Sirte University Scientific Journal (Applied Sciences) *Vol. 6 (2), 01–14, December 2016*

Experimental Model Design For Oilwell Drilling Rig Circulation System Studies, Part I

Mohamed Milad Ahmed

Department of Petroleum, Faculty of Engineering, Sirte University, Sirte, Libya
E-mail: massiwi@su.edu.ly

Abstract

In oil and gas industry, flow through the annulus between the rotating wall and stationary wall is a crucial issue, mainly for oil and gas well drilling processes. Good understanding of the flow behavior of drilling fluids between rotating drill pipes and open or cased hole is an essential element for successful and trouble free drilling operations. So in order to understand the behavior of flow through an annulus in most cases it wise to experimentally investigate the flow behavior. In most cases building an experimental model with real dimensions is a big challenge, also the large number of the parameters that associated with the physical phenomenon being studied may extra complicates the situation, so application of dimensional analysis and similarity approach will help in reducing the number of the parameters into limited number of dimensionless groups. In this part of the experimental model design, a dimensional analysis of the experimental model to be built were performed, it was found that, dimensional analysis helped in reducing the large number of the experimental parameters model dimensions to small limited number of dimensionless groups.

Keywords: *Dimensionless, Similarity, Parameters, Model.*

Abbreviations and Acronyms

A	Cross-sectional-Area
B	Empirical constant (Law of the Wall)
D	Diameter (mm)
d_e	External diameter of the drill pipe (mm)
E	Empirical constant (Law of the Wall)
k-ε	Turbulence model
k-ω	Turbulence model
Re	Reynolds number
Re_Q	Axial Reynolds Number
r_i	Inner radius (mm)
r_o	Outer radius (mm)
U	x Component of mean flow velocity (m/s)
$\overline{U}$	Average velocity (m/s)
u^+	Dimensionless velocity

u_i^+	Inner wall dimensionless velocity
u_o^+	Outer wall dimensionless velocity
V	y Component of mean flow velocity (m/s)
y^+	Dimensionless distance from wall
y_i^+	Dimensionless distance from the inner wall
y_o^+	Dimensionless distance from the outer wall
CFD	Computational Fluid Dynamics
UDF	User defined functions
Greek	
ν	Kinematic viscosity (m^2/s)
κ	Von Karman's constant (law of the wall)

1. Introduction

Flow through annulus may experience different geometries such as sudden reduction in inner wall such as changes in diameter of drill pipes and sudden expansion such as change in diameters between open and cased hole as fluid flows up the annuals and, the more complex geometry such that found inside and around the drilling bit.

As a first step towards building understanding of these complex flows, this study is intended to experimentally and 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.

There are various drilling problems may encountered while drilling gas and oilwell 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 Velocity-meter (LDV) [6] and [7] technique with model simulations using CFD software. This paper as a first part of the study will consider the preliminary design of a 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 drill string.
5. Sufficiently simple to focus comparison on modeling of only swirling developing flow.

2. Industrial Aspects and Experimental Objectives

Oil well drilling is carried out with different drilling stages, starting normally with 26 *in* (660 *mm*) hole size. The most important drilling stages are 17 ½ *in* (444.5 *mm*), 12 ¼ *in* (311 *mm*), 8 ½ *in* (216 *mm*), and in some cases it is necessary to drill an extra hole with slim diameter 6 *in* (152 *mm*), mainly for deep wells. Fig 1 shows different hole stages. This study is aimed at investigating hole cleaning and efficient lifting of cuttings to the surface through different hole stages. This very complex problem will be broken down into simple steps to facilitate investigation of specific aspects of CFD code. To assist in this, Fig 2 shows three different sections with flows of different levels of complexity to be studied:

1. Simple section with uniform drill string and hole diameters:
    - A- using no suspended particles
    - B- incorporating suspended solids
2. More complex section with change in drill string or hole diameter.
    - A- effect of drill string diameter reduction on lifting of cuttings
    - B- to study effect of hole enlargement on lifting of cuttings
3. Highly complicated section at the drilling bit at the bottom of the hole, to study the most important factor which is bit nozzle velocity and its effect on hole cleaning, where the nozzle velocity should be high enough to promptly remove cuttings underneath the bit to avoid regrinding which reduces drilling rate and increases drilling time.

