Exercise 1E: Gas flow in pipes

Course 28121: Chemical Unit Operations Laboratory

Team B

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Abstract

In this experiment we use air to verify different laws and properties of gas. The air is pumped using a fan and the velocities , pressure differences and temperatures are used to study the properties of gases. Law of Affinity is verified using different frequency. Pressure Head is found to vary with square of frequency, Power consumed is found to vary with the cube of frequency. The fan properties in terms of characteristic curve are observed to be correct. Various methods used for measuring gaseous flow and flow profiles in pipes are the venturi meter, the orifice and the hot film anemometer. All the methods give a slightly different value of the flow rate and the reasons are discussed. Pressure drops are measured across the components are compared and verified with theory. The validity of Bernoullis equation is tabulated at different sections of the pipe and theoretical velocity profiles are justified by measuring velocities at different frequencies. Also the gas velocity profile for laminar and turbulent flow using the pitot tube is analyzed with theoretical equations. The energy consumption, efficiency and temperature increase in the system is found to be increasing with the frequency.Apparent fan frequency varies approximately from 89 % to 94 % and increases with frequency. Absolute static pressure is noted at each point on the system and is found to mostly obey Bernoullis principle.

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Introduction

Flow or application of gases in chemical process plants are widely used – either as a main component or supplied as utilities for instance as compressed air or steam. For many conditions the law of ideal gas is used to identify the properties of the gas; flow behavior and measurement techniques for gases may be more demanding than for liquids because of the large dependency of gas density with temperature and pressure.

In this exercise we will cover friction pressure drops across various components and different methods for measuring gas flow can be studied, and experimental loss coefficients determined for comparison with literature values. The validity of thermodynamic laws for gas compression and the Bernoulli flow equation can be justified. Fan characteristic properties, flow profiles in the duct relative to varying Reynolds numbers and pressure drop across heat exchangers in various configurations may also be investigated.

Design and construction

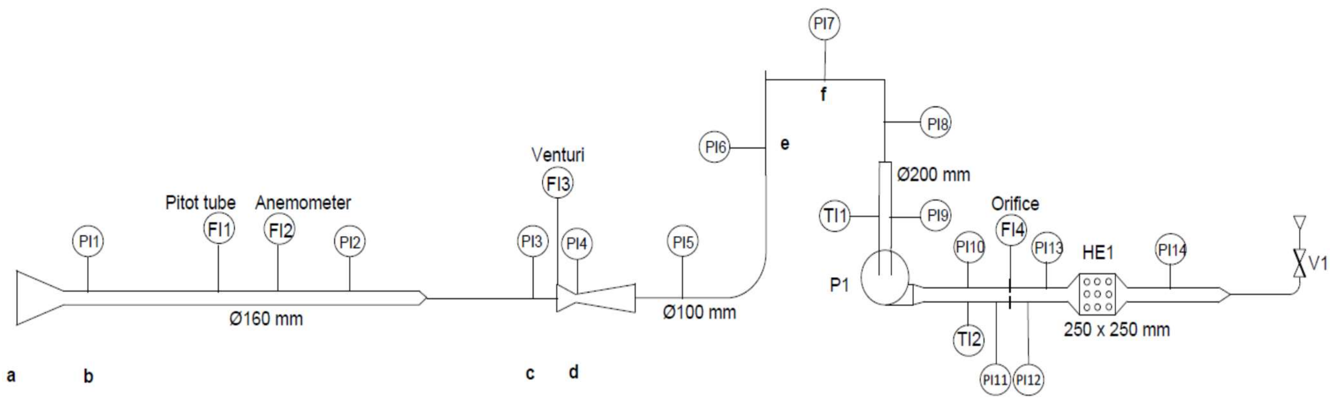


Figure 1 : PI Diagram of the System

The system consists of a fan blowing air from the surroundings, a duct with varying dimensions where the flow can be measured by a pitot tube, a venturi, an orifice and a modern instrument (hot film anemometer). The flow can be changed using the frequency converter to adjust the fan speed or by means of an outlet valve which also changes the pressure level inside the system. In the duct a number of obstacles are located: Two bends, a pipe-T, pipe contraction and expansion and a bundle of heat exchanger pipes arranged perpendicular to the gas flow direction. The differential pressure drop across the components can be measured on the left and right manometer-panels. Various temperature and absolute pressure sensors are used to support the flow and differential pressure measurements.
The reading from the venturi meter FI3 is taken as the pressure difference between PI3 and PI4. In a similar manner the reading from the orifice FI4 is taken as the difference between PI11 and PI12. The reading from the pitot tube measurement is on the “U”- tube instrument on the wall table.

Purpose of the exercise

1. Investigation of fan properties: Characteristic curve, power consumption and efficiency.
2. Controlling the validity of Bernoullis equation.
3. Measuring gas flow rate using the venturi, the orifice and the Pitot tube
4. Determine the gas velocity profile for laminar and turbulent flow using the pitot tube.
5. Determine pressure drop and friction factor at two Re-numbers for straight pipe, pipe bends, pipe-T, contraction/expansion and heat exchanger tube banks and comparing them with theory.

