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Design and Fabrication of Compressed Air Storage using Spent Refrigerant Cylinder

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ABSTRACT

The design and fabrication of compressed air storage system was carried out using recycled refrigerator compressor and refrigerant cylinder. Conventional air compressors used in vulcanizing employ environmentally unfriendly fossil fuel and or electricity which can be epileptic in supply in Nigeria. Therefore, this present research aimed to use alternative materials such as recycled refrigerant compressors and cylinders to produce a cheap DC-operated air compressing and storage unit. In doing so, two concepts were significant considered. The first concept was the use of a refrigerant compressor and LPG gas cylinder. The second concept was the use of a refrigerant compressor and a refrigerant gas cylinder commonly found in domestic fridges and air-conditioners. The refrigerant cylinder was the air storage tank. The second concept was selected using a decision matrix based on some design considerations. Test and analysis carried out on the locally made compressed air storage machine showed that its efficiency was 74.56% which exhibited a good operational output. It was observed that the refrigerant compressor took an overall time of 52 minutes to fill a 5kg refrigerant cylinder to its full holding capacity of 6 bars. The portable air compressing and storage machine could be hand-pushed from one place to another for comfortability and could be used with or without electric current for inflating tires, beds, balls, and other inflatables within its designed and operating pressure.

1.0 Introduction

Air compressors are a vital instrument used for a number of tasks and facilities like powering pneumatic tools, air-operated control devices, and moving fly ash. For various purposes, air may be used in its purified, natural, compressed or non-compressed forms and it is environmentally friendly with no attendant pollution and degradation to the environment. Compressing air is literally to force it into a smaller space and as a result, brings the molecules closer to each other. [1]. An air compressor compresses air, and with a well-designed pipe network, transports the flow medium from the compressor to a pneumatic cylinder [3]. Deflated tires, tubes, etc. are often pumped using a compressed air equipment [7]. In modern industrial civilization where compressed gas is required for various processes, it has become pertinent to have such equipment handy for on-the-spot usage where necessary without any source of power. This could be possible with the use of air compressing and storage equipment portable enough to be carried comfortably from one place to another by the user or kept in a car trunk. Conventional air compressors used by vulcanizers make use of electrical or petrol engine-driven motors. The air generated is stored in a high-pressure cylinder making the equipment quite heavy for portable handling. Given Nigeria's epileptic electricity power supply and the need for clean energy utilization, the use of petro a fossil fuel is considered an environmentally unfriendly fuel [2] while electricity from the power grid may not always suffice in times of need. These setbacks associated with conventional air compressing and storage systems have brought about portable electronic compressors which are powered by car batteries and often used for pumping car tires. The shortcomings of such devices are less durability, absence of storage tanks and low compressing power. Identifying these setbacks has necessitated an investigation into the use of alternative components such as refrigerant compressors which are often discarded as waste from faulty fridges and air conditioners. These refrigerant compressors have the potential to be recycled and used as dry air compressors without any significant refurbishment even as a waste material. This research study therefore was aimed at exploring the potential of using recycled refrigerant compressors to generate and compress air for immediate use or stored in storage tanks for future use. Air is used both biologically and non-biologically. It can be used for a variety of commercial and household tasks, such as tire inflation, spray painting, the application of insecticides, mechanical fastening and loosening, etc., by storing it above atmospheric pressure.

Typical air compression equipment is relatively expensive and uses electrical or environmentally unfriendly petrol driven motors making them bulky. They also become too heavy for flexible handling. To proffer a solution to such setbacks, it is pertinent to explore the potential of using spent refrigerant compressor in its dry operating state to generate and compress air for immediate or future use without polluting the environment.

1.1 Review of Related Literatures

The authors in [7]. performed a five-minute conceptual design and finite element analysis of a DC-driven small air compressor for inflating automobile tires. The researcher successfully developed a DC-powered tire inflator that could inflate tires within 5 minutes. The design had two units comprising of the compressor side and the motor side. The compressor-side components included a piston, crankshaft, cylinder, cylinder head, rings, crankcase, valves, pressure gauge, and 4 studs. The volumetric and working efficiencies of the machine were 80% and 62.5% respectively. The conceptual design was deemed manufactural based on design analysis and evaluation.

