# CHAPTER II
# LITERATURE REVIEW

## 2.1 Drilling Concept

### 2.1.1 Principles of Drilling

The operation of drilling a well into a potential reservoir is the only way to prove that there is hydrocarbon. The main component of drilling rig is shown in Figure 2.1 (Archer and Wall, 1986). This rig can be float for offshore drilling or may be permanently set up on onshore. The drill hole is built using drill bits and make it more strength by casing. Drill bits are lubricated during the drilling operation with fluid known as drilling mud. This fluid contains special component provided by engineers balances the pressure with the formation pressure to avoid well collapse and fluid influx (Gucuyener and Turkish Petroleum Company, 2003).

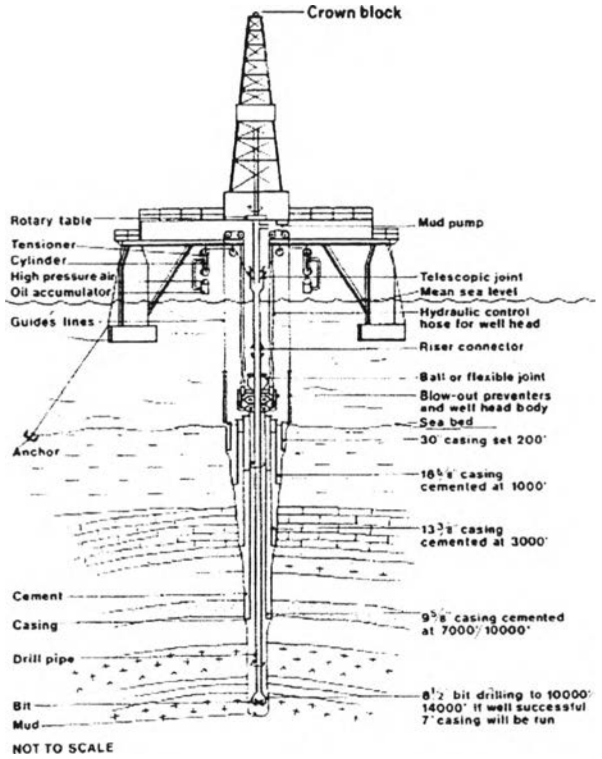

**Figure 2.1** Main component of a well drilling operation (Archer and Wall, 1986).

### 2.1.2 Directional Drilling

Directional drilling is a drilling operation to target zone with an inclination above five degrees. This technique can approach the reservoir under unstable environment whereas the vertical drilling cannot achieve the target. There are three parameters that can define directional drilling which are build rate, hold & drop inclination, and kick of point (Garden and Grace, 2007). A simple build/hold/drop well trajectory is known as 'S' shape as shown in Figure 2.2. The kick of point is the beginning of build section which designs the curvature by buildup rate until it ends at end of build section. The tangent section maintains the angle and direction constantly until the next target is reached. The drop section is designed by dropping inclination rate (Halliburton, 1997).

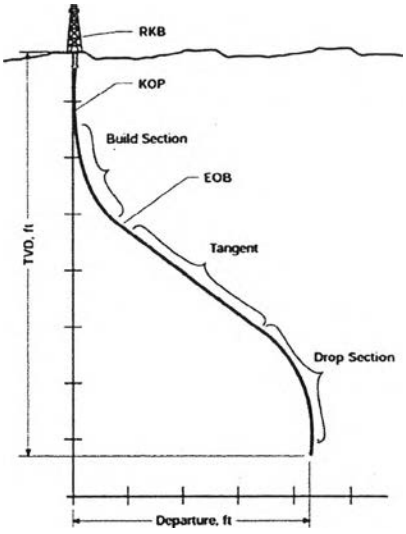

**Figure 2.2** Well profile terminology (Halliburton, 1997).

## 2.2 Geomechanics

### 2.2.1 Pore Pressure

Pore pressure is the pressure of fluid which is in pore space of rock or reservoir. Typically, pore pressure is simply equal to the weight of overlying fluid. This pressure is often referred to hydrostatic pressure which is exerted by the column of fluid from the formation's depth to the sea level. In subsurface which is high compacted sediment in sand layer, the pore fluid cannot escape from these porous and it will lead to high formation pressure.

### 2.2.2 Fracture Pressure

Fracture pressure is the pressure that the rock formation can be cracked, and the fluid lost circulation. This pressure usually express as a gradient with the ratio of pressure per depth. The higher depth formation has the higher fracture gradient because of high compacted rock formation.

The pressure while drilling are always concerned both pore pressure and the fracture pressure in the drilling pressure window. To drill effectively, the pressure in wellbore should stay in the safe zone, lower than fracture pressure and higher than pore pressure as shown in Figure 2.3 (Tercan, 2010). The overburden is the highest mud weight to avoid lost circulation, and the collapse is the lowest mud weight to avoid fluid influx.

