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**Research Article**

# The Influence of Collar on Surge Pressure Caused by the Drilling Fluid Viscous Force under Pumping Condition

[1]Jun Li, [2]Zhen Huang, [3]Ke Li and [1]Wei Wu
[1]College of Petroleum Engineering, China University of Petroleum, Beijing, 102249, China
[2]CNPC Southwest Oil and Gas Field Subsidiary Company, China
[3]CNPC GWDC, China

**Abstract:** The study of surge pressure is of significant importance for the safety of drilling process because field practice shows that the surge pressure caused by fluid viscous force can cause a great damage to the drilling operation. The accurate calculation of surge pressure is directly related to the safety of the drilling process. However, the existing surge pressure models rarely take the impact of the collar into consideration and thus will inevitably affect the precision of the surge pressure calculation. In this study, based on the pumping condition, a steady-state calculation model for surge pressure caused by drilling fluid viscous force is developed considering the presence of collar. In the end a case study is presented to demonstrate the importance of collar during the calculation of surge pressure.

**Keywords:** Casing, closed pipe, collar, drilling fluid, surge pressure

## INTRODUCTION

During the drilling process, a constant operation is the tripping in/tripping out of a drill string in the wellbore. Due to the displacement effect of the drill string to the drilling fluid in the wellbore, an additional pressure will be generated: A pressure increase inside the wellbore due to a downward string movement is called surge pressure; while on the contrary, the pressure decrease inside the wellbore due to an upward string movement is called swab pressure. Excessive surge pressures may fracture weak formations and lead to a lost circulation scenario, while swab pressures may initiate a well kick or even a blowout scenario. Therefore, the accurate calculation of surge and swab pressures is of great significance for the drilling program design, the drilling accident prevention and the penetration rate improvement.

Early studies suggest that lost circulation, formation fracturing and well kick are all related to surge pressure (Cannon, 1934; Horn, 1950; Goins *et al*., 1951). Until the 1960's have a number of studies trying to explain the reasons of pressure surge and to investigate the size of it. Burckhardt proposed a semi-empirical model to calculate the surge pressure of Bingham fluid (Burkhardt, 1961). Schuh (1964) proposed a simplified model to calculate the surge pressure with Power-law fluid. In the past three decades, the investigation of surge pressure based on unsteady flow began to be developed. Lal (1983) considered the impact of the compressibility of drilling fluid and borehole enlargement factors. Wagner *et al*. (1993) considered the impact of temperature on the fluid rheology when calculating dynamic surge pressures (Robello *et al*., 2003; Rommetveit *et al*., 2005). Hussain and Sharif (1997) found that the eccentricity have a great impact on dynamic surge pressure in a recent study.

The steady state surge pressure calculation method is not as accurate as dynamic method, but due to its simplicity and accuracy to a certain extent, it is still used in some oil fields. There are four scenarios with regarding to the movement of the drill assembly: closed pipe without pumping, closed pipe with pumping, open pipe without pumping, open pipe with pumping. As long as the pump is running, the fluid in annulus will not flow into the drilling assembly regardless of closed pipe or open pipe, so the closed pipe with pumping and open pipe with pumping can be considered as one scenario. The literature review shows that the impact of the collar had not been taken into consideration while calculating the steady state surge pressure. Therefore, under the pumping condition, this study will develop a steady state surge pressure calculation model and discuss the impact of collar on surge pressure caused by the viscous force of drilling fluid.

**Corresponding Author:** Jun Li, College of Petroleum Engineering, China University of Petroleum, 102249 Beijing, China

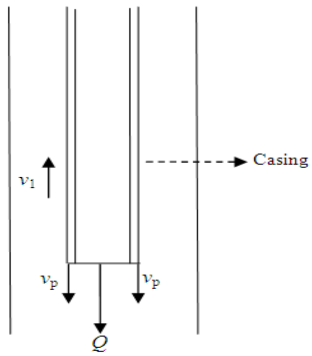


Fig. 1: Drilling fluid flow analysis (pumping, no collar)

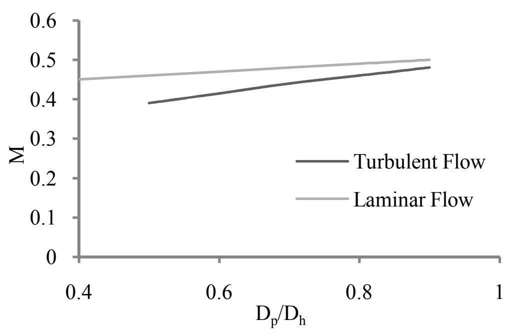


Fig. 2: Mud clinging constant

## THE CALCULATION MODEL OF SURGE PRESSURE CAUSED BY THE VISCOUS FORCES OF THE DRILLING FLUID UNDER PUMPING CONDITION IGNORING THE IMPACT OF COLLAR

