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The Study of Dimensional Flow of Particles and Calculation of Drag Coefficients under Different Viscosity Fluids

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Abstract

An experimental study was conducted to find the drag coefficient of small spheres of diameter 5.0, 3.45, 5.7, 5.45, and 5.20 mm under ethylene glycol, castor oil, and glycerol. Six liquids with different viscosities and densities are used so as to explore a large range of Reynolds numbers. The tubes are divided into different zones of known length. Different spherical balls of various materials and diameters are taken to observe the drag coefficient. The materials of the spherical balls are made up of glass and steel. The setup also included a stopwatch to determine the time duration of various distance intervals, a measuring scale to measure the distance of the intervals on the cylindrical tubes, a screw gauge to note down the diameters of the various spherical balls, a thermometer to note down the temperature.

Keywords: Drag coefficient, Reynolds number, Fluid flow, Stokes law.

Introduction

While processing fluids via pipes and channels, a friction force shows to be a useful quantity. An analogous factor known as drag coefficient is utilized for immersed solids [1, 2]. It is defined as CD = (FD/ AP)/ ρuo2/2g [3].

Where,

FD is the total drag

uo is the free stream velocity

Ap is the projected area of the particle

Dp is the diameter of the particle

For a sphere, Ap = (π/4) Dp2

For particles other than spherical, it is necessary to specify size and geometric form of the object and its orientation with respect to the direction of the flow of the fluid.

For a cylinder so oriented that its axis is perpendicular to the flow, Ap is LDp.

For a cylinder with its axis parallel to the direction of the flow, Ap is (π/4) Dp2.

From dimensional analysis, the drag coefficient of a smooth solid in an incompressible fluid depends upon a Reynolds number and necessary shape ratios. For a given shape,

$$C_D = \varphi \times Re_p \quad (1)$$

The movement of a particle through a fluid requires external force acting on the particle.

Three forces act on a particle moving through a fluid:

- The external force
- The buoyant force, which acts parallel with the external force but in opposite direction
- The drag force, which appears whenever there is relative motion between the particle and the fluid and it acts to oppose the motion and acts in direction opposite to that of the fluid.

Consider a particle of mass m moving through a fluid under the action of an external force Fe

U: velocity of the particle relative to the fluid

Fb: Buoyant force on the particle

FD: drag force

Then the resultant force on the particle is:

$$F_e - F_D - F_B \quad (2)$$

Therefore,

$$m\frac{du}{dt} = F_e - F_D - F_B \quad (3)$$

The external force can be expressed as a product of the mass and the acceleration ae of the particle from this force

$$F_e = m \times a_e \quad (4)$$

The drag force is given by

$$F_D = \frac{C_D u_o^2 \rho A_p}{2} \quad (5)$$

The buoyant force is, by Archimedes' principle, the product of the mass of the fluid displaced by the particle and the acceleration from the external force and is given by

$$F_B = \frac{m\rho a_e}{\rho_n} \tag{6}$$

Substituting equations 4, 5, 6 in equation 3

$$\frac{du}{dt} = a_e - \frac{\rho a_e}{\rho_p} - \frac{C_D u_0^2 \rho A_p}{2m} = a_e \frac{\rho_p - \rho}{\rho_p} - \frac{C_D u_0^2 \rho A_p}{2m} \tag{7}$$

At terminal velocity put $\frac{du}{dt} = 0$ and we get

$$u_t = \left(\frac{2g(\rho_p - \rho)m}{A_p \rho_p C_D \rho}\right)^{0.5} \tag{8}$$

If the particles are spheres of diameter Dp

$$m = \frac{\pi}{6}(D_p^3 \times \rho_p) \tag{9}$$

$$A_p = \frac{\pi}{4}(D_p^2) \tag{10}$$

Using the above two equations in equation (7)

$$u_t = \left(\frac{4g(\rho_p - \rho)D_p}{3C_D \rho}\right)^{0.5} \tag{11}$$

Stokes' law:

