MEMORANDUM

To: Christian Valoria, Department of Mechanical Engineering, Cal Poly SLO
crvalori@calpoly.edu

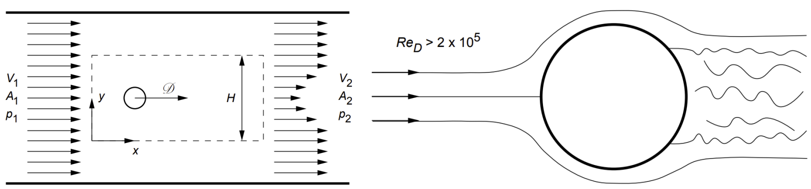
From: David Smoots, dsmoots@calpoly.edu
James Whealan, jwhealan@calpoly.edu
Christopher Ng, cng42@calpoly.edu
Katie Kellum, kellum@calpoly.edu

Group: Hearts Group 3

Date: March 8, 2023

RE: **Cylinder in Uniform Flow Stream**

The purpose of the lab is to observe boundary layer separation and flow around a cylindrical rod stretching the width of the windtunnel. We used a rod of 1.5 inch diameter and freestream velocity set at 20 Hz which results in about 50 ft/s airflow. We then collected data using two methods to help us learn more about the boundary layer separation and drag force that occurs with the cylindrical rod: Momentum Wake Profile Method and Surface Pressure Method. Figures 1 and 2 depict the cylindrical rod setup in the windtunnel as well as the expected boundary layer separation.



Figures 1 & 2.

For the surface pressure method, we first had to center the cylinder by finding the orientation that resulted in the highest stagnation pressure for the cylinder using the pressure tap on the outside surface of the rod. We then measured the stagnation pressure values for each position by rotating the cylinder from 0 to 180 degrees in 5 degree increments. From these pressures, we will be able to determine a pressure gradient over the cylinder which will help us find information for drag and separation. Next, for the momentum wake profile method, we used a pitot static tube to measure pressure values at different y locations downstream of flow from the rod. Using these pressures, we will be able to determine air flow velocities downstream of the rod which will have a velocity profile similar to that seen in Figure 1. This information will be useful for finding drag and separation information.

Attachments

- Experimental Upstream Velocity and Reynolds Number Calculations
- Tabulated Pressure and Pressure Coefficients about the Cylinder Surface
- Experimental Cylinder Vs Sphere Pressure Coefficients about the Surface
- Tabulated Wake Velocities and Positions
- Plotted Wake Velocity Distribution along the Vertical Distance from the Cylinder's Center
- Sample Calculations for Finding the Drag Coefficient Using the Surface Pressure Method
- Sample Calculations for Finding the Drag Coefficients Using the Momentum Method
- Tabulated Experimental and Theoretical Drag Coefficients
- Flow Distribution around the Cylinder and Wake

Attachment 1: Experimental Upstream Velocity and Reynolds Number Calculations

PROBLEM 1

Calculate U for wind tunnel @ 20 Hz + the corresponding Re_D from the Pitot-static tube measurements.

Pitot-static tube reading: $P = 0.528 \text{ in} H_2O$

$P = hg\rho$

$$P = (0.528 \text{ in}H_2O)\left(32.2 \frac{ft}{s^2}\right)\left(\frac{ft}{12 in}\right)^2\left(62.4 \frac{lb}{ft^3}\right)\left(\frac{lbf}{32.174 \, lbm \frac{ft}{s^2}}\right)\left(\frac{ft}{12 in}\right)\left(\frac{12 in}{ft}\right)^2$$

$P = 2.748 \ lbf/ft^2$

$$\rho_{air} = \frac{P}{RT} = \frac{(100.43 \ kPa)(1000 \ Pa/kPa)}{\left(287.05 \frac{J}{kg K}\right)(21.5 + 273.15 \ K)} = 1.187 \ kg/m^3$$

$$\left(1.187 \ kg/m^3\right)\left(\frac{1 \ m}{100 cm}\right)^3\left(\frac{2.54 cm}{in}\right)^3\left(\frac{12 in}{ft}\right)^3\left(\frac{slug}{14.594 \ kg}\right)\left(\frac{lbf s^2/ft}{slug}\right) = 0.0023 \frac{lbf \, s^2}{ft^4}$$

$$U = \sqrt{\frac{2(P_T - P)}{\rho}} = \sqrt{\frac{2(2.748 \ lbf/ft^2)}{0.0023 \frac{lbf \, s^2}{ft^4}}}$$

$$\boxed{U = 48.88 \ ft/s}$$

$$Re_D = \frac{\rho U D}{\mu} = \frac{\left(0.0023 \frac{lbf s^2}{ft^4}\right)(48.88 \ ft/s)\left(1.5 \ in \cdot \frac{ft}{12 in}\right)}{\left(3.85 \times 10^{-7} \ lbf \cdot s/ft^2\right)}$$