Characteristic Curves

Characteristic curve i.e. Plot for Volume Flow vs Pressure head for 40 Hz frequency is given below

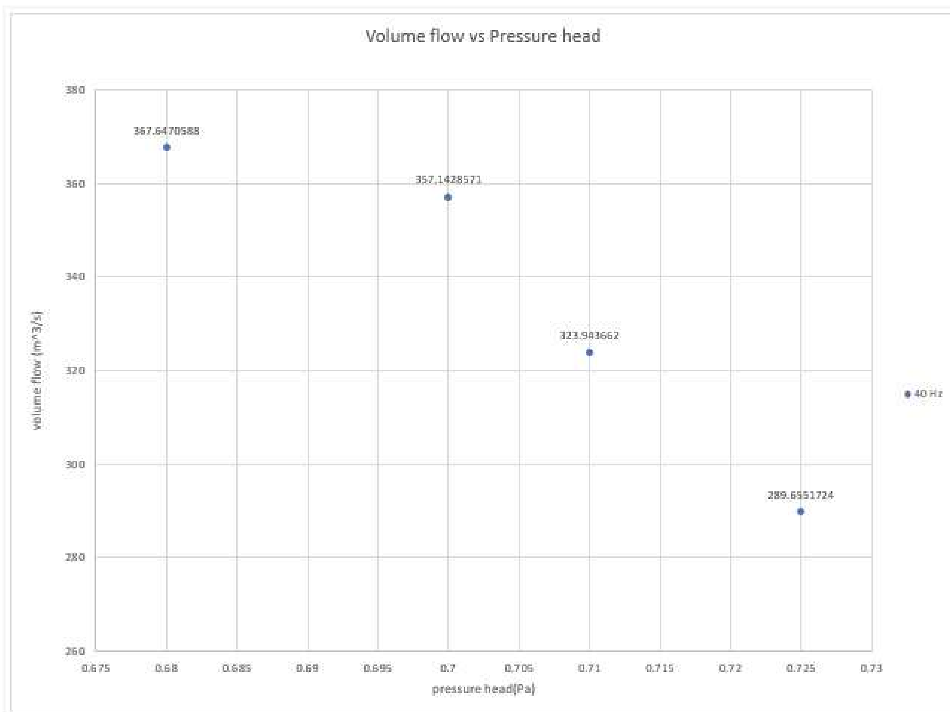


Figure: 1-*Characteristic curve for 40 Hz frequency*

Laws of Affinity

According to the laws of affinity for centrifugal fans the rotational speed is directly proportional to the frequency of the imposed voltage as well as to the volumetric flow. The pressure difference (head) is proportional to the second power of the frequency, and the power consumption proportional to the third power of frequency

