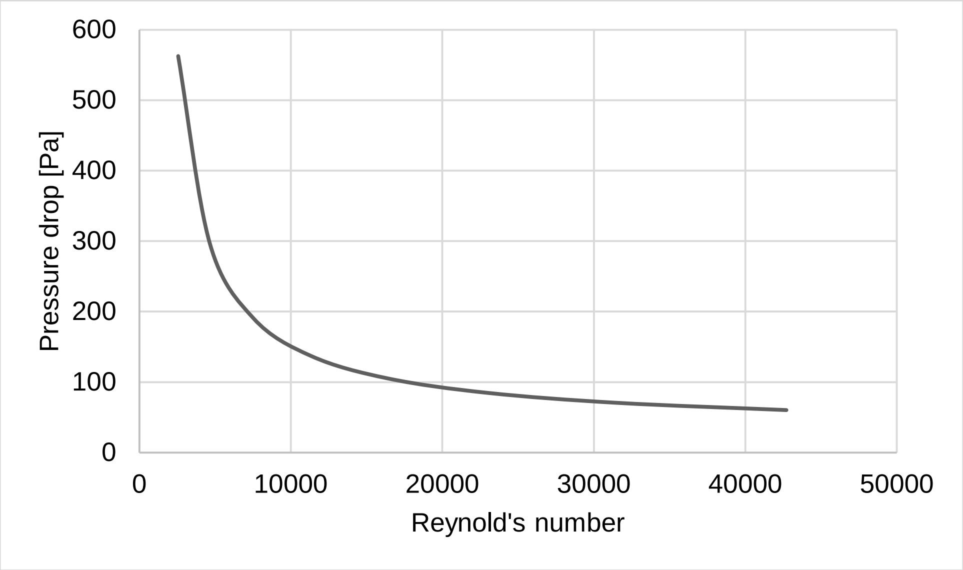


Figure 8-9: Reynolds number versus pressure drop

The graph in Figure 8-9 shows that for increasing turbulence in the main flow, the lower the pressure drop, because of a lower required energy dissipation for providing satisfying mixing. This can be explained by the fact that to achieve a turbulent flow, energy is added, and this energy has provided some mixing before the main flow reaches the mixing station. In other words, energy required from the power mixing system decreases when the turbulence already present in the flow increases.

9 DISCUSSION

The discussion in this report has been divided into three parts. First, the uncertainties regarding the assumptions and calculations are considered. The main part of this chapter is the discussion of the recommended solutions, and lastly any suggestions for further work is presented.

9.1 Uncertainties

For static mixing there are several uncertainties that will affect the results. When calculating the length of the static mixer, the correlation of variance CoV, is a deciding factor. This factor, as explained in chapter 6.1, is a measurement of how homogeneous the fluid is. The CoV value was set to be 0.03, which is equivalent to a good mixing. Increasing this value to 0.05 would result in a shorter mixing length and a smaller pressure drop, although the quality of the mixture would decrease, but still be considered reasonable.

The pressure drop ratios used for calculating the pressure drop for the static mixers vary depending on the type of static mixer. It is reasonable to assume that these ratios will decrease as the technology improves, and because the source for these numbers is over ten years old it could be that these ratios are outdated. In addition to this, calculations performed for the transient flow regime ($2000 < Re < 4000$) are not accurate because the equations are only valid for laminar and turbulent flows. To be as conservative as possible, a flow with Reynolds number above 2000 is treated as turbulent.

The largest contributing element when calculating the pressure drop in the power mixing system is the filter. The recommended size for the filter was 40 mesh, which is the smallest grid that is used in the oil industry. It is uncertain if a 30 mesh filter will be able to provide the necessary protection for the pump. Selecting this filter would result in decreasing the pressure drop in the recycle loop.

In order to design the diameter of the recycle loop, a value for the flow rate and velocity was set. These values were chosen based on reasonable pipe design for the mixing loop. It is possible that the combination of these two parameters is not the optimal choice, but in order to create a design some assumptions had to be made. The optimal amount of the main flow that is going to be recycled can be determined by simulation, and thereby the optimal diameter and velocity in the recycle loop could be evaluated.

Because of the surface tension between two immiscible liquids, it is not reasonable to assume that no mixing is required when the density difference between them approaches 0. Equation (7.10) does not take this into consideration, and it is therefore inaccurate when the density difference between water and oil approaches 0.

The distance of homogeneous flow, ΔX, is ten main pipe diameters according to international standard 3171. This is a rough estimate and could make the calculations unrepresentative, which was taken into account by making the distance between the recycle- and sampling probe less than ΔX.