At low Reynolds numbers, the drag coefficient varies inversely with Rep and the equations for CD, FD and ut are [3, 4]:

The above equation is a form of Stokes' law, which applies when the particle Reynolds number is less than 1.

$$C_D = \frac{24}{Re_p} \tag{12}$$

$$F_D = 3\pi\mu u_t D_p \tag{13}$$

Thus,

$$u_t = \frac{g D_p^2(\rho_p - \rho)}{18\mu} \tag{14}$$

The above equation is a form of Stokes' law, which applies when the particle Reynolds number is less than 1.

Newton's law:

For 1000<Rep<200000, the drag coefficient is approximately constant, and the equations are

$$C_D = 0.44 \tag{12}$$

$$F_D = 0.055\pi D_p(2u_t)2\rho \tag{13}$$

Thus,

$$u_t = 1.75\left(\frac{gD_p(\rho_p - \rho)}{\rho}\right)^{0.5} \tag{15}$$

The above equation is Newton's law and applies only for fairly large particles falling in gases or low viscous fluids.

From the equation given by Turton and Levenspiel:

$$C_D = \frac{24}{N_{Re}}(1 + 0.173N_{Re}^{0.657}) + \frac{0.413}{1 + \frac{16300}{N_{Re}^{1.09}}} \tag{16}$$

This equation defines the complete solid drag curve for < 2*

Experimental Procedure

The temperature was noted down using a thermometer.

The viscosities and densities of six different liquids taken in cylindrical tubes were noted.

5 spherical balls of different sizes and material were taken and their diameter using screw gauge was noted.

Cylindrical tube was divided into different zones of known length having a static liquid.

A spherical ball of known diameter was dropped into the cylindrical tube, taking care that it does not touch the boundaries by dropping it almost from the middle of the tube.

The time of fall of each ball in each interval was noted carefully with the help of the bulb.

For each ball the reading was taken at least three times to reduce the error.

The same procedure was repeated for the remaining tubes.

Recordings

Density of Glass = 2600 kg/m3

Density of Steel = 7800 kg/m3

Table 1: Properties of fluids.

Fluid	Density (kg/m3)	Viscosity (kg/m s)
PIPE 1	900	0.2
PIPE 2	911	0.084

Table 2: Specifications of balls used.

Ball	Name	Diameter (mm)
Big steel ball	S1	5
Medium steel ball	S2	3.45
Large Glass ball	G1	5.7
Medium glass ball	G2	5.45
Small glass ball	G3	5.2

Observations

Table 3: Observation table for ethylene glycol.

Ball	t1 (sec)	t2 (sec)	t3 (sec)
	s1 = 0.297m	s2 = 0.316m	s3 = 0.279m
Small Glass Ball	0.88	1.14	1
	0.95	1.13	1.08
	1.14	1.17	1.2
Medium Steel Ball	0.12	0.37	0.61
	0.18	0.2	0.44
	0.18	0.45	0.28
	0.22	0.54	0.36
Small Steel Ball	0.4	0.41	0.16
	0.29	0.39	0.22
	0.2	0.41	0.38
	0.26	0.47	0.28
Large Glass Ball	0.86	1.1	0.72
	0.89	1.14	0.85
	0.73	0.84	0.88
	0.91	0.69	0.63

Table 4: Observation table for castor oil.

Ball	t1	t2	t3
	s1 = 0.297m	s2= 0.316m	s3= 0.279m
Small Glass Ball	20.21	25.49	22.92
	21.59	24.21	22.64
	14.92	15.34	25.11
Medium Steel Ball	4.3	4.52	4.93
	4.46	4.99	6.36
	4.18	4.55	4.65
	4.2	4.32	4.59

Small Steel Ball	6.55	6.58	6.8
	6.43	6.63	6.07
	6.44	7.06	11.38
	6.43	6.7	7.26
Large Glass Ball	17.58	17.81	19.1
	17.36	18.8	20.8
	14.7	15.09	15.83
	20.71	22.54	23.68

Table 5: Observation table for glycerol.

