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Conversion of a Refrigerator Compressor into a Portable Silent Air Compressor for Use Onboard Vessels

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Abstract The noise emitted by portable electric air compressors can often be annoying or potentially hazardous to the operator or others nearby. In present scenarios the demand for a portable silent air compressor which can retain its efficiency is increasing on daily bases as efficient and portable silent air compressors can earn so much significance. Therefore reducing the noise level of these air compressors is desired. In order to provide solutions to these challenges, this study was developed which is aimed at creating a quiet air compressor with a target below 55decibels for the efficient and conducive performance of machineries and humans as well. The methodology was based on the replacement of the electric motor of conventional air compressor with a refrigerator compressor which is hermetically sealed and thus quieter. The results using a Sound Level Meter and dB sound Meter software at various frequency bands ranging from 25Hz to 8000Hz and at 100seconds test time showed that the design is the quietest amongst other air compressors tested at same rated conditions. The Portable (Chuko) Silent air compressor maintains a volumetric efficiency of 72.24% and an average sound level of about 38.4dB which is rated as a whisper sound and thus reducing the sound level by 51% when compared with other conventional air compressors. This result also affirms the fact that air compressors should be seen and not heard.

Keywords: *conversion, refrigerator compressor, electric air compressor, portable silent air compressor, noise level, volumetric efficiency*

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1. Introduction

An air compressor is a device that converts power using an electric motor, diesel or gasoline engine into potential energy stored in pressurized air [1]. Air compressors are used in variety of vessels to provide compressed and pressurized air for many applications such as starting of the main engine, auxiliary engine, emergency generator and emergency fire pump [2]. Air compressors found on board vessels are main air compressor, emergency air compressor and topping up air compressor [3].

By one of several methods, air compressor forces more and more air into a storage tank thereby increasing the pressure. When tank pressure reaches its upper limit, the air compressor shuts off. The compressed air is then held in the air tank until called into use [1]. When the air is released in a quick burst, it releases an amount of kinetic energy that can be harnessed for a number of purposes, including activation of pneumatic devices, air transfer and cleaning operations [4]. As air is released, the tank depressurizes. When tank pressure reaches its lower limit, the air compressor turns on again and re-pressurizes the tank. According to design and principle of operation, air compressors being used for variety of applications are very loud and requires hearing aid for operations [5].

Figure 1. Conventional Compressor [5]

In present scenario the demand for a portable silent air compressor which can retain its efficiency is increasing day by day. Efficient and portable silent air compressor can earn so much significance because, whether an air compressor is on board, work environment or in the home, when it makes excessive noise it can become annoying [6]. The sleep interruption can be caused by transient noises, for example, the ones caused by the starting of a refrigerator compressor [7].

The idea of a quiet or silent air compressor seems like a fantasy to a lot of people, and back in the days it used to be just a fantasy. Now air compressors can be built from the ground up to not only be quiet, but to do so without losing their efficiency. This is a big improvement over the older models that were so loud they could wake the crew [8].

The most significant criteria for air compressors are performance and reliability [9,10]. However, noise also plays a significant role. One of the major complaints about air compressor is that, they are noisy. During operation, the noise emitted by these compressors can become an annoyance and possibly a danger for the operator and others nearby often to the point where hearing protection is needed [11].

Due to the risk and annoyance towards the operator, it would be of benefit to use a quieter air compressor which would allow the operator to work easily without distracting others nearby. Additionally, air compressors are generally perceived as loud devices. So, an air compressor that is marketed to be quieter than other competitor units would be more enticing to customers when deciding which compressor to purchase [6].

Based on these two reasons, the goal of this paper is to create a quiet air compressor with a target and sound level less than 55dBA which could operate light pneumatic devices without losing its efficiency. The new design will be tested against unmodified (virgin) compressors for comparison. The paper will be primarily focused on portable electric air compressor with a single stage reciprocating piston refrigerator compressor.

Refrigerator Compressor

The compressor shell is constructed from a steel sheet with the top cover being welded together with the bottom housing. That connection is hermetically sealed, ensuring that refrigerant and air cannot leak to the outside [12]. In order to guarantee that the mechanical unit (motor, cylinder and valve) of the hermetic compressor remains within the center of its housing, four springs are used to keep it in its dedicated position. The external interfaces of the shell include two base plates, enabling the mounting of the compressor within the appliance. It is a priority to ensure that noise levels are kept to a minimum, and for this reason, the motor is mounted on springs which results in reduced levels of vibration.

