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Controlled Solar-Pneumatic Energy Storage System for Green Power Generation

[1]Godwin O. Uzedhe and [2]Benjamin O. Akinloye
Department of Electrical and Electronics Engineering, Federal University of Petroleum Resources,
Effurun, Delta State, Nigeria
[1]*uzedhe.godwin@fupre.edu.ng* [2]*akinloye.benjamin@fupre.edu.ng*

Abstract

This paper presents a controlled solar air storage system for electrical power generation in with renewable energy sources. Fossil fuel has been the main source of energy globally with its use currently facing diverse regulations due to environmental factors. Alternatively, the use of renewable energy sources has been emphasized and seems to be gaining more support. These renewable sources however require some storage media. Several storage media have been used over the years with limitations in cost, bulkiness and short operational duration. This research presents renewable energy storage and preservation in form of compressed air for micro-scale electric power generation at low cost. Here, energy drawn from the sun, through photovoltaic (PV) cells, is used to compress air into a cylinder from where it can be used to turn an air turbine at regulated pressures. The study shows that external environmental conditions may influence air pressure in the storage media and therefore requires consideration. Results obtained shows that compressed air pressure in the storage cylinder is logarithmic in nature and will attain maximum charge at a short period of time. Results also indicate that with appropriate control of the system's operation, air pressure in the a storage cylinder can be maintained at regulated compressor temperature.

Keywords: Air Pressure, Control, Renewable Energy, Air compression, Compressor temperature

1. Introduction

Long use of fossil fuel is the main cause of some serious environment issues like greenhouse effect, fog and haze, ozone layer depletion etc., thus the need for environmental protection became imperative. Renewable energy sources are the alternative. These sources, most especially wind and solar, are largely available but are faced with challenges of reliability for energy generation due to their intermittency, uncertainty and availability at all time. To overcome these challenges is the need for energy storage. The concept of energy storage has a long time application and several storage media have been developed the most common being the chemical battery. Storage batteries can be used to store the various renewable energy sources by first converting them into electricity. Storage batteries are not permanent; they degrade with time and ultimately require replacement and therefore are a relatively expensive means of electrical energy storage. Hence, research into a cheaper, more durable form of energy storage informs the use of compressed air energy storage (CAES) systems. Energy in compressed air (pneumatic) can be utilized to solve many critical problems facing the electrical generations, including operation of pneumatic tools/ devices for both on-grid and off-grid system.

Compressed air energy storage (CAES) is a developing technology with currently more attractive economic advantage compared to other bulk energy storage systems. CAES systems are capable of delivering tens of megawatts of electrical power and are currently being compared to the performance of Pumped Hydroelectric Energy Storage (PHES) systems (Miroslav et al, 2013). This work is an extension of a paper presented by (Uzedhe and Akinloye, 2019) on the Investigation of Solar-Pneumatic Storage System in the 2019 Power Africa IEEE PES/IAS conference.

1.1 Existing Cases Systems

A number of work have been done on the application of CAES systems for solving electricity problems in large scale power solutions just like in PHES (Jidai Wang et al, 2017). Currently, the use of CAES in small scale mini-grid and standalone systems (Coriolano et al, 2017 and Vorrapath et al, 2013) is fast becoming a research topic. Luo et al (2014) looked at current development and growth in multi-scale CAES technologies and in summary notice that small-scale CAES systems may be able to provide a combination of long lifecycle, improved performance, and low cost compared to that of other available storage such as chemical batteries. A review of the different electrical energy storage systems in use in the USA was carried out by (Eugene et al, 2016) and discussed the driving factors for energy storage, describing the various technologies in use. Environment concerns and the unstable nature of renewable energy sources are listed as reasons for energy storage. Their review shows that cost is the highest determining factor in the consideration of storage technology for use.

Earlier, over dependence on fossil fuel support and appropriate underground cavern location for the deployment of CAES systems became serious hindrance to advancement in CAES. To overcome these challenges, research and development currently seek improved conventional CAES methods, Advanced Adiabatic CAES (AACAES) and Small Scale CAES that can use small man-made storage vessels (Haisheng et al, 2013).