Without considering the impact of collar on surge pressure, the downward movement of the drilling string can be shown as Fig. 1:

The flow rate of the drilling fluid in the annulus $v_1$ is comprised of three parts: flow rate $v_a$ caused by the drill string displacement force, flow rate $v_b$ caused by drill string adhesive force, flow rate $v_c$ caused by pump circulation, then we have:

$$v_1 = v_a + v_b + v_c \tag{1}$$

from

$$\frac{\pi}{4}(D_2^2 - D_{2i}^2)v_p = \frac{\pi}{4}(D_1^2 - D_2^2)v_a \tag{2}$$

It can be obtained:

$$v_a = \frac{(D_2^2 - D_{2i}^2)v_p}{D_1^2 - D_2^2} \tag{3}$$

where,
$D_1$ = The diameter of the wellbore
$D_2$ = The outer diameter of casing
$D_{2i}$ = The inner diameter of casing
$v_p$ = The drill string velocity

Substituting annular flow with slot flow, Buvkhardt derived a complex formula based on Bingham model and proposed a relationship between $v_b$ and drilling string $v_p$:

$$v_b = Mv_p \tag{4}$$

where, M is the mud clinging constant. M can be determined from the Fig. 2:

According to the relationship between the volume and flow rate, when the mud pump rate is Q, the flow velocity $v_c$ can be determined as follows:

$$v_c = \frac{Q}{\frac{\pi}{4}(D_1^2 - D_2^2)} \tag{5}$$

Therefore:

$$v_1 = v_a + v_b + v_c = v_p\left(\frac{D_2^2 - D_{2i}^2}{D_1^2 - D_2^2} + M\right) + \frac{Q}{\frac{\pi}{4}(D_1^2 - D_2^2)} \tag{6}$$

The same analysis can be applied on tripping out situation, where the drilling fluid flows downward. Equation (5) can be written as:

$$v_1 = -v_p\left(\frac{D_2^2 - D_{2i}^2}{D_1^2 - D_2^2} + M\right) + \frac{Q}{\frac{\pi}{4}(D_1^2 - D_2^2)} \tag{7}$$

**Calculation of surge pressure:** Knowing the drilling fluid flow rate caused by drill string movement and pump circulation, the surge pressure can be directly calculated by flow rate $v_1$, the procedures are as follows:

First determine flow pattern based on Reynolds numbers:

$$R_e = \frac{(D_1 - D_2)^n v^{2-n} \rho}{12^{n-1} K \left(\frac{2n+1}{3n}\right)^n} \tag{8}$$

where,
*Re* = Reynolds number, dimensionless
$D_1$ = Diameter of the wellbore, cm
$D_2$ = The outer diameter of casing, cm
$\rho$ = The density of drilling fluid, g/cm$^3$
$v$ = Average drilling fluid velocity, m/s
$K$ = Consistency coefficient, 0.01 mpa.s$^n$
$n$ = Flow behavior index

*Re*<2000 indicates laminar flow while *Re*>2000 indicates turbulent flow. Use various equations with regarding to different flow patterns to calculate surge pressure.

Surge pressure equation for laminar flow pattern:

$$p = \frac{4KL}{D_1 - D_2}\left[\frac{4(2n+1)v}{n(D_1 - D_2)}\right]^n \quad (9)$$

where,
$p$ = Pressure drop
L = Measured depth

Surge pressure equation for turbulent flow pattern:

$$p = \frac{2f\rho L v^2}{D_1 - D_2} \quad (10)$$

where,
P = Surge pressure, $kg/cm^2$
L = Measured depth, m
$D_2$ = The outer diameter of casing, cm
$D_1$ = The diameter of the wellbore, cm
v = Annular drilling fluid velocity, m/s
ρ = Density of drilling fluid, $g/cm^3$
f = Friction coefficient, dimensionless

In all the above equations, the fluid flow rate value is positive when flowing upward and negative when flowing downward. A positive $p$ value indicates surge pressure and a negative value indicates swab pressure.