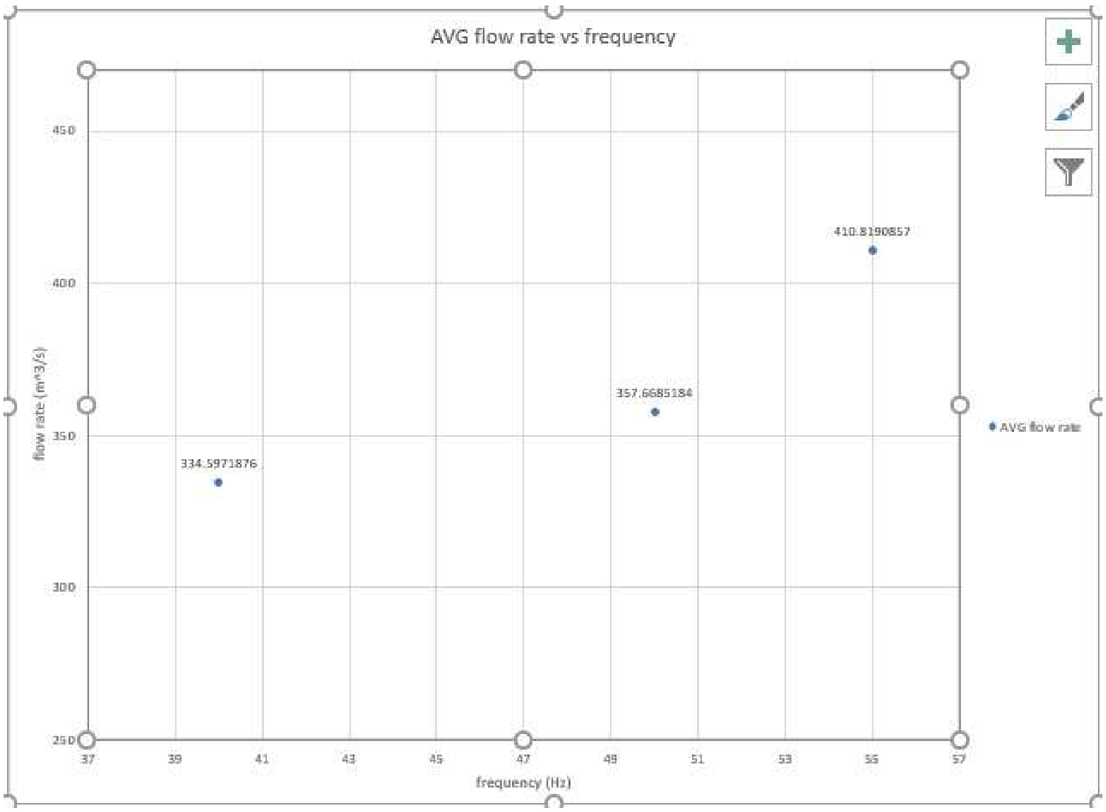


***__Figure: 2__*-Average flowrate vs frequency*

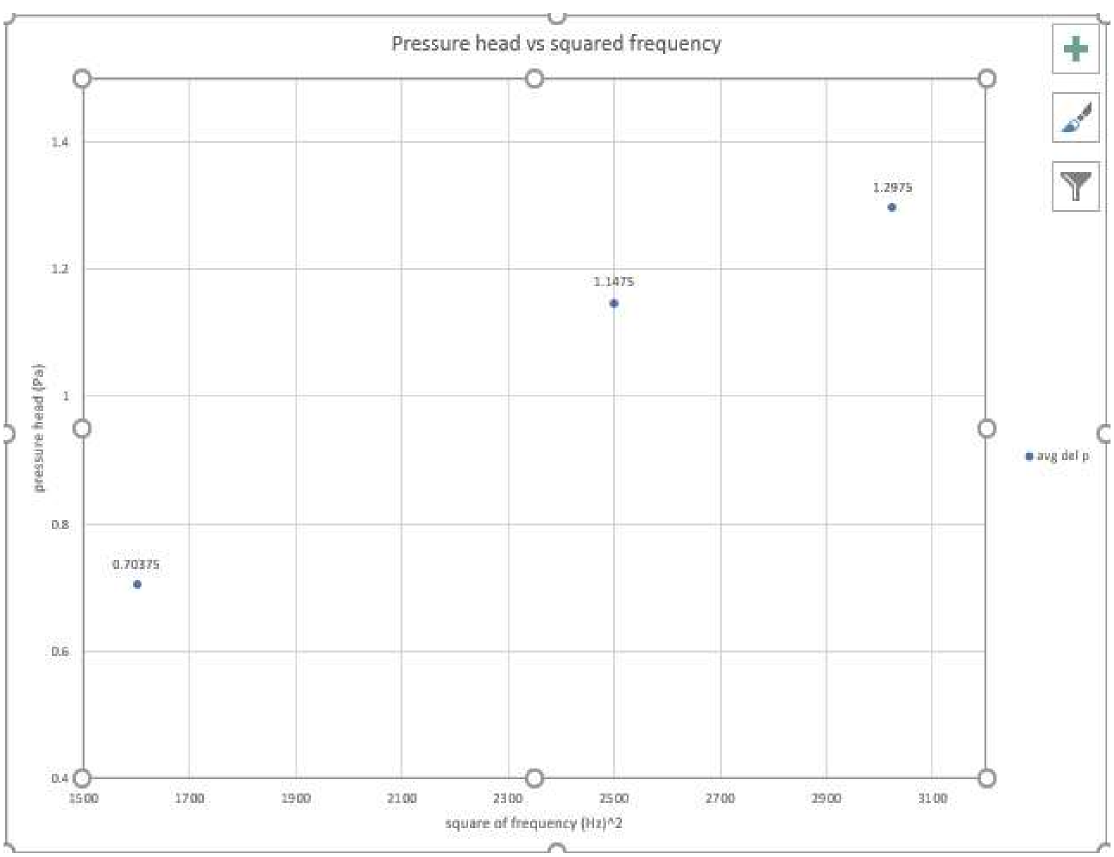


***__Figure: 3-__*Pressure Head vs Square of frequency*

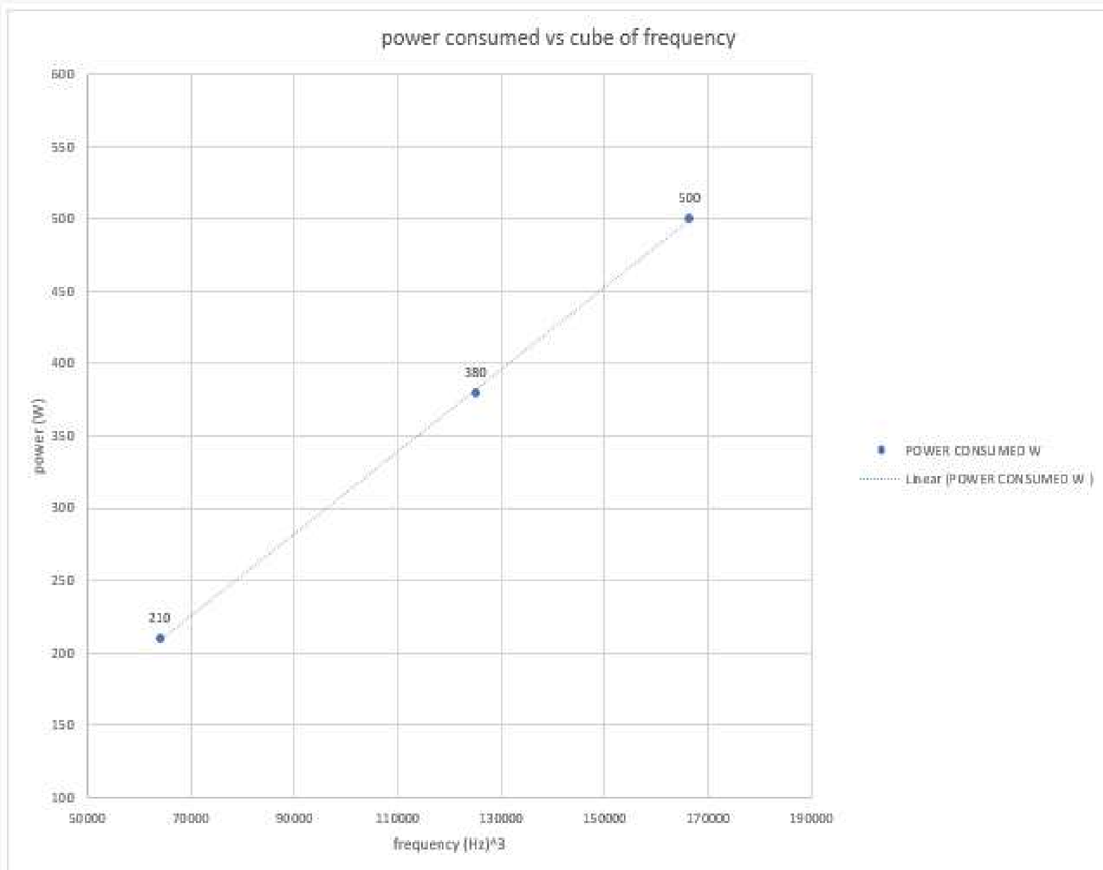


Figure: 4-*Power consumed vs Cube of frequency*

Bernoulli equation

For every cross section a, b, c, d, e and f individual terms in Bernoullis equation (static pressure, velocity pressure, height pressure) are given in Table 1.

Bernoulli equation is given as :

$$p + \frac{1}{2} \cdot \rho \cdot V^2 + \rho \cdot g \cdot h = Constant$$

Table 1: Terms in Bernoullis Equation

Position	$V1$	*Static pressure* (p) $\left(\frac{J}{m^3}\right)$	*Height pressure* $(\rho g h)$ $\left(\frac{J}{m^3}\right)$	*Velocity pressure* $(0.5 \cdot \rho \cdot V^2)$ $\left(\frac{J}{m^3}\right)$	*Total* $\left(p + \frac{1}{2} \cdot \rho \cdot V^2 + \rho \cdot g \cdot h\right)$
a	0	13421.05	0	0	13421.05
a	.33	13421.05	0	0	13421.05
a	.67	13421.05	0	0	13421.05
a	1	13421.05	0	0	13421.05
b	0	13419.05	0	2.211125	13421.26113

b	.33	13415.05	0	6.670125	13421.72013
b	.67	13406.05	0	16.562	13422.612
b	1	13405.05	0	21.321125	13426.37113
c	0	13436.05	0	14.4908288	13450.54083
c	.33	13459.05	0	43.7133312	13502.76333
c	.67	13502.05	0	108.5407232	13610.59072
c	1	13523.05	0	139.7301248	13662.78012
d	0	13586.05	0	35.378	13621.428
d	.33	13859.05	0	106.722	13965.772
d	.67	14352.05	0	264.992	14617.042
d	1	14573.05	0	341.138	14914.188
e	0	13638.05	19.208	14.4908288	13671.74883
e	.33	14000.05	19.208	43.7133312	14062.97133
e	.67	14664.05	19.208	108.5407232	14791.79872
e	1	14964.05	19.208	139.7301248	15122.98812
f	0	13653.05	24.01	14.4908288	13691.55083
f	.33	14050.05	24.01	43.7133312	14117.77333
f	.67	14784.05	24.01	108.5407232	14916.60072
f	1	15094.05	24.01	139.7301248	15257.79012

Validity of Bernoullis equation

