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Experimental Study on Flow Characteristics in a Specified Duct

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Abstract

Fan characteristic is significant for design and production of manufacture, and selection and usage of customers. The experiment provides an opportunity to do practice on dimensional analysis and to research into the characteristics of fan with specific shape.

Keywords

Fan characteristic, electronic manometer, thermo fluid.

1. Introduction

In the thermo fluid section, dynamic similarity is an important concept when investigating the flow characteristics in a specified duct. In order to acquire a comprehensive understanding, the experiment has three tests with different fan speeds. This lab report is aimed to explore the features of a fan in a duct and find the relationships between significant parameters of the air flow by using groups of data, tables and graphs.

2. Description of Apparatus and Method

2.1. Apparatus

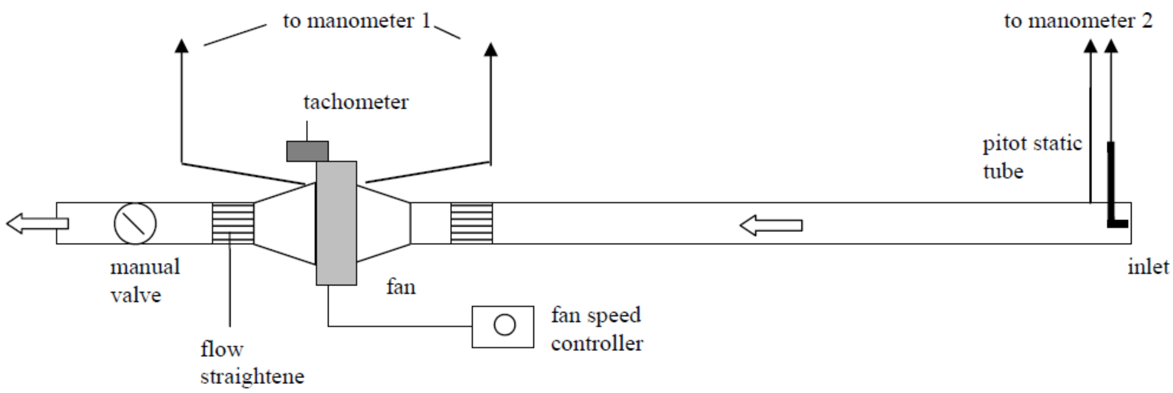

Figure 1: Apparatus used for the Laboratory Exercise

It is a simple straight circular duct with a fan which is used to draw the air inside. There is a fan speed controller utilized for manual adjustment. Then the rotational speed in rpm can be displayed on the tachometer, which gives feedback to controller. Using a long sloping tube is to measure the static pressure change across the fan. The total electric power supplied to fan is obtained by the wattmeter (1).

On the left side, it is the air outlet with a manual valve to change the flow resistance.

On the right side, it is the air inlet with an electronic manometer to provide the readings of the dynamic pressure at the centre of the duct (2).

2.2. Method

Before the experiment, take notes of the atmospheric pressure and ambient temperature.

The experiment is basically measure the pressure difference across the fan and the dynamic pressure at the inlet under various conditions (3), in this case, which means with three distinct rotor speeds. Test processes are described as follows.

Test 1

Make sure the manometers to be zeroed, fully close the manual valve, and set the fan speed controller to maximum position. Check the range on the electronic manometer to 0.5.

Use something to seal up the inlet. Switch on the device and wait for the reading of tachometer to be stable.

Rotate the controller to regulate the fan speed to be approximately 2600 rpm within +/- 50 rpm fluctuation. This probably requires several adjustments and some time.

After it is stable, record the readings of Manometer 1, Manometer 2, tachometer and wattmeter.

Move away the seal at the inlet side.

Rotate the manual valve anticlockwise by one marked division.

Repeat Step 3, 5 and 6 to gain10 groups of data in total.

Test 2

Change the range on the electronic manometer to 0.15 and make sure it to be zero.

Follow the same method in Test 1 but the only difference is altering the fan speed to 2000 rpm with +/- 50 rpm.

Test 3

Keep the range to 0.15 and repeat Test 1 method with about 1000 rpm.

Finally, collect all data and transfer them into appropriate units.

3. Basic Results

The basic data for the three tests are shown below in Table in next page.

(Note: the static pressure change across the fan is measured by Manometer 1. To find it in Pa, use the relation 1 cm = 10 Pa. The dynamic pressure at the centre of the duct in Pa is obtained in the similar by multiplying the reading by 249.1.)

$$\rho = \frac{np_{atm}}{R_g T}$$

where p_{atm} = the atmospheric pressure (N/m^2),

T = the absolute temperature of air (K)

n = the molecular weight of the gas (29.0 for air)

Rg = the universal gas constant (8314 J/kg K)

(Note: in this case ignore the moisture content effect on the air density since the influence is insignificant (4).)