Huanran et al (2013) presented a PHES combined with compressed air energy storage system suitable for wind power industry in China. Their work concluded on advantages of simple, effective and low cost structure comparable to the efficiency of a traditional PHES system. Hussein et al (2015) considered different usage alternatives of CAES in electrical power generation among which micro-grid, small-scale distributed, UPS and stand-alone application of CAES are expected to offer better alternatives to chemical batteries. A hybrid Wind-Diesel-Compressed air system (WDCAS) for Nordic remote Canadian areas was considered in (Ibrahim et al, 2011 and Hussein et al, 2015). Their result shows considerable improvement in annual fuel savings, maintenance and operational cost in a wind-diesel hybrid system with CAES. Hybrid energy storage systems that combine compressed air and other media such as super capacitors have also been extensively discussed in (Sylvian and Alfred, 2005). Analytical simulation of useful and waste energy in an adiabatic air storage by (Lukasz et al 2017) shows that the highest energy waste occurs at the compressor and turbine stages. Such wasteful energy must therefore be harvested for use in other areas in order to maximize systems energy throughput. In large CAES systems, the method is by heat storage to some other media where it is reapplied to heat up the air during discharge (Young-Min et al, 2012). This method may differ in micro-scale application of CAES and such waste energy can be used for home heating needs. The thermodynamics of compressed-air energy storage systems and their integration in a computer model with special indication to small scale industrial applications are described in (Georg and Valentin, 2013). Results obtained indicate that low pressure level systems with high storage volume may be more energy-efficient.

This research focused on the use of CAES in small-scale man-made storage media for power generation that could be installed in the home for off-grid electrical power generation.

2. Experimental Methods

2.1 Small-Scale Solar-Pneumatic Electric Generator Concept

Several energy storage concepts have been used over the years and that includes recently the large-scale air storage systems in use in some parts of the world. The pneumatic concept however has not been utilized in the areas of small-scale electrical energy generation in renewable applications. Figure 1 shows a micro-scale solar-pneumatic energy storage system for rural home renewable (solar) electrical energy generation. In this concept, energy from a renewable source (sun) is trapped and used to compressed air into a storage vessel. The air in then escaped through a turbine where it is used to turn a generator for electricity production in the home.

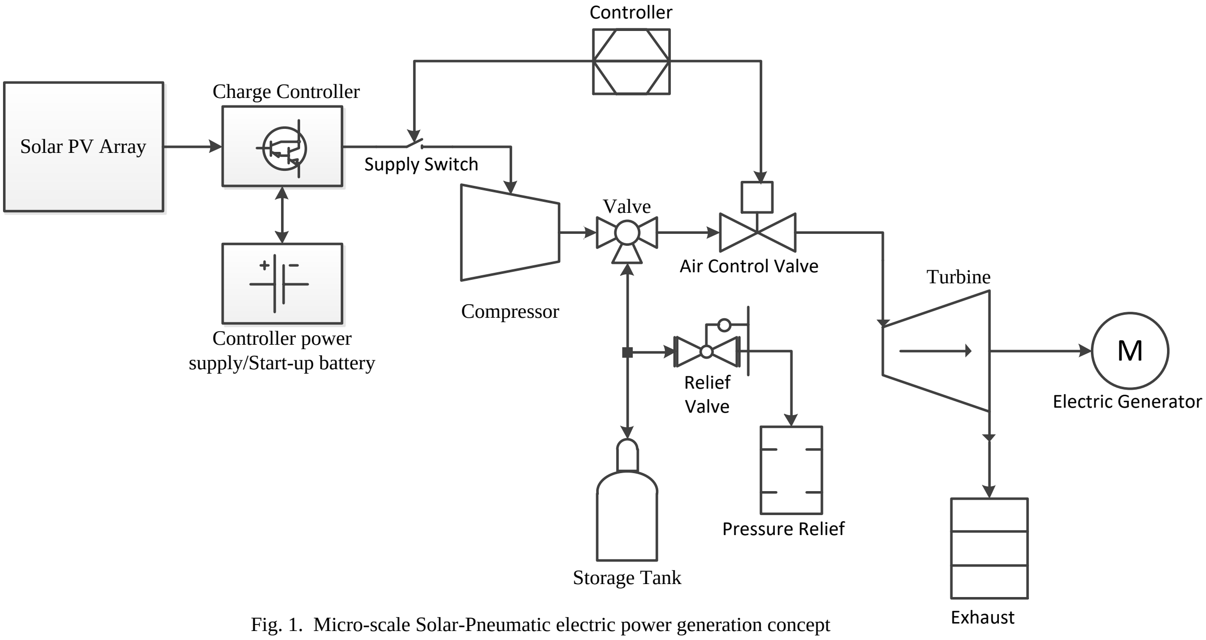

Fig. 1. Micro-scale Solar-Pneumatic electric power generation concept

Large-scale CAES depend on availability of a suitable underground geological cave. Although there are potential sites for large-scale CAES plants, finding appropriate storage caverns is a major challenge. Small-scale CAES system requires man made storage vessels for storage. Storing the compressed air into such vessels can be of two possible processes, either by cooling the air or by storing the air at the same temperature. If the compressed air is allowed to cool we get an isothermal system and if we do not allow it to cool we get an adiabatic system. For a small scale CAES system, it is very important to simplify the structure as much as possible. Therefore, implementing a small scale CAES system can be of low pressure which minimize the temperature differences during compression and expansion; or use of high pressure systems in which the heat and cold from compression and expansion can be harnessed for household applications.

