A STUDY OF THE PROCESS OF LOCAL MANUFACTURE OF PNEUMATIC PUMPS

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ABSTRACT

This project examines the possibility of manufacturing a pneumatically actuated diaphragm pump locally to compete with imported pumps of similar capacity. The study also includes a review of the basic theories of compressed air and also covers conceptual and detailed design, manufacturing, cost analysis and finally testing. The analysis of the study shows that the pump has a theoretical volume flow rate of 34 litres/min, an inlet pressure of 6 bar, a suction head of 10.4m and a discharge head of 65m.The work also looked at the various problems encountered during manufacturing process and proposes solutions and recommendation to surmount these difficulties, to ensure that the pump can be locally produced to meet international standard.

Key Words:
Pumps
Pneumatics
Design
Manufacture
Standard

1.0 INTRODUCTION

A pump is a machine which when interposed in a conduit, transfers energy from some external source to the fluid thereby causing the fluid to flow through the conduit. The applications of pumps are many and varied. Pumps are applied in areas such as the refinery and chemical industries, slurries, sludge piping and in water supply. A careful review of the pumps used in these fields in Nigeria reveals they have all been imported. Pumps reviewed include the following:

- Centrifugal pumps
- Piston plunger pumps
- Vane pumps
- Screw pumps
- Diaphragm pumps

The inflationary trend and activities of middlemen in the goods supply system make pumps purchasing a very horrible experience and hence a very costly venture. There is also the need for a technological venture because when we finally have a technological breakthrough, essential goods such as the pump will be readily available to users conveniently and at reduced prices.

Against the above background, the need has arisen for us to develop a pneumatically actuated diaphragm pump from locally available materials. Such a pump would attain international standard. Specifically, the pump should be able to pump water at a theoretical volume flow rate of 34 litres/minutes given a maximum compressed air of six bar. It should also be used to pump chemical solutions such as a solution of chlorine in water so that it can have application in the water works where a solution of chlorine is added to water in the water treatment plant. We took the challenge to design and manufacture the pump.

1.1 OBJECTIVES

The objectives of the project are as follows

i To develop new ideas and designs of pneumatically actuated diaphragm pumps

ii To source for materials and manufacture the pump locally.

Iii To produce the pump to meet international standard at a reduced cost.

iv Consequent upon the third point is to be able to save foreign exchange for the nation.

2.0 METHODOLOGY

The method of carrying out the project includes the review of pumps and pneumatically actuated diaphragm pumps, review of the basic theory of compressed air, conceptual design and value analysis, selecting from among alternative concepts and detail design. It also includes manufacture and testing of the design, cost analysis and conclusion and recommendation of further steps/actions to be taken.

2.1 THEORIES OF COMPRESSED AIR

Air is matter in the gaseous phase. Air is a mixture of 78% Nitrogen, 21% oxygen by volume, water being the most important remaining ingredient as far as pneumatic is concerned[7].

The relationship between pressure and volume of compressed air follows Boyle's law stated as follows[8]:

$$PV = C \quad \ldots \quad (2.1)$$

Where

P = pressure, N/m^2

V = Volume, m^3

C = Constant, provided the temperature remains constant.

From equation (2.1),

$$P_1V_1 = P_2V_2 \quad \ldots \quad (2.2)$$

The relationship between force, pressure and surface area trapped by compressed air is given as follows[5]:

$$P = F/A \quad \ldots \quad (2.3)$$

Where P = pressure, N/m^2

F = Force, N

A = Surface Area, m^2

The power delivered by compressed air in motion is related to the force as follows[5]:

$$P = F \times V \quad \ldots \quad (2.4)$$

Where P = Power, (watts)

F = Force, N

V = Velocity, m/s

The relevant equations for the quantity of air passed by a valve for which the CV factor is known is given as follows[7]

$$Q = CV\sqrt{\Delta P(P + 14.7 - \Delta P)} \quad \ldots \quad (2.5)$$

Where

Q = Quantity (m^3) free air per min

P = Inlet pressure, N/m^2 (Gauge)

ΔP = Pressure drop across valve but must not be greater than 1/2P

Where $\Delta P > 1/2P$ then the flow is the same as when $\Delta P = 1/2P$

i.e Max Flow $= CV\sqrt{\frac{P}{2}(P+14.7)-\frac{P}{2}}$

or $CV\sqrt{\frac{P^2}{4}+14.7\frac{P}{2}}$ .... (2.6)

Air is compressible and follows a compressible flow pattern. The compression for the compressible air flow through a duct follows a polytropic curve.

