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EFFECTS OF SALINITY ON THE HYDRAULIC CHARACTERISTICS OF WELAN GUM FLUIDS IN STRAIGHT AND COILED TUBING

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ABSTRACT

At low concentrations, welan gum fluids have high viscosity, excellent suspending properties, shear thinning (pseudoplastic) rheological properties, viscosity retention at high temperatures and provides excellent friction pressure reduction. Hence, they are used in oilfield operations including hydraulic fracturing, wellbore cleanup, cementing and drilling for viscosity enhancement and friction pressure reduction purposes. In drilling and completion operations, brine solutions are commonly used as base fluids, therefore it is essential to quantify the effects of salinity on the rheological and hydraulic properties of welan gum.

In this work, the effects of salinity on the rheological and hydraulic properties of welan gum fluids of various concentrations (0.5, 1, 2 and 3 lb/bbl) in fresh water, 2% and 4% KCl has been evaluated through experimental studies. The experimental set-up includes a ½-in. OD flow loop with a 15-ft straight section and 18-ft coiled tubing with curvature ratio of 0.019. From the experimental data gathered, it is confirmed that rheology of welan gum fluids is sensitive to the concentration of salt. The sensitivity is seen as a reduction in viscosity of fluid as the concentration of salt is increased.

For flow in straight tubing, it is observed that at low concentrations of 0.5 and 1.0 lb/bbl, welan gum fluids in brine solutions exhibit lower drag reduction compared to that in fresh water. The opposite effect is observed at higher concentrations of 2.0 and 3.0 lb/bbl. It is also observed that in coiled tubing, the drag reduction characteristics of welan gum fluids in brine solutions increased when compared with those prepared with fresh water.

The friction pressure data for welan gum fluids in straight and coiled tubing as observed in the experimental investigation are correlated using the following dimensionless

parameters – Fanning friction factor and generalized Reynolds number. These correlations are found to provide good accuracy for prediction purposes when compared to the experimental data from larger tubing sizes.

CHAPTER 1

INTRODUCTION

The use of water soluble polymers is fundamental in oil and gas production operations such as drilling, hydraulic fracturing, wellbore cleanup, cementing and acidizing. In drilling muds they function as drill bit cooling, cleaning and protecting agents, and as drag reducing fluids allowing for faster drilling speeds. In workover and completion fluids, the polymers help to achieve and maintain maximum well productivity by contributing to hole cleaning, rock cutting suspension, and drag reduction. In tertiary oil recovery, polymeric aqueous solutions are injected into oil reservoirs to displace the oil to production wells (Lapasin et al. 1995). They are also used for fluid loss control, shale stabilization and flocculation purposes. All the polymers used in these applications possess high molecular weight, high swelling at low polymer concentration, high pseudoplasticity, high efficiency as suspending agents, thermal stability and compatibility with high concentration of various salts.

Three categories of water soluble polymers are commonly used in oil and gas production: polysaccharides (biopolymers), modified polymers, and synthetic polymers. Polysaccharides are formed from the polymerization of saccharide molecules through the process of bacterial fermentation; their molecules are bonded through glycosidic linkages and they are relatively non-ionic. Commonly used polysaccharides in the oilfield include Xanthan, guar and welan gum. The modified polymers are obtained by chemically treating polymers to achieve certain desired properties, through the addition of side chains. Examples of modified polymers are hydroxyethyl cellulose (HEC), hydroxypropyl guar (HPG) and carboxymethyl cellulose (CMC). Synthetic polymers used in the oilfield include polyacrylamides and partially hydrolyzed polyacrylamide (PHPA).

Welan gum (formerly known as S-130) is a commercial available bacterial polysaccharide produced by an *Alcaligenes* species (ATCC-31555) in an aerobic, submerged fermentation (Kang et al. 1982). It has found a wide range of uses in oilfield operations including hydraulic fracturing, wellbore cleanup, cementing and drilling for viscosity enhancement and friction pressure reduction purposes. Welan gum at low concentrations has high low shear rate viscosity (LSRV) at low concentrations, excellent suspending properties, pseudoplastic (shear thinning) rheological properties, excellent stability in a wide pH range (2-12), and excellent retention of viscosity at temperatures up to 150 °C.

Welan gum is an anionic polysaccharide and therefore must have polyelectrolyte properties due to the presence of D-glucuronic acid in its chemical structure. Polyelectrolytes are polymers whose repeating units bear an electrolyte group, which will dissociate in aqueous solutions, making the polymers charged. Thus, polyelectrolyte properties are similar to both electrolytes and polymers, and are sometimes called polyions because their charge arises from many ionized functional groups positioned along the chain contour. Electrostatic repulsion between the ionized groups in solution lead to an increase in the hydrodynamic volume of the polymer chains and subsequent increase in solution viscosity. However, adding electrolyte (for example brine) to the polyelectrolyte solution leads to decrease in viscosity due to the screening of the electrostatic repulsions. The charge screening causes a reduction in hydrodynamic size of the molecule, which when not accompanied by increased intermolecular association, results in a decrease in solution properties (Campana et al. 1990; Rochefort et al. 1987). The effects of brines on the solution properties of polelectrolytes is illustrated in Figure

1.1. Polyelectrolytes are classified as strong or weak and the net charge of the later varies with pH.

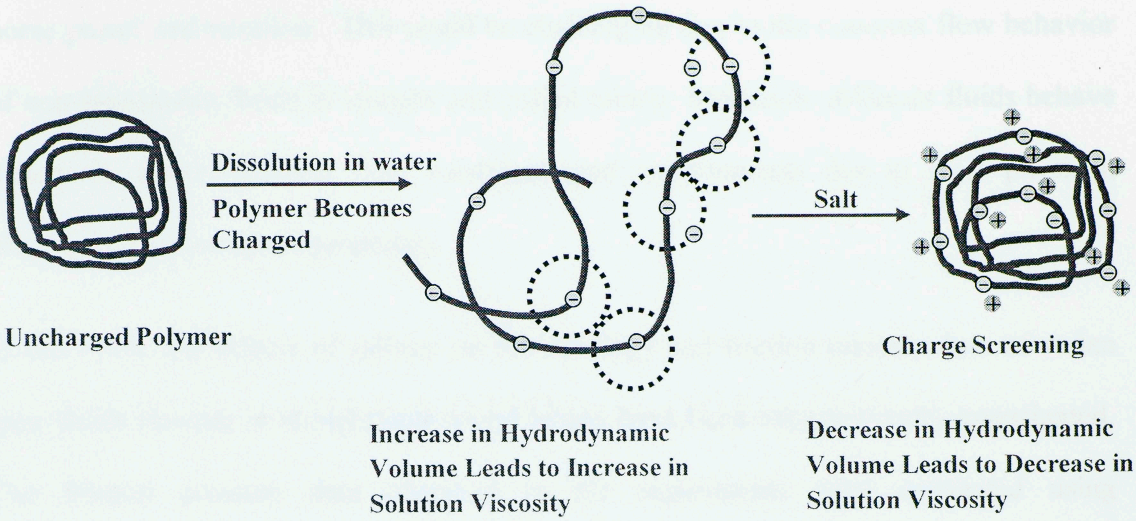

Fig. 1.1 Effects of Salinity on the Solution Properties of Polyelectrolytes

Brines are normally used as base fluids, to prevent clay swelling and shale instability, in oilfield applications where welan gum fluids are used. Welan gum fluids are compatible with common oilfield monovalent and divalent brines within the normal range of application needs in the oilfield. Examples of monovalent brines used in the oilfield include – sodium chloride, sodium bromide, potassium chloride, and potassium bromide, and divalent brines include – calcium chloride, calcium bromide, and zinc bromide. Divalent brines have higher ionic strength when compared with monovalent brines of same concentration, hence, they are expected to cause more significant decrease in solution viscosity of welan gum fluids. The high density brines from 11.6 – 19.2 lb/gallon are usually obtained by blending calcium chloride, calcium bromide and zinc bromide. Improved performance can be obtained by formulating the brines for a minimum ionic strength.

During oilfield operations such as hydraulic fracturing, acidizing and wellbore cleanout, aqueous solutions of welan gum are pumped downhole through straight and coiled tubing. Therefore, development of correlations to accurately predict the frictional pressure losses in the tubings is essential for engineering design purposes and for pump horse power optimization. This could be challenging due to the complex flow behavior of non-Newtonian fluids in straight and coiled tubing. Moreover, different fluids behave differently under different flow conditions and environments due to their physical, chemical and rheological properties.

In this work, the effects of salinity on the rheology and friction pressure loss of welan gum fluids flowing in straight and coiled tubing have been experimentally investigated. The friction pressure data observed in the experiments were correlated using dimensionless variables.

1.1. OBJECTIVES

The objectives listed below were accomplished by performing a comprehensive experimental study of welan gum fluids of various concentrations and salinities at ambient conditions, using the straight and coiled tubing flow loop, located at the Well Construction Technology Center of the University of Oklahoma. The objectives of this study include:

- Rheological characterization of welan gum fluids.
- Study the effect of salinity on the rheological characteristics of welan gum fluids
- Investigation of the effect of salinity on friction pressure losses of welan gum fluids.
- Development of correlations for the prediction of friction factor for flow of welan gum fluids in both straight and coiled tubing.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1. LITERATURE REVIEW

Welan gum is a commercial bacterial polysaccharide produced by an *Alcaligenes* species (ATCC-31555) in an aerobic, submerged fermentation. The medium contains 3% glucose as the carbon source, phosphate as a buffer, ammonium nitrate and soy peptone as sources of nitrogen and trace elements such as iron, magnesium, molybdate, cobalt, zinc, copper manganese, and borate. The fermentation process usually last 60 – 70 hours, after which the polysaccharide is recovered by precipitation of the polymer with isopropanol (Kang et al. 1982).

Welan gum has found a wide range of uses in oilfield operations including hydraulic fracturing, wellbore cleanup, cementing and drilling for viscosity enhancement and friction pressure reduction purposes. Hoskin et al (1991) invented crosslinked welan gum gels for selectively plugging regions of higher permeability within an oil bearing subterranean formation, thereby improving sweep efficiency during fluid flood oil recovery. These gels will form in lower salinity brines and under virtually all pH conditions. They are stable under the conditions encountered in flooding operations including high temperatures. Aqueous solutions of welan have higher suspension capability, low shear rate viscosity and thermal stability compared with that of hydroxypropyl guar, hydroxyethylcellulose (HEC) and Xanthan (Kang et al. 1983; Sanford et al. 1984; Whistler and BeMiller 1993).

Several investigators have studied the chemical structure and solution properties of welan gum. In 1985, Jansson et al. determined the chemical structure of welan and their findings were later confirmed by O'Neill et al. (1986). They found that it contains Lmannose, L-rhamnose, D-glucose, and D-glucuronic acid. Figure 1 shows the molecular structure of welan gum. It is structurally similar to gellan which has the same tetrasaccharide repeating units, but without the side chains (Jansson et al. 1985). Despite their structural similarities, both biopolymers have different aqueous solution properties, notably, gellan forms gels whereas welan is a non-gelling polysaccharide (Sanford et al. 1984). A study by Crescenzi et al (1986; 1987) to investigate the influence of side-chains on the dilute-solution properties of welan and gellan found that the side chains mediated against conformational ordering.

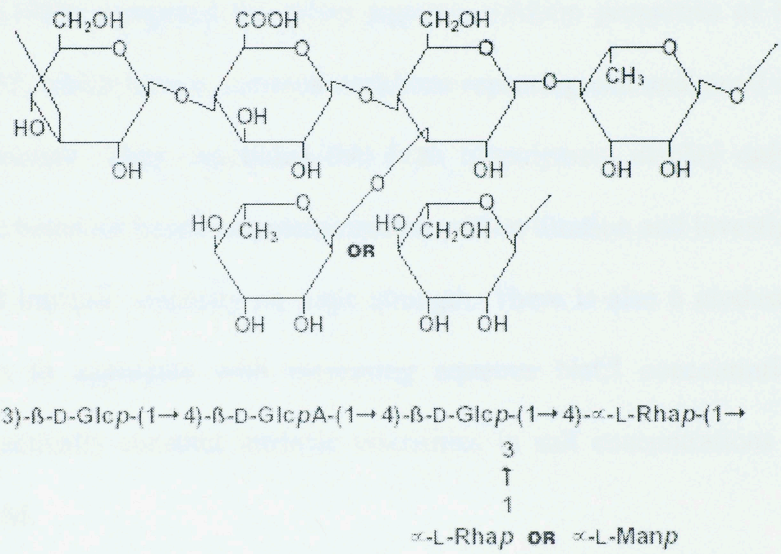

Fig. 2.1 Molecular Structure of Welan Gum (After Urbani and Brant, 1989)

Welan gum must have polyelectrolyte properties due to the presence of D-glucuronic acid in its chemical structure. In 1990, Campana et al investigated the polyelectrolyte and rheological behavior of dilute and semi-dilute aqueous welan gum solutions. It was shown, based on its thermodynamic properties, that the conformation of welan gum is compatible with an extended double-helix similar to gellan. The polyelectrolyte behavior of welan gum was confirmed from the decrease of viscosity with the addition of salt without any conformational change. They also noted that the initial source of welan gum, industrial powder or unpasteurized broth, could affect its polyelectrolyte character, a finding that was confirmed by Lopes et al. in 1994. They showed that the rheological properties of welan gum and the extension of the welan chain due to electrostatic repulsions are influenced by the origin of welan gum sample and the method of purification used. This behavior is attributed to the presence and shape of aggregates which are irreversible when simple purification is used. However, welan gum solutions do not exhibit aggregate-like behavior when the welan broth is treated by a mild alkaline process before precipitation.

Urbani et al. (1989) compared the dilute aqueous solution properties of S-130 (welan gum) and S-657, which have a common backbone repeating unit and small differences in side chain structure. They concluded that both biopolymers display only very weak polyelectrolyte behavior based on potentiometric proton titration and investigations of the dependence of intrinsic viscosity on ionic strength. There is also a modest tendency of both polymers to aggregate with increasing aqueous NaCl concentration and they maintained practically constant intrinsic viscosities in salt concentrations in the range 0.001 – 0.100 M.

Budd (1995) conducted ultracentrifuge studies of the polyelectrolyte behavior of welan gum, the results of which showed that it exhibits typical polyelectrolyte properties at very low ionic strength. However at NaCl concentrations greater than about 0.1 mol/dm^3 the charge effects due to increasing salt concentration are eliminated. He suggested that screening of the carboxylate groups through intramolecular interactions with the side chains and weak intermolecular association could lead to the observed insensitivity of solution properties to salt concentration above 0.1 mol/dm^3. However, Campana et al. (1997) attributed the weak polyelectrolyte behavior to the high stiffness of the welan gum chain, which has been compared to the stiffness of DNA (Campana et al.1990). Their results showed that the value of the intrinsic viscosity at low ionic strength was close to that obtained at higher salt concentration. Stokke et al. (1988) used electron microscopy to investigate the structure of Xanthan and welan gum, and concluded that the very stiff structural chains of these polysaccharides resulted in the high viscosity and salt-tolerance of their solutions.

The solids suspension and transportation properties of welan gum and Xanthan based fluids can be directly correlated to their low-shear-rate-viscosity (LSRV) and elasticity (Powell et al. 1991). In their study, they also determined that a minimum effective or critical polymer concentration (CPC) must be reached or exceeded in order to achieve optimal fluid performance during oilfield drilling or workover operations. The CPC is affected by different factors including temperature, salinity, average shear rate, velocity gradients, hole angle, polymer molecular properties, and the size and concentration of the suspended solids.

For oil-field applications, welan gum solutions are pumped downhole through straight and coiled tubing, therefore it is essential to understand the flow characteristics of these solutions under the conditions encountered in the field. Recently, an experimental investigation of the effect of polymer concentration and coiled tubing curvature ratio on the hydraulic characteristics of welan gum fluids in straight and coiled tubing was carried out by Asubiaro and Shah (2008). They developed correlations to predict Fanning friction factor for flow of welan gum fluids in straight and coiled tubing. However, only welan gum fluids in fresh water were considered in their work. In drilling and completion operations, brine solutions are commonly used as base fluids to prevent clay swelling and shale instability. Therefore, it is important to quantify the effects of commonly used oilfield brines on the rheological and flow properties of welan gum fluids of concentrations typical in oilfield applications, especially in straight and coiled tubing. In this work, the effect of salinity on the flow characteristics for welan gum fluids in straight and coiled tubing has been experimentally investigated. The friction pressure data as observed in the experimental investigation are correlated using dimensionless parameters. These correlations are found to provide good accuracy for prediction purposes when compared to the experimental data.

2.2. RHEOLOGICAL CHARACTERIZATION

Rheology is the study of deformation and flow of matter. Fluid is substance that undergoes continuous deformation when force is applied and is generally classified as Newtonian (shear rate independent) or Non-Newtonian (shear rate dependent). An accurate knowledge of the rheological behavior of fluids is important in engineering design to determine their ability to perform certain functions.

2.2.1. Rheological Models

Figure 2.2 illustrates Newtonian and three kinds of non-Newtonian flow behavior. For Newtonian fluids the applied shear stress is directly proportional to the shear rate in laminar flow. The viscosity is the ratio of shear stress to shear rate and can be obtained as the slope of the shear stress versus shear rate plot (which passes through the origin). It is constant at a given temperature and pressure regardless of the shear rate. The shear stress for a Newtonian fluid is expressed as:

$$\tau = \mu\gamma \tag{2.1}$$

where, $\tau =$ shear stress, $\gamma =$ shear rate, and $\mu =$ viscosity

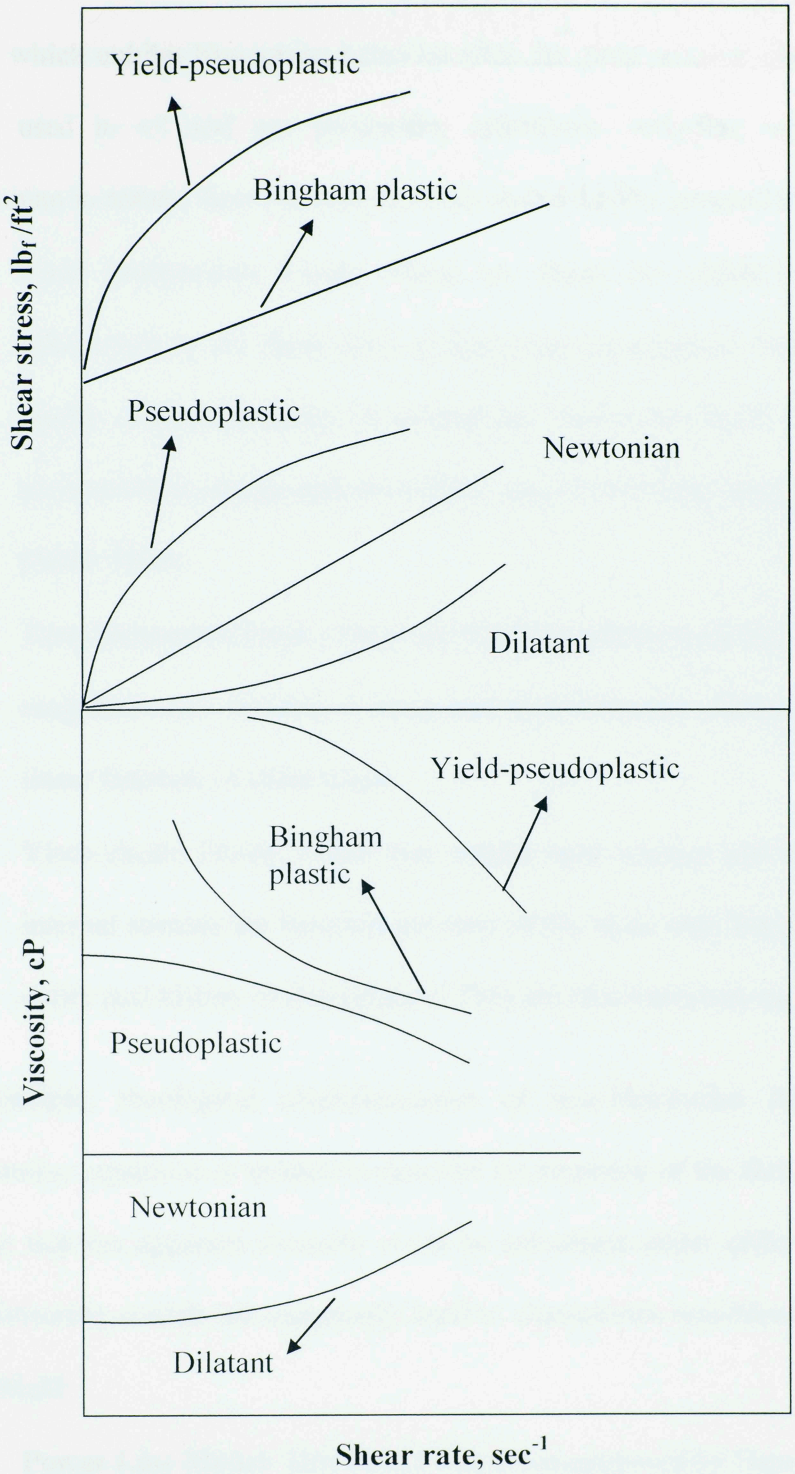

Fig. 2.2 Newtonian and Non-Newtonian Behavior

A non-Newtonian fluid is that whose rheogram (shear stress versus shear rate plot) is non-linear or does not pass through the origin (Chhabra and Richardson 2008). The apparent viscosity for these fluids is dependent on shear rate, except for Bingham plastic fluids which exhibit Newtonian behavior after the yield stress is overcome. Most of the fluids used in oil and gas production operations, including welan gum, are non-Newtonian in nature. Non-Newtonian fluids can be further grouped into three categories:

- Time Independent Fluids: These are fluids for which the rate of shear is determined by the shear stress at that point and instance. They are also known as purely viscous, inelastic or generalized Newtonian fluids. The shear rate at a given point is unique and not a linear function of shear stress except for Bingham plastic fluids.
- Time Dependent Fluids: These are fluids for which shear rate is a function of both magnitude and duration of shear and their kinematic history. Shear rate is not a linear function of shear stress.
- Visco-elastic Fluids: Fluids that exhibit both viscous and elastic behavior. The internal stresses are function not only of the shear rate, but also depend upon the entire past history of deformation. They are also known as memory fluids.

In principle, rheological characterization of non-Newtonian fluids requires using constitutive equations or models to describe the response of the fluid to changes in shear rate so that the apparent viscosity could be calculated under different flow conditions. The following models are commonly used to characterize non-Newtonian fluids used in the oilfield:

- **Power Law Model**: This model which was proposed by Ostwald and de Waele, is the most popular expression for describing the flow behavior of oil field fluids. It describes the relationship between shear stress and shear rate for shear thinning fluids using two parameters. It is only applicable over a limited range of shear rate (or stress) where the rheogram (plotted on double logarithm coordinates) can be approximated using a straight line. The non-linear rheogram curve passes through the origin and can be mathematically expressed as:

$$\tau = k(\gamma)^n \tag{2.2}$$

where k = fluid consistency index ($lb_f\text{-}sec^n/ft^2$)

and n = flow behavior index.

When $n < 1$ the fluid exhibits pseudoplastic or shear thinning properties. The apparent viscosity of these fluids decreases with increase in shear rate. Fluids for which $n > 1$ are referred to as shear thickening or dilatant fluids. The fluid is Newtonian when $n = 1$.

- **Bingham Plastic Model**: This model describes the flow behavior of fluids exhibiting viscosity that is independent of shear rate but require a finite stress known as yield stress to initiate flow. The plastic viscosity is obtained from the slope of the linear portion of the shear stress versus shear rate curve. Mathematically, the two parameter model can be expressed as:

$$\tau = \tau_o + \mu_p \gamma, \qquad \tau \geq \tau_o \tag{2.3}$$

where τ = shear stress, lb_f/ft^2

τ_o = yield stress, lb_f/ft^2

γ = shear rate, sec^{-1}

μ_p = plastic viscosity, cP

- **Herschel-Bulkley Model**: This model generalizes the Bingham plastic model using three parameters to define the non-linear flow curve. It exhibits a yield stress and plastic viscosity that is shear rate dependent and can be represented mathematically as:

$$\tau = \tau_o + k(\gamma)^n, \qquad \tau \geq \tau_o \tag{2.4}$$

where τ = shear stress, lb_f/ft^2

τ_o = yield stress, lb_f/ft^2

γ = shear rate, sec^{-1}

k = fluid consistency index ($lb_f\text{-}sec^n/ft^2$)

and n = flow behavior index.

The model reduces to power law when there is no yield point and to Bingham plastic model when $n = 1$.

2.3. RHEOLOGY MEASUREMENT METHODS

The rheological characterization of fluids used in the production of oil and gas is challenging due to their non-linear and complex mechanical properties. For non-Newtonian fluids, variations in shear rate within the flow geometry could undermine the accurate determination of the shear stress – shear rate relationship. Such limitations could be overcome by utilizing proper measuring strategies and careful design of the measuring instruments. The basic features and working principles of some of the most commonly used rheometers in the oil and gas industry are discussed below:

- **Pipe or Capillary Viscometer**: Due to their simplicity, low cost, structural similarities to many process flows and accuracy (in the case of long capillaries) capillary viscometers are the most common instruments used for viscosity measurement. In the capillary viscometer, fluid is allowed to flow through a known length of a small diameter pipe at a desired flow rate, and the pressure drop across the tubing length is determined. The flow rate, under laminar flow conditions, is converted to wall shear rate while the measured pressure drop is converted to wall shear stress. The power law parameters are then obtained from a logarithmic plot of wall shear stress and wall shear rate. The pipe viscometer is a slight modification of the capillary viscometer, in which a larger pipe diameter is used. Capillary viscometers are the instruments of choice to accurately determine the viscosity of Newtonian fluids and highly diluted systems.

