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Improved Model for Equivalent Circulating Density and Improved Annular Pressure Drop Estimation: Drilling Approach

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Abstract

This study focused on the modelling of the pressure losses in the annulus and Equivalent Circulating Density (ECD) at low shear rate yield point. Laboratory measurements of rheological properties and mud weight were done according to API standard. The combined annular pressure loss model, Bingham Plastic and Power Law annular pressure loss models were then evaluated. The combined model gave the best result in terms of annular pressure loss and ECD. This is then followed by the Bingham plastic annular pressure loss model and the Power law annular pressure loss model. Predictions of equivalent circulation density for yield point and low shear rate yield point models showed absolute average error values of 0.0242 and 0.00581 respectively, compared with field data.

Keywords: *Annular pressure; Bingham plastic annular pressure loss model; ECD, Low shear rates power law annular pressure loss model; Yield point; Yield stress.*

1. Introduction

Pressure drop in the annulus is experienced as drilling fluids transport cuttings to the surface. Proper estimation of these pressure losses is very important in the calculation of the ECD to avoid fracturing of the formation. Most times, the annulus eccentricity determines the annular pressure loss. Hence, calculation of total annular pressure loss is made from the three annular well sections to be treated individually as single annular clearance. This will help the annular pressure loss and ECD to be estimated properly for these sections using the three rheological models used for this study. It is streamlined in checking the annular pressure drop, which is the function of the ECD and hole cleaning capability of each model considered. The study is focused on the use of the combined model (Herschel-Bulkley) to estimate annular pressure loss and ECD specifically, alongside comparing Bingham Plastic and Power Law fluids. It is important to understand that low shear rate yield point or simply yield stress especially in the annulus is responsible for hole sweep, while yield point is for cuttings removal during oil and gas drilling operations. Yield point is calculated at higher shear rates of 600 rpm and 300 rpm, while low shear rate yield point is estimated at lower shear rates of 6 and 3 rpm. This is therefore, to improve the existing annular pressure loss models which include LSRYP instead of YP in their equations.

Annular pressure is generated from the mud column in the wellbore (i.e. hydrostatic pressure). As drilled well depth increases so also does annular pressure drop increase thereby indicating that it is a function of depth. However, static annular pressure is created by hydraulic pressure of mud plus cuttings suspended in the mud when there is no flow in the annulus, while dynamic annular pressure is static annular pressure plus pressure drop along the annulus of the wellbore. This pressure drop is created by the friction between mud particles and wellbore and pipes due to mud flowing in the annulus.

Formation solids must be closely checked and controlled in order to minimize its adverse effect on equivalent mud weight or force required by a mud to exert hydrostatic pressure on the mud. For easy comparison to critical mud density limits, the annular pressure is often transformed into a virtual density value. ECD is utilized in the control of annular pressure profile and also to avoid kicks and mud losses.

ECD can be measured through the following ways:

1. By converting annular pressure to density equivalent on both sides [12]:

$$ECD = MW\left(\frac{lb}{gal}\right) + \frac{P_a\,(psi)}{0.052 * TVD} \quad (1)$$

2. By using the yield point value, this is the only ideal for mud weight equal to or less than 13.0 ppg [2, 7].

$$D = MW + \frac{0.1\ x\ YP}{Hole\ ID - Pipe\ OD} \quad (2)$$

There is a good direct relationship between the drilling fluids rheology and the associated annular hydraulics on one hand and the effectiveness of the borehole cleaning status [10]. A good understanding of this principle is vital for engineering the drilling fluid and will compliment drilling objective [4, 15]. The models are idealized relationship of rheological behavior expressible in mathematical form [8]. It has also been observed that while Bingham Plastic model over-estimates, Power Law model under estimates annular pressure losses. Hole cleaning is dominated by a zone with low shear rate and extremely high viscosity. It is important to understand drilling fluid properties at low shear rates for effective hole cleaning and cuttings suspension [11]. Mud in the annulus undergoes a transition from a higher shear rate region exiting the bit nozzles to a lower shear rate in the annulus. Hence, a better approach is to modify this model. This study thus, seeks to utilize these two models to develop a new formula, aimed at a better appreciation of the essence of ECD calculation, in the analysis of pressure drop in annulus to improve hole cleaning. The efficiency of drilling operations depends on the ability of the operations to remove drilled cuttings. Hence, the cutting removal and hole cleaning efficiency are very vital requirements for ensuring the drilling objective [9]. Also, hole cleaning issue is more pronounced in non-vertical drilling and its adverse impact can cause various severe drilling problems which may include stuck pipe, inaccurate drill string rotation, wrong inclination and inadequate rate of penetration [5]. As drilling progresses, drilling fluid has a basic function to transport the generated cuttings from wellbore but if this function is not performed efficiently, the generated cuttings will begin to accumulate in the annulus. In addition, it is required that the drilling fluid should be able to hold (keep in suspension) the cuttings, when not in circulation [19]. The performance of the drilling fluid is fundamental for the success of any drilling operation. As soon as bit creates cuttings, the cuttings need be cleared up the hole to avoid it being drilled over again which may hinder the rate of penetration and cause other problems to the mud and the bit [14].