Bernoulli's principle states that an increase in the speed of a fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy [1] . But the net total value of energy remains constant throughout the pipe flow. Table 1 suggests that at different positions in the pipe flow we can observe that the total value of energy varies a bit for different open values of valve *V 1* but the overall energy for a particular open value of *V*1 remains almost constant. hence the Bernoullis Equation is verified.

Gas Flow

3 Methods used to measure gas flow through the pipe are

- The Pitot tube : The reading from the pitot tube measurement is on the “U”- tube instrument on the wall table.
- The Orifice flow meter : The reading from the orifice FI4 is taken as the difference between PI11 and PI12
- The Venturi Meter : The reading from the venturi meter FI3 is taken as the pressure difference between PI3 and PI4.

Calculations :

Venturi Meter

$$\varepsilon = \sqrt{\alpha^{\frac{2}{\gamma}}\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{1-\alpha^{\frac{\gamma-1}{\gamma}}}{1-\alpha}\right)\left(\frac{1-\beta^4}{1-\beta^4\alpha^{\frac{2}{\gamma}}}\right)}$$

β is the ratio between the venturi contraction and the pipe diameter (= 0.5)

$$\alpha = \frac{P_b}{P_a} = 0.996 \text{ for (35 Hz)}$$

$$\alpha = \frac{P_b}{P_a} = .9124 \text{ for (55 Hz)}$$

$$\gamma = 1 + \frac{R}{C_v} = 9.45 \text{ for (35 Hz)}$$

$$\gamma = 1 + \frac{R}{C_v} = 9.45 \text{ for (55 Hz)}$$

$$\varepsilon = 0.983 \text{ for (35 Hz)}$$

$$\varepsilon = 0.987 \text{ for (55 Hz)}$$

$$Q = \frac{\varepsilon \cdot C_o A_b}{\sqrt{1-\beta^4}} \sqrt{\frac{2(p_a - p_b)}{\rho}}$$

$$Q = 11.4 \ \frac{l}{\sec} \text{ for (35 Hz)}$$

$$Q = \ \frac{l}{\sec} \text{ for (55 Hz)}$$

Orifice flow meter

$$Q \text{ (liter/sec)} = k \sqrt{\Delta p}\text{ , } \Delta p \text{ in Pa}$$

k = 10 (given orifice factor)