Ball	**t1**	**t2**	**t3**
	s1 = 0.297m	**s2= 0.316m**	**s3= 0.279m**
Small Glass Ball	7.23	6.69	7.49
	6.78	7.23	8.45
	6.82	7.29	8.72
Medium Steel Ball	1.38	1.58	1.48
	1.41	1.45	1.69
	1.54	1.32	1.85
Small Steel Ball	1.98	2.07	2.49
	1.79	2.08	2.48
	1.83	2.16	2.46
	4.22	5.03	5.47
Large Glass Ball	3.99	4.34	4.93
	4.95	5.22	5.97

Calculations

Table 6: Calculations for ethylene glycol.

Ball	**t1**	**t2**	**t3**	**v1**	**v2**	**v3**	**v average**	**Exp. Terminal Velocity**	**Re**	**Theo. Terminal Velocity**	**CD, experimental**	**CD, theoretical**
	s1 = 0.297m	**s2 = 0.316m**	**s3 = 0.279m**									
Small Glass Ball	0.88	1.14	1	0.3375	0.277193	0.279	0.297898	0.278602	6.740951	0.06166	3.5603286	5.7183054
	0.95	1.13	1.08	0.3126316	0.279646	0.258333	0.283537					
	1.14	1.17	1.2	0.2605263	0.270085	0.2325	0.254371					
Medium Steel Ball	0.12	0.37	0.61	2.475	0.854054	0.457377	1.262144	1.142446	31.90704	0.36946	0.7521851	2.0192587
	0.18	0.2	0.44	1.65	1.58	0.634091	1.28803					

	0.18	0.45	0.28	1.65	0.702222	0.996429	1.116217					
	0.22	0.54	0.36	1.35	0.585185	0.775	0.903395					
Small Steel Ball	0.4	0.41	0.16	0.7425	0.770732	1.74375	1.085661	1.013381	22.41776	0.23179	1.0705798	2.5002378
	0.29	0.39	0.22	1.0241379	0.810256	1.268182	1.034192					
	0.2	0.41	0.38	1.485	0.770732	0.734211	0.996647					
	0.26	0.47	0.28	1.1423077	0.67234	0.996429	0.937026					
Large Glass Ball	0.86	1.1	0.72	0.3453488	0.287273	0.3875	0.340041	0.357212	10.66791	0.09394	2.2497388	4.0935011
	0.89	1.14	0.85	0.3337079	0.277193	0.328235	0.313045					
	0.73	0.84	0.88	0.4068493	0.37619	0.317045	0.366695					
	0.91	0.69	0.63	0.3263736	0.457971	0.442857	0.409067					

Table 7: Calculations for castor oil.

Calculations for glycerol.

Ball	**t1**	**t2**	**t3**	**v1**	**v2**	**v3**	**v average**	**Exp. U**	**Re**	**Theo. U**	**CD, experimental**	**CD, theoretical**
	s1 = 0.297m	**s2= 0.316m**	**s3= 0.279m**									
Small Glass Ball	20.21	25.49	22.92	0.0146957	0.012397	0.012173	0.013088	0.0144461	0.083775	0.018866	286.48244	296.20162
	21.59	24.21	22.64	0.0137564	0.013052	0.012323	0.013044					
	14.92	15.34	25.11	0.0199062	0.0206	0.011111	0.017206					
Medium Steel Ball	4.3	4.52	4.93	0.0690698	0.069912	0.056592	0.065191	0.0645425	0.374291	0.104888	64.121256	69.937562
	4.46	4.99	6.36	0.0665919	0.063327	0.043868	0.057929					
	4.18	4.55	4.65	0.0710526	0.069451	0.06	0.066834					
	4.2	4.32	4.59	0.0707143	0.073148	0.060784	0.068216					
Small Steel Ball	6.55	6.58	6.8	0.0453435	0.048024	0.041029	0.044799	0.0434492	0.251968	0.065805	95.250217	101.91209
	6.43	6.63	6.07	0.0461897	0.047662	0.045964	0.046605					
	6.44	7.06	11.38	0.046118	0.044759	0.024517	0.038465					
	6.43	6.7	7.26	0.0461897	0.047164	0.03843	0.043928					
Large Glass Ball	17.58	17.81	19.1	0.0168942	0.017743	0.014607	0.016415	0.0162906	0.094471	0.028742	254.04528	263.37201
	17.36	18.8	20.8	0.0171083	0.016809	0.013413	0.015777					
	14.7	15.09	15.83	0.0202041	0.020941	0.017625	0.01959					
	20.71	22.54	23.68	0.0143409	0.01402	0.011782	0.013381					

