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Design and Fabrication of a Prototype Car Tyre Inflator

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Abstract **– This paper detail the design and fabrication of a portable car tyre inflator to deliver compressed air at high pressure (200kpa). The aim is to build a working proto-type of a portable car tyre inflator and test it for efficiency and effectiveness. The device has a mass flow rate of $\dot{m}$=7.09x 10^{-6} kg/s and a volumetric flow rate of VD =3.55x10^{-2} m^3/s. it was designed to pump a deflected non punctured car tyre in the shortest possible time of about 3-5minutes. The tyre inflator device comprises a single cylinder reciprocating compressor, gear drive, a dc electric motor, a dc battery of 12V 75A, transformer, etc. The device is to be connected to the car battery via the cigarette lighter socket provided in the car. The design consideration, analysis and calculation are based on thermodynamic principles of positive displacement reciprocity machine, strength and rigidity of the mechanical element. The materials selected for the design are so chosen in view of economy, light weight and compatibility for easy handling. The device was tested after fabrication and it was found to be very efficient in its performance. 10 car tyres were inflated with the device and it was found that the time it took to inflate the tyres was with the time range of 3-5 minutes, showing that it objective was achieved. The functioning of the compressor was appreciable in all the tests conducted delivering a volumetric efficiency of 0.85 about 85% which shows more air is been used in the piston compression stroke.**

Keywords **– Tyre, Inflator, Mass Flow Rate and Volumetric Flow Rate.**

I. Introduction

Car tyres are the only part of the car that have contact with the road. Tyres are fitted on the rims and inflated [1]. Safety in acceleration, steering, cornering and braking depends on tyre's contact with the road. There are different types of tyres, ranging from radial ply to self-supporting run flat. These tyres must be kept at correct pressure for optimum performance. Driving over pot-holes, kerbs, pointed objects even at low speed can cause puncture which results in flat tyres.

However, when tyre pressure decrease it makes the car to be unbalanced, it also affects the speed of the car and can cause damage to the tyre. Therefore, the need to inflate the tyre when the pressure reduce cannot be over emphasized. Hence this work tends to proffer solution to drivers whose tyre pressure has reduced, especially when the place to volcanize the tyre is not close at hand.

II. Literature Review

Having flat tyre cause great inconveniences especially at night or when it is raining. Replacing a spare tyre with a spare one is often a herculean task, it gets even worse if one does not know how to install the spare or in a situation where one cannot vulcanize the tyre at the moment. To curb this challenge, designed automatic tyre pressure inflation system for small cars [2]. This is device delivers pressurize fluid (air) to a deflated non-punctured light vehicle tires, but takes a lot time to inflate one tyre.

Designed an emergency tire inflation tube (a pneumatic device) used to transfer air from an inflated tire to a deflated tire using a flexible tube [3]. The transfer tube is flexible and allows the flow of air in one direction because it has a one way check valve intersected in the tube. This prevents loss of air from the tyres being inflated using no gauges or mechanical devices. The device is comprised of materials that can be easily folded and stored inside the vehicle providing years of service, but his design method of inflating a tire with air from tyres of the same vehicle is only a temporary measure as it reduces the air pressure in the other tyres and fails to consider a case of deflation in all the four tires.

Invented the ancient Husky 120volts tire inflators with pancake air compressor with 50feet of orange hose [4]. Pancake compressor weight about 70lbs, psi of about 130. It could even be used to pump up a tire of about 18 wheelers. The husky 120volts is ideal for homes, shops and garage. Mainly used to inflate sports equipment. Movable with a convenient carrying handle. One major disadvantage of this design is that it requires an extension cord between the power source and inflator device and it cannot be plug directly into the car cigarette lighter socket.

Invented a 12V tyre inflator with sealant [5]. This seals and inflates pneumatic tyres that is punctured while the car is on transit. The inflating product is a condensed gas with sealant placed in a container with a valve depressor. When a car gets flat tyre, the container burst and releases the content through the valve to the interior part of the tyre. This condensed gas expands with sufficient volume and inflate the tire to a drivable condition. At the same time, the glue like sealant material is distributed onto the interior surface of the tire and finds the puncture in the tire because the pressurized gas is leaking through the puncture. This in turn allows the sealant material to react with air and seal the puncture. However, the major setback in this design is that volume of gas supplied to the interior of the tyre not be sufficient to raise the tire to the normal tyre pressure, but only to a manageable drivable condition at a very low speed. This is because not all the liquid sealant is converted to gas upon discharged into the tyre.