Without knowing the exact size of the equipment in the power mix loop, it is difficult to dimension the necessary pipe length. The only limiting factor is space required by the equipment, and it is beneficial to keep the length as short as possible to reduce pressure drop. To ensure that all equipment had enough space, the horizontal pipe length in the power mix loop was set to be six main pipe diameters.

9.2 Recommended Solutions

The mechanically agitated vessel was excluded due to the high power consumption and because it is not an efficient in-line mixing system. An in-line design made with turbine impellers and baffles with two steps will be able to mix the two immiscible liquids. However, the amount of energy required for mixing in a vessel will be too high compared to the other mixing methods.

A fast loop sampling system is recommended because it prevents valuable oil from going to waste, and the samples will be of a higher accuracy. CoJetix sampler provides the lowest uncertainty to the samples, but can only be installed in a power mixer. An intermittent type of sampler is suggested to be used for extraction of the samples, because it has the ability to vary the sampling frequency or grab volume in proportion to the flow rate.

The static- and power mixing systems were suggested to be designed in a vertical pipe for the worst case scenario because it is easier to achieve a good mixture than in a horizontal system. The gravitational force will not affect the separation of the water and oil as much in a vertical pipe as in a horizontal pipe.

When comparing static mixers for the worst case scenario, the structured packing type is recommended even though it has a higher pressure drop than the helical type. When the pipe is vertical, space quickly becomes an issue, and the structured packing type has a shorter mixing length than the helical mixer. If space is no issue, helical mixer might be more suited. These results correlate to other previous studies. [24]

When the Reynolds number reaches values above 2000, the pressure drop created by static mixers becomes significantly larger because the obstructions cause more resistance to the flow. When the main pipe diameter increases, the mixing length increases to an extent that will most likely cause space issues. The limit was set to a pipe diameter of 0.4 m, which correspond to a mixing length of 3 m for the structured packing mixer. A larger pipe diameter is possible if space is no issue.

For the probe and nozzle, the dimensions will change accordingly to the diameter of the main pipe. The pressure drop increases, and thereby the velocity of the re-injection through the nozzle and the total area of the outlets increases with increasing diameter. The design of the nozzle should be evaluated so that any modifications that will provide a more sufficient, or simpler, mixing can be conducted.

The allowed length of probe and nozzle, as mentioned in chapter 7.2.1, will be of a higher value then the main pipe diameter for all variations of parameters. Because of this, it is possible to insert these utilities at the preferred or recommended length into the main pipe diameter.

For the case where the density difference decreases, the orientation of the pipe can be discussed. As the density difference decreases, the force that the gravity exerts on the water decreases, and at some limit the power mixing can be performed in a horizontal pipe without negligible negative effect on the degree of mixing.

When varying the different parameters for the mixing loop it is necessary to make some modifications.

The pump that was recommended for this process was based on the different ranges of the parameters. When the centrifugal pump was the only type of pump that was able to work for all the different criteria it can still be used when varying the different parameters. When varying the parameters that changes the power required to achieve a homogeneous flow, the sizing of the pump needs modifications. When the required energy increases a larger pump is required and vice versa.

The valves for the power mixer was chosen with respect to the pump used for the mixer. One gate valve installed before and one after the pump to provide a tight shut off. Because the pump type can remain the same when varying the parameters the valves does not have to be changed either.

For the power mixer, two 90° flanged long radius elbows were recommended because they caused the least pressure drop for the process. Flanged elbows can handle more pressure compared to the threaded type, therefore the pressure increase in the process should not be a problem. When varying the worst case parameters the elbows will not get affected.

The filter that was recommended for this power mixer will work for the worst case parameters. When the volume flow increases the pressure drop through the filter will increase significantly. Parameters that affect the volume flow are the diameter of the pipe and velocity of the fluid. The pump is designed to handle the pressure drop for this process with a 20 % increase of the velocity. If the velocity escalates with more than 20 % the pump will not be powerful enough to maintain the pressure needed.

When comparing static mixing to power mixing in the worst case scenario, there are two important arguments; pressure drop and costs. Static mixing provides a lower pressure drop as well as lower capital and operation costs, and is therefore the suggested method. When the turbulence in the flow increases, the required energy and thereby the pressure drop in the power mixing loop decreases. Because of this, when the flow is no longer laminar, the pressure drop in the static mixer will be higher than in the power mixing system, and the power mixer is the suggested method.

9.3 Suggestions for Further Work

When the flow reaches a Reynolds number high enough that the mixing will happen naturally has to be determined by simulation. An optimal design of the nozzle and the distance of a homogeneous flow, ΔX, should to be determined this way as well. In order to confirm or disprove the conclusions, simulations for different scenarios should be performed.