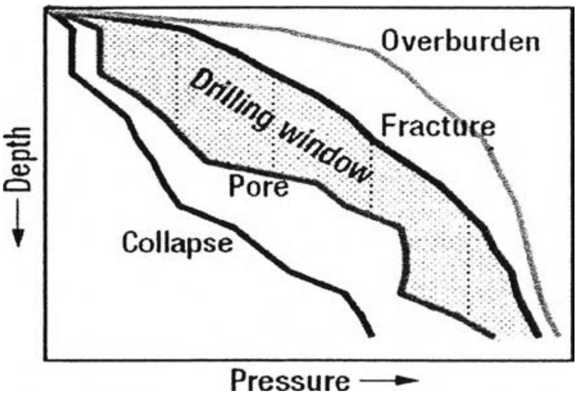

**Figure 2.3** Example of pressure window *(Tercan, 2010)*.

## 2.3 Drilling Fluid

### 2.3.1 Drilling Fluid Functions

Drilling fluid, also referred to a mud, plays an important function in the drilling operation. Fluid can control the pressure that exist in wellbore providing hydrostatic pressure to prevent formation fluid from entering into the wellbore, and also other functions for example lubricating the drill string, keeping the drill bit cool and clean, carrying the cutting to the surface, suspending the cutting while drilling is paused, also stabilizing the well.

### 2.3.2 Drilling Fluid Categories

Drilling mud consists of four basic parts: (1) base fluids – water, oil, synthetic material, or varying combinations – which classify as the mud; (2) active solids – to control viscosity of fluid, often bentonite clays; (3) inert solids – to control density of fluid, such as barite; and (4) other additives – to control the chemical, physical, and biological properties of the mud, such as polymers, starches, and various other chemicals. Mud is also classified into three general categories: water-based mud (WBM), oil-base mud (OBM), and synthetic-based mud (SBM). WBM is made with fresh water and is used for most types of drilling. It consists of dissolved salt, additives, polymer, clay, and weight material such as barite (Kaiser, 2009). OBM is composed of oil as the continuous phase and water as the dispersed phase. The oil base can be diesel, kerosene, fuel oil, selected crude oil or mineral oil. SBM is a mud where the base fluid is a synthetic oil which are olefins and paraffins.

## 2.4 Drilling Method

Typically, drilling operations are mostly dependence on pressure profile in the subsurface. Based on pressure while drilling, there are two types of drilling. The worldwide drilling condition is conventional drilling or the other names is conventional over balanced drilling (OBD) which wellbore is drilled with the fluid pressure higher than the formation pressure. Another type is underbalanced drilling (UBD) which the wellbore is drilled with fluid pressure less than the formation pressure.

### 2.4.1 Conventional Drilling Condition

Conventional drilling is the general term used to describe the typical onshore and offshore drilling operation involve in various equipment, procedures and personnel. In the drilling operation, well is drilled with the balancing fluid pressure and the formation pressure by a circulation system. The conventional drilling is normally known as overbalanced drilling which the fluid pressure is higher than the formation pressure. This causes the fluid lose into the formation and the formation is damaged due to the hydrostatic pressure and dynamic pressure. This technique allows the occurrence of fluid loss, so there is no influx of fluid into wellbore. The circulation system is controlled in the open system. On surface wellhead, there is blow out preventer (BOP) to control the fluid blow out, hence in the open system BOP always opens to atmosphere.

The conventional drilling is supposed to maintain over the pressure which can cause the drilling fluid loss and the formation is easily damaged due to fracturing. The strong effect of over pressure forces the drilling fluid passing through the formation porous media which will create the filter cake on wellbore wall, it will reduce the rate of penetration, and also cause pipe stuck. There are also other advantages and disadvantages of conventional drilling as following (Nauduri, 2009).

- Advantages
    - The wells are comparatively inexpensive.
    - The equipment and drilling crew are generally available.
    - The well design and planning operations are uncomplicated.
    - The regulatory permitting issues are less strict.

- Disadvantages
    - Drilling crew might run into a drilling problem that could result in loss of time and money.
    - In very rare case lack of advanced equipment and drilling experts might cause blowouts, health, safety and environment (HSE) issue.

### 2.4.2 Underbalanced Drilling Condition (UBD)

Underbalanced drilling (UBD) technology is increasingly used worldwide as an alternative technology to the conventional drilling. This technology maintains pressure during drilling operation less than the formation pressure to reduce the formation damage while the conventional drilling damage the formation by fracturing. Fluid formation are also allowed invading into wellbore, and are controlled in close system at the surface. In UBD operation BOP is closed to control fluid, but BOP is opened to the atmosphere in conventional drilling due to no fluid influx as shown in Figure 2.4.

#### *2.4.2.1 Underbalanced Drilling Fluid*

Drilling fluid in UBD condition might be different from the conventional drilling because the wellbore pressure is slightly less than the formation pressure. UBD usually involves in two phase flow to adjust the fluid density. The generally used method is to inject gas while injecting drilling mud to decrease the fluid density as shown in Figure 2.5. These gases can be air, nitrogen, natural gas, carbon dioxide, or inert gas which are non-condensable gas, and are entrained in liquid to lower fluid density to the point where the UBD is obtained (Zhu *et al.*, 1995).