The authors in [2]. designed and developed a compressed air machine with a compressed air energy storage system. The authors asserted that their proof of concept required no fossil fuels and was powered by compressed air as a fuel source which demonstrated the concept of a new engine technology that is green and environmentally friendly for future generations. Their experimental results showed a maximum efficiency of 23.60% at a maximum load of 4.5 bar.

In [9]. The authors carried out the design of a Hydraulic Air Compressor (HAC). The (HAC) Project was used to measure and verify the electricity savings potential of new HAC technology primarily for deep mining applications. A 30-metre-high HAC demonstrator rig was installed in an elevator shaft. The author asserted that conventional mechanical refrigeration systems for deep mining applications (below 2,500 meters) consumed significant amounts of electricity and add considerable costs to mining operations, impacting mines’ competitiveness. Therefore, HACs offered a more energy efficient and reliable approach to air compression.

Following the review of this literature, one may contend that not much has been done on the recyclability of refrigerant compressors as a means of generating and compressing air. Though different researchers based their work on computational analysis of air compressors, others have focused on air compressing machines which cannot be said to be portable for ease of use and mobility as can be achieved with the use of scrap refrigerant compressors which forms the basis of the present research.

1.2 Determination of Input Variables and Equations

The air compressing and storage machine is intended for use to inflate tires and to spray liquid-based paints to surfaces. Following such uses, the expected pressure of an inflated tire of a utility vehicle such as a Toyota Corolla 2006 model is used for evaluation.

Inflated pressure of tire = 40psi
Intended duration for continued operation of the air compressor machine = 8hr
Suction pressure of refrigerant compressor = 5 psi (as specified in manufacturers manual)
Discharge pressure of refrigerant compressor = 65 psi (specified by manufacturer)
Molecular weight of air; dry air is 28.97 grams per mole
Critical pressure of air; 905.5 psi
Critical temperature of air; 97 @3°F
Critical density; 0.231g/ml
n- Value; 1.40
Where n = the specific heat ratio expressed as;

$$n = \frac{m_w \, x \, C_p}{m_w C_p - 1.99} \qquad (1)$$

Where; m_w = molecular weight of air and C_p = specific heat at constant pressure.
Site Elevation: 1,000 ft. elevation, outdoors, Ambient of 0° to 100°F.
Site elevation is used to determine the local Barometric Pressure, P_{amb}). If P_{amb} is not listed in the specifications it can easily be determined from Tables as shown in Tables 2
Since the site data elevation is listed as 1,000 ft., the local barometric pressure is 14.16 psia from Table 2; hence; the absolute suction and discharge pressure can be calculated as
Ps = 5 psig + 14.16 psia = 19.16 psia
P_d = 65 psig + 14.16 psia = 79.16 psia

1.2.1Compressor pressures

In order to size a compressor, the pressures must be expressed in absolute and gauge pressures relationship expressed as

$$\text{PSIA} = \text{PSIG} + \text{Pamb} \quad \text{Bar-a} = \text{Bar-g} + \text{Pamb} \qquad (2)$$

Where;
PSIA = pounds per square inch, absolute
PSIG = pounds per square inch, gauge
Pamb= local barometric pressure (psia or Bar-a)
Bar-a Bars, absolute
Bar-g Bars, gauge

1.2.3 Suction Temperatures

This is expressed as absolute (°R, °K) or gauge (°F, °C) values.
The compressor suction temperature should be expressed in absolute terms (°R or °K).

$$°R = °F + 460 \quad °K = °C + 273 \; - \qquad (3)$$

Where;
°R = Degrees Rankine, an absolute value
°F = Degrees Fahrenheit, a gauge value
°K = Degrees Kelvin, an absolute value
°C = Degrees Centigrade, a gauge value