$Re_D = 36501.3$

$$\boxed{Re_D = 3.65 \times 10^4}$$

Attachment 2: Tabulated Pressure and Pressure Coefficients about the Cylinder Surface

theta (degrees)	p-p0 (lbf/ft^2)	Uncertainty (lbf/ft^2)	Cp
0	2.3463	0.0028	0.8539
5	2.2651	0.0039	0.8244
10	2.0560	0.0045	0.7483
15	1.7064	0.0037	0.6210
20	1.2361	0.0105	0.4499
25	0.7148	0.0063	0.2602
30	0.1363	0.0102	0.0496
35	-0.5286	0.0078	-0.1924
40	-1.1622	0.0097	-0.4230
45	-1.8604	0.0162	-0.6771
50	-2.5658	0.0095	-0.9338
55	-3.0673	0.0280	-1.1163
60	-3.3961	0.0208	-1.2360
65	-3.7509	0.0324	-1.3651
70	-3.7935	0.0298	-1.3807
75	-3.6406	0.0421	-1.3250
80	-3.4627	0.0620	-1.2602
85	-3.2400	0.0275	-1.1792
90	-3.1204	0.0266	-1.1356
95	-3.0964	0.0248	-1.1269
100	-3.1318	0.0353	-1.1398
105	-3.1391	0.0318	-1.1425
110	-3.1547	0.0219	-1.1481
115	-3.1557	0.0416	-1.1485
120	-3.1984	0.0376	-1.1640
125	-3.1953	0.0467	-1.1629
130	-3.2057	0.0615	-1.1667
135	-3.2910	0.0369	-1.1978
140	-3.4502	0.0465	-1.2557
145	-3.4523	0.0328	-1.2564
150	-3.4190	0.0537	-1.2443
155	-3.4491	0.0730	-1.2553
160	-3.5365	0.0797	-1.2871
165	-3.6104	0.0805	-1.3140
170	-3.6770	0.0401	-1.3382
175	-3.6895	0.0533	-1.3428
180	-3.6073	0.0667	-1.3129

Table 1: Measured Differential Pressure and Calculated Pressure Coefficient at Various Angles Across the Surface of the Cylinder, as well as, the Uncertainty in the Differential Pressure Measurements.

<u>Attachment 3:</u> Experimental Cylinder Vs Sphere Pressure Coefficients about the Surface