2.2 Theoretical Background

2.2.1 Storage Modelling

Small-scale CAES systems required appropriate storage sizing in order to meet the expected system autonomy. This autonomy depends on how much time the system is to run independently and therefore, how much air must be stored. Dry air contains about 23.053% Oxygen (O_2), 74.99% nitrogen (N_2) and 1.957% trace elements. Air can therefore be assumed as an ideal diatomic gas as it contains more of nitrogen. Therefore, the pressure, volume and temperature of air in the cylinder can be modelled with the ideal gas equation of equation (1).

$$PV = nRT \tag{1}$$

Where P is the pressure of the air inside the cylinder, V is the volume occupied by air, n is the molecular weight of air compressed into the cylinder, R is the specific gas constant and T is temperature of the compressed air. It is assumed that the storage tank is properly lagged such that the system's pressure-temperature relationship can be adiabatically expressed as in equation (2) leading to equation (3).

$$PV^{\gamma} = k \tag{2}$$

$$P_1V_1^{\gamma} = P_2V_2^{\lambda} \tag{3}$$

Where $\gamma = 1.4$ is the ratio of specific heats of air at constant pressure and constant volume.

A 25kg (0.060167m^3) air storage cylinder was considered for investigation and assumed to have an atmospheric pressure of 101.325kPa (14.6959Psi) at 300.15K (27^{0}C) ambient temperature. Using equation (2) and these initial values, the adiabatic constant is 1980.6982Pa.m$^{4.2}$ and using a compression volumetric ratio of 4:1, the new volume of air is expected to be 0.0150175m^3 and applying equation (3) the air pressure in the tank can be estimated to be 705.6683kPa.

Equation (4) and (5) are used to determine the new temperature of air in the storage cylinder T_2 and is expected to be 522.577K (249.427^{o}C)

$$P\left(\frac{nRT}{P}\right)^{\gamma} = P^{1-\gamma}T^{\gamma} = \text{constant} \qquad (4)$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad (5)$$

These high temperatures are dissipated as heat at the compression stage and represent the amount of work done by the compressor to pressurize air into the cylinder.

2.2.2. Effect of External Temperature on Stored Air Pressure

To establish a practical relationship between the pressure and atmospheric temperature, a practical model was set up by pressuring air vessel to a set point. The temperature and pressure reading were recorded on a chart using ITT-Barton recorder under atmospheric conditions over time. The readings from the recorded chart were picked at 15minutes interval as presented in Table 1, interpreted and analyzed using Microsoft Excel as shown in Figure 2. The analysis shows that change in atmospheric temperature at different time of the day causes a linear change in the tank pressure.

Table 1: Recorded cylinder air pressure under environmental temperature

S/N	TIME (Min)	CHART READING		EQUIVALENT VALUE	
		PRESSURE (1:3psi)	TEMPERATURE (1:2°F)	PRESSURE (psi)	TEMPERATURE (°C)
1	3:30	32.50	50.00	97.50	37.78
2	3:45	32.50	52.50	97.50	40.56
3	4:00	33.00	53.00	99.00	41.11
4	4:15	33.50	54.00	100.50	42.22
5	4:30	35.00	56.00	105.00	44.44
6	4:45	34.50	55.00	103.50	43.33
7	5:00	34.00	52.00	102.00	40.00
8	5:15	34.00	50.00	102.00	37.78
9	5:30	33.90	49.50	101.70	37.22
10	5:45	33.75	48.00	101.25	35.56
11	6:00	33.70	47.00	101.10	34.44
12	6:15	33.50	46.00	100.50	33.33
60	6:15	29.75	38.00	89.25	24.44
61	6:30	29.75	38.00	89.25	24.44
62	6:45	29.75	38.00	89.25	24.44
63	7:00	29.75	39.00	89.25	25.56
70	8:45	30.50	45.50	91.50	32.78
71	9:00	31.00	46.00	93.00	33.33
72	9:15	31.00	47.00	93.00	34.44