Thus $\rho = \frac{29\times101000}{8314\times283} = 1.245\ \mathrm{kg/m^3}$

4. Fan Characteristic at the Three Fan Speeds

With the internal duct diameter, d=100 mm=0.1 m,

the internal duct area, $A = \frac{\pi\cdot d^2}{4} = \frac{\pi\cdot 0.1^2}{4} = 7.854\times10^{-3}\ \mathrm{m}^2$.

Two formulas are used to compute velocities and mass flow rate respectively.

$$u = \sqrt{\frac{2\cdot\Delta P_2}{\rho}} \qquad Q = u\cdot A$$

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Table 1: Basic data for the three tests

Test 1	Manometer 1 (cm)	Static Pressure Change across the Fan, $\triangle P_1$ (Pa)	Manometer 2 (inch water)	Dynamic Pressure at the Centre of Duct, $\triangle P_2$ (Pa)	Rotational Speed (rpm)	Electrical Power to Fan, P_{elec} (W)
Fully Closed	32.0	320	0.00000	0.00000	2590	86
	32.5	325	0.03250	8.09575	2573	103
↓	33.0	330	0.03750	9.34125	2588	105
	34.5	345	0.05000	12.45500	2590	108
	33.3	333	0.07500	18.68250	2585	113
	32.8	328	0.12000	29.89200	2593	119
	31.8	318	0.18500	46.08350	2587	125
	30.9	309	0.25750	64.14325	2595	129
Fully Opened	29.6	296	0.32000	79.71200	2593	130
	28.6	286	0.37000	92.16700	2589	131
Test 2	Manometer 1 (cm)	Static Pressure Change across the Fan, $\triangle P_1$ (Pa)	Manometer 2 (inch water)	Dynamic Pressure at the Centre of Duct, $\triangle P_2$ (Pa)	Rotational Speed (rpm)	Electrical Power to Fan, P_{elec} (W)
Fully Closed	18.6	186	0.00250	0.62275	1983	61
	19.0	190	0.01875	4.67063	1978	77
↓	20.2	202	0.02250	5.60475	2021	79
	19.7	197	0.02750	6.85025	1983	80
	19.6	196	0.04375	10.89813	1985	84
	19.2	192	0.07125	17.74838	1984	90
	19.5	195	0.10750	26.77825	1981	94
	18.5	185	0.20000	49.82000	2018	98
Fully Opened	17.3	173	0.24000	59.78400	1972	98
	16.8	168	0.26000	64.76600	2000	100
Test 3	Manometer 1 (cm)	Static Pressure Change across the Fan, $\triangle P_1$ (Pa)	Manometer 2 (inch water)	Dynamic Pressure at the Centre of Duct, $\triangle P_2$ (Pa)	Rotational Speed (rpm)	Electrical Power to Fan, P_{elec} (W)
Fully Closed	4.5	45	0.00000	0.00000	962.4	30
	5.0	50	0.00500	1.24550	1005	38
↓	5.3	53	0.00500	1.24550	1032	40
	5.1	51	0.00750	1.86825	998.0	39
	5.0	50	0.01125	2.80238	999.3	41
	4.9	49	0.01750	4.35925	995.3	43
	4.8	48	0.02750	6.85025	1000	46
	4.7	47	0.03875	9.65263	1004	47
Fully Opened	4.7	47	0.04750	11.83225	1019	49
	4.6	46	0.05625	14.01188	1037	50

In order to calculate the useful power supplied to air by fan is

$$P_{use} = Q \cdot \Delta p_{fan}$$

The results are shown below in Table 2 below.

