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FULL LENGTH ARTICLE

Experimental and modeling hydraulic studies of foam drilling fluid flowing through vertical smooth pipes

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Abstract Foam has emerged as an efficient drilling fluid for the drilling of low pressure, fractured and matured reservoirs because of its the ability to reduce formation damage, fluid loss, differential sticking etc. However the compressible nature along with its complicated rheology has made its implementation a multifaceted task. Knowledge of the hydrodynamic behavior of drilling fluid within the borehole is the key behind successful implementation of drilling job. However, little effort has been made to develop the hydrodynamic models for the foam flowing with cuttings through pipes of variable diameter. In the present study, hydrodynamics of the foam fluid was investigated through the vertical smooth pipes of different pipe diameters, with variable foam properties in a flow loop system. Effect of cutting loading on pressure drop was also studied. Thus, the present investigation estimates the differential pressure loss across the pipe. The flow loop permits foam flow through 25.4 mm, 38.1 mm and 50.8 mm diameter pipes. The smaller diameter pipes are used to replicate the annular spaces between the drill string and wellbore. The developed model determines the pressure loss along the pipe and the results are compared with a number of existing models. The developed model is able to predict the experimental results more accurately.

1. Introduction

Foam finds its application as an efficient fluid in drilling of low pressure, marginal or highly fractured fields because of its inherent advantages over conventional drilling fluids [1–3]. It has the ability to reduce formation damage, lost circulation, differential sticking etc. Moreover, it can control the effective circulation density of the drilling fluid which helps in maintaining the desired bottom hole pressure [4–7]. Thermodynamically, foam

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Nomenclature

ΔP, p, ∂p	pressure, M/Lt^2	u_s	velocity of solids, L/t
ΔX, L, ∂x	conduit length, L	V_E	entrainment velocity of solids
D	pipe diameter, L	Q	flow rate of foam, L^3/t
r	pipe radius, L	C_s	volumetric concentration of solids, dimensionless
A	area of cross section, L^2	C_f	volumetric concentration of foam, dimensionless
g	acceleration due to gravity, L/t^2	μ_f	viscosity of foam, M/Lt
ρ_f	density of foam, M/L^3	τ	foam quality, dimensionless
ρ_s	density of solids, M/L^3	β_c	slip correction factor, L^3/Mt
k	consistency index, Mt^{n-2}/L	f	friction factor, dimensionless
n	behavior index, dimensionless	N	number of data points
τ_w	wall shear stress, M/Lt^2	SD	Standard Deviation
τ_o	initial shear stress, M/Lt^2	s	solids
u_f	foam velocity, L/t	f	foam

is an unstable system in nature which is formed by trapping pockets of gas in a liquid film of base fluid. Addition of surfactant and polymers to the base fluid helps to enhance the stability and apparent viscosity of the foam to a great extent [8–10].

The high viscosity of foam enables the efficient cutting transportability but at increased pressure drop [11–13]. Compressible nature and complex rheological properties of the foam makes the predictions of its performance a difficult task [14,15]. Change in shearing affects the rheology and pressure losses during the flow of foam for a given foam quality [12,16]. Studies are being performed to predict the hydrodynamic behavior of the foam along with its cutting transport ability when subjected to different shear rates and flow velocities [17–19]. Foam quality which is the fraction of gas entrapped in liquid film, plays a vital role in governing the behavior of foam under flow condition. In dynamic bore hole condition, it is very hard-hitting job to have a control over fluid rheology and foam quality to understand the hydrodynamics of fluid. Detailed investigation is necessary to understand the foam hydraulics with variable injection rates, pipe diameters, cutting loading, foam characteristics etc.

In literature, different investigations on rheological foam flow behavior have been reported to model the rheological characterization of foam in recent years. But, the disagreement among the different studies and flow models in the literature is due to the complexity of foam hydrodynamics owing to the difference in analytical approaches and experimental setups. The two techniques that have been used for studying the hydrodynamics of the foam are primarily qualitative approach and volume equalized approach [20,21]. In Qualitative approach the foam is considered as single phase fluid characterized by its quality. In volume equalized approach the foam normalizes the quality using the volume expansion ratio which is defined as the ratio of density of liquid to that of foam. This approach is valid for all foam qualities. Valko and Economides and Saintpere have utilized this volume equalization principle for estimating the pressure losses for foam flowing through the pipe at different inclinations, while some other researchers like Blauer and Shanghani have utilized the quality approach for the same. The experimental results documented by Ozbayoglu are compared with the existing model. The existing model is able to predict the actual hydrodynamics for all experimental variations in flow rate, foam quality, pipe diameter and cutting loading properties [19,22–25].

In the present study an indigenously designed flow loop system was used for the study of differential pressure losses across the pipe for foam flowing through it with and without the cuttings. The qualitative approach was used for further study of the hydrodynamic behavior. The foam flow inside the pipe is treated as a homogeneous system, whereas, multiphase flow is considered when solid cuttings were introduced into the system [26,27]. Unlike other studies, the foam under present study was able to carry most of the cuttings loaded along with it. The cuttings were observed to be trapped within the gelled structure of the foam. In order to predict the best hydraulic model applicable for the foam flow, two of the best fitted models – qualitative and volume equalized systems are compared with the experimental data [25,29,30]. The estimated results exhibit an appreciable deviation from the experimental data. A new model has been developed to estimate the differential pressure loss across the test section using the principles of conservation of mass and momentum. The developed model is found to predict the pressure losses for the foam flow with and without cuttings more accurately compared to the existing models.

2. Material and method

2.1. Material

Different chemicals used for the present investigation were of high purity (>99.5%) and were used without further treatment. Anionic surfactant SDS (sodium dodecyl sulfate) was purchased from Fisher Scientific, Mumbai, India. The non-ionic polymer, Hydroxy Ethyl Cellulose used in the present study was obtained from Otto Kemi, Mumbai, India. KCl was purchased from Qualigens Chemicals Pvt. Ltd., India. The Coal Cuttings were collected from a coalbed methane (CBM) drill site and was sieved for a size (8/10) with an average diameter of the cuttings to be 2 mm. The density of coal cutting was determined to be 2.18 g/cm^3.

2.2. Experimental setup

Investigation of foam flow through vertical pipe was conducted on an indigenously designed flow loop as shown in Fig. 1. It consists of a test section (18) made up of an acrylic pipe 2.2 (length = 2 m, diameters = 50.8 mm, 38.1 mm and

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