- **Rotational Rheometer:** Rotational rheometers are usually preferred for the determination of the rheological properties of non-Newtonian fluids. Rotational rheometers are generally classified as controlled shear rate and controlled stress rheometers. In the rate-controlled instruments, the velocity of rotation of one member of the measuring system is controlled, and the resulting couple is measured either on the same member (Searle system) or on the other (Couette system). On the other hand, in stress controlled instruments the couple is applied to one member of the measuring system and its rate of rotation is measured (Lapasin and Pricl, 1995). The concentric cylinder, cone-and-plate and parallel-plate measuring geometries can be used with the rotational rheometers.

The rotational viscometer (model 35 Fann viscometer), shown in Figure 2.3, is one of the most common rotational viscometers used in the oilfield. The measuring system consists of two concentric cylinders: the inner cylinder or bob (which is stationary) and the outer cylinder or sleeve (which rotates). The test fluid is contained in the narrow annular space between the cylinders. The sleeve is rotated at a known speed and torque due to the fluids viscous drag is exerted on the bob. The deflection of a helically wound spring, which balances the toque, can be read on a calibrated dial at the top of the viscometer. The rotor speed (measured in rotations per minute, rpm) can be converted to shear rate and the torque indicated by the dial reading is converted to shear stress, for a given bob-sleeve geometry and torque spring. The power law parameters are obtained by plotting the shear stress and shear rate on a logarithmic scale.

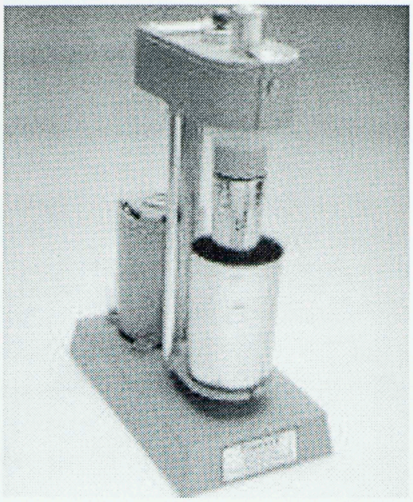

Fig. 2.3 Rotational Viscometer (Model 35 Fann)

2.4. DRAG REDUCTION

The resistance to flow encountered during fluid flow through pipes is known as drag or friction. It has long been established that drag could be drastically reduced during turbulent flow, by adding small amounts of specific high molecular and long-chain polymers to the fluid flow, thereby increasing fluid pumping capacity (Drag reductions of up to 80% over the solvent could be achieved with these "drag reducers"). The drag reducing capability of polymers depends on its molecular weight, molecular weight distribution, molecular structure and solubility in the solvent. The phenomenon has found many applications in various processes in the petroleum industry such as hydraulic fracturing, acidizing, wellbore cleanup, cementing and drilling. Drag reduction, which is usually expressed in percentage, can be computed from the friction pressure-flow rate data obtained during the flow of the solvent and polymer solution.

Mathematically, drag reduction can be expressed as:

$$DR = 1 - \left({f_p}/{f_s} \right) \tag{2.5}$$

where f_p = Fanning friction factor of polymer solution

f_s = Fanning friction factor of the solvent

In the above equation, it is assumed that the density of the polymer solution is equal to the density of the solvent, which is true for the low welan gum fluid concentrations used in this study.

2.5. IONIC STRENGTH

The ionic strength of a solution is a measure of the concentration of ions contained in that solution. Ionic compounds like salt dissolve and dissociate in water forming charged particles known as ions. Ionic strength has significant impact on the solution properties of polymers, such as the viscosity or solubility. Mathematically, ionic strength is expressed as:

$$I = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2 \quad (2.6)$$

where c_i = molar concentration of i-th ion, mol/dm^3

z_i = charge number of ion.

The sum is taken over all the ions in the solution.

CHAPTER 3

EXPERIMENTAL SETUP AND TEST PROCEDURE

The purpose of this experimental study is to investigate the effects of salinity on the hydraulic characteristics of welan gum fluids of concentrations typical in oilfield applications, at ambient temperature conditions (75°F). To achieve this purpose, the ½ in. fluid flow loop at the Well construction Technology Center as described in this chapter was utilized.

3.1. EXPERIMENTAL SETUP

The fluid flow loop, shown in Figure 3.1 is a pipe flow viscometer designed to characterize hydraulic behavior of fluids. The main components of the flow system are: ½- in. OD (0.435-in. ID) straight and coiled tubing as flow conduit, fluid mixing and pumping equipment, and data acquisition system. The fluid flow loop has a 15 ft long straight section with 3 ft entrance and 2 ft exit lengths and 18 ft long coiled tubing with curvature ratio of 0.019. The fluid to be characterized is mixed in a 1000 gal tank. Pumping is achieved by the use of a progressive cavity pump (Model 6P10 Moyno) and a centrifugal pump (Model 5M Deming) which serves to boost the suction of the progressive cavity pump. The maximum flow rate achievable by the progressive cavity pump depends on the type of fluid being pumped. The maximum working pressure of the flow loop is 1200 psi. The valves in the flow loop are all full-opening ball type valves. The data collected in the flow test included: flow rate, differential pressure across various sections of straight and coiled tubing, fluid density, fluid temperature and system pressure. A Coriolis flowmeter (Micromotion® Elite Model CMF050) was used for the measurement of the flow variables including the following:

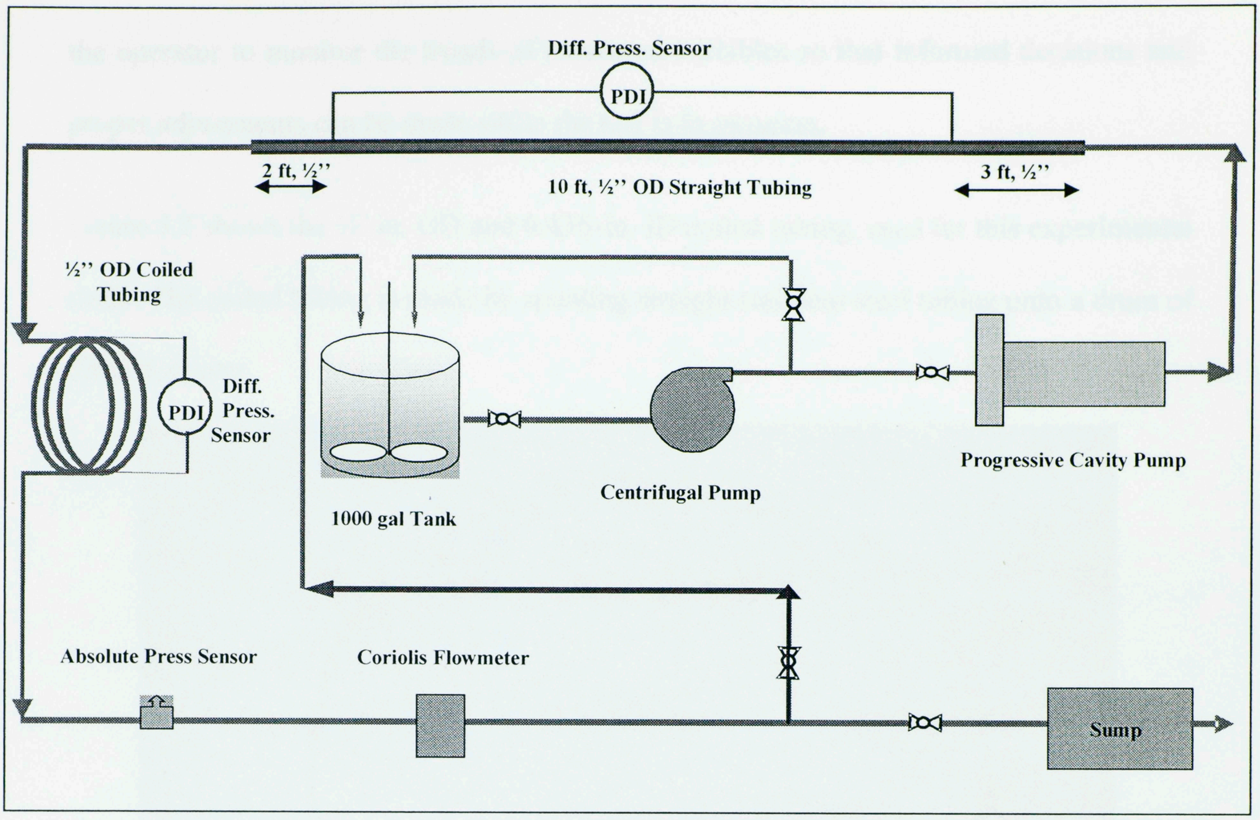

Fig. 3.1 Schematic Diagram of Experimental Setup

i. Flow rate in the range 0-30 gal/min with accuracy of ± 0.05%

ii. Density with accuracy ± 0.0005 g/cc.

iii. Temperature with accuracy ± 1°C.

Differential pressure transducers to determine the frictional pressure losses in straight and coiled tubing sections were placed across a known length of tubing. The maximum differential pressure span for these transducers is 0 – 100 psi with accuracy of ± 0.075%. The span used for the straight pipe section was 0 – 50 psi while that for the coiled tubing was 0 – 100 psi. The measured data from the flowmeters, pressure transducers as well as pressure gauges were collected and transmitted to a microcomputer where the data were displayed and saved for analysis. This task was accomplished using a data acquisition system (Fluke Hydra) which communicates with a host computer via a wireless modem radio link. The data acquisition system software provides the operator the option of displaying the data signals graphically while the test is in progress. This feature enables the operator to monitor the trends of measured variables so that informed decisions and proper adjustments can be made while the test is in progress.

Figure 3.2 shows the ½ -in. OD and 0.435-in. ID coiled tubing, used for this experimental study. The coiled tubing is made by spooling straight stainless steel tubing onto a drum of fixed diameter.

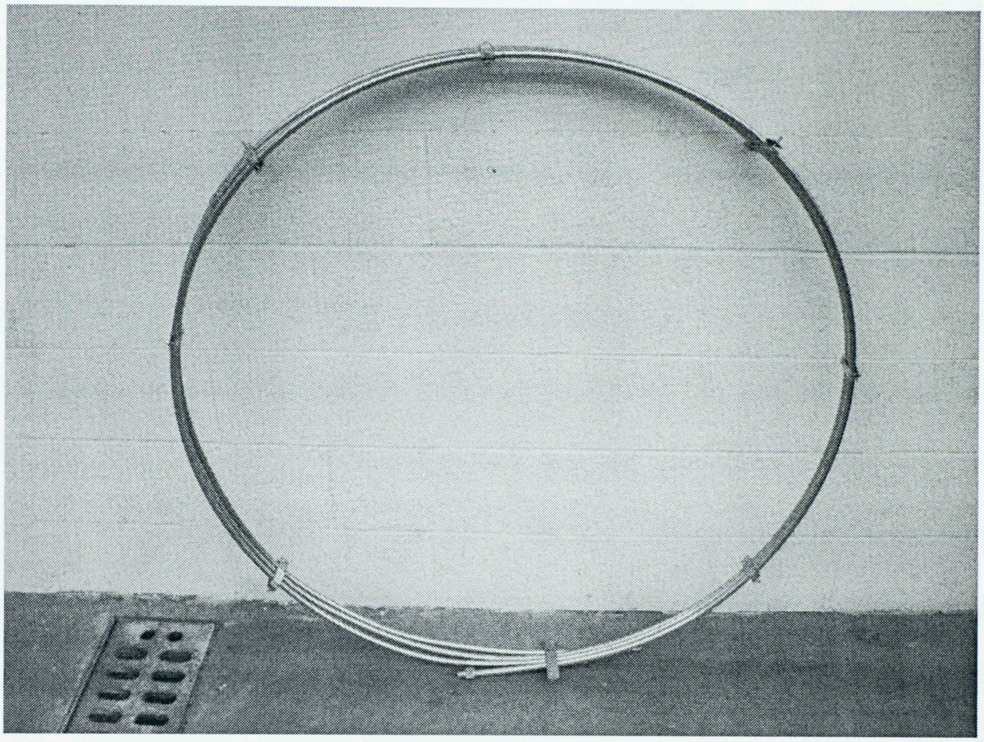

Fig. 3.2 ½ inch Stainless Coiled Tubing Used for Study

3.2. EXPERIMENTAL PROCEDURE

Proper fluid mixing procedures must be followed in the preparation of the test fluids. Therefore, the manufacturer's recommended mixing procedure for welan gum was followed for the preparation of the four fluid concentrations (0.5, 1.0, 2.0 and 3.0 lb/bbl) at different salinities (fresh water, 2% KCl and 4% KCl). Desired welan gum suspension was prepared by adding the proper amount of polymer to water in the mixing tank while operating the agitator at a moderate speed. The pH of the suspension was lowered to about 3 by adding a measured amount of muriatic acid to facilitate proper dispersion of the polymer. Once adequate mixing was achieved, the pH of the fluid system was increased to about 8.5 to 9 by adding sufficient quantity of sodium hydroxide solution. It is important to mention that dry caustic soda should never be used since it might lead to localized increase in pH resulting in the gellation of the polymer. The required amount of salt was then added to achieve the desired salinity. The fluid was allowed to hydrate for 24 hours. The following day, a fluid sample was collected from the tank and its rheological properties were measured with the rotational viscometer.

Prior to pumping test fluid through the flow loop, water at ambient temperature conditions (75^{o}F) was circulated to conduct system calibration. Then, welan gum fluid was pumped through the straight and coiled tubings at various flow rates and the corresponding pressure drop readings were recorded. Flow rate was set at a desired value and the steady-state pressure drop data across straight and coiled tubing lengths were recorded. Subsequently, flow rate was increased and corresponding pressure drop was noted. Test fluid was pumped in a single-pass to avoid polymer degradation due to excessive shear. Before terminating the test, another fluid sample was collected from the flow loop and the fluid rheology was again measured with the rotational viscometer for any possible degradation due to heating and/or shear. At the end of testing, system was flushed by pumping water and displacing the test fluid. It is important to mention that the system was calibrated every time a new test was performed to ensure that reliable data were generated.

3.3. DATA REDUCTION AND ANALYSIS

The measured flow rate, pressure drop, temperature and density data in straight and coiled tubings were recorded for analysis. Only stabilized region data were averaged and used for analysis.

3.3.1. Fluid Characterization

The rheological properties of the fluids tested were measured using the rotational viscometer with a bob and cup measuring geometry. The ratio of the bob to cup radius, β, for the viscometer is 0.936.

The dial readings were converted to obtain wall shear stress values, using the following equation.

$$\tau_w = 0.01066 N\theta_i \quad \textbf{(3.1)}$$

where, τ_w is wall shear stress (lb_f/ft^2), N is spring factor (1.0 for no. 1 spring) and θ is the dial reading. Wall shear rates were calculated from the speeds of the sleeve using the following equation.

$$\gamma_w = 1.703 \times RPM \quad \textbf{(3.2)}$$

where, γ_w is wall shear rate (s^{-1})

Logarithmic plots of wall shear stress versus wall shear rate were made to determine the power law parameters: flow behavior index, n, and consistency index, K_v.

Consistency index, K_v, obtained from the viscometer data, was converted to pipe consistency index, K_p by using the following equation (Shah 2008):

$$K_p = \frac{K_v}{\left[\frac{4n\sigma}{3n+1}\right]^n} \quad \textbf{(3.3)}$$

where, σ is a constant defined by:

$$\sigma = \left[\frac{\beta^{\frac{2}{n}}}{n\,\beta^2}\right]\left[\frac{\beta^2 - 1}{\beta^{\frac{2}{n}} - 1}\right] \quad \textbf{(3.4)}$$

Where Flow rate and pressure drop values were first converted to Fanning friction factor and generalized Reynolds number. These two dimensionless groups were used in characterizing fluid flow through straight and coiled tubing. The following equations (in field units) were used in the data analysis.

Generalized Reynolds number, (N_{Reg}), a dimensionless variable, for non-Newtonian fluids flowing through pipe was calculated using the following formula (Shah 2008):

$$N_{\text{Reg}} = 0.024 \times (3.85)^{-n} \frac{d_i^n \rho}{K_p 8^{n-1}} \left[\frac{q}{A} \right]^{2-n} \tag{3.5}$$

where, A is the cross-sectional area of the pipe ($in.^2$); d_i is the internal diameter of straight or coiled tubing ($in.$); q is the flow rate (gal/min); ρ is the fluid density (lb_m/gal); K_p is the pipe consistency index of the fluid ($lb_f\text{-}sec^n/ft^2$), and n is the flow behavior index of the fluid.

Fanning friction factor f, is a dimensionless variable used to determine friction pressure gradient and is defined by the following expression:

$$f = 25.8 \left[\frac{d_i \Delta p}{l v^2 \rho} \right] \tag{3.6}$$

where, l is the length between pressure ports (ft) and Δp is the pressure drop (psi).

Average velocity, v, (ft/sec) is calculated from the following equation.

$$v = \frac{q}{2.448 d_i^2} \tag{3.7}$$

3.3.2. Experimental Error Analysis

The maximum experimental percentage errors were computed for the dimensionless parameters: generalized Reynolds number and Fanning friction factor, based on the accuracy of physical measurements including flow rate, density and pressure drop from the Micromotion flow meter and differential pressure transducers. The accuracy of the pipe length and diameter measurements were taken to be ± 0.125 in. and ± 0.0001 in. respectively. The maximum experimental percentage error for the dimensionless parameters used in the analysis of welan gum fluids flow characteristics are presented in Table 3.1. The detailed error propagation analysis is shown in Appendix A.

Table 3.1 Experimental Percentage Error for Generalized Reynolds Number and Fanning Friction Factor

Tubing Type	Maximum % Experimental Error	
	Generalized Reynolds Number	Fanning Friction Factor
Straight Tubing	0.1	3.0
Coiled Tubing, r/R = 0.019	0.2	1.0

3.3.3. System Calibration

For system calibration and establishment of baseline for comparison, water data were acquired through ½-in. straight and coiled tubing at ambient temperature conditions (75°F). The pressure drop – flow rate data for water is shown in Appendix B. Data acquired from the flow loop were converted to Fanning friction factor and Reynolds number. The accuracy of the acquired water data from the straight pipe was examined by comparing with the following Drew et al. (1932) correlation for turbulent flow in smooth pipes.

$$f = 0.0014 + 0.125(N_{\mathrm{Re}})^{-0.32} \qquad \textbf{(3.8)}$$

This correlation is applicable in the Reynolds number range of $2100 < N_{Re} < 3 \times 10^6$ and is for Newtonian turbulent flow in smooth pipes.

The accuracy of the acquired water data from the coiled tubing was examined by comparing with the following Srinivasan et al (1970) correlation, which is valid for smooth coiled tubing in the turbulent flow regime.

$$f = \frac{0.084}{N_{\text{Re}}^{0.2}}\left(\frac{r}{R}\right)^{0.1} \quad \textbf{(3.9)}$$

where, r/R = curvature ratio, r = radius of coiled tubing and R = radius of coiled tubing reel. It is valid for Dean number range of, $N_{De\ critical}$ to N_{De} = 14,000 and curvature ratio from 0.0097 to 0.135.

Dean number (Dean et al. 1928) was introduced to characterize the flow in curved pipes and is given by,

$$N_{De} = N_{\text{Re}}\left(\frac{r}{R}\right)^{0.5} \quad \textbf{(3.10)}$$

Srinivasan et al. (1970) proposed the following Critical Dean number :

$$N_{De\,critical} = 2100\left[1 + 12\left(\frac{\text{r}}{\text{R}}\right)^{0.5}\right] \quad \textbf{(3.11)}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1. WATER TESTS

The water tests are performed to calibrate the flow system and to generate a baseline for comparison with the frictional pressure data of test fluids. The logarithmic plots of Fanning friction factor vs. Reynolds number for water through straight and coiled tubing is shown in Figure 4.1. It is observed that the water data from the straight and coiled tubing are in good agreement with the Drew and Srinivasan correlations for straight pipe and coiled tubing respectively. This is the expected result since both the straight and coiled tubing sections are made of stainless steel tubing which could be considered as smooth pipes with negligible roughness effect. It is important to mention that the system was calibrated every time a new test was performed to ensure that reliable data were generated.

From Figure 4.1, it can be observed that at a given Reynolds number, water flowing through straight pipe exhibit lower friction factor when compared to that in coiled tubing. The flow pattern through coiled tubing is different from that in straight pipe due to the presence of secondary flow. The variation in centrifugal forces across the pipe creates a non-uniform pressure distribution, with the maximum pressure occurring at the outer wall and the minimum pressure at the inner wall. This imbalance in pressure distribution creates secondary flow at right angle to the main flow that bringing about additional flow resistance and hence, increased frictional pressure loss. The secondary flow pattern is composed of counterrotating vortices, commonly called Dean vortices.

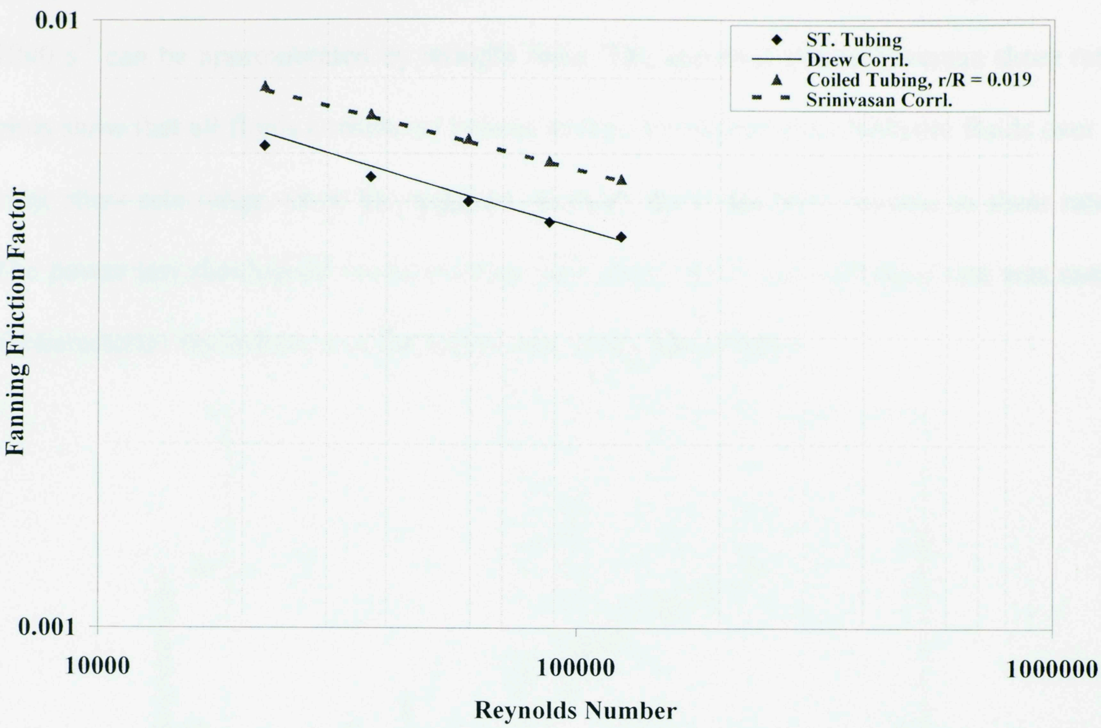

Fig. 4.1 Water Flow Data through ½-in. Straight and Coiled Tubing (r/R=0.019)

The maximum deviation of the measured values of friction factor from the predicted values for straight pipe and coiled tubing are 3.2 percent and 1.0 percent respectively. The maximum deviation values are within the acceptable range of experimental error and confirm the reliability of the friction pressure data obtained from the straight and coiled tubing. This also confirms the accuracy of the tubing diameter used for data analysis in this experimental set-up.

4.2. RHEOLOGICAL CHARACTERIZATION

Logarithmic plots of wall shear stress and wall shear rate (rheograms) obtained from rotary viscometer measurements for all welan gum concentrations considered in this study are shown in Figures 4.2 – 4.5. The corresponding apparent viscosity against shear rate plots are depicted in Figures 4.6 – 4.9. The rotational viscometer data for welan gum fluids investigated in this work are shown in Appendix C.

The plots of shear stress and viscosity versus shear rate for the shear rate range of 10.2 – 1000 s^{-1} can be approximated by straight lines. The apparent viscosity versus shear rate plots show that all fluids considered behave as non-Newtonian pseudoplastic fluids over a large shear rate range, since the apparent viscosity decreases with increase in shear rate. The power law rheological model relating wall shear stress and wall shear rate was used to characterize the behavior of the welan gum fluids investigated.