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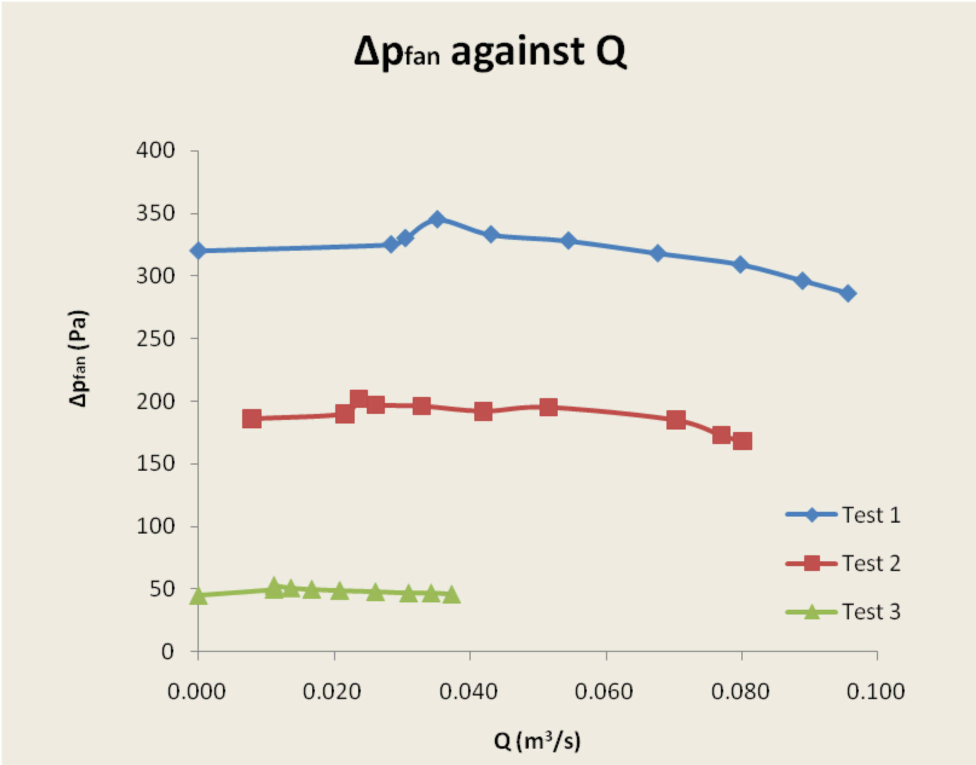
The fan characteristics are presented in three graphs as follows.

Table 2: Results

Test 1	The Velocity, u (m/s)	The Flow Rate, Q (m^3/s)	Increase of Static Pressure across Fan, $\triangle p_{fan}$ (Pa)	Rotational Speed of Rotor, Ω (rads/s)	Useful Power Supplied to Air by Fan, P_{use} (W)	Electrical Power Supplied to Motor, P_{elec} (W)	Overall Efficiency of Fan, η (%)
Fully	0.000	0.000	320	271.09	0.00000	86	0.00
Closed	3.606	0.028	325	269.31	9.20520	103	8.94
	3.874	0.030	330	270.88	10.04009	105	9.56
	4.473	0.035	345	271.09	12.12027	108	11.22
	5.478	0.043	333	270.56	14.32791	113	12.68
	6.930	0.054	328	271.40	17.85141	119	15.00
	8.604	0.068	318	270.77	21.48924	125	17.19
	10.151	0.080	309	271.61	24.63515	129	19.10
Fully	11.316	0.089	296	271.40	26.30721	130	20.24
Opened	12.168	0.096	286	270.98	27.33222	131	20.86

Test 2	The Velocity, u (m/s)	The Flow Rate, Q (m^3/s)	Increase of Static Pressure across Fan, $\triangle p_{fan}$ (Pa)	Rotational Speed of Rotor, Ω (rads/s)	Useful Power Supplied to Air by Fan, P_{use} (W)	Electrical Power Supplied to Motor, P_{elec} (W)	Overall Efficiency of Fan, η (%)
Fully	1.000	0.008	186	207.55	1.46114	61	2.40
Closed	2.739	0.022	190	207.03	4.08754	77	5.31
	3.001	0.024	202	211.53	4.76048	79	6.03
	3.317	0.026	197	207.55	5.13264	80	6.42
	4.184	0.033	196	207.76	6.44100	84	7.67
	5.340	0.042	192	207.66	8.05196	90	8.95
	6.559	0.052	195	207.34	10.04493	94	10.69
	8.946	0.070	185	211.22	12.99855	98	13.26
Fully	9.800	0.077	173	206.40	13.31557	98	13.59
Opened	10.200	0.080	168	209.33	13.45873	100	13.46

Test 3	The Velocity, u (m/s)	The Flow Rate, Q (m^3/s)	Increase of Static Pressure across Fan, $\triangle p_{fan}$ (Pa)	Rotational Speed of Rotor, Ω (rads/s)	Useful Power Supplied to Air by Fan, P_{use} (W)	Electrical Power Supplied to Motor, P_{elec} (W)	Overall Efficiency of Fan, η (%)
Fully	0.000	0.000	45	100.73	0.00000	30	0.00
Closed	1.414	0.011	50	105.19	0.55547	38	1.46
	1.414	0.011	53	108.02	0.58880	40	1.47
	1.732	0.014	51	104.46	0.69392	39	1.78
	2.122	0.017	50	104.59	0.83321	41	2.03
	2.646	0.021	49	104.17	1.01841	43	2.37
	3.317	0.026	48	104.67	1.25059	46	2.72
	3.938	0.031	47	105.09	1.45359	47	3.09
Fully	4.360	0.034	47	106.66	1.60936	49	3.28
Opened	4.744	0.037	46	108.54	1.71406	50	3.43



Graph 1: Δp_{fan} against Q for the three tests (Situation 1)

Comment for Situation 1:

The curves produced by observed data looks like parabolas. According to the curves and the detailed information from table, the common point is that all their Δp_{fan} firstly reach a maximum value and then fall down step by step as Q rises. The increments or decrements are relatively small since the curves always have gentle slope. It also indicates that in a certain range in each test, to obtain an identical volume flow rate, we probably have two different values of Δp_{fan} (not work for the peak).