At every step it will necessary to study the effect of different factors that affect the lifting of cuttings for efficient hole cleaning. The factors are:

1. Drilling flow properties:
    - Flow velocity
    - Flow pattern
2. Drill string rotation and its effect on hole cleaning:
3. Drilling fluid properties:
    - Viscosity
    - Density

4. Diameters:
   - Hole / string diameter ratio
   - Changes in diameters
5. Hole inclination.

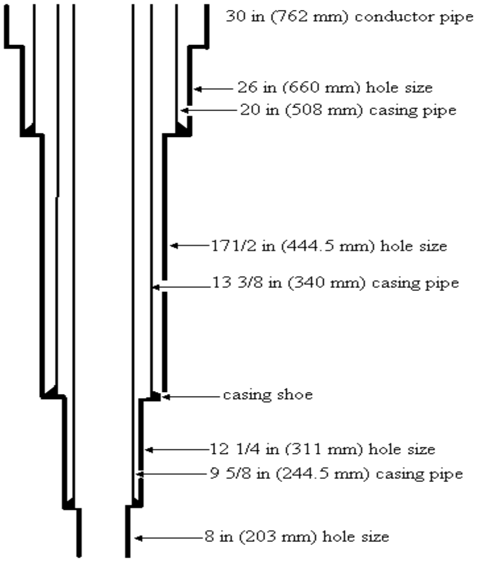

Figure 1. Typical oil well drilling stages

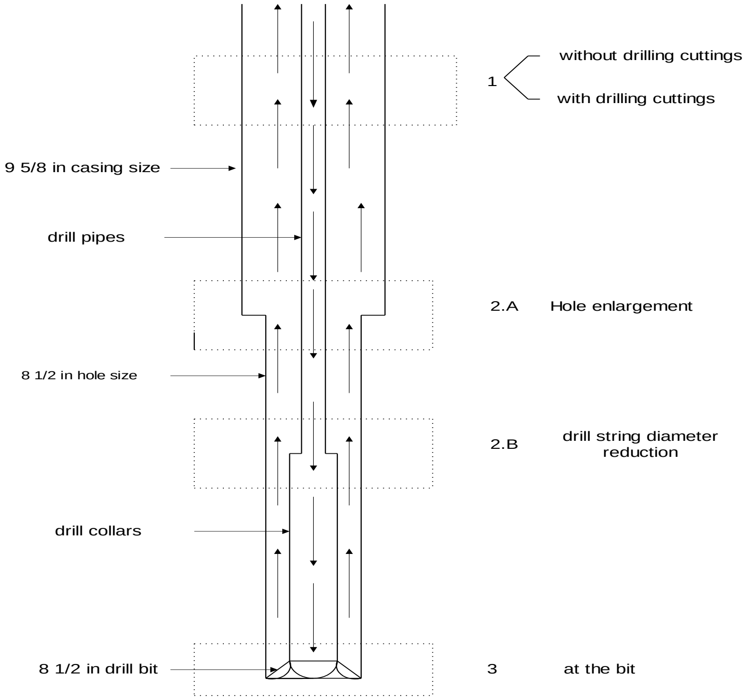

Figure 2. Examples of different flow sections in oil well drilling stages.

3. Preliminary Model Scaling From Field Data

The available field variables and values, Offshore-Libya, Bouri project[5] for one typical stage of drilling the oil well, which is 12 ¼ *in* (311 *mm*) hole size, are as in Table 1 and Fig 3. To complete these data, certain assumptions have to be made:

1. Simplified pipe layout as in Fig 3, showing typical field dimensions for a typical well stage with 12 ¼ *in* (311 *mm*) hole size.
2. The drilling fluids are modeled as Newtonian fluid, therefore plastic viscosity and yield point will be ignored, and viscosity will be assumed to be have been given as seconds Saybolt Universal. Real drilling fluids are non-Newtonian, but as such introduce additional modeling complexity duet the plastic viscosity and yield point. To keep the experiment simple, and to aid comparison with calculation, the experiment will be conducted with simple Newtonian fluid.
3. Pipe wall roughness will be assumed to be 0.05 *mm* based on a typical value for steel.
4. Pump pressure and fluid power are related to the whole drill string and not just the end region, as shown in Fig 3, so they are not appropriate as variables.

