ENERGY STORAGE IN THE FORM OF COMPRESSED AIR WITH AN AIR PVT FIELD : INFLUENCE OF INPUT PARAMETERS ON THE AIR RESERVOIR

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ABSTRACT

The use of compressed air, one of the alternatives to the use of batteries as an innovative renewable energy (RE) storage solution, is characterised by a remarkable stored energy density (kWh.m^{-3}) and high reliability (days of operation) with no environmental impact. The compressed air stored in the reservoirs, during periods of excess production by the thermal air photovoltaic field (high insolation), is used to turn a Compressed Air Motor (CAM) for use during periods of low or no solar irradiation. Our work involves developing a numerical model capable of simulating a compressed air energy storage (CAES) system powered by a CPVTA air-cooled photovoltaic array and a system for cooling photovoltaic panels by using fresh air at the CAES outlet. In this paper, mathematical models for estimating the relevant reservoir parameters (the energy stored in the reservoir, the useful energy stored, the utilisation factor of the stored pressure, the volume of the air reservoir, the reservoir charge time, the reservoir discharge time and the volume of air produced in the reservoir) are developed. The study concludes with analyses of the influences of the CAES-CPVTA system input parameters on the compressed air storage tank, such as : global solar irradiation, the power of the photovoltaic panel field, the number of compressor and MAC stages, and the maximum and minimum stored pressure.

Keyword : - *Solar radiation, storage, reservoir, pressure, energy, photovoltaic, thermal, compressed air.*

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1. INTRODUCTION

Like other renewable sources, the direct large-scale integration of solar photovoltaic energy is problematic due to its intermittency and variability. Solar energy storage is a reliable and effective strategy for controlling the overall system and ensuring smooth operation and continuity of power supply for stand-alone sites. In recent years, a great deal of scientific research has shown alternatives to batteries in the form of compressed air energy storage (CAES) [1,2,3,4,5,6,7]. The aim of this article is to demonstrate the possibility of storing solar electrical energy in the form of compressed air using a CAES-CPVTA system, specifically by studying the input parameters influencing the air reservoir in Mahajanga's climate. The electrical energy produced by the thermal photovoltaic field is used in the compression system to compress the air [1]. This air will be stored in a tank to power a 5 kW compressed air motor (C.A.M.). This engine does not use all the stored energy to convert it into electrical energy. As a result, some of the air passing through the air motor at a pressure higher than atmospheric pressure will be lost. This is why it was decided to couple the pneumatic motor to a CPVTA in order to recover this lost air to cool the photovoltaic cells, thereby optimising the system. To understand the impact of the key parameters on the system, mathematical models were developed to calculate : the energy stored in the tank, the useful energy stored, the utilisation factor of the stored pressure, the volume of the air tank, the charging time of the tank, the discharge time of the tank and the volume of air produced in the tank.

2. METHODOLOGIES

Mathematical models (RESERVOIR) have been introduced to study the parameters influencing the system. Figure 1 shows a diagram of the model studied:

Fig -1 : System modelling

2.1 Architecture of the system studied

Our system consists of a 50 m^2 field of Air Thermal Photovoltaic panels. This feeds a compressed-air storage system, with a 3 kW electric motor, a 200 L tank strong enough to withstand high pressures (70 bar to 200 bar) and an expansion system consisting of a compressed-air motor (MAC) connected to a 5 kW to 8 kW alternator [1].