1.2.4 Compressor capacity

To size the compressor, the capacity must be stated as the volume it will occupy at the compressor's suction. This volume is normally referred to as inlet cubic feet per minute (ICFM). The metric equivalent is inlet cubic meters per hour (Im3/hr). If the term ACFM is used, it must be made clear the volume is measured at suction pressure and temperature.
The required compressor capacity (flow) in SCFM (or Nm^3/hr) = 20
This is the normal maximum flow expected from the compressor.
Average ICFM is expressed as;
ICFM = 20 SCFM (14.7 psia / 19.16 psia) (510°R / 520°R) = 15.05 ICFM
Where;
ICFM - Inlet Cubic Feet per Minute
Im^3/hr - Inlet Meters Cubed per Hour
This is the volume the gas will occupy at the compressor's suction. In order to size the compressor, the ICFM must be known.
SCFM - Standard Cubic Feet per Minute
Nm^3/hr - Normal Meters Cubed per Hour
The use of this form of gas volume implies a standard reference value for pressure and temperature. Standard references for SCFM are 14.7 psia and 520 °R and (Nm^3/hr 1.014 Bar and 273 °K).
The relationship between ICFM and SCFM is expressed as follows;
$ICFM = SCFM\ (P_{std}/Ps) \times (T_s / T_{std})$ (4)
Where;
Pstd Standard barometric pressure 14.7 psia (1.014 Bar-a)
Tstd Standard temperature 520 °R (273 °K)
Ps Compressor suction pressure psia (Bar-a)
Ts Compressor suction temperature °R (°K)

1.2.5 Free air volume of the compressor

Free Air volume is the volume occupied at the ambient pressure and temperature at the compressor. These two values will vary depending on the local weather and elevation above sea level. It is expressed as;
Free air = (ICFM) / (Pamb / Ps) (Ts / Tamb) (5)

Where;
Pamb Local barometric pressure psia (Bar-a)
Tamb Local ambient temperature °R (°K)
Ps Compressor suction pressure psia (Bar-a)
Ts Compressor suction temperature °R (°K)

1.2.5 Compression ratio (R)

This is the ratio of discharge pressure to suction pressure expressed as:
$R = P_d/P_s$ (6)
Where;
Pd and Ps are absolute values
A single-stage compressor has only a single R value.
A two-stage compressor has three R values.
R = total compression ratio for the compressor
R_1 = compression ratio for the first stage
R_2 = compression ratio for the second stage
R = Pd/Ps R1 = Pi/Ps R2 = Pd/Pi
Ps = Suction pressure
Pd = Discharge pressure

PI = Interstage pressure - the pressure between the 1st and 2nd stages of the compressor.

1.2.6 Discharge temperature

The compressor's discharge temperature directly affects the life of the piston rings and valves. For the discharge temperature for an air cooled single-staged compressor which is preferred considering the decision matrix consideration on cost on less complexity:

$T_d = Ts\ (P_d/P_s)^{(n-1)/n} = Ts\ R^{(n-1)/n}$ (7)

Where;
Ts = Suction temperature °R (°K)
Ps = Suction pressure PSIA (Bar-a)
P_d= Discharge pressure PSIA (Bar-a)
R = Compression Ratio (P_d/Ps)
N = specific heat ratio of the gas

1.2.7 Volumetric efficiency

It is the ratio of the amount of gas compressed versus the physical size of the compressor's cylinder volume. It is evaluated as follows;

For the single-stage compressor; $VE\% = 93 - R - 8(R^{1/n} - 1)$ (8)

Where;
R = Compression ratio (Pd/Ps)
n = Gas specific heat ratio.

1.2.7 Stresses on the storage cylinder

The air storage cylinder is subject to forces internally, hence care must be taken to ascertain its ability to hold a given amount of air. From Figure 5 a ring or hoop from the cylindrical profile is isolated from the rest of the cylinder. The free body is obtained by cutting the hoop on the line of the diameter. The moment equilibrium is satisfied about the hoop center. The force equilibrium in the x-direction is satisfied as a result of the symmetry, and thus to ensure equilibrium, force balances in the direction is considered.