Table 1. Field variables with typical values.

Variable	Symbol	Value	
		Field units	SI units
Hole size	D	12.25 *in*	311.2 *mm*
Drill-pipe external diameter	d_e	5 *in*	127 *mm*
Drill-pipe internal diameter	d_i	3 *in*	76.2 *mm*
Drill-pipe wall thickness	t	1 *in*	25.4 *mm*
Drill-pipe wall roughness	k	0.05 *mm* (assumed value based on typical value for steel)	
Bottom-hole pipe clearance	C	1 *ft*	304.8 *mm*
Drill-pipe rotational speed	ω	86 *rev/min*	9 *rad/s*
Drilling fluid flow rate	Q	685 *gal/min*	$43.2\times10^{-3}\ m^3/s$
Drilling fluid density	ρ	1.44 *g/cc*	$1440\ kg/m^3$
Drilling fluid kinematic visc.	ν	53.7 *s* (assumed Saybolt Universal)	* $8.5\times10^{-6}\ m^2/s$
Drilling fluid plastic viscosity	PV	25 *cp*	
Drilling fluid yield point	YP	$13.5\ lb/100ft^2$	
Drilling fluid pump pressure	p	2910 *psi*	
Surface hydraulic horsepower	SHHP	1158 *hp*	
Bit hydraulic horsepower	BHHP	163 *hp*	

* http://www.processassociates.com/process/convert/cf_vkn.htm

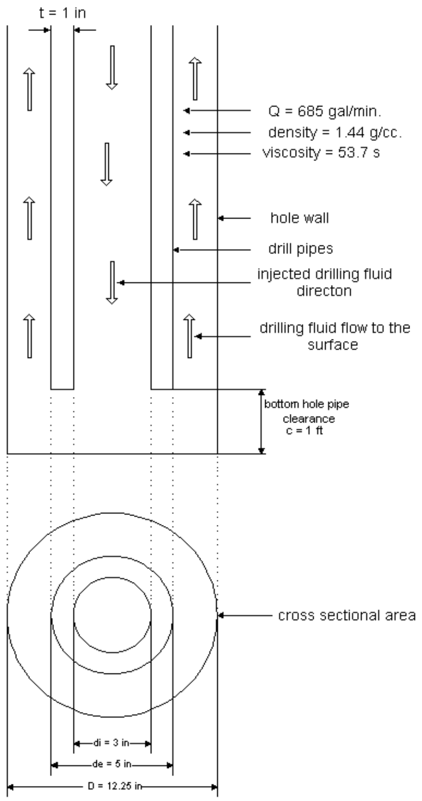

Figure 3. Typical field dimensions for 12 ¼ *in* hole size

4. Dimensional Analysis

For dimensional analysis there are 10 variables (n =10) as shown in Table 2, with their dimensions (where M is mass, L is length, and T is time).

Table 2. Field variables with their dimensions.

Variable	Symbol	Dimensions
Drilling fluid flow rate	Q	L^3T^{-1}
Drilling fluid density	ρ	ML^{-3}
Drilling fluid viscosity	ν	L^2T^{-1}
Hole diameter	D	L
Pipe external diameter	d_e	L
Pipe internal diameter	d_i	L
Drill pipe thickness	t	L
Bottom hole drill pipe clearance	C	L
Drill pipe wall roughness	k	L
Drill pipe rotation speed	ω	T^{-1}

Using the Buckingham *Pi* theorem[8], where the number of variables n = 10 with 3 dimensions, then ρ, ν, and D were chosen to be repeating variables (j = 3), therefore K= n-j = 10 – 3 = 7 where K is the number of dimensionless groups (non-dimensional scaling parameters), which were found to be:

$$r_{de} = \frac{d_e}{D} \quad (1)$$

$$r_{d_i} = \frac{d_i}{D} \quad (2)$$

$$r_t = \frac{t}{D} \quad (3)$$

$$r_{\mathrm{C}} = \frac{\mathrm{C}}{D} \quad (4)$$

$$Re_Q = \frac{Q}{\nu D\left(1 + \frac{d_e}{D}\right)} \quad (5)$$

$$Re_\omega = \frac{\omega d_e^2}{\nu} \quad (6)$$

$$r_{\mathrm{k}} = \frac{\mathrm{k}}{D(1 - \frac{d_e}{D})} \quad (7)$$

Using the field values from Table 1, the non-dimensional parameters would have the values given in Table 3.