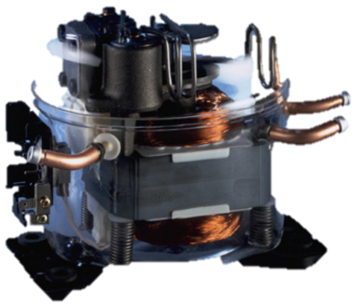


Figure 2. Refrigerator Compressor [12]

2. Materials and Methods

The design of the quiet air compressor, Chuko was performed in four stages which are namely: design considerations, design requirements or specifications, generation of data or equations prototype and fabrication process. In the development, some design considerations were made to guide the design methods and they include considerations on portability, considerations on compressed air production cost, and availability of materials and resources. The development and selection of means to quiet noise sources using refrigerator compressor was inculcated. It might not last 100,000 miles but it is quiet and will deliver more than enough pressure and volume for airbrushing, and operating pneumatic devices or cleaning small parts.

Compressed air can be very dangerous and may cause injury or death. For safety purposes, an adjustable compressor or pressure switch with an unloading valve was used to control the quantity of air to be withheld by the air receiver. A check or one way valve which permits an unidirectional air flow to the air receiver, drain valve to drain off moisture from the air tank, relief valve to relief off pressure when the pressure switch fails, and a bulb valve to supply air to pneumatic tools. The refrigerant was drained, and oil installed which is used to lubricate the pump. A high pressure tube to supply air was also used.

Capacity of the Air Tank

This is the volume of the air tank. Gross capacity (stored volume) is the capacity of the tank up to the maximum safe filling length of the tank.

Air tank (Air receiver):

- Material used: Alloy Steel (ASME standards)
- Properties: great formability and durability, high tensile and yield strength.
- Colour: red oil painted.
- Maximum tank pressure capacity, 10bar.
- Maximum safe operating pressure, 7.9bar.
- Length of air tank (l): 550mm (0.55m)
- Diameter of air tank (d): 240mm (0.24m)
- Radius of air tank (r): 120mm (0.12m)
- Air Tank Capacity: $V = \pi r^2 l$.

SELECTION OF THE MOTOR

From refrigerator compressor ratings, Fisher & Paykel model was selected. Model number FN910176. In this model, the compressor operates at different speeds between 1600rpm and 3000rpm to reduce the variation in sound produced by the compressor. The air compressor is fitted with a variable capacity compressor (VCC). This improves energy efficiency and maintains a more stable temperature. The VCC represents an excellent opportunity for a direct overall noise reduction because it offers the possibility to operate most of the time at speeds lower than 3000 or 3600rpm.

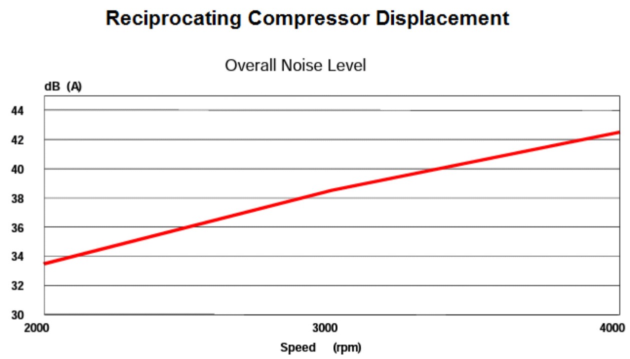


Figure 3. overall noise level of a variable capacity compressor [13]

Compressor ratings:

- Material: steel
- Model number: FN910176
- Frequency: 50Hz
- Capacity: 35kcal/h

- Power rating: 1/2Hp
- Voltage rating: 220/240volts
- Full load: 1.39A
- Efficiency η=0.81kcal/wh
- Lubricant type: ISO22.

Free Air Delivery: The free air delivery (FAD) is the actual quantity of compressed air at the discharge of the compressor. It is the rating for the capacity of an air compressor. The units for FAD are cfm in the imperial system and l/min in the SI system. The units are measured according to the ambient inlet standard conditions ISO1217 of 1bar abs and 20ºc, working pressure at outlet 7 bar absolute, R.H 0% at standard conditions [14].

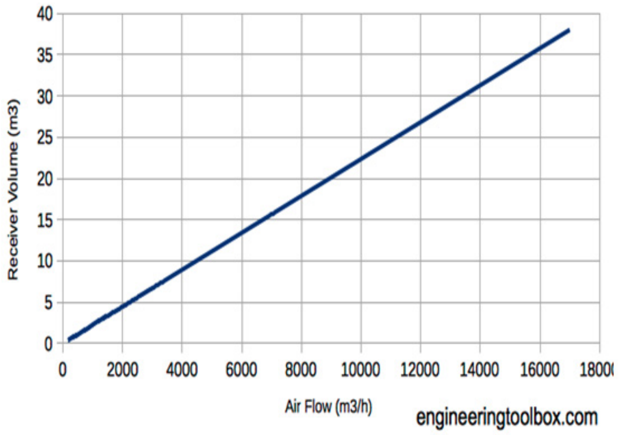


Figure 4. Relationship between Compressor Capacities with Air Tank Capacity [15]

SOUND MEASUREMENT

In order to checkmate the sound level of the design, a comparison was made between two conventional compressors. The two conventional compressors are the SUMAKE PRO LIGHT AIR (2.5hp, 220v/50Hz, 50l) and MAX AIR COMPRESSORS (2hp, 230v/50Hz, 50l). dB Sound Level Meter software was used to compare the sound intensity of the compressors via microphone source at a distance of 1m away from the compressor in use. With a selected band size of 1/3 octave, window size (FFT size) = 4096, time weighted correction dF = 10.8Hz Fast, A-weighted frequency, and series of frequencies ranging from 25 Hz to 8000 Hz.