For the calculations of required energy, variations in viscosity result in unreliable values. The reason behind this should be studied further.

10 CONCLUSION

The mechanically agitated vessel is not a recommended mixing system for this process due to high power consumption. The power- and static mixers are more suited for mixing in pipelines.

For the sampling system, an intermittent sampler is the recommended method for extraction of samples. It will be installed into a horizontal fast loop with three sampling probes, which will be placed at the top, bottom and one in the cross section of the pipe where the flow is homogeneous.

The suggested static mixer for the worst case scenario parameters is the structured packing type. When the diameter becomes too large, this type of mixing becomes difficult because of a large required mixing length. If the mixing orientation is vertical, a long mixing length could cause space issues. Another problem area is when the flow leaves the laminar region, as this results in a high pressure drop.

When designing the power mixing system, choosing type of utilities is essential. A centrifugal pump is suggested, and it requires two gate valves. A filter has to be installed, and in this case a 40 mesh is recommended. The chosen type elbows for this system is the flanged 90° long radius.

A problem area for the designed power mixing system is when the velocity changes by more than 20%, because the pressure drop caused by the nozzle or filter increases to a value that the pump can’t compensate for.

A static mixer is recommended for Reynolds numbers below 2000 and a main pipe diameter below 0.4 m. The suggested mixing method for a main pipe diameter above 0.4 m and/or Reynolds Numbers above 2000 is a power mixing system. When the Reynolds number reaches a certain point, it is reasonable to assume that the flow is naturally mixed by turbulence, and no further mixing is required. This is illustrated in Figure 10-1.

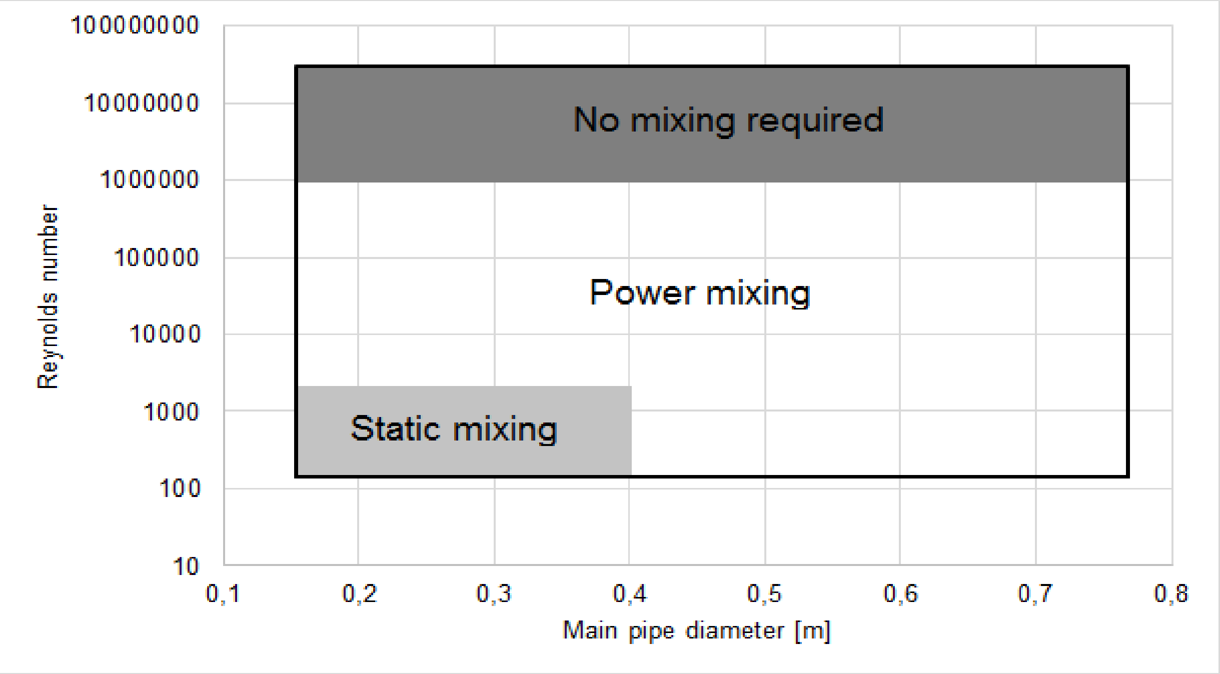


Figure 10-1: Suggested mixing method for the range of diameters and Reynolds number.