## THE CALCULATION MODEL OF SURGE PRESSURE CAUSED BY THE VISCOUS FORCES OF THE DRILLING FLUID UNDER PUMPING CONDITION CONSIDERING THE IMPACT OF COLLAR

The downward movement of the drilling string under pumping condition considering the impact of collar can be shown as Fig. 3:

$v_1$ is the flow rate of the drilling fluid in the casing annulus, $v_2$ is the flow rate of the drilling fluid in the collar annulus, the relationship between $v_1$ and $v_2$ is shown below:

$$\frac{\pi}{4}(D_1^2 - D_2^2)v_1 = \frac{\pi}{4}(D_1^2 - D_3^2)v_2 \quad (11)$$

where,
$D_1$ = The diameter of the wellbore
$D_2$ = The outer diameter of casing
$D_3$ = The outer diameter of collar

The flow rate of the drilling fluid in the annulus of casing $v_1$ and the flow rate in the annulus of collar $v_2$ are both comprised of three parts: flow rate $v_{a1}$ and $v_{a2}$ caused by the drill string/collar displacement force, flow rate $v_{b1}$ and $v_{b2}$ caused by drill string/collar adhesive force, flow rate $v_{c1}$ and $v_{c2}$ caused by pump circulation:

$$v_1 = v_{a1} + v_{b1} + v_{c1} \quad (12)$$

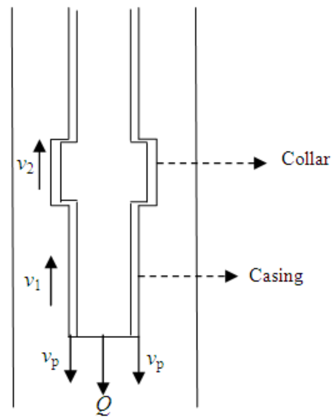


Fig. 3: Drilling fluid flow analysis (pumping, with collar)

$$v_2 = v_{a2} + v_{b2} + v_{c2} \quad (13)$$

Based on the law of conservation of mass, we have:

$$\frac{\pi}{4}(D_2^2 - D_{2i}^2 + D_3^2 - D_{3i}^2)v_p = \frac{\pi}{4}(D_1^2 - D_2^2)v_{a1} + \frac{\pi}{4}(D_1^2 - D_3^2)v_{a2} \quad (14)$$

where,
$D_{2i}$ = The inner diameter of casing
$D_{3i}$ = The inner diameter of collar

From Eq. (4), we can obtain the formula to calculate the flow rate caused by drill string/collar adhesive forces, $v_{b1}$ and $v_{b2}$:

$$v_{b1} = M_1 v_p \quad (15)$$

$$v_{b2} = M_2 v_p \quad (16)$$

In Fig. 2 the $M_1$ and $M_2$ value can be determined on the vertical axis by identifying $D_2/D_1$ and $D_3/D_1$ value on the horizontal axis. The flow rate caused by drill string/collar adhesive forces can be obtained from Eq. (15) and (16).

Based on the relationship between volume and flow rate:

$$v_{c1} = \frac{Q}{\frac{\pi}{4}(D_1^2 - D_2^2)} \quad (17)$$

$$v_{c2} = \frac{Q}{\frac{\pi}{4}(D_1^2 - D_3^2)} \quad (18)$$

Knowing the flow rate $v_{b1}$ and $v_{b2}$ caused by drill string/collar adhesive force and the flow rate $v_{c1}$ and $v_{c2}$ caused by pump circulation, calculating the simultaneous Eq. (11)~(14), the flow rate of the drilling fluid in the annulus of casing $v_1$ and the flow rate in the annulus of collar $v_2$ can be obtained as follows:

$$v_1 = \frac{(D_2^2 - D_{2i}^2 + D_3^2 - D_{3i}^2)v_p + (D_1^2 - D_2^2)(v_{b1} + v_{c1}) + (D_1^2 - D_3^2)(v_{b2} + v_{c2})}{2(D_1^2 - D_2^2)} \quad (19)$$

$$v_2 = \frac{(D_2^2 - D_{2i}^2 + D_3^2 - D_{3i}^2)v_p + (D_1^2 - D_2^2)(v_{b1} + v_{c1}) + (D_1^2 - D_3^2)(v_{b2} + v_{c2})}{2(D_1^2 - D_3^2)} \quad (20)$$

**The calculation of surge pressure:** Measured depth L can be divided into two parts: casing length $L_1$ and casing collar length $L_2$. Knowing the flow rate of the drilling fluid in the annulus of casing/collar $v_1$ and $v_2$, the surge pressure calculation steps are as follows:

First determine the flow pattern in the casing and collar annulus based on the Reynolds number (Power-law fluid):

$$R_{e1} = \frac{(D_1 - D_2)^n v_1^{2-n} \rho}{12^{n-1} K (\frac{2n+1}{3n})^n} \quad (21)$$

$$R_{e2} = \frac{(D_1 - D_3)^n v_2^{2-n} \rho}{12^{n-1} K (\frac{2n+1}{3n})^n} \quad (22)$$

where,

$R_{e1}$ = Casing annular fluid Reynolds number, dimensionless
$R_{e2}$ = Collar annular fluid Reynolds number, dimensionless
$\rho$ = Drilling fluid density
$v$ = The average flow rate of drilling fluid
$K$ = Consistency coefficient
$n$ = Flow behavior index

Re<2000 indicates laminar flow while Re>2000 indicates turbulent flow. Use different equations with regarding to various flow patterns in casing and collar annulus to calculate surge pressure.

