INVESTIGATING THE EFFECT OF SOLID POWDER PARTICLE TYPE ON THE TURBULENT MULTIPHASE FLOW IN PIPELINES

KOR YUE KIM

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Faculty of Chemical & Natural Resources Engineering
Universiti Malaysia Pahang

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ABSTRACT

Drag has long been identified as the main reason for the loss of energy in fluid transmission like pipelines and other similar transportation channels. The main contributor to this drag is the turbulence of the flow as well as friction against the pipe walls, which will results in more pumping power consumption. In this study, metal solid particle (i.e. iron and nickel)'s role as a drag reducing agent was investigated. The experimental procedure was divided into two parts; to study the effect of metal particle addition on the turbulent multiphase flow, where the metal type, concentration and particle size served as testing variables. The other part was to investigate the influence of magnetic field on the turbulent flow behavior in pipelines. A custom-made portable magnetic device was used to apply magnetic force to the flow in the pipe. It was concluded that iron solid particles are better and suitable drag reducing agent compared to nickel particles. The experimental results also showed that the drag reduction is more superior towards smaller particle sizes and higher particle concentration. The presence of turbulence can be reduced under the influence of magnetic field; stronger magnetic field increases the effectiveness of drag reduction. But, the effect of magnetic field decreases as Reynolds Number (Re) increases. The maximum value recorded for nickel is 54% taken at Re = 52155 for concentration 500ppm. While for iron particle of size 45µm, the highest drag reduction value reached 46% and highest value; 38% for size 120µm both at concentration 500ppm.

ABSTRAK

Daya geseren telah lama dikenalpasti sebagai sebab utama bagi kehilangan tenaga dalam sistem penghantaran bendalir di dalam saluran paip dan saluran pengangkutan yang semirip. Penyumbang utama kepada daya ini adalah disebabkan oleh pergolakan dalam aliran bendalir tersebut serta geseran terhadap dinding paip, yang akan menyebabkan lebih penggunaan kuasa mengepam. Dalam kajian ini, peranan zarah pepejal logam (iaitu besi dan nikel) sebagai agen penggurangan geseran telah diselidiki. Prosedur eksperimen telah dibahagi kepada dua bahagian, iaitu yang pertama untuk mengkaji pengaruh penambahan zarah logam terhadap aliran turbulen yang multifasa, di mana jenis, kepekatan dan saiz zarah logam dijadikan pembolehubah. Bahagian kedua adalah untuk menyiasat pengaruh medan magnet terhadap perilaku aliran turbulen dalam paip. Sebuah alat mudah-alih yang dibuat secara khususnya telah digunakan untuk menghasilkan medan magnet untuk diaplikasikan kepada aliran dalam paip. Adalah disimpulkan bahawa zarah pepejal besi merupakan agen penggurangan geseran yang lebih baik dan sesuai dibandingkan dengan zarah nikel. Keputusan kajian juga menunjukkan bahawa pengurangan geseran adalah lebih cenderung kepada saiz zarah yang lebih kecil dan kepekatan yang lebih tinggi. Pergolakan dalam aliran dapat dikurangkan di bawah pengaruh medan magnet; medan magnet yang kuat dapat meningkatkan keberkesanan pengurangan geseran. Namun, kesan medan magnet menurun apabila nombor Reynolds (Re) meningkat. Nilai maksimum tercatat untuk nikel adalah 54% diambil pada Re = 52155 untuk kepekatan 500ppm. Sedangkan untuk zarah besi saiz 45µm, nilai peggurangan geseran tertinggi mencapai 46% dan nilai tertinggi, 38% untuk saiz 120µm, kedua-dua bagi kepekatan 500ppm.

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LIST OF SYMBOLS AND ABBREVIATIONS

DR(%)	-	Percentage of drag reduction
DRA	-	Drag reduction agent
ΔP	-	Pressure drop
ΔP_L	-	Pressure loss
Re	-	Reynolds number
Re_{cr}	-	Critical Reynolds number
ρ	-	Density of fluid
V_{avg}	-	Average flow velocity
V	-	Volumetric flow rate
D	-	Diameter of pipe
μ	-	Absolute viscosity
v	-	Kinematic viscosity
ppm	-	Part per million
f	-	Darcy friction factor
L	-	Length of pipe
CT-DNA	-	Calf-thymus DNA
PDRA	-	Drag reducing polymer
SLES	-	Sodium Lauryl Ether Sulphate
DNS	-	Direct numerical simulation

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Since from the past, drag has been identified as the main reason for the loss of energy in pipelines and other similar transportation channels. The contribution of this drag is due to mainly turbulence of the flow as well as friction against the pipe walls. These energy losses can be identified through pressure drop, which will results in more pumping power consumption.