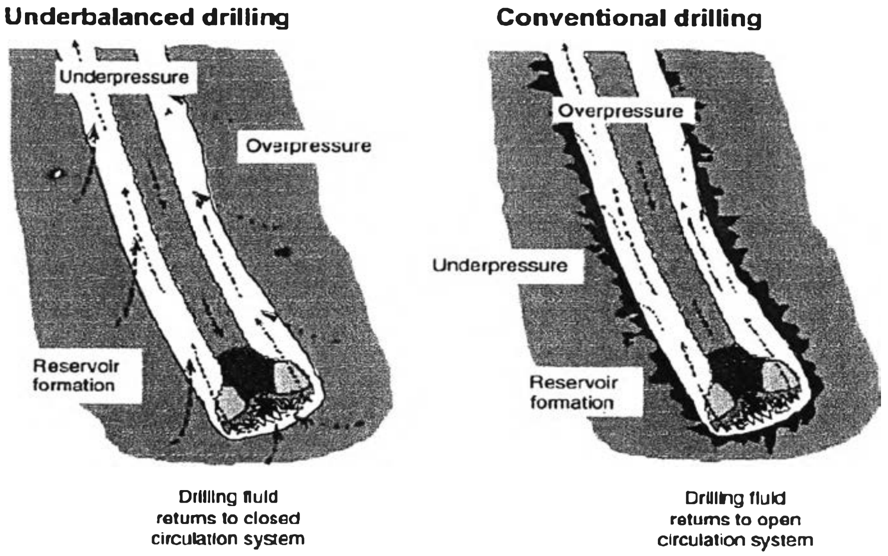

**Figure 2.4** Open vs. closed circulation systems (Lake, 2006).

#### *2.4.2.2 Advantages and Disadvantages*

The main advantage of using UBD is to reduce formation damage due to formation being sensitive. There are additional advantages for UBD by increasing rate of penetration (ROP), reduce lost circulation and different sticking. The different sticking is worldwide drilling problem because of time and money it takes to correct the problem. In conventional drilling, the filter cake will be created inside wellbore wall which can cause the low rate of tripping in/out of pipe, and require some fluid loss. The nature of UBD will not create filter cake on wall that is greatly reducing possibility of sticking and also reducing nonproductive time (NPT). Furthermore, the UBD offers several advantages over conventional drilling as following (Bennion, 1999, Lake, 2006)

- improve bit performance
- elimination of differentially pressure stuck
- low mud cost
- reduce lost circulation risk
- reduce environmental impact

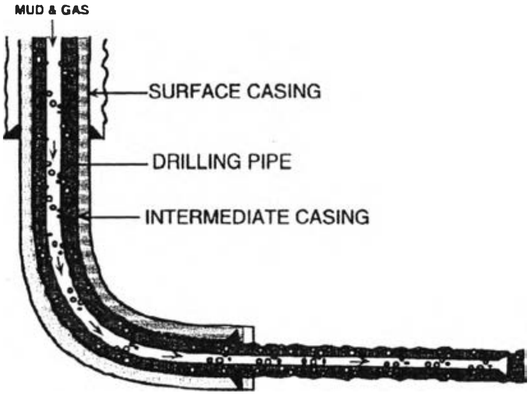

**Figure 2.5** Two phase injection method for underbalanced drilling (Zhu *et al.*, 1995).

## 2.5 Downhole Pressure

During the drilling at reservoir condition, the pressure while drilling at the bottom of hole is concerned in the drilling window. This pressure is known as downhole pressure or bottomhole pressure (BHP) to balance the wellbore pressure with the formation pressure. Fluid is injected inside drillstring, then moves passing through drill bit and flows back up to surface through annular gap between wellbore and drill string or casing as shown in Figure 2.6. The hydrostatic pressure exerted by column of fluid and annular pressure loss due to fluid circulating generates donwhole pressure. To keep well stability, downhole pressure should be maintained in the pressure window. If downhole pressure is too low, well may collapse and fluid influx into well. In contrast, if it is too high, the formation is fractured and fluid circulation is lost. Hence it is necessary to control the pressure balance by avoid an instable well condition.

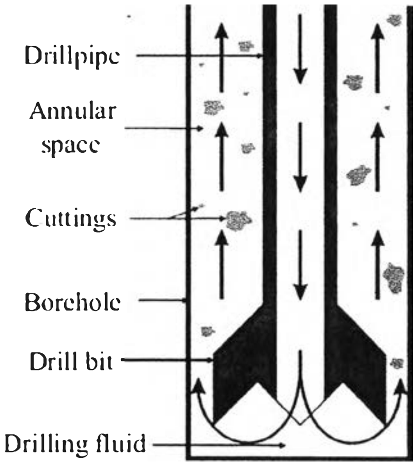

**Figure 2.6** Illustration of drilling fluid circulation in the wellbore (Oliveira et al., 2013).

### 2.5.1 Hydrostatic Pressure

To determine the downhole pressure, it is the sum of hydrostatic pressure, annulus pressure loss and surface pressure if it exists. The hydrostatic pressure is occurred by the column of fluid overlying above and depends on the density of drilling fluid and vertical depth by an equation following (2.1).