The calculation of ECD is dependent on accurate estimation of the annular pressure losses [15]. The annular pressure loss for each length of the pipeline sections is calculated differently but summed up in order to obtain the total annual pressure loss [2]. In order to maximize the effects of hydraulics and realize a sizeable cuttings removal, the summation of the different pressure losses through the whole system need to be considered [7]. Also, it's been thought that the turning on and off of mud pumps is usually the cause of fluctuation in ECD [17]. The authors discovered that the repeated formation and erosion of cuttings deposit bed are causes. Also, drilling interruption for making a connection repeatedly causes a significant level of irregular fluctuation of ECD. Fluid velocity, drilling fluid properties (density, viscosity), cuttings size and density, hole-pipe eccentricity, drill pipe rotation, and annular diameter ratios affect proper prediction of pressure losses and cuttings concentration in wells [21]. Similarly, the practical drilling factors need to be controlled properly to ensure effective cuttings transport [18]. To ensure efficient hole cleaning, several parameters affect the transported cuttings in the annulus. If drilling problems such as pack off, formation fracture and hole cleaning issues must be avoided then annular pressure must be properly monitored.

2. Application of annular pressure and equivalent circulating density

i. Mud weight adjustment – for the formation to be kept in check, to prevent collapse, the mud weight is critical. The mud weight is adjusted accordingly as the ECD is calculated using the corresponding annular pressure to have balance in formation fracture gradient and formation pressure.

ii. Hole cleaning – drilled cuttings must be transported to the surface. If cuttings are not properly transported, and they begin to pile up in the wellbore, problems will be caused such as torque increase or pack off. Improvement of hole cleaning can be done by:

a) Lowering the rate of penetration

b) Reduction in cuttings size by reducing settling velocity; this can be achieved by using smaller cutters.

c) Annular velocity can be increased by increasing the mud pump rate which in turn will transport cuttings out of the annulus.

iii. Mud gel strength breaking force – mud pumps are stopped during drill pipe stand connection, and during this state, the mud becomes gelled for cuttings suspension. When the pumps are restarted, the pressure used to break the gel is slightly higher than the annular pressure used during drilling.

3. Empirical review

Theoretical frictional pressure losses have been compared with experimental data [6]. Hydraulic diameter approach for Bingham Plastic model and Power Law model were employed. After the analyses, it was discovered that the calculated pressure losses overestimated the measured values in both laminar and turbulent flow conditions. An attempt has also been made to develop a model to bridge the gap between existing models after treating factors affecting removal of cuttings, in which a single model was proposed [22]. He also developed charts for use in conjunction with existing hole cleaning charts in the field. Also, the importance of accurate estimation of annular pressure losses in drilling and well completion operations has been emphasized [15]. He was able to calculate the pressure loss gradients/ECD using annular frictional pressure equations as the basis of relating the results obtained using the rheological model- equivalent diameter definition combinations. Yield Power law fluid in eccentric annuli has also been modeled [16]. They emphasized on the need to have more accurate predictions from existing hole cleaning models.

In summary, a lot have been presented of YP as a measure of the hole cleaning capability of a drilling fluid. It results from attractive forces between particles in a fluid, and serves as a measure of shear thinning behavior of a drilling fluid. Its methods of estimation exist and each would yield different result. However, since YP is measured at low shear rate conditions, an improved prediction technique (at lower shear rate conditions) will be proposed, by the use of the LSRYP as a parameter.