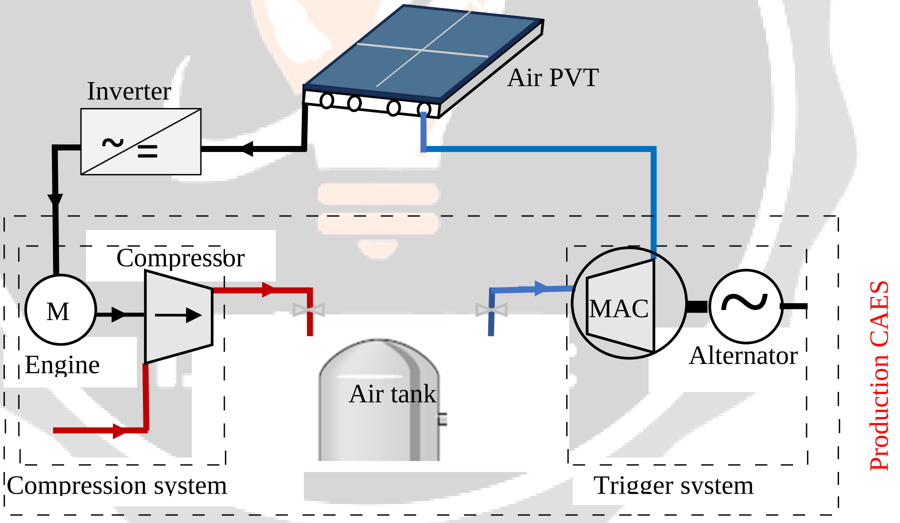

Fig -2 : System configuration (PVT-CAES) [1]

2.2 Assumptions for modelling the overall system

Throughout this study, we will consider the following hypotheses [1,2,3,4,8,9] :

- Air has the properties of a perfect gas (air is considered dry).
- The pressure losses of the working fluids will be neglected (CAES).
- The humidity level in the system is negligible (CAES).
- The kinetic and potential energies inside the CAES are negligible.
- Gravity is negligible in the compression and expansion stage.
- The modelling is carried out dynamically, but some components are treated statically, since for these components the terms of heat accumulation and mass are not taken into account (CAES).
- Compression and expansion are polytropic transformations.
- The dead volume of the compressor is negligible.

2.3 Air tank

In this work, we will use the constant volume storage mode. This means that the air pressure in the reservoir will be a function of the charge and discharge of the reservoir. There are many methods of storing compressed air in the literature [8]. Our study focuses on air storage in cylindrical cylinders that are strong enough for high pressures.

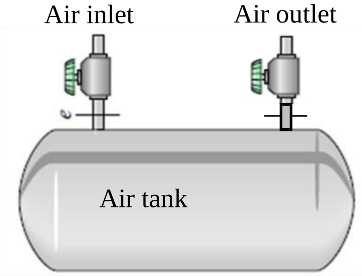

Fig -3 : Air storage tank.

2.3.1 Energy stored in the tank

The energy stored per unit volume depends on the pressure in the tank and the subsequent use (expansion) of the stored air [3] :

$$E_{st} = p_{st}\frac{kn_d N_d}{n_d - 1}\left(1-\left(\frac{p_a}{p_{st}}\right)^{\frac{n_d-1}{n_d N_d}}\right) \tag{1}$$

2.3.2 Stored useful energy

During expansion, some of the stored energy is not used. At this point, the generator's minimum operating pressure is higher than atmospheric pressure. Useful energy is therefore defined as the difference between the energy stored at maximum pressure and the energy stored at minimum pressure [2,3] :

$$E_u = E_{st}(\mathrm{p}_{\max\_st}) - E_{st}(\mathrm{p}_{\min\_st}) \tag{2}$$

2.3.3 Stored pressure utilisation factor

As the stored pressure can vary up to a minimum useful pressure in the tank, another parameter, the pressure utilisation factor, can be defined as follows [2,3] :

$$FUP = 1 - \frac{E_{st}(\mathrm{p}_{\min\_st})}{E_{st}(\mathrm{p}_{\max\_st})} \tag{3}$$

2.3.4 Air tank volume

The volume of the tank needed to compress the air depends on a number of parameters: the maximum and minimum pressure required for expansion, the desired range and the maximum volume flow rate [2,3].

$$V_r = \frac{p_a \dot{V}_{\max\_d}}{p_{\max\_d} - p_{\min\_d}} \tag{4}$$

2.3.5 Tank charging time

According to our assumptions, the instantaneous air mass flow rate stored can be calculated by the ratio between the power required for compression and the energy per unit mass absorbed by the compressor. This same flow rate can be calculated from the conservation of mass equation [2,3,9]:

$$\dot{m}_{st} = \frac{dm_{st}}{dt} = \frac{P_c}{E_c} \tag{5}$$

According to the perfect gas equation : $m_{st} = \dfrac{pV_{st}}{rT}$.