Toms (1948) first discovered the idea of drag reduction when he studied the effect of polymer added into a turbulent Newtonian fluid. He revealed that the addition of small amount of polymers in turbulent flow can produce a significant result in reducing frictional drag. In present day, drag reduction is served as a typical approach to save pumping power in pipelines or other transportation channels and equipments, particularly those which handle crude oil and refinery products. Pumping power saving corresponds to the reduction of pressure drop in these media. Studies on the drag reduction agent have proven its ability in reducing pressure drop (Li *et al*., 2006; Cho *et al*., 2007; Abdul Bari *et al*., 2008).

Ding and Wen (2005) illustrated that higher concentration of nanoparticle suspension in laminar pipe flows leads to a blunter velocity distribution, advantage to

drag reduction. According to Abdul Bari and Mohd Yunus (2009), who investigated the effect of suspended solid particle addition and effect of Sodium Lauryl Ether Sulphate (SLES) surfactant to the suspension transported, verified that drag reduction will be enhanced with the increase of suspended solid particles concentration and size, as well as the addition of SLES surfactant.

In this current study, the influence of metal solid particle suspension under the action of magnetic fields on the turbulent drag reduction was investigated. Using magnetic fields as a flow improver is believed to be a new attempt as there was no evident experimental-based research on this particular subject matter. The only approach found was a simulation done to model a turbulent flow subjected to magnetic fields. Kenjeres *et al.* (1999) mentioned that a very strong magnetic field can suppress the turbulence and almost laminar profiles can be obtained in the central part of the magnet, regardless of high Reynolds number. There was also a model developed to study the influence of a localized magnetic field to the turbulent flow of a biomagnetic fluid (blood) by Tzirtzilakis *et al.* (2006). They found that the effect of magnetic field significantly reduces in the presence of turbulence.

But, in some other different areas of study, researches have been conducted to study the effect of magnetic fields on the flow characteristics and properties in various fluid transportation channels (Kuzhir *et al*., 2005; Nakaharai *et al.*, 2007). The effect of magnetic field on the flow past a circular cylinder decreases as Reynolds Number (Re) increases. It is also discovered that as the magnetic field is increased, a convection motion in a direction opposite to the flow is produced and results in the increasing of drag coefficient values (Sekhar *et al.*, 2007). Recebli and Kurt (2008) demonstrated that increasing the magnetic field intensity causes the local velocity of a two-phase steady flow along a horizontal glass pipe to decrease. They explained that the magnetic fields affect the flow of the second phase, that is the pure water which has low conductivity and is not magnetizable, via the first phase, that is the micron-sized iron powder which has high conductivity and magnetizable.

1.2 Problem Statement

Cost saving is one of the most essential concerns in any industry. One of the key to the present concern is by cutting down on the power consumption. Fluids transportation in pipelines and other similar transportation channels tends to consume loads of power for the reason that in moving fluid, energy will be dissipated due to mainly frictional drag, as well as turbulence. For the past decades, many researches were conducted to reduce the turbulent drag in pipelines as an answer to power consumption saving and flow improvements. Numerous drag reduction techniques have been studied, comprising the addition of polymers, fibers or surfactants as drag reduction agent, addition of suspended solid particle and usage of riblet-covered surface in turbulent flows.

In the present, polymers are the most commonly used drag reduction agent in the pipeline industry. It was believed that polymers stretched along its axis and this elasticity supply the energy to suppress the turbulence in pipelines. However, a fully prolonged polymer is incapable in retaining its structure because the polymer chains tend to change their properties as they are very poor in resisting mechanical degradation caused by the pumping shear. This will cause the polymers to lose their drag reducing ability permanently. Moreover, at high temperatures the polymers will degrade thermally. Intensive consumption of polymer drag reducer may also cause problem to the environment because they may be toxic or environmental pollutant. In some cases polymers are used at low concentration to avoid toxicity effect. And so, in this current study metal solid particle suspension is studied as drag reduction agent, instead of polymer.

Quite a number of direct numerical simulation (DNS) models have been presented to demonstrate the effect of magnetic fields on the turbulent flow behavior in fluid transportation channels in different areas of study. DNS is a computational fluid simulation used to solve Navier–Stokes equations numerically. But, modeling a turbulent flow ought to take various properties into consideration such as heat and momentum transfer, furthermore turbulent flows are stochastic. Making assumptions is inevitable, for that reason the reliability of the simulation models is significantly reduced. Hence in this study, the influence of metal solid particle suspension under

the action of magnetic fields on the turbulent drag reduction was investigated using an experimental approach.