4. Materials and method

This study focused on modeling of annular pressure loss and ECD. The mud properties from the laboratory and other field data were applied. The drilling fluid was formulated in the laboratory, and tests were carried out according to API standard, using the materials shown in Table 1. In almost all cases, functions of additives are complementary. The Fann V-G meter (Model 35A) was used to determine the rheological properties which were used to analyze the hole cleaning function of the mud system as shown in Table 2.

Procedure:

i. The required amount of each material compositions were measured

ii. Fresh water was measured in a measuring cylinder

iii. Samples and water were mixed using Hamilton Beach mixer for about 15 minutes, and poured into viscometer cup

iv. Sample was stirred and readings at 600 rpm, 300 rpm, 200 rpm, 100 rpm, 6 rpm and 3 rpm were taken

v. Temperature and pressure at ambient conditions were noted, 77°Fand 14.7 psi respectively
vi. After the test, rheological parameters were determined

Table 1. Formulation and composition of the water based mud

Product/Brand name	Function	Product specific gravity	Product concentration, field bbl lbs/bbl	Product concentration, laboratory gm	mls
Fresh Water	Base fluid	1.0	333.36	333.36	333.36
XCD Polymer	Viscosifier	1.43	1.40	1.40	0.98
PAC-Lo-vis	Fluid loss control	1.54	2.40	2.40	1.56
Soda Ash	Inhibitor	2.51	0.260	0.260	1.04
Sodium chloride	Densifier and Inhibitor	1.20	15.20	15.20	12.67
Sodium hydroxide	pH control	1.52	0.24	0.24	0.16
Biocide	Bactericide	1.06	0.24	0.24	0.23
Total					350

Table 2. Water based mud laboratory rheological measurement

Mud properties/calcium carbonate	0ppb	30ppb	60ppb	90ppb	120ppb
Mud Density, ppg	8.8	9.2	9.5	10.3	10.8
10 Seconds Gel, lb/100ft2	20	24	27	32	38
10 Minutes Gel, lb/100ft2	32	38	44	56	64
600RPM	56	62	74	86	106
300RPM	45	47	53	64	76
200RPM	39	42	47	51	65
100RPM	28	30	34	39	43
6RPM	19	20	26	29	38
3RPM	15	15	22	24	32

4.1. The basis of the combined model

Modified Power law model is the foundation of principle upon which the combined annular pressure drop model is based, which is the combination of the features of Bingham Plastic model and Power Law model as stated in Equations 3 and 4:

$$\tau = \tau_{\gamma} + \mu\gamma \quad \text{(Bingham Plastic model)} \quad (3)$$

$$\tau = K\gamma^{n} \quad \text{(Power Law model)} \quad (4)$$

Combination of Equations 3 and 4 gave rise to Equation 5 [20]; equation 5 is called a modified Power Law model.

$$\tau = \tau_{\gamma} + K\gamma^{n} \quad (5)$$

Annular pressure drop equations

For Bingham Plastic model, pressure loss [3];

$$\frac{dP_f}{dL} = \frac{\mu V_a}{1{,}000(d_2 - d_1)^2} + \frac{\tau_{\gamma}}{200(d_2 - d_1)} \quad (6)$$

For Power Law pressure drop;

$$\frac{dP_f}{dL} = \frac{KV_a^{n}}{144{,}000(d_2 - d_1)^{1+n}}\left(\frac{2 + 1/n}{0.0208}\right)^{n} \quad (7)$$

For the combined model pressure drop, this is based on Herschel – Bulkley principle;

$$\frac{dP_f}{dL} = \frac{\tau_Y}{200(d_2 - d_1)} + \frac{KV_a^{\,n}}{144{,}000(d_2 - d_1)^{1+n}}\left(\frac{2 + {}^{1}/_{n}}{0.0208}\right)^{n} \tag{8}$$

However, other forms of Equation 8 for hydraulics of annular flow exist [1, 13].