REFERANCE

[1] *Petroleum liquids – Automatic pipeline sampling*, ISO 3171, 1988

[2] Wikipedia. (2015). *Petroleum*. Available: 22.03.2015, http://en.wikipedia.org/wiki/Petroleum

[3] Smithsonian. (2010). *Oil and Water Do Mix*. Available: 22.03.2015, http://www.smithsonianmag.com/science-nature/oil-and-water-do-mix-38726068/?no-ist

[4] Wikipedia. (2015). *Mixing (process engineering).* Available: 24.02.2015, http://en.wikipedia.org/wiki/Mixing_(process_engineering)

[5] N. Harnby, et al. *Mixing in the process industries second edition.* London: Butterworth-Heinemann Ltd, 1992.

[6] StaMixCo. *Principle of Operations.* Avaliable 15.05.2015: http://stamixco.com/images/principle-of-operations/schema2.jpg

[7] Journey to Forever. *Still Designs.* Avaliable 15.05.2015: http://journeytoforever.org/biofuel_library/ethanol_motherearth/z/fig7-1.jpg ¨

[8] Jiskoot. (2014). *Jet Mixing*. Available: 22.02.2015, http://www.jiskoot.com/downloads/TS005-0812-3%20JetMixing.pdf

[9] Jiskoot. (2014). *Which Mixer is Best*. Available: 26.02.2015, http://www.jiskoot.com/Teach_Me/Which_mixer_is_best/Which_mixer_is_best.html

[10] Jiskoot. (2014*). Comparison of In-line (with JetMix) and static mixing sampling systems*. Available: 20.05.2015:http://jiskoot.com/files/0000/1111/2222/JetMix%20v%20StaticMix-R1.pdf

[11] Jiskoot. (2014). *Jet Mixing*. Available: 12.05.2015, http://www.jiskoot.com/downloads/TS005-0812-3%20JetMixing.pdf

[12] E. L. Paul, *Handbook of Industrial Mixing*. Hoboken, New Jersey: John Wiley & Sons, Inc., 2004.

[13] J.R. Couper, et al. *Chemical Process Equipment.* U.S.A: Gulf Professional Publishing, 2012.

[14] University of Babylon. (Year of original upload unknown). *Mixing and Agitation of Fluids.* Avaliable: 21.03.2015, http://www.uobabylon.edu.iq/uobColeges/ad_downloads/5_4863_857.pdf

[15] Jiskoot. (2014). *Power point presentation of sampling.* Avaliable: 21.03.2015, http://es.slideshare.net/PaulBagnall/sampling-rev-1-presentation

[16] Steve Watson Gabriel, Meeting with FMC, 12.03.2015

[17] Jiskoot. (2014). *Sampling systems – the options*. Available: 19.05.2015: http://www.jiskoot.com/services/sampling/teach-me/sampling-system

[18] T. Marlin. (2013). *Onstream Analyzers*. Available: 20.04.2015, http://www.pc-education.mcmaster.ca/Instrumentation/analyzer.htm

[19] T. Walters, *Industrial Sampling Systems*, U.S.A: Swagelok Company, 2013

[20] Jiskoot. (2014). *Fast Loop Sampling*. Available: 10.02.2015, http://www.jiskoot.com/Calculation_System_Solutions/Fast_Loop/index.html

[21] Sulzer Ltd. *Multitube Heat Echanger Type SMXL^{TM}*. Available: 13.05.2015, https://www.sulzer.com/en/Products-and-Services/Agitators-Mixers-and-Dispensers/Static-Mixers/Heat-Exchangers-and-Reactors/SMXL-Multitube

[22] Chemineer. *KM Mixers*. Avaliable 15.05.2015: http://www.chemineer.com/products/kenics/km-mixers.html

[23] StaMixCo. *X Grid Static Mixer for Laminar Flow Applications.* Avaliable 15.05.2015: http://stamixco.com/X-Grid-Static-Mixer-laminar-flow-mixing-and-or-dispersion-of-viscous-fluids

[24] D. Rauline et. al., "*A Comparative Assessment of the Performance of the Kenics and SMX Static Mixers*," *Chemical Engineering Research and Design*, vol. 78, p. 389-396, 2000.

[25] Statiflo International Ltd. (2015). *Coefficient of Variation (CoV).* Avaliable 13.05.2015: http://www.statiflo.com/en/about-static-mixing/mixture-quality/145-coefficient-of-variation-cov

[26] Wikipedia. (2015). *Nozzle*. Available: 15.03.2015, http://en.wikipedia.org/wiki/Nozzle

[27] The Engineering Toolbox. (2015). *Minor Loss Coefficients in Pipes and Tubes Components*. Available: 12.03.2015, http://www.engineeringtoolbox.com/minor-loss-coefficients-pipes-d_626.html

[28] E. Ignatowitz. *Prosess-kjemi.* Norge: Gyldendal Norsk Forlag AS, 2002.