1.3 Objectives

Serving as a clue to pumping costs reduction and productivity increasement, research was conducted to achieve the following objectives:

1. To study the effect of concentration, size and type of suspended metal solid particle on the turbulent multiphase flow behavior in pipelines.
2. To study the effect of fluid flow rate on the turbulent multiphase flow behavior in pipelines.
3. To study the mechanism controlling the drag reduction in the multiphase flow pipelines.
4. To study the influence of suspended metal solid particle under the action of magnetic field on the turbulent multiphase flow behavior in pipelines.

1.4 Scopes of Study

The following scopes were identified in order to achieve the objectives:

1. Two different types of metal solid powder that are iron and nickel were experimented with significance to their functions in the turbulent drag reduction in pipelines. The metal solid powders tested are micron-size particles (i.e. 45μm and 120μm).
2. Magnetic fields were applied using a custom-made magnet device to study the influence of suspended metal solid particle under the action magnetic field on the turbulent multiphase flow in pipelines.

3. Water was used as the transporting fluid in this study.
4. The pressure readings of the testing section were collected to calculate pressure drops, followed by the percentage of drag reduction.
5. Volumetric flow rate of fluid was used to calculate the velocity and Reynolds Number (Re) of the fluid.

1.5 Benefit and Significance of Study

The significance of this study was to discover a new scheme to reduce the turbulent drag, in which is the clue to the pumping power saving, and ultimately cost saving. It was believed that using magnetic fields as a flow improver was a new attempt as there was no evident experimental-based research on this particular subject matter. This study has ascertained the addition of suspended metal solid particle was indeed a good drag reduction practice. The effect of magnetic field on the drag reduction of the suspended metal solid particles was revealed, it was showed that the presence of turbulence can be reduced under the influence of magnetic field. Stronger magnetic field can results in higher drag reduction performance of the metal particle.

CHAPTER 2

LITERATURE REVIEW

2.1 Fluid flow

Fluid is a substance that existed in liquid or gaseous phase. The difference between a solid and fluid is distinguished based on the substance's ability to resist an applied shear or tangential stress that would change its shape. A solid can resist an applied shear stress and deformed temporarily or permanently depending on the force of the stress; whereas a fluid will continuously deforms under the influence of the stress (Cengel and Cimbala, 2006). The intermolecular cohesive forces exist in the fluid molecules are not strong enough to hold the molecules together, results in continuous fluid flow as long as even a slightest stress is applied (Finnemore and Franzini, 2002).

There are many types of fluid flow classification and following are some general examples.

2.1.1 Viscous versus inviscid regions of flow

A frictional force will develop in-between when two layers move relative to each other and the slower layer will tries to hold back the faster layer. This fluid property is referred as viscosity, which is the measure of internal resistance to flow of a fluid. Viscosity is triggered by the cohesive and collision forces between the molecules in the fluid. Fluid with zero viscosity does not exist. Flows which have high frictional effects are called viscous flows. However, there are regions, typically regions distant from solid surfaces have negligible viscous force compared to inertial and pressure force. This inviscid flow region can be neglected to simply the analysis without much loss in accuracy (Cengel and Cimbala, 2006).

2.1.2 Internal versus external flow

Depending on whether a fluid is flowing through a confined channel or over a surface, fluid flow can be divided into internal or external flow. Internal flow is when the fluid is completely bounded by solid surfaces for example flow in a pipe or duct; whereas external flow is when an unbounded fluid flow over a surface such as a plate, a wire or a pipe. Internal flows are greatly affected by viscosity; however in external flows, the influence of viscosity is minimal and limited to boundary layers near solid surfaces and wake regions downstream of bodies (Cengel and Cimbala, 2006).

2.1.3 Compressible versus incompressible flow

A flow is considered as incompressible if the density remains the same, therefore resulting in constant volume of the fluid over the course of its motion. Liquid flows are incompressible because the densities of liquid are essentially constant. On the other hand, gas flows is approximated as incompressible if the density changes are under about 5 percent, meaning the flow of a gas is not necessarily a compressible flow (Cengel and Cimbala, 2006).