Work required for this compression is given by the equation[9]

$$W = \frac{n}{n-1}P_0V_0\left[1-\left(\frac{P_1}{P_0}\right)^{\frac{n-1}{n}}\right] \quad \dots \quad (2.7)$$

Where

W = Compression work

n = Polytropic index of compression

P_0 = Pressure of ambient air (atmospheric)

P_1 = Pressure of air in reservoir

V_0 = Volume of air at atmospheric pressure

For isothermal compression,

$W = P_0V_0Ln(P_0/P_1)$... .... (2.8)

2.1 DESIGN CONCEPT : FOUR-WAY AIR VALVE DOUBLE DIAPHRAGM CHAMBERS WITH ONE LIQUID PUMPING CHAMBER

The arrangement is as shown in Fig.1

The pump operates as follows: compressed air flows through the four-way air valve into one chamber at a time. The mechanism of operation of the four-way air valve is shown in Fig 1 As air flows into the air side of the chamber on the right of the diagram, it pushes the diaphragm to the right. This causes the inlet check valve to open and water flows into the pumping chamber on the diaphragm. At the same time air is discharged from the air side of the left diaphragm chamber through the four-way air valve to the air exhaust.

During the discharge, the inlet check valve is closed while the discharge check valve is open. The process is

On completion of a stroke, the air distribution valve automatically transfers the compressed air to the back side of the left diaphragm and exhausts air from the right chamber. This causes the reciprocating shaft to move to the left thereby causing the water to be discharged.

repeated at the completion of the discharge stroke.

2.2 DETAILED DESIGN

2.2.1 POWER REQUIREMENT

Max. quantity of air passed by the valve[7]

$$Q = CV\sqrt{\frac{P^2}{4} + 14.7\frac{P}{2}} \quad \ldots \quad 3.1$$

Where

Q = Quantity ft^3 free air per minute

P = Inlet pressure (Psi gauge) = 88.2 psi (6bar)

CV = 0.02 (Assumed for the valve of orifice of 5.7mm)

$$Q = 0.02\sqrt{\frac{88.2^2}{4} + 14.7\frac{88.2}{2}}$$

$= 1.02\ ft^3/min$

$= 1.02 \times (0.305)^3\ m^3/min$

$= 0.0289\ m^3/min$

Work required is given by the equation[6]

$$W = \frac{n}{n-1} P_0 V_0 \left[1 - \left(\frac{P_1}{P_0} \right)^{\frac{n-1}{n}} \right] \quad \ldots \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3.2)$$

Where

W = Compression work

n = Polytropic index of compression =1.4

P_0 = Pressure of ambient air (atmospheric) $=10^5\ N/m^2$

P_1 = Pressure of air in reservoir $= 6 \times 10^5\ N/m^2$

V_0 = Volume of air at atmospheric pressure $= 0.0289\ m^3$

But power = W/S, i.e., work per unit time

$$= \frac{1.4}{0.4} x 10^5 x \frac{0.0289}{60} \left[1 - (6)^{\frac{0.4}{1.4}} \right]$$

= -113 watts (-ve sign implies that work is done on the system)

Assuming 20% losses,

Power = 113 + 20%

= 135 watts.

2.3.2 VOLUMETRIC DISCHARGE

The diaphragm chamber is an arrangement of two conical vessels as shown in Fig 2.