$$Q = 10 \cdot \sqrt{60}$$

$$Q = 77.45 \ \frac{l}{\sec}$$

Pitot Tube

$$\Delta p = \frac{1}{2} \rho V^2$$

$$Q = V \cdot A$$

$$Q = \sqrt{\frac{2\,\Delta p}{\rho}} \cdot A$$

Table 2: Flow Rate Methods

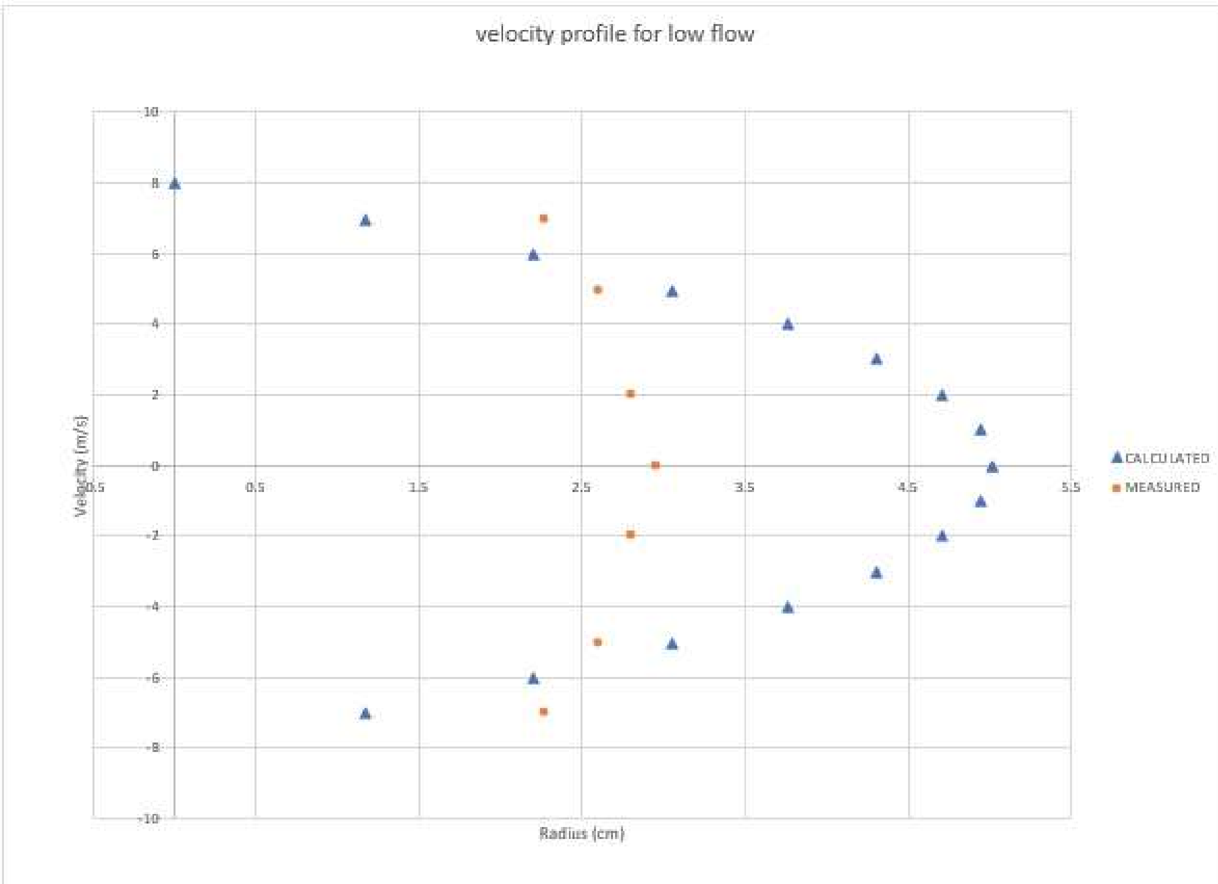
Method	*Pressure difference* 35 *Hz*	*Pressure difference* 55 *Hz*	*Flow Rate at frequency* 35 *Hz*	*Flow Rate at frequency* 55 *Hz*
Pitot tube	7.2	2.8	68.9	32.47
Orifice flow meter (*PI11 − PI12*)	60	150	77.45	122
Venturi Meter· (*PI3 − PI4*)	50	28	11.4	33.8

Velocity Profiles

Drawings of the velocity profiles for low flow (35 Hz) and high turbulent flow (55 Hz) and the average gas flows based on the profiles. Comparison of the measured profiles with the rate profiles calculated from equations below

The rate profile in undisturbed laminar flow in a pipe is given by

$$V(r) = 2\, V_{average}\left(1 - \left(\frac{r}{R}\right)^2\right)$$



<u>Figure: 5-</u>Measured velocities and calculated velocities across the 140mm diameter pipe at 35 Hz (laminar flow)≡

For turbulent flow the maximum velocity in the center of the pipe is twice the average velocity and the rate profile is given by

$$V(r) = V_{\max} \cdot \left(\frac{(R-r)}{R}\right)^{\frac{1}{7}}$$

where R is the radius of the pipe and r is the distance from the pipe center.