Replacing the stored mass in equation (5) and integrating from the start of loading to the end gives :

$$\int_0^{t_{ch}} dt = \int_{p_a}^{p_{st}} \frac{E_c V_{st}}{r P_c T} dp \qquad (6)$$

After solving equation (6), the charging time is expressed as :

$$t_{ch}(\tau_c) = N_c Ct_{ch} \left(\frac{\tau_c^{(\gamma_{ch}+1)}}{\gamma_{ch}+1} - \tau_c \right) \qquad (7)$$

With : $Ct_{ch} = \dfrac{V_p C_A p_a}{r P_c}$ *et* $\gamma_{ch} = \dfrac{n_c - 1}{n_c N_c}$

2.3.6 Air tank discharge time

The discharge time of a reservoir depends on the nature of the expansion. In this study, the expansion ensures the operation of a pneumatic motor (MAC). We will carry out the same calculations as above. However, we will use the parameters of the compressed air motor (the useful mass flow rate of the MAC, the power produced by the MAC and the energy produced per unit mass by the MAC) : The expression for the discharge time is therefore [2,3] :

$$t_{dech}(\tau_d) = N_d Ct_{dech} \left(\frac{\tau_d^{(\gamma_{dech}+1)}}{\gamma_{dech}+1} + \frac{\gamma_{dech}}{\gamma_{dech}+1} - \tau_d \right) \qquad (8)$$

With : $Ct_{dech} = \dfrac{V_{st} C_A p_a}{r P_M}$, $\tau_d = \dfrac{p_{e\_M}}{p_{s\_M}}$ *et* $\gamma_{dech} = \dfrac{n_d - 1}{n_d N_d}$

2.3.7 Volume of air produced in the tank

By replacing the time constant by its expression (which is a function of the volume of air stored) in the charging time equation, we can derive the volume of air produced as a function of the PVT power. Thus, the following expression [2,3] :

$$V_p = \frac{P_{PVT} r t_{ch}}{p_a c_A N_c} \left(\frac{\tau_c^{(\gamma_{ch}+1)}}{\gamma_{ch}+1} - \tau_c \right)^{-1} \qquad (9)$$

3. RESULTS AND DISCUSSION

For the simulations (using MATLAB), we used the same characteristics of the PVT/compressor field, which we have already dealt with [1], as well as the meteorological data for the Mahajanga site : 15°43' South (latitude), 46°19' East (longitude). The Page model was used to estimate the mean annual global irradiance at the site [1,10,11]. The choice of relevant parameters influencing the system studied (PVT-Reservoir) is set to run a 5 kW MAC for future use. Table 1 shows the limits and choices of some of the parameters used in this work.

Table 1 : Limits of the parameters studied and the proposed choice [1].

Parameter studied	Limit	Choice	Unit
PVT field area	Variable	50	m^2
PVT field power	Variable	3	kW
Maximum stored pressure	5 - 500	200	bar
Tank volume	Variable	200	L
Number of stages (Compressor)	1 - 5	3	-
Charging time (tank)	Variable	1.8	h
Discharge time (tank)	Variable	1	h
Product power (MAC)	1 - 12	5	kW
Efficiency (Compressor)	Variable	73	%

3.1 Influence of number of stages, maximum and minimum pressure on stored energy

The amount of energy stored, per unit (m^3) of volume in a 200 L air tank, is significant with an increase in the maximum permissible pressure in the tank and the minimum useful pressure for the compressed air motor. For example, Figure 4-a shows that 1 m^3 of volume at 200 bar pressure provides 23.4 kWh for an N = 3-stage MAC. On the other hand, a 1-stage MAC for a cubic metre of air gives 15 kWh of work. Figure 4-b shows the variation in the useful energy density as a function of the minimum pressure at which the MAC operates for different values of maximum pressure. This useful energy for producing electricity from compressed air is high with low minimum pressures admissible to the pneumatic motor. For example, with a 200 L tank, at a maximum pressure of P_{max} = 200 bar, the useful stored energy density is E_u = 23.4 $kWh.m^{-3}$. On the other hand, with the same tank but a different maximum pressure P_{max} = 50 bars, the stored density is E_u = 4.5 $kWh.m^{-3}$.