[29] Piping Study. (2015). *90° Elbows*. Available: 01.05.2015, http://www.pipingstudy.com/elbow.html

[30] Marine Sight. (2012). *Pipes and Bends – An Essential Guide for Second Engineers: Part 2*. Available: 01.05.2015, http://www.marineinsight.com/marine/marine-news/headline/pipes-and-bends-an-essential-guide-for-second-engineers-part-2/

[31] Pompetravaini. (År). *Operating Manual for Centrifugal Pumps*. Available: 04.05.2015, http://www.travaini.nl/Manual/Centrifugaal/ManualeCentrifughe.pdf

[32] F. Evans. (ÅR). *Rules to Follow to Avoid Pump Problems*. Available: 04.05.2015, http://www.pumps-filters.com/images/Rules_to_Follow_to_Avoid_Pump_Problems,_2-16-00.pdf

[33] The Engineering Toolbox. (2015). *Viscosity Converting Chart*. Available: 05.05.2015, http://www.engineeringtoolbox.com/viscosity-converter-d_413.html

[34] Eaton Corporation. (2013). *Pressure Drop Calculations*.

[35] Norsok Standard. (1994). *Materials Selection*. Available: 07.05.2015, http://www.standard.no/pagefiles/1174/m-dp-001r1.pdf

[36] Ak Steel. (2007). 316/316L Stainless Steel. Available: 07.05.2015, http://www.aksteel.com/pdf/markets_products/stainless/austenitic/316_316l_data_sheet.pdf

APPENDIX

Enclosure A	Task from FMC
Enclosure B	Historical Data from FMC

Enclosure A – Task from FMC

Bachelor Student’s Project – Power Mixing System

Table of Contents

1 INTRODUCTION

Measurement of oil comprises both quantity and quality. Custody transfer (or Fiscal measurement) valuation is based on the "useable" oil so both measures are significant to trade and integrity.

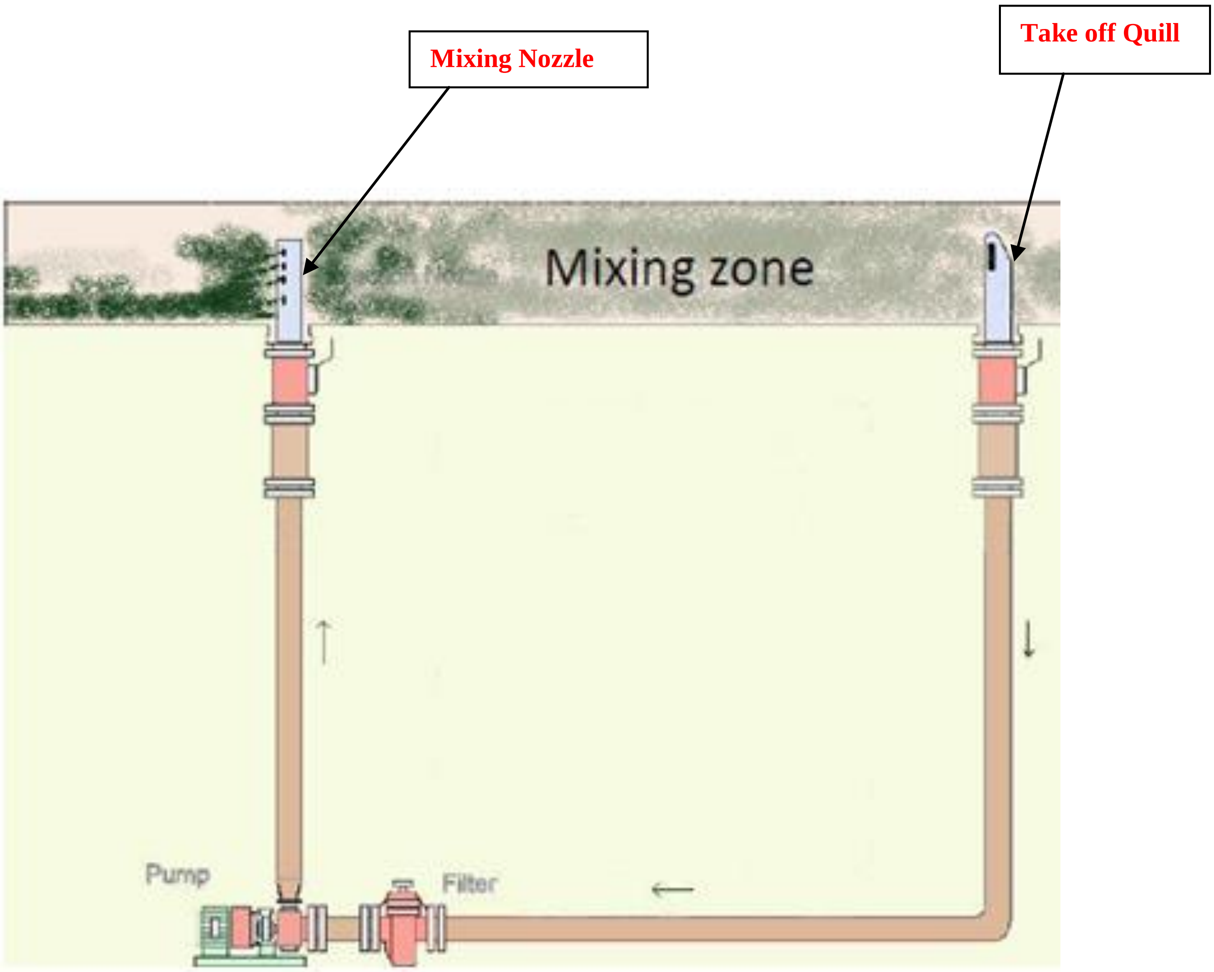
Quality is determined by sampling the oil. The oil is sampled to establish the composition quality, density and water content. To evaluate the water content of crude oil requires that the sample shall be fully representative.