This study therefore is meant to design and fabricate a working proto-type portable car tyre inflator, powered from the 12volt cigarette lighter port in the car. The compressor design was governed by a simple thermodynamic principle of compression, discharge, expansion and suction of fluid (air) while the fabrication and assembled was from the locally available materials considering the cost factor.

III. Material Selection

The specific materials that was chosen for the fabrication of the frame and handle is highlighted in table 1.

Table 1. Materials and reason (s) for selection.

S/N	Component	Material Selected	Reason (s) for Selection
1	Machine Bed	Mild Steel	Rigidity, Availability, Cost and Machinability
2	Frame (Covering)	Mild Sheet Steel	Availability, Machinability and Cost
4	Machine Handle	Mild Steel (Angular Bar)	Cost, Availability, Machinability.

Design Consideration

During the design of the tyre inflator, the following factors were considered;

- Reliability.

- Strength and rigidity.
- Discharge volume for a given period of time.
- Discharge air pressure.
- Economic factors (availability of the construction materials, cost of materials).
- Social factors (aesthetics of the machine, machine dimension and size).

Design Specification

In the light of the above factors, the following specification where made in the design of the prototype tire inflator as shown in table 2 below.

Table 2. Design specification.

S/N	Machine parts	Dimension
1	Length of the machine bed	300mm
2	Width of the machine	220mm
3	Height of the machine	245 mm
4	Length of the delivery hose	1yard
5	Thickness of the covering sheet metal	1.5 mm
6	Diameter of output shaft from motor	5 mm
7	Bore	20 mm
8	Stroke	35 mm
9	dc motor	12volt, 10amp

Design Operation Sequence

The sequence of design operation are as follows;

I. Obtain information on the maximum volume of air to completely fill a car tire of specification rim 13, 14, 15 and delivery volume (dv) which is about $32m^3$.

II. Calculation of the delivery volume (dv).

III. Computing the parts sizes.

IV. Selecting a 12v dc motor to provide the mechanical torque to run the compressor.

V. Producing the working diagrams.

VI. Selecting the materials for the parts.

VII. Design specification.

The Design theory and Formulae

The thermodynamic process used in the compressor and expansion of air in the cylinder is the polytrophic process. A polytrophic process is a process where no specific restrictions except reversibility is imposed. The pressure volume relationship of such process can generally be given as PV^r = Constant.

Where r = polytrophic index = 1.3, the temperature, pressure relationship for such a process may be summarized as

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)\frac{r-1}{r} \quad (1)$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)\frac{r-1}{r} \quad (2)$$

Recall from the ideal gas Law.

$$P_2V = RT_2 \Rightarrow \frac{P}{\rho} = \text{RT} \quad (3)$$

Since $V = \frac{1}{\rho}$

Where V = Specific volume R = Gas constant, T_2 = Exit temperature P_2 = Outlet pressure ρ = Density , ($\rho_{air} = \frac{P_2}{RT_2}$), Angular speed in (rad/s)

$$\omega = \frac{2\pi N}{60} \quad (4)$$

where (n $= \frac{N}{60}$) (Cycle/second) (4b)

$$V_s = \frac{\pi}{4}B^2 \text{ x } L \text{ x n} \quad (5)$$

Where V_S = Swept volume, n = Number of cylinders, L = Length of Stroke, B = Bore or Diameter

$$V_C = 0.08V_S \quad (6)$$

Where *Vc* = Clearance volume

$$V_{1=V_S}(1 + C) \quad (7)$$

Where *C* = Clearance factor (= 0.08), Recall volumetric efficiency

$$\eta_{V=}1 + C - C\left(\frac{P_1}{P_2}\right)\frac{1}{r-1} \quad (8)$$

$$V_1 - V_4 = \eta_{V\,x}\, V_s \quad (9)$$

$$V_2 - V_3 = (V_1 - V_4)\left(\frac{P_1}{P_2}\right) \quad (10)$$

$$V_0 = (V_2 - V_3)\left(\frac{P_2}{P_0} - \frac{T_0}{T_2}\right) \quad (11)$$

Where P_0 = 101.325kpa T_0 = 298.15kpa (T_0 and P_0 are in ambient conditions)

$$V_D = V_0 \text{ x n} \quad (12)$$

$$PV = \text{mRT} \quad (13)$$

$m = P_2(V_2 - V_3)/RT_2$

Design Calculation of the Delivery Volume and the Mass Flow Rate

In the determination of the delivery volume VD, the following considerations were adhered to:

I. That the device is design to deliver air at the pressure P_2 = 200KPa (2 bar) at a delivery volume of VD (to be determine

II. That the bore (B) of the cylinder is 20mm

III. That the stroke is 35mm

IV. That intake pressure P_3 = atmospheric (100KPa)

V. That the intake temperature T_1 = standard (298.15k)

VI. The speed of the motor provided is 1400rpm

VII. The clearance volume is 0.08 of the swept volume

VIII. The compression process is polytrophic

IX. $V^r = C$ with polytrophic index r = 1.

Table 3 below shows the analysis and computations using different formulae to determine the various performance characteristics of the reciprocating compressor.

Table 3. Computation using the relationship and formulae.

S/N	Qty	Unit	Source/ formulae/ Computation	Computed values
1.	T_2	K	Eqn.1 $298.1(400/100)^{0.231}$	9349.9
2.	ρ_{air}	Kg/m^3	Eqn. 3 $\frac{200}{287x410.7}$	$3.39\, X10^{-3}$
3.	ω	Rad/s	Eqn. 4 $\frac{2\pi X\, 1400}{60}$	
4.	N	Cycles/Sec	Eqn. 4b $\frac{1400}{60}$	23.33
5.	V_S	m^3/cycle	Eqn.5 $\frac{\pi}{4} X\, 0.02^2\, X\, 0.035\, X\, 1$	$1.099X10^{-5}$
6.	V_C	m^3	Eqn.6 $1.099\, X\, 10^{-5}(1+0.08)$	$1.1869\, X10^{-5}$
7.	V_1	m^3	Eqn.7 $1.099\, X\, 10^{-5}(1+0.08)$	$1.1869\, X10^{-5}$
8.	η_v	-	Eqn.8 $1+0.08-0.08(200/100)^{0.769}$	0.85
9.	V_1-V_4	m^3	Eqn.9 $0.85X1.099X10^{-5}$	9.3415×10^{-6}
10.	V_2-V_3	m^3	Eqn.10 $9.3415X10^{-6}(100/400)^{0.769}$	3.217×10^{-6}
11.	V_D	m^3/cycle	Eqn.11 $3.217\, X10^{-6}\, X\, \frac{400}{101.325} X \frac{298.15}{410.7}$	9.22×10^{-6}
12.	V_D	m^3/sec	Eqn.12 $9.22\, X\, 10^{-6} X\, 23.3$	3.55×10^{-2}
13.	M	Kg/sec	Eqn.13 $\frac{200\, X\, 3.217\, X\, 10^{-6}}{287\, X\, 410.7}$	7.09×10^{-6}

Since the rate of air delivery

$V_D = 3.55\ X10^{-2}\text{m}^3/\text{sec}$, it could be analyzed that for 10min;

$V_D = 21.3\text{m}^3$, i.e. since 10 min = 600 sec

$V_D = \left(\frac{3.55\ X\ 10^{-2}}{\text{sec}}\right)\text{m}^3 X\ 600\ \text{sec}$

$V_D = 21.3\text{m}^3$

This will correspond to delivery mass flow rate, 7.09 x 10^{-6}kg/sec. This mass of air is sufficient to fill a deflated tyre. Figure 1 below shows a pressure volume diagram for a single cylinder reciprocating compressor cycle.