Table 3. Dimensionless groups with their field values

Group	Field value
$r_{de} = \frac{d_e}{D}$	0.4082
$r_{d_i} = \frac{d_i}{D}$	0.2449
$r_t = \frac{t}{D}$	0.0816
$r_{\mathrm{C}} = \frac{\mathrm{C}}{D}$	0.9796

$Re_Q = \dfrac{Q}{\nu D\left(1+\frac{d_e}{D}\right)}$	11.6×10^3
$Re_\omega = \dfrac{\omega d_e^2}{\nu}$	17.08×10^3
$r_\text{k} = \dfrac{\text{k}}{D(1-\frac{d_e}{D})}$	2.72×10^{-4}

5. Design and Suggested Experimental Conditions

The original strategy was to start with a relatively simple model and simple flow and start using water as the drilling fluid instead of drilling mud for simplicity measuring tools (with LDV), safety and availability. Choosing such a simple model and flow is intended to enable general solution accuracy to be determined by an easily measured criterion and also to focus attention on specific aspects of the CFD codes. It is intended to introduce all the significant factors into this simple model to test their influence on solution accuracy.

The Eqn. 1–4 give the required experimental model dimensions, and Eqn. 5–7 give model rotational speed, flow rate and model wall roughness respectively.

For physical experiments it is simplest to use water as the drilling fluid with properties:

$\nu = 10^{-6}\ m^2/s$ (at lab temperature = $20\,^{o}C$)

$\rho = 1000\ kg/m^3$

The physical model diameter was chosen to be D = 150 mm. The resulting experimental variables with their typical values are shown in Table 5. As the Reynolds Number shows the flow rate is turbulent, so the length of the model should be long enough to provide a fully developed flow, suggesting an initial estimate to model length to be $20\times D = 3\ m$. Fig 4 shows the experimental model layot:

$$\text{Using Eq. 1: } r_{d_e}\,(field) = r_{d_e}\,(\text{experiments}) = \frac{d_e\,(mm)}{150\,mm} = 0.4082$$

$$d_e\,(\text{experiments}) = 150\ mm \times 0.4082 = 61.23\ mm$$

$$\text{Using Eq. 2: } r_{d_i}(\mathit{field}), r_{d_i} \;=\; r_{d_i}\,\text{(experiments)} = \frac{d_i\,(mm)}{150\,mm} = 0.245$$

$$d_i\,\text{(experiments)} = 150\,mm \times 0.245 = 36.74\,mm$$

$$\text{Experimental pipe thickness } t = \left(d_e - d_i\right)/2 = (61.2\,mm - 36.74\,mm)/2 = 12.23\,mm$$

$$\text{Using Eq. 4: } r_{\mathrm{C}}(\mathit{field}) = r_C\,\text{(experimental)} = \frac{\mathrm{C}\,(mm)}{150\,mm} = 0.9796$$

$$\mathrm{C}\,\text{(experiments)} = 150\,mm \times 0.9796 = 147\,mm$$

The rotational speed for the experimental model will be given by:

$$Re_{\omega} = \left[\frac{\omega . d_e^2}{\nu}\right]_{field} = \left[\frac{\omega . d_e^2}{\nu}\right]_{\exp .} \longrightarrow \omega_{exp} = \omega_{field}\left[\frac{d_{e\,field}}{d_{e\exp .}}\right]^2 . \left[\frac{\nu_{\exp .}}{\nu_{field}}\right]$$

$$= 9\,{}^{rad}\!/_{s}\left[\frac{127\,mm}{61.23\,mm}\right]^2 . \left[\frac{10^{-6}\,{}^{m^2}\!/_{s}}{8.5\times 10^{-6}\,{}^{m^2}\!/_{s}}\right]$$

$$= 4.6\,rad/s = 44\,rev/min \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\;(8)$$