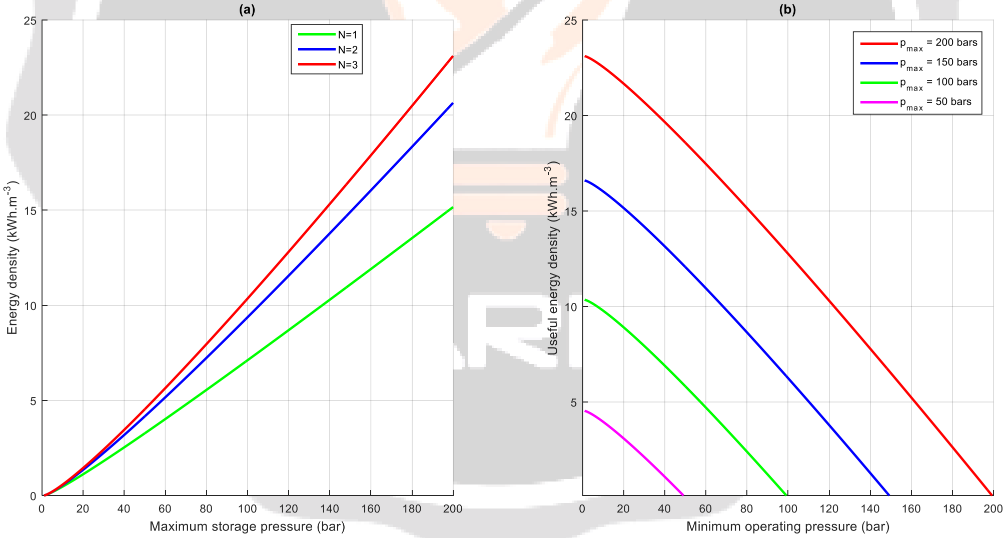

Fig -4 : Effect of stored pressure and number of stages on energy density

3.2 Influence of working pressure on the pressure utilisation factor

Figure 5 shows the fluctuations in the pressure utilisation factor for an open cycle as a function of the minimum storage pressure for a C.A.M. with N = 3 stages. This coefficient is zero (FUP = 0) if the minimum storage pressure (which drives the compressed air motor) is equal to the maximum pressure stored in the tank. It is equal to one (FUP = 1) if the minimum pressure is the same as the ambient pressure. This factor shows an approach to the energy performance of pneumatic energy storage. In fact, to have good efficiency in converting pneumatic energy into electrical energy, the FUP must be greater than 0.8. Therefore, in practice, the minimum pressure must be lower than the maximum storage pressure.