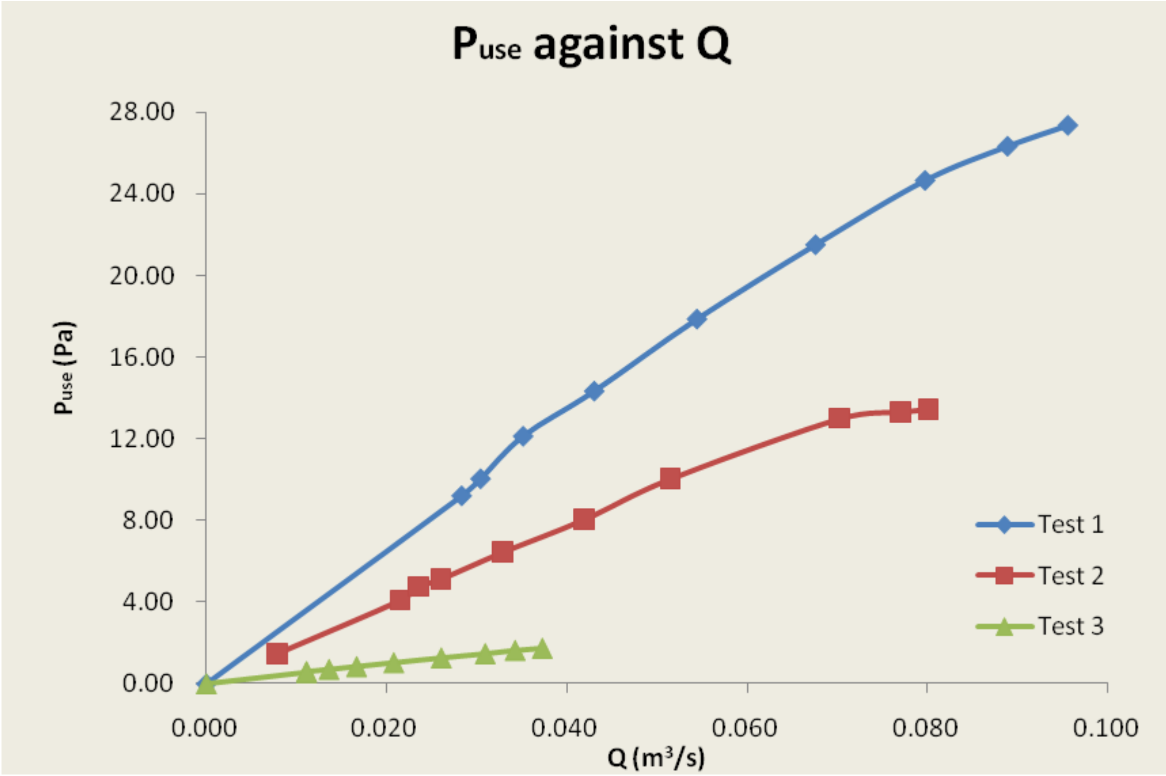
Furthermore, the sort ascending of the Δp_{fan} at the same Q is Test 3 – Test 2 – Test 1 (from low fan rotational speed to high fan rotational speed). In addition, the magnitude at least doubles the previous one when the Q is same.

Comment for Situation 2:

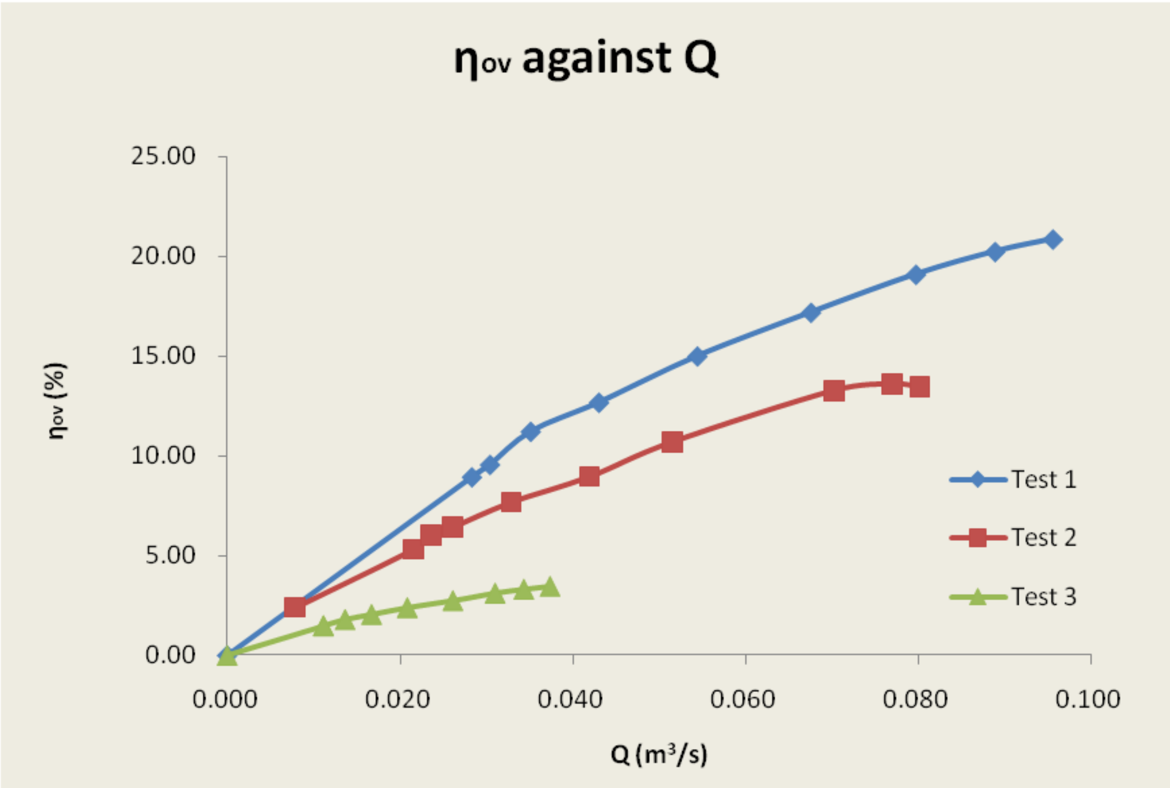
Transparently, for each test, P_{use} enhances as the Q enlarges. Among them, the speed of increasing of Test 1 is largest since the gradient is steepest, followed by Test 2 and then Test 3. It is reasonable that at the same flow rate, the fan with high rotational speed requires more useful power (5).

Comment for Situation 3:

This figure is similar to Graph 2. η_{ov} enhances as the Q enlarges. The gradient steepness from highest to lowest is Test 1 – Test 2 – Test 3.



Graph 2: P_{use} against Q for the three tests (Situation 2)



Graph 3: η_{ov} against Q for the three tests (Situation 3)

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5. Investigation of Dynamic Similarity

Take one example calculation showing the process to evaluate the nondimensional parameter. Except Δp_{fan} is dependent on the rotational speed, Ω, diameter of the rotor, d, volume flow rate, Q, the air density, ρ, and viscosity of the fluid, μ (6).

$$\Delta p_{fan} = f(Q, \Omega, \rho, \mu, d)$$

where f denotes a function which is unknown.

Table 3: Relevant parameters

	Δp_{fan}	Q	Ω	ρ	μ	d
M	1	0	0	1	1	0
L	-1	3	0	-3	-1	1
T	-2	-1	-1	0	-1	0

Thus, m = 3, n = 6, n – m = 3, there are three dimensionless groups.

Choose ρ,d and Ω as the primary quantities. And the rest are used to form three dimensionless groups. Using a, b, and c to determine the form of dimensionless group (7).

$$\Delta p_{fan} \rightarrow \frac{\Delta p_{fan}}{\rho^a \Omega^b d^c}$$

Equating the dimensions gives $[ML^{-1}T^{-2}] = [M^a L^{-3a}][T^{-b}][L^c]$

Equating the dimensions of M gives 1 = a

Equating the dimensions of L gives -1 = -3a + c

Equating the dimensions of T gives -2 = -b

Therefore, a = 1, b = 2, and c = 2.

The first dimensionless group is $\Pi_1 = \frac{\Delta p_{fan}}{\rho \Omega^2 d^2}$

$$Q \rightarrow \frac{Q}{\rho^a \Omega^b d^c}$$

Equating the dimensions gives $[L^3 T^{-1}] = [M^a L^{-3a}][T^{-b}][L^c]$

Equating the dimensions of M gives 0 = a

Equating the dimensions of L gives 3 = -3a + c

Equating the dimensions of T gives -1 = -b

Therefore, a = 0, b = 1, and c = 3.