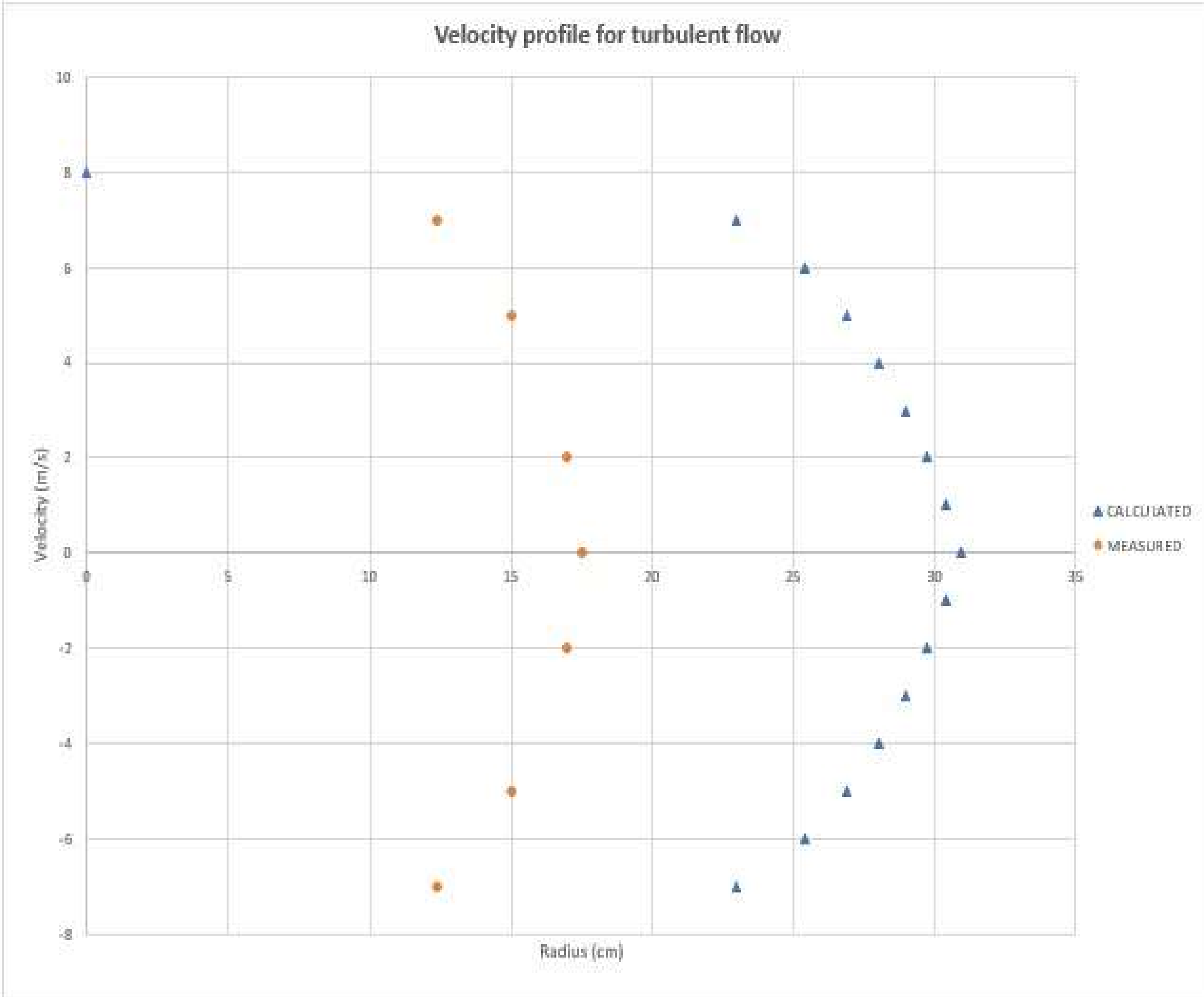


***Figure: 6-**Measured velocities and calculated velocities across the 140mm diameter pipe at 55 Hz (turbulent flow)*

Is the low flow laminar?
To check either flow is laminar or turbulent we can use Reynold's number, which is given by this formula –

$$Re = \frac{DV\rho}{\mu}$$

where,

Re = Reynolds number

D = Internal Diameter of pipe

V = Average velocities

ρ = Fluid density

μ = Dynamic Viscosity

D = 160 mm

V = 2.51 m/s

ρ = 1.225 kg/m3

μ = 1.81 × 10-5 kg/m

Re = 27180

Now since the calculated value of Reynold's number is >>> 2300 hence is too high that shows that low flow is not laminar.

Friction Factor and Loss Coefficients

For incompressible fluids the friction pressure drop for laminar flow in a straight pipe of length L, diameter D and average linear velocity V can be calculated from Poiseuilles law:

$$-\Delta p_f \text{ (pipe)} = \frac{32 \cdot V \cdot L \cdot \eta}{D^2}$$

where η is the dynamic viscosity. For turbulent flow Fannings equation is valid:

$$-\Delta p_f \text{ (pipe)} = \frac{\rho V^2 \cdot 4 \cdot f \cdot L}{2 \cdot D}$$

Friction pressure drop across fittings and components at turbulent flow can be calculated from the loss coefficient K using the relation

$$-\Delta p_f \text{ (fitting/component)} = \frac{\rho \cdot V^2 \cdot K}{2}$$

The friction factor is determined from the plot in figure below :

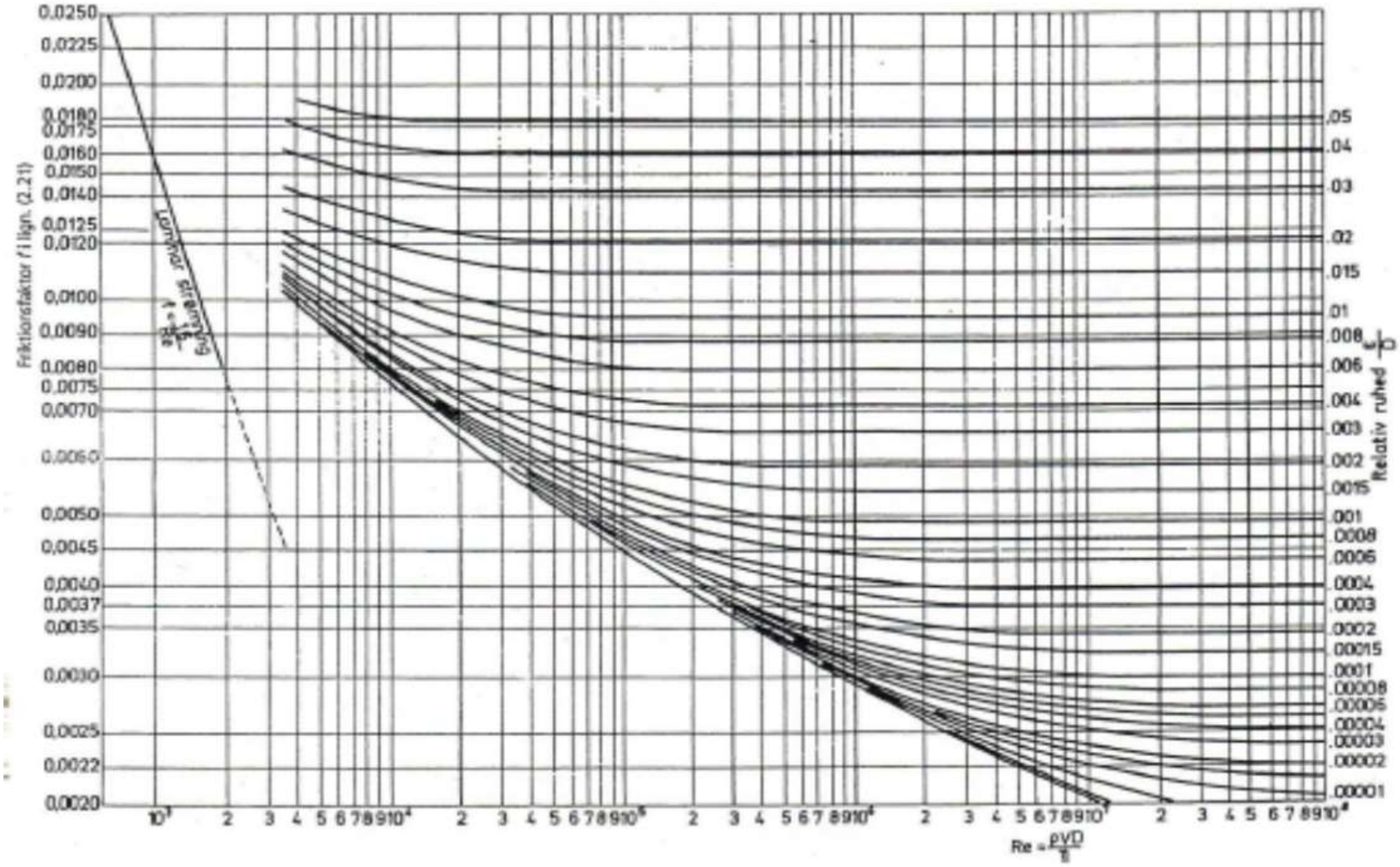


Figure: 7- *plot of friction factor VS Renould's number*

Reynold's number is given by-

$$\mathrm{Re} = \frac{DV\rho}{\mu}$$

Where,

D = Internal Diameter of pipe

V = Average velocities

ρ = Fluid density

μ = Dynamic Viscosity

Using the relative roughness as "e/D" , in which "e" varies with the quality of material used in a pipe and by calculating Reynold's number , friction factor "f" can be determined by using the above Figure.

Table :3-Loss Coefficients, Velocity, and Friction Factors for all Piping Fixtures

Component	*Loss coefficient, K*	*Velocity*	*Friction Factor*
90 *degree elbow, radius* 1 *x pipe diameter*	0.4 − 0.7	4.86	0.0067
90 *degree elbow, radius* 4 *x pipe diameter*	0.3 − 0.5	1.2	0.007
Tee, used as elbow	1.0 − 1.5	4.86	0.0067
Gradual expansion, diameter ratio 1 : 2	2.5	4.86	0.0067
Gradual contraction, diameter ratio 2 : 1	0.06	19.45	0.0053
Sudden expansion, diameter ratio 1 : 2	9	1.2	0.007
Sudden contraction, diameter ratio 2 : 1	0.45	1.9	0.0071
Orifice, diameter ratio 2 : 1	0.9	19.45	0.0053

Power Consumption and Efficiency

Table :4-Raw Data

Frequency	$T1 \cdot (Celcius)$	$T2 \cdot (average) (Celcius)$	*temperature increase*
40 *Hz*	23	25.6	2.6
50 *Hz*	23	26.5	3.5
55 *Hz*	23	26.9	3.9

The above raw data was directly observed and used to find the temperature increase for each frequency and it is observed that the as the frequency increases the temperature difference increases which is quite correct as the energy dissipated in the fan system is increased the temperature difference increases.

Table :5-Theoretical power consumption, the apparent fan efficiency, and the temperature increase for fan speeds of 50Hz, 55Hz, and 40Hz

Frequency	*Theoretical power consumption*	*Experimental Power Consumption* $\cdot (watts)$	*apparent fan efficiency*
40 *Hz*	235	210	89.3 %
50 *Hz*	410	380	92.6 %
55 *Hz*	532.5	500	93.8 %

Efficiency of the fan is controlled by frequency. At lower flow rates fan efficiencies decreases as their motor efficiencies decrease [6]. The fan with the lowest power consumption will be running at the lowest frequency. Increase in frequency give rises to increase in temperature thus fans operating at higher frequency require more power and have higher temperature losses. The temperature losses are offset by fewer momentum losses to produce a higher efficiency fan at higher frequencies.