Other related formulas

These include the following:

$$\text{Plastic viscosity,} \quad (cP)\mu = \theta_{600} - \theta_{300} \tag{9}$$

$$Yield\ Stress\ (LSRYP) = 2\theta_3 - \theta_6 \tag{10}$$

$$Annular\ Velocity, V_a = \frac{q}{2.448(d_2^{\,2} - d_1^{\,2})} \tag{11}$$

Validating equations

Since all the mud weights in this study are less than 13ppg [2, 7];

$$ECD = MW + \frac{0.1 * YP}{Hole\ ID - Pipe\ OD} \tag{12a}$$

Equation 12a is only applicable to the validation of Bingham plastic model. Based on the principle earlier stated, Equation 12a can be improved using yield stress which is the low shear rate yield point as defined in the combined model. The result would be Equation 12b. Comparison with Equation 12a and further validation was carried out.

$$ECD = MW + \frac{0.1 * LSRYP}{Hole\ ID - Pipe\ OD} \tag{12b}$$

5. Results and discussion

5.1. Annular pressure loss and ECD

Annular pressure drop and ECD results were calculated. The laboratory mud properties, measurements and the field data were applied to obtain the required results. Annular pressure loss and ECD at different concentrations of the weighting material were then calculated as indicated in Tables 3 and 4 respectively.

Table 3. Annular pressure loss estimation using Bingham plastic, Power Law and the combined annular pressure loss models

Calcium carbonate	0ppb	30ppb	60ppb	90ppb	120ppb
Bingham plastic model annular pressure Drop, psi	33.895	32.008	32.186	42.064	46.206
Power law model annular pressure drop, psi	0.153	0.157	0.207	0.231	0.282
Combined model annular pressure drop, psi	11.037	10.052	18.018	19.032	26.009

Table 4. ECD estimation using Bingham plastic annular pressure loss (BPM), power law annular pressure loss (PLM) and the combined annular pressure loss models

	0ppb	30ppb	60ppb	90ppb	120ppb
BPM, ppg	9.02	9.4	9.7	10.59	11.13
PLM, ppg	8.7	9.1	9.4	10.2	10.7
Combined model, ppg	8.8	9.19	9.57	10.38	10.94

Tables 3 and 4 were obtained from the models by substituting the required laboratory results and the field data in the three models. From Table 4, the combined model, based on equal concentrations of the base fluid, weighting material and other additives gave the best result, followed by Bingham Plastic and finally the Power law annular pressure loss equations. Although, the Power law model gave the least result because of the non-availability of the yield stress, so it is not good for estimation of annular pressure drop and the ECD. Bingham Plastic model is not also good in the estimation of annular pressure drop and ECD; it conveys only what happens at high shear rate of 600rpm and 300rpm and that is the reason their values are higher than Power law and the Combined annular pressure loss models. Since the annular well bore is not well cleaned, the ECD must be high when compared with the combined model that considered the two attributes of hole cleaning at 6rpm and 3rpm, and the possession of the yield stress.

Figures 1 and 2 showed that ECD increases with increase in both low shear rate yield point and yield point. In Figures 3 and 4, the combined model gave a better representation of annular pressure loss which is a typical characteristic of a drilling fluid behavior which is the function of the hole cleaning.

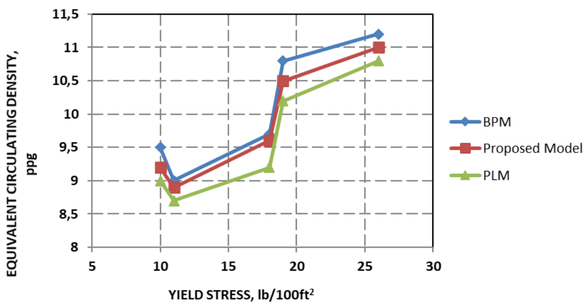

Figure 1. Effect of yield stress on equivalent circulating density

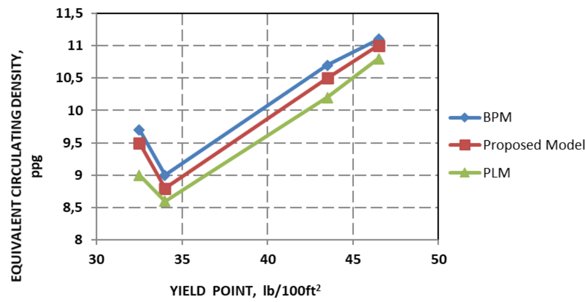

Figure 2. Effect of yield point on equivalent circulating density

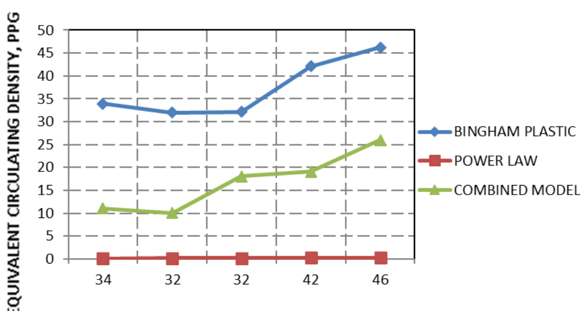

Figure 3. Annular pressure drop/loss (psi) against yield point (lb/100ft²)