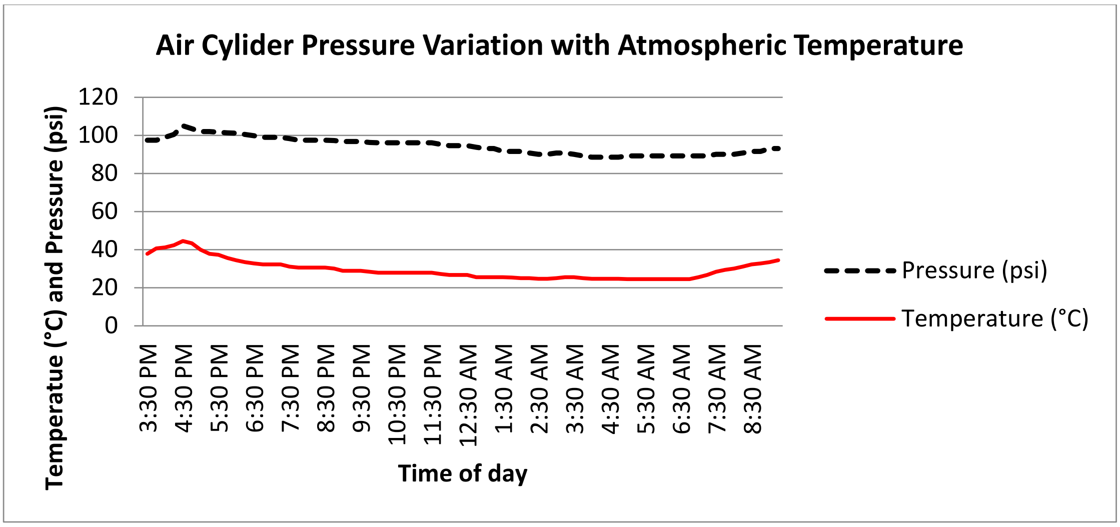

Figure 2: Air cylinder Pressure variation with atmospheric temperature over time

2.3 The Control Unit

In order to achieve better performance, improve efficiency and ensure safety of the system, a digital control system was applied to automatically adjust the operational points with respect parametric changes as shown in Figure 3. The aim of this control system is to ensure that the physical variables of the storage cylinder and that of the compression system remain relatively constant in time as desired. The control sequence is initiated by parametric reading through sensors, conversion of the analogue value variation into digital data by and ADC, and data storage in a temporary register. The ADC unit and the storage registers are embedded in the PIC18F4520 microcontroller applied here. The respective values measured are weighed with set points and the corresponding condition codes are raised. These codes are consistently used to adjust the operational condition of the system.

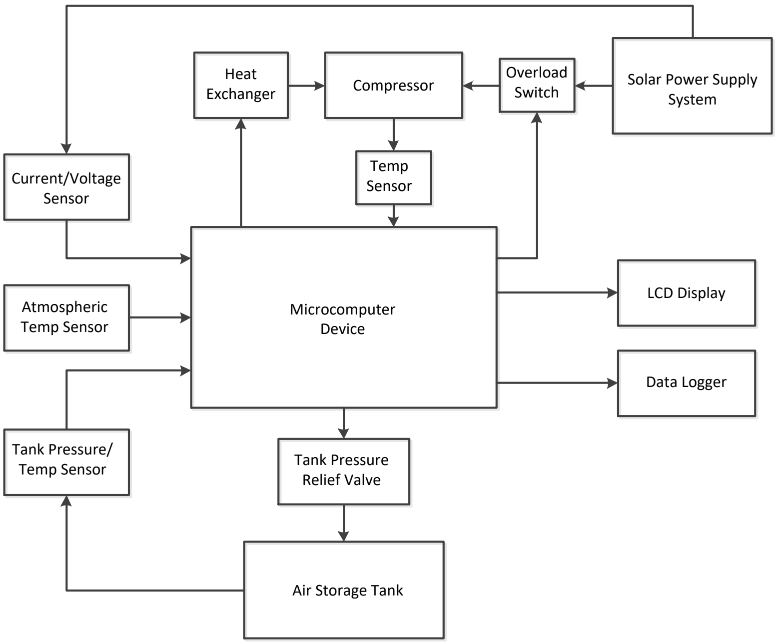

Fig. 3: Simplified block diagram of Pneumatic modular solar energy storage control system

2.4 Pressure Control

The cylinder air pressure is raised by an air compressor through the inlet of a two-way input/output valve. A pressure regulator installed at the output of the cylinder is used to regulate the air outflow as illustrated in Figure 4. The compressor has a constant running speed as such the pressuring effect on the storage cylinder is controlled using a discrete ON/OFF signal from the microcontroller.