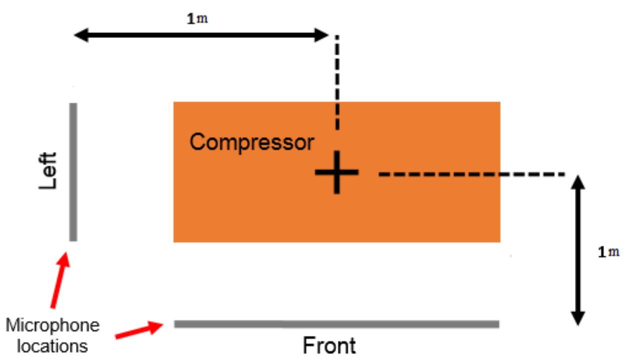


Figure 5. Sound Measurement Location

Generation of Data/Equations

Capacity of the Air tank

The storage capacity of the air tank is given as in equation 1.

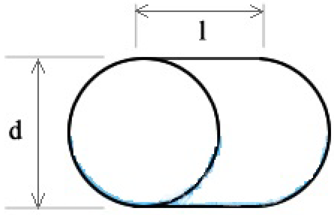


Figure 6. Calculating volume of air tank

Therefore:

$$V = \pi r^2 l \qquad 1$$

Where: the radius, $r = \frac{d}{2} = \frac{0.24}{2} = 0.12m$

Length, $l = 0.55m$; $A = \pi r^2$

Therefore,

$$V = \pi \times 0.12^2 \times 0.55 (m^3)$$

$$V = 0.0248\text{m}^3 \cong 25\text{litres.}$$

Compressor Calculation

Simple Capacity Assessment Method of the Compressor [9].

- Isolate compressor and receiver and close receiver outlet
- Empty the receiver
- Start the compressor and activate the stopwatch
- Note time taken to attain the normal operational pressure P_2 (in the receiver) from initial pressure P_1
- Calculate the capacity of free air delivery (FAD).

$$FAD = Q = \frac{P_2 - P_1}{P_0} \times \frac{V}{t} (m^3 / \min) \qquad 2$$

Where:

P_2 = the final pressure after filling, bar.

P_1= the initial pressure after bleeding, bar.

P_0 = the atmospheric pressure = 1.0135bar (ISO1217 standard)

V = the storage volume in m^3 which includes the receiver and delivery pipe.

t = time taken to build up pressure to P_2 in minutes.

From ISO standard we can calculate the standard free air delivery in standard cubic feet per minute (SCFM) at conditions between 1 – 7bars.

Therefore from the above equation when:

$$P_2 = 7bar, P_1 = 1bar, P_0 = 1.0135bar$$

$$Standard\ FAD = \frac{7-1}{1.0135} \times \frac{0.0248}{6.14} = 0.0239m^3 / \min.$$

Therefore, SCFM = 0.0239 × 35.31 = 0.84 (CFM)

Calculating the actual free air delivery from the experiment we get

When:

$$P_2 = 7.93bar, P_1 = 0.0689bar, t = 7.55minutes$$

$$Actual\ FAD = \frac{7.93 - 0.0689}{1.0135} \times \frac{0.0248}{7.55} = 0.0255m^3 / \min.$$

Therefore,

$$\text{ACFM} = 0.0255 \times 35.31 = 0.90CFM.$$

Efficiency of the Compressor

Volumetric efficiency is defined as the ratio of actual capacity to piston displacement or compressor displacement [16].

$$\eta_v = \frac{actual\ capacity\ Q}{piston\ displacement} \times 100\%. \qquad 3$$

Piston displacement is the swept volume of the piston per unit time, normally expressed in cfm [17].

$$Piston\ displacement = \frac{\pi d^2}{4} \times l \times n \times N \ .. \qquad 4$$

Where: $bore,\ d = 25mm;\ stroke,\ l = 24mm,$ $number\ of\ cylinders, n = 1, revolution\ in\ rpm, N = 3000rpm.$

$$D_p = \frac{\pi \times 0.025^2}{4} \times 0.024 \times 1 \times 3000 = 0.0353m^3 / \min.$$

Therefore equation 4 gives:

$$\eta_v = \frac{0.0255}{0.0353} \times 100\% = 72.24\%.$$

SOFTWARE SIMULATION OF THE SILENT AIR COMPRESSOR SYSTEM

The silent air compressor system was modeled and simulated using solid works software. Solid Works is a computer aided design tool that enables the engineer to design engineering systems. Figure 7, Figure 8, Figure 9 and Figure 10 were generated from the Solid Works Software.