Hydrostatic pressure = density x gravity constant x vertical depth (2.1)

### 2.5.2 Annulus Pressure

Fluid flows through the drill string until it reaches the bottom of well, then it flows back through the space between the drill string and inside the borehole wall. While the fluid is flowing up to the surface, there is a pressure drop in this annular section which is called annulus pressure drop due to the moving fluid. The present of annulus pressure gives an ability to circulate the fluid. The circulation is conduct to ensure that there is no accumulation of excess drilling cuttings in wellbore.

The downhole pressure calculation can be written as expressed in equation (2.2) (Samuel, 2010). Figure 2.7 shows both hydrostatic pressure as blue line and dynamic pressure as red line. An increase in annular pressure comes from the dynamic of fluid that moves through the annulus section to the surface which imply that it will equal the energy consumption in pump system to move the fluid along the whole wellbore.

$$\text{BHP} = \text{hydrostatic pressure} + \text{surface pressure} + \text{annulus pressure loss} \qquad (2.2)$$

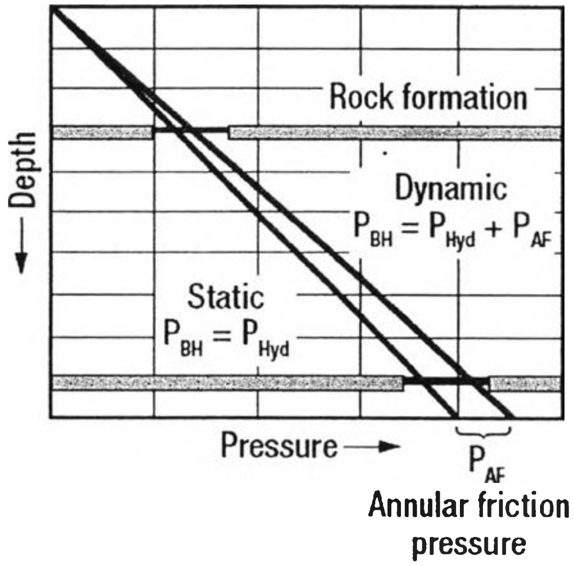

**Figure 2.7** Static (blue line) and dynamic (red line) pressure profile *(Tercan, 2010)*.

### 2.5.3 Equivalent Circulating Density (ECD)

The physical properties that relate to balance the pressure is mud density. Without any flow in well, this density is called static density which came only from the hydrostatic pressure. ECD differs from static density in the way that if there is fluid flowing to the drill string and flow back through annulus space to the surface, this ECD is an effective density. Hence, ECD is the effective mud density which derive from the sum of hydrostatic pressure and pressure lose in annular.

The ECD can be calculated from the equation (2.3) which need to know the pressure drop in annulus (Samuel, 2010) where pressure is in psi, vertical depth is in feet and density is in pounds per gallon(US). The pressure drop in annulus will be explained in the section of fluid flow model. Thus, ECD always plays the significant role in drilling functions to control the well stability, and has to maintain the pressure in pipe.

$$\text{ECD} = \frac{annulus\ pressure\ loss}{0.052\ x\ depth} + static\ density \tag{2.3}$$

## 2.6 Fluid Flow Model

### 2.6.1 Fluid Rheology

Typically, fluid rheology are normally classified into two types, Newtonian fluid and non-Newtonian fluid depend on the relationship between shear stress and shear rate. The linear relationship is called Newtonian fluid and nonlinear relationship is called non-Newtonian fluid. Baker Hughes Company (INTEQ, 1995) proclaims that mostly in drilling operation, drilling fluid that common use is non-Newtonian fluid. Flow behaviors can be described by three common models: Bingham plastic model, power law model and yield power law model as shown in Figure 2.8. Most drilling fluids do not confirm exactly to any of these models, but drilling fluid behavior can be determined with sufficient accuracy to one of these models. Flow models are visualized by consistency curves, which are plot between shear stress and shear rate (Lake, 2006).