2.1.4 Laminar versus turbulent flow

Laminar flow is the highly ordered fluid motion characterized by smooth layers of fluid; whereas turbulent flow is the highly disordered fluid motion that naturally occurs at high velocities and is characterized by velocity fluctuation. The flows occur in-between laminar and turbulent is called transitional. The key parameter to determine the type of flow in pipes is by using the dimensionless Reynolds number (Re), which was established by Osborn Reynolds in the 1880s through experiments (Cengel and Cimbala, 2006).

2.1.5 Natural (unforced) versus forced flow

Fluid flow is regarded as natural or forced depending on how the fluid is initiated. Forced flow occurs when a fluid is forced to flow over a surface or in a pipe by an external force using equipments such as pumps or fans; while for natural flow, the fluid flow is caused by natural means for example the buoyancy effect (Cengel and Cimbala, 2006).

2.1.6 Steady and unsteady flow

Steady means no change at a point with time and unsteady is the most general term to refer any flows that are not steady. In steady flow, the fluid properties may vary from point to point but at any fixed point it will remain the same. Hence, the volume, mass and total energy of a flow in steady state will remain constant. For unsteady flow, the fluid properties will change with time in a periodic manner (Cengel and Cimbala, 2006).

2.2 Flow in pipes

Flows in a pipe are considered as internal flow because the fluid is completely bounded by solid surfaces, where the flow is driven primarily by pressure difference. There are two types of pipes, which are the circular pipes and noncircular pipes. Circular pipes can withstand large pressure difference without undergoing much deformation; whereas noncircular pipes are usually used in the heating and cooling systems of building, where the pressure difference is relatively low (Cengel and Cimbala, 2006).

2.2.1 Reynolds number (Re)

A British engineer, Osborne Reynolds (1842 – 1912) discovered that the transition from laminar to turbulent flow is manipulated by the ratio of inertial forces to viscous forces of the fluid. This dimensionless ratio is now known as Reynolds number and is used for internal flow in a circular pipe.

$$\mathrm{Re} = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{V_{avg} D}{v} = \frac{\rho V_{avg} D}{\mu}$$

where V_{avg} = average flow velocity (m/s), D = diameter of pipe (m), and $v = \mu/\rho$ = kinematic viscosity of the fluid (m^2/s).

At high Reynolds numbers, the inertial forces, which are proportional to the fluid density and the square of the fluid velocity, are more significant compared to viscous forces, and therefore the viscous forces cannot inhibit the random and rapid fluctuation of the fluid. This condition of flow is known as turbulent flow. Whereas in low or moderate Reynolds number, the viscous forces are significant enough to restrict the fluid fluctuation and keep the fluid under smooth ordered motion; and this is known as laminar flow.

Critical Reynolds number, Re_{cr} is the value where the flow becomes turbulent and this value varies for different geometries and flow conditions. The transition from laminar to turbulent flows is also dependent on other factors; such as pipe surface roughness, surface temperature, vibration and fluctuations in the flow. In most practical conditions, having Reynolds number lower than 2300 is considered as laminar flow, above 4000 is turbulent flow and in-between is transitional (Cengel and Cimbala, 2006).

2.2.2 Laminar and turbulent flow

Laminar and turbulent flow is illustrated in Figure 2.1, where it is shown that in a low velocity, the fluid flows in a streamline, however it would start to fluctuate when the velocity is increased beyond a critical value. In nature, most flows are turbulent, however there are also fluid flows with high viscosity such as oil flows in narrow pipes, which are consider as laminar (Cengel and Cimbala, 2006).

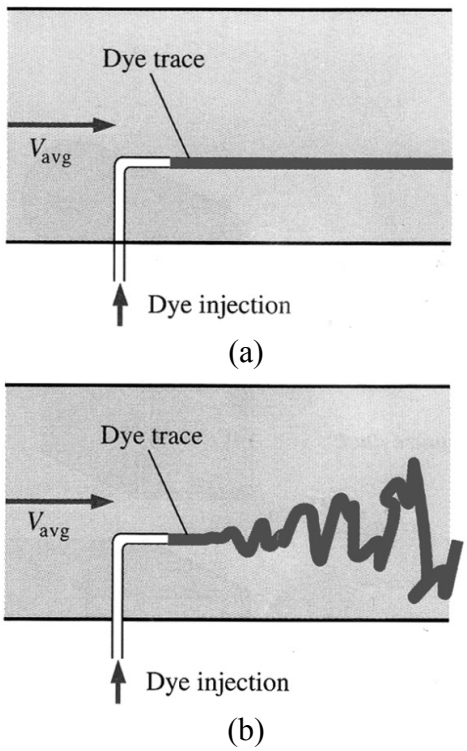

Figure 2.1: The behavior of colored fluid injected into the flow in laminar and turbulent flows in a pipe. (a) Laminar flow, and (b) Turbulent flow

