Springer

Journal of Mechanical Science and Technology 22 (2008) 1914~1920

Journal of Mechanical Science and Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0732-y

A study on the solid-liquid 2 phase helical flow in an inclined annulus †

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(Manuscript Received April 16, 2008; Revised July 2, 2008; Accepted July 23, 2008)

Abstract

An investigation is conducted to understand hydraulic transport characteristics of a solid-liquid mixture flowing vertically upward. Namely, this is the instance that solid particles are carried by non-Newtonian fluids in a slim hole concentric annulus with rotating inner cylinder. In this study a clear acrylic pipe was used in order to observe the movement of solid particles. The bulk axial velocities varied from 0.4 m/s to 1.2 m/s. The mud systems which were utilized included aqueous solution of sodium carboxymethyl cellulose (0.2~0.4%CMC) and 5% bentonite solutions. Solid volumetric concentration and pressure drops were measured for the various parameters such as inclined annulus, flow rate, and rotational speed of inner cylinder. For both CMC and bentonite solutions, the higher the concentration of the solid particles are, the larger the pressure drops become.

Keywords: Solid-liquid mixture flow; Pressure drop; Slip velocity; Solid concentration

1. Introduction

Rotating flows in annular passages are important, since they have many engineering applications in bearings, rotating-tube heat exchangers and, especially, annulus flows of mud in case of slim hole drilling of oil well.

When an oil well is drilled, it is necessary to transport the cuttings up to the surface. To this end, fluid is pumped through the center of drill pipe and back up to the surface through the annular gap between the drill pipe and the drilled hole. The fluid is viscous, non-Newtonian, and will typically have gel strength. The flow up to the annulus might be laminar or it might be turbulent, depending on the situation.

With the increase in use of deviated, highly deviated and long reach drilling, greater consideration must be given to the fluid mechanics of transportation in situation where none, or only a small component, of the bulk flow acts against the tendency for cuttings to drop out of suspension and form a bed on the low side of the annulus. This is even more important in slim hole drilling.

Therefore, numerous mathematical and empirical models for the prediction of cuttings transport in horizontal and directional wells have been developed by several researchers. A detailed study reveals that the cuttings transport characteristics change with an increase in wellbore angle. Tomren et al. [1] and Ford et al. [2] carried out experimental studies on cuttings transport in inclined annulus and observed the existence of different layers that might occur during the mud flow and cuttings in an annulus. They noted that rotation of the drill pipe had little effect unless the annulus is eccentric and the drill pipe is on the low side of a horizontal geometry. In this condition, rotation helped to prevent a bed of cuttings being formed.

Interest has been growing in the interaction between particle and local flow structure in particulate two-phase flow. Pigot [3] discussed the application of Stoke's law for laminar flow and Rittinger's formula for turbulent flow to drilled particle settling velocity

† This paper was presented at the 9th Asian International Conference on Fluid Machinery (AICFM9), Jeju, Korea, October 16-19, 2007.
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calculation. He concluded that high fluid viscosity was not necessary and suggested that laminar flow in the annulus would lead to more efficient cleaning. For trouble-free operation, he also recommended that the volumetric cuttings concentration in the annulus be kept less than 5%.

Sifferman et al. [4] found that annular velocity and fluid rheological properties are the most important factors influencing the transport ability of a fluid. Other variables such as particle size, drill pipe rotation, drill pipe eccentricity have only moderate effects on carrying capacity in their study.

Sellgren [5] and Ozbelge et al. [6] discussed the pressure drop and the choice of operating velocities in the vertical upward pipe flows of solid-liquid mixtures. He reported that additional turbulence was created due to the relative velocity between the solid and fluid phases.

This paper concerns an experimental and numerical study of fully developed solid-liquid mixture flow of non-Newtonian fluid, 0.2-0.4% CMC and 5% bentonite solutions through a concentric annulus with combined bulk axial flow and inner cylinder rotation.

The flow characteristics of solid-liquid mixtures, flowing upward through a vertical annulus in a closed loop system, is investigated by measuring the concentration profiles of solids and the axial pressure drops in the apparatus. It is expected that the results of this study will be useful to understand the effect of several important parameters on solid-liquid mixture transport mechanism in the annular geometry.

2. Experimental method

The objective of the solid-liquid mixture flow experiments was to provide high quality data on the effects of pipe rotation, flow regime, fluid properties, solid concentration on pressure loss in a slim hole annulus. The set-up used in the experiments is a closed-loop system consisting of a centrifugal slurry pump with a by-pass line, a vertical annulus and a feed slurry tank as shown in Fig. 1. The flow configuration and instrumentation are described by Kim and Hwang [7].

The outside diameter of the inner pipe (D_1) and the inside diameter of the outer pipe (D_2) being 30 mm and 44 mm, respectively, yield a radius ratio of 0.7 for the annulus. To ensure fully developed flow in the measuring section, the length of straight pipe upstream of the test section is 1.8 m, corresponding to 116 hydraulic diameters, in order to produce an artificially thickened boundary layer.

A cylindrical head tank was used for the preparation of the feed particles. The tank having a conical bottom in order to avoid the settling of the solids and it is connected from its bottom to a centrifugal pump with a vertical pipe.

The flow rate has been measured with a magnetic flow meter whose accuracy is within the limit of ± 0.5 percent. The inner cylinder may be rotated at any speed up to a maximum of 400 rpm by means of an A.C. motor. And the axial velocity of solid particle was measured by using high speed camera installed outside of the cylinder. The outer cylinder was made of transparent acryl pipe.

Static pressures are measured with holes of 0.5 mm diameter distributed longitudinally in the outer cylinder. 2 static pressure taps are installed along the flow direction in measuring part. The static pressures are read from a calibrated manometer bank with 1 mm resolution. The specific gravity of the manometer fluid CCl_4 is 1.88.

The head tank was filled with water up to a marked level and the pump was started. Particles, at a desired feed solid concentration were prepared in the head tank by adding the uniformly sized sand particle. The mixture flow rate was adjusted manually by the by-pass valve installed after the outlet of the pump. When the mixture flow reaches steady state, the axial

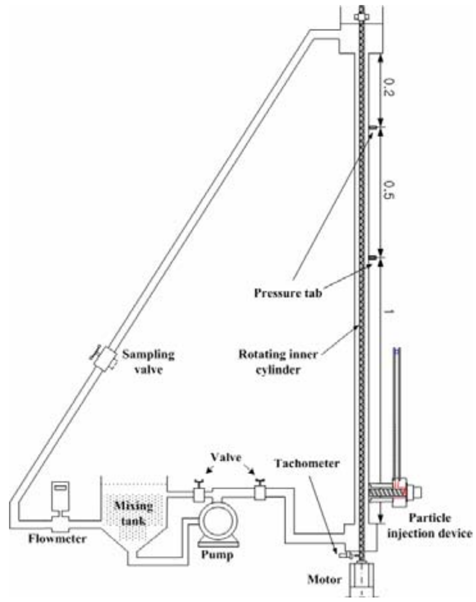


Fig. 1. Schematic diagram of experimental apparatus.

pressure drops and velocity of solid particle were measured simultaneously. The mean diameter of particles was 0.1 cm and a material density of 2.55 g/cm^3 were used in the experiments.

Firstly, experiments with water were carried out to determine the accuracy of the present experimental set-up. Later, experiments with the solid-liquid mixtures were performed in a similar manner.

The tank was filled with water up to the marked level and the pump was started. Slurry, at a desired feed solid concentration was prepared in the tank by adding the weighted amount of uniformly sized particles. The mixture flow rate was adjusted manually by the valve and the simultaneous measurement of the axial pressure drops and the solid volume concentration (C_{VT}) were carried out in the test section.

The drilling fluids usually have non-Newtonian properties. Non-Newtonian fluids are those for which the strain rate and stress curve are not linear, i.e., the viscosity of non-Newtonian fluids is not constant at a given temperature and pressure but depends on other factors such as the rate of shear in the fluid, the apparatus in which the fluid is contained or even the previous history of the fluid.

In the case of CMC and bentonite solutions, n <1 and the power law relating the shear stress τ to the shear rate γ is given by

$$\tau = K\gamma^n \tag{1}$$

where, n is the flow behavior index and K is the consistency factor. The apparent viscosity μ_a for a power law fluid may be expressed in terms of n and K as follows,

$$\mu_a = K\gamma^{n-1} \tag{2}$$

The effective viscosity of 0.4% CMC solution for the flow rate of 6 LPM becomes 22 cp at 0 rpm and 18 cp at 200 rpm and n is measured as 0.76.

3. Numerical method

Traditionally, the annulus between drill pipe and the borehole has been represented as a concentric annulus as shown in Fig. 2. There are two main approaches to modeling multi phase flows that account for the interaction between the phases. These are the Eulerian-Eulerian and the Eulerian-Lagrangian approaches. The former is based on the concept of interpenetrating continua, for which all the phases are treated as continuous media with properties analogous to those of a fluid. The Eulerian-Lagrangian approach adopts a continuum description for the liquid phase and tracks the discrete phases using Lagrangian particle trajectory analysis.

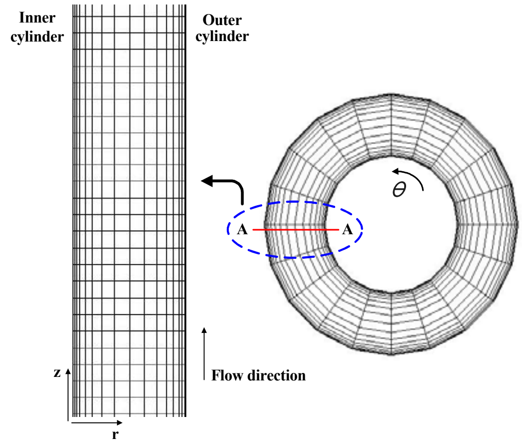


Fig. 2. Computational grid of concentric annulus.

In the numerical study, the Eulerian-Eulerian approach for granular flow is used that allows the determination of the pressure and viscosity of the solids phase instead of empirical correlations.

In a numerical study of solid-liquid mixture, a laminar flow of water in an eccentric annulus has been calculated. A control volume based finite volume method is used to solve the equations of motion. The problem reduced to the solution of the conservation of mass and momentum equations along with the appropriate boundary and initial conditions.

The governing set of partial differential equations was discretized using a finite volume technique. The discretized equations along with the initial and boundary conditions were solved using FLUENT. Particle-particle interactions via friction were also included.

The solids volume fraction in a domain of known volume was specified at the beginning of each simulation to correspond to the desired solids loading. The particles used in the simulation were solid spheres with a density of 2.55 g/cm^3. Values of the coefficient of restitution and the friction coefficients for these particles were assumed to be 0.9 and 0.09, respectively. The same coefficient of friction was also assumed for interactions between the walls and the particles.

No-slip boundary conditions are imposed on all the solid surfaces for the continuous phase. The same conditions are also applied to the discrete phase and imposed in the corresponding momentum equations. The inlet liquid velocity and the outlet pressure were specified. No-slip boundary conditions were assumed at the walls for the liquid phase. Interactions of particles with the walls were modeled with the same formulation used for solids pressure and granular viscosity for the particle-particle interactions.

4. Result and discussion

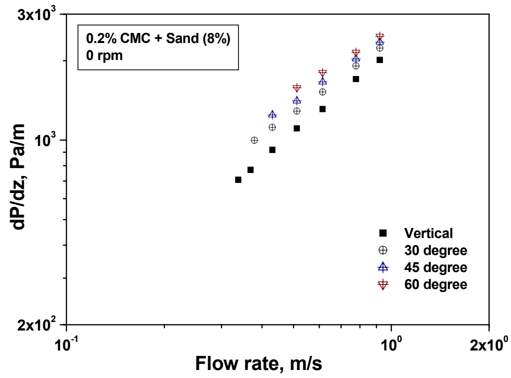
Hydrodynamic characteristics of single phase flows are known well, but the same is not valid for solid-liquid mixture flow. In this study, the flow characteristics of solid-liquid mixture flows are investigated experimentally at different operating conditions.

For solid-liquid mixture flows, the experimental and numerical parameters are the feed solid concentration, mixture velocity in the annulus, rotational speed of inner cylinder, and inclination of annulus from vertical. The important characteristics of solid-liquid flows are the pressure drop versus mixture velocity relationship and solid particle volumetric concentration.

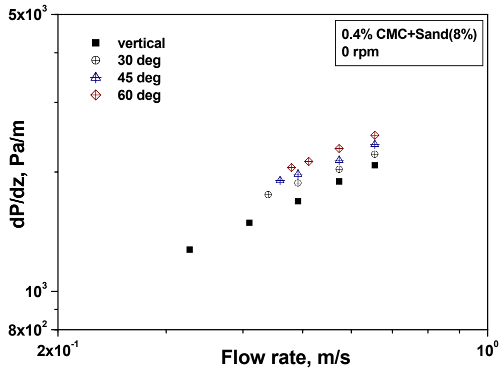
In slim hole it is important to remember that because of the reduced annular clearance the effect of the pressure losses is different than that experienced in conventional drilling. In conventional drilling 90% of the pressure losses occurs in the drill pipe and through the bit nozzle. In slim hole up to 60% of the pressure losses occur in the annulus (Sagot et al. [8]).

The pressure drop versus mixture velocity and annular inclination are shown in Fig. 3, for the mean particle size of 2 mm. As shown in Fig. 3, the pressure drop increases along the increase of inclination of annulus from vertical and mixture velocity. For higher inclination, the hydraulic pressure drop of solid-liquid mixture increases due to the friction between the wall and solids or among solids.
The inclination of annulus affects the magnitude of the pressure drop, but the shape of the pressure drop curves is not changed. The pressure drop increases as the viscosity of carrier fluid is increased. The viscos ity of carrier fluids is increased in order of 0.2% CMC, 0.4% CMC, and 5% bentonite solutions.

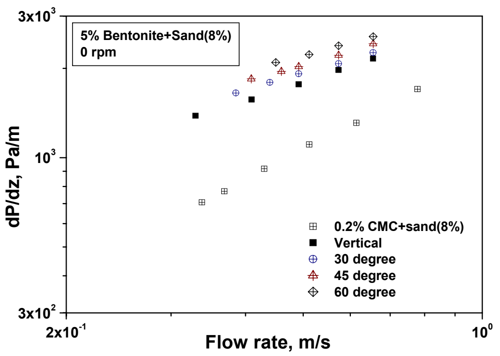
Successful and economic drilling of highly deviated slim hole wells requires the efficient transportation of cuttings to the surface. Fig. 4 shows graphical correlation of solids volume concentration (C_{VT}) in terms of relevant drilling parameters. The C_{VT} can give a good indication of drilling fluid transport efficiency. The C_{VT} is the ratio of the occupied volume of solids for the occupied volume of mixture flow. The lower the concentration is, the better the transport.



(a) 0.2% CMC solution

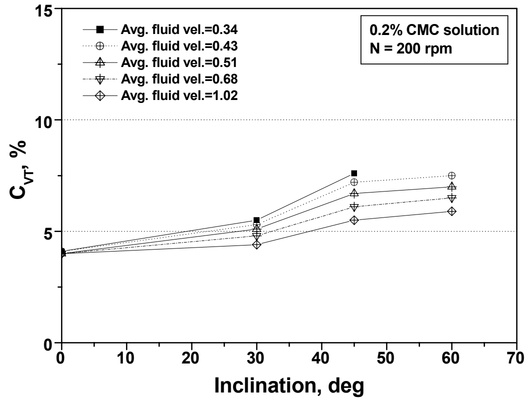


(b) 0.4% CMC solution

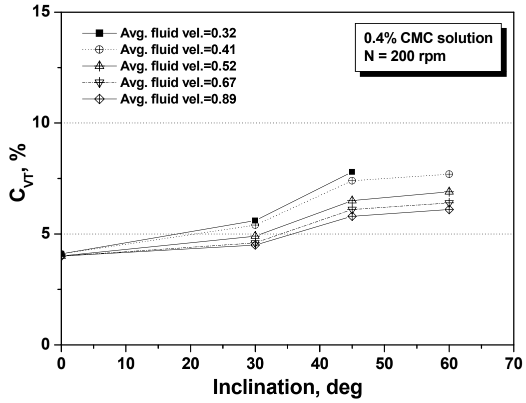


(c) 5% bentonite solution

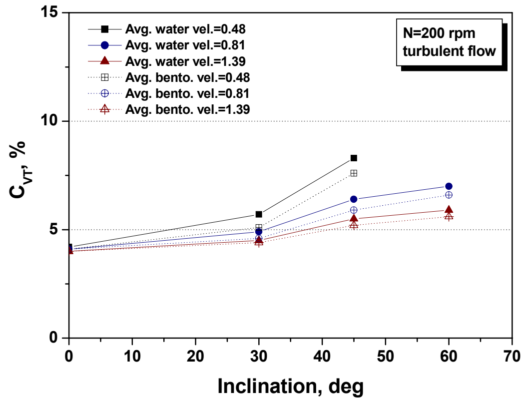
Fig. 3. Variation of pressure loss with mixture velocity (sand: 8%) at 0 rpm : (a) 0.2% CMC solution, (b) 0.4% CMC solution, (c) 5% bentonite solution.



(a) 0.2% CMC solution



(b) 0.4% CMC solution



(c) 5% bentonite solution

Fig. 4. Variation of concentration with fluid velocity and inclination at 200 rpm : (a) 0.2% CMC solution, (b) 0.4% CMC solution, (c) 5% bentonite solution.

From this point of view, it is obvious form Fig. 4 that all drilling fluids perform best at low angles of hole inclination. And the higher the fluid velocity, the more effective the cuttings transportation in all hole angles.

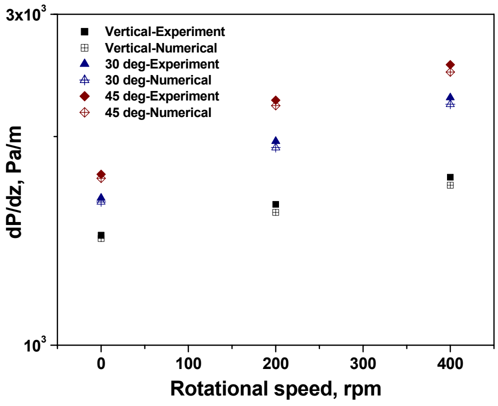


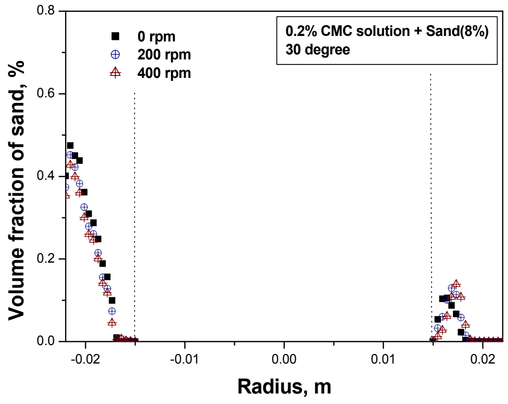
Fig. 5. Comparison of pressure drop in 0.2% CMC solution as a function of rotational speed at v_z =0.67 m/s.

The fluid velocity of 0.2% CMC solution is much smaller than that of water for solids transport at the same conditions. That is, the transport efficiency of 0.2% CMC solution is much better than that of water. This is because of the viscosity of 0.2% CMC solution is about 6 times of water. But the transport efficiency is not improved in 0.4% CMC solution, although the viscosity of 0.4% CMC solution is about 2 times of 0.2% CMC solution.

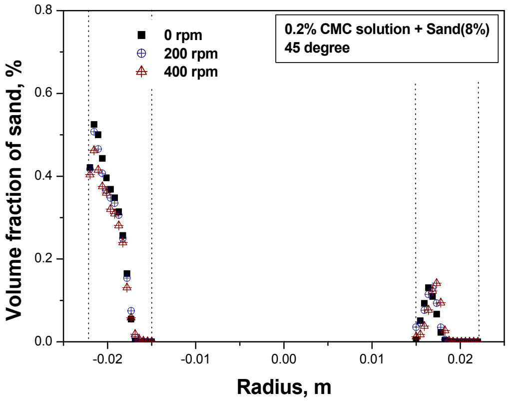
Fig. 4(c) shows the transport efficiency of 5% bentonite solution compared to 0.4% CMC solution. The transport efficiency of 5% bentonite solution is obviously improved over 0.4% CMC solution. The main reason of this improvement is the specific gravity of 5% bentonite solution. Viscosity and density of fluid are important elements in the drilling fluid design.

Both visual observations and flow measurement show that the effects of liquid viscosity on cuttings behavior depend on the flow regime. In laminar flow, bed formation in high viscosity fluid was slow compared to the low viscosity fluid. In turbulent flow, however, although a slightly smaller bed of cuttings did form in the higher viscosity fluid, bed formation was just as fast as in each case. These phenomena may be related to particle slip velocities in turbulent flow being greater than in laminar flow.

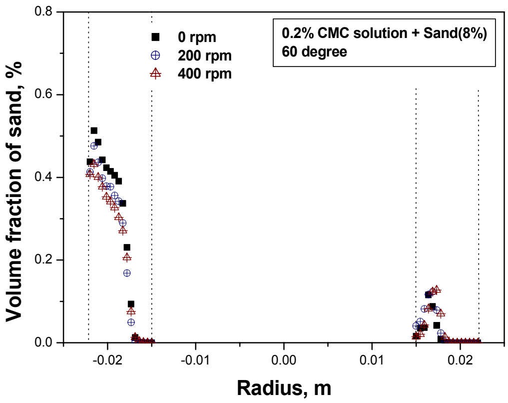
To obtain a more realistic representation of the drilling operation, the solid-liquid mixture flow in concentric annulus for a power law fluid was considered. Numerical calculations have been extended for the case where the inner cylinder rotates about its own axis at a constant rotational speed. Detailed calcula-



(a) 30 degree



(b) 45 degree



(c) 60 degree

Fig. 6. Volume fraction of sand in 0.2% CMC solution with inclination at v_z=0.43 m/s : (a) 30 degree, (b) 45 degree, (c) 60 degree.

tions have been carried out for radius ratio of 0.7 covering rotational speed of the inner cylinder up to 400 rpm.

The computational domain consists of 15, 96, and 500 nodes in the radial, azimuthal and axial directions respectively. And the calculation results were compared with experimental data in terms of pressure drop.

As shown in Fig. 5, Calculation results were compared to experimental data in order to validate numerical model results. The calculation results showed a good agreement with experimental data for the pressure drop, but numerical results are slightly lower than experimental values.

Calculations were run for 0.2% CMC solution as carrier fluid, flowing at an average fluid velocity of 0.43 m/s through annuli of radius ratio of 0.7 to understand the particle behavior and bed formation mechanism of solid-mixture flow in an inclined annulus. The solid concentration is set to 8 percent. And the inclination of annulus is changed from vertical to 60 degree.

It is difficult to calculate exactly the behavior of particles in bed and the bed formation in numerical method. But, a pattern in the results is visible. Fig. 6 shows the simulated solid content profiles from Fluent at several flow conditions. Fluent predicted that almost all sand particles settle down to the lower part of the annulus and some particles were suspended in the upper part of the annulus. As the hole inclination is increased from vertical, the volume fraction of sand is increased.

At each angle of inclination, the rotation of inner cylinder scatters the particles located in bed and decreases the volume fraction. But the effect of rotation appears to be weakened over 200 rpm.

5. Conclusion

In this study the steady laminar upward flows of solid-liquid mixtures through a concentric annulus has been investigated experimentally and numerically.

The solid-liquid mixture flow pressure drop increases with the feed concentration, the flow rate, and the inclined annulus. For higher solid concentration, the hydraulic pressure drop of solid-liquid mixture flow increases due to the friction between the wall and solids or among solids.

Rotation of the inner cylinder generally improves the transport of solid particles and it is more pronounced at lower mixture velocities and appears to be weakened at high flow rate. Generally, 5% bentonite solution is observed to provide better transport than 0.2% and 0.4 % CMC solutions. The main reason for this is the combined effects of viscosity and specific gravity of 5% bentonite solution and uniform velocity profile of shear-thinning fluid.

Numerical calculations were run for 0.2% CMC solution as carrier fluid and the calculation results showed a good agreement with experimental data for the pressure drop, but numerical results are slightly lower than experimental values.

Numerical calculation predicted that almost all sand particles settle down to the lower part of the annulus and some particles were suspended in the upper part of the annulus. As the hole inclination is increased from vertical, the volume fraction of sand is increased.

Acknowledgements

This work was supported by the Brain Korea 21 Project in 2007, and the Korea Institute of Geoscience & mineral Resources.

Nomenclature

C_{VT} : Solid volume concentration, (%)
dP/dz : Axial Pressure loss, (Pa/m)
D_h : Hydraulic diameter, (m)
Re : Reynolds number
R_1 : Radius of inner cylinder, (mm)
R_2 : Radius of outer cylinder, (mm)
η : Ratio of radius, (R_1/R_2)
μ : Absolute viscosity, ($Pa \cdot s$)
ρ : Density of fluid, (kg/m^3)
θ : Slope of annulus, (°)

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