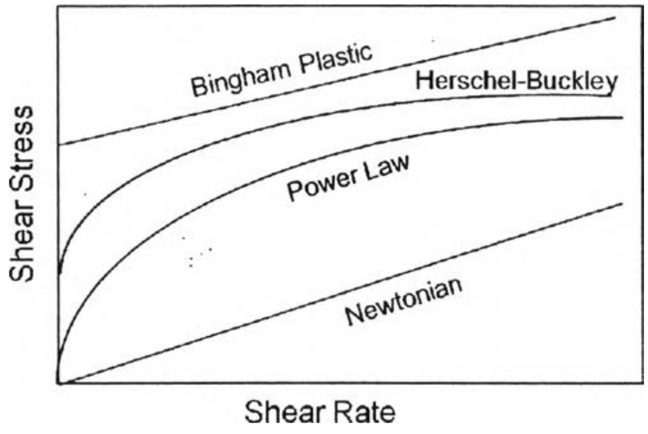

**Figure 2.8** Rheology of Fluid.

Shear stress is the force per unit area and expressed in term of shear rate as shown in equation (2.4) for Newtonian fluid,

$$\tau = \mu\gamma \tag{2.4}$$

where $\gamma$ is velocity gradient. The viscosity is the resistance offered by a fluid to deformation when the shear stress is subjected.

### *2.6.1.1 Bingham Model*

A Bingham plastic model is widely used in drilling industry because it requires two practical parameters to determine. The relationship between shear stress and shear rate is linear as expressed in equation (2.5),

$$\tau = \tau_y + \mu\gamma \tag{2.5}$$

where $\tau_y$ is yield point (YP) which is the threshold stress to start mud drilling fluid flow. YP must be high enough to carry cuttings up to surface, but not so large as to create excessive pump pressure. Plastic viscosity (PV) or $\mu$ in equation (2.5) indicates Bingham fluid viscosity.

#### *2.6.1.2 Power Law Model*

Power law model is also described by two practical parameters, and also widely used in industry. The viscosity of this fluid increases as shear rate decreases. The power law fluid can be described mathematically as following equation (2.6)

$$\tau = K\gamma^{n} \qquad (2.6)$$

where K is consistency index, and n is fluid behavior index. Thus the apparent viscosity of power law ($\mu_a$) is expressed in equation (2.7),

$$\mu_a = K\gamma^{n-1} \qquad (2.6)$$

#### *2.6.1.3 Yield Power Law Model*

It is also known as Herschel-Bulkley fluids, which require a finite shear stress, $\tau_y$, below which the fluids will not flow. Above this finite shear stress, referred to as yield point, the shear rate is related to the shear stress through a power-law type relationship. The shear stress can be written as

$$\tau = \tau_y + K\gamma^{m} \qquad (2.7)$$

where $\tau_y$ is called yield point, K is consistency index, and m is exponent, referred to as power law index.

### 2.6.2 Mathematical Pressure Loss Model

Many researches have studied the annular pressure loss model and proposed many experiments to investigate the fluid flow behavior inside annular space, since it is important in downhole pressure calculation.

Subramanian and Azar (2000) investigaged the friction pressure drop for five different non-Newtonian drilling fluids in pipe and annular flow. They found that predicting the pressure loss in larminar, polymer mud is agreed with Bingham model in pipe flow and yield power law and power law in annular. Bentonite and MMH mud are agreed with yield power law and power law in both pipe and annular flow. Glycol mud is agree with yield power law in both pipe and annular flow. Petro-free Vegetable oil mud are not agreed with any models due to its sensitivity with temperature. Predicting pressure loss in turbulent, polymer mud, glycol and Petro free vegetable oil mud are more agree with the yield power law in smooth pipe and annular that is rough pipe. Bentonite and MMH mud are agreed with the yield power law in a rough pipe and annular.

Pereira *et al.* (2007) investigated the prediction of drilling velocity and pressure profile using computational fluid dynamic (CFD) techniques and compared the simulated results with experimental data. The laminar flow of non-Newtonian was considered in two tubes in concentric and eccentric arrangement of horizontal sections. They observed that the flow rate was the operational variable with the highest impact on pressure drop. The effect of pipe geometry and rotation also had been investigated and observed that both geometry and rotation effects impact on the pressure losses and velocity profile in horizontal system.

Sorgun and Ozbayoglu (2010) predicted the frictional pressure loss in horizontal drilling section for the non-Newtonian fluid using the CFD numerical method. Their simulation was performed in both horizontal concentric and eccentric using the power law fluid in both laminar and turbulent flow model to compare with an experimental data. Their results show that CFD model simulation is capable of estimating annular frictional pressure drop with an error for less than 10% which are very good agreement with an experiment data.

Qi *et al.* (2013) proposed the general method to calculate annular laminar pressure drop of drilling fluids using non-Newtonian fluid for both traditional drilling fluid model such as Bingham, power law and Casson and some practical models such as three parameter model (Herschel-Buckley, Robertson-Stiff, Sisko models etc.) and four parameter model. The general calculation algorithm which considered the annular flow section as two thin rings flow were compared with the traditional calculation algorithm which use an annular uniform laminar flow equation. This general method can achieve the pressure drop from equation that relate the flow rate and shear rate. The result showed that this proposed method can accurately predict the annular pressure drop and can be used with any rheological models no matter flow rate is high or low. They also suggests that the accurate result usually came from the rheological model that has good agreement with actual drilling fluid.