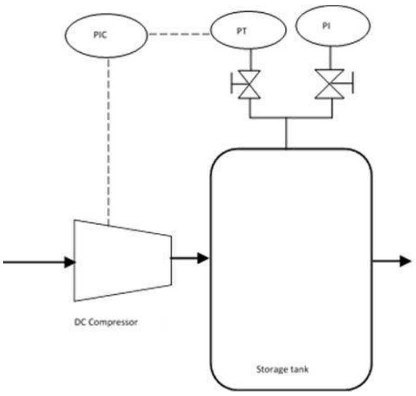

Figure 4: Pressure control loop for CAES

A pressure sensing element (SKU237545) mounted on the storage tank was used to monitor the tank pressure. Analogue signal generated by the sensor is presented in form of voltage (0-5V) to the microcontroller and is converted by the ADC unit to its digital equivalent to an accuracy of approximately 4.883mV per bit.

2.5 Temperature Control

In order to check the heat variation of the system, the cylinder temperature is also monitored through temperature sensor (LM35) inserted in a thermo well and connected to the microcontroller through its ADC unit. The atmospheric and compressor temperature are also monitored by the control unit. The temperature data are both used for the system heat variation analysis in other to determine the best environmental conditions for the operation of the system. While the compressor temperature data were used to provide cooling for the compressor with respect to control set points

2.6 Control Algorithm

In order to provide appropriate control of the system with respect to each parameter variation, algorithms of figures 5 to 8 were developed. Figure 5 is the main control loop and provides access to parametric measurements and determination of control direction using selected flags. When flags are true, corresponding parametric deviations (errors) are calculated and the result used to decide on appropriate action to be taken. Figure 6 deals with parameter measurement, and enable the system to read parametric analogue value, convert this value to its digital form for the microprocessor to manipulate. This manipulation may involve scaling to required accuracy and flag generation. Figures 7 and 8 provides detail control operation of the compressor with respect to its operating current/voltage and temperature.