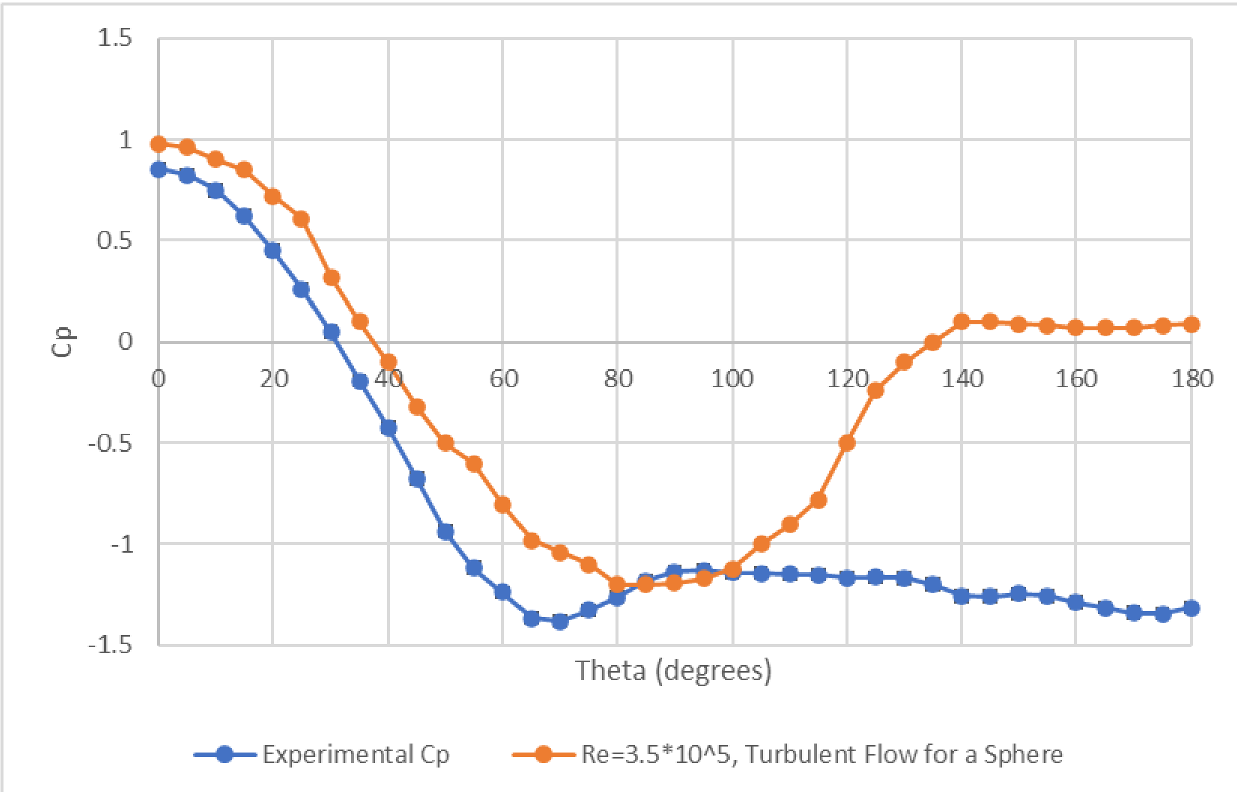


Figure 3: Experimental Pressure Coefficient Curve Across the Cylinder Surface Taken at 5º Measurements, Compared to Turbulent Flow for a Sphere

Comparing our Figure 3 with Figure 9.12 in the Fox and McDonald textbook, our data mirrors a similar trend of the measured pressure distribution around a smooth sphere for a laminar boundary layer. This means that there was a wide turbulent wake behind the cylinder. This agrees with our calculated Reynolds number of 36501.3 because it is within the range of Reynolds numbers, 1000 to 200000, where this laminar flow pattern exists. We observe in Figure 3 that, similar to the smooth sphere case, we have an initial decrease of pressure coefficient during the front of the cylinder, but once it reaches a little before 90º, we see an early decrease in this value. Once it reaches 90º, we can interpret the flat section as boundary layer separation where the pressure is about constant. Since we have a rough surface, we would expect this to occur relatively early compared to the smooth sphere case, just like we observe.

Attachment 4: Tabulated Wake Velocities and Positions

Table 2: Wake Normalized Velocities at Varying Vertical Positions and x=17.57 in from the Cylinder

Streamwise Position, x = 17.57 in					
Vertical Position, y (in)	Normalized Vertical Distance, y/D	Average Pitot-Static Probe Pressure, p (inH2O)	Uncertainty (inH2O)	Velocity, u (ft/s)	Normalized Velocity, u/U
3.98	31.84	0.464	0.0051	50.9696	1.0427
3.51	28.08	0.4626	0.0007	50.9074	1.0415
3.04	24.32	0.4618	0.0018	50.8718	1.0407
2.5	20	0.4532	0.0035	50.4878	1.0329
2.01	16.08	0.4364	0.0022	49.7291	1.0174
1.5	12	0.4112	0.0085	48.5688	0.9936
0.99	7.92	0.3504	0.0068	45.6481	0.9339
0.48	3.84	0.2854	0.0087	42.3032	0.8655
-0.03	-0.24	0.2176	0.0166	38.5059	0.7878
-0.53	-4.24	0.2728	0.0085	41.6237	0.8515
-1.04	-8.32	0.3488	0.0065	45.5687	0.9323
-1.52	-12.16	0.3996	0.0083	48.0253	0.9825
-2.03	-16.24	0.4366	0.0031	49.7382	1.0176
-2.51	-20.08	0.4576	0.0024	50.6846	1.0369
-3.01	-24.08	0.4624	0.0014	50.8985	1.0413
-3.53	-28.24	0.4606	0.0018	50.8184	1.0397
-4.02	-32.16	0.4606	0.0012	50.8184	1.0397