The second dimensionless group is $\Pi_2 = \frac{Q}{\Omega d^3}$

$$\mu \rightarrow \frac{\mu}{\rho^a \Omega^b d^c}$$

Equating the dimensions gives $[ML^{-1}T^{-1}] = [M^a L^{-3a}][T^{-b}][L^c]$

Equating the dimensions of M gives 1 = a

Equating the dimensions of L gives -1 = -3a + c

Equating the dimensions of T gives -1 = -b

Therefore, a = 1, b = 1, and c = 2.

The second dimensionless group is $\Pi_3 = \frac{\mu}{\rho \Omega d^2}$

The final result is $\frac{\Delta p_{fan}}{\rho \Omega^2 d^2} = f(\frac{Q}{\Omega d^3}, \frac{\mu}{\rho \Omega d^2})$

Table 4: New results

Test 1	Flow coefficient $C_Q=Q/(\Omega d^3)$	Pressure coefficient $C_{\triangle p}=(\Delta p_{fan})/(\rho\Omega^2 d^2)$	Power coefficient $C_P=P_{use}/(\rho\Omega^3 d^5)$	Efficiency η_{ov} (%)
Fully Closed	0.0000	0.3498	0.0000	0.00
	0.1052	0.3599	0.0379	8.94
↓	0.0810	0.1879	0.0152	9.56
	0.1296	0.3771	0.0489	11.22
	0.1590	0.3654	0.0581	12.68
	0.2005	0.3577	0.0717	15.00
	0.2496	0.3484	0.0869	17.19
	0.2935	0.3364	0.0988	19.10
Fully Opened	0.3275	0.3228	0.1057	20.24
	0.3527	0.3128	0.1103	20.86
Test 1	Flow coefficient $C_Q=Q/(\Omega d^3)$	Pressure coefficient $C_{\triangle p}=(\Delta p_{fan})/(\rho\Omega^2 d^2)$	Power coefficient $C_P=P_{use}/(\rho\Omega^3 d^5)$	Efficiency η_{ov} (%)
Fully Closed	0.0378	0.3468	0.0131	2.40
	0.1039	0.3561	0.0370	5.31
↓	0.1114	0.3626	0.0404	6.03
	0.1255	0.3673	0.0461	6.42
	0.1582	0.3647	0.0577	7.67
	0.2020	0.3576	0.0722	8.95
	0.2484	0.3643	0.0905	10.69
	0.3327	0.3331	0.1108	13.26
Fully Opened	0.3729	0.3262	0.1216	13.59
	0.3827	0.3079	0.1178	13.46
Test 1	Flow coefficient $C_Q=Q/(\Omega d^3)$	Pressure coefficient $C_{\triangle p}=(\Delta p_{fan})/(\rho\Omega^2 d^2)$	Power coefficient $C_P=P_{use}/(\rho\Omega^3 d^5)$	Efficiency η_{ov} (%)
Fully Closed	0.0000	0.3562	0.0000	0.00
	0.1056	0.3630	0.0383	1.46
↓	0.1029	0.3649	0.0375	1.47
	0.1303	0.3754	0.0489	1.78
	0.1593	0.3671	0.0585	2.03
	0.1995	0.3627	0.0724	2.37
	0.2489	0.3519	0.0876	2.72
	0.2943	0.3419	0.1006	3.09
Fully Opened	0.3210	0.3319	0.1065	3.28
	0.3433	0.3136	0.1077	3.43

And the further modified form can be $\frac{\Delta p_{fan}}{\rho\Omega^2 d^2} = f(\frac{Q}{\Omega d^3}, \frac{\rho\Omega d^2}{\mu})$

Since in this case the velocity can be the product of Ω and d, the term $\frac{\rho\Omega d^2}{\mu}$ turns to be $\frac{\rho v d}{\mu}$, which is Reynolds Number (Re) (8).

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So, $\frac{\Delta p_{fan}}{\rho\Omega^2 d^2} = f(\frac{Q}{\Omega d^3}, Re)$