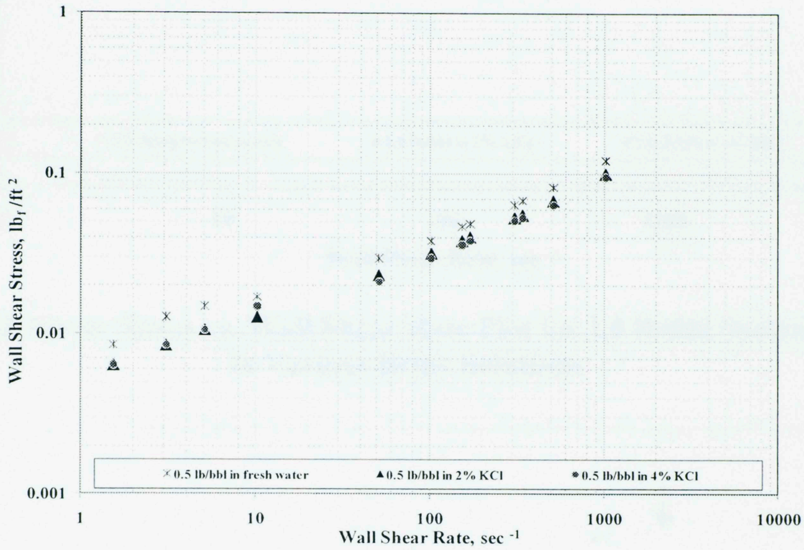

Fig. 4.2 Wall Shear Stress vs. Wall Shear Rate Plot for 0.5 lb/bbl Welan Gum Fluid in Various Brine Solutions

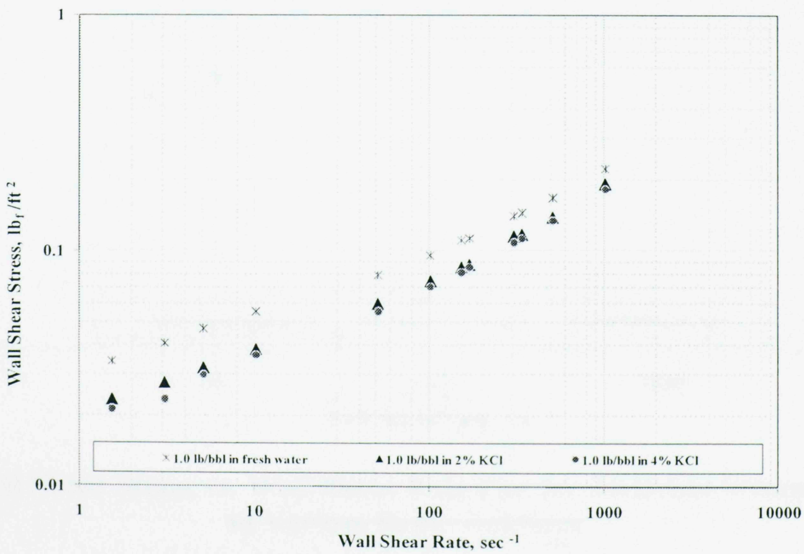

Fig. 4.3 Wall Shear Stress vs. Wall Shear Rate Plot for 1.0 lb/bbl Welan Gum Fluid in Various Brine Solutions

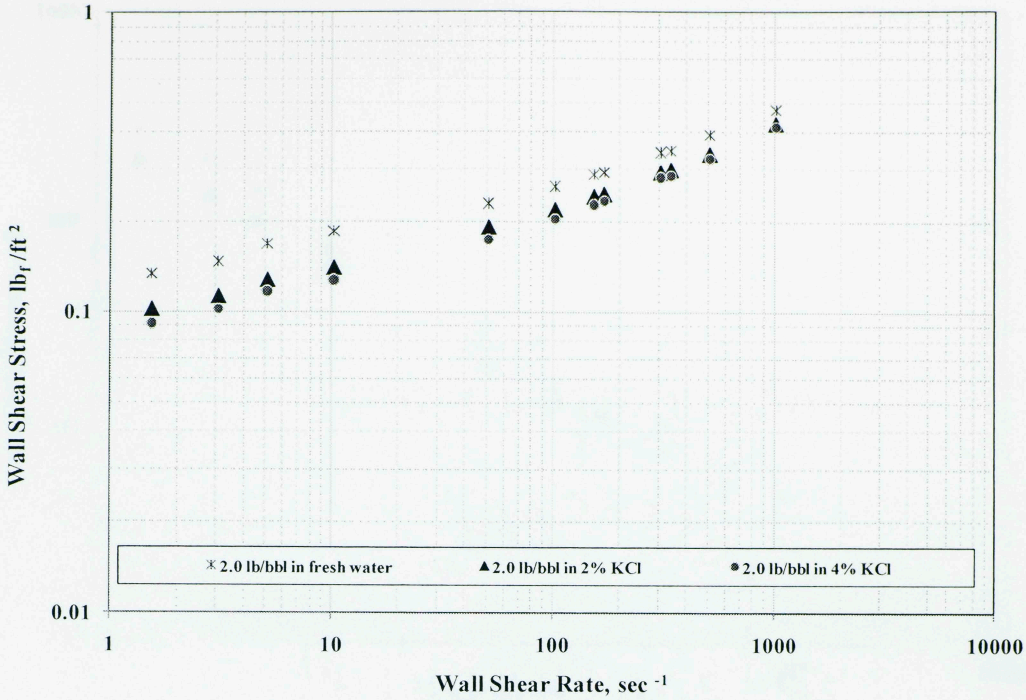

Fig. 4.4 Wall Shear Stress vs. Wall Shear Rate Plot for 2.0 lb/bbl Welan Gum Fluid in Various Brine Solutions

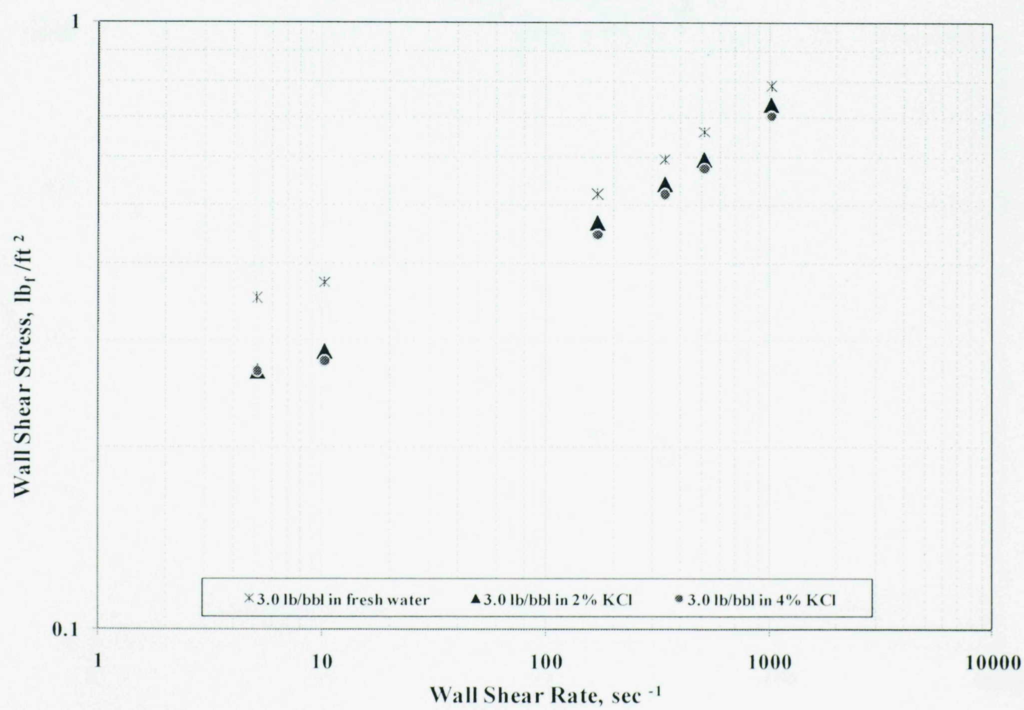

Fig. 4.5 Wall Shear Stress vs. Wall Shear Rate Plot for 3.0 lb/bbl Welan Gum Fluid in Various Brine Solutions

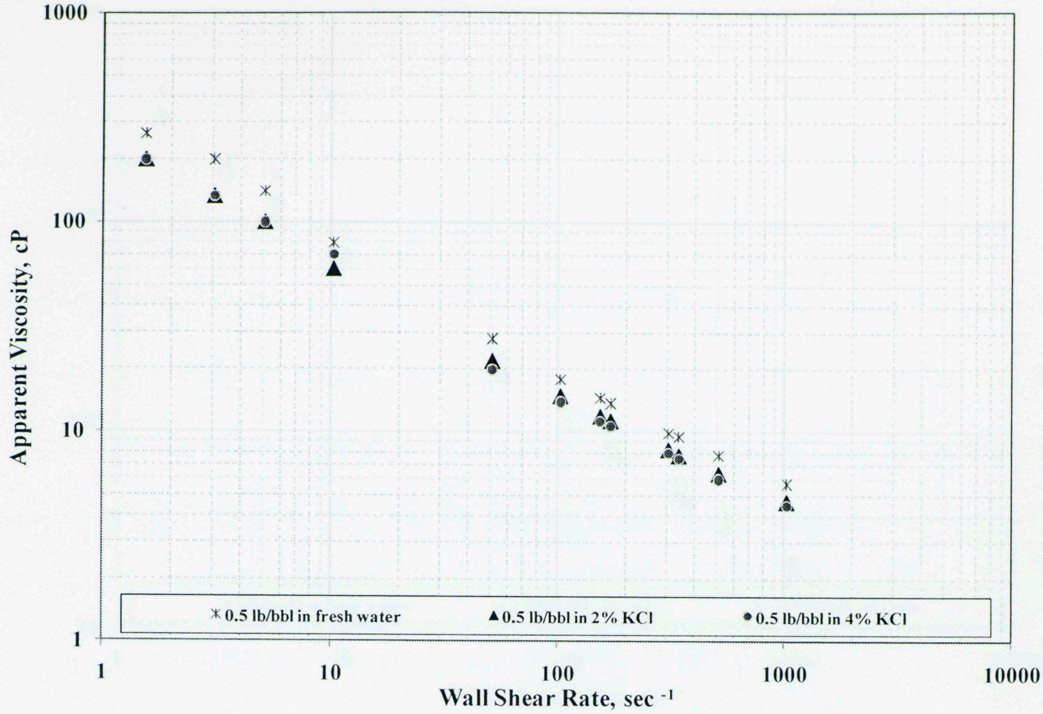

Fig. 4.6 Apparent Viscosity vs. Wall Shear Rate Plot for 0.5 lb/bbl Welan Gum Fluid in Various Brine Solutions

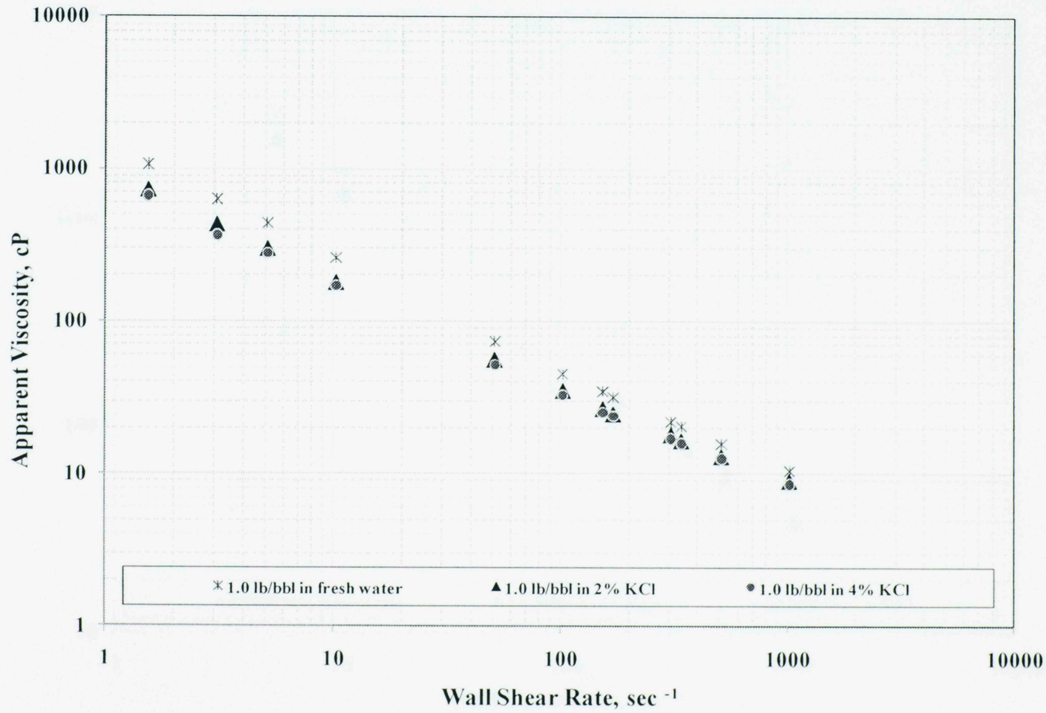

Fig. 4.7 Apparent Viscosity vs. Wall Shear Rate Plot for 1.0 lb/bbl Welan Gum Fluid in Various Brine Solutions

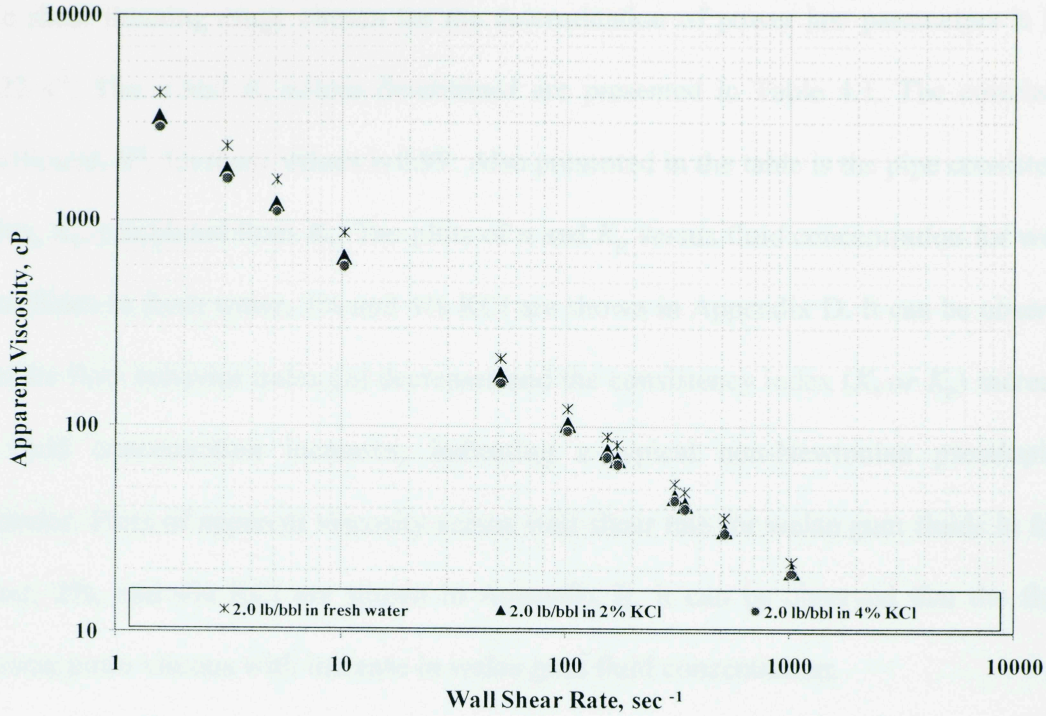

Fig. 4.8 Apparent Viscosity vs. Wall Shear Rate Plot for 2.0 lb/bbl Welan Gum Fluid in Various Brine Solutions

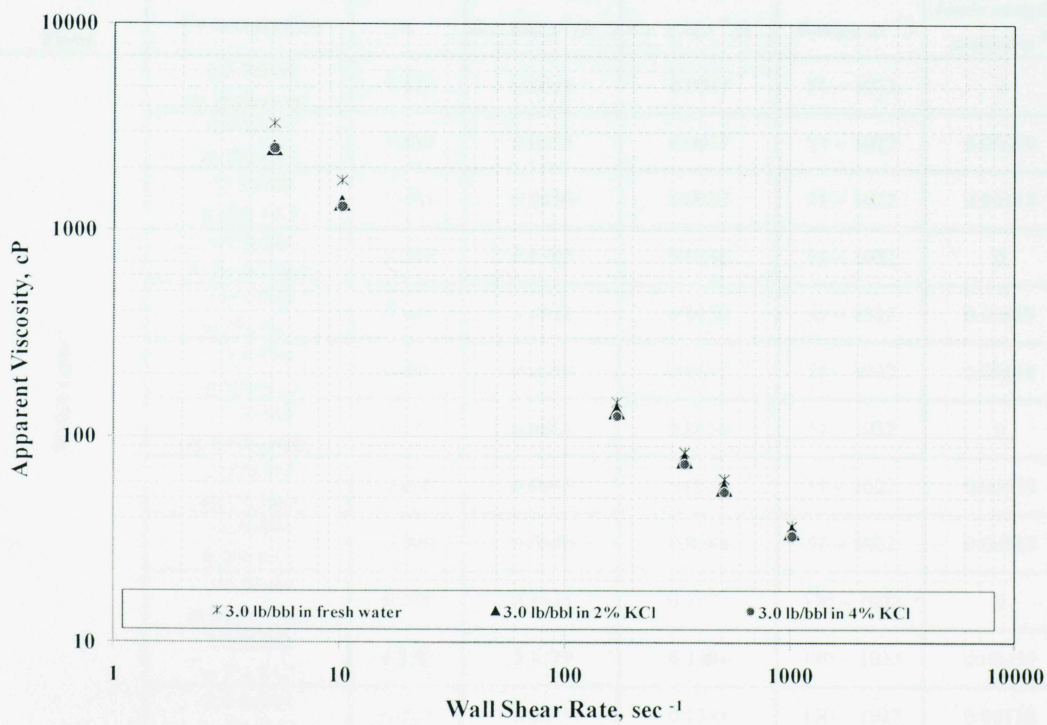

Fig. 4.9 Apparent Viscosity vs. Wall Shear Rate Plot for 3.0 lb/bbl Welan Gum Fluid in Various Brine Solutions

The shear thinning range chosen for the determination of power law parameters is 51 - 1022 s^{-1}. The n and K_v values determined are presented in Table 4.1. The correlation coefficient, R^2, for these values is 0.99. Also presented in the table is the pipe consistency index, K_p, calculated from K_v. The plots of n and K_p versus fluid concentration for welan gum fluids in fresh water, 2% and 4% KCl are shown in Appendix D. It can be observed that the flow behavior index (n) decreases and the consistency index (K_v *or* K_p) increases as fluid concentration increases, indicating a typical non-Newtonian pseudoplatic behavior. Plots of apparent viscosity versus wall shear rate for welan gum fluids in fresh water, 2%, and 4% KCl are shown in Appendix E. It can be observed that the fluids become more viscous with increase in welan gum fluid concentration.

Table 4.1 Power Law Model Parameters for Welan Gum Fluids

Fluid	Concentration	n	K_v $(lbf.s^n/ft^2)$	K_p $(lbf.s^n/ft^2)$	Range (s^{-1})	Ionic stregth, $mole/dm^3$
Welan Gum	0.5 lb/bbl in fresh water	0.471	0.0044	0.0047	51 – 1022	0
	0.5 lb/bbl in 2% KCl	0.480	0.0035	0.0037	51 – 1022	0.00059
	0.5 lb/bbl in 4% KCl	0.495	0.0030	0.0027	51 – 1022	0.00118
	1.0 lb/bbl in fresh water	0.349	0.0193	0.0180	51 – 1022	0
	1.0 lb/bbl in 2% KCl	0.391	0.0122	0.0150	51 – 1022	0.00059
	1.0 lb/bbl in 4% KCl	0.401	0.0110	0.0147	51 – 1022	0.00118
	2.0 lb/bbl in fresh water	0.242	0.0861	0.0676	51 – 1022	0
	2.0 lb/bbl in 2% KCl	0.266	0.0645	0.0573	51 – 1022	0.00059
	2.0 lb/bbl in 4% KCl	0.290	0.0540	0.0548	51 – 1022	0.00118
	3.0 lb/bbl in fresh water	0.231	0.1575	0.1727	170 – 1022	0
	3.0 lb/bbl in 2% KCl	0.250	0.1279	0.1404	170 – 1022	0.00059
	3.0 lb/bbl in 4% KCl	0.252	0.1215	0.1334	170 – 1022	0.00118

Figures 4.10 and 4.11 show the plot of the power law parameters versus the ionic strength of the fluid. The effects of salinity can be observed as n values increase and K_v *or* K_p values decrease with increase in salinity from fresh water to 2% KCl. This is the typical

polyelectrolyte behavior with increase in salinity due to the screening of the intermolecular electrostatic repulsions that exist in aqueous solutions of polyelectrolytes, hence allowing for a more compact structure (Campana et al. 1990; Rochefort et al. 1987). The charge screening causes a reduction in the hydrodynamic size of the molecule, which when not accompanied by increased intermolecular associations, results in a decrease in solution properties (Rochefort et al. 1987). However, as salinity increases from 2% KCl to 4% KCl, the charge effects due to increasing salt concentration are eliminated. Budd (1995) suggested that screening of the carboxylate groups in welan gum through intramolecular interactions with the side chains and weak intermolecular association could lead to the observed insensitivity of solution properties to higher salt concentration. Campana et al. (1997) attributed the weak polyelectrolyte behavior to the high stiffness of the welan chain.

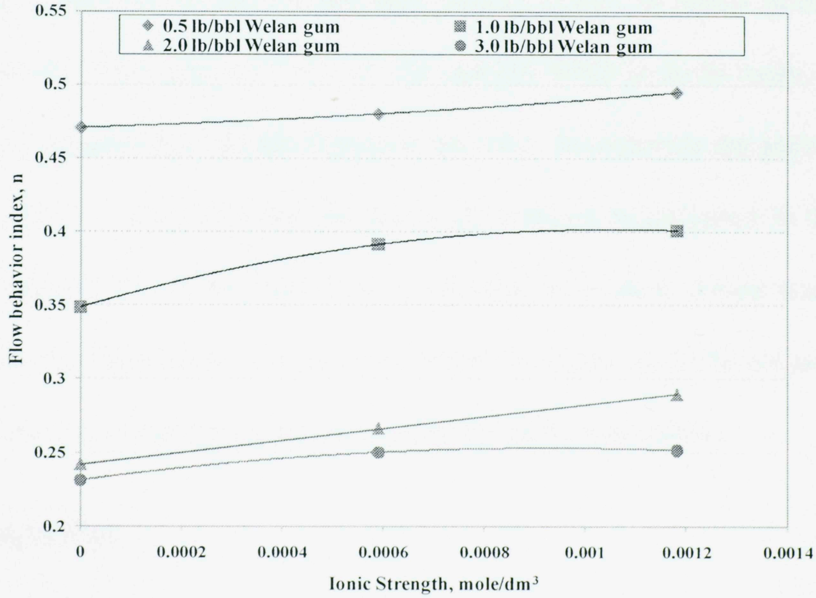

Fig. 4.10 Flow Behavior Index vs. Ionic Strength Plot for Welan Gum Fluids

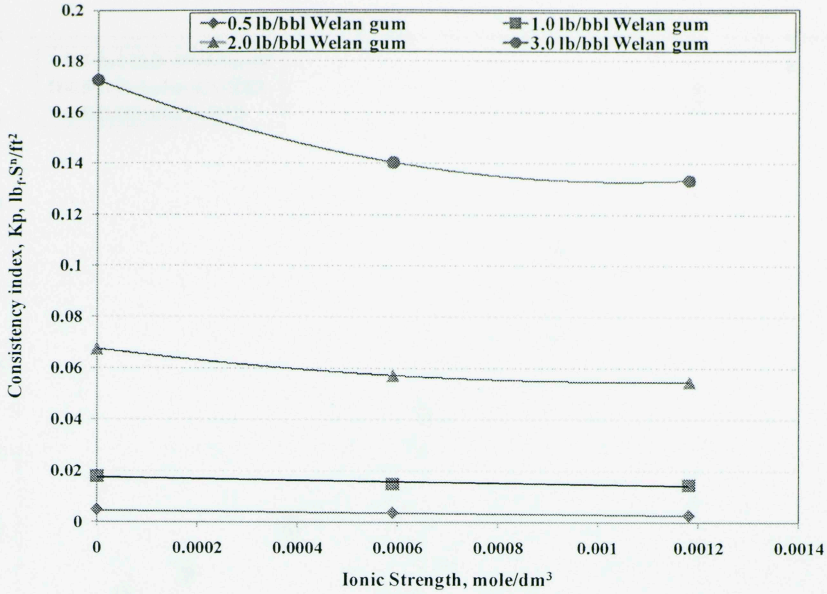

Fig. 4.11 Consistency Index vs. Ionic Strength Plot for Welan Gum Fluids

4.3. FLOW TEST OF WELAN GUM FLUIDS: EFFECT OF SALINITY

To study the effects of salinity on the flow characteristics of welan gum fluids, four concentrations of welan gum i.e. 0.5, 1.0, 2.0 and 3.0 lb/bbl in fresh water, 2% KCl and 4% KCl were pumped through the experimental setup described in the previous chapter. The pressure drop – flow rate data for welan gum fluids investigated in this work are shown in Appendix F. All the tests were conducted at ambient temperature conditions (75°F) conditions. This section discusses the effect of salinity on frictional pressure losses in both straight and coiled tubing based on experimental observations.

4.3.1. Straight Pipe

To better investigate the effect of salinity on friction factor of welan gum fluids in straight tubing, linear plots of pressure drop gradient against flow rate for each welan gum concentration investigated were prepared and presented in Figures 4.12 through 4.15.

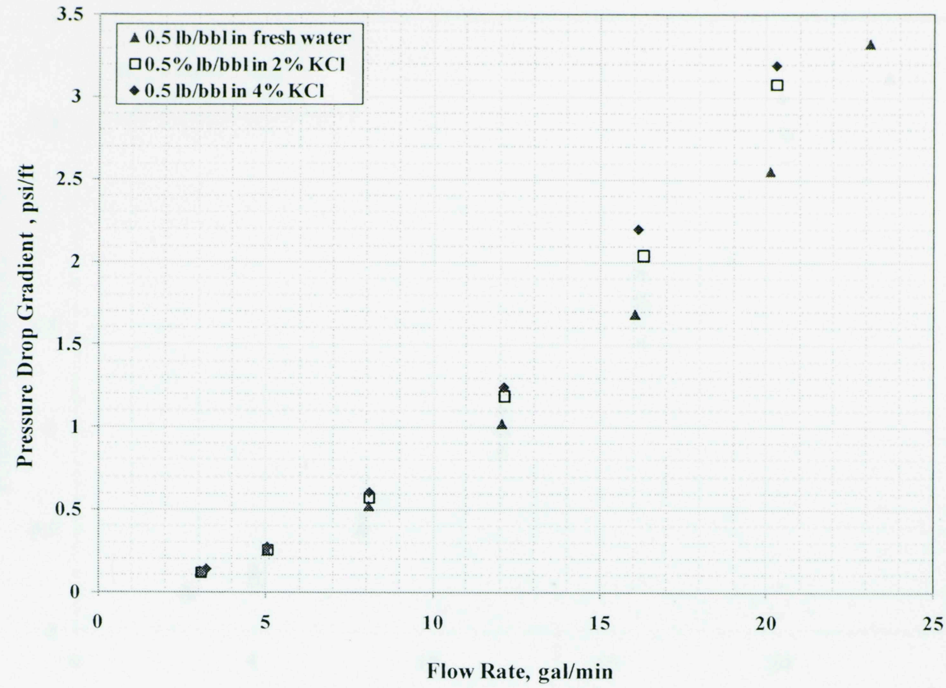

Fig. 4.12 Pressure Drop Gradients in ½ in. Straight Tubing for 0.5 lb/bbl Welan Gum Fluids

For 0.5 lb/bbl welan gum fluids flowing in straight tubing, it can be observed that the pressure drop increases with increase in salinity from fresh water to 2% KCl, especially at the higher flow rates. The pressure drop increases by as much as 21% at a flow rate of 20 gal/min. However, further increase in salinity to 4% KCl leads to an increase of only about 5% in pressure drop.