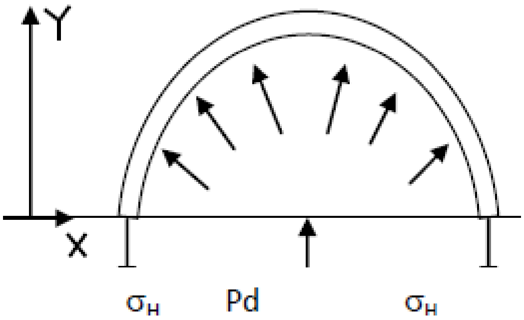

Fig. 5 Cross Section of cylindrical shell

Upward forces F_y = Pressure x Area
= P x 1 x d (9)
If balanced by downward force f_T which is stress x Area
$F_y = P(D_1) - 2f_T = 0$
But $f_T = \sigma_H \times 2(1 \times t)$ (10)
And $D_1 = 2rl$
Replacing f_t in equation 9 with equation 10
$F_y = P(2rl) - 2(\sigma_H(tl) = 0$
Making σ subject of the formula we have
$\sigma_H = 2Prl/\ (2tl) = Pr/(t)$

i.e.

$\sigma_H = \frac{PD}{2t}$

Where P = operating pressure
D = diameter of the cylinder
t = thickness of the cylinder

Thus, thickness of the cylinder can be calculated

$$t = \frac{PD}{2t\sigma} \quad (11)$$

The cylinder thickness will determine its capacity to hold air at a given operating pressure. For the selected refrigerant storage cylinder, its holding pressure is specified and when matched with the holding pressure for a car tire which is 35-40psi, it was high enough to hold air and discharge it above 40psi.

2.0 Methodology

In this section, we present the methodology that was employed in this research.

2.1 Materials

Scrap metal and regional suppliers provided the materials needed for the production of the air compressing and storage cylinder. The materials include the followings: Used refrigerant cylinders, Replaced refrigerant compressor, Pressure hose, Air filter, Plumbing nipple and socket, Hand drill, Oxyacetylene and oxygen gas, Brazing rod, Mini tires, Welding electrode, Brazing torch, Compressor switch.

2.2 Methods

Waste or malfunctioning compressors are collected, repaired, and transformed into pumps for air suction and storage in storage cylinders. These compressors are originally filled with refrigerant gas for use in refrigerators, but with time due to vibrations or malfunctions, they tend to leak and become problematic to use until they are replaced with a new one. However, these allegedly defective compressors can be repaired and modified with air suction nozzles and filters to suck and transmit air directly for usage or storage, as opposed to being filled with refrigerant gasses. This procedure recycles these compressors in some way that inhibits environmental degradation. To demonstrate the procedure in this work, two concepts based on materials selection were considered before a preferred choice was made. Design factors were considered to select the most suitable concept for production. The two-concept considered were;

Concept 1

Compressor and LPG gas cylinder storage. The cylinder depicted in Figure 2, which is frequently seen in household kitchens, is available in a variety of weight specifications depending on how much gas it can carry. They come in 3kg, 4kg, 6kg, 12kg, and 25kg varieties.

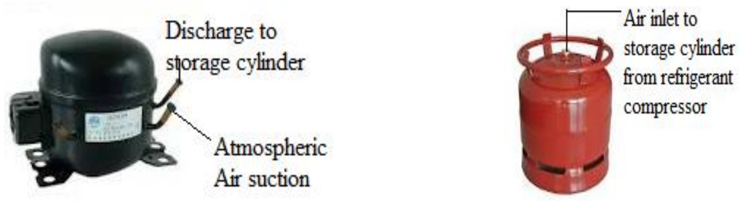

Fig 2: Recycled refrigerator compressor with LPG gas cylinder

Concept 2

Employing a HVAC compressor and an empty refrigerant gas cylinder shown in Figure 3. Refrigerant gas cylinders are commonly found HVAC materials sales and repair centers.