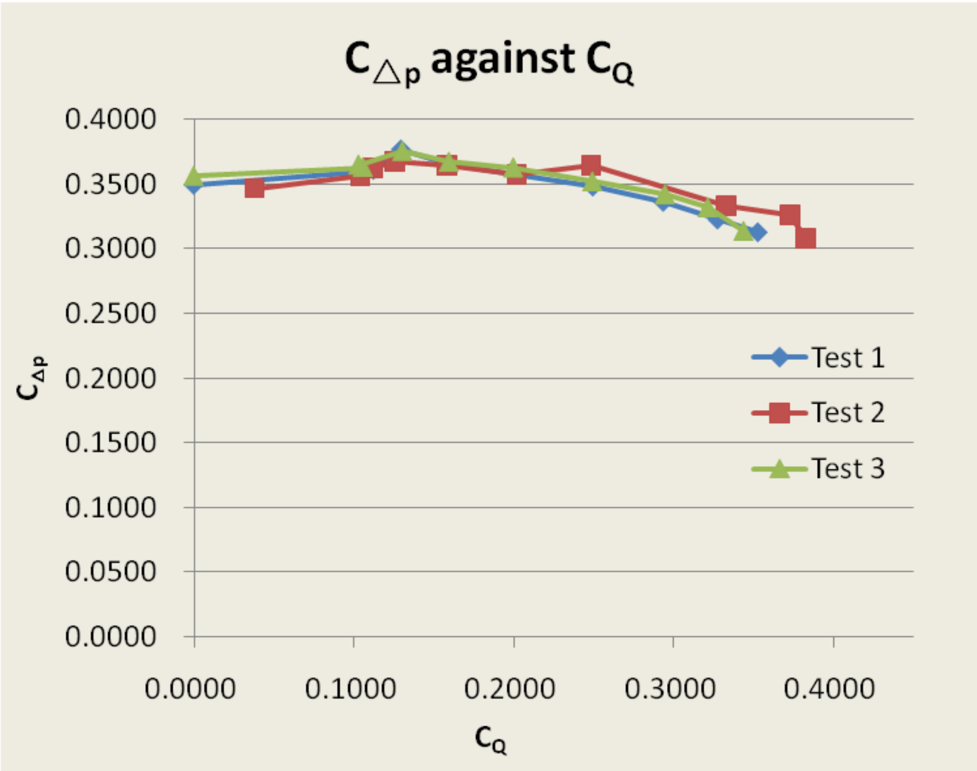
In addition, the air flow is in the duct. So it is an internal flow, which means it weakly depends on Re. Here, Re can be ignored, $\frac{\Delta p_{fan}}{\rho\Omega^2 d^2} = f(\frac{Q}{\Omega d^3})$.

Then use the same method to find another two nondimensional parameters. And the results are indicated below.

$$\frac{P_{use}}{\rho\Omega^3 d^5} = g(\frac{Q}{\Omega d^3})$$

The last parameter η_{ov} is already nondimensional, defined as the useful power divided by the electrical power, so present it in the relationship with flow coefficient (i.e. $\frac{Q}{\Omega d^3}$) used in comparison (9).

Based on the analysis above, tabulate the required information to produce three new graphs showed in Table 4.



Graph 4: $C_{\Delta p}$ against C_Q (Situation 4)

Comment for Situation 4, 5 and 6:

The lines for three tests are very close in Figure 4 and Figure 5, merely with some little difference. However, in Figure 6, the three lines are quite separated with the increasing tendency. In other words, the first and second graphs display dynamic similarity since three lines appear nearly one curve in each graph. The last graph does not display dynamic similarity since the lines are not combined together. The reason may be that the overall efficiency is not only related with the flow characteristics, but also has a certain connection with other parameters, since the overall efficiency is a ratio of useful power to total electrical power, not the exact ratio of useful power to the shaft power, which means there may be some energy loss caused by other component operation in the system or inner resistance of electrical circuit.

As previously assumed, the pressure coefficient and power coefficient both highly rely on the flow coefficient but less depend on Re. Thus the graphs are based on the assumption and