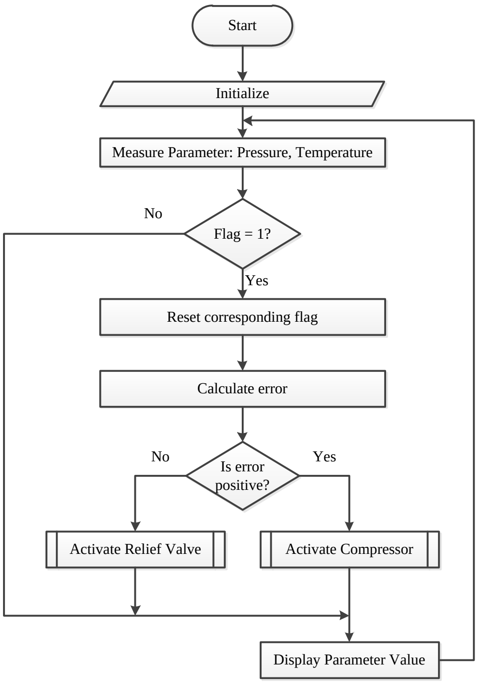

FigUre 5:. Storage tank parameter control algorithm

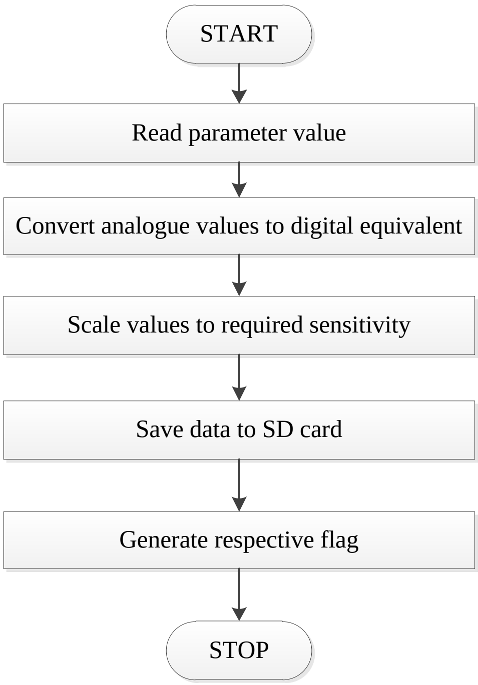

Figure 6: Parameter measurement routine

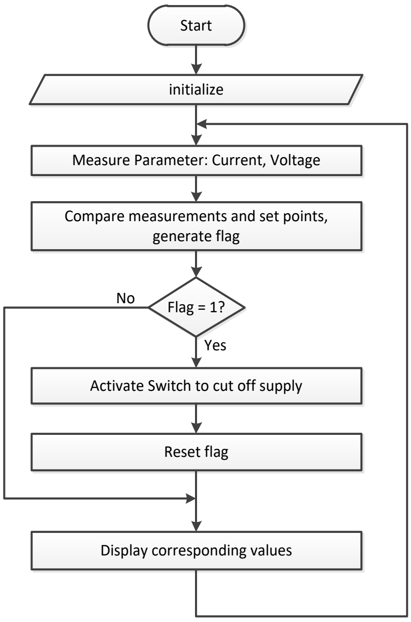

Figure 7: Compressor current/voltage subsystem control algorithm

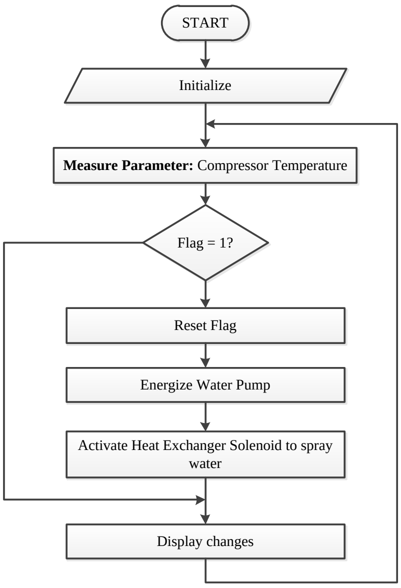

Figure 8: Compressor temperature control algorithm

The software code executing these algorithms were compiled and burned into the microcontroller internal memory. The controller therefore executes the program and issues necessary commands using the systems operational circuit of Figure 9.

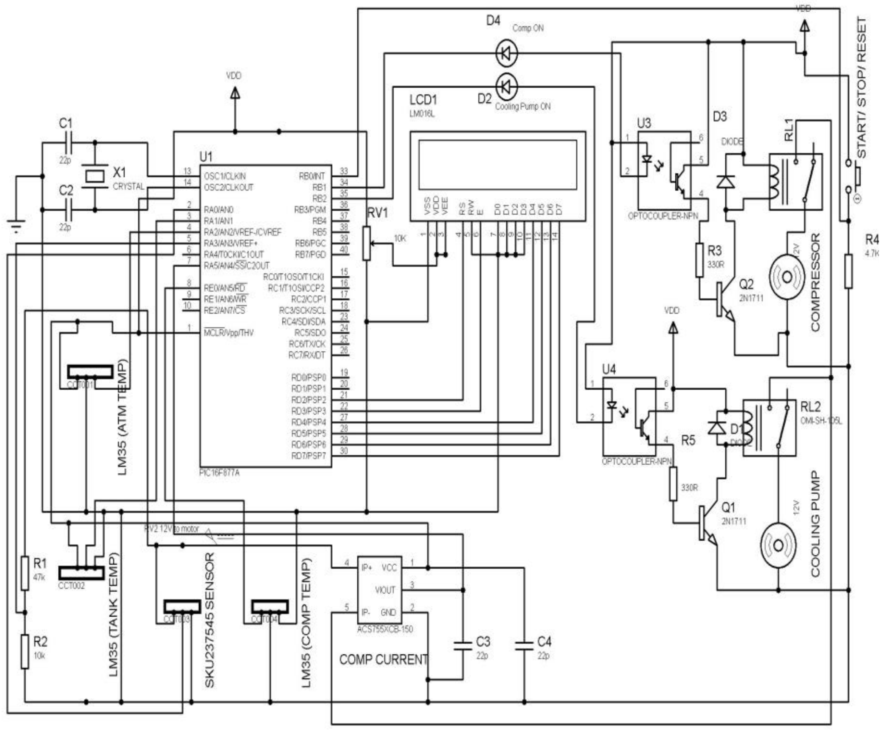

Figure 9: System control circuit

2.7 Experimental Setup of the Storage System

The completed system was setup to test and investigate operational behavior with respect to its input changes and required set-points. In doing this, the solar panels were placed under the sun and coupled to the rest of the system indoor as shown in Figure 10.