Similarly, for 1 lb/bbl welan gum fluid flowing in straight tubing, the pressure drop across the tubing increases by about 16% and 7% with increase in salinity from fresh water to 2% KCl and from 2% to 4% KCl respectively at a flow rate of 20 gal/min.

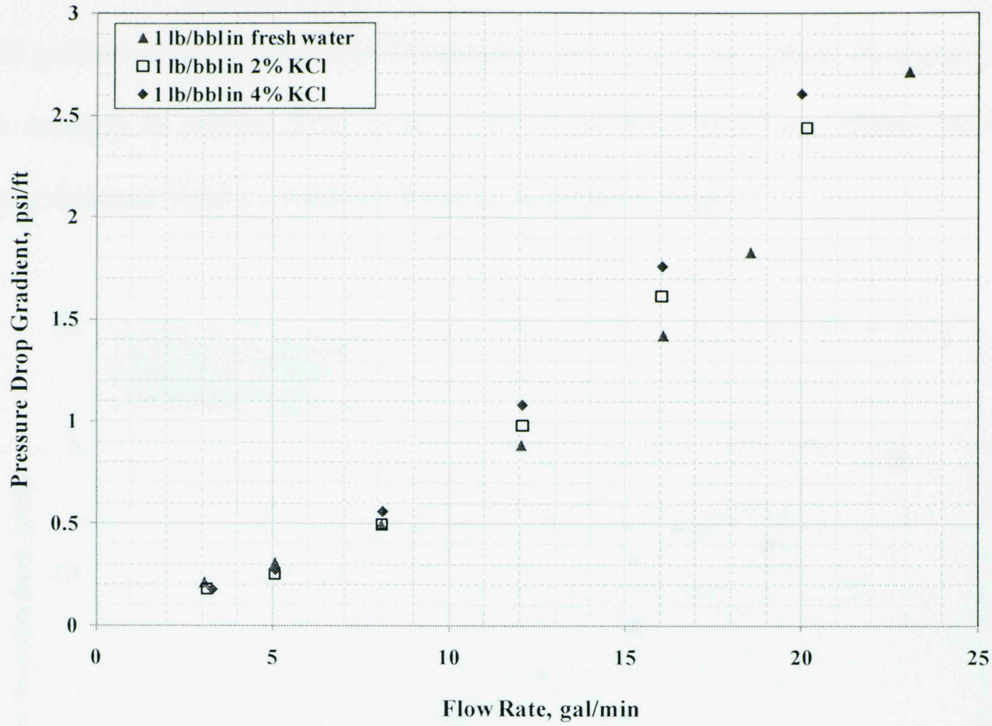

Fig. 4.13 Pressure Drop Gradients in ½ in. Straight Tubing for 1.0 lb/bbl Welan Gum Fluids

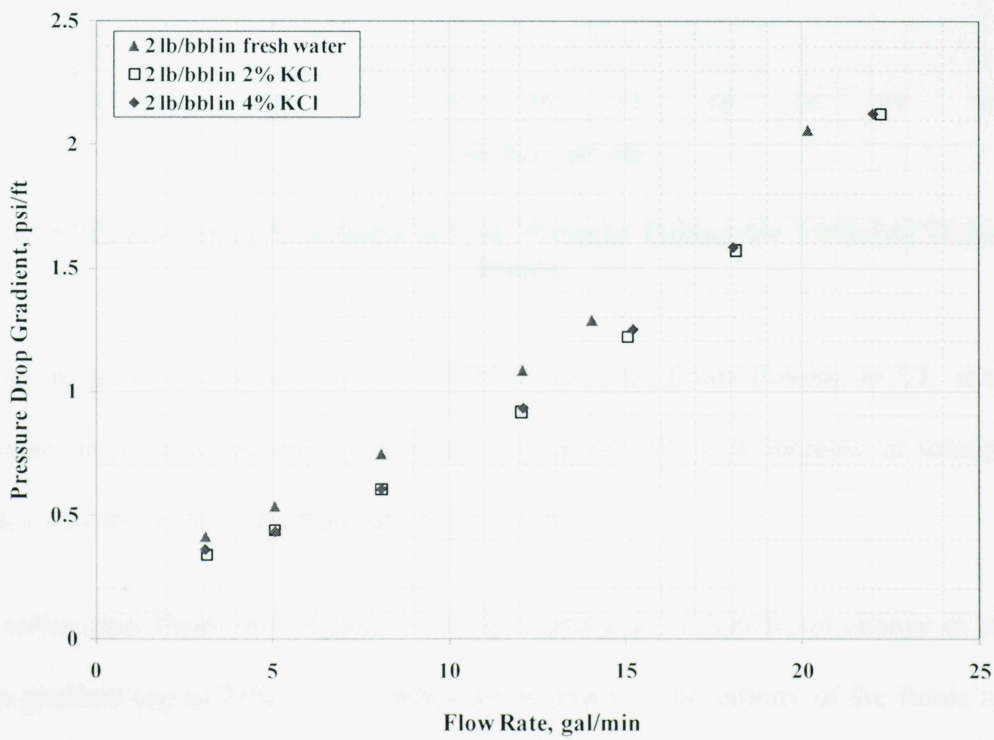

Fig. 4.14 Pressure Drop Gradients in ½ in. Straight Tubing for 2.0 lb/bbl Welan Gum Fluids

For 2.0 lb/bbl welan gum fluid flowing in ST, interpolating the data points at a flow rate of 20 gal/min, it is observed that the pressure drop across the tubing decreases by 12% with increase in salinity from fresh water to 2% KCl. However, further increase in salinity does not yield a significant decrease in pressure drop.

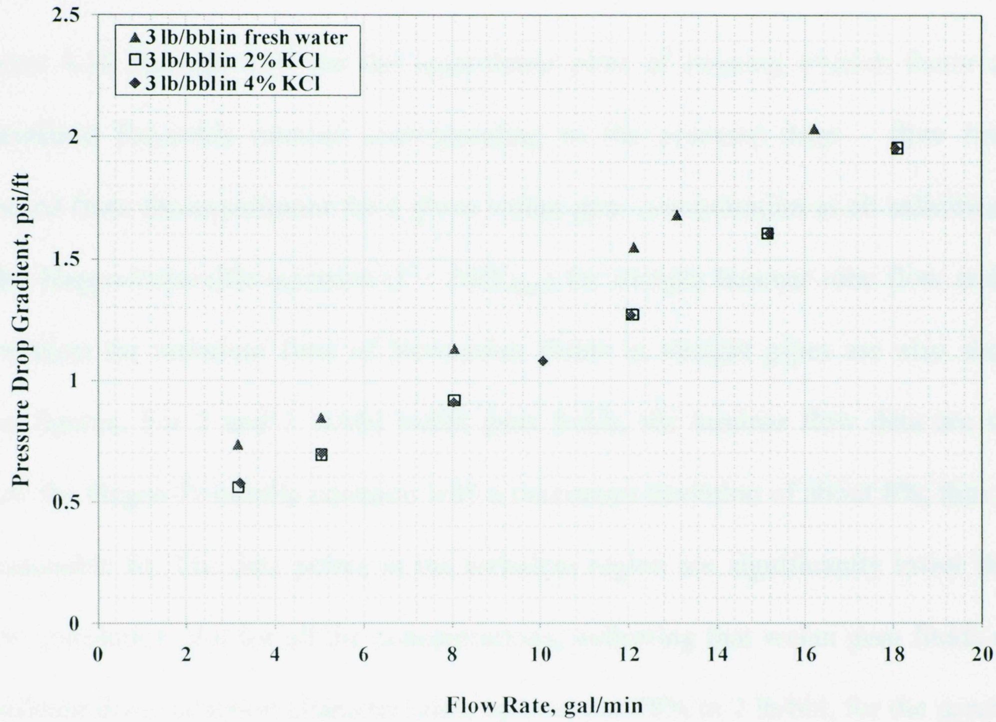

Fig. 4.15 Pressure Drop Gradients in ½ in. Straight Tubing for 3.0 lb/bbl Welan Gum Fluids

A similar trend is observed for 3.0 lb/bbl welan gum fluids flowing in ST, where the pressure drop across the tubing decreases by about 15% with increase in salinity from fresh water to 2% KCl at a flow rate of 16 gal/min.

All welan gum fluids investigated in straight tubing show significant change in pressure drop gradient (up to 21% for 0.5 lb/bbl welan gum) as the salinity of the fluids increase from fresh water to 2% KCl. However, further increase in salinity from 2% KCl to 4% KCl does not result in significant change in pressure drop gradient. Moreover, it can be observed that at low concentrations of 0.5 and 1.0 lb/bbl, welan gum fluids in brine exhibit higher pressure drop gradient compared to that in fresh water. This indicates that salinity decreases the drag reduction ability of welan gum fluids at concentrations of 0.5 and 1.0 lb/bbl, opposite to what is observed at higher concentrations of 2.0 and 3.0 lb/bbl (Figures 4.12 and 4.15). These trends are due to dominant viscous effects or delay in onset of drag reduction as a result of increased fluid concentration.

Figures 4.16 through 4.19 are the logarithmic plots of Fanning friction factor against generalized Reynolds number corresponding to the pressure drop – flow rate data gathered from the experiment for a given welan gum concentration at all salinities. Plots of the Hagen-Poiseuille equation ($f = 16/N_{Reg.}$) for straight laminar tube flow and Drew correlation for turbulent flow of Newtonian fluids in straight pipes are also shown in these figures. For 2 and 3 lb/bbl welan gum fluids, the laminar flow data are slightly below the Hagen-Poiseuille equation with a maximum deviation of about 8%, thus giving a reasonable fit. The data points in the turbulent region are significantly lower than the Drew correlation plot for all the concentrations, indicating that welan gum fluids exhibit significant drag reduction characteristics, up to about 78% in 2 lb/bbl, for the generalized Reynolds number range investigated. The percentage drag reduction plots for the welan gum fluids investigated are shown in Figures 4.20 through 4.23.

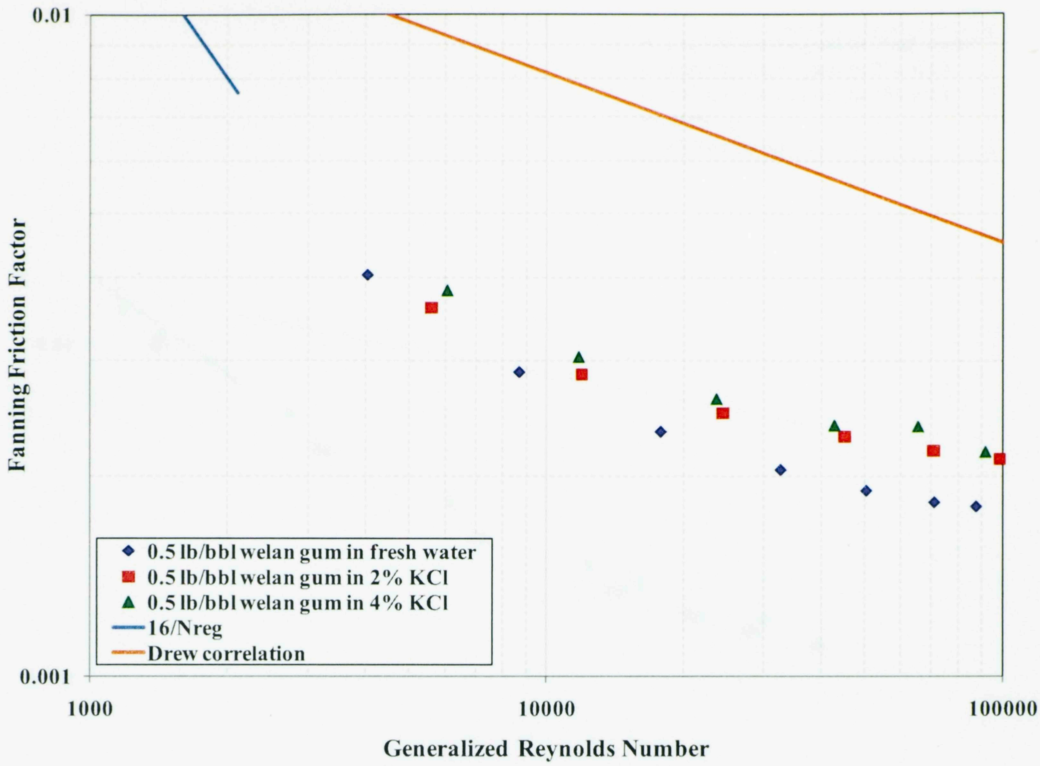

Fig. 4.16 Friction Factors in ½ in. Straight Tubing for 0.5 lb/bbl Welan Gum Fluids

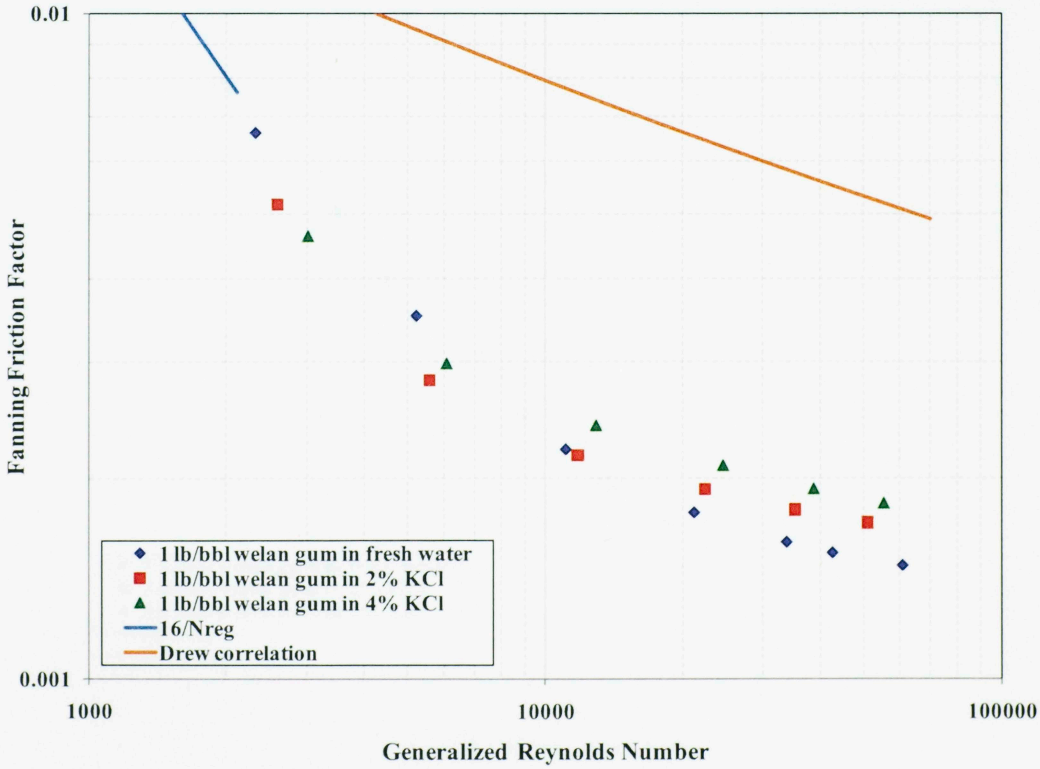

Fig. 4.17 Friction Factors in ½ in. Straight Tubing for 1.0 lb/bbl Welan Gum Fluids

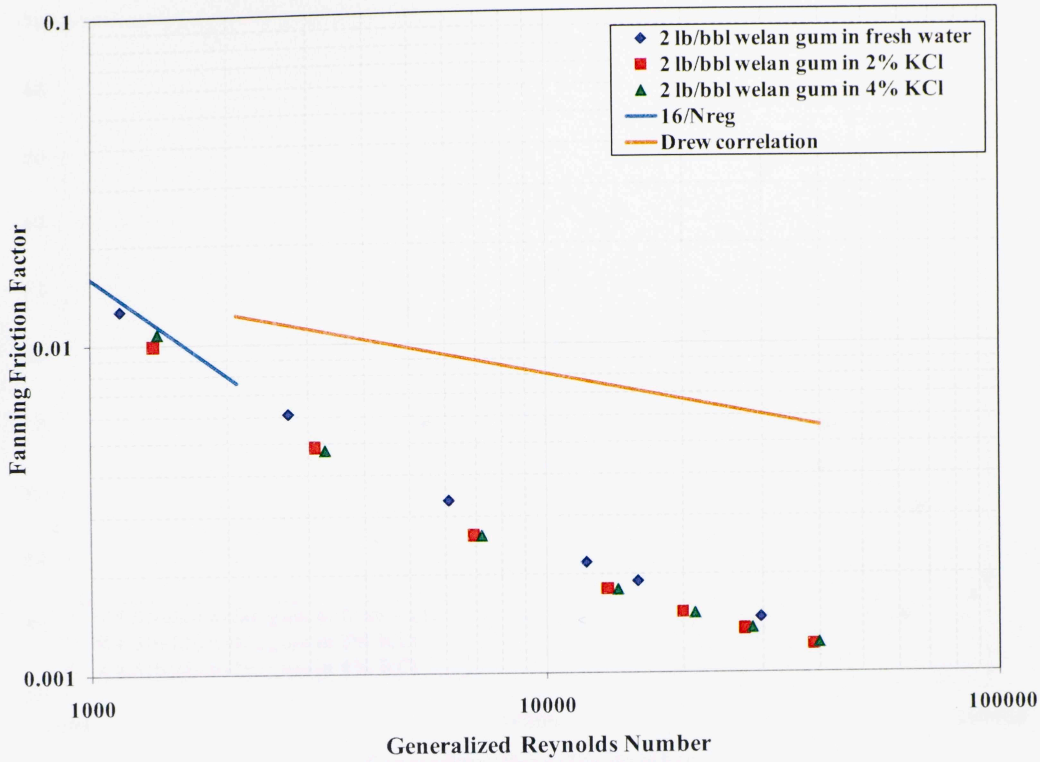

Fig. 4.18 Friction Factors in ½ in. Straight Tubing for 2.0 lb/bbl Welan Gum Fluids

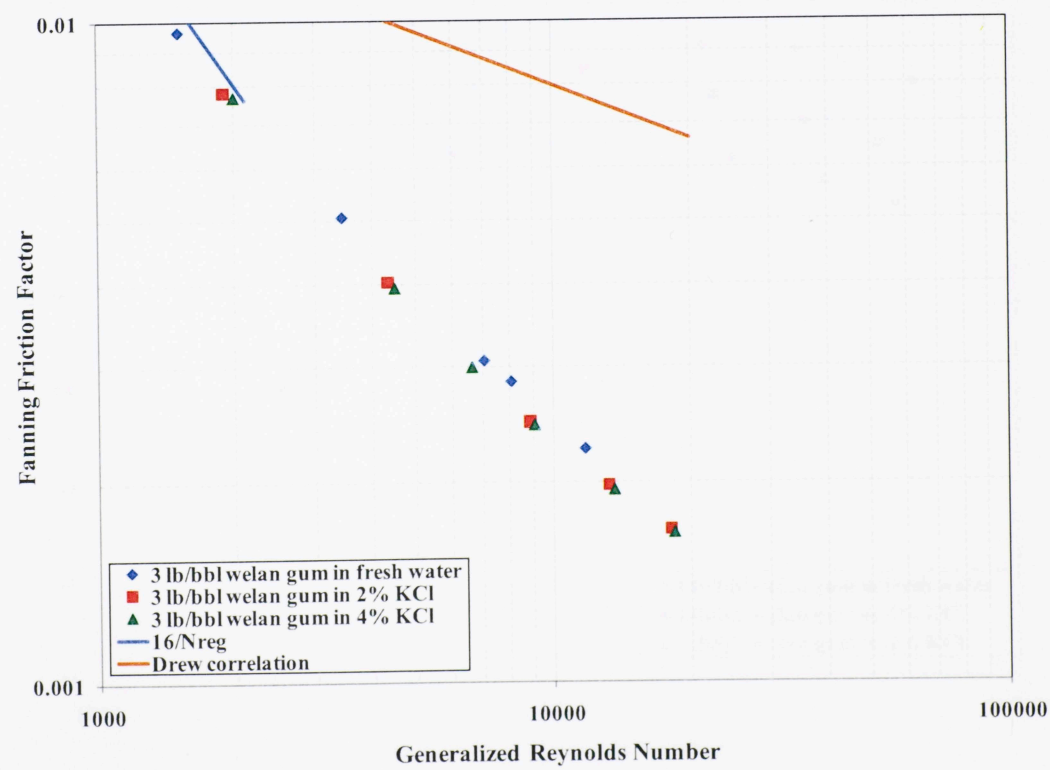

Fig. 4.19 Friction Factors in ½ in. Straight Tubing for 3.0 lb/bbl Welan Gum Fluids

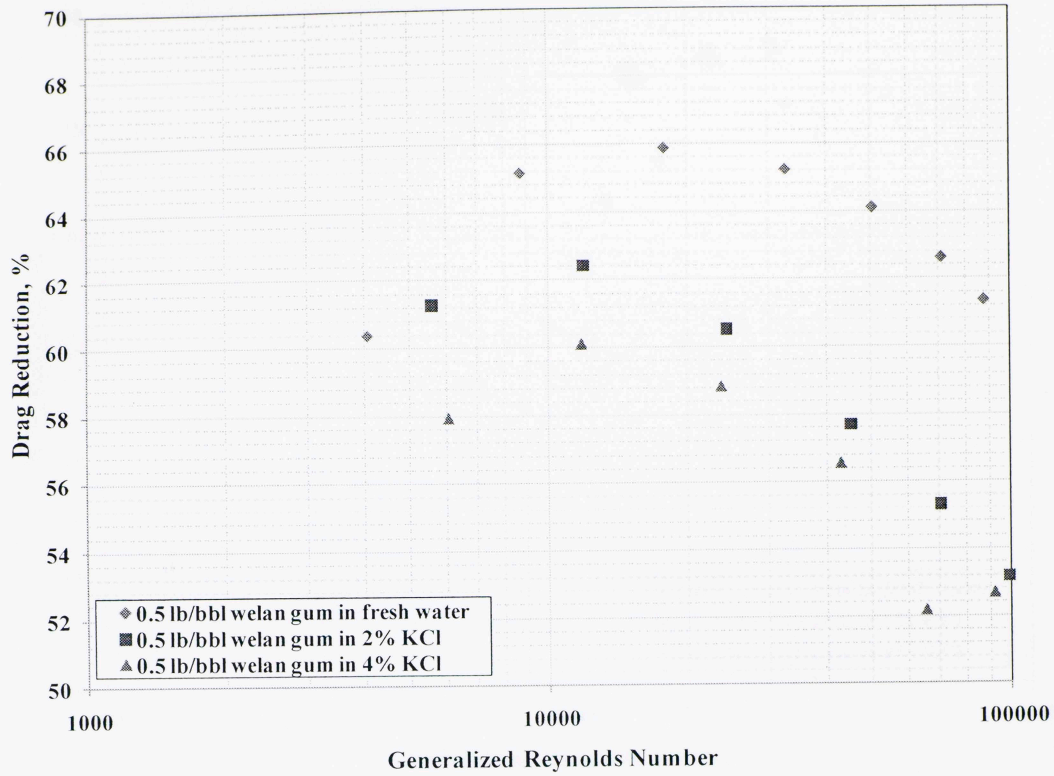

Fig. 4.20 Drag Reduction in ½ in. Straight Tubing for 0.5 lb/bbl Welan Gum Fluids

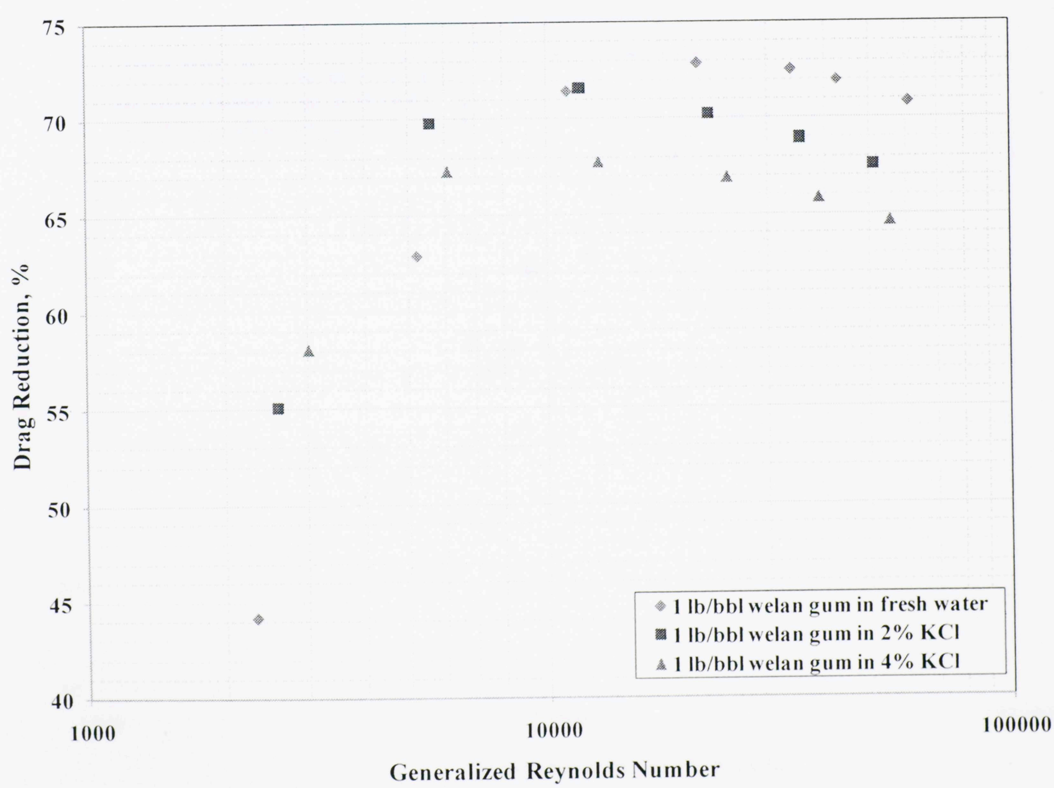

Fig. 4.21 Drag Reduction in ½ in. Straight Tubing for 1.0 lb/bbl Welan Gum Fluids

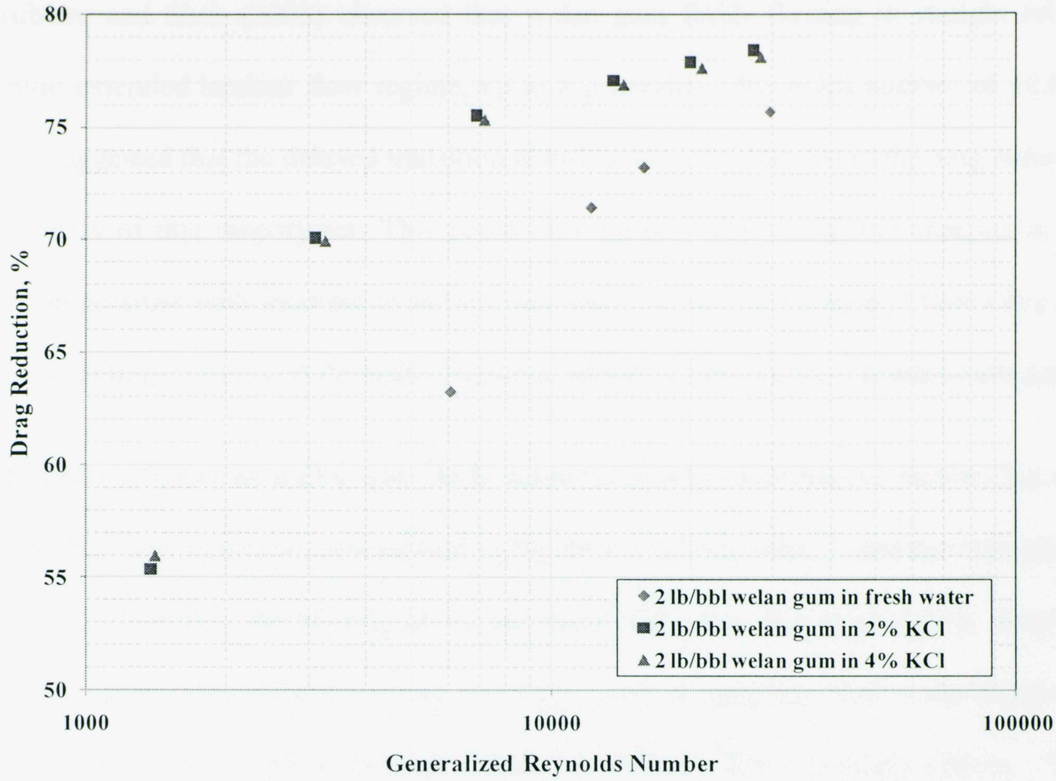

Fig. 4.22 Drag Reduction in ½ in. Straight Tubing for 2.0 lb/bbl Welan Gum Fluids

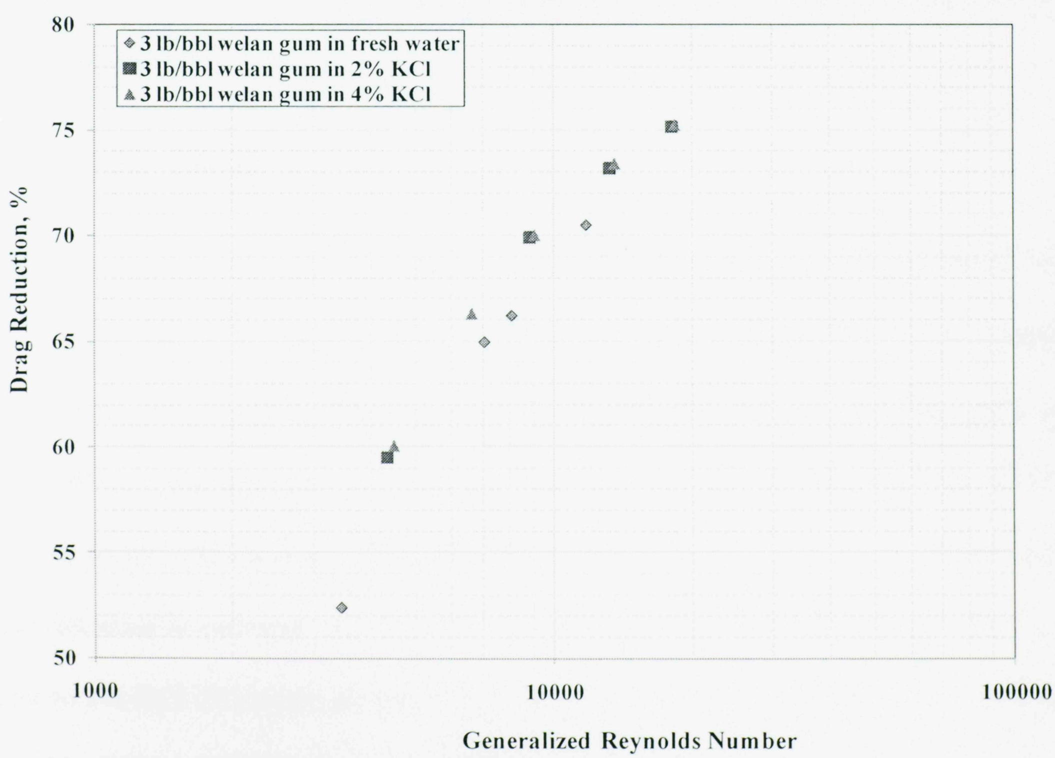

Fig. 4.23 Drag Reduction in ½ in. Straight Tubing for 3.0 lb/bbl Welan Gum Fluids

Asubiaro and Shah (2008) observed that welan gum fluids flowing in straight tubing exhibit extended laminar flow regime, up to a generalized Reynolds number of 10,000. They suggested that the delayed transition to turbulence could be due to the drag reducing properties of this biopolymer. This could also explain why significant changes in the friction pressure with increase in salinity are observed only at the higher flow rates and corresponding generalized Reynolds numbers, when the flow regime becomes turbulent.

The friction factors of welan gum fluids depends not only on Reynolds number but also on the fluid characteristics represented by the flow behavior index, *n* and the consistency index, *k*. Generally, the friction factor decreases and more drag reduction is observed with decrease in the fluid flow behavior index, until an optimum fluid concentration is reached above which flow resistance starts to increase due to viscous effects. This optimum concentration is between 2 and 3 lb/bbl for welan gum fluids flowing in straight tubing and the maximum drag reduction is obtained when 2 or 4% KCl is used as base fluid compared with water.

4.3.2. Coiled Tubing

Adopting an approach similar to the flow of welan gum fluids in straight tubing, linear plots of pressure drop against flow rate for all welan gum concentration investigated in coiled tubing were prepared and are presented in Figures 4.24 – 4.27. The linear plots give a direct representation of the effects of salinity on the flow characteristics of welan gum fluids in coiled tubing. All welan gum concentrations considered in coiled tubing show decrease in pressure drop gradient as the salinity of the fluids increase from fresh water to 2% KCl. However, as was observed in straight tubing, further increase in salinity from 2% KCl to 4% KCl does not result to significant change in pressure drop gradient. For 0.5, 1.0 and 2.0 lb/bbl welan gum fluids flowing in coiled tubing, at a flow rate of 20 gal/min, the pressure drop across coiled tubing decreases by 5, 10 and 16% respectively with increase in salinity from fresh water to 4% KCl. Similarly, for 3.0 lb/bbl welan gum fluids, at a flow rate of 16 gal/min, the pressure drop across the coiled tubing decreases by 17% with increase in salinity from fresh water to 4% KCl. It should be recalled that for welan gum fluids flowing in straight tubing we observed decrease in pressure drop gradient with increase in salinity for only 2 and 3 lb/bbl welan gum fluids and a reverse effect for 0.5 and 1 lb/bbl welan gum fluids.

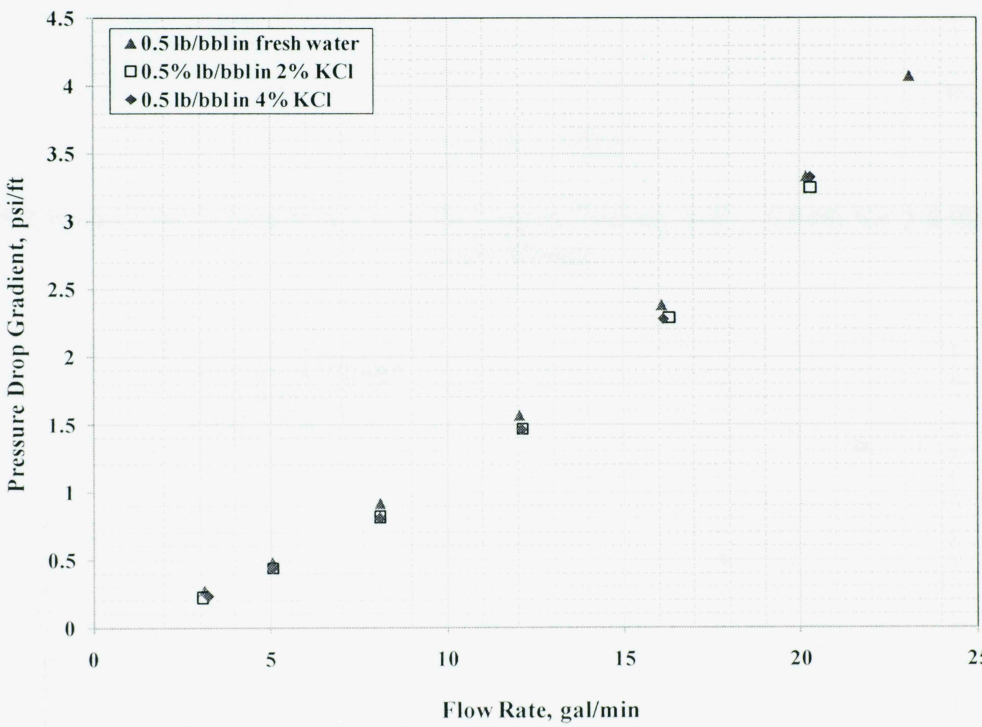

Fig. 4.24 Pressure Drop Gradients in ½ in. Coiled Tubing (r/R = 0.019) for 0.5 lb/bbl Welan Gum Fluids

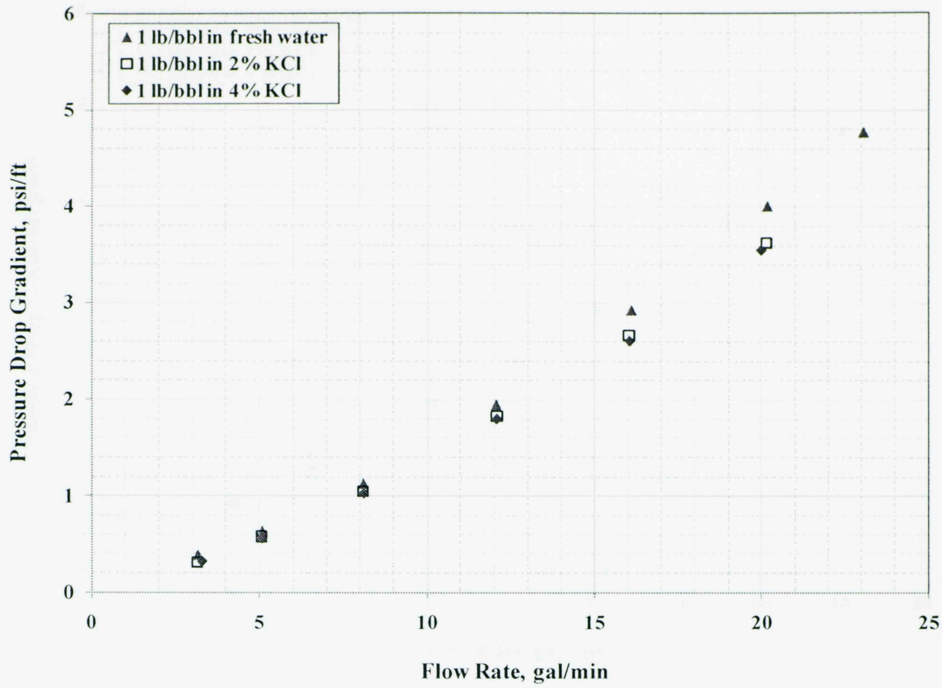

Fig. 4.25 Pressure Drop Gradients in ½ in. Coiled Tubing (r/R = 0.019) for 1.0 lb/bbl Welan Gum Fluids

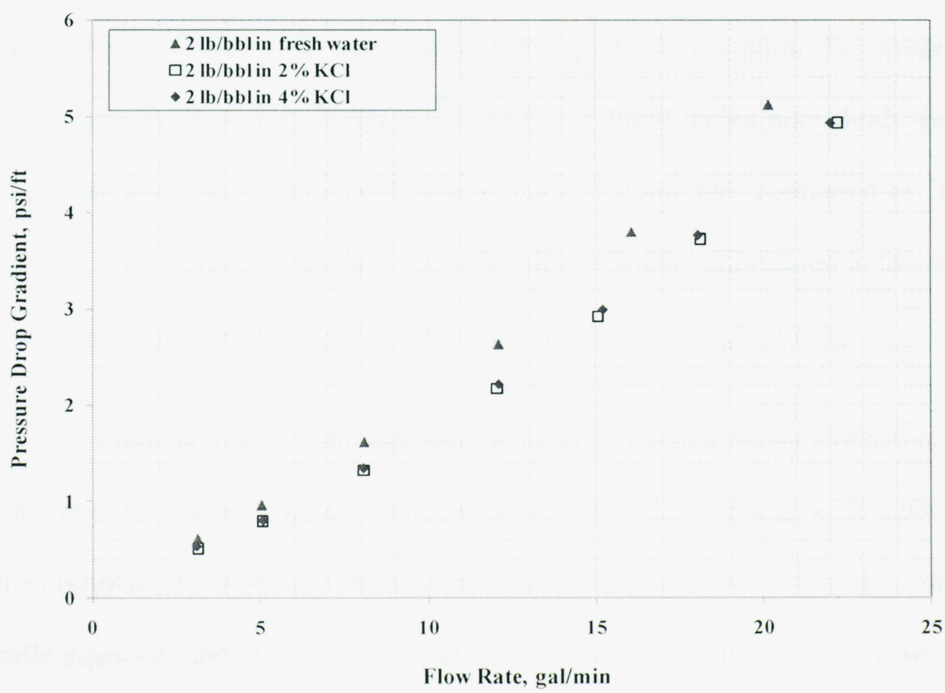

Fig. 4.26 Pressure Drop Gradients in ½ in. Coiled Tubing (r/R = 0.019) for 2.0 lb/bbl Welan Gum Fluids

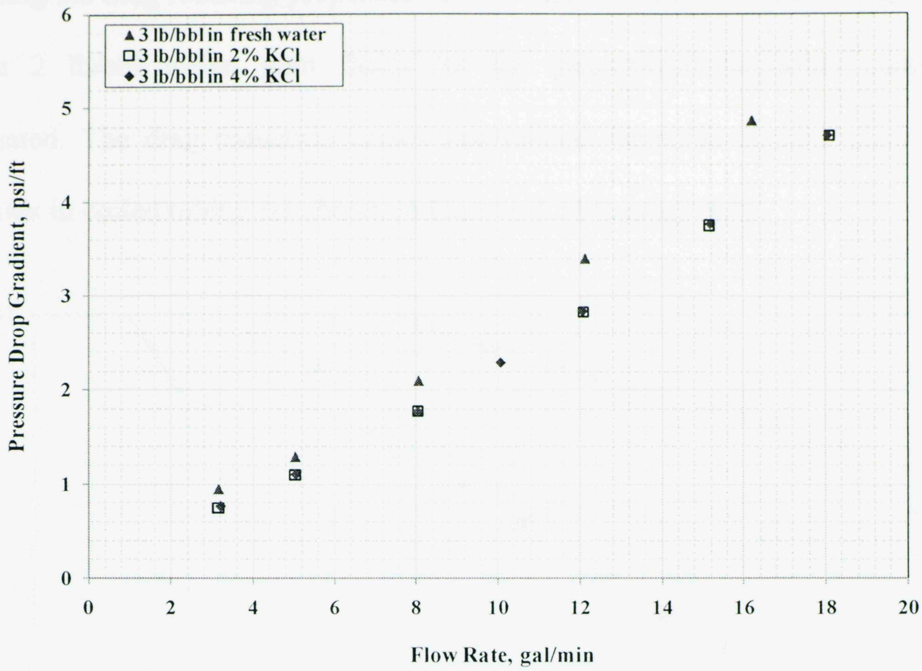

Fig. 4.27 Pressure Drop Gradients in ½ in. Coiled Tubing (r/R = 0.019) for 3.0 lb/bbl Welan Gum Fluids

Also, it is observed that the sensitivity of the welan gum fluids to increase in salinity becomes more significant with increase in welan gum concentration. For instance, with increase in salinity from fresh water to 4% KCl, 0.5 lb/bbl welan gum fluids show a 5% decrease in pressure drop gradient at a flow rate of 20 gal/min, compared to 16% for 2 lb/bbl welan gum fluids at same flow rate. For all the fluids investigated in this study, the pressure drop in the coiled tubing is higher than that in the straight tubing.

Figures 4.28 through 4.31 are the logarithmic plots of friction factor against generalized Reynolds number for all polymer concentrations and salinity along with corresponding Hagen-Poiseuille equation and Srinivasan correlation for coiled tubing. The Hagen-Poiseuille equation underpredicts the friction pressure loss in the laminar flow region in coiled tubing, since much higher pressure losses are experienced in this region for coiled tubing than in straight tubing. As was mentioned earlier, this is due to the secondary flow effects which provide additional resistance to fluid flow in coiled tubing. Also the friction pressure values in the coiled tubing are lower than predicted by Srinivasan correlation, confirming the drag reducing properties of welan gum fluids in coiled tubing, up to about 58% in 2 lb/bbl welan gum fluids for the generalized Reynolds number range investigated. The drag reduction versus generalized Reynolds number plots for welan gum fluids in coiled tubing are shown in Figures 4.32 through 4.35.

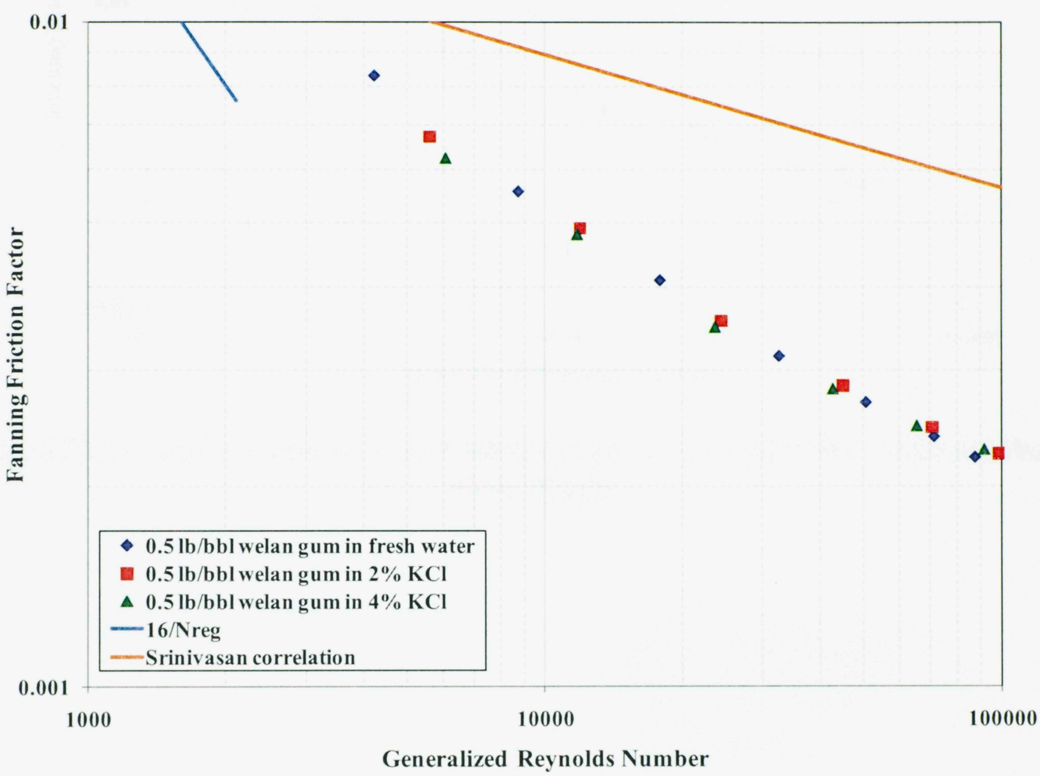

Fig. 4.28 Friction Factors in ½ in. Coiled Tubing (r/R= 0.019) for 0.5 lb/bbl Welan Gum Fluids

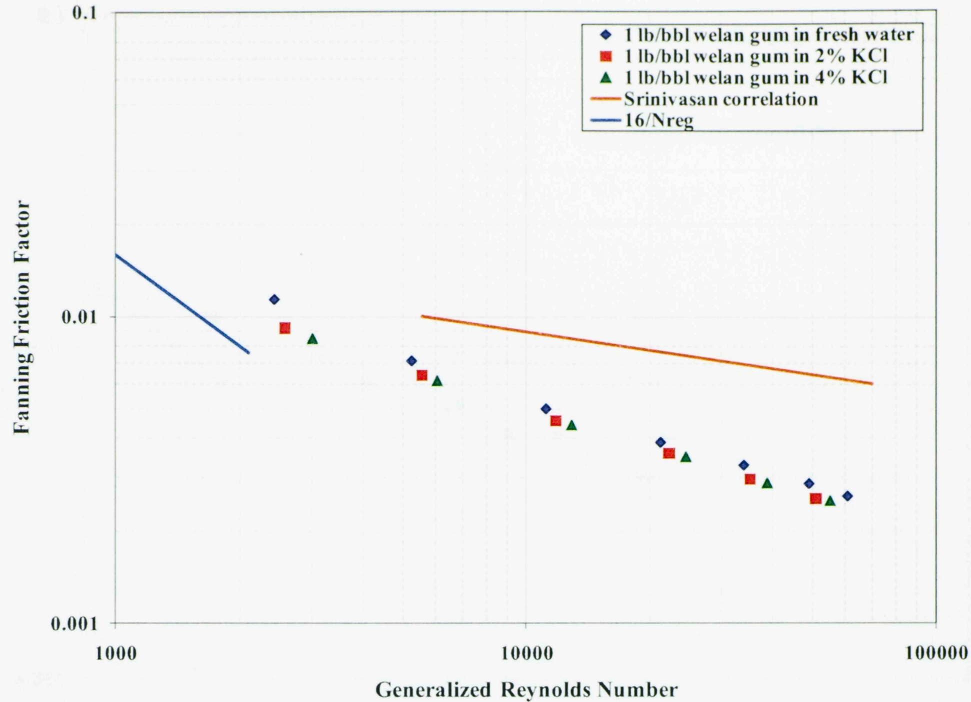

Fig. 4.29 Friction Factors in ½ in. Coiled Tubing (r/R= 0.019) for 1.0 lb/bbl Welan Gum Fluids

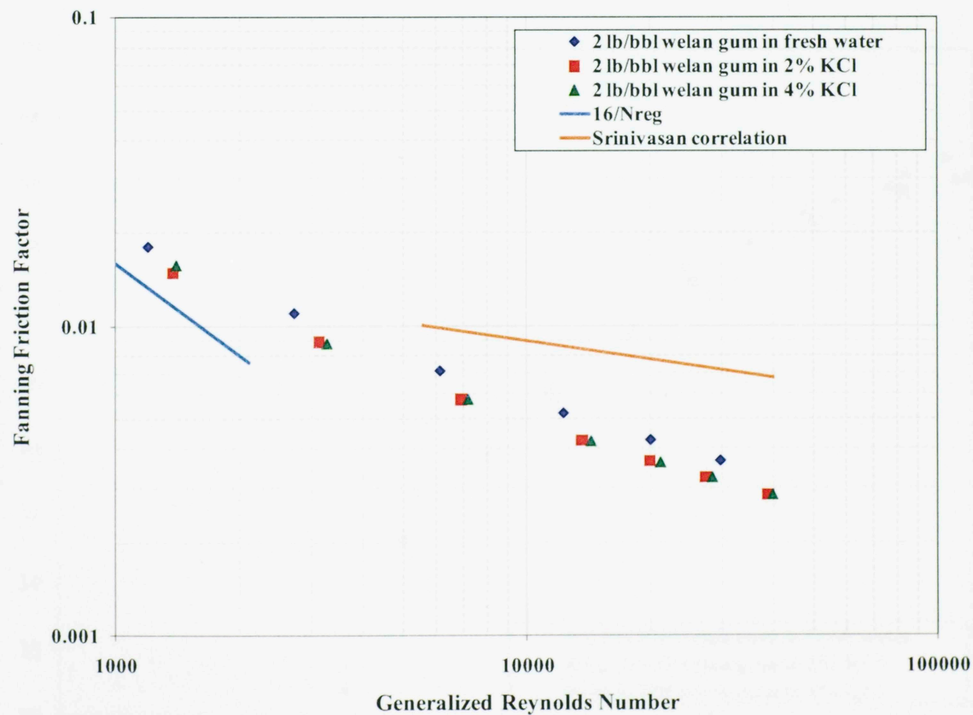

Fig. 4.30 Friction Factors in ½ in. Coiled Tubing (r/R= 0.019) for 2.0 lb/bbl Welan Gum Fluids