Similarly the volume flow rate for the experimental model will be given by:

$$Re_Q = \left[\frac{Q}{\nu . D(1+\frac{d_e}{D})}\right]_{field} = \left[\frac{Q}{\nu . D(1+\frac{d_e}{D})}\right]_{\exp}$$

$$\longrightarrow Q_{\exp} = Q_{field}\left[\frac{D_{\exp}}{D_{field}}\right] . \left[\frac{\nu_{\exp}}{\nu_{field}}\right] . \left[\frac{(1+\frac{d_e}{D})_{\exp}}{(1+\frac{d_e}{D})_{field}}\right]$$

According to geometrical similarity, the diameter ratios of experimental and field dimensions would have the same value, accordingly the values of $\left(1+\frac{d_e}{D}\right)_{\exp}$ and $\left(1+\frac{d_e}{D}\right)_{field}$ will cancel out, so experimental flow rate would be:

$$Q_{\exp} = 0.043155\,{}^{m^3}\!/_{s}\left[\frac{150\,mm}{311.15\,mm}\right] . \left[\frac{10^{-6}\,{}^{m^2}\!/_{s}}{8.5\times 10^{-6}\,{}^{m^2}\!/_{s}}\right]$$

$$= 2.45\times 10^{-3}\,{}^{m^3}\!/_{s} = 2.45\,{}^{l}\!/_{s} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\;(9)$$

The data obtained are for steel cased holes for which the steel surface roughness will be typically 0.05 *mm*, (obviously uncased holes may have variable diameter and surface roughness). Experimental outer flow wall roughness scaling ratio is:

$$r_{\mathrm{k}} = \left[\frac{\mathrm{k}}{D(1-\frac{d_e}{D})}\right]_{field} = \left[\frac{\mathrm{k}}{D(1-\frac{d_e}{D})}\right]_{\exp.} \longrightarrow \mathrm{k}_{\exp.} = \mathrm{k}_{field} \cdot \left[\frac{D_{\exp.}}{D_{field}}\right] . \left[\frac{(1-\frac{d_e}{D})_{\exp}}{(1-\frac{d_e}{D})_{field}}\right]$$

Again according to geometrical similarity, the diameter ratios of experimental and field dimensions would have the same value, accordingly the values of $\left(1-\frac{d_e}{D}\right)_{\exp}$ and $\left(1-\frac{d_e}{D}\right)_{field}$ will cancel out so theoretically:

$$\mathrm{k}_{\exp.} = 0.05\times10^{-3}\left[\frac{150\,mm}{311.15\,mm}\right] = 0.024\,mm \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

It is not practical to attempt to scale wall roughness in this way. However, if the flow Reynolds Number and wall relative roughness fall into the hydraulically smooth wall region, then the effect of wall roughness should not be significant.

The inner surface of a sample of a similar perspex tube to that used in the experimental model was measured in a Mitutoyo "Surftest" surface finish analyzer. A standard R_a = 3 μm sample was measured first to check the calibration. The tube was divided into three equal 120° segments and three longitudinal strips were recorded in each segment, with measurements carried out over a cut-off length of 8 *mm* for 5 samples each. The surface finish parameter R_a was chosen as being most representative of the actual mean wall roughness seen by the flow. The nine measurements ranged from R_a = 0.1 μm to 0.2 μm, with an average value of $R_a \approx 0.13$ μm both overall and for each segment, indicating consistency around the tube. Table 4 gives field and experimental relative roughness.

Table 4. Field and experimental relative roughness

Field dimensions		Experimental dimensions		
Cased hole	Inner steel pipe	Outer perspex	Outer steel pipe	Inner steel pipe
$\frac{0.05}{(244.5-127)}$ $= 0.4 \times 10^{-3}$	$\frac{0.05}{(244.5-127)}$ $= 0.4 \times 10^{-3}$	$\frac{0.13 \times 10^{-3}}{(172-60)}$ $= 1 \times 10^{-6}$	$\frac{0.05}{(172-60)}$ $= 0.4 \times 10^{-3}$	$\frac{0.05}{(172-60)}$ $= 0.4 \times 10^{-3}$

The use of perspex for the fixed outer wall is unavoidable to permit the use of LDV flow measurements, but these results indicate that wall roughness is much less than the scaled wall roughness of 0.024 *mm* given above. However, at the field and experimental axial flow Reynolds Numbers, the relative roughness ($k/(D-de)$) $\approx 4 \times 10^{-4}$ for the field annulus gives on a Moody-Stanton pipe friction factor diagram a flow condition which is very close to hydraulically smooth, so that the wall behavior in the model should be similar to that in a cased hole.