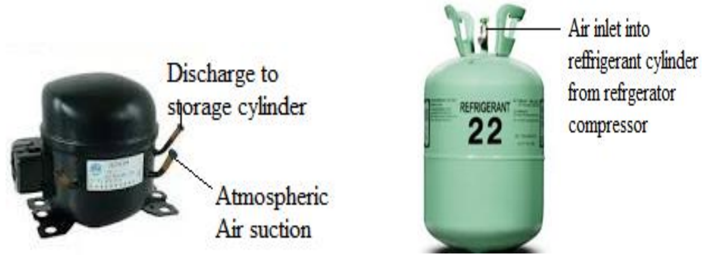

Fig. 3: Recycled refrigerator compressor with refrigerant storage tank

The selection and use of the concept 1 was decided using a decision matrix based on selected design considerations as shown in the decision matrix in Table 1 . The decision matrix table contain criteria which are weighted for choices and the choice with the highest weighted total is selected. A maximum weight value of 2 is allocated to a concept if it better performs a function or exhibit a quality. Following the factors considered, air compressing and storage unit using refrigerant cylinder as shown in Figure 4 was considered to be more viable for production. The concept two had a total weighted factors grade of 8 compared to that of concept one which had 4.

2.3 Detail design

Schematic CAD designs of the proof concept of air compressor machine using refrigerant compressor is shown in the Figure 4.