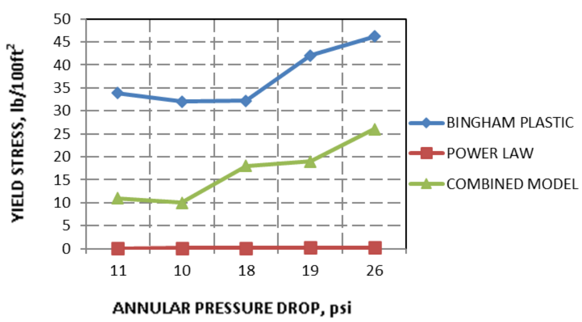

Figure 4. Graph of Annular Pressure Drop/Loss (psi) against Yield Stress (lb/100ft²)

5.2. Validations of the model

Validations of the combined model could be done through the following ways:
(1) Dimensionality
(2) Using direct formula as shown in Table 5 obtained from Equations 2 and 12 and
(3) Validation using regression coefficient method.

Table 5. ECD Estimation of Bingham Plastic and the Combined Equations

	0ppb	30ppb	60ppb	90ppb	120ppb
BPM Direct Method, ppg	9.02	9.4	9.7	10.6	11.14
Combined Model Direct Method, ppg	8.8	9.2	9.57	10.38	10.95

The curves of predictions from conventional (Equation 12a) and proposed (Equation 12b) models are shown in Figure 5. The curve for the model with low shear rate yield point matches closely with the field data compared with the model with yield point as given.

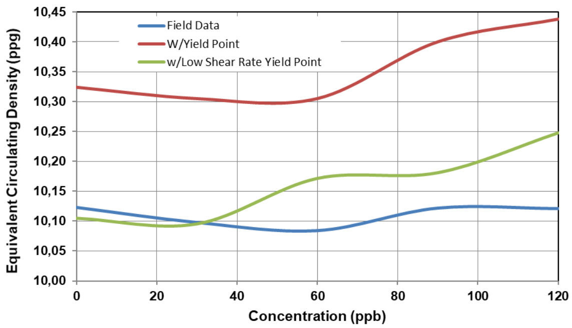

Figure 5. Comparison of field data with model predictions

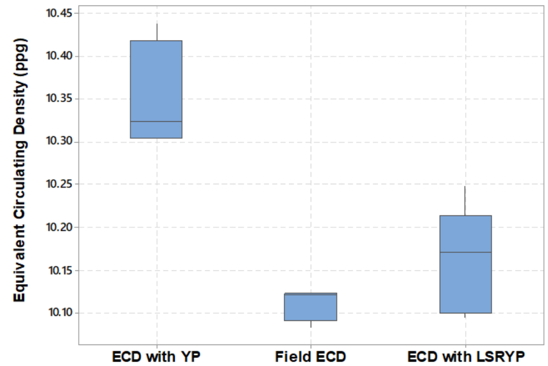

Figure 6. Comparison of equivalent circulating density prediction distributions

From Figure 6, for ECD prediction for model with yield point, 75% of the predicted values are less than or equal to 10.42 ppg, with median of 10.32 ppg. Also, for low shear rate yield point, 75% of the predicted values are less than or equal to 10.21 ppg, with median of 10.17 ppg. The median of the field data is 10.12 ppg. There were no outliers in the predictions. Only less than 25% of the predictions from model with low shear rate yield point are less that the field median. Generally, ECD predictions for model with yield point showed higher values compared to predictions for model with low shear rate yield point. Similarly, the predictions for yield point and low shear rate yield point models showed absolute average error values of 0.0242 and 0.00581 respectively. Hence, the later is an improved model and better predictor of ECD compared with the conventional model for muds with less than 13 ppg density.