Oliveira *et al.* (2013) investigated annular pressure loss model using the governing equation or mass and momentum balance equation to describe single phase fluid dynamic behavior, and can also predict downhole pressure by following equations (2.8) and (2.9).

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial v}{\partial z} + v \frac{\partial \rho}{\partial z} = 0 \tag{2.8}$$

$$\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial z} = -\frac{\partial p}{\partial z} - \frac{4}{d_h} \tau_w + \rho g \tag{2.9}$$

Where v is the average velocity across the geometry cross-section, $\rho$ is the fluid density, p is the pressure, g is the gravity acceleration, $\tau_w$ is the average value of the shear stress on the pipe or annular space wall, $d_h$ is the hydraulic diameter of the drill pipe (d) or annular space ($d_2$-$d_1$), t is the time and z is the axial coordinate. The value of shear stress is function of frictional factor and velocity, so its value depends on the fluid behaviors: Bingham, power law and yield power law, and fluid flow patterns: laminar and turbulent regime. These mechanistic models require analytical method or numerical method to solve complex differential equations.

Ofei *et al.* (2014) studied the method to predict annular pressure losses and cuttings concentration in horizontal well using computational fluid dynamic (CFD). This study employs inhomogeneous model to simulate a two phase solid-liquid flow in horizontal well with difference eccentric geometry in horizontal section and also determine the cuttings concentration. The two different fluid model were considered in turbulent flow, first one was water considered as Newtonian fluid and another one was drilling mud considered as non-Newtonian fluid with power law model. The results from numerical method were compared with the experimental results, and they observed that using both water and drilling mud as carrier fluid are confirmed with the validity of the CFD model. In addition, they also found that the rotation of drill pipe effects the pressure losses and cuttings concentration.

Several estimating annular pressure loss models have been studied in both mechanistic and empirical model. A widely used pressure loss model in the drilling engineering for practical purposes is narrow slot equation for pipe flow. To transform annular flow to pipe flow, the effective diameter which replaces the diameter in term of the friction factor has been developed. Anifowoshe and Osisanya (2012) found that the definition of hydraulic diameter ($D_e$) as expressed in equation (2.10) is the best estimation of pressure loss for power law fluid. Hence frictional pressure loss inside an annulus using slot equation is defined as equation (2.11).

$$D_e = D_o - D_i \tag{2.10}$$

$$\frac{dP}{dz} = \frac{f_f \rho v_a^2}{25.81(D_o - D_i)} \tag{2.11}$$

Where $D_o$ and $D_i$ are wellbore diameter or casing diameter and drillpipe diameter respectively, $\rho$ is static density, $v_a$ is average annular velocity and $f_f$ is friction factor.

A friction factor significantly depends on fluid flow state either in laminar regimes or turbulent regimes so flow state should be determined. The flow in annulus is either laminar flow or turbulent flow depending on the parameters such as flow rate, density, and diameter ratio. A friction factor in laminar regime can be describe in equation (2.12), and for turbulent regime in equation (2.13). However, a common friction factor for power law fluid in turbulent regime, Blasius formula, is also proposed as equation (2.14)

For laminar regime, $$\mathbf{f_f = \frac{16}{N_{Re}}} \tag{2.12}$$

For turbulent regime, $$\mathbf{f_f = \frac{4}{n^{0.75}} \log\left(N_{Re} f_f^{\,1-\frac{1}{n}}\right) - \frac{0.395}{n^{1.2}}} \tag{2.13}$$

$$\mathbf{f_f = \frac{0.0791}{N_{Re}^{\,0.25}}} \tag{2.14}$$

where $N_{Re}$ is Reynolds number and n is fluid behavior index. Although predictive pipe flow model is proposed, it only considers fluid flow without any other effects. By the way, there are many effects that influence on pressure loss calculation such as drillpipe rotation and pipe eccentricity.

### 2.6.3 Drillpipe Rotation Effect

In drilling operation, the drillstring and bit are rotated at different speed to penetrate the formation while circulating drilling fluid. The rotation of drillstring significantly influence the downhole pressure. As presented by Skalle (2013), pipe rotation in laminar flow leads to an additional shear velocity component. When rotating the drillpipe, it will give an increase in total shear stress with a decrease of viscosity, leading to a reduction of axial pressure drop. Typically, a laminar flow with Newtonian fluid did not agree with the described effect because the viscosity of Newtonian fluid is independence in shear rate. For most drilling operations, an increasing pressure drop will be experienced when pipe is rotating. An increase of pressure drop described by Marken *et al.* (1992) that the centripetal forces was created by pipe rotation throw away the fluid close to the pipe, leaving the void. This void will be filled with the rest of fluid in annulus, and Taylor vortices were created as shown in Figure 2.9. This would have the same effect of turbulent mixing.