Representativeness is ensured by good mixing of the oil before sampling is done. Mixing is achieved by the natural turbulence in the pipes or by static mixer or power mixer.

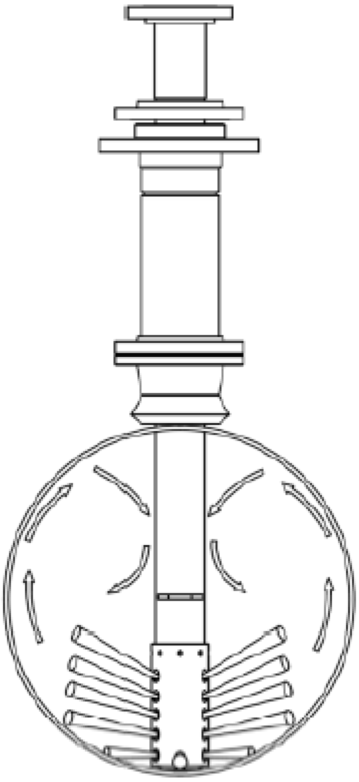
2 CONCEPT

One method of achieving homogeneous flow is called power mixing. Which means mixing is achieved when a portion of the flow is re-introduced into the pipeline via a pump and high-velocity injector.

The power mixer system, designed to ensure that the process fluid in the main line is fully homogeneous and ready for sampling. It consists of a take-off ‘Quill’, used to extract a portion of liquid from the mainline, a pump to provide the mixing energy required and a mixing ‘Nozzle’ assembly.



In operation, a proportion of the process fluid is withdrawn from the main pipeline and pumped to the Nozzle assembly. The Mix Nozzle is precision machined with a series of holes so that the fluid is re-injected back into the main pipeline in the form of high velocity jets.



Nozzle

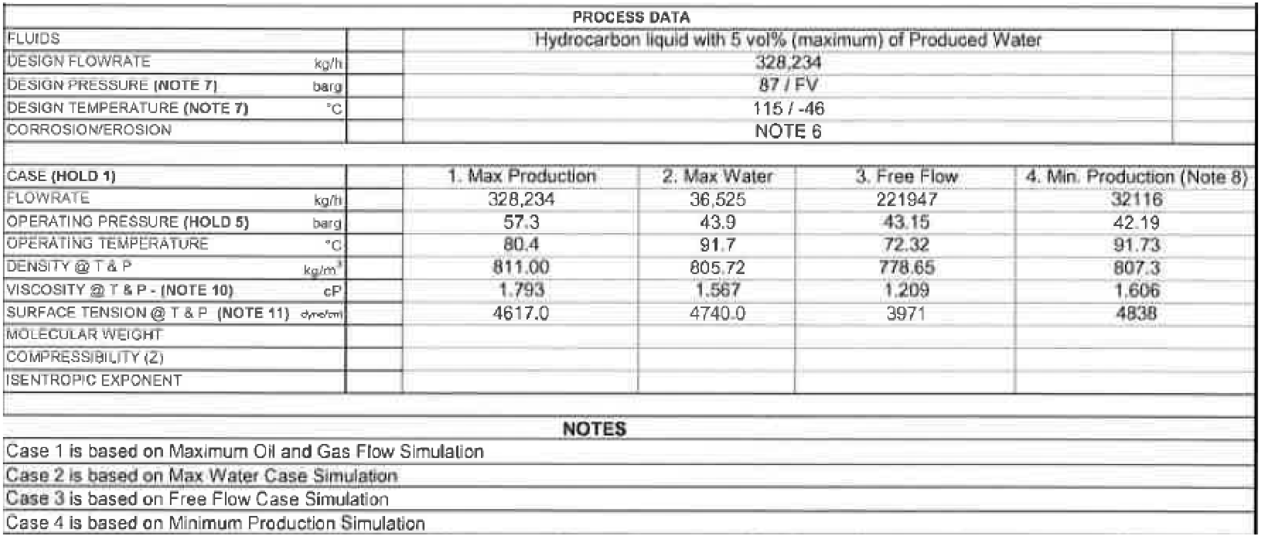
The Nozzle is inserted into the main pipeline so that these are positioned to ensure that the maximum energy addition is directed to where the water concentration is highest. This is especially advantageous for low flow rates where stratification will occur and free water may flow along the bottom of the pipeline.
These jets disperse any transient slugs of water and reduce any large globules of water into small droplets, then distribute these smaller droplets across the pipe cross section.