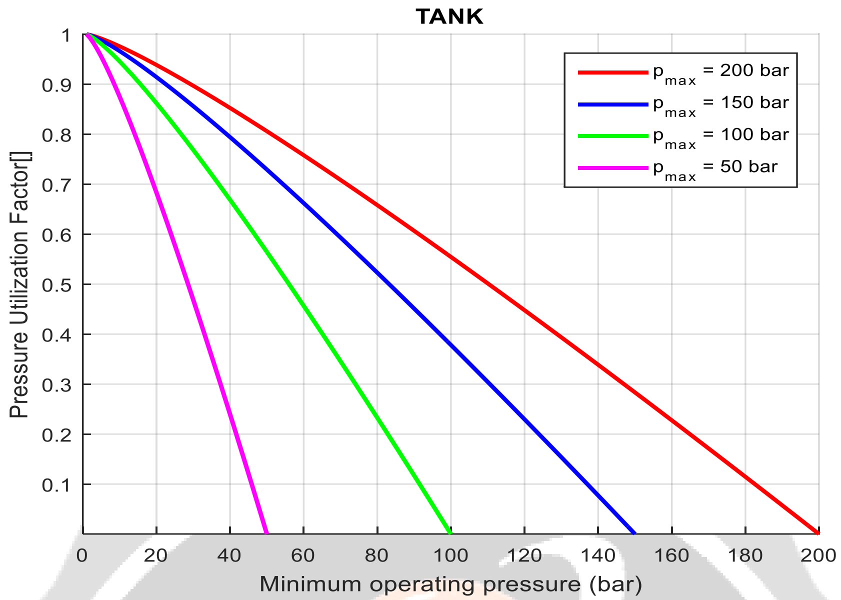

Fig -5 : Effect of the pressure utilisation factor on the minimum useful pressure for the 3-stage MAC.

3.3 Influence of solar irradiation on the volume of stored air

The volume of air stored is a function of the increase in power of the PV array, solar irradiation, surface area of the air-cooled PVT array, charging time and number of compressor stages. Figure 6 shows that the volume of air stored in the reservoir (a) increases as a function of the increase in power of the air-cooled PVT array and the number of compressor stages. For example, for a 20 kW compressor with N = 3 stages and an average running time of 1.38 h, the volume of compressed air required is 864 litres. On the other hand, for N = 1 with the same load duration and power, the useful volume of the tank is 583 L. In tank (b) with an air PVT field surface area of 50 m^2, irradiation of the order of 1000 W.m^{-2}, a tank charging time t = 1.38 h and a 3 kW compressor with a number of stages N = 3, the volume of compressed air stored is 200 litres. On the other hand, with the same parameters but a different number of stages (N = 1), the volume of air stored is 135.3 L.

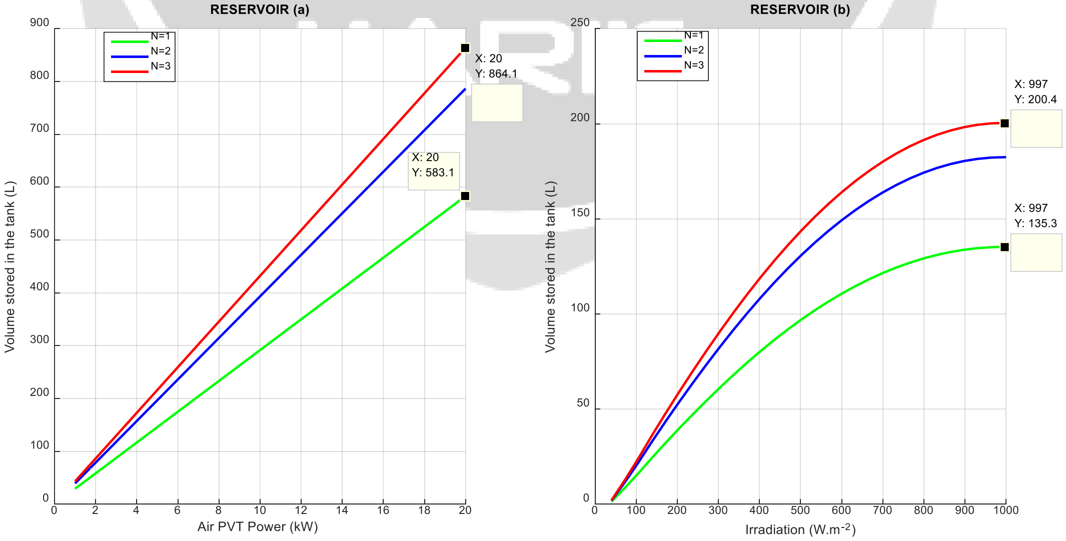

Fig -6 : Effect of solar irradiation and the power consumed by the compressor on the volume stored