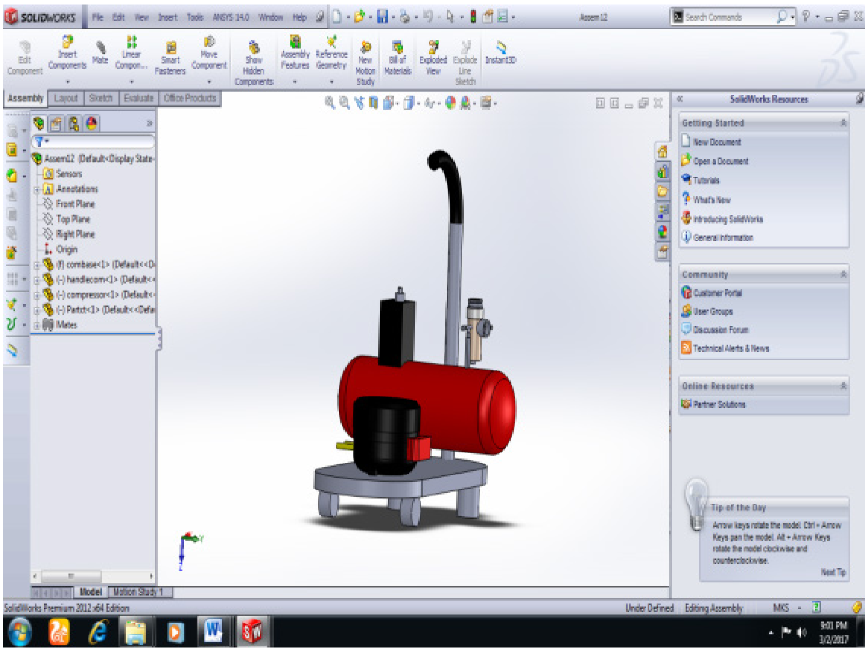
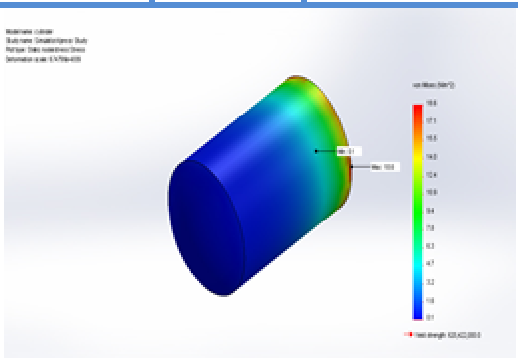


Figure 7. Chiko Air compressor assembly

Type	Min	Max
VON: von Mises Stress	0.103711 N/m^2 Node: 2509	18.6026 N/m^2 Node: 8964