Validity of the ideal gas law

Ideal Gas Law states that

$$PV = nRT$$

$$\frac{PV}{nR} = T$$

i.e the pressure should increase with Temperature if the Flow rate is kept constant so we can consider the flow rate near P9 and P10 as we have the temperature near T1 and T2 so we can observe the validity of the equation as

$$\frac{(\Delta P)\cdot V}{nR} = (\Delta T)$$

$$\frac{(\Delta P)}{(\Delta T)} = \frac{nR}{V} = Constant$$

hence,

$$(\Delta P) \propto \nabla(\Delta T)$$

Table :6- Validity of Ideal gas law

$Frequency$	$P9$	$P10$	(ΔP)	$T1$	$T2$	(ΔT)
40	625	1350	725	23	25.6	2.6
50	750	1850	1100	23	26.5	3.5
55	750	2070	1320	23	26.9	3.9

thus (ΔP) is increasing with an increase in (ΔT) which confirms the ideal gas theory.

Absolute static pressure

Drawing showing how the absolute static pressure along the system change with the actual position in the pipe system.

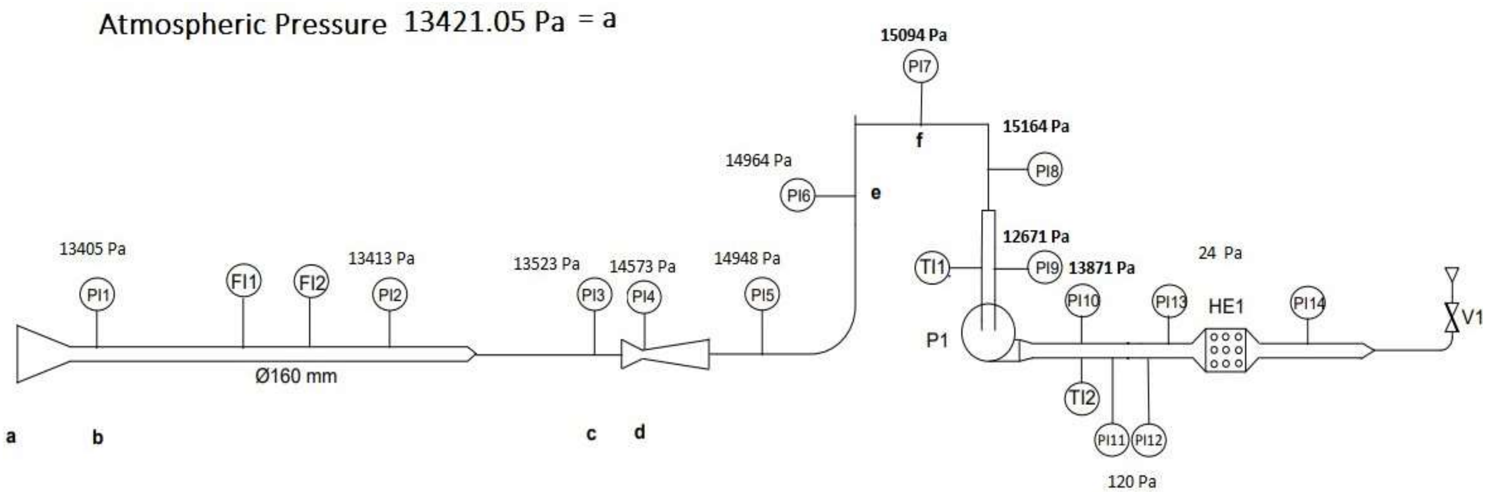


Figure: 8-_Pressure across the piping system used in this experiment at 55Hz_

Discussion and conclusions

Investigation of fan properties , pressure, temperature and velocity of air through a pipe the following conclusions can be made that the Characteristic curve for 40 Hz frequency is quadratic decreases in nature. Volume flow decreases with the pressure head and this result is expected as the bernouli equation states that velocity decreases with increase in pressure. By observing the graphs for Average flowrate vs frequency, Pressure Head vs Square of frequency and Power consumed vs Cube of frequency we can say that the affinity laws are valid and this is the expected result. It is seen that increasing fan frequency increases volumetric flow rate. Bernoulli's equation is valid in this experiment as we can see from the table 1 that the total energy is almost constant as the theory suggests also the speed of the gas moving increases, as the velocity and static pressures increases.We can also conclude that the validity of Bernoulli's equation is decreases as we increase the frequency of measurement. The gas flow measurements done using the pitot tube, the orifice flow meter and the venturi meter vary hugely this may be explained by the fact that the values of measurement from each of these instruments are not so exact and their is room for measurement errors. The plots for the velocity profile suggest that as the frequency increases the graphs for the experimental values shifts towards the graph of turbulent equation. This is expected as the velocity across the pipe should theoretically become increasingly turbulent with increasing frequency. The apparent fan efficiency and the temperature difference increase with the increase in the frequency of the fan. which is expected as more kinetic energy the fan has more their is heat production and hence more rise in temperature. Validity of ideal gas law is also observed. The law is not exactly satisfied but the relations are not wrongly dependent. Lastly we saw how does the absolute static pressure changes along the pipe.

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