3.4 Influence of source power and number of stages on charging time

This figure shows the variation in charging time for a 200 L tank as a function of the number of stages of a P_C = 3 kW compressor and the power of the PVT air field. Thus, as the number of stages and the power consumed increase, the charging time decreases. Figure 7-a shows that a single-stage compressor (N_C =1) can fill the 200 L volume in 2.72 h, whereas approximately 1.83 h will be sufficient to fill the same volume if the compressor has N_C = 3 stages. Figure 7-b shows that at a power of 3 kW (S=50 m^2 and G= 500 $W.m^{-2}$), it will take 1.8 h to fill a 200 L tank, whereas the same volume will be filled in about 12 min when the solar panels have a power of 20 kW (very large surface area of the PVT air field).

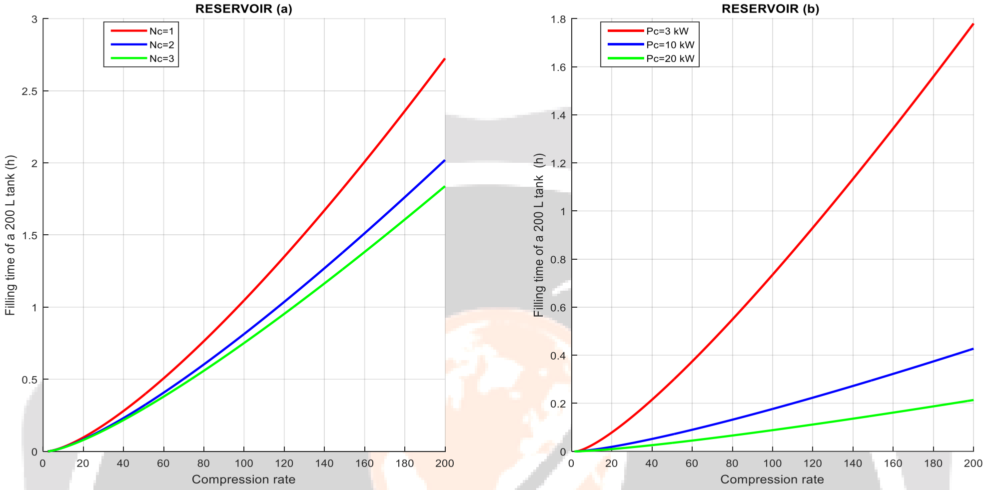

Fig -7 : Effect of power consumption and number of stages on tank charging time.

3.5 Influence of solar radiation on charging time

In Figure 8, the charging time for a 200 L tank decreases with increasing solar irradiation. Thus, with a PVT air field surface area S= 50 m^2 and irradiation G= 100 $W.m^{-2}$, after t_{ch} = 7.78 h the tank will be full. For solar irradiation G= 500 $W.m^{-2}$, approximately 1.83 h will be sufficient to fill the 200 L tank. On the other hand, with solar irradiance G= 1000 $W.m^{-2}$, for the same volume, after t_{ch} = 1.38 h the tank will be full.

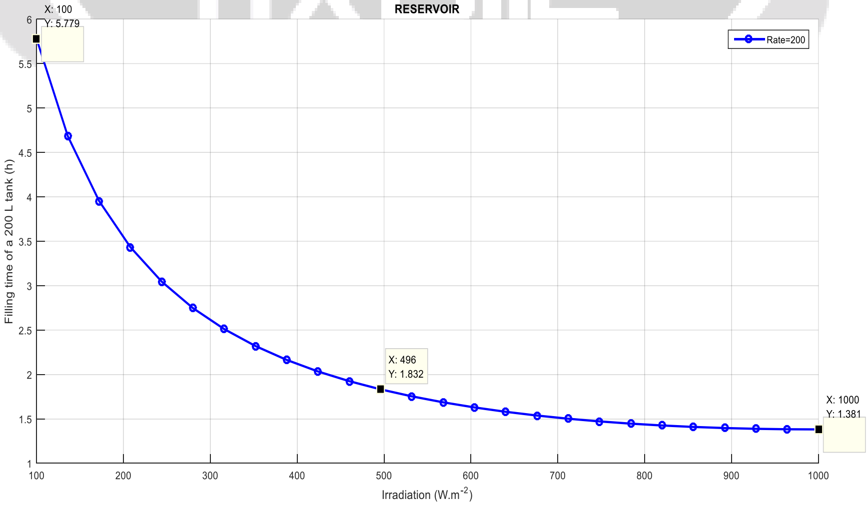

Fig -8 : Effect of illumination on tank charging time.