In Fig 3, by Pythagoras theorem,

$$Y = \sqrt{35^2 + 20^2}$$

= 40.3 mm (stretch of diaphragm)

Also by similar triangles,

$$\frac{x}{45} = \frac{x+20}{80}$$

80X = 45X +900

X = 900/35 = 25.7 mm

Volume of the bucket shape equals volume of bigger cone minus volume of smaller cone

$$= \frac{1}{3\pi}\left(0.08^2 x0.0457 - 0.045^2 x0.6257)\right)$$

$$= 0.000252 \text{ m}^3$$

Volume of Chambers $= 2 \times 0.000252$

$= 0.000504 \text{ m}^3$

$= 0.504$ litres

Velocity of compressed air flowing[3]

$$V = K\sqrt{\frac{2g}{\rho}(p_1 - p_2)} \dots \dots \quad \dots \quad \dots \quad \dots \quad (3.3)$$

Where

V	= Compressed air velocity	
K	= orifice coefficient	= 0.25 (assumed)
G	= gravitational constant	= 9.81 m/s^2
P_1	= pressure at inlet	= 6 x 10^5 N/m^2
P_2	= pressure at outlet	= 3 x 10^5 N/m^2
ρ	= Air density at inlet	= 1.22 kg/m^3

$$V = 0.25\sqrt{\frac{2x9.81}{2x1.22}\left(6x10^5\right)}$$

$$= 549\text{m/s}$$

Sonic velocity is given by the equation[1]

$$V_{sonic} = \sqrt{\frac{\gamma p}{\rho}}$$

$$= \sqrt{\frac{1.4x6x10^5}{1.22}} \qquad = 830\text{m/s}$$

$\therefore$ Flow velocity is subsonic.

Orifice diameter = 5.7 mm (Fig 4)

Orifice area $= \frac{\pi d^2}{4}$

$$= \pi * \frac{\left(5.7x10^{-3}\right)^2}{4}$$

$= 2.55 \times 10^{-5}\ m^2$

Volume of air discharged = AV

V $= 2.55 \times 10^{-5} \times 549$

$= 0.014\ m^3/s$

When the chamber is fully pressurised,

P $= 6 \times 10^5\ N/m^2$

Assuming constant temperature,

$P_1V_1 = P_2V_2$

$P_1V_1 = 2\ P_1V_2$

$V_2 = V_1/2$

$= 0.014/2$

$= 0.0057\ m^3/s$

$\therefore$ Angular speed = 0.0057/(2 x 0.000504)

= 5.67 rps

$\therefore$ Angular speed = 5.67 x 60

= 340.5 rpm

Accounting for frictional losses with 80%

Angular speed = 68 rpm

Hence volume displaced in one minute

= 0.504 x 68

= 34.3 litres/min

This is the discharge of the phmp.

2.3.3 PRESSURE HEADS

General equations for the absolute head[1]

$$H = Hat - Hs \pm \frac{L}{g} x \frac{Aw^2 r}{a} - \frac{4fL}{2dg} x \left(\frac{VA}{a}\right)^2 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (3.4)$$

Where

V	= Flow velocity of the liquid pumped (Water), m/s	
A	= Area of diaphragm, m^2	
a	= Area of pipe, m^2	
F	= Friction coefficient, dimensionless = 0.01	
L	= Length of pipe, m	
d	= pipe diameter, m	
g	= acceleration due to gravity	= 9.81 m/s^2
w	= rotational speed, rad/s	= 1.1 rad/s
r	= Half stroke length	= (20×10^{-3})m
Hs	= Static head	
Hat	= Atmospheric head	
H	= Absolute head	

__Suspicion__

Inlet is flooded

$\therefore$ Hs $= 0$, L $= 0$

At start of suction stroke,

V $= 0$

H_{at} = 10.4 m of water

$\therefore$ H $= 10.4 - 0 - 0 - 0$

$= 10.4$ m

At mid suction stroke,

$$H = Hat - Hs - \frac{L}{g} x \frac{\delta u}{\delta t} - \frac{4fL}{2dg} x \left(\frac{VA}{a}\right)^2$$

$= 10.4 - 0 - 0 - 0$

$= 10.4$ m

At end of suction stroke, H $= 10.4$ m

Discharge

Head at start of discharge stroke, assuming L = 7.6 m

$$H = 10.4 + 7.6 + \frac{7.6}{9.81} x \left(\frac{160}{20}\right)^2 (1.1x2\pi)^2 x \frac{20}{1000}$$