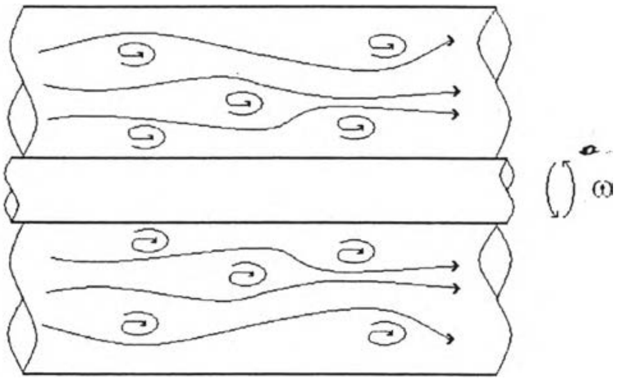

**Figure 2.9** Formation of Taylor vortices when pipe is rotated resulting in turbulent-like mixing (Skjold, 2012).

Although a study of flow behavior when pipe is rotating is still complex especially in drilling operation, there are several literatures proposed empirical correlations and mechanistic models.

Johanson *et al.* (2003) proposed the model for calculating pressure loss in pipe and annulus in both laminar and turbulent regime. They also developed the equation for considering pipe rotation effect and compared with the experimental data with different fluid. The results showed that the effect of pipe rotation on pressure loss depends on the rheology of drilling fluid. The non-Newtonian fluid is mostly related to the effect of pipe rotation which increasing in rotation speed and it will increase pressure loss.

Hemphill *et al.* (2007) gathered the field data of pressure drop and equivalent circulating density (ECD) while pipe rotating from various locations. They observed that the pressure drop and ECD increase when an increasing in rotation speed. Then, the general equation for increased pressure loss with rotation in term of diameter ratio and rotation speed (rpm) was developed by using several finger prints of field measurement (Hemphill *et al.*, 2008) which is expressed as

$$\Delta P_{\mathrm{rotate}} = -1.0792\left(\frac{D_i}{D_o}\right) + 17.982\left(\frac{D_i}{D_o}\right)^2 (0.00001 \times L \times N) \qquad (2.15)$$

where L is length section and N is rotation speed.

Ahmed and Miska (2008) and Ahmed *et al.* (2010) proposed pressure loss ratio (PLR) to predict frictional annular pressure loss with pipe rotation effect in laminar flow which analyzed from the published field measurement. This pressure loss ratio which is the ratio of pressure while pipe rotation at that speed and pressure loss with no pipe rotation as expressed in equations (2.16) and (2.17).The developed pressure loss model was good agreement when drill in vertical well, but it was acceptable for deviated well because flow in vertical well is less complicated than in deviated well. In addition, some actual drilling conditions such as tool joint, cutting present, and rate of penetration were not considered in development of pressure loss ratio due to the complexity.

$$\mathrm{PLR} = 0.36 \times \left(13.5 + \frac{\tau_y}{\rho U^2}\right)^{0.428} \times \varepsilon_{\mathrm{ave}}^{0.158} \times n^{0.054} \times \mathrm{Ta} \times \mathrm{Re}_{\mathrm{eff}}^{0.042} \times k\left(\frac{1}{k} - 1\right)^{-0.0152} \quad (2.16)$$

$$\mathrm{PLR} = \frac{\left(\frac{dP}{dL}\right)_{\omega}}{\left(\frac{dP}{dL}\right)_{\omega=0}} \quad (2.17)$$

where $\tau_y$ is yield stress, U is average velocity, $\varepsilon_{ave}$ is average pipe eccentricity which its details are described in that literature, n is fluid behavior index, Ta is Taylor number, and k is consistency index.

Ozbayoglu and Sorgun (2009) proposed the empirical correlation for friction factors not only as a function of axial Reynolds number ($N_{Re_a}$), but also rotational Reynolds number ($N_{Re_r}$). In order to increase the accuracy of developing correlation, different equations are introduced for various total Reynolds ranges. Total Reynolds number can be defined as

$$N_{Re_T} = N_{Re_a} + N_{Re_r} \quad (2.18)$$

Reynolds number in the axial direction and due to rotation are given by

$$N_{Re_a} = \frac{757\,\rho\,v_a(D_o - D_i)}{\mu_{e_a}} \quad (2.19)$$

$$N_{Re_r} = \frac{757\,\rho\,v_a(D_o - D_i)}{\mu_{e_r}} \quad (2.20)$$

where $\mu_{e_a}$ is an effective viscosity for axial direction, and $\mu_{e_r}$ is an effective viscosity for radial direction. The effective viscosity of both axial and radial direction are express as

$$\mu_{e_a} = \left(\frac{K(D_o - D_i)^{1-n}}{144\,v^{1-n}}\right)\left(\frac{2+\frac{1}{n}}{0.0208}\right)^{n} \quad (2.21)$$

$$\mu_{e_r} = K\left(\frac{1}{n}\right)^{n}(\xi)\left(\frac{1}{\omega}\right)^{1-n} \quad (2.22)$$

$$\xi = \left(\frac{D_o^2 - D_i^2}{D_o^2}\right)\left(\frac{15}{\pi}\right)^{1-n}\left(\frac{1}{\left(1-\left(\frac{D_o}{D_i}\right)^{-\frac{2}{n}}\right)}\right)^{n} \quad (2.23)$$

The friction factor equations generated are presented below.