3.6 Influence of number of stages and discharge time on storage pressure

Figure 9 shows the variations in pressure versus discharge time for a 200 L tank, respectively, as a result of the effect of maximum storage pressure and number of stages. Thus, with a large maximum storage pressure and a small number of air motor stages, the discharge time is long. On the other hand, for a small storage pressure and a large number of MAC stages (large motor), the tank discharge time is small. Figure 9-a shows a tank with a maximum stored pressure of P_{max} = 200 bar and a number of stages N = 3. The discharge time for a tank with a volume of 200 L is t_{disch} = 1 hour. Whereas with the same MAC and tank, storage pressure 50 bar, the discharge time is about ten minutes. In Figure 9-b, a single-stage MAC discharges the 200 L of compressed air after one and a half hours. In contrast, a 3-stage MAC discharges the same compressed air tank after one hour.

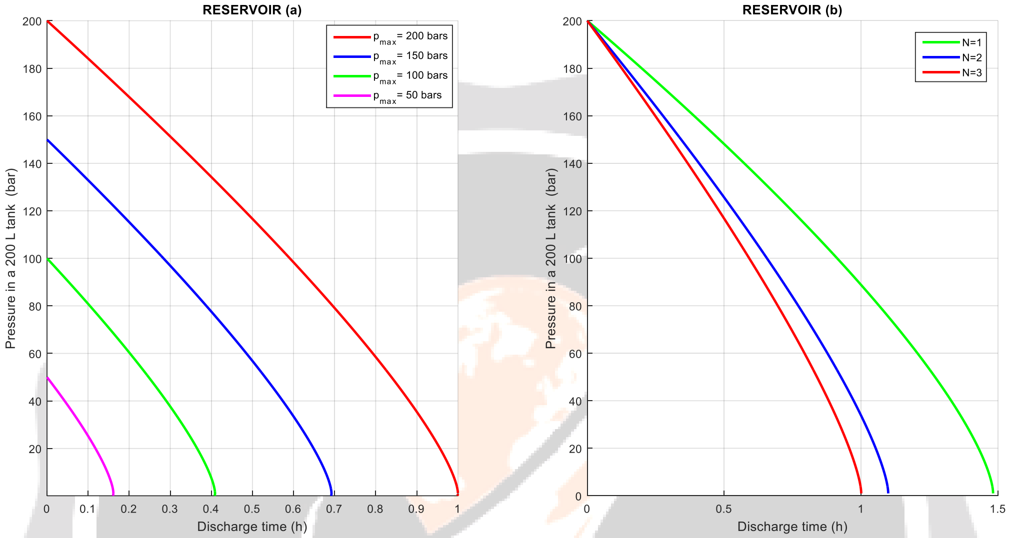

Fig -9 : Effect of discharge time and number of stages on the pressure stored in a tank.

4. CONCLUSION

In conclusion, this study demonstrates the feasibility of a compressed-air storage system with a CPVTA, taking into account the key parameters that overly influence the system (storage tank). With regard to the results of the analysis of the influence of the relevant input parameters of the system studied, it is clear that the insolation of the site, the power of the photovoltaic panel field, the number of compressor and MAC stages, and the maximum and minimum stored pressure play major roles in the design and sizing of a compressed air tank. Although among these parameters, another was neglected (solar irradiation) in almost all the domestic studies encountered in the literature. The simulations produced satisfactory solutions. Thus, with an increase in: solar irradiation, the power of the CPVTA and the number of compressor stages, the air reservoir is charged too quickly. On the other hand, if these factors are reduced, the time taken to charge the tