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Experimental Model design For Oilwell Drilling Rig Circulation System studies Part II.(Rig constrains, parameters and rig construction)

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Abstract

This paper is the second part in the series of the experimental apparatus design for vertical annular concentric pipes flow studies with rotation of the inner pipe. Part one in this series considered the preliminary design of the experimental rig, in terms of preliminary scaling from field data, dimensional analysis and design and suggested experimental conditions. In the present paper (part II), the rig design constrains, rig parameters, and rig construction were considered. The main deign consideration were, to use water as working fluid for reasons of availability, safety, well established properties as well as its transparently to enable the laser Doppler velocity-meter to measure the velocity of the fluid, for the same reason the outer wall of the experimental model was chosen to be transparent perspex tube. As for experimental rig parameters in terms of volumetric flow rate and rotational speed were calculated based on actual filed well ranges of flow rates and drill pipe rotational speed, also the proposed experimental model in part I was constructed.

Keywords: *Computational Fluid Dynamics CFD, laser Doppler velocimeter, Rig Parameters, circulation.*

1. Introduction

Over balance oil well drilling fluids are nontransparent and non-Newtonian fluids, this will render measuring fluid velocity using laser Doppler velocimeter impossible, such a constrain along with some others should be considered while designing an experimental rig for annular flow modeling.This part of series is intended to construct the experimental apparatus and to evaluate the experimental parameters mainly volumetric flow rates and inner pipe rotation speed, and later on a computationally investigate incompressible Newtonian fluid flow behaviour in terms of axial and tangential velocities through the annulus of vertical uniform concentric pipes, with rotation of the inner pipe. The computational work was based on commercially available CFD software (Fluent)[1], typical of that likely to be used in industry, this study will be carried out in parts, the general strategy was to start with a simple geometry consisting of uniform vertical concentric pipes with and without rotation of the inner pipe carrying single phase working fluid (without solids).

Future study could move on to more complicated geometries, such as sudden expansion of the outer pipes and expansion or contraction of the inner pipes, with and without solids carried by the flow and, eventually, to model the most difficult flow at the rotating drilling bit itself. In this paper a physical experimental model of uniform vertical concentric pipes with rotation of the inner pipe was designed with dimensions scaled from real dimensions of actual oil well. The geometry of the model was investigated by Fluent to check validity of the model, were the results were very acceptable.

There are various drilling problems may encountered while drilling gas and oil well due to poor hole cleaning (lifting solids) related to drilling fluid properties and flow behavior, such as slow drilling rates or excessive drill pipe torque. Some merely render the drilling less efficient. Others, such as a stuck drill pipe or loss of circulation, interrupt the drilling progress for weeks which raises the cost and loss time of drilling and sometimes leads to abandonment of the well[2] and [3]. The problem becomes more critical during drilling of directional and horizontal wells, due to the hole inclination and tendency of the drilled cuttings to accumulate in the lower side of the hole.

Drilling fluid properties and flow behavior are key factors in avoiding such problems[2],[3]and [4] ,. This study is aimed at finding optimum flow and drilling fluid properties to be used in a typical offshore oil field such as Bouri, Libya[5]. Computational Fluid Dynamics (CFD) is potentially a powerful tool for achieving these objectives, but the first step is to verify that it can be applied successfully to the problem. The study will compare experimental velocities measured using a Laser Doppler Velocimeter (LDV) [6] and [7] technique with model simulations using CFD software. This paper as a second part of the study will consider the constrains and construction of the physical experimental model.

The experimental apparatus used should be:

1. Easy to construct and operate.
2. Able to provide clearly defined boundary conditions for comparison with CFD codes.
3. Representative of field flows, ie be scaled to operate at similar Reynolds and swirl numbers.
4. Able to allow detailed LDV measurements of flow properties in the annular flow region between well casing and drilling string.
5. Sufficiently simple to focus comparison on modeling of only swirling developing flow.

2. Experimental Rig Design Considerations

The experimental test rig was built to enable measurements of velocity profiles to be obtained, in order that they could be compared with those measurements obtained from computational models that would be achieved in next parts of this series of study. As discussed in part I, the proposed physical experimental model is as shown in Fig 1.)[8],

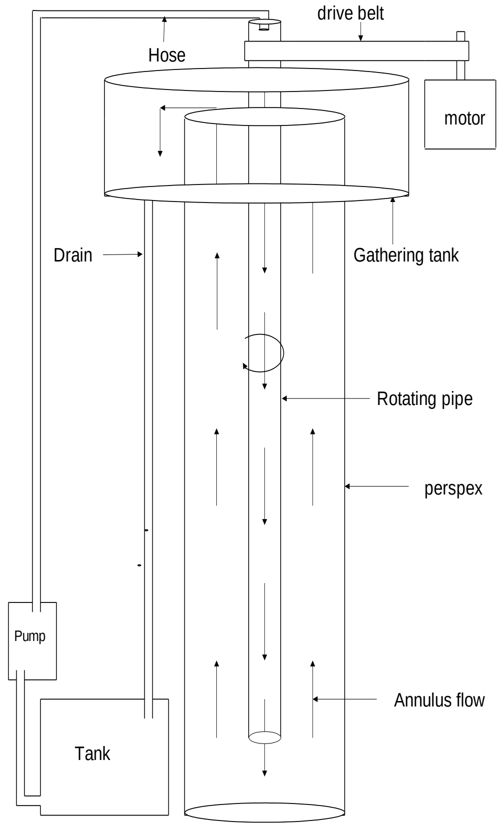

Figure 1 proposed physical experimental model layout.

The followings are the design constraints and considerations:

i. Water will be used as the working fluid instead of drilling mud for the following reasons:
   - It does not contaminate the area of working
   - Eases measurement by LDV as it is a transparent fluid
   - Its properties (ρ, ν) are well established.

ii. LDV system imposed restrictions on the design of experimental rig. The LDV system requires optical access to the fluid flowing in the annulus to allow velocity data to be collected. The outer pipe that represents the hole should therefore be perspex tube.

iii. The physical experimental rig diameter ratio should be within the range of field diameter ratios for the different stages of typical drilled wells from Libyan shelf of Bouri oil field. The field diameter ratios are shown in Table 1. Regarding these values the physical model diameter ratio *D/de* should be within the range of (1.4 – 3.5). From the materials available, the actual experimental rig tube diameters were chosen to be $de_{\exp} = 60\ mm$ and $D_{\exp} = 172\ mm$ for the external diameter of the inner pipe and internal diameter of the outer perspex pipe respectively. These diameters give a diameter ratio $\frac{D_{\exp}}{de_{\exp}} = 2.87$, which is within the range of field diameter ratios shown in Table 1.

iv. The height of the open flow over the upper end of the outer pipe should not be higher than the height of the gathering tank to avoid overflow. According to Henderson (1966 p175)[9] for the flow over a sharp-crested weir:

$$Q = \pi . d_i . \tfrac{2}{3} . C_d \sqrt{2g} . H^{2/3} \quad \text{...} (1)$$

Rearrangement of the equation yields:

$$H = \sqrt[\frac{3}{2}]{\frac{Q}{\pi\, d_i\, \frac{2}{3} \times C_d \sqrt{2g}}} \quad \text{.. ....} (2)$$

Regarding the range of flow rates to be used in the experimental rig, from Table 2 the maximum flow rate is $4.1 \times 10^{-3}\ m^3/s$, and substituting this value into Eqn 2 gives;

$$H = \sqrt[\frac{3}{2}]{\frac{4.1 \times 10^{-3}}{\pi \left(172 \times 10^{-3} - 60 \times 10^{-3}\right) \times \frac{2}{3} \times 0.6 \sqrt{2 \times 9.8}}} = 35\ mm$$

3. Ranges Of Experimental Rig Parameters

Ranges of flow rates and rotational speeds for the physical experimental rig can be calculated using the ranges of dimensionless groups calculated for field values of ranges of flow rates and rotational speeds shown in Table 3, in conjunction with the suggested experimental dimensions and properties of water as working fluid. Field minimum and maximum values of flow rates and drill pipe rotational speeds are shown in Table 3 that correspond to the minimum and maximum dimensionless groups for flow rates and rotational speed. The ranges of variables to be used for physical experiments are shown in Table 2, and are calculated as follows:

The minimum value of field flow rate dimensionless group is $Re_Q = 4\times10^3$ related to the 8 ½*in* (216 *mm*) hole size section shown in Table 3. The experimental value of the flow rate would be:

$$Re_Q = \frac{Q}{\upsilon.D\left(1+\frac{d_e}{D}\right)} \rightarrow Q_{exp} = Re_Q.\nu_{exp}.D_{exp}\left(1+\frac{de_{exp}}{D_{exp}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3)$$

$$\text{Minimum } Q_{exp} = 4\times10^{+3}\times10^{-6}\times172\times10^{-3}\left(1+\frac{60\times10^{-3}}{172\times10^{-3}}\right) = 0.93\times10^{-3}\, m^3/s$$

For the maximum value of field dimensionless group $Re_Q = 18\times10^3$ related to the 17 ½ in (444.5 *mm*) hole size section, the experimental value of flow rate Q would be:

$$\text{Maximum } Q_{exp} = 18\times10^3\times10^{-6}\times172\times10^{-3}\left(1+\frac{60\times10^{-3}}{172\times10^{-3}}\right) = 4.1\times10^{-3}\ m^3/s$$

As for rotational speeds, the minimum value is $\omega_{exp} = 0\ (^{Rad}/_{s})$. For the maximum value of the field dimensionless group $Re_\omega = 39\times10^3$, the experimental value would be:

$$\text{Maximum } \omega_{exp} = 39.02\times10^3\left(\frac{10^{-6}}{(60\times10^{-3})^2}\right) = 10.8\ (^{Rad}/_{s})$$

Table 2 shows the experimental rig ranges of operating parameters of flow rates, inner pipe rotational speed and ranges of axial and swirl Reynolds Numbers.

Table 1. Field data of diameter ratios of hole sizes to drill pipe.

Open hole size *D*		Cased hole size *D*		Drill-pipe *de*		Ranges of diameter ratios *D/de*
Field units (*in*)	SI units $(m)\times10^{-3}$	Field units (*in*)	SI units $(m)\times10^{-3}$	Field units (*in*)	SI units $(m)\times10^{-3}$	
17 ½	444.5	13 3/8	339.7	5	127	3.50–2.67
12 ¼	311.2	9 5/8	244.5	5	127	2.45 – 1.92
8 ½	215.9	7	177.8	5	127	1.70 – 1.40

Table 2. Ranges of physical rig values of flow rate Q, rotational speed ω and axial and swirl Reynolds Numbers.

Parameter	Minimum value	Maximum value
$Q\ (m^3/s)$	0.93×10^{-3}	4.1×10^{-3}
$\omega\ (rad/s)$	0	10.8
$Re_Q = \dfrac{Q}{\nu\times D\,(1+\frac{d_e}{D})}$	4×10^3	18×10^3
$Re_\omega = \dfrac{\omega\, de^2}{\nu}$	0	39×10^3

Table 3. Field data of ranges used of flow rates and rotational speeds and their corresponding dimensionless groups.

Open hole size		Range of Q		Range of $Re_Q = \dfrac{Q}{\nu D(1+\frac{de}{D})}$ $\times10^3$	Range of ω		Range of $Re_\omega = \dfrac{\omega\times(de)^2}{\nu}$ $\times10^3$
Field units (in)	SI units $(m)\times10^{-3}$	Field units (gal/min)	SI units (m^3/s) $\times10^{-3}$		Field units (rev/min)	SI units (rad/s)	
17 ½	444.5	600-925	37.8-58	6 -18	0-170	0-17.8	0-31
12 ¼	311.2	525-772	33-48.6	6 -13	0-145	0-15	0-33
8 ½	215.9	216-489	14-31	4 -11	0-150	0-15.7	0-39

4. Experimental Rig Construction

The intention of this experimental rig was to investigate axial and tangential velocity distributions of swirling steady turbulent flow through a vertical uniform annulus of concentric pipes of diameter ratio of $\dfrac{D}{de} = 2.87$. For stability, the rig was vertically constricted on a flat leveled metal plate of 793 *mm* length, 700 *mm* width and 20 *mm* thickness. The outer Perspex tube of inside diameter 172 *mm* was positioned by resting it in a machined groove on a round flat plate located at the center of the base plate. The core pipe of external diameter 60 *mm* and internal diameter 54 *mm* was supported by 3 vertical 30 *mm* square tube supports, which were radially adjusted to allow centering of the core pipe. The vertical supports were provided at 120 degrees tangential spacing around the pipe. Each was located at a distance of 400 *mm* from the center of the pipes. The inner pipe consists of two sections. The main section at the annulus test section is 2 *m* long with outside diameter 60 *mm*. The top section of length 450 *mm* is coated with a 6 *mm* metal sleeve machined at both ends to provide positions for a thrust bearing housing at lower end and normal bearing housing at the top end of the sleeve with 400 *mm* spacing. From these two bearing housings horizontal thrust supports were provided to be welded to the vertical supports. The thrust bearing was mainly to provide 150 *mm* spacing between the base of Perspex tube and the bottom end of the internal pipe by providing suspension of the inner pipe. The experimental rig outline is shown in Fig 1 with a picture of the rig in Appendix (A). A Perspex material matching mask of flat face of 250 * 250 *mm* and curved back edges to fit the curvature of the Perspex pipe was designed and fastened on the Perspex pipe at measuring height with flat face against the probe and filled with water to lessen the laser beam refraction (two pictures of the matching tank in Appendix A). The matching tank may not be necessary with the relatively large perspex outer pipe, but it is used because of the perspex wall curvature to ensure that the refraction index is the same at both sides of the perspex to avoid the “lens” effect (water at both sides). Where the fluids are different on each side of the perspex (air, water) at the outer wall of the matching tank, this is plane so that the “lens” effect should not arise.

The model rotating system consists of a DC motor of maximum 1800 *rev/min* shaft speed with a 52.96*mm* inner diameter drive pulley mounted on the shaft and a 195.45*mm* inner diameter driven pulley positioned on the top end of the inner pipe with its axis parallel to the axis of the annulus. The two pulleys provide a gear ratio of 0.271. A normal ball bearing was located in the top bearing housing to provide rotation of the inner pipe when needed. The motor was positioned on a base welded on cross bars between two of the vertical supports of the inner pipe in such a way that the axis of the drive pulley is parallel to the axis of the annulus and with same height of the driven pulley. The two pulleys were joined with a suitable belt of diameter 10 *mm*. Altering the inner pipe rotation is obtained by turning the DC motor controller connected to the driving motor. The speed of the inner pipe rotation is measured by the speed of the motor shaft by means of a hand-held tachometer and multiplying the obtained value by the ratio of the pulley diameters.

An immersible pump delivers the working fluid (water) from a supply tank located at the floor to the top inlet end of 2.45 *m* length inner metal pipe with 54 *mm* inside diameter. After the fluid flows down to the bottom of the model, it returns through the annulus between the perspex outer pipe of 172 *mm* inside diameter and the inner pipe of outside diameter of 60 *mm*, providing a diameter ratio of 2.87. A gathering tank was mounted around the top end of the outer pipe, drained into the supply tank to be circulated again into the system. The volumetric flow rate was measured from integration of axial velocity profiles. There was insufficient straight pipe length so that the flow meter installed did not give accurate readings (due to the proximity of pipe bend). “Bucket and stop-watch” flow measurement was not adopted because the relatively low volume of fluid in the apparatus (to minimize the seeding particles necessary and ensure they were uniformly mixed) would have made it difficult to maintain steady-state flow conditions while doing this. Table 4 shows the measured flow rate corresponding to the rotational speeds employed.

Table 4 Experimental rotational speeds, volumetric flow rates and axial and swirl Reynolds Numbers employed.

Rotation (*rev/min*)	Measured annulus average velocity $\overline{U}$ (m/s)	Volumetric flow rate (m^3/s)	Axial Reynolds Number $Re_Q = \frac{Q}{v \times D\,(1+\frac{d_e}{D})}$	Rotational Reynolds Number $Re_\omega = \frac{\omega\, de^2}{v}$
0	0.1355	2.76×10^{-3}	12×10^{3}	0
50	0.1355	2.76×10^{-3}	12×10^{3}	18×10^{3}
100	0.134	2.76×10^{-3}	12×10^{3}	38×10^{3}
150	0.136	2.77×10^{-3}	12×10^{3}	56×10^{3}
322	0.157	3.2×10^{-3}	13.9×10^{3}	121×10^{3}

Once the experimental rig has constructed, the measuring tools Laser Doppler Velocimeter (LDV) and computationally testing the experimental test rig using commercially available CFD software (Fluent) will be carried out later on in the next parts of this study.

5. Summary And Conclusion

- The a broach of dimensional analysis helped in specifying experimental rig diameter ratios and axial and swirl Reynolds Numbers to ensure geometric and dynamic similarity of the test rig to field conditions, Tables (1 to 4).

- Avoiding rig constrains, well established properties transparent working fluid such as water helps in measuring the other physical quantities such as axial and swirling velocities of the annular flow using LASER light as measuring tools.

- Also LASER beam requires transparent medium to pass through, for this reason, transparent Perspex tube was chosen as outer pipe of the experimental rig, and to avoid LASER beam refraction due to curvature of outer Perspex pipe, a Perspex material matching tank with curved to fit the curvature of the outer pipe was designed and fastened on the Perspex pipe at measuring height with flat face against the probe and filled with water to lessen the laser beam refraction

Abbreviations

C_d	Discharge coefficient
D	Diameter (mm), (in)
d_e	External diameter of the drill pipe (mm), (in)
d_i	Internal diameter (*mm*)
g	Acceleration of gravity (m^2/s)
H	Head over weir (mm)
Q	Volumetric flow rate (m^3/s), (*gal/min*)
Re	Reynolds number
Re_Q	Axial Reynolds Number
Re_ω	Rotational Reynolds Number
$\overline{U}$	Average velocity (m/s)

Acronyms

DC	Direct current.
CFD	Computational Fluid Dynamics
LDV	Laser Doppler Velocimeter

Greeks

ρDensity (kg/m^2)

ν	Kinematic viscosity (m^2/s)
ω	rotational speed of the inner pipe (rad/s),(rev/min)

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APPENDIX A

Rig pictures

Figure A.1 Experimental rig.

1. Driving motor
2. Gathering tank
3. Gathering tank drains
4. Outer perspex pipe
5. Inner rotating pipe
6. Matching tank
7. Rig stands
8. Inner pipe supports
9. Traverse table
10. Traverse table wheels
11. Probe
12. Traverse table stand

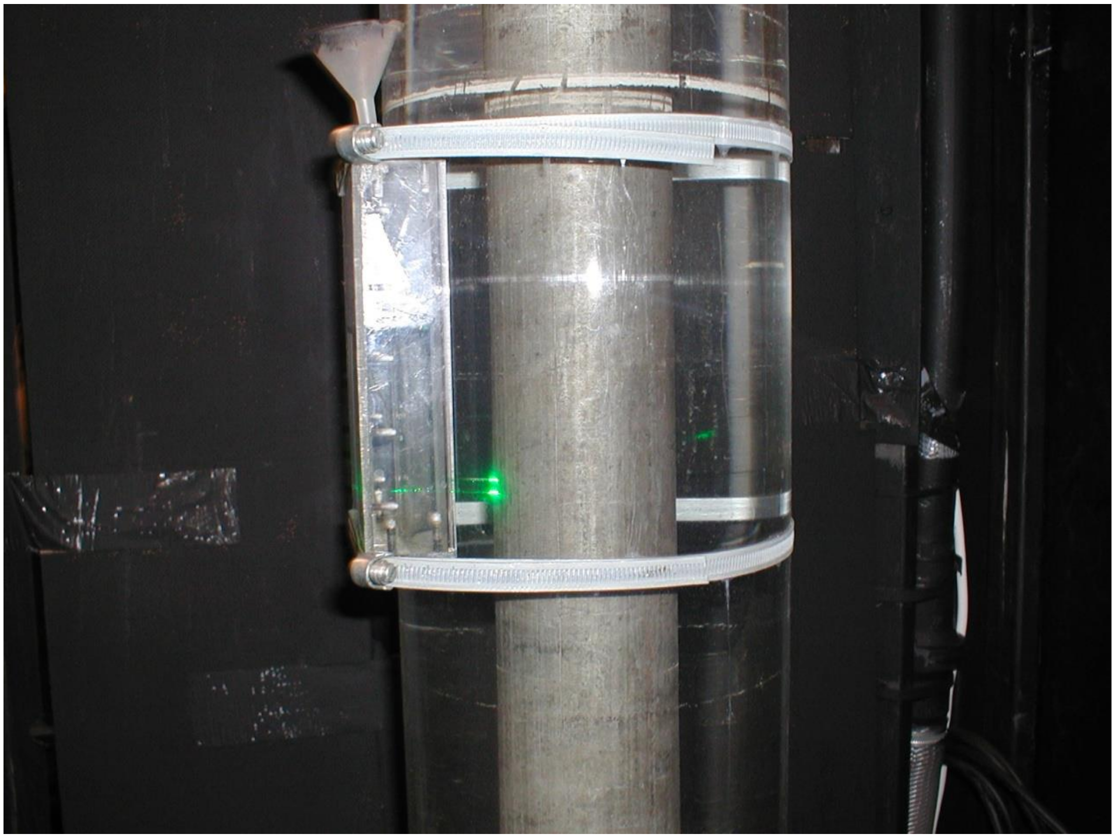

Figure A.2 Matching tank.

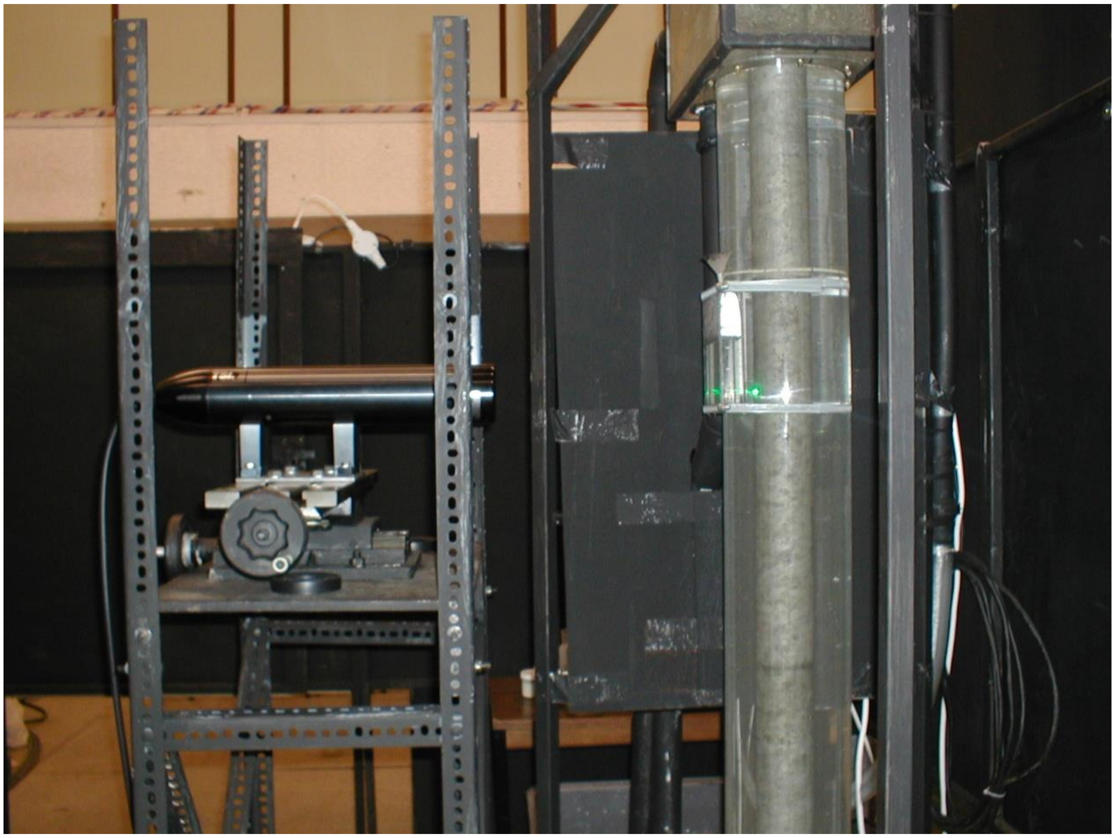

Figure A.2 Position of matching tank against the probe.