$= 65.36$ m

2.3.4 DESIGN OF CONICAL VESSELS

The thickness of the conical vessels[4] is given by

$$t = \frac{PD}{2\cos\alpha(SE - 0.6P)} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3.5)$$

where

t = shell thickness, m

P = Pressure, N/m^2 = 6 bar = 6×10^5 N/m^2

S = allowable stress, N/m^2

E = Joint efficiency, dimensionless, assume 0.5

D = diameter of wider area, m = 160 mm = 0.16 m

Material for vessel = mild steel

S_y = 1200×10^6 N/m^2

Safety factor , N_y = 2

$$S = \frac{S_y}{N_y}$$

$= (1200 \times 10^6\ N/m^2)/2$

$= 600 \times 10^6\ N/m^2$

$\alpha = 45^o$

Cos α = 0.7071

$$\therefore \quad t = \frac{6x10^5 x0.16}{2x0.7071(0.5x6.00x10^6 - 0.6x6x10^5)}$$

$= 0.00023$ m

$= 0.23$ mm (Minimum thickness of material)

Therefore material of 3 mm thickness is safe.

2.3.5 SHAFT DESIGN

The area of shaft was tentatively fixed at 15 mm

∴ Total effective area

= Total Area of diaphragm – area of shaft

$$= \frac{\pi D^2}{4} - \frac{\pi d^2}{4}$$

$$= \frac{\pi}{4}\left(D^2 - d^2\right)$$

$$= \frac{\pi}{4}(D + d)(D - d)$$

$$= \frac{\pi}{4}(0.16 + 0.015)(0.16 - 0.015)$$

$$= 0.0165 \text{ m}^2$$

Force on diaphragm

$F = PA$ … … … … … … … (3.6)

$= 6 \times 10^5 \times 0.0165$

$= 9900$ N

For worst loading condition, pressure on both side is the same

= 6 bar

$= 6 \times 10^5$ N/m^2 (Fig 3.7a)

This can be assumed to be concentrated at the centre of the shaft in tensile sense (Theory of St. Venant).

Now $F = S_d A$ … … … … … … … (3.7)

Where F = Force

S_d = Design stress

A = Area

But $S_d = S_y/N_y$

Where S_y = yield stress of the material

N_y = Safety factor= 2

Material for shaft is stainless steel

$S_y = 1200 \times 10^6\ N/m^2$

$S_d = \dfrac{1200x10^6}{2}$

$=600 \times 10^6\ N/m^2$

$A = F/S_d$

$= \dfrac{9900}{600x10^6} = \dfrac{\pi d^2}{4}$

$d = \sqrt{\dfrac{4x9900}{\pi x600x10^6}}$

$= 0.00458$ m

$= 4.58$ mm

A shaft diameter of 18 mm was used. This is safe enough.

2.3.6 BEARING SELECTION

Loading is completely axial and is double direction. Using the SKF chart

$F_{am} = A\left(\dfrac{n}{1000}\right)^2$

Where F_{am} = Minimum axial load

A = Minimum load factor

n = rotational speed = 68 rpm

with internal diameter d = 1.5 mm

A = 5.1

$F_{am} = 5.1\left(\dfrac{68}{1000}\right)^2$

$= 0.024$ N

Bearing 52204 is selected .

2.3.7 PARAMETERS

Power required	= 135 watts
Volumetric discharge	= 34.0 litres
Suction head	= 10.4 m
Discharge head	= 65.36 m/s