cylinder-SimulationXpress Study-Stress-Stress

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 1	2.66748e-007 mr Node: 99

Figure 8. Von Mises Stress

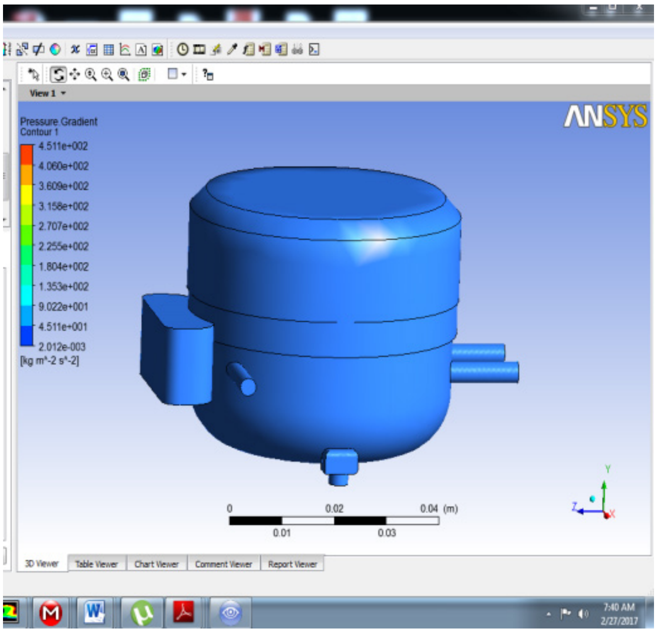


Figure 9. Pressure gradient

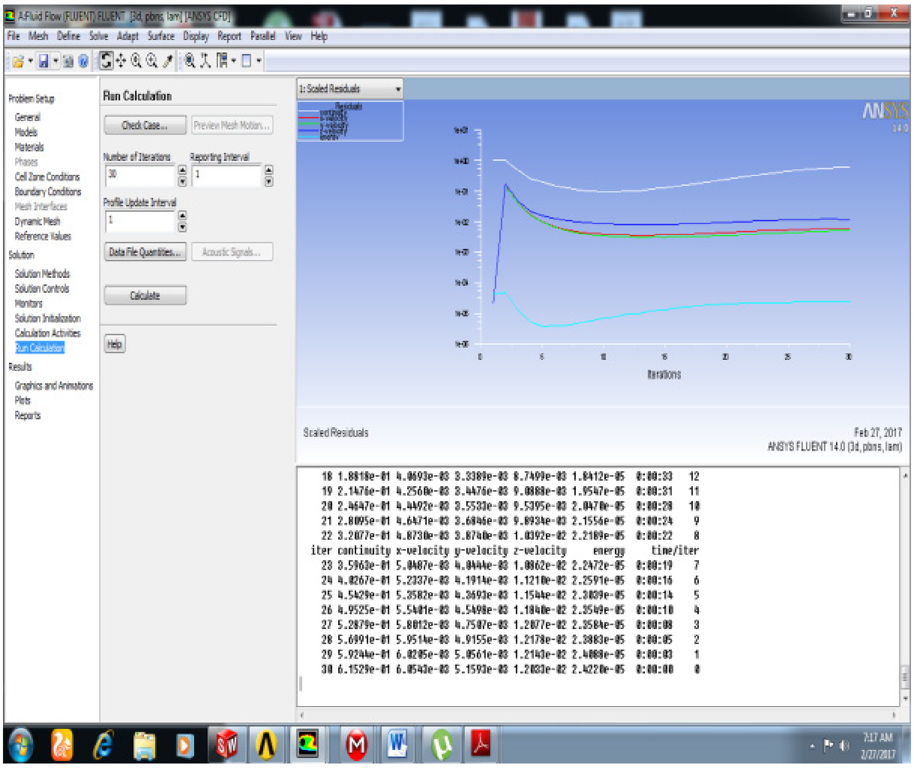


Figure 10. Computational Analysis

3. Results and Discussion

Capacity of Air Tank

$$V = 0.0248m^3 \cong 25litres.$$

From the result above, we can deduce that the storage capacity of the air tank is about 25litres**.** To calculate how much compressed air stored in the air tank we use the condition stated below:

1 cu ft. (28.33litres) of free air at 7.58bar is reduced to 1/10 original volume [18]. Therefore for 25litres (6.60 US gal) tank pressurized to 7.58bar, the tank would store about 6.60 $\times$ 10 = 66.0 gallons (250litres) of air.

Capacity of Compressor

$$SCFM = 0.0238m^3 / \min$$

$$ACFM = 0.0255m^3 / \min.$$

This result implies that the actual quantity of compressed air delivered to the discharge system at rated speed and under rated conditions between 1-7.93bar, at 7.55minutes is 0.90cubic feet of air per minute (25litres of air per minute) of work cycle. Various rated conditions for calculating the Actual FAD at $P_0 = 1.035 bar$ and $P_1 = 1bar$, gave the results as shown in Table 1.

Table 1. Relationship between operating pressure and ACFM at various time intervals

P_2 (bar)	V (m^3)	t (minutes)	FAD (m^3/min)
7.93	0.0248	7.55	0.0255
7.03	0.0248	6.57	0.0261
6.00	0.0248	5.50	0.0263
5.03	0.0248	4.59	0.0263
4.00	0.0248	3.59	0.0266
3.03	0.0248	2.56	0.0283