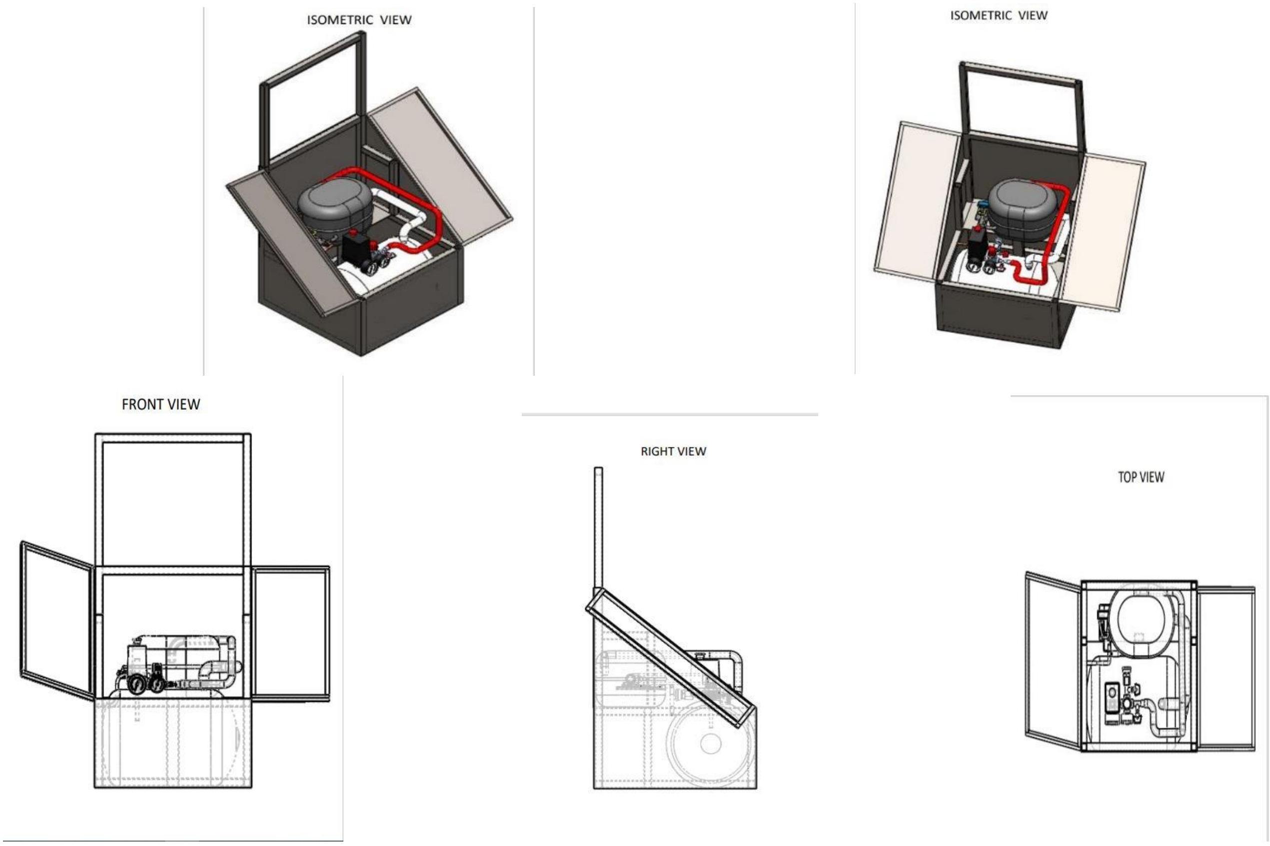

Fig. 4: Conceptual design of air compressor machine.

3.0 Results and discussion

To determine its operating appropriateness and efficiency, a test of the designed and constructed refrigerant air compressor and storage tank was conducted. The system was turned on, and air was allowed to enter the refrigerant cylinder for storage till it was filled to its maximum holding capcity. The time it took to generate and store air inside the storge cylinder at various pressures bars was recorded as shown in Table 3. A corresponding graph showing the relationship between time and pressure was ploted as shown in Figure 2.

Table 3: The results of the experimental testing of the compressor

Pressure in bar	Time in (minutes)	Cummulative time diffrence ($T_2 - T_1$) min
1	6	6
2	13	7
3	19	6
4	29	10
5	40	11
6	51	12
7	64	12
8	74	10
9	86	12
10	109	25

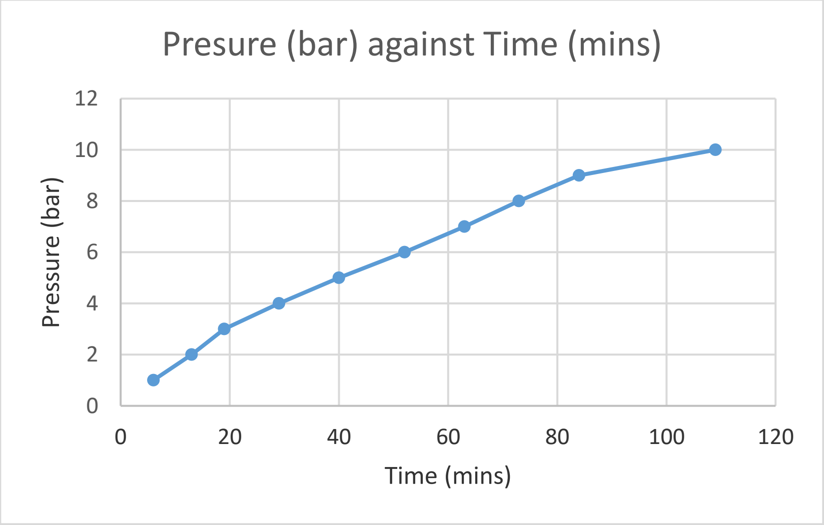

Fig. 6 graph of pressure of compressor against time

3.1 Discussion of Results

From the Table 3 representing the results of the experimental testing of the compressor: the time in minutes it took the compressor to fill the storage tank to different holding pressure capacity. It was observed that the compressor took an overall time of 109 minutes to reach its full designed capacity of 10 bars. There was an increase in time to fill the air storage tank as the holding pressure increased. This direct relationship is depicted in the graph of pressure against time in Figure 6. As pressure in the tank increased the rate of pumping in more air decreased. This is observed from the cumulative time difference column in Table 3 where the time it took ($T_2 - T_1$) to increase the cylinder storage pressure from initial pressure P_1 to next pressure P_2 took seemingly longer time. This was inferred o be due to back pressures from the already stored air in the cylinder which exerts pressure on all internal points of the storage cylinder.