Table 3: Wake Normalized Velocities at Varying Vertical Positions and x=25 in from the Cylinder

Streamwise Position, x = 25 in					
Vertical Position, y (in)	Normalized Vertical Distance, y/D	Average Pitot-Static Probe Pressure, p (inH2O)	Uncertainty (inH2O)	Velocity, u (ft/s)	Normalized Velocity, u/U
3.99	31.92	0.4698	0.0016	51.2265	1.0480
3.49	27.92	0.4622	0.0014	50.8896	1.0411
3.02	24.16	0.4476	0.0063	50.2362	1.0277
2.49	19.92	0.4338	0.0038	49.6106	1.0149
2	16	0.419	0.0042	48.9309	1.0010
1.48	11.84	0.3994	0.0142	48.0159	0.9823
0.99	7.92	0.3478	0.0104	45.5190	0.9312
0.5	4	0.3054	0.0078	43.3599	0.8871
0.02	0.16	0.289	0.0133	42.4954	0.8694
-0.49	-3.92	0.2852	0.0081	42.2925	0.8652
-0.99	-7.92	0.3514	0.0071	45.6977	0.9349
-1.5	-12	0.3946	0.0066	47.7891	0.9777
-2	-16	0.4186	0.0080	48.9124	1.0007
-2.51	-20.08	0.4354	0.0074	49.6836	1.0164
-3.01	-24.08	0.4566	0.0041	50.6400	1.0360
-3.51	-28.08	0.4678	0.0025	51.1380	1.0462
-4.02	-32.16	0.4694	0.0008	51.2088	1.0476

Attachment 5: Plotted Wake Velocity Distribution along the Vertical Distance from the Cylinder's Center