With the Quill positioned in the homogeneous zone downstream of the Nozzle assembly, some of the liquid injected back into the pipeline will be drawn back into the quill and passed through the system again. This recirculation has an averaging effect on any quality transients, which improves the accuracy of intermittent type samplers. As the main line flow rate drops so the percentage of process fluid re-circulated increases.

Using a constant pump flow rate, the total rate of energy added to the liquid in the pipeline is constant. Thus, as the flow rate in the pipeline decreases so the energy added per unit of the main line flow increases. As a result the power mixing system copes with an almost infinite flow rate turndown. The Nozzle assembly forms only a small obstruction in the pipeline and the pressure drop caused by it, even at high flow rates, is negligible

3 SCOPE OF THE PROJECT

The scope of project is to develop a power mixing system, including the design of mixing nozzle, sizing of pumps and the sample quill which ensures proper mixing of the oil based on the following Process data:



PROCESS DATA						
FLUIDS			Hydrocarbon liquid with 5 vol% (maximum) of Produced Water			
DESIGN FLOWRATE	kg/h		328,234			
DESIGN PRESSURE **(NOTE 7)**	barg		87 / FV			
DESIGN TEMPERATURE **(NOTE 7)**	°C		115 / -46			
CORROSION/EROSION			NOTE 6			
CASE **(HOLD 1)**			1. Max Production	2. Max Water	3. Free Flow	4. Min. Production (Note 8)
FLOWRATE	kg/h		328,234	36,525	221947	32116
OPERATING PRESSURE **(HOLD 5)**	barg		57.3	43.9	43.15	42.19
OPERATING TEMPERATURE	°C		80.4	91.7	72.32	91.73
DENSITY @ T & P	kg/m³		811.00	805.72	778.65	807.3
VISCOSITY @ T & P - **(NOTE 10)**	cP		1.793	1.567	1.209	1.606
SURFACE TENSION @ T & P **(NOTE 11)**	dyne/cm		4617.0	4740.0	3971	4838
MOLECULAR WEIGHT						
COMPRESSIBILITY (Z)						
ISENTROPIC EXPONENT						
NOTES						
Case 1 is based on Maximum Oil and Gas Flow Simulation						
Case 2 is based on Max Water Case Simulation						
Case 3 is based on Free Flow Case Simulation						
Case 4 is based on Minimum Production Simulation						

Parameters which will determines the good mixing can be

1. The flow rate in the pipe line and the flow rate in the sampling branch.
2. The water fraction and the distribution of the water drops in the pipe cross section upstream the mixing nozzle .
3. The pipe diameter, the diameter of the branch pipe and the diameters of the holes in the mixing nozzle.
4. The geometry of the mixing nozzle, number of holes and the directions of the emerging jets.
5. The length of the injector protruding into the pipe line.
6. The length in the pipe line between the mixing nozzle and take off quill.
7. The fluid properties (density, viscosity) for both oil and water.
8. The size of the water drops.
9. The turbulence level in the pipe due to flow and upstream equipment (pumps, valves).

The size of the pipe line where power mixing system will be applied varies from 8” to 32”.

We also welcome any alternative economical solutions which meet mixing requirements.

4 STANDARDS FOR SAMPLING

The following relevant standards are identified:

1. ISO 3171:1988
2. API MPMS Chapter 8.2

Enclosure B – Data from FMC

Screened Range	
	Target Range (Initial Screening)
Header Size Range (in inches)	6 to 30"
Min Velocity in Header (m/s)	0,15
Density (Kg/m3)	600 to 1000
Viscosity (cP)	.4 to 100
Pressure (Bar g)	0 to 100
Temperature (Deg C)	150
Water Cut (%)	.5 to 5
Interfacial tension between HC and Water (typically 25 mN/m)	25

Project	Header Size (in inches	Mixing System Used	Flow rate (m3/h)			Header Velocity (m/s)			Density (Kg/ m3)		
			Min	Nom	Max	Min	Nom	Max	Min	Nom	Max
Valhall (GM-2001)	12	Static Mixer	60		1000				650		850
Gjøa Oil Export(GM-2002)	8	Static Mixer	61,5		615	0,46		4,86	740,18		766,5
Gjøa Vega Oil (GM-2002)	4	Static Mixer			218,6			6,61	742,7		742,7
Aker Smart (GM-2003)	24	No Mixing	770	6000	8000	0,78	4,5	8,1	778		778
Skarv (GM-2004)	30	??	1478,48		7000	0,99		4,69	736		813
Tupi (GM-2010)	4	No Mixing	25		203	0,85		6,89	788.4		788.4
Azedegan (GM-2015)	16	No Mixing	200	2120	2332	0,49	5,17	5,68	904		930
MIS (GM-2017)	10	Static Mixer	75		210	0,46		1,28	840,7		840,7
Papa Tera (GM -2018)	24	No Mixing	200	5500	6000	0,021	5,75	6,08	980		980
Goliat (GM-2020)- Export Oil	30	No Mixing	302	7200	8000	0,2	4,82	5,35	791,6		791,6
Goliat (GM-2020)- Test Sep. Oil	8	No Mixing	16,77		807,4	0,14	2,73	6,38	758.4		792,8
Huntington (GM-2021)	12	No Mixing	250	2000	3400	0,58	4,64	7,88	776,9		776,9
Knarr (GM-20204)	24	Jet Mix	462	4619	5081	0,47	4,68	5,15	780,3		780,3
Edward Grieg (GM-2025)	12	Static Mixer	62,5		861,2	0,24		3,36	826,4	827,6	827,7
Dong Herje (GM-2026)	6	Jet Mix	8,5		242,4	0,14		4	754		757
Hiedrun (GM-2027)	30	Static Mixer	302		8000	0,2		5,21	880,64		10,4
Ivar Aasen (GM-2028)	8	Jet Mix	39,8	285	404,7	0,34	2,45	3,48	778,65	806	811
Nyhamna (GM-2029)	4	No Mixing	14,9		213,7	0,77	15,43	15,43	675,6	689	704,9
Gina Korg (GM-2030) Oil to FSU	8	Static Mixer	5,9	440	484	0,05	3,79	4,16	835,4	835,4	835,4
Gina Korg (GM-2030) Test Seap Oil	6	Static Mixer	11,61	12,7	116,1	0,19	1,73	1,9	763,9	763,9	763,9
Aasta Hansteen (GM-2032)	16	Static Mixer	302		2000	0,68		4,49	790		813

Viscosity (cP)			Pressure (Bar g)			Temperature (Deg C)			Vapour Pressure (Bar)			Water Fraction			
Min	Nom	Max	Min	Nom	Max	Min	Nom	Max	Min	Nom	Max	Min	Nom	Max	Remarks
3,8		5	20		65	30		60	1			0,2699		0,1649	Mole Fraction
0,636		0,862	9,1		9,1	65,3		77,5	0,79			0,5			RVP
0,74		0,74	24,5		24,5	40		100	25						VP=25 bara; TVP=24,47 at 87,8 Deg C
1,36		1,36	11,5		11,5	40		40				0,5			
0,576		2,441	10		10	40		40				0,5			
13		13	5		5	45		45							
21,5		28,8	5,5		5,5	32		32							
5,722		5,722	42		55	60		65							
720,3		720,3	5		5	60		60							
2,535		2,535	12,1		12,1	35		35				3,8			mol%
1,41		2,289	9		9	40		55				19,07		55,13	mol%
2,813		2,813	3,5		5	40		40							
1,789		1,789	14		14	40		40							
1,898	1,904	1,919	9		9	69	70,8	71	0,965						TVP @37,5 Deg C
1		1	8		53	36		49				2,5			% of produced water
10,4		10,4	12		12	50		50							
1,2	1,6	1,79	42,19	43,15	57,3	72,3	80,4	91,73				5			Volume %
0,404	0,49	0,526	24	46,2	46,2	5	5	5							
10,44	10,44	10,44	4,9	13,1	13,1	60	60	60				0,5			
1,36	1,36	1,36	60		60	109,9		109,9				0,0095			Mole Fraction
1,5		2,5	7		7	4		30							