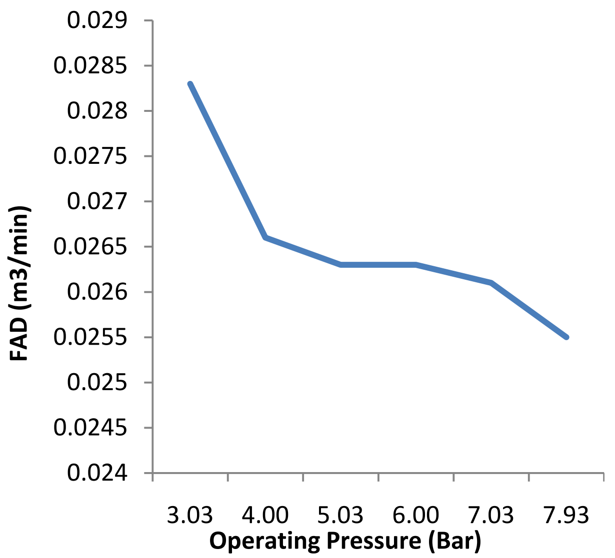


Figure 11. Air Delivery Versus Operating Pressures

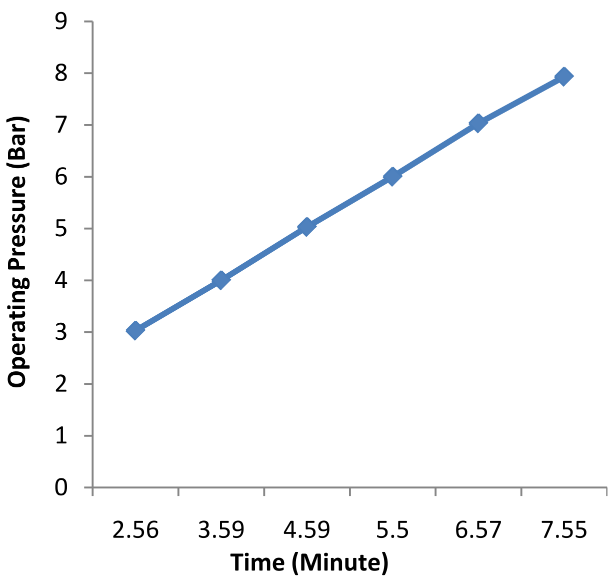


Figure 12. Operating Pressures Versus Time

From the illustration of Figure 11, it is clear that the free air delivery is dependent on the operating pressure. This can be seen as the free air delivery increases with decrease in operating pressure. The rating of free air delivery is usually associated with pressure. It is also a function of time in that as the time increases with increase in operating pressure, the free air delivery decreases. From Figure 11, the actual free air delivery is 0.0255 m^3/min at 7.93 bar. According to the ratings of air compressors by the Compressed Air and Gas Institute (CAGI), it is evident that the portable silent air compressor is perfect for light pneumatic duty.

NOISE LEVEL RESULTS

The results gotten from the Sound Level Meter at various operating frequencies are as seen in Figure 13, Figure 14, Figure 15, Figure 16, Figure 17 and Figure 18. The values are then tabulated for the various sets of frequencies as in Table 2 and Table 3.