Table 5. Experimental variables with typical values required for annular modeling.

Variable	Symbol	Value
Drilling fluid flow rate	Q	2.45×10^{-3} m^3/s
Drilling fluid density	ρ	1000 kg/m^3
Drilling viscosity	ν	10^{-6} m^2/s
Hole diameter	D	150 *mm*
Drill pipe external diameter	d_e	61.2 *mm*
Drill pipe internal diameter	d_i	36.74 *mm*
Drill pipe thickness	t	12.23 *mm*
Bottom hole drill pipe clearance	C	147 *mm*
Drill pipe rotation speed	ω	4.6 *rad/s*

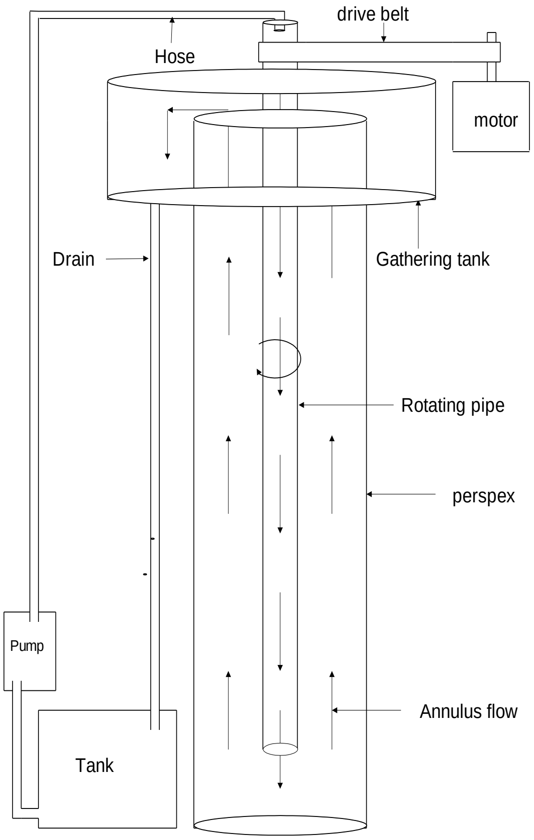

Figure 4. Physical experimental model layout.

6. Conclusions

Application of dimensional analysis reduces the large number of field parameters into a limited set of dimensionless groups and simplifies the experimental and computational considerations. In particular, dimensional analysis helps to specify experimental rig diameter ratios and axial and swirl Reynolds Numbers to ensure geometric and dynamic similarity of the test rig to field conditions.

While the objective of this study was to verify the CFD model in this application, nevertheless preliminary modelling was used to support the design of the experimental rig:

i. A rig configuration minimised the impact of the user-specified inflow and outflow boundary conditions.

7. References

[1] Fluent Inc. (2001). Fluent 6.0 Users Guide, Dec. 2001. 5 Vols, Fluent Inc, Lebanon NH, USA.
[2] George R. Gray and Darley, H.C.H. (1980). Composition and Properties of Oil Well Drilling Fluids, Fourth Edition, Gulf Publishing Company, Houston.
[3] Rabia, H. (1985). Oil Well Drilling Engineering: Principles and Practice. Graham & Trotman Ltd, London.
[4] Preston L. Moore (1986). Drilling Practices Manual, PennWell Publising Company, Tulsa, Oklahoma USA.
[5] Agip Oil Company, L. B., S.P.L.A.J., (1992). Bouri Field Development. Tripoli.
[6] Durrani, T. S. and C. A. Greated (1977). Laser Systems in Flow Measurement. Plenum Press, New York.
[7] Durst, F. et al (1981). Principles and Practice of Laser-Doppler Anemometry. Academic Press Inc, London.
[8] White, Frank M. (1979). Fluid Mechanics. McGraw-Hill Book Company, New York