Velocity of flow at discharge = 0.133 m/s

Reciprocating speed = 68 rpm

2.4 BILL OF ENGINEERING MEASUREMENT AND EVALUATION (BEME)

Table 1 Bill of Engineering Measurement and Evaluation

S/N	COMPONENT	MATERIAL	DIMENSION (mm)	QTY
1	Check valves	Brass	$\phi 20$	2
2	Conical vessels	Mild steel	$\phi 160 \times \phi 100 \times 25$	4
3	Metal disc	Mild steel	$\phi 90 \times 3$	4
4	Shaft	Stainless steel	$\phi 18 \times 230$	1
5	Thrust bearing	Brass	$\phi 18 \times 15$	2
6	Rectangular plate	Mild steel	120 x 140	4
7	Middle section	Mild steel	$\phi 100 \times 140$	1
8	Diaphragm	Synthetic rubber	$\phi 180 \times 1.5$	2
9	Bearing seating	Mild steel	$\phi \times 25$	2
10	Bolts and nuts	Mild steel	$\phi 6$	64
11	Bolts and nuts	Mild steel steel	$\phi 10$	2
12	Air valve	Stainless steel	$\phi 26 \times \phi 11$	1

Table 2 Cost of Materials

S/N	COMPONENT	MATERIAL	DIMENSION (mm)	QTY	UNIT COST (₦)	AMT (₦)
1	Check valves	Brass	ϕ20	2	300.00	600.00
2	Conical vessels	Mild steel	ϕ160 x ϕ100 x 25	4	90.00	360.00
3	Metal disc	Mild steel	ϕ90 x 3	4	25.00	100.00
4	Shaft	Stainless steel	ϕ18 x 230	1	350.00	350.00
5	Thrust bearing	Brass	ϕ18 x 15	2	250.00	500.00
6	Rectangular plate	Mild steel	120 x 140	4	25.00	100.00
7	Middle section	Mild steel	ϕ100 x 140	1	300.00	300.00
8	Diaphragm	Synthetic rubber	ϕ180 x 1.5	2	50.00	50.00
9	Bearing seating	Mild steel	ϕ18 x 25	2	80.00	160.00
10	Bolts and nuts	Mild steel	ϕ6	64	25.00	1600.00
11	Bolts and nuts	Mild steel	ϕ10	2	50.00	100.00
12	Air valve	Stainless steel	ϕ26 x ϕ11	1	2,500.00	2,500.00
TOTAL COST OF MATERIALS						6,720.00

2.4.1 COST OF LABOUR

In evaluating the cost of labour, machine hour rate was used. The labour cost was calculated on the basis of employing the service of one machinist and one welder, each rated per hour. The table below shows the summarised production activities, time and cost.

Table 3 Cost of Labour

S/N	COMPONENT	OPERATION	TIME (HR)	COST/HR (₦)	AMOUNT (₦)
1	Conical vessels	Cutting/welding	4	200.00	800.00
2	Diaphragm disc	Cutting/machining	2	200.00	400.00
3	Shaft	Cutting/Drilling	1	200.00	200.00
4	Rectangular Plates	Cutting/Drilling	2	200.00	400.00
5	Middle Section	Cutting/Welding	1	200.00	200.00
6	Bearing Seating	Cutting/Machining	2	200.00	400.00
Total Labour Cost					**2,400.00**

2.4.2 MISCELLANEOUS

This includes all the expenses incurred during the manufacturing process that are not reflected in the cost analysis tables above. Such include: transportation cost among others. This cost was taken as 50% of labour cost.

Hence, miscellaneous cost = 50% x ₦ 2400.00

= ₦1000.00

2.4.3 ESTIMATED COST OF MANUFACTURE

Table 4.4 Estimated Total Cost of Manufacture

S/N	ITEM	COST (₦)
1	Material Cost	6,720.00
2	Labour Cost	2,400.00
3	Miscellaneous Cost	1,200.00
TOTAL COST		**10,320.00**

3 TESTING

Pumps are tested to determine their performance characteristics which are very important in determining their suitability to carry out certain duties. The parameters measured in our test were the suction and discharge heads and the volumetric flow rate.

To achieve this, we first of all coupled the various parts of the pump and ensured that we sealed the parts where leakage may arise from as best as we could. Thereafter, we introduced compressed air through the inlet duct from a compressor via the air valve into the pump. The inlet pressure of air applied was 6 bars, which when incident on the diaphragm surface causes the shaft to reciprocate thereby creating suction and discharge to take place alternately.