3.2 Compressor Efficiency;

The system's volumetric efficiency was also determined using equation **3.8** and it was calculated V.E% = 93 - 4.13 - 8(4.131/1.40 - 1) = 74.56%

4.0 Conclusion

The produced compressor machine was found to be suitable and viable for use for pumping tires and jet spraying of paint or suspension fluids. It was a god alternative to conventional air compressors used by vulcanizes which utilized environmental polluting fossil fuel or alternating current. The present air compressor uses a DC instead and can still work in the absence of electric current when the pressured air in the storage tank is used. The study unmistakably demonstrated that a portable compressor machine unit may be created using recycled waste materials that can be sourced locally within the garage, repairs centers or scrap yards. This made it cheaper to produce compared to purchasing conventional air compressors. The installation of pressure gauges and an automatic pressure shutoff switch ensured that the compressor and air storage unit was safely operated and shut off upon reaching its operational pressure. It then re-engaged to pump and supply air when the storage pressure fell below the calibrated operational pressure.

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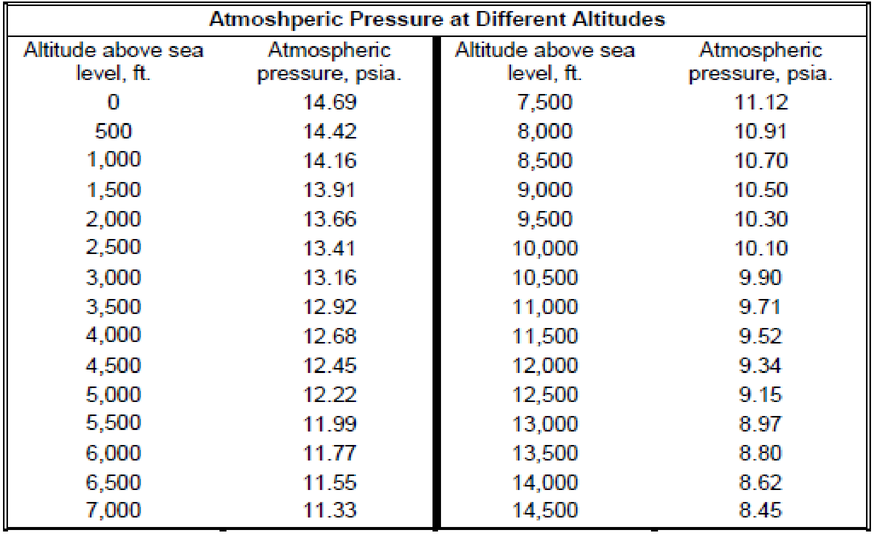
Appendix

Table 1A: Decision matrix table for concepts of air compressing and storage unit.

Design factors	Concept 1 Compressor with LPG gas cylinder.	Concept 2 Compressor with refrigerant storage cylinder.
Light weight	1	2
Ease of fabrication	1	2
Low cost of procurement	1	2
Safety	1	2
Total	4	8

Table 2A. Atmospheric pressures at different altitudes. [10].



Atmoshperic Pressure at Different Altitudes

Altitude above sea level, ft.	Atmospheric pressure, psia.	Altitude above sea level, ft.	Atmospheric pressure, psia.
0	14.69	7,500	11.12
500	14.42	8,000	10.91
1,000	14.16	8,500	10.70
1,500	13.91	9,000	10.50
2,000	13.66	9,500	10.30
2,500	13.41	10,000	10.10
3,000	13.16	10,500	9.90
3,500	12.92	11,000	9.71
4,000	12.68	11,500	9.52
4,500	12.45	12,000	9.34
5,000	12.22	12,500	9.15
5,500	11.99	13,000	8.97
6,000	11.77	13,500	8.80
6,500	11.55	14,000	8.62
7,000	11.33	14,500	8.45