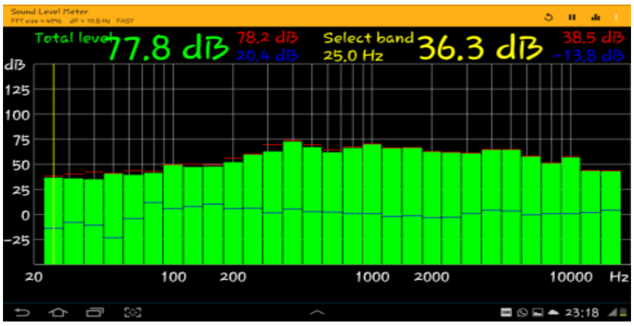


Figure 13. Sound level of Sumake Pro Light Air Compressor at 25.0Hz

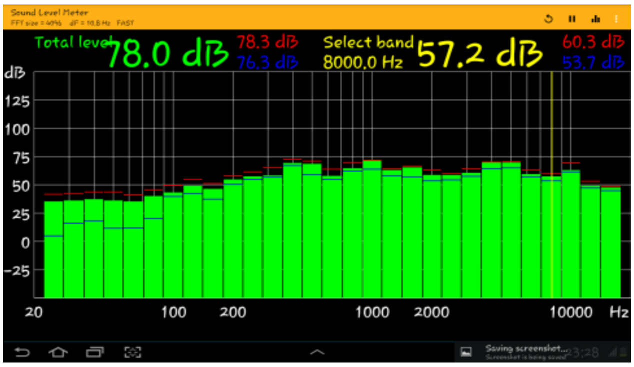


Figure 14. Sound Level of Sumake Pro Light Air Compressor at 8000Hz

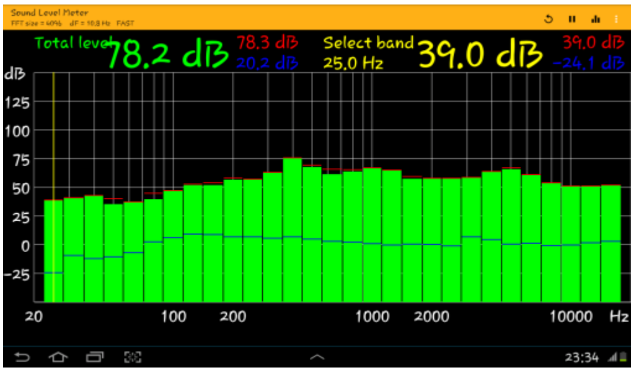


Figure 15. Sound Level of Max Air Compressors at 25.0Hz

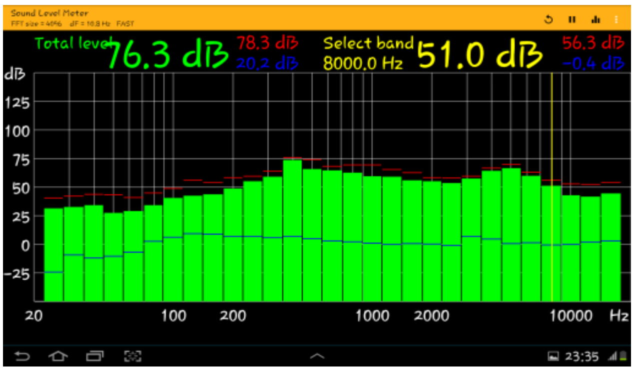


Figure 16. Sound Level of Max Air Compressors at 8000.0Hz

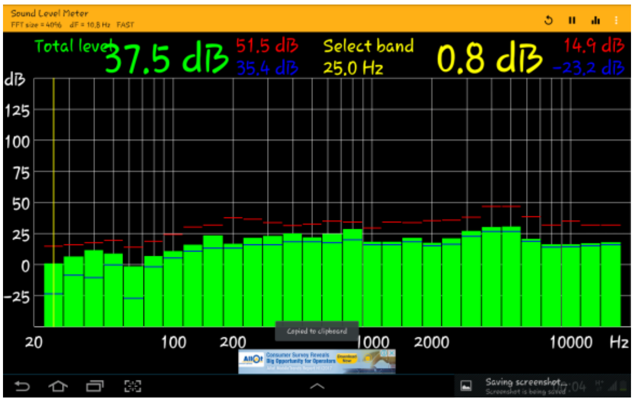


Figure 17. Sound Level of Silent Air Compressor at 25.0Hz

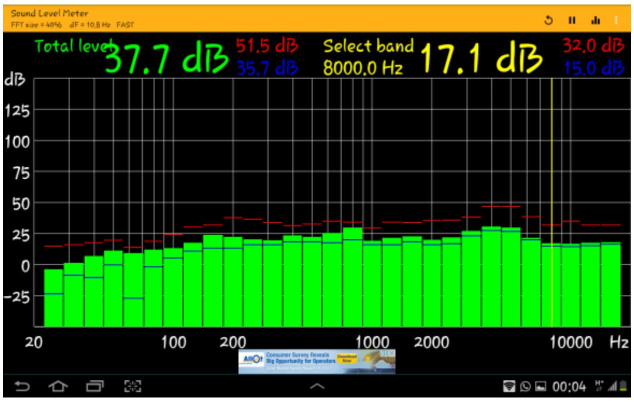


Figure 18. Sound Level of Silent Air Compressor at 8000.0Hz

Table 2. Sound Comparison between Chiko Silent Air Compressor and Two Conventional Air Compressors

Time (s)	Sumake Pro Light (dB)A	Max Air (dB)B	Chiko Silent Air (dB)C
10	77.4	78.7	38.5
20	78.4	78.7	37.7
30	78	78.6	40
40	78.2	79	39
50	77.1	78	39.3
60	76.8	78.5	37.7
70	78	78.7	38.2
80	77.9	79	36.7
90	77	79.1	37.6
100	78.3	78.4	37.6

Table 3. Average Results gotten from the dB Sound Meter Software for 100seconds Sound Test of the Three Air Compressors

Frequency (Hz)	Sumake Pro Light (dB) A	Max Air (dB) B	Chiko (dB) C
25	77.8	78.2	37.5
31.5	78.0	77.0	40.0
40	76.7	77.2	40.5
63	76.3	76.8	38.7
125	77.7	76.7	39.3
250	77.5	77.0	36.6
500	76.8	77.0	38.4
1000	77.5	77.2	37.1
2500	77.0	76.9	35.7
5000	77.1	77.4	37.1
8000	78.0	76.3	37.7

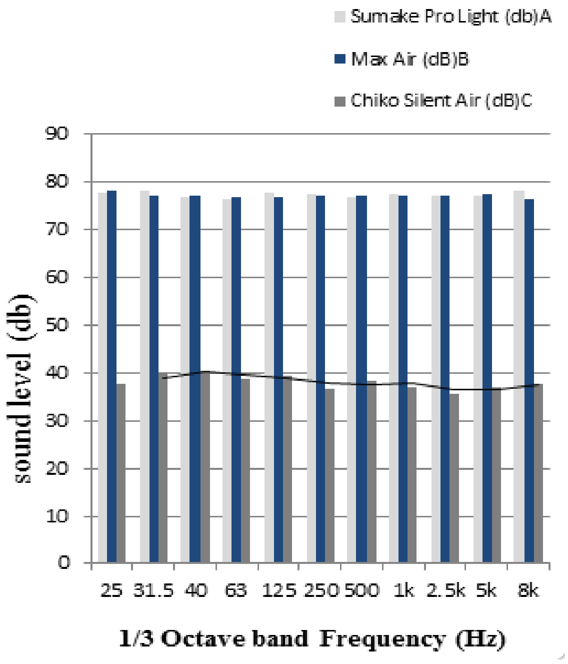


Figure 19. Sound Comparison Chart between Silent Air Compressor With Two Conventional Air Compressors