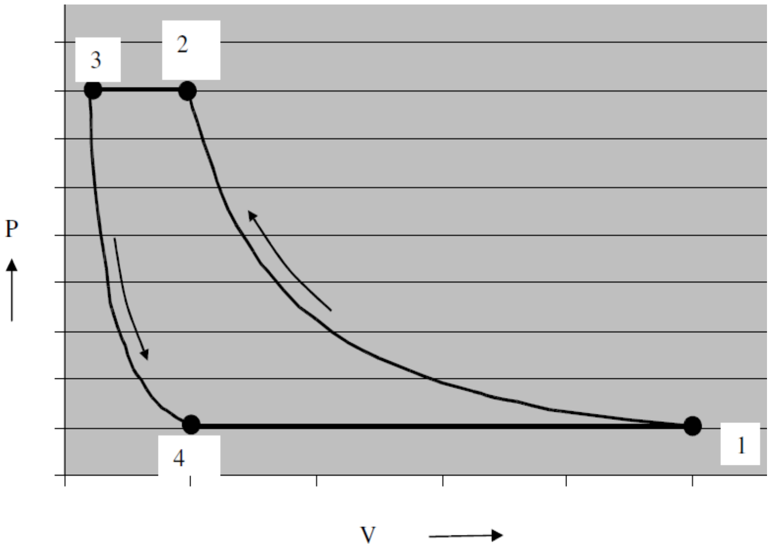

Fig. 1. PV graph of a single cylinder reciprocating Engine.

Figure 1 is a PV graph showing the different process in the compressor. Induction process 4 to 1, as the inlet valve open, fresh atmospheric air is induced into the cylinder at constant pressure and temperature. Compression process 1 to 2, both valves is closed. The induced air is compressed according to the polytrophic law ($PV^r = C$) until pressure and temperature is increased. Delivery process 2 to 3, the exhaust valve open, the compressed air is delivered out of the cylinder at constant pressure and temperature. Expansion process 3 to 4, the piston begins the induction stroke. The compressed air occupying the clearance volume expand according to the polytrophic law until temperature and pressure fall to T1 and P1 respectively [8].

Design Calculation of the Radial Stress δr, and the Tangential Stress δt in the Cylinder

For a reciprocating compressor having a single hydraulic cylinders, gun barrels and pipes, carrying fluids at high pressures, develops both radial and tangential stresses with values that are dependent on the radius of the elements under consideration. To determine the radial and tangential stresses it is assumed that the longitudinal elongation is constant around the circumference of the cylinder.

The tangential and radical stresses have magnitude,

$$\partial_t = \frac{P_1 r_1 - P_0 r_0 - r_1 r_0 (P_0 - P_1)/r_o}{r_0 - r_1} \quad (14)$$

$$\partial_r = \frac{P_1 r_1 - P_0 r_0 - r_1 r_0 (P_0 - P_1)/r_o}{r_0 - r_1} \quad (15)$$

Note, positive values indicate the sum, and negative values compression, Where

r_1 = Inside radius of the cylinder.

r_o = Outside radius of the cylinder.

p_1 = Internal pressure.

p_o = External pressure.

For a special case where $p_o = 0$ (that is there is no external pressure) gives

$$\partial_{t=} \frac{r_1 P_1 (1+r_0/r_1)}{r_0 - r_1} \quad (16)$$

or

$$= \frac{r_1 P_1 (1+r_0/r_1)}{r_0 - r_1} \quad (17)$$

Longitudinal stress is determined when the end reaction to the internal pressure is by the pressure vessel itself, and it is found to be

$$\partial_t = \frac{r_1 P_1}{r_0 - r_1} \quad (18)$$

The known parameters are

$P_1 = 200\text{kpa} = 2\text{bar}$

$P_0 = 101.325kpa \cong 2\text{bar}$

$r_1 = 10mm = 0.01m$

$r_0 = 13mm = 0.013m$

Table 4 below shows the computation analysis of the radial and the tangential stresses.

Table 4. Computation analysis of the above listed formulae.

S/N	Qty	Unit	Source/ formula/ computation	Computed value
1	δ_t	N/m^2	Eqn14: $\frac{40-17.12+29.88}{7.424\ X\ 10^5}$	$7.10X\ 10^6$
2	δ_r	$N/m^{2\backslash}$	Eqn15: $\frac{40-17.12+29.88}{7.424\ X\ 15^5}$	$7.10X\ 10^6$
3	δ_c	N/m^2	Eqn18: $\frac{200\ x\ 10^3 x 0.01^2}{(0.013^2-0.01^2)}$	$5.797X\ 10^6$

Design of the Shaft

A machine shaft is a rotating device that transmit power. Gear or flywheel are mount on the shaft to transmit the power. In this design the shaft extends from the 12V d.c motor [9].