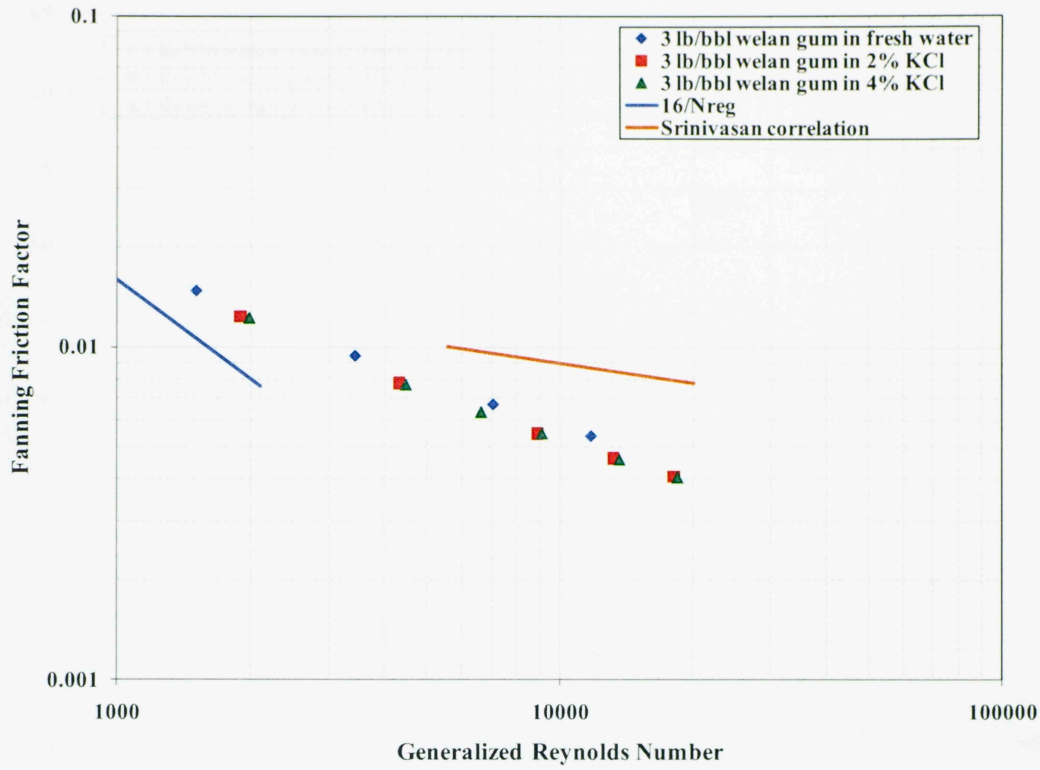

Fig. 4.31 Friction Factors in ½ in. Coiled Tubing (r/R= 0.019) for 3.0 lb/bbl Welan Gum Fluids

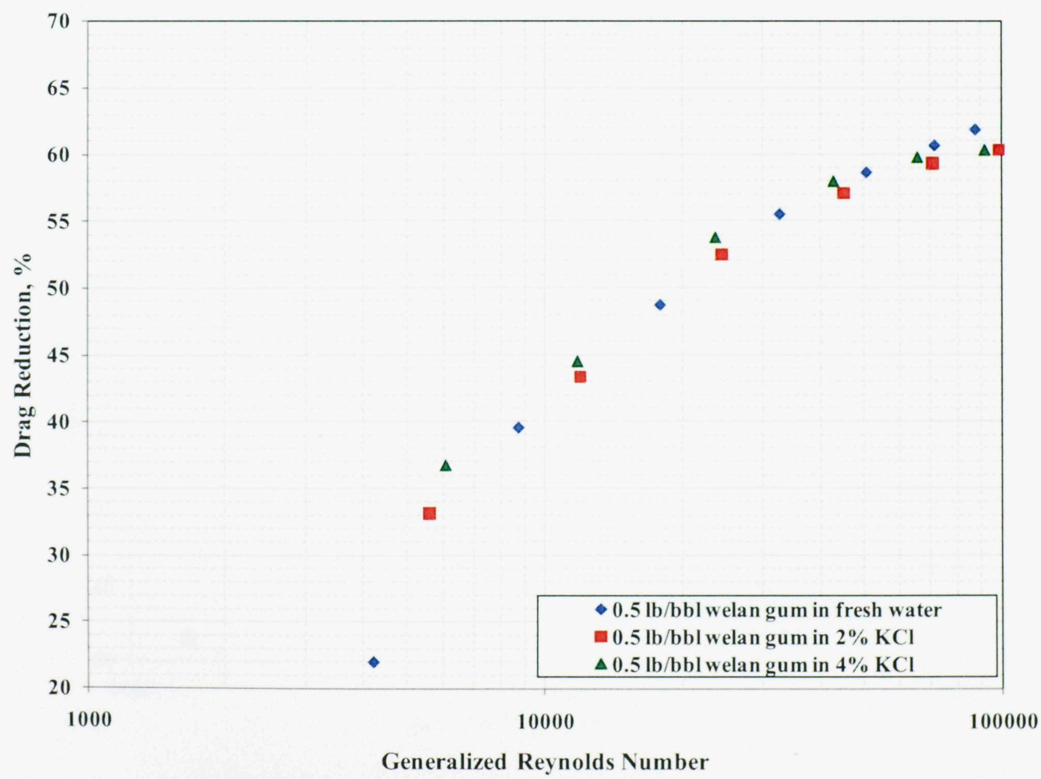

Fig. 4.32 Drag Reduction in ½ in. Coiled Tubing for 0.5 lb/bbl Welan Gum Fluids

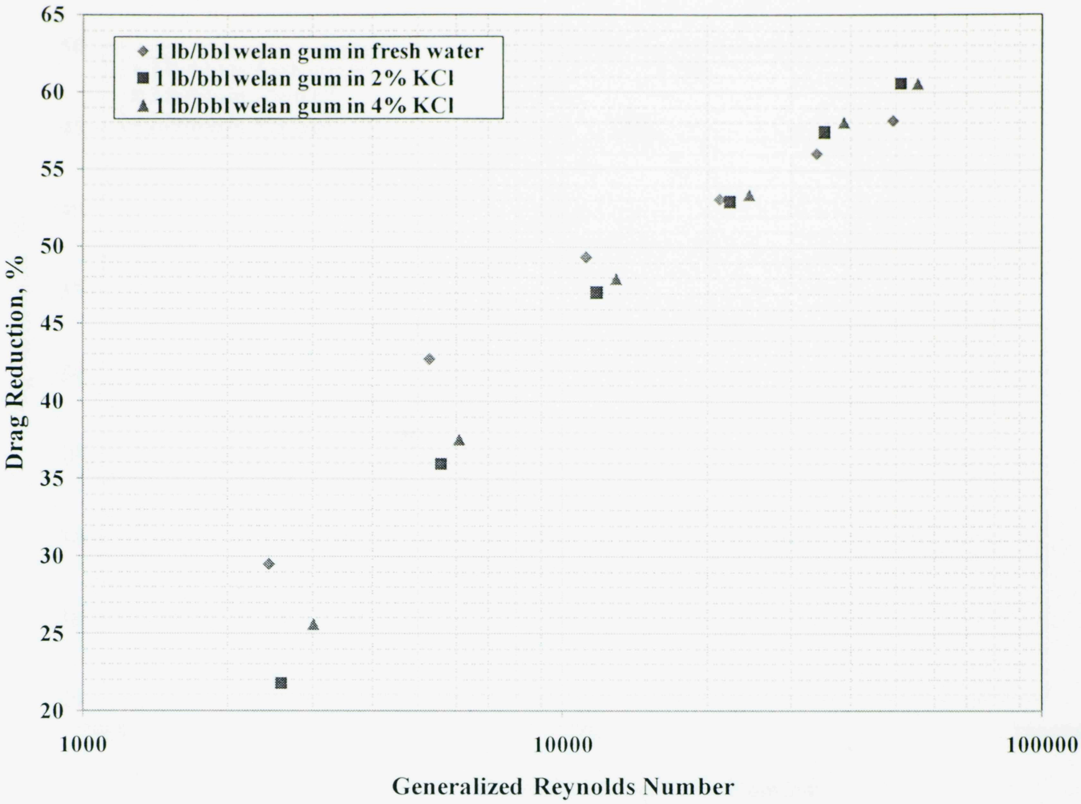

Fig. 4.33 Drag Reduction in ½ in. Coiled Tubing for 1.0 lb/bbl Welan Gum Fluids

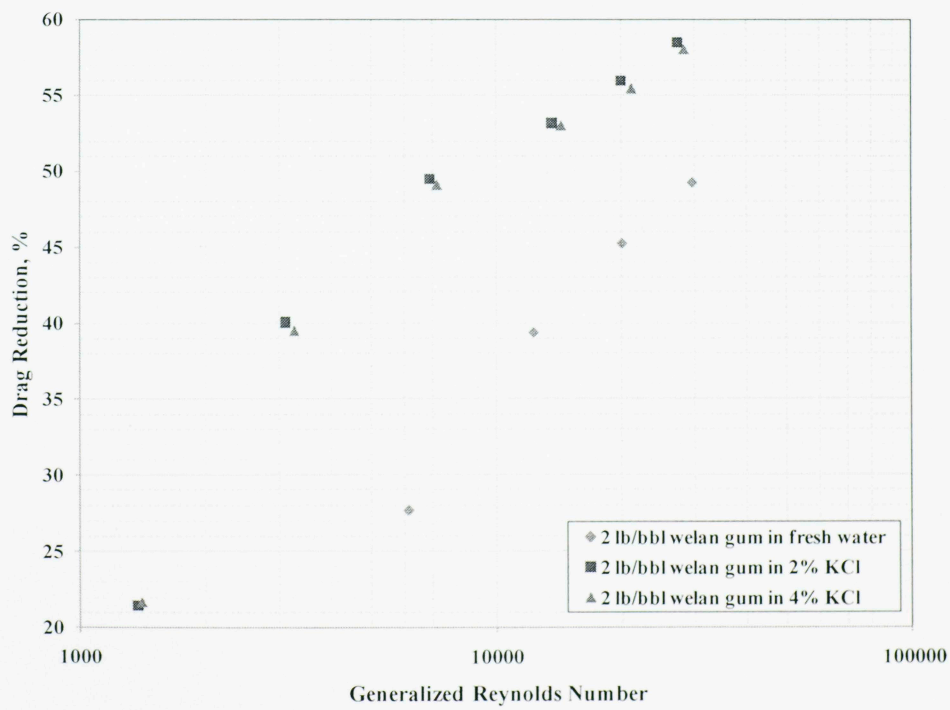

Fig. 4.34 Drag Reduction in ½ in. Coiled Tubing for 2.0 lb/bbl Welan Gum Fluids

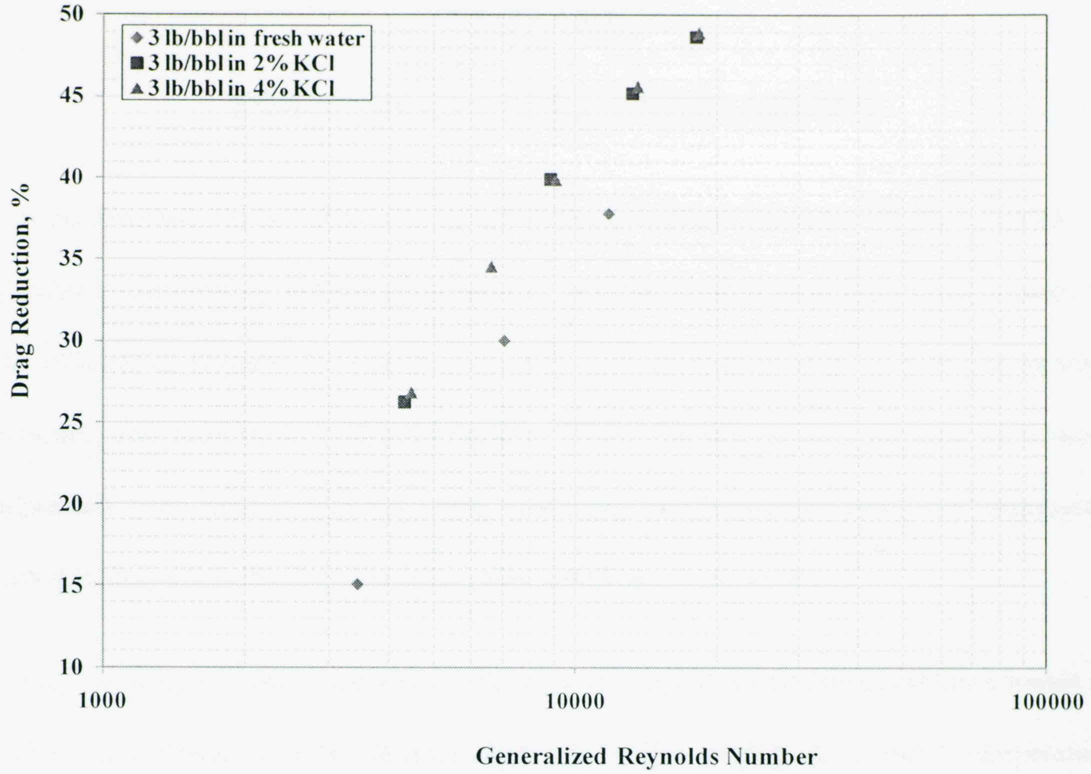

Fig. 4.35 Drag Reduction in ½ in. Coiled Tubing for 3.0 lb/bbl Welan Gum Fluids

CHAPTER 5

FRICTION FACTOR CORRELATIONS

For engineering design purposes, prediction of friction pressure losses of fluids is extremely important in pumping operations. Accurate prediction of the pressure losses in the tubular, is required to estimate the horse power requirement, bottomhole treating pressure, and maximum wellhead pressure. These correlations have become even more important since most recent fracturing treatments are for deeper wells and employing coiled tubing where friction loss in the pipe could be a limiting factor.

In the following sections, empirical correlations to predict the frictional pressure losses of welan gum fluids in both straight pipe and coiled tubing at ambient temperature conditions (75°F) are presented. Previous correlations developed by Asubiaro and Shah (2008) were based on welan gum fluids only in fresh water. However, here the effects of salinity on the flow behavior of welan gum fluids in fresh water, 2% KCl and 4% KCl are considered in developing correlations.

5.1. FRICTION FACTOR CORRELATION FOR STRAIGHT PIPE

The friction pressure data for welan gum fluids flowing through straight tubing are correlated using dimensionless parameters; Fanning friction factor, f, and generalized Reynolds number, N_{Reg} and the flow behavior index, n and apparent viscosity, μ_a of fluid. Commercially available curve fitting softwares, Labfit and Datafit, were used in developing the correlation. The straight pipe correlation for flow of welan gum is expressed as:

$$f_{st} = A + \frac{B}{N_{\text{Reg}}} \tag{5.1}$$

where A and B are correlation constants for a particular fluid and depend on the apparent viscosity, μ_a of fluid at 511 sec^{-1} shear rate and the flow behavior index, n. The parameters, A and B are calculated from the following equations:

$$\ln(A) = 0.0074(\mu_a)^{1.5} - 0.08\mu_a - 5.77 \qquad \textbf{(5.2)}$$

$$B = 1138n^3 - 1242n^2 + 417n - 31.4 \qquad \textbf{(5.3)}$$

The correlation has a coefficient of determination, R^2 of 0.99, which indicates a good fit. For this correlation, the average absolute percent deviation of the predicted friction factor from the measured values for the flow of welan gum fluids through straight tubing is 4.05% with a maximum deviation of about 13%. This confirms the validity of the correlation for predicting friction factor of welan gum fluids in straight tubing. Plots of the parameters A and B vs apparent viscosity at 511 sec^{-1} shear rate and flow behavior index respectively, are shown in Appendix G. The comparison between the predicted and experimental friction factor values for flow in straight tubing is shown in Figures 5.1 to 5.3. The correlation is valid for $3,000 < N_{Reg} < 90,000$, and $0.20 < n < 0.52$. Figure 5.4 shows a cross plot of the measured Fanning friction factor against predicted values from developed correlations for straight tubing. This figure further confirms the accuracy of the proposed correlation.

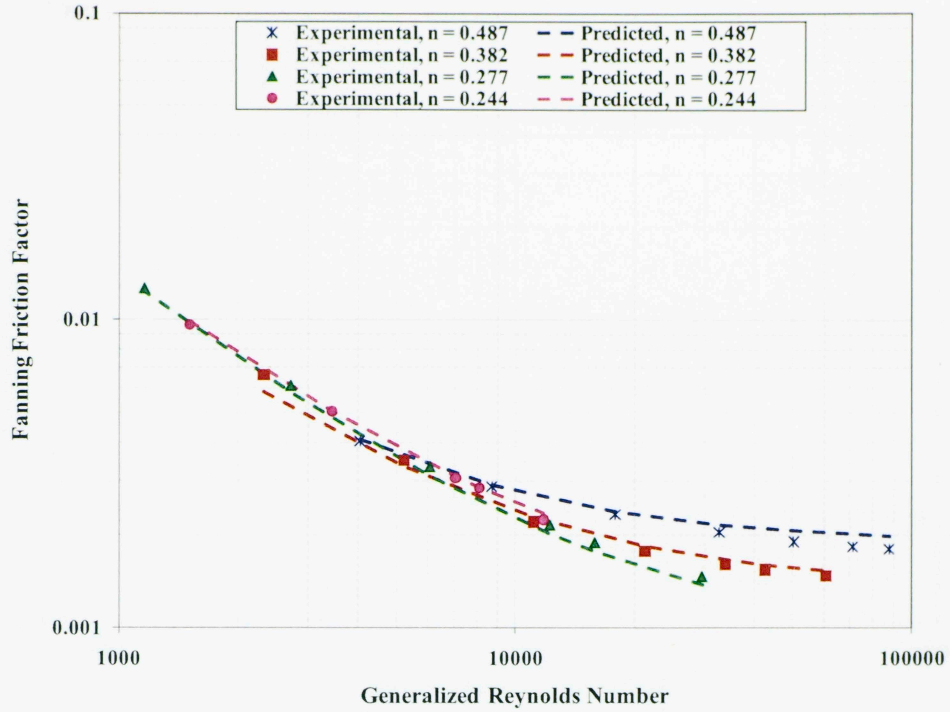

Fig. 5.1 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in Fresh Water (Straight Tubing)

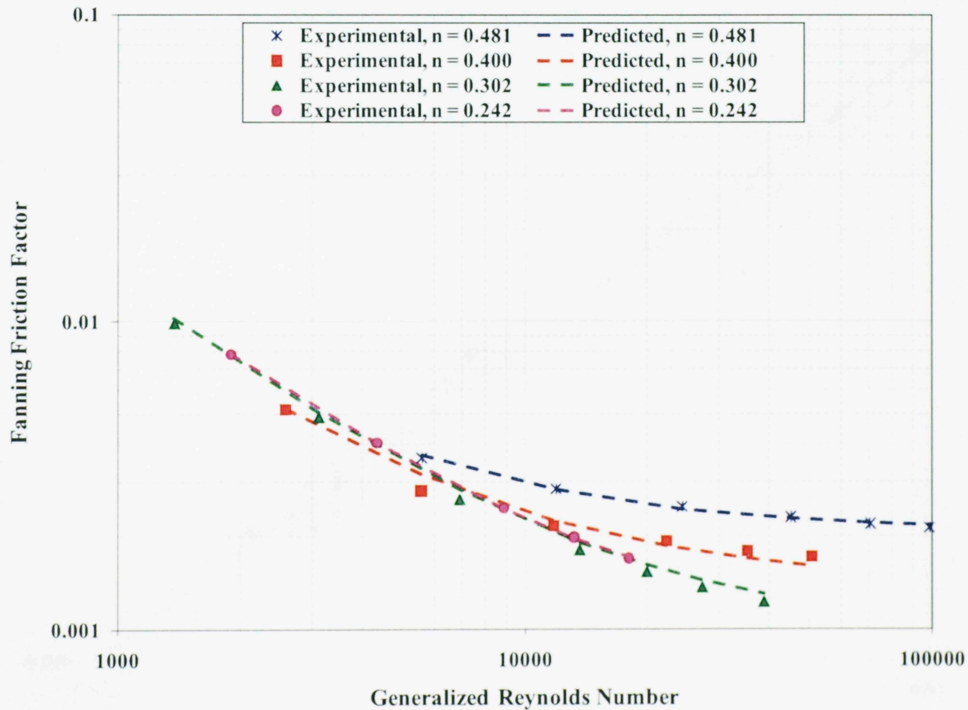

Fig. 5.2 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in 2% KCl Brine (Straight Tubing)

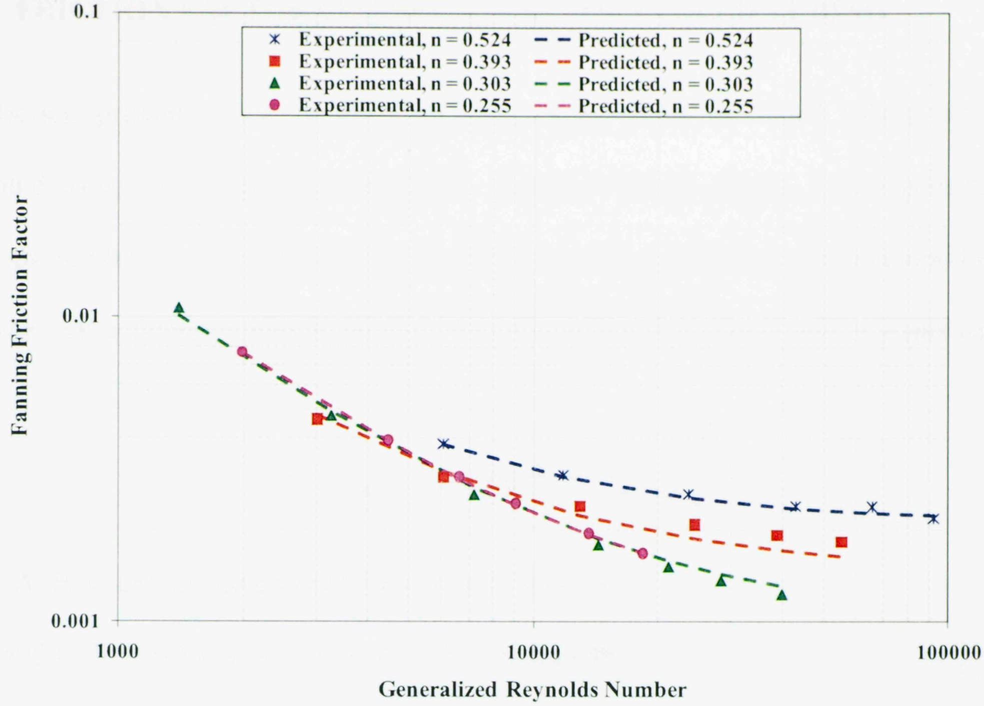

Fig. 5.3 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in 4% KCl Brine (Straight Tubing)

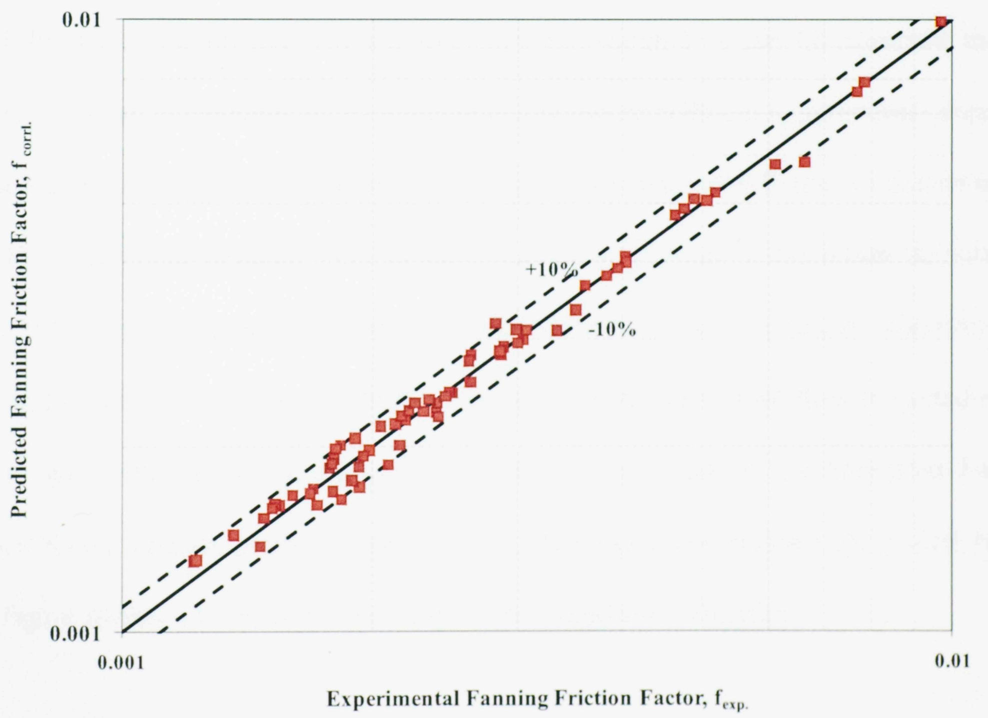

Fig. 5.4 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in Straight Tubing

5.2. FRICTION FACTOR CORRELATION FOR COILED TUBING

The friction pressure data for flow of welan gum fluids in coiled tubing are also correlated using dimensionless parameters; Fanning friction factor, f, and generalized Reynolds number, N_{Reg} and flow behavior index, n. The correlation was developed using the same curve fitting software as with straight tubing correlation and is expressed as follows:

$$f_{ct} = A * N_{\text{Reg}}^{\left(B + \frac{C}{n}\right)} + D * n \quad \textbf{(5.4)}$$

where, A, B, C and D are correlation constants given as:

A = 0.5059 ; B = -0.5484 ; C = 0.01227 ; D = 0.002186.