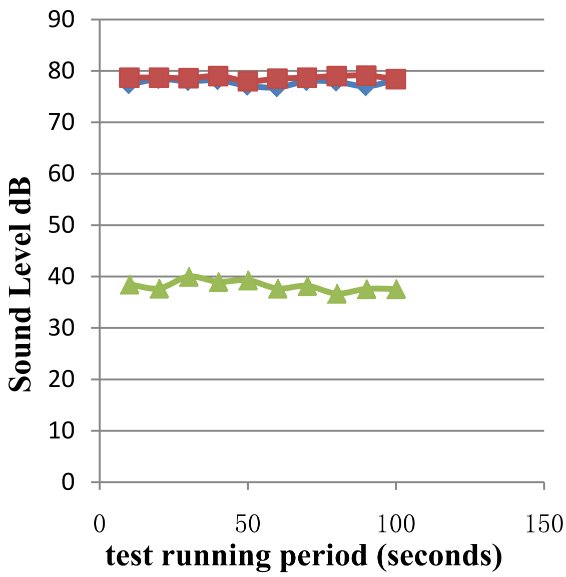


Figure 20. A Graph Showing dB Sound Meter Software for 100 Seconds Sound Test of Three Compressors

From the charts in Figure 20, it is obvious that the silent air compressor is the quietest of the three compressors during the sound level tests both at various rated conditions of time of operation and frequency. It has an average sound level of about **38.4dB.** The percentage decrease in noise level is calculated below.

PERCENTAGE DECREASE IN NOISE LEVEL

Average sound level of Sumake pro light and Max Air compressor $= \dfrac{77.71 + 78.67}{2}$

$$Average\ sound\ level_{A,B} = \frac{(dB)A + (dB)B}{2} = 78.19dB$$

$$\%\ decrease = \frac{Avg_{A,B} - Avg_{C}}{Avg_{A,B}} \times 100\%$$

$$\% \, decrease = \frac{78.19 - 38.4}{78.19} \times 100\% = 51\%.$$

Therefore, with the Silent air compressor design, there was a decrease in the sound level by 51% when compared with other conventional air compressors.

According to the Occupational Safety and Health Administration (OSHA), a sound level of 38.4dB is rated as whisper, and workers can be exposed to this level of sound intensity over a long period of working hours without being prone to hearing damages. This is definitely a bonus compared to other conventional air compressors whose operations require the use of hearing aids.

Some reasons which make the design silent: the compressor is hermetically sealed and houses the pump and rotor which is suspended at four different points by springs which absorbs vibration, the compressor is oil lubricated, and is electrically operated.

The silent air compressor operates at an average sound level of 38.2dB without losing its volumetric efficiency of 72.24%. It has an actual free air delivery of 0.0255m^3/min at 7.93bar, and maintains a high discharge pressure. This makes it a better option when carrying out a light duty pneumatic activities compared to other conventional air compressors. The problem of inconvenience is overcome by stipulating a 4 minutes charge up time for the air compressor when run over a long period of time.

SIMULATION RESULTS

From the results shown in the Figure 8, it is noted that the maximum stress in the pressure vessel is 18.6 N/m^2 and the container displacement is minimal. With a factor of safety of 1.0 hence the design is safe and capable of storing the air with less vibration hence there is a silent production of air.

From the pressure gradient contour in Figure 9, the reaction of the internal and external walls of the compressor container towards the high velocity and kinetic energy of the air is less thereby accommodating the high speed entrance and volume of the air with little or no vibration resulting from a silent state.

4. Conclusion and Recommendations

The noise emitted by potable electric air compressors can often be a nuisance or potentially hazardous to the operator and others nearby. Therefore, reducing the noise intensities of these air compressors is desired. The Chiko air compressor maintains a sound level of about 38.4dB and a volumetric efficiency of 72.24% which according to the Occupational Safety and Health Administration (OSHA) noise exposure standard makes this design desirable over other conventional air compressors.

The free air delivery of this design at 115Psi is about 0.9cfm, which according to International Standardization Organization (ISO) and Compressed Air and Gas Institute (CAGI) makes this design appropriate for light pneumatic duties without losing its efficiency as it is characterized with high discharge pressure.

Finally, this modification cleared the fantasy about the idea of a quiet air compressor and solved the aims of this design by reducing the sound level of conventional air compressors by 51% as air compressors should be seen and not heard.

RECOMMENDATIONS

For increased free air delivery, the refrigerator compressors should be doubled or triple or more as the case may be depending on the customers work demands.

For increased efficiency, air filters should be regularly checked and cleaned as more continuous and smooth air is provided to make the air flow maximum at the output of the compressor.

Safety fittings of air compressor should never be tampered with.

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