Figure 10: Experimental setup

3. Results and Discussion

3.1 Presentation of Results

Acquired data from the system were stored into a memory device attached to the system. An extract from this data is as shown in Table 2. Graphical representation of these data as shown in Figures 11 indicates that there is a strong co-relation between air compression rate and the cylinder air pressure over time. Figure 12 depicts the path followed by the compressor temperature when placed under control. Figure 13 shows that the compressor temperature affects to a high degree the rate of air compression by the compressor and that this relationship can be affected positively through application of a control mechanism.

Table 2: Acquired data from Air Storage system

TIME (MIN)	**STORAGE TANK**		**ATMOSPHERIC TEMPERATURE (°C)**	**COMPRESSOR TEMPERATURE (°C)**	**REMARKS**
	PRESSURE (psi)	**TEMPERATURE (°C)**			
0	2	26.36	29.29	28.14	Comp ON, Pump ON
1	4	26.36	29.29	28.20	Comp ON, Pump ON
2	8	26.36	29.29	28.20	Comp ON, Pump ON
3	12	26.63	29.29	29.29	Comp ON, Pump ON
4	16	26.36	29.29	29.29	Comp ON, Pump ON
155	76	27.83	33.38	35.39	Comp OFF, pump ON
156	76	27.83	33.38	34.77	Comp ON, Pump ON
157	76	27.83	33.38	35.84	Comp ON, Pump ON
158	76	27.83	33.38	37.72	Comp ON, Pump ON
159	76	27.83	33.38	38.85	Comp ON, Pump ON
160	76	27.83	33.38	40.08	Comp OFF, pump ON