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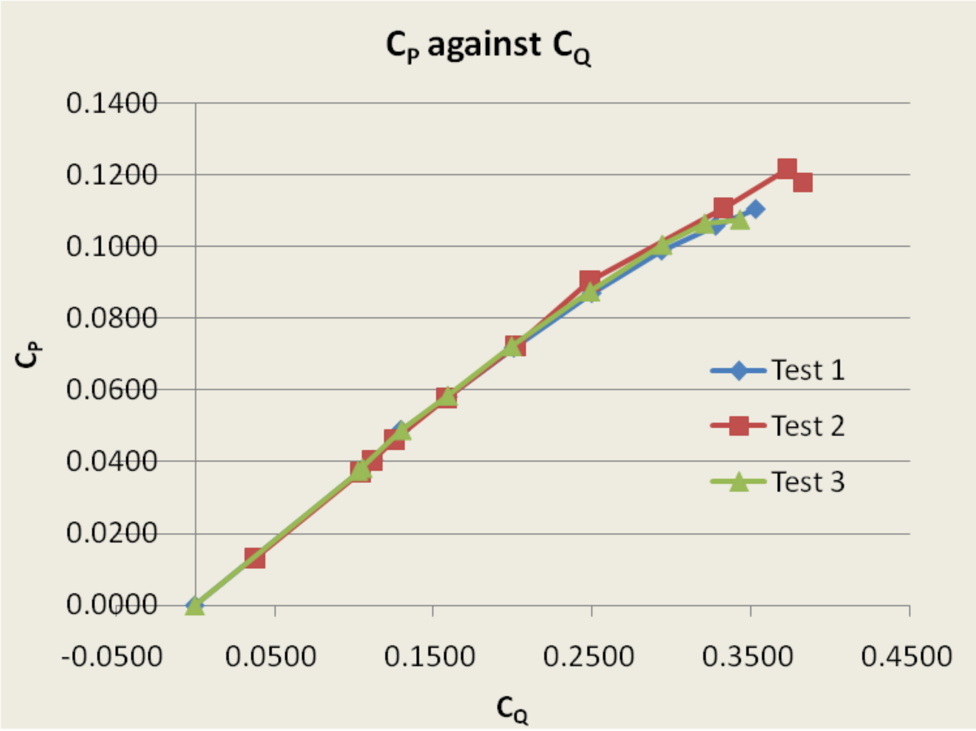
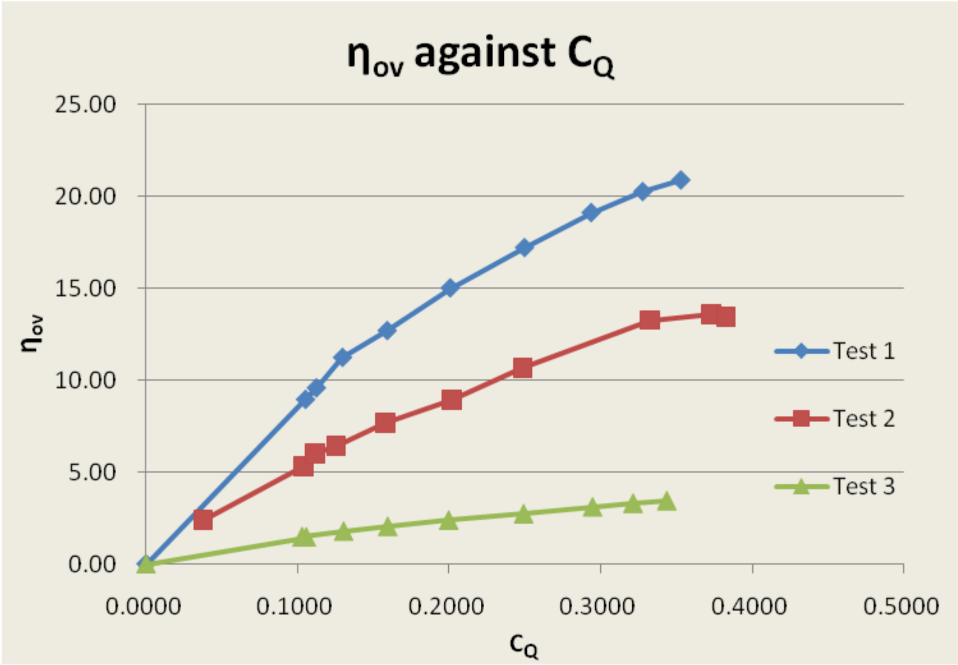
accordingly the consequence proves that it is reasonable and rational since the three lines for different fan rotational speed are located in approximately identical positions. In a word, the effect of Re is rather weak and can be neglected in this situation.

To think it deeply, the tests are taken place for the internal flow, the flow in duct, which the air is surrounded by solid walls, leading to turbulent flows with high Re commonly. And high Re implies low significance.



Graph 5: C_p against C_Q (Situation 5)



Graph **6:** η_{ov} against C_Q (Situation 6)

6. Conclusion

The experiment consists of three test groups with the only variable fan rotational speed. The procedure is simple but need some time to wait for the stabilization since the test is to investigate the performance of air flow in duct and estimate the fan characteristics by plotting the related coefficients on appropriate figures. The final resultant curves of first group are very close to the estimation, even though they cannot perfectly match what we expected initially. These are inevitable since the existence of the reading errors and apparatus depreciation, such as the tiny cracks along the duct. Despite these, the experiment is still comparative successful since the consequence can lead the experimenters to find the proper relationship between the parameters. As a result, only first two graphs of second group illustrate the dynamic similarity here for the high closeness of the three test lines. The reason for the curve which do not perform the dynamic similarity should be the difference between the shaft power and the total electricity power. In this particular case, after the dimensional analysis and suitable suggestion (regardless of Re in the graphs), the final curves show that the suggestions are feasible, which indicates that Re has low impact on in these relationships.

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