This correlation is valid for 3,000 < N_{Reg} < 10,0000; 0.20 < n < 0.52, and r/R = 0.019.

Figures 5.5 through 5.7 show comparison of predicted friction factor using the correlation with experimental values for coiled tubing for the three salinities considered; fresh water, 2 and 4% KCl respectively. For the salinities investigated, it can be observed that the predictions from correlation are in reasonable agreement with the experimental data, thus validating the correlation. The correlation has a correlation coefficient of determination of 0.98, an average absolute percent deviation of 4.97% and a maximum deviation of about 10% for all fluids investigated, further validating the correlation. Therefore, the proposed correlation can predict friction factor of welan gum fluid flow in coiled tubing with a reasonable accuracy. Figure 5.8 shows a cross plot of the measured Fanning friction factor against predicted values from developed correlations for coiled tubing. This figure further confirms the accuracy of the proposed correlation.

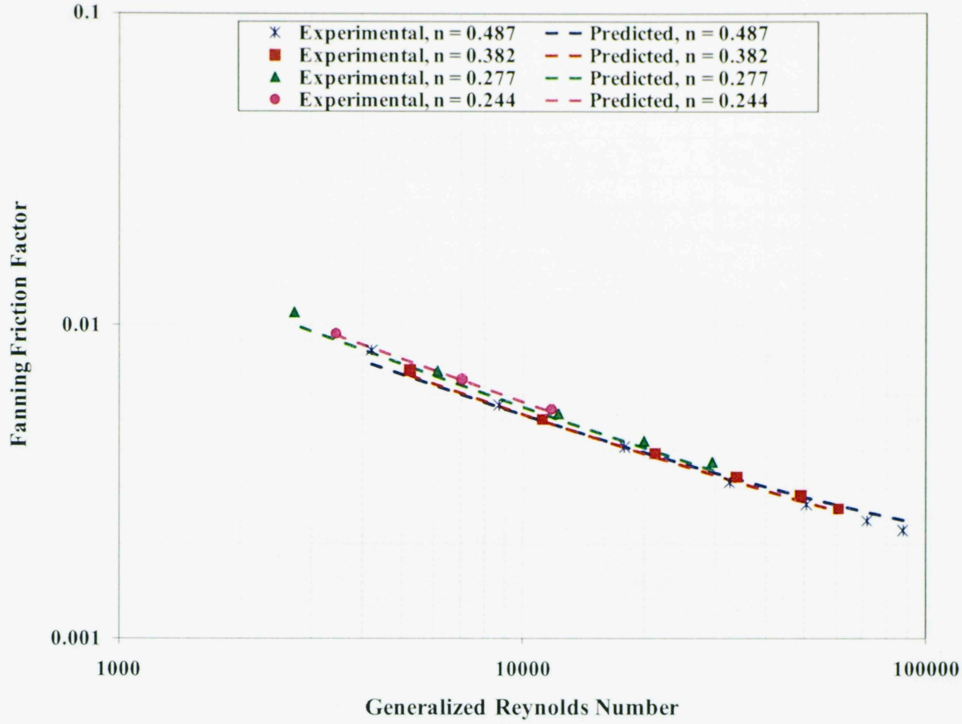

Fig. 5.5 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in Fresh Water (Coiled Tubing, r/R = 0.019)

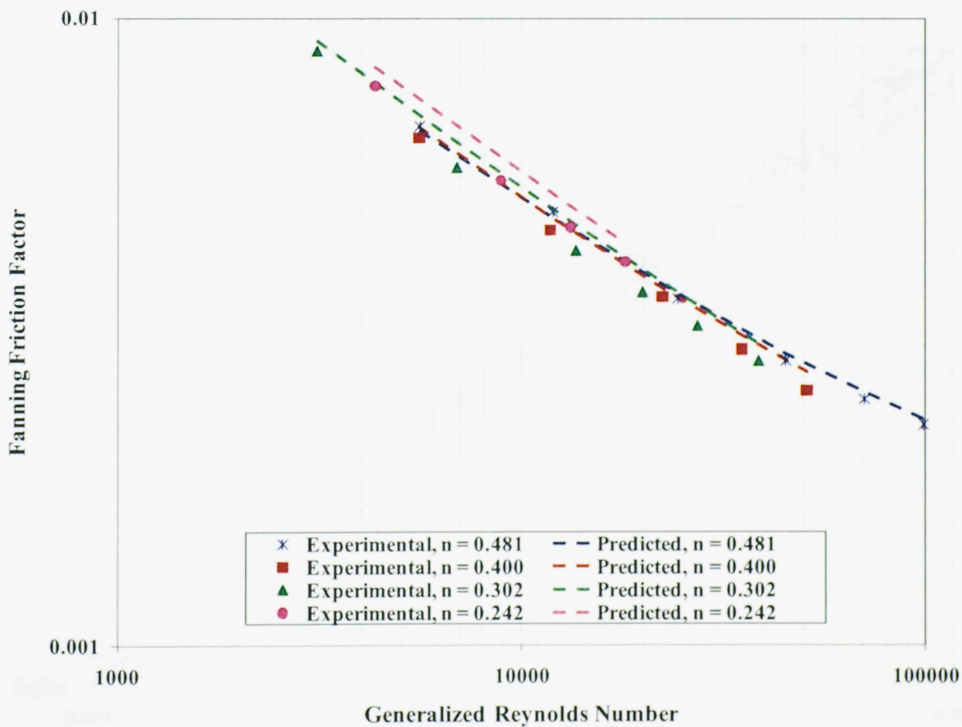

Fig. 5.6 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in 2% KCl Brine (Coiled Tubing, r/R = 0.019)

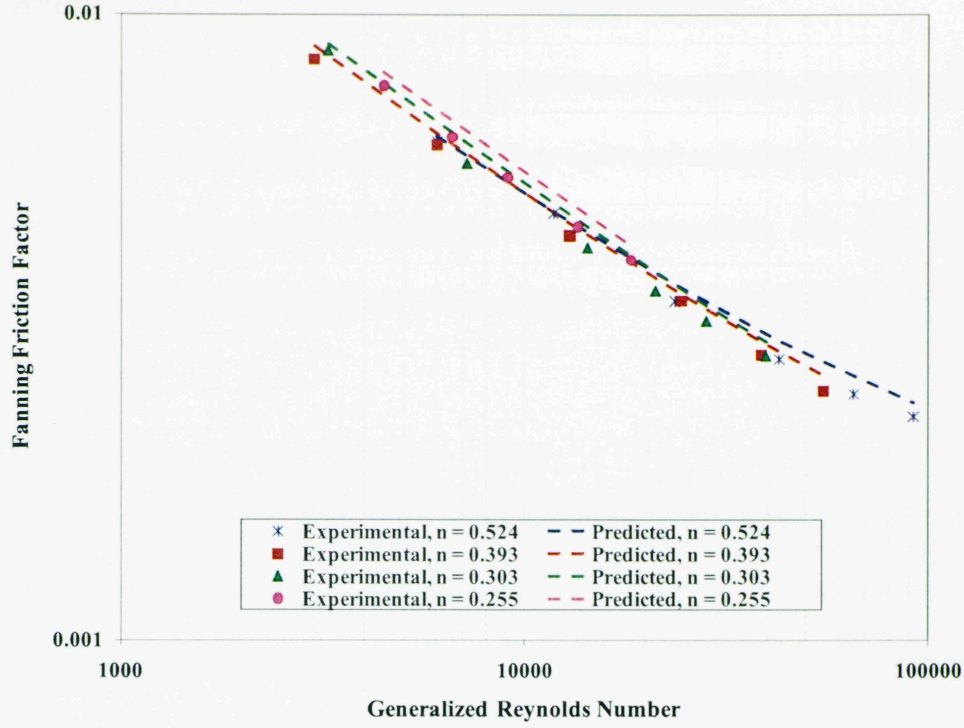

Fig. 5.7 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in 4% KCl Brine (Coiled Tubing, r/R = 0.019)

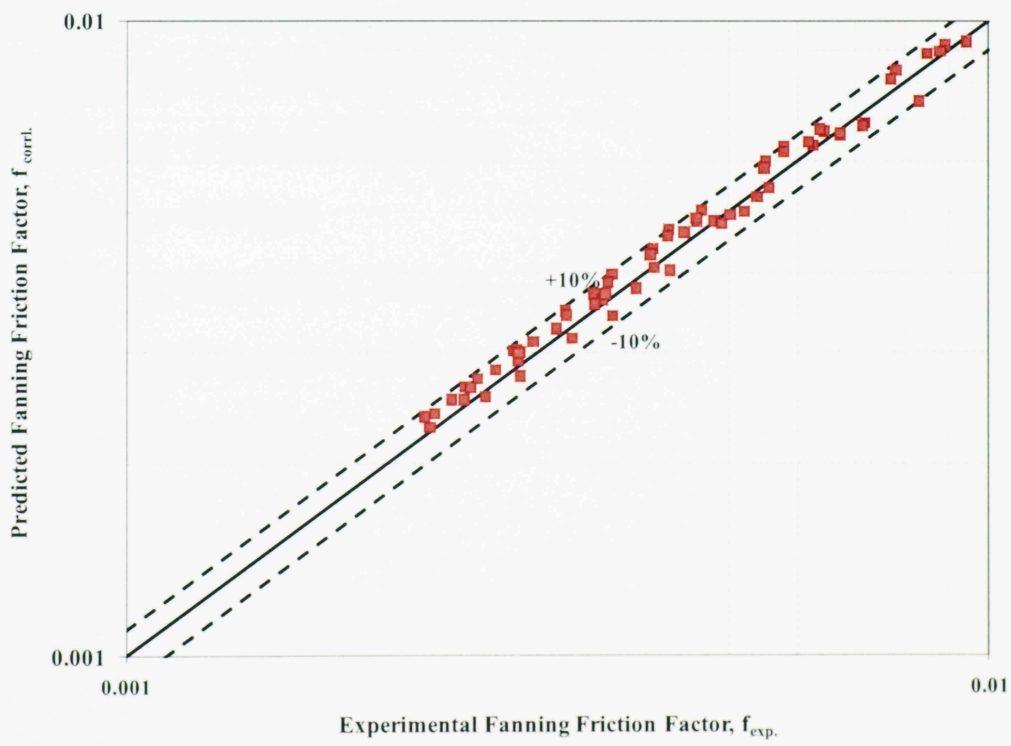

Fig. 5.8 Comparison between Predicted and Experimental Friction Factors for Welan Gum Fluids in Coiled Tubing (r/R = 0.019)

5.3. APPLICATION OF DEVELOPED CORRELATIONS

This section demonstrates an application of the developed correlations for tubular friction pressure loss prediction of welan gum fluids in straight and coiled tubing. The example used here is specifically related to hydraulic fracturing operations. The objective is to determine the horse power requirement for pumping a welan gum fluid through straight and coiled tubing.

Example

A formation at a depth of 7,000 ft is to be hydraulically fractured using coiled tubing. Given the following information, compute the friction pressure loss across the tubular and the resulting horse power requirement for pumping a fracturing fluid through the tubing.

Fluid Type = 2.0 lb/bbl welan gum in 4% KCl base fluid

Fluid Density, ρ = 8.60 lb/gal

Flow Behavior Index, n = 0.303

Consistency Index, K_p = 0.0548 $lb_f s^n/ft^2$

Injection Rate, q = 5 bbl/min (210 gal/min)

Liquid Volume = 80,000 gal

Tubing Size = 2 3/8 in. OD (d_i = 2.063 in.)

Reel Diameter = 109 in. (r/R = 0.019)

Tubing Length = 14,000 ft.

Solution

To perform the hydraulic fracturing treatment, 7,000 ft of the coiled tubing length will be lowered into the wellbore as straight section leaving 7,000 ft on the reel as coiled tubing. Fluid is therefore pumped through both straight and coiled sections.

Straight Section: From Eq. 3.5, $N_{Reg} = 0.02393 \times (3.8499)^{-n} \dfrac{d_i^{\,n} \rho}{K_p 8^{n-1}} \left[\dfrac{q}{A} \right]^{2-n}$, the generalized Reynolds number is computed as $N_{Reg} = 7{,}784$.

Using the developed correlation for predicting Fanning friction factor in straight tubing, Eqs. 5.1 – 5.3, the friction factor is computed to be: $f_{st} = 0.00251$.

The pressure drop gradient is then calculated using Eq. 3.6, $f = 25.8 \left[\dfrac{d_i \Delta p}{l v^2 \rho} \right]$, resulting in $\Delta p/l = 0.165$ psi/ft. Total pressure drop across the straight section (7,000 ft) is 1,152 psi.

The hydraulic horse power, P_H, requirement for this pumping operation is computed using the expression below:

$$P_H = \frac{\Delta p q}{1{,}714} \qquad \textbf{(5.5)}$$

Hence the pump power needed to overcome friction losses in the straight section is computed to be: $P_H = 141$ hp.

Coiled Tubing: From Eq. 3.5, the generalized Reynolds number again is computed as $N_{Reg} = 7{,}784$.

Using the developed correlation for predicting Fanning friction factor in coiled tubing, Eq. 5.4, the friction factor is computed to be: $f_{ct} = 0.006$.

The pressure drop gradient is then calculated using Eq. 3.6, resulting in $\Delta p/l = 0.394$ psi/ft. Total pressure drop across the entire tubing length (7,000 ft) is 2,759 psi.

The hydraulic horse power, P_H, requirement for pumping through the coiled tubing from Eq. 5.5. is $P_H = 338$ hp.

Total power required to overcome friction losses in both straight and coiled sections is equal to 479 hp.

The results of the calculations are summarized in Table 5.1.

Table 5.1 Pumping Operation Design Calculations

	Length, ft	Δp/l, psi/ft	Δp, psi	P_H, hp
Straight tubing	7,000	0.165	1,152	141
Coiled tubing	7,000	0.394	2,759	338
Total	14,000	0.559	3,911	479

From the above example, it is observed that the pump power required to overcome friction losses in the coiled section is about 140 % higher than the straight section of same length. This is in agreement with experimental observations.

5.4. SCALABILITY OF DEVELOPED CORRELATIONS

The generalized Reynolds number range in this study is typical of those encountered in oilfield operations. However, larger tubing sizes are normally used in oilfield operations, where the fluids are pumped at higher flow rates compared to the ½-inch OD (0.435-inch ID) straight and coiled tubing used for the experimental investigation and development of friction pressure loss correlations in our study. Hence, it is important to verify the applicability of the developed correlations to predict frictional pressure losses in larger tubing sizes. For the straight tubing, this exercise was carried out with 2⅞-inch OD (2.499-inch ID) tubing and 1.75 lb/bbl and 2.25 lb/bbl welan gum fluids in fresh water. However, we were not able to verify the scalability of the developed correlations in the coiled tubing due to insufficient welan gum polymer. Figure 5.9 shows the comparison of the experimental and predicted friction pressure values for 1.75 lb/bbl (n = 0.426) and 2.25 lb/bbl (n = 0.220) welan gum fluids flowing through 2⅞-inch OD straight tubing.

From the plot it can be observed that our correlation predicts Fanning friction factors in the 2⅞-inch tubing with an acceptable degree of accuracy. For 1.75 lb/bbl welan gum fluids, the average and maximum percentage deviations between the experimental and predicted Fanning friction factors are 3.6 and 9.3 % respectively, while for 2.25 lb/bbl welan gum fluids the deviations are 4.6 and 10.9 % respectively. Hence, for the straight tubing, the Fanning friction factor correlations developed with experimental data from ½-inch tubing can be used to predict Fanning friction factors in the 2⅞-inch tubing, further validating the scalability and accuracy of the correlations.

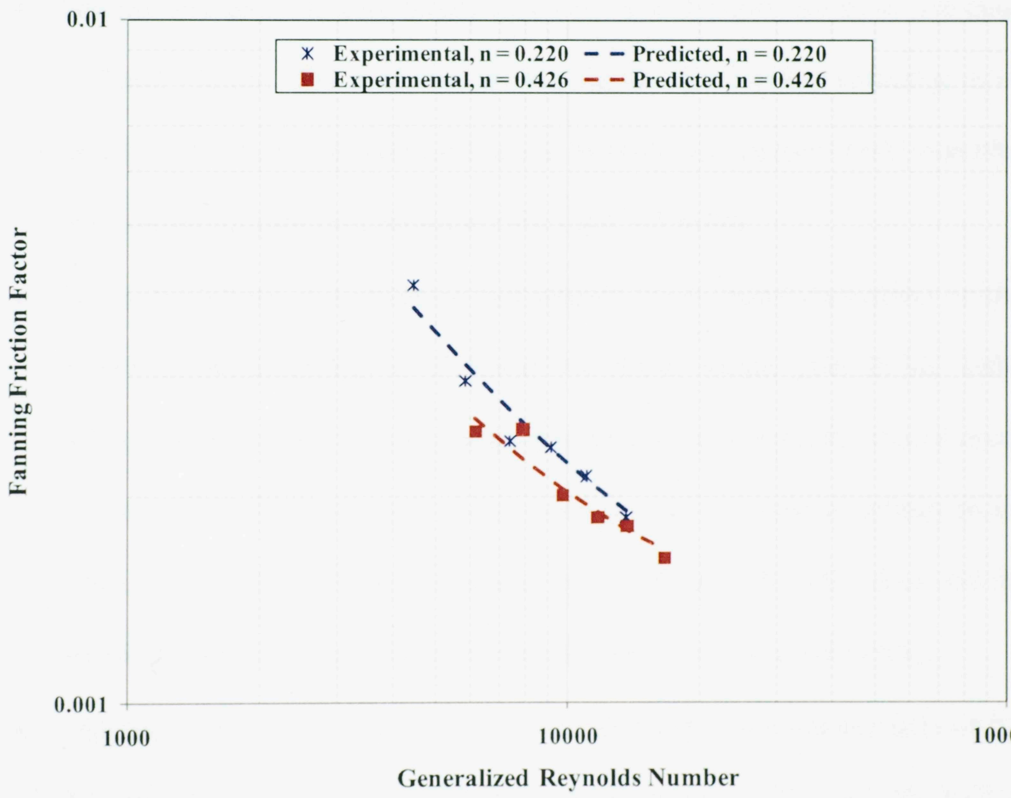

Fig. 5.9 Comparison between Predicted and Experimental Friction Factors for 1.75 and 2.25 lb/bbl Welan Gum Fluids in Fresh Water (2⅞-inch ST)

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

- Correlations for predicting Fanning friction factor for flow of welan gum in both straight and coiled tubing have been developed.
- From the rheology data gathered in this study, it is confirmed that welan gum fluids viscosities are sensitive to salt (KCl). The sensitivity is seen as a reduction in viscosity of fluid as the concentration of salt is increased.
- Salinity increases the drag reduction ability of welan gum fluids at concentrations of 2 and 3 lb/bbl. This could be due to delay in onset of drag reduction in straight tubing as fluid concentration increases. Notably, an opposite trend was observed at lower welan gum concentration of 0.5 and 1.0 lb/bbl.
- For coiled tubing, it is observed that salinity has no significant effect on the drag reduction characteristics of 0.5 and 1.0 lb/bbl welan gum fluids within the generalized Reynolds number range investigated. However, the drag reduction of 2.0 and 3.0 lb/bbl welan gum fluids increases with increase in salinity from fresh water to 2% KCl. Further increase in salinity to 4% KCl does not have a significant effect on the drag reducing characteristics in coiled tubing.
- Fanning friction factor correlations developed with experimental data of 0.5, 1.0, 2.0, and 3.0 lb/bbl welan gum fluids in fresh water, 2%, and 4% KCl and in ½-inch tubing were used to accurately predict Fanning friction factors in 2⅞-inch straight tubing for 1.75 and 2.25 lb/bbl welan gum fluids in fresh water.

6.2. RECOMMENDATIONS

- The generalized Reynolds number range used in this study is typical of oilfield applications. However, experimental investigation should be conducted in larger coiled tubing sizes and at higher flow rates, typical of oilfield applications to further verify the findings of this study. Large scale tests were not carried out due to insufficient amount of welan gum for testing.
- In this study, tests were conducted at room temperature which is usually not the case for field applications. In the field, the fluid temperature varies due to heat generated in the pumping equipment or weather conditions. Temperature affects the solution properties of polymeric fluids such as viscosity and solubility. Therefore, it is important to investigate the effects of temperature on the hydraulic properties of welan gum fluids of concentrations typical in oilfield applications, especially in straight and coiled tubing. One way to achieve this purpose would be to investigate the effect of temperature on the power law parameters – *n* and *k*.
- Only monovalent brine (KCl) in the concentration range commonly used in field operations to prevent clay swelling and shale instability has been considered in this study. Based on the results from our experimental study, further increase in KCl concentration will have insignificant effect on the viscosity and hydraulic properties of welan gum fluids in straight and coiled tubing. Divalent brines such as $CaCl_2$ are also used as base fluids in field operations. They have higher ionic strength when compared with monovalent brines of same concentration, and are expected to cause more significant decrease in solution viscosity of welan gum fluids. Therefore, it is important to investigate the effects of divalent brines on the rheological and hydraulic properties of welan gum fluids in straight and coiled tubing and friction factor correlations developed accordingly.

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APPENDIX A

ERROR PROPAGATION ANALYSIS

If a variable Z depends on (one or) two variables (A and B) which have independent errors (ΔA and ΔB), then the rule for calculating the error in Z is tabulated in Table A.1 for a variety of simple relationships (Taylor, 1997):

Table A.1 Rules for Calculating Error Propagation

Relation between Z and (A, B)	**Relation between errors ΔZ and (ΔA, ΔB)**
$Z = A + B$	$(\Delta Z)^2 = (\Delta A)^2 + (\Delta B)^2$
$Z = A - B$	$(\Delta Z)^2 = (\Delta A)^2 + (\Delta B)^2$
$Z = A \cdot B$	$\left(\frac{\Delta Z}{Z}\right)^2 = \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2$
$Z = \frac{A}{B}$	$\left(\frac{\Delta Z}{Z}\right)^2 = \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2$
$Z = A^n$	$\frac{\Delta Z}{Z} = n\frac{\Delta A}{A}$
$Z = \ln A$	$\Delta Z = \frac{\Delta A}{A}$
$Z = e^A$	$\frac{\Delta Z}{Z} = \Delta A$

Error in velocity calculation is computed as:

$$\Delta v = v\sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(2\frac{\Delta d}{d}\right)^2} \tag{B.1}$$

Error in generalized Reynolds number calculated as:

$$\Delta N_{\mathrm{Reg}} = N_{\mathrm{Reg}}\sqrt{\left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta v}{v}\right)^2 + \left(\frac{\Delta d}{d}\right)^2} \tag{B.2}$$

Error in Fanning friction factor calculated as:

$$\Delta f = f\sqrt{\left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta(\Delta p)}{\Delta p}\right)^2 + \left(\frac{\Delta l}{l}\right)^2 + \left(2\frac{\Delta v}{v}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2} \tag{B.3}$$

Table A.2 shows the error associated with each measured parameter for both straight and coiled tubing.