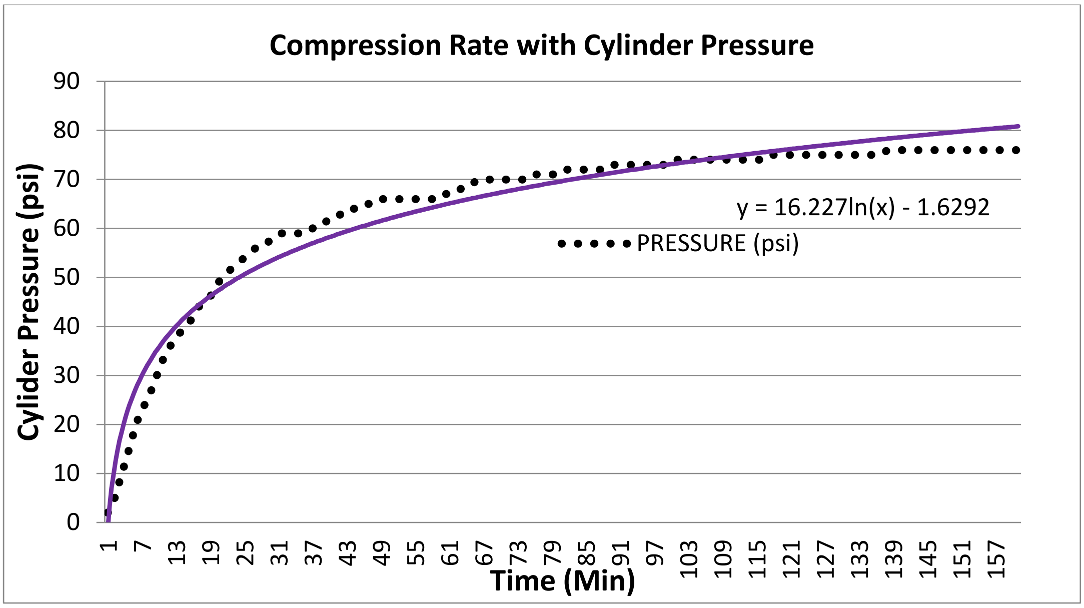

Figure 11: Air Compression rate with cylinder pressure

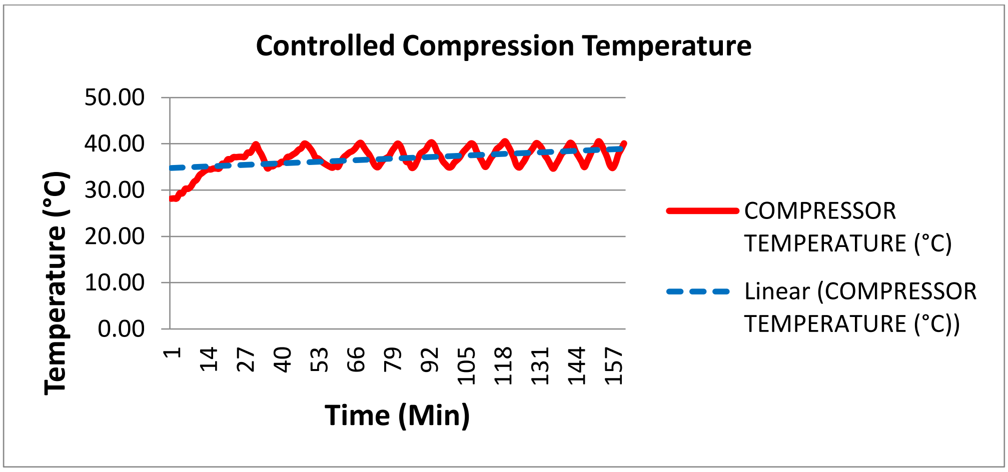

Figure 12: Controlled compressor temperature

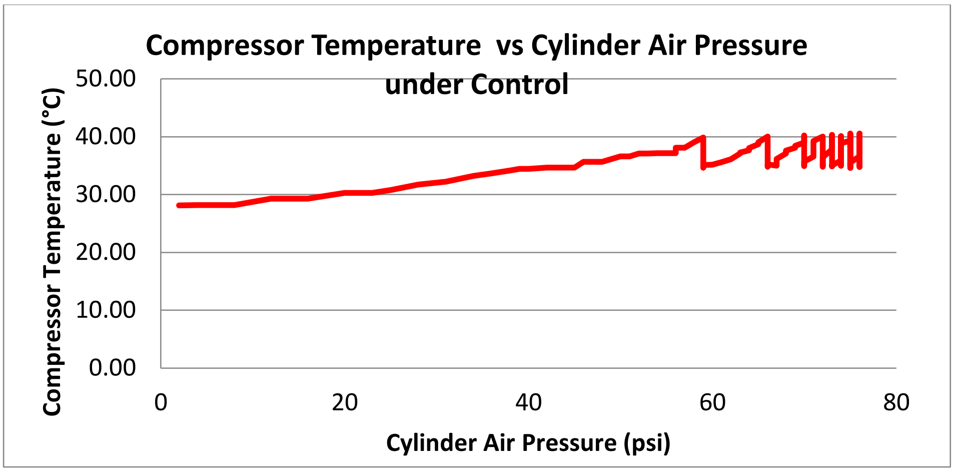

Fig. 9: compressor temperature against pressure under control

3.2 Discussion of Result

Figure 8 shows the rate of change of the cylinder air pressure with time and indicate that the compressor will pump air into the cylinder at a rate closely describe by a logarithmic function of equation (12) as:

$$y = 16.227 \ln x - 1.6292 \qquad (12)$$

With a deviation of about ±2.5% the general equation for the air compression rate is as shown in equation (13)

$$p = 16.227 \ln t \qquad (13)$$

From which the time required to attain a given pressure and vice versa can be determined.

Figure 9 shows how the control system helps maintain the compressor temperature within its operational range. The control ensures that the compressor temperature does not exceed a set limit through continuous power switching and cooling process. Without this control, as seen from the Figure 9, the compressor temperature will grow rapidly in about 30 minutes above its operational point and will lead to system damage.

From Figure 10, it can be established that the compressor temperature varies proportionally to cylinder air pressure with deviations related to the compressor performance and the environmental conditions. It also shows that at about 59psi the compressor temperature has risen to 40^0C which is the maximum compressor temperature in 30mins. After the first cool down cycle, the rate of cool down is seen to increase as the cyliner air pressure increases. This indicates that the cooling cycle is being effectively regulated by the control subsystem resulting to a more balanced operation.

Conclusion

In order to investigate the use air as storage medium for energy derived from renewable sources such as solar energy, an experimental module of micro-scale green power generation storage system was setup. For proper investigation, several parameters of the system were monitored including temperature changes during compression, atmospheric temperature and pressure of the storage cylinder through a control system to ensure better efficiency. From the investigation so far, solar pneumatic modular energy storage for green power generation at micro-scale level is practicable. The small scale CAES system will serve as a primary energy storage system in several renewable applications due to its high life cycle, high efficiency, low maintenance cost and zero emission. It however requires the development of more efficient air compression systems that can be directly connected to DC sources. Such compressors are expected to produce a better compression ratio compare to those currently available.

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