Power input = 120 watt, Outlet shaft diameter from the motor = 5mm. Permissible Speed = 1400rpm

According to ASME code for commercial steel shafting, the allowable shear stress $\tau \leq 40MNIm^2$

Stress Analysis

The stresses acting on the shaft are;

- Torsional shear stress due to rotational torque velocity.
- Tensile stress; the tensile stress is very small and can be neglected.
- There is also negligible bending stress.

The equation for a solid shaft with little or no axial loading is given as

$$\frac{\pi}{16}\tau d^3 = \sqrt{(K_m x M_b) + (KtxT)}^2 \quad (19)$$

$$d^3 = \frac{16}{\pi\tau}\sqrt{(KmxM_b) + (KtxT)}^2 \quad (20)$$

Where

τ = Twisting shear stress (N /m^2), T = Twisting moment (N/m).

M_b = Bending moment (N/m), K_t = Fatigue factor for twisting.

K_m = Fatigue factor for bending, d = Diameter the shaft.

K_t = 1 for load suddenly applied minor shock.

For the situation under control M_b = 0. Since the shaft has a very small allowable stress τ < 40 MN/m^2 Equation 2 reduce to

$$d^3 = \frac{16TK_t}{\pi\tau} \quad (21)$$

The Torsional mechanical power can be obtained from the equation

$$P = T.\omega \quad (22)$$

$$\omega = \frac{2\pi N}{60} \quad (23)$$

Therefore

$$P = \frac{2\pi NT}{60} \quad (24)$$

And N = Permissible speed = 1400 rpm

$$T = \frac{px60}{2\pi N} \quad (25)$$

The Tangential force, $F_t = \frac{T}{r}$ eqn. (10)

Where r = shaft radius from equation (5) $\tau = \frac{16TK_t}{\pi d^3}$

Table 5. Computation analysis of the above listed formulae.

S/N	Quantity	Unit	Source/ Formula/ Computation	Computed values
1	T	N –m	Eqn. 3.2 $\frac{120\times 60}{2\pi\times 1400}$	0.819
2	F_t	N	Eqn. 10 $\frac{0.819}{2.5\times 10^{-3}}$	327.40
3	τ	MN/m^2	Eqn. 5 $\frac{16\times 0.819\times 1}{\pi\times(5\times 10^{-3})^3}$	33.4
4	P	Watts	$input\ power = v.i = 12\ x\ 10$	120

Since the calculated value of the allowable stress $33.4MN/m^2$ is less than $40MN/m^2$. It implies that the shaft is safe. Therefore, an electric motor with a shaft diameter of 5mm is required for the project.

Design Calculations for the Delivery Pressure

Table 6 below summarizes the analysis and the computation of the given pressure of air delivered to the tyre for a given time interval.

Where,

Area of bore $= \frac{\pi d^2}{4}$ (26)

Pressure (p) $= \frac{F}{A}$ (27)

Table 6. Computation analysis of the above listed formulae.

S/N	Quantity	Unit	Source/ Formula/ Computation	Computed values
1	T	N –m	Eqn. 3.2 $\frac{120\times 60}{2\pi\times 1400}$	0.819
2	F_t	N	Eqn. 10 $\frac{0.819}{2.5\times 10^{-3}}$	327.40
3	A	m^2	Eqn. 26 $\frac{(\pi\times 5\times 10^{-3})^2}{4}$	7.83×10^{-3}
4	p	kPa	Eqn. 27 $\frac{327.4}{7.83\times 10^{-3}}$	41.8

The Electric Dc Motor

This is the prime mover of the device since the device was primary designed to be powered by the car battery, a 12V dc motor with speed of 1400 rpm was chosen. The factors considered before selecting the dc motor of this capacity.

I. The load on the motor

II. Compactible with the 12v cigarette port in car

III. The power of the car battery

IV. The mass of air to be delivered in a specified time.

The electrical energy from the battery is converted to mechanical energy by the electric motor. This involves two process:

1. *Input Electrical Power (P_{in}); given as*

$P_{in} = V.I$ (28)

2. *Mechanical Load Power (Mechanical Rotational Power) i.e. the Motor Exerts*

$P = T\omega = \frac{2\pi nT}{60}$ (29)

Note: $P_{mec} < P_{in}$ due to the second law of the thermodynamics.