Table A.2 Parameter Errors for Friction Factor Calculations

Parameter	**Error**	
	Straight Tubing	Coiled Tubing
q (gal/min)	± 0.05%	± 0.05%
Δp (psi)	± 0.075%·Calibration Span	± 0.075%·Calibration Span
ρ (lb/gal)	± 0.0042 lb/gal	± 0.0042 lb/gal
d (in.)	± 0.0001 in.	± 0.0001 in.
l (ft)	± 0.01 ft	± 0.01 ft

APPENDIX B

PRESSURE DROP – FLOW RATE DATA FOR FRESH WATER

Table B.1 Flow Data for Fresh Water through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.01	0.20	0.25	8.27
5.02	0.48	0.61	8.28
8.01	1.11	1.40	8.28
10.10	1.70	2.17	8.28
12.10	2.35	2.97	8.29
16.05	3.95	4.97	8.29

APPENDIX C

ROTATIONAL VISCOMETER DATA FOR WELAN GUM FLUIDS

Table C.1 Rotational Viscometer (Fann Model 35, # 1/5 Spring) Data for 0.5 lb/bbl Welan Gum Fluids in Various Brine Solutions

Shear Rate, RPM	Dial Reading		
	Fresh Water	2% KCl	4% KCl
600	57	47	45
300	39	32	30
200	32	26	25
180	30	25	24
100	23	19	18
90	22	18	17
60	18	15	14
30	14	11	10
6	8	6	7
3	7	5	5
1.8	6	4	4
0.9	4	3	3

Table C.2 Rotational Viscometer (Fann Model 35, # 1/5 Spring) Data for 1.0 lb/bbl Welan Gum Fluids in Various Brine Solutions

Shear Rate, RPM	Dial Reading		
	Fresh Water	2% KCl	4% KCl
600	105	90	86
300	79	65	63
200	68	55	53
180	66	54	51
100	53	41	40
90	52	40	38
60	45	35	33
30	37	28	26
6	26	18	17
3	22	15	14
1.8	19	13	11
0.9	16	11	10

Table C.3 Rotational Viscometer (Fann Model 35, # 1/5 Spring) Data for 2.0 lb/bbl Welan Gum Fluids in Various Brine Solutions

Shear Rate, RPM	Dial Reading		
	Fresh Water	2% KCl	4% KCl
600	222	200	195
300	183	158	153
200	162	140	134
180	160	137	132
100	137	116	110
90	135	114	107
60	123	103	96
30	108	90	82
6	87	66	60
3	79	60	55
1.8	69	53	48
0.9	63	48	43

Table C.4 Rotational Viscometer (Fann Model 35, # 1 Spring) Data for 3.0 lb/bbl Welan Gum Fluids in Various Brine Solutions

Shear Rate, RPM	Dial Reading		
	Fresh Water	2% KCl	4% KCl
600	74	69	66
300	62	56	54
200	56	51	49
100	49	44	42
6	35	27	26
3	33	25	25

APPENDIX D

FLOW BEHAVIOR INDEX AND FLUID CONSISTENCY INDEX FOR WELAN GUM FLUIDS

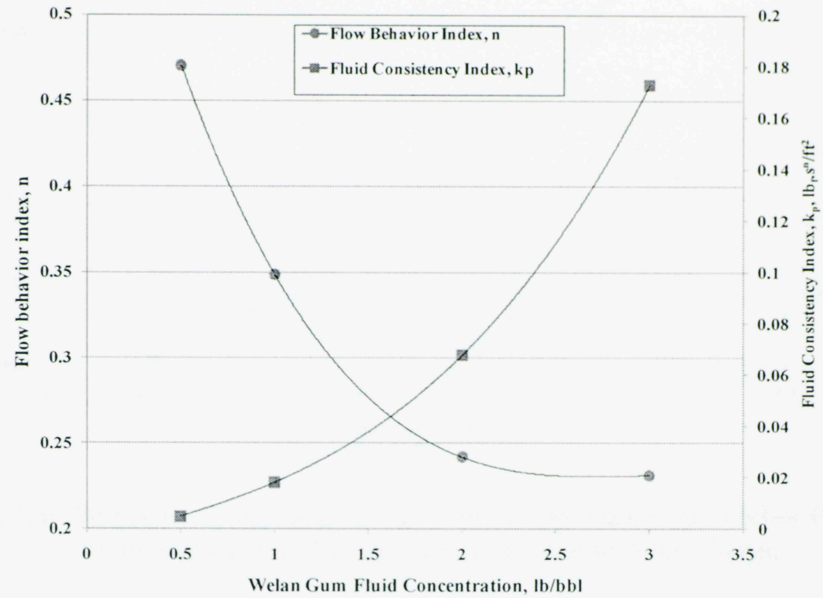

Fig. D.1 Flow Behavior Index and Fluid Consistency Index vs. Welan Gum Fluid Concentration for Welan Gum Fluids in Fresh Water

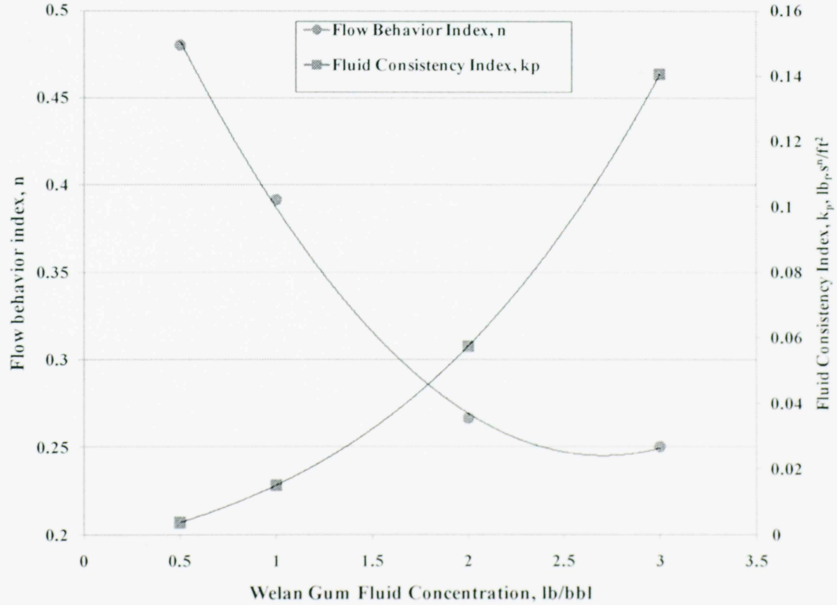

Fig. D.2 Flow Behavior Index and Fluid Consistency Index vs. Welan Gum Fluid Concentration for Welan Gum Fluids in 2% KCl Brine

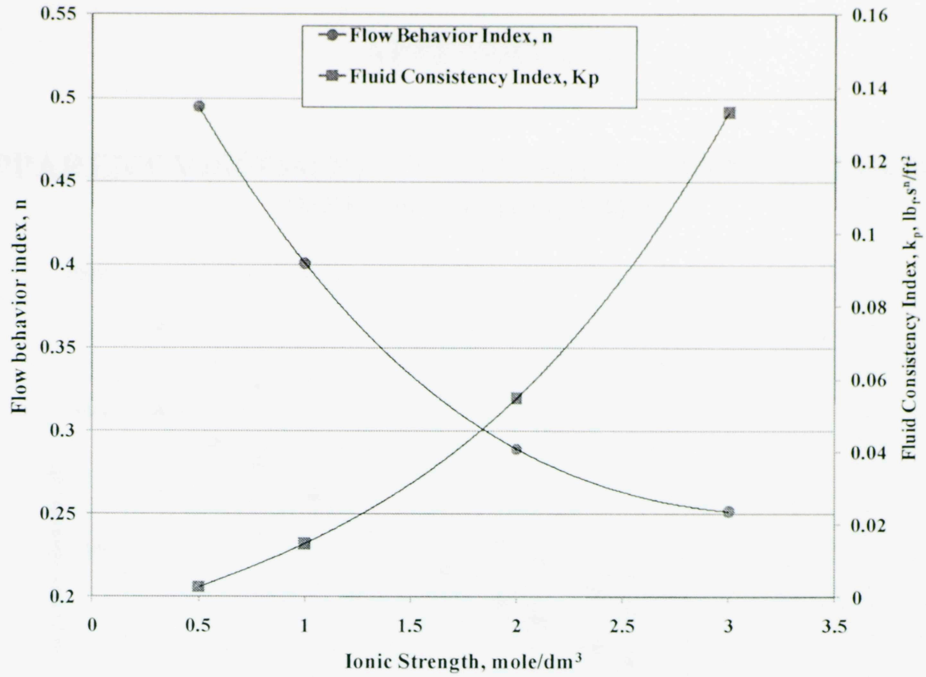

Fig. D.3 Flow Behavior Index and Fluid Consistency Index vs. Welan Gum Fluid Concentration for Welan Gum Fluids in 4% KCl Brine

APPENDIX E

APPARENT VISCOSITY – WALL SHEAR RATE PLOTS FOR WELAN GUM FLUIDS

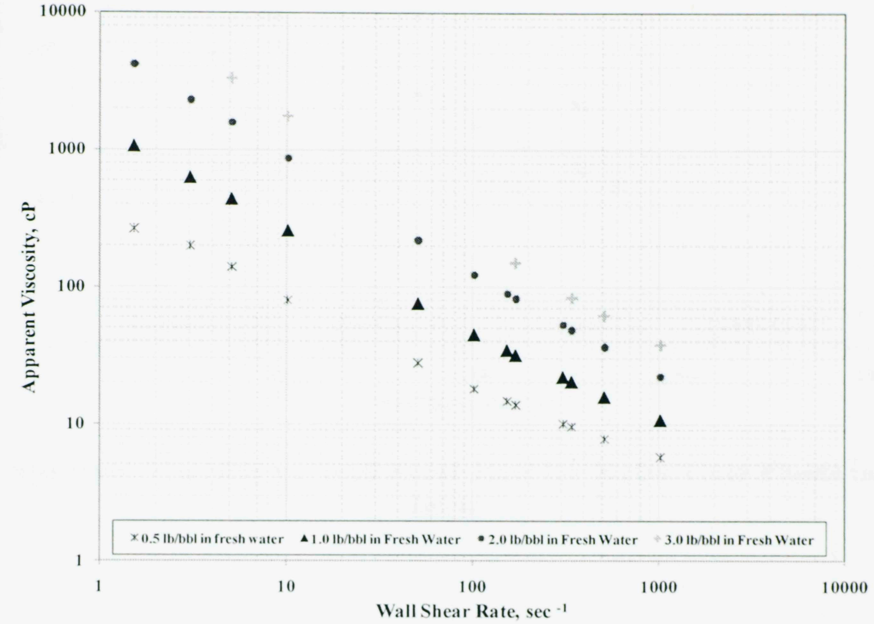

Fig. E.1 Apparent Viscosity vs. Wall Shear Rate for Welan Gum Fluids in Fresh Water

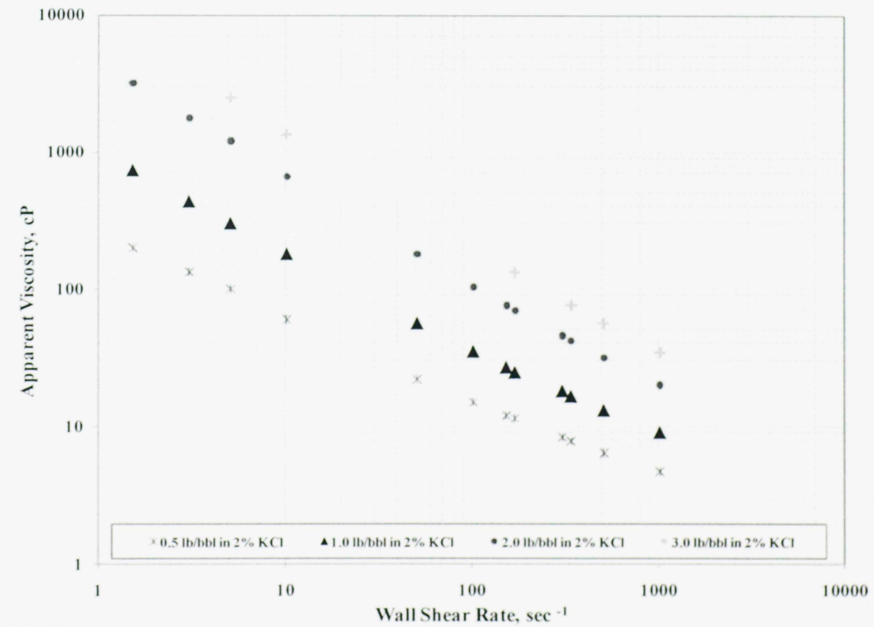

Fig. E.2 Apparent Viscosity vs. Wall Shear Rate for Welan Gum Fluids in 2% KCl Brine

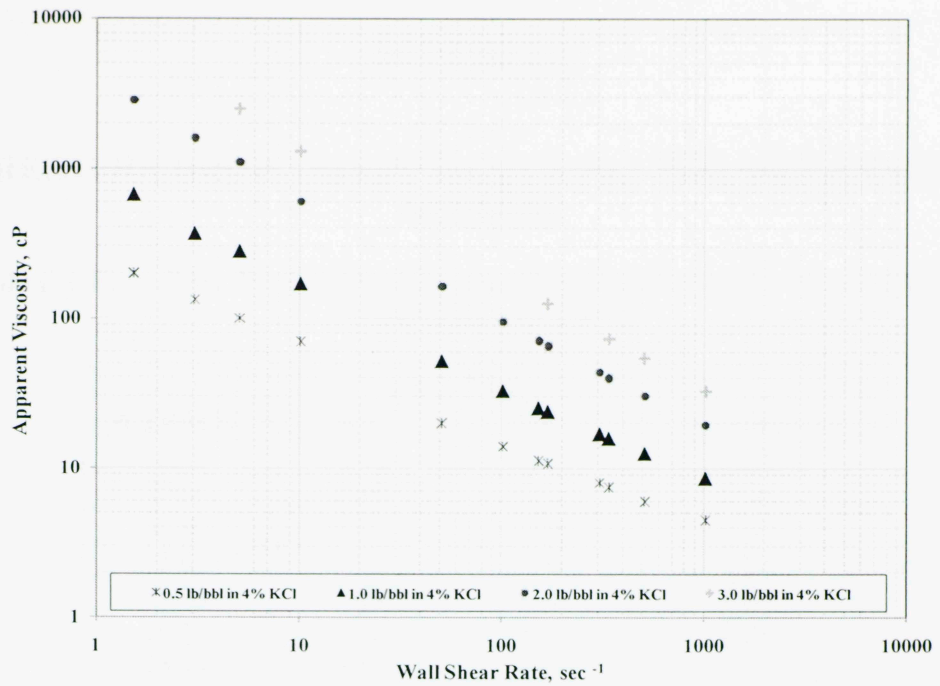

Fig. E.3 Apparent Viscosity vs. Wall Shear Rate for Welan Gum Fluids in 4% KCl Brine

APPENDIX F

PRESSURE DROP – FLOW RATE DATA FOR WELAN GUM FLUIDS

Table F.1 Flow Data for 0.5 lb/bbl Welan Gum Fluid in Fresh Water Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.03	0.13	0.28	8.28
5.03	0.25	0.48	8.28
8.08	0.52	0.92	8.27
12.05	1.02	1.57	8.28
16.04	1.69	2.38	8.28
20.11	2.55	3.33	8.30
23.10	3.33	4.07	8.31

Table F.2 Flow Data for 0.5 lb/bbl Welan Gum Fluid in 2% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.07	0.12	0.22	8.41
5.05	0.26	0.44	8.43
8.09	0.57	0.81	8.42
12.14	1.19	1.46	8.42
16.29	2.04	2.29	8.44
20.30	3.08	3.25	8.45

Table F.3 Flow Data for 0.5 lb/bbl Welan Gum Fluid in 4% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.23	0.14	0.23	8.47
5.05	0.27	0.43	8.52
8.09	0.61	0.81	8.52
12.11	1.24	1.46	8.53
16.12	2.20	2.28	8.54
20.28	3.20	3.32	8.55

Table F.4 Flow Data for 1.0 lb/bbl Welan Gum Fluid in Fresh Water Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.06	0.21	0.39	8.27
5.06	0.31	0.64	8.28
8.07	0.50	1.13	8.28
12.04	0.89	1.95	8.28
16.07	1.43	2.93	8.29
18.54	1.83		8.29
20.16		4.01	8.30
23.04	2.71	4.77	8.31

Table F.5 Flow Data for 1.0 lb/bbl Welan Gum Fluid in 2% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.14	0.18	0.32	8.39
5.06	0.25	0.58	8.42
8.09	0.50	1.05	8.42
12.08	0.98	1.83	8.41
16.03	1.62	2.66	8.43
20.14	2.44	3.63	8.45

Table F.6 Flow Data for 1.0 lb/bbl Welan Gum Fluid in 4% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.28	0.18	0.32	8.49
5.07	0.27	0.56	8.52
8.11	0.56	1.03	8.52
12.08	1.08	1.80	8.53
16.04	1.76	2.61	8.54
19.99	2.61	3.56	8.55

Table F.7 Flow Data for 2.0 lb/bbl Welan Gum Fluid in Fresh Water Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.08	0.41	0.61	8.28
5.04	0.54	0.96	8.28
8.06	0.75	1.61	8.28
12.08	1.08	2.63	8.29
14.05	1.29	3.80	8.30
20.17	2.06	5.13	8.30

Table F.8 Flow Data for 2.0 lb/bbl Welan Gum Fluid in 2% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.13	0.34	0.51	8.41
5.05	0.44	0.80	8.44
8.08	0.60	1.32	8.45
12.05	0.92	2.17	8.45
15.07	1.22	2.92	8.46
18.12	1.57	3.72	8.47
22.23	2.12	4.93	8.48

Table F.9 Flow Data for 2.0 lb/bbl Welan Gum Fluid in 4% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.08	0.36	0.53	8.54
5.06	0.43	0.80	8.55
8.06	0.60	1.34	8.55
12.11	0.93	2.21	8.56
15.22	1.25	2.98	8.57
18.06	1.59	3.76	8.58
22.03	2.13	4.93	8.59

Table F.10 Flow Data for 3.0 lb/bbl Welan Gum Fluid in Fresh Water Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.16	0.74	0.95	8.25
5.04	0.84	1.29	8.27
8.07	1.13	2.10	8.27
12.13	1.55	3.40	8.28
13.10	1.68		8.29
16.21	2.04	4.87	8.28

Table F.11 Flow Data for 3.0 lb/bbl Welan Gum Fluid in 2% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.15	0.56	0.75	8.40
5.03	0.69	1.10	8.44
8.05	0.92	1.77	8.45
12.09	1.27	2.83	8.46
15.16	1.60	3.75	8.47
18.10	1.96	4.71	8.48

Table F.12 Flow Data for 3.0 lb/bbl Welan Gum Fluid in 4% KCl Brine Through ½-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
3.22	0.58	0.77	8.55
5.05	0.70	1.11	8.56
8.05	0.91	1.77	8.56
10.07	1.08	2.30	8.57
12.06	1.27	2.84	8.57
15.19	1.61	3.77	8.58
18.06	1.96	4.71	8.59

Table F.13 Flow Data for 1.75 lb/bbl Welan Gum Fluid in Fresh Water Through 2⅞-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
32.1	0.022	0.023	8.45
50.3	0.021	0.028	8.45
100.4	0.028	0.044	8.44
150.0	0.031	0.062	8.44
175.7	0.043	0.072	8.44
200.6	0.045	0.084	8.44
225.5	0.053	0.098	8.44
248.7	0.063	0.112	8.44
281.8	0.072	0.131	8.44

Table F.14 Flow Data for 2.25 lb/bbl Welan Gum Fluid in Fresh Water Through 2⅞-inch ST and CT

q, gal/min	ΔP/L, psi/ft		ρ, lb/gal
	ST	CT	
30.9	0.033	0.036	8.45
49.6	0.035	0.038	8.45
100.3	0.042	0.057	8.45
150.4	0.052	0.077	8.45
175.3	0.051	0.087	8.45
199.7	0.054	0.106	8.44
225.3	0.067	0.120	8.44
250.2	0.075	0.130	8.45
281.2	0.083	0.151	8.44

APPENDIX G

CORRELATION PARAMETERS A VERSUS APPARENT VISCOSITY AND B VERSUS FLOW BEHAVIOR INDEX

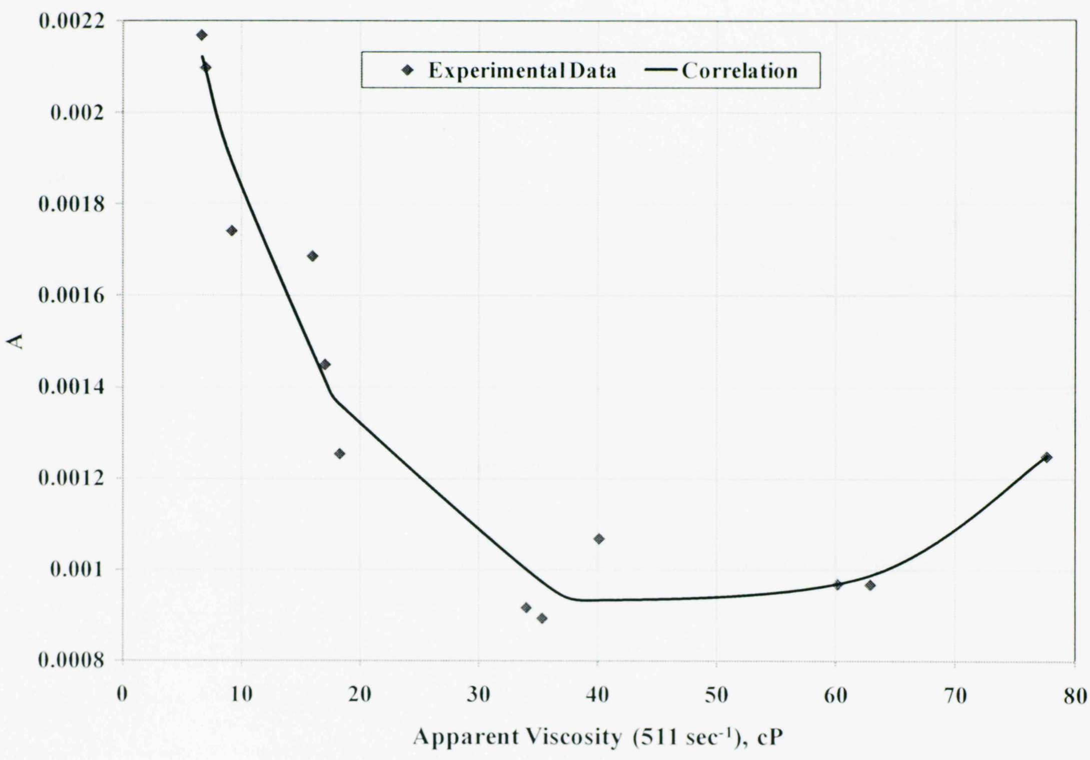

Fig. G.1 Correlation Parameter A vs. Apparent Viscosity (511 sec^{-1})

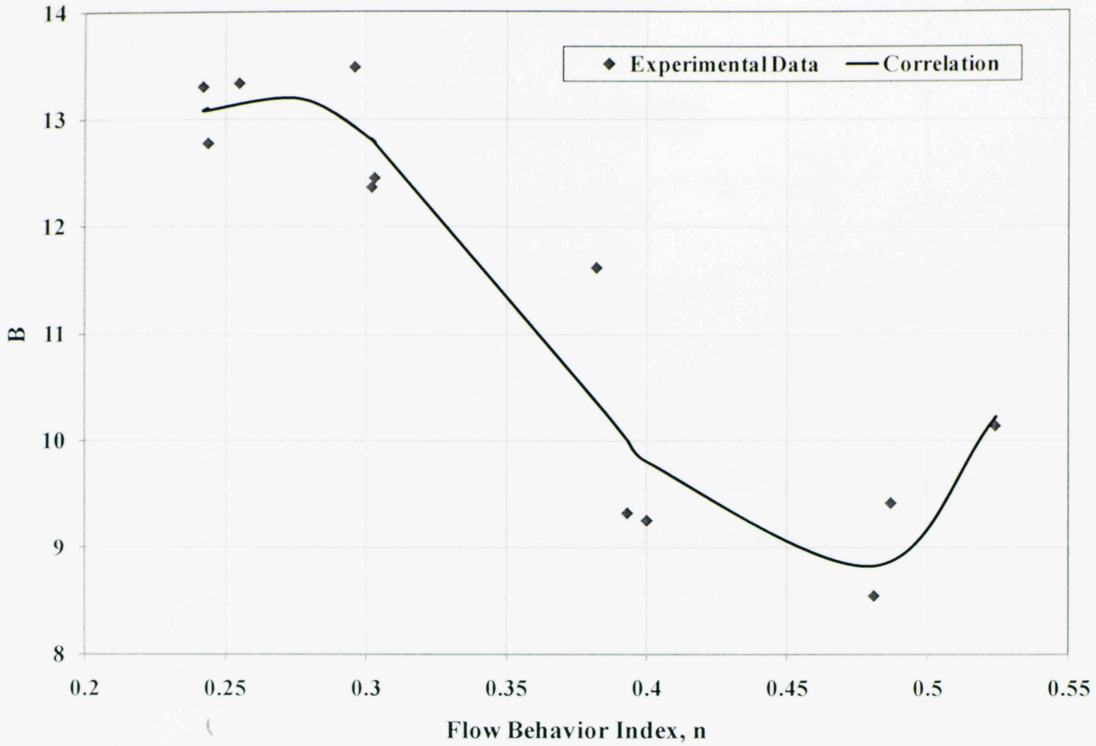

Fig. G.2 Correlation Parameter B vs. Flow Behavior Index

APPENDIX H

NOMENCLATURE

A	=	Pipe cross sectional area, *(in.^{2})*
b, c and d	=	Correlation Constants
d_i	=	Internal diameter of tubing, (*in.*)
DR	=	Drag Reduction
f	=	Fanning friction factor, *dimensionless*
f_p	=	Fanning friction factor of polymer solution, *dimensionless*
f_s	=	Fanning friction factor of solvent, *dimensionless*
k	=	Consistency index of power law fluid ($lb_f s^n/ft^2$)
K_p	=	Pipe Consistency index, ($lb_f s^n/ft^2$)
K_v	=	Viscometer consistency index, ($lb_f s^n/ft^2$)
l	=	Length between pressure ports (*ft*)
N	=	Spring factor for Fann 35 viscometer
n	=	Flow behavior index of power law fluid, *dimensionless*
N_{De}	=	Dean number, *dimensionless*
$N_{DeCritical}$	=	Critical Dean number, *dimensionless*
N_{Deg}	=	Generalized Dean number, *dimensionless*
N_{Re}	=	Reynolds number, *dimensionless*
$N_{ReCritical}$	=	Critical Reynolds number, *dimensionless*
N_{Reg}	=	Generalized Reynolds number, *dimensionless*
N_{Res}	=	Reynolds number of solvent, *dimensionless*
OD	=	Outside tubing diameter, (*in.*)
P_H	=	Pump horse power
q	=	Flow rate (*gpm*)
r	=	Radius of coiled tubing, (*in.*)
R	=	Radius of curvature of coiled tubing reel, (*in.*)
r/R	=	Coiled tubing curvature ratio, *dimensionless*
R^2	=	Correlation coefficient, *dimensionless*
RPM	=	Revolutions per minute
v	=	Average fluid velocity, (*ft/sec*)
Δp	=	Pressure drop (*psi*)

GREEK SYMBOLS

$\dot{\gamma}$	=	Shear rate, (s^{-1})
$\dot{\gamma}_w$	=	Wall shear rate, (s^{-1})
β	=	Ratio of bob to cup radius for rotational Viscometer
θ	=	Viscometer dial reading
σ	=	Constant in Eqs. 3.3 and 3.4, *dimensionless*
τ	=	Shear stress (lb_f/ft^2)
τ_o	=	Yield stress (lb_f/ft^2)
τ_w	=	Wall shear stress (lb_f/ft^2)
μ	=	Viscosity of fluid, (*cP*)
μ_a	=	Apparent Viscosity of fluid, (*cP*)
μ_p	=	Plastic Viscosity of fluid, (*cP*)
ρ	=	Fluid density, (lb_m/gal)

SUBSCRIPTS

ct	=	Coiled Tubing
st	=	Straight Tubing
CT	=	Coiled Tubing
ST	=	Straight Tubing

NAME AND ADDRESS	DATE