5.3. Dimensionality

With reference to Equation 8 and dimensioning using units (primary approach), the Left-Hand-Side is justifiably equal to the Right-Hand-Side in terms of dimensionality.

ECD calculation using Bingham Plastic model has a direct formula which is used as its validation as shown in Table 3. Based on the principle of the combined model, the yield point in the Bingham Plastic direct ECD calculation was then modified to yield stress for an accurate description of a drilling mud. These two ECD direct formulas, for Bingham plastic model and the proposed annular pressure loss model act as their validation as shown in Table 5. ECD calculated using the annular pressure loss estimate are approximately the same as the ones calculated using the direct formula. An $\mathbf{R^2}$ value of 0.9983 (approximately 1.0) shows the validation.

6. Conclusion

The following conclusions were derived:

1. The combined annular loss model gave the best for ECD estimation than the other models.
2. The annular pressure loss model and direct formula for calculating ECD were established and validated.
3. The combined model from annular pressure drop and direct formula gave a good estimate while Bingham Plastic model and Power Law model overestimated and underestimated the ECD respectively.

Currently the industry majorly uses Bingham plastic model for calculating annular pressure loss and equivalent circulating density. Based on our findings, the Bingham plastic model does not account for yield stress which is responsible for hole sweep and cleaning. Since low shear rate yield point is a representation of annular conditions, we highly recommend that the combined model be given an opportunity to be used to do annular pressure loss and ECD estimation. Based on our findings, the combined model proved to give better estimation.

Recommendation

An improved model for prediction of ECD for mud densities less than 13 ppg has been proposed for the oil and gas industry. It is recommended, henceforth, for field applications and in well design where ECD values are required to apply the proposed model for better predictions. The equation 12b is a better representation of prediction in the annulus.

Abbreviations

ECD - Equivalent Circulating Density, ppg
MW - Mud weight, ppg
Hole ID - Hole diameter, inches
OD - Outside Diameter of pipe, inches
μ - Plastic Viscosity, cP
TVD - True Vertical Depth, ft
YP - Yield Point, $lb_f/100ft^2$
LSRYP - Low Shear Rate Yield Point, $lb_f/100ft^2$
BPM - Bingham plastic model
PLM - Power Law model
τ - shear stress, $lb_f/100ft^2$
γ - shear rate, s^{-1}
τ_Y - yield point for Bingham plastic or yield stress for power law, $lb/100ft^2$
k - consistency index, $Pa\text{-}S^n$
n - flow behavior index, dimensionless
V_a - Average velocity, ft/min.
$d_2 - d_1$ - Hydraulic diameter, inches
q - Pump rate, gpm

Field data

Pump rate	=	*854gpm*
TVD	=	*6745ft*
Length of drill pipe	=	*6804ft*
Length of drill collar	=	*492ft*
Length of Casing	=	*6975ft*
Hole ID	=	*16 inches*
Drill pipe OD	=	*5.5 inches*
Drill collar OD	=	*7.785 inches*
Cuttings diameter	=	*~ 0.13-inch*
Cuttings shape	=	*Rounded and wrinkled*
Average density of cuttings	=	*18.5 ppg*
Hole inclination	=	*0, 45°*
Drillpipe eccentricity	=	*0.75*
Drilling fluid	=	*Water-based mud (Table 1)*
Fluid density	=	*10 ppg*

Basic dimensionality

With Equation 8;

$$\frac{lb/in^2}{ft} = \left(\frac{lb/100ft^2}{in}\right) + \left[\left(\frac{lb.Sec^n}{100ft^2}\right) * \left(\frac{ft^n}{Sec^n}\right) * \left(\frac{1}{in(in^n)}\right)\right]$$

$$LHS = \left(\frac{lb}{100ft^2}.\frac{1}{in}\right) + \left(\frac{lb.Sec^n}{100ft^2}.\frac{144.in^n}{Sec^n}.\frac{1}{in.in^n}\right)$$

$$LHS = \left(\frac{lb}{100ft^2}.\frac{1}{in}\right) + \left(144.\frac{lb}{100ft^2}.\frac{1}{in}\right)$$

$$LHS = \frac{lb/in^2}{ft} = \frac{lb}{100 * 144in^2} * \frac{1}{in} * \frac{12in}{ft}$$

$$Neglecting\ constants; \frac{lb}{in^2 * ft} = \frac{lb}{in^2 * ft}$$

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