2.2.2.1 Laminar flow in pipes

In a laminar flow, the fluid molecules will flow in an orderly manner along pathlines with constant axial velocity and the velocity profile of the flow will remain the same in the flow direction. The velocity in the direction normal to the flow is zero, because there is no motion in the radial direction. Since the velocity of the flow is constant and the flow is steadily, fully developed, there will be no acceleration in the fluid flow. Momentum and energy are transferred across streamlines by molecular diffusion (Cengel and Cimbala, 2006).

Figure 2.2 shows the velocity profile of both laminar and turbulent flow. A laminar flow has a true parabola velocity profile, slightly pointed at the middle and tangent to the wall of the pipe. The average velocity of a fully developed laminar flow is about one-half of the maximum velocity flow in a pipe. In turbulent flow, the profile is resembles a flattened parabola and the average velocity is about 0.8 times the maximum velocity (Abulencia and Theodore, 2009).

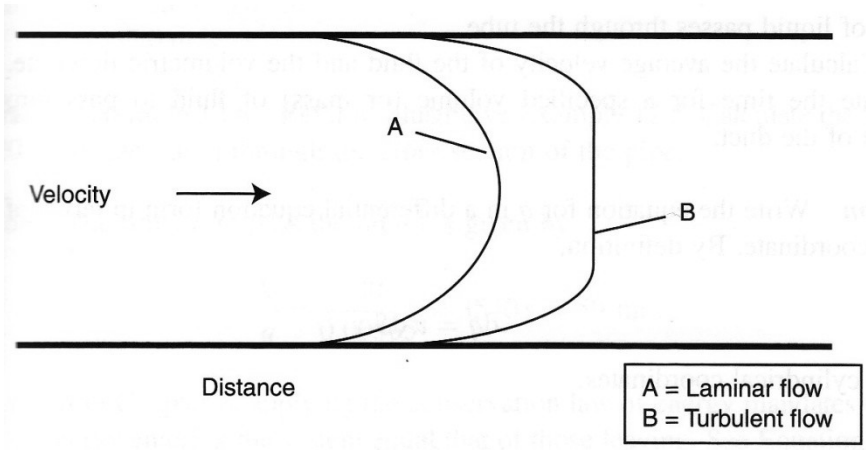

Figure 2.2: Velocity profile of laminar and turbulent flow

2.2.2.2 Turbulent flow in pipes

When a flowing fluid is being obstructed by a bend, valve or even the roughness of the pipe wall, compression would take place. When this happens, local temperature and pressure of the fluid will increase. This will results in a turbulent flow as the momentarily higher pressure of the fluid takes off along the path with least resistance, converting static energy for kinetic energy (Mulley, 2004).

The random and rapid fluctuation in turbulent flows, simply known as eddies increases the momentum and energy transfer between the fluid molecules. The swirling eddies transfer mass, momentum and energy much more rapidly compared to molecular diffusion, resulting in higher friction factor, heat transfer coefficient and mass transfer coefficient (Cengel and Cimbala, 2006). The eddies impinge upon irregularities in a pipe wall or even upon other eddies, becoming self-propagating (Mulley, 2004).

The eddies in turbulent flow can cause fluctuation in parameter values like velocity, temperature and pressure even when the flow is steady. Figure 2.3 shows the fluctuation of the velocity component u with time in a turbulent flow.

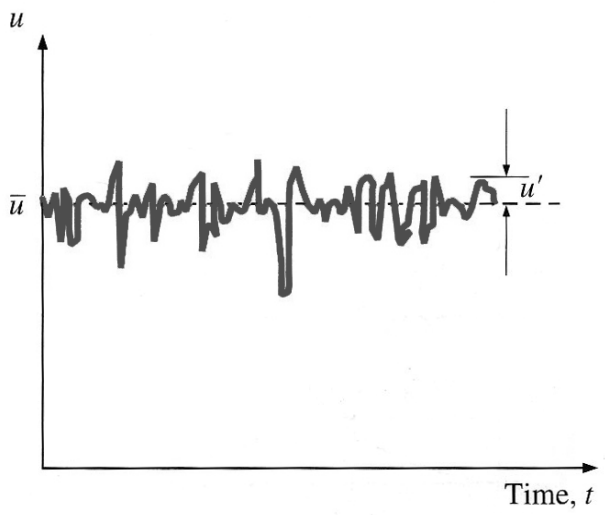

Figure 2.3: Variation of the velocity component u with time at a specified location in turbulent flow.