If $N_{Re_T} < 3000$ $\quad f_f = 8.274 N_{Re_a}{}^{-0.9075} + 0.00003 N_{Re_r}$ (2.24)
If $3000 < N_{Re_T} < 7000$ $\quad f_f = 0.0729 N_{Re_a}{}^{-0.3017} + 0.000011 N_{Re_r}$ (2.25)
If $7000 < N_{Re_T} < 10000$ $\quad f_f = 0.006764 N_{Re_a}{}^{-0.0286} + 0.00001 N_{Re_r}$ (2.26)
If $10000 < N_{Re_T} < 25000$ $\quad f_f = 8.28 N_{Re_a}{}^{-0.7258} + 0.000001 N_{Re_r}$ (2.27)
If $25000 < N_{Re_T} < 40000$ $\quad f_f = 0.06188 N_{Re_a}{}^{-0.2262}$ (2.28)
If $N_{Re_T} > 40000$ $\quad f_f = 0.03039 N_{Re_a}{}^{-0.1542}$ (2.29)

Ozbayoglu and Sorgun (2010) investigated pressure loss estimation in horizontal well with considering the pipe rotation and present of cuttings using computational fluid dynamics (CFD) technique. The simulated results were reasonably good agreement when compare with the result from experiment. They also observed that the pipe rotation significantly effect on pressure loss when drilling fluid is non-Newtonian fluid.

Erge *et al.* (2014) presented a new correlation models for estimating annular pressure in transition from laminar to turbulent regions to predict annular pressure loss considering pipe rotation, pipe eccentricity, and pipe buckling configuration. Their proposed models gave a good agreement with results in experiments using yield power law model, however it can be applied with power law model. The proposed friction factor are described as below.

$$f_0 = (c) f_{Mod.N.S.} \tag{2.30}$$

For laminar flow:

$$c = 0.2287N - 0.0580\, F_d + 0.1237\, \omega_d + 0.4289 \tag{2.31}$$

For transition flow:

$$c = -1.0267N - 0.0096\, F_d + 0.0390\, \omega_d + 1.2422 \tag{2.32}$$

For turbulent flow:

$$c = 1.7821\, N - 0.0132\, F_d + 0.1388\, \omega_d + 1.7983 \tag{2.33}$$

where N is consistency index, $F_d$ is the dimensionless force and $\omega_d$ is the dimensionless rotation.

### 2.6.4 Drillpipe Eccentricity

When drillpipe is drilling through formation in subsurface, the perfectly drill is the center of drillpipe and wellbore are at the same position which is called concentricity. In field operation, concentric can possible occur in vertical well but not in deviate well due to the well geometry and pipe buckling. The eccentric occurs when the center of drillpipe deviate from center of wellbore as shown in Figure 2.10, leading to influence on flow pattern of circulating fluid and annular pressure loss. The eccentricity can be calculated as

$$\varepsilon = \frac{2\,\delta}{D_o - D_i} \tag{2.30}$$

where $\delta$ is the distance between center of inner and outer pipes. However, the eccentricity is also a critical issue that need to be considered in the cementing operation in horizontal well (Osgouei *et al.*, 2013). When the annular is laminar flow, the pressure loss is decreased as the annulus becomes eccentric. However, a change from concentric to a slightly eccentric affects the flow to reach turbulent regime at lower flow rate than standard concentric flow rate (Marken *et al.*, 1992).

Ozbayoglu and Omurlu (2006) proposed the finite element method to predict the pressure loss using the developed empirical or semi empirical approach which were used to predict pressure but not well performed. The three different drilling fluids were used to experiment with various pipe eccentricity. The results from FEM method can estimated the pressure loss more accurately than conventional method, and were compared with the literature result. They observed that as the eccentricity is increased, pressure loss is decreased.

(Ofei *et al.* (2014)) investigated the effect of eccentricity and pipe rotation speed on pressure loss in horizontal well using CFD method. The results were confirmed with the published literature, and found that an increasing eccentricity tend to decrease annular pressure loss. However, the slightly change in pipe rotation did not result in pressure loss.

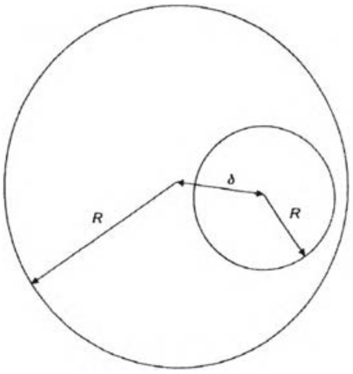

**Figure 2.10** Cross section of an eccentric annulus (Pilehvari and Serth, 2009).