Results

Figure 1: Plot of CD experimental versus CD theoretical.

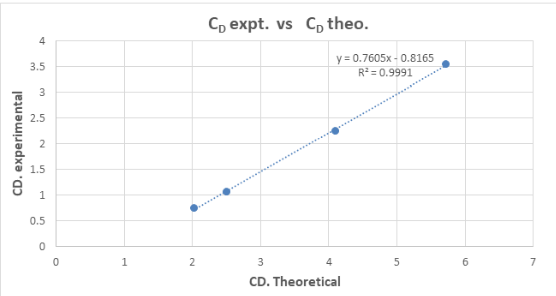


Figure 2: Plot of CD experimental versus Reynolds number.

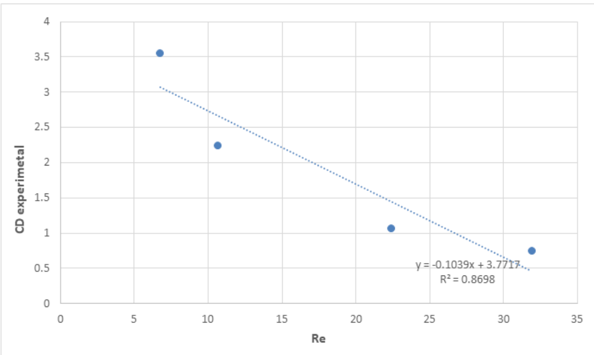


Figure 3: Plot of U theoretical versus U experimental.

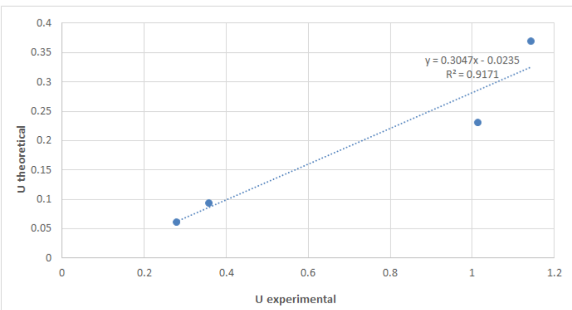


Figure 4: Plot of CD experimental versus CD theoretical.

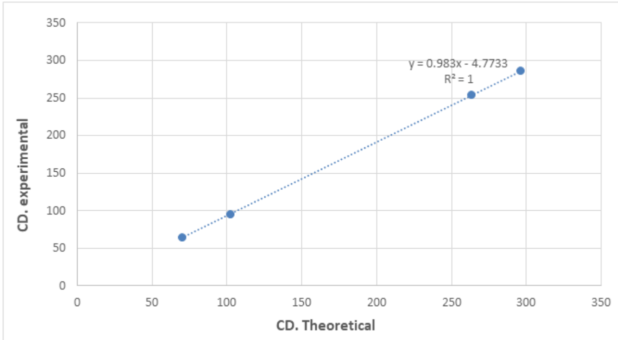


Figure 5: Plot of CD experimental versus Reynolds number.

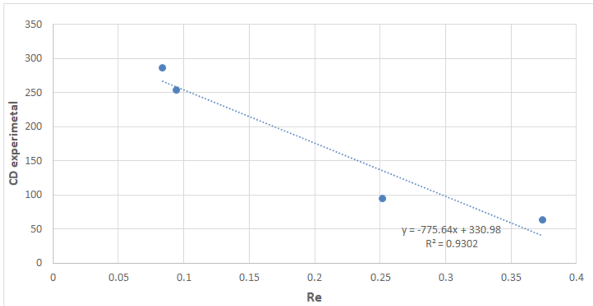


Figure 6: Plot of U theoretical versus U experimental.

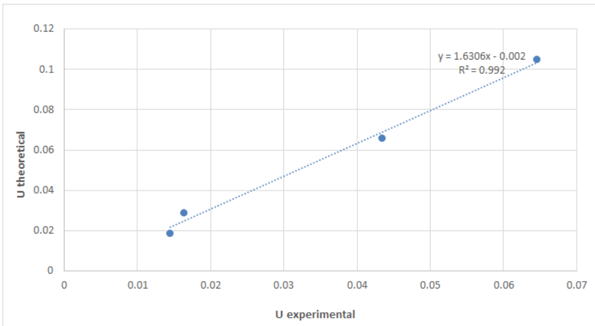


Figure 7: Plot of CD experimental versus CD theoretical.

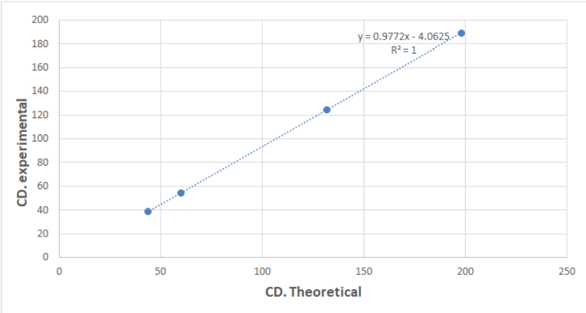


Figure 8: Plot of CD experimental versus Reynolds number.

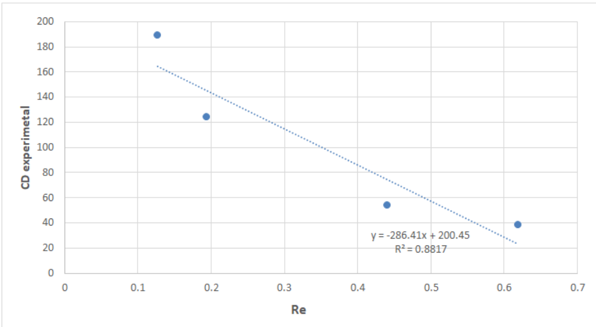
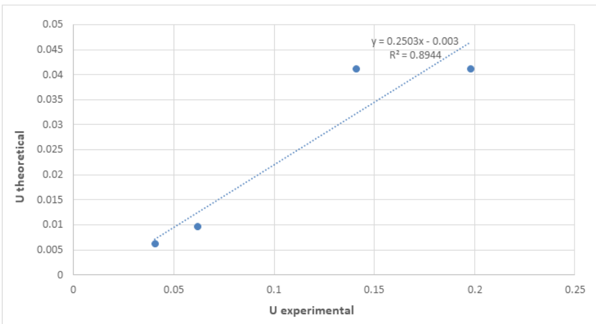


Figure 9: Plot of U theoretical versus U experimental.



Discussion of Result

From the experiment we studied the nature of different fluids of different densities and viscosities. We saw the variation in drag coefficient by varying the Reynolds No. i.e. we used spherical balls of various materials as well as diameters. We saw there were quite discrepancies in the experimental and the theoretical plot of velocity and coefficient of drag vs Reynolds no. The discrepancies may be due to parallax, error in noting the time, wall effects, instrumental error due to screw gauge in measuring the diameter and human error might also have crept in due a large no. of people working at the same time.

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