The random motion of eddies transporting the fluid particles bears a similarity to the random motion of gas molecules, where molecules collide into each other after travelling a certain distance and transfer momentum in the process. Therefore, momentum transfer by eddies in a turbulent flow is similar to the molecular momentum diffusion but in a more rapid manner. Eddy motion is more centered and significant in the core region of a turbulent boundary layer, as it loses its intensity close to the wall and diminished at the wall of the pipe (Cengel and Cimbala, 2006).

2.2.3 Pressure drop and head loss

For long pipes, pressure drops are mainly due to friction (drag) caused by molecules colliding against each other and against the pipe wall (Miesner and Leffler, 2006). In single phase flow, this friction-induced pressure drop is dominated by Reynolds number which is a function of fluid density, fluid viscosity, fluid velocity and pipe size. However, in multiphase flow, the pressure drop is subjected to factors such as density, viscosity, velocity, volume fraction of each phases, and the system pressure and temperature. These properties control the distribution of fluid interfaces, which reflects the mechanism of momentum, heat and mass transfer among the fluids; and thus inducing different pressure drop (Guo *et al*., 2005).

Pressure drop is proportional to the head loss, h_L, which is the additional height that the fluid needs to be pumped in order to overcome the frictional losses in the pipe. These pressure losses are irreversible. If there is no friction in the flow that is an inviscid flow, the pressure drop would be zero.

In most practice, the pressure loss for any fully developed internal flow (laminar or turbulent) can be expressed as:

$$\Delta P_L = f \frac{L}{D} \frac{\rho V_{avg}^2}{2}$$

where $\rho V_{avg}^2/2$ is the dynamic pressure and f is the Darcy friction factor (Cengel and Cimbala, 2006).

The total pressure drop of a system can be considered to consist the sum of the following pressure drops:

- To accelerate the fluid to maintain the velocity
- To overcome the pipe wall friction on the fluid
- To regenerate the momentum lost, and
- To support the fluid in vertical pipes (Abulencia and Theodore, 2009).

There are also minor losses due to local disturbances in the flow such as changes in cross section, elbows, valves and fittings. These minor losses are insignificant when dealing with very long pipes or channel, because they are relatively small compared to the major losses caused by pipe (wall) friction. However, in very short pipes or channel, changing in direction or magnitude will cause the average velocity of turbulent flow to alter; resulting in large eddies that would eventually cause significant energy losses (Finnemore and Franzini, 2002).

2.3 Drag reduction

Drag reduction offers the possibility to decrease pressure drop in a pipe, as an approach to lower the power requirement (Chhabra and Richardson, 2008). Drag reduction is only applicable in turbulent flow and is enhanced with decreasing viscosity and pipe diameter, together with increasing Reynolds number (Vancko, 1997).

Drag reduction can be identified as the increase of the pumpability of a fluid when a small amount of foreign substances, such as high molecular weight polymers is added into the flow. It is recognized through the reduction of pressure drop over some length of pipe when the polymers fused together with the flow. There are factors that affect the degree of drag reduction achievable in a flow, that are

solubility of the polymer in the continuous phase, effectiveness in dispersing the polymer, molecular weight of the polymer and concentration of the polymer (Nelson, 2003).

2.3.1 Drag reduction agent (DRA)

Drag reduction agent (DRA) has been wide used in existing systems for its benefit in increasing production (without mechanical modification), reduction of operating costs such as pumping power, reduction of pipe pressure while maintaining productivity, and boosting refinery handling (Vancko, 1997).

For the past decades, numerous drag reduction techniques have been studied as a typical approach to save pumping power in pipelines or other transportation channels. For example, the addition of polymers, fibers or surfactants as drag reduction agent, the addition of suspended solid particle and the usage of riblet-covered surface in turbulent flows.

2.3.1.1 Polymer as drag reduction agent

Ever since Toms (1948) first discovered the idea of drag reduction (DR) when he studied the effect of polymer added into a turbulent Newtonian fluid, it was used as a core for researchers to further discover and develop effective drag reduction agents (DRA). Nelson (2003) mentioned that a polymer is considered as a good DRA depending on its dispersion in the fluid, to whether the drag reducing polymer will lead to an optimal dissolution in the flow. Therefore, ensuring the right injection technology is used is important so as to ascertain an optimal dissolution of