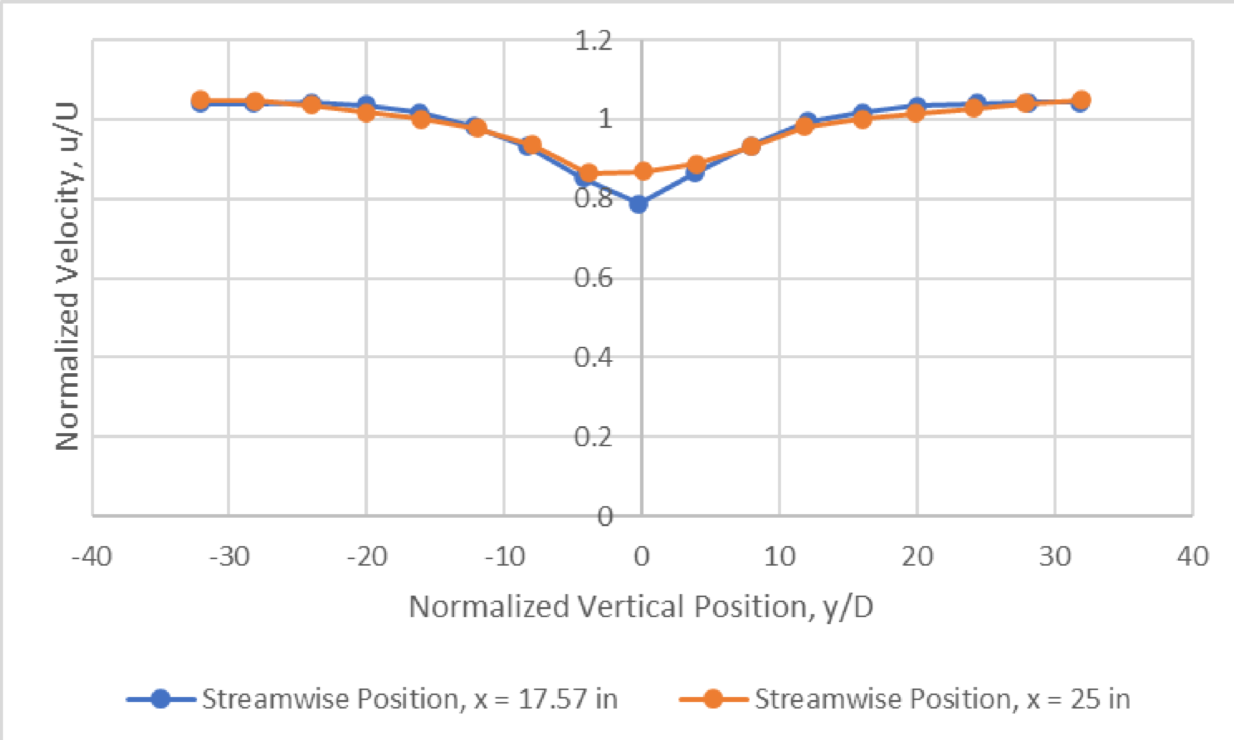


Figure 4: Normalized Velocity Distribution Vertically Across the Wake at Streamwise Positions x=17.57 and 25 in

As seen in Figure 4, we observe the wake's velocity profile to decrease near the center behind the brass cylinder and flattens out to the freestream velocity as we get vertically further from the cylinder. This is prominent directly behind the cylinder at x=17.57 in, where the velocity is lower than at the same position at x=25in. Theoretically, we would expect random and variating velocities due to the random vortices right behind the cylinder, but generally, this distribution is what we would expect as we get further since the freestream velocity air particles are mixing with the wake air particles.

Attachment 6: Sample Calculations for Finding the Drag Coefficient Using the Surface Pressure Method

Attachment 6

Sample Calculation for C_D using surface pressure method

$$C_{D_p} = \int_0^{\pi} C_p \cos\theta \, d\theta$$

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho V^2}$$

Using Numerical Integration given

$\Delta p(\theta=0) = 0.0163 \text{ lbf/in}^2$ $\rho = 0.0023 \text{ lbf s}^2/\text{ft}^4$

$\Delta p(\theta=5^\circ) = 0.0157 \text{ lbf/in}^2$

$U = 48.8 \text{ ft/s}$

$$C_p(\theta=0) = \frac{0.0163 \text{ lbf/in}^2 \left(\frac{12 \text{ in}}{1 \text{ ft}}\right)^2}{\frac{1}{2}(0.0023 \text{ lbf s}^2/\text{ft}^4)(48.8 \text{ ft/s})^2}$$

$$= 0.8539$$

$$C_p(\theta=5^\circ) = \frac{0.0157 \text{ lbf/in}^2 \left(\frac{12 \text{ in}}{1 \text{ ft}}\right)^2}{\frac{1}{2}(0.0023 \text{ lbf s}^2/\text{ft}^4)(48.8 \text{ ft/s})^2}$$

$$= 0.8244$$

$$C_p \cos\theta \big|_{\theta=0^\circ} = 0.8539 \cos 0^\circ$$
$$= 0.8539$$

$$C_p \cos\theta \big|_{\theta=5^\circ} = 0.8244 \cos 5^\circ$$
$$= 0.8212$$

Using Trapezoidal Riemann Sum

$$C_{D_p}\Big|_0^{5^\circ} = \frac{0.8539 + 0.8212}{2} \cdot 5^\circ \left(\frac{\pi \text{ rad}}{180^\circ}\right)$$
$$= 0.0731$$

Repeat for each 5° increment in Excel to find C_{D_p}

We find our drag coefficient, C_D to be 1.1403 using the surface pressure method.

Attachment 7: Sample Calculations for Finding the Drag Coefficients Using the Momentum Method

Attachment 7

Sample Calculation for C_D using wake vel profiles

$$C_D = \frac{2}{D}\int_0^H \left(1-\frac{V_2}{U}\right)\left(\frac{V_2}{U}\right)dy$$

Using Numerical Integration given for $x = 17.57\,in$

$D = 1.50\,in = 0.125\,ft$ $\quad \rho_{H_2O} = 62.4\,lbm/ft^3$

$H = 8\,in$ $\quad \rho_{air} = 0.0023\,lbf\,s^2/ft^4$

$U = 48.88\,ft/s$

$\Delta p(y=0\,in) = 0.4606\,in\,H_2O$

$\Delta p(y=0.5\,in) = 0.4624\,in\,H_2O$

$$V_2 = \sqrt{\frac{2\Delta p}{\rho}}$$

$$= \sqrt{\frac{2\rho_{H_2O}\,g\,h}{\rho_{air}}}$$

$$V_2(y=0\,in) = \sqrt{\frac{2(62.4\,lbm/ft^3)\left(\frac{1\,lbf}{32.2\,lbm\,ft/s^2}\right)(32.2\,ft/s^2)\left(0.4606\,in\left(\frac{1\,ft}{12\,in}\right)\right)}{0.0023\,lbf\,s^2/ft^4}}$$