In our test we used water. The flow rate was measured with the aid of a venturimeter while the suction and discharge pressures were measured with a mercury manometer

3.1 TEST RESULTS

The results got from our test shows that our pump performed below expectation due to the problems encountered during the manufacturing process. And as such we had a suction head of 10m, a discharge head of 12m and a flow rate of 8 litres/min

3.2 DISCUSSION

3.2.1 PROBLEMS

The task of manufacturing the pump was not easy right from material selection to assembly. We had to embark on intensive research work, specifically in the area of compressed air and air valve. Our original idea was to manufacture the pump and buy the valve which is a separate unit. But market survey revealed to us that the valve was not available in the market. Many industrial parts markets such Alaba International, Idumota and Ilasamaja in Lagos and McDermott in Warri were visited and it dawned on us that we had to manufature it.

Due to the unavailability of the right equipment to get the precision needed for the valve, there were distortions on the surface of the valve. This caused misalignment which eventually led to leakage and losses, thereby reducing the efficiency of the pump.

Also, in the area of manufacturing the valve casing, we had difficulties. This arose when the casting was welded to the pump. The heat applied led to uneven contraction of the valve case leading to misalignment and leakage.

Another problem was in selecting the diaphragm material. The synthetic nylon-reinforced rubber initially chosen proved to be too hard and unsuitable for the job.

There was also the problem of constructing the bearing seating. We could not get the precision needed and as such there were alignment problems when the shaft started reciprocating.

4.0 CONCLUSION AND RECOMMENDATIONS

4.1 CONCLUSION

The research work on the possibility of manufacturing a pneumatically actuated diaphragm pump was carried out in this project. The cost analysis shows that the pump can be manufactured locally at a cost that compares favourably with imported pumps of similar characteristics.

The test shows good results but the difficulties encountered made the machine to work below expectation. The recommendations set out can go a long way in correcting the errors and this can lead to the achievement of the desired objectives.

4.2 RECOMMENDATIONS

1. The air valve housing should be cast to seal off leakage and the air valve should be screwed to the pump as a separate component.
2. The conical vessels should also be cast while the check valves should be compatible with the fluid being pumped.
3. A thin and tough material that can withstand the applied pressure should be selected for the diaphragm.
4. Both chambers should pump with a common suction and discharge to maintain a continuous flow and reduce pulsation.

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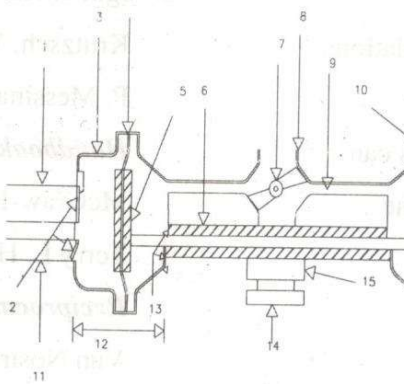

FIG 1 : CONCEPTUAL DESIGN OF PNEUMATIC DIAPHRAGM PUMP.

Project	Drawing Information		
DESIGN AND MANUFACTURE OF A PNEUMATICALLY ACTUATED DIAPHRAGM PUMP	Designed By	Osame P.U.	
	Drawn By	Osame P.U.	
	Checked By	Engr (Prof.) J.O. Asalor	
	Scale	Drawing No	Date
	1:2	1	January 2000

S/no	Component Parts of Pump	Material
1	Suction pipe	PVC
2	Suction and Delivery Check Valves	Brass
3	Diaphragm Casing	Synthetic Rubber
4	Diaphragm (Flexible Membrane)	Synthetic Rubber
5	Metal Disc	Mild Steel
6	Reciprocating Shaft	Stainless Steel
7	Four Ways Air Valve	Stainless Steel
8	Air Inlet Line	Mild Steel
9	Air Actuation Line	Mild Steel
10	Flanged End	Mild Steel
11	Delivery Pipe	PVC
12	Pumpng Chamber	Mild Steel
13	Thrust Bearing	Brass
14	Exhaust	Mild Steel
15	Exhaust Pot	Mild Steel