When the flow pattern in casing annulus is turbulent flow, the flow pattern in collar annulus will also be turbulent flow. When the flow pattern in casing annulus is laminar flow, the flow pattern in collar annulus could be either turbulent flow or laminar flow. So the formulas of surge pressure are:

The flow pattern is laminar flow both in casing annulus and collar annulus:

$$p = \frac{4KL_1}{D_1 - D_2}[\frac{4(2n+1)v_1}{n(D_1 - D_2)}]^n + \frac{4KL_2}{D_1 - D_3}[\frac{4(2n+1)v_2}{n(D_1 - D_3)}]^n \quad (23)$$

The flow pattern is turbulent flow both in casing annulus and collar annulus:

$$p = \frac{2f\rho L_1 v_1^2}{D_1 - D_2} + \frac{2f\rho L_2 v_2^2}{D_1 - D_3} \quad (24)$$

where,
$f$ = Friction coefficient

The flow pattern is laminar flow in casing annulus while it is turbulent flow in collar annulus:

$$p = \frac{4KL_1}{D_1 - D_2}[\frac{4(2n+1)v_1}{n(D_1 - D_2)}]^n + \frac{2f\rho L_2 v_2^2}{D_1 - D_3} \quad (25)$$

## CASE STUDY

The measured depth is 900 m which includes 870 m of casing length and 30 m of total collar length. The wellbore diameter $D_1$ is 215.9 mm, the casing outer diameter $D_2$ is 177.8 mm, the casing inner diameter $D_{2i}$ is 150.4 mm, the collar outer diameter $D_3$ is 194.5 mm, the collar inner diameter $D_{3i}$ is 165 mm, drill string movement velocity $v_p$ is 1.8 m/s, the drilling fluid flow behavior index n is 0.65, the consistency coefficient K is 0.5 mpa.s$^n$, the drilling fluid friction coefficient $f$ is 0.008, the drilling fluid density is 1.3 g/cm$^3$ and the mud pump rate $Q$ is 30 L/s.

In order to make the calculations more conservative, the mud clinging constant value will be chose from the trend line of turbulence flow in Fig. 2.

**Consider the impact of collar on surge pressure:** From $D_2/D_1 = 0.82$, $D_3/D_1 = 0.9$, it can be obtained that $M_1 = 0.48$, $M_2 = 0.5$. From Eq. (15) and (16) it can be obtained that $v_{b1} = 0.864$ m/s, $v_{b2} = 0.9$ m/s. According to Eq. (17) and (18), it can be obtained that the flow rate caused by pump circulation $v_{c1} = 2.546$ m/s, $v_{c2} = 4.349$ m/s. Based on Eq. (19) and (20), it can be obtained that $v_1 = 4.42$ m/s, $v_2 = 7.55$ m/s, from Eq. (21) and (22) the Reynolds number in casing/collar annulus can be obtained as $R_{e1} = 9879$, $R_{e2} = 13987$, therefore the casing/collar annulus flow pattern can be determined as turbulent flow. From Eq. (24) we can calculate the surge pressure as 109.3 kg/cm$^2$.

**Ignore the impact of collar on surge pressure:** Neglecting the impact of collar, from $D_2/D_1 = 0.82$, $M_1 = 0.48$ can be obtained. From Eq. (4), $v_b = 0.864$ m/s can be obtained. From Eq. (1) and (2), $v_1 = 4.489$ m/s can be obtained, From Eq. (6) the Reynolds number of casing annulus fluid flow can be calculated as $Re = 3528$, therefore, the casing annulus flow pattern can be determined as turbulent flow. From Eq. (8) we can calculate the surge pressure as 99 kg/cm$^2$.

The final calculation results clearly shows that when considering the impact of collar, the calculated surge pressure value is 9.4% higher than ignoring the collar. Therefore, neglecting the impact of collar could cause a large error to the calculation of surge pressure.

## CONCLUSION

Under the pumping condition, this study developed a steady state surge pressure calculation model and used a case study to demonstrate the impact of collar on surge pressure caused by the viscous force of the drilling fluid. The results show that neglecting the impact of collar could cause a large error to the calculation of surge pressure and thus could lead to down-hole incidents. Therefore, the impact of collar must be considered while calculating the surge pressure.

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