$$\approx 45.64\,ft/s$$

$$V_2(y=0.5\,in) = \sqrt{\frac{2\cdot 62.4\cdot 0.4624/12}{0.0023}}$$

$$= 45.73\,ft/s$$

$$\left(1-\frac{V_2}{U}\right)\left(\frac{V_2}{U}\right)\Big|_{y=0} = \left(1-\frac{45.64\,ft/s}{48.88\,ft/s}\right)\left(\frac{45.64\,ft/s}{48.88\,ft/s}\right)$$

$$\approx 0.0619$$

$$\left(1-\frac{V_2}{U}\right)\left(\frac{V_2}{U}\right)\Big|_{y=0.5} = \left(1-\frac{45.73\,ft/s}{48.88\,ft/s}\right)\left(\frac{45.73\,ft/s}{48.88\,ft/s}\right)$$

$$\approx 0.0604$$

Using Trapezoidal Riemann Sum

$$C_D\frac{D}{2}\Big|_{0\,in}^{0.5\,in} = \frac{0.0619+0.0604}{2}\cdot 0.5\,in\left(\frac{1\,ft}{12\,in}\right)$$

$$= 0.0025\,ft$$

Repeat for each 0.5in increment in Excel to find $C_D\frac{D}{2}\Big|_0^H$

then $C_D = \frac{2}{D}\left(C_D\frac{D}{2}\Big|_0^H\right)$

We find our drag coefficient, C_D to be 1.1716 and 1.1811 at x=17.57 and 25in, respectively, using the momentum method.

Attachment 8: Tabulated Experimental and Theoretical Drag Coefficients

Table 4: Experimentally Calculated Drag Coefficients, C_D, Using the Momentum and Surface Pressure Method along with Drag Coefficient Found using Reynolds Number

Drag Coefficients, C_D			
Momentum Method		Surface Pressure Method	Estimated at Re=3.65*10^4
x=17.57 in	x=25 in		
1.1716	1.1811	1.1403	~1

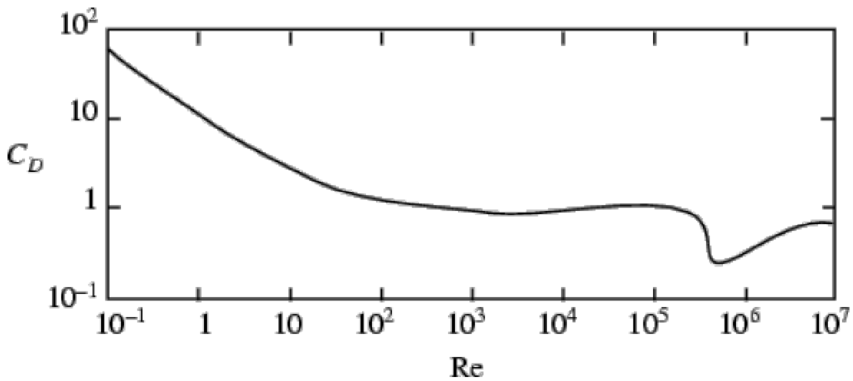


Figure 5: Drag Coefficient using Reynolds Number for a Smooth Cylinder

Attachment 9: Flow Distribution around the Cylinder and Wake

After collecting all the data for the experiment we used a flow visualization device to qualitatively analyze the effects of the cylinder on the flow field. When we placed this instrument upstream of the cylinder we saw the strings off the end go straight in the direction of the flow showing a non rotational laminar flow field. However, when we put this device behind the object the strings directly behind the cylinder kept moving in the direction of the flow but now with much more wobble thus showing the effect of a turbulent flow field caused by boundary layer separation caused by the cylinder in the form of wake. As we moved the instrument farther back we saw the turbulent, wobbly flow increase in size as the wake increased in size. Although this part of the experiment did not provide us with definitive quantitative values it did allow us to better understand the flow field and the effect of the cylinder.