Fabrication Process

Although, some components were gotten off the shelf with respect to design specification such as electric dc motor, piston - cylinder arrangement, gear, delivery hose, cigarette lighter, plug etc. however, other components were manufactured and processed to specification with figure 1 below showing the construction of the machine bed with a manually operated touch light to aid night vision.

Fig. 2. Machine bed construction of a prototype inflator.

The table 7 below shows the detailed and variation in manufacturing processes used in the fabrication of the device.

Table 7. Fabrication processes.

S/N	Components	Operators	Equipment used
1	Machine bed	Marking, cutting and welding	Cutting machine and welding machine
2	Machine covering	Marking out, cutting, welding and drilling	Cutting machine, welding machine and drilling machine
3	Machine handle	Cutting and welding	Cutting machine and welding machine

IV. Result and Discussion

The device was assembled and power was supplied via the 12 volt cigarette port in a car to pump a deflated non punctured for a period of 3 to 5 minutes in other to certify that the various components that makes up the device were functioning properly. It was observed that the machine delivered pressurized air of 209kpa (30.1psi), with a mass flow rate of m = 7.09×10^{-6} kg/s and a volumetric flow rate of $V_D = 3.55 \times 10^{-2}$ m^3/s during the said time interval. The volumetric efficiency was also evaluated to give 0.85 about 85% which shows more air is been used in the piston compression stroke. The compressor volumetric efficiency depends directly on the cylinder piston displacement. Figure 2 shows a pictorial view of open prototype tyre inflator showing the various parts and the arrangements of components. Figure 3 shows an assembly drawing of the prototype inflator. Figure 4 shows the fabricated prototype tyre inflator with an external hose (1 yard), 3mm in diameter connected to the device to deliver pressurized air to the car tyre, inflatables.

Fig. 3. A pictorial view of the open prototype tire inflator.

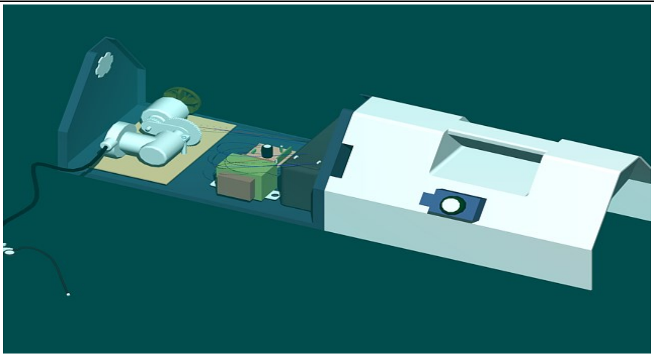

Fig. 4. An assembly drawing of the prototype tire inflator.

Fig. 5. A pictorial view of a closed fabricated prototype tire inflator with pressure gauge.

Caution for the Device

I. This device should not be connected to a power source above 12V 10amps.

II. The device is designed for emergency use, hence should not be used over an extended period of time as it will over heat the unit and damage the compressor.

III. This device should not be used to left heavy duty vehicle eg trucks.

V. Summary and Conclusion

The device was tested after fabrication and it was found to be very efficient in its performance. 10 car tyres were inflated with the device and it was found that the time it took to inflate the tyres was with the time range of 3-5 minutes, showing that it objective was achieved.

The functioning of the compressor was appreciable in all the tests conducted delivering a volumetric efficiency of 0.85 about 85% which shows more air is been used in the piston compression stroke. The machine delivered pressurized air of 209kpa (30.1psi), with a mass flow rate of m = 7.09×10^{-6} kg/s and a volumetric flow rate of $V_D = 3.55 \times 10^{-2}$ m^3/s during 3-5 minutes' time interval.

Area of further improvement and modification can be done on this design, by automating the device so that the mass of air to be delivered is pre-set and the device shuts off when it has delivered exactly the pre-set mass of air. Also the number of cylinders can be increased while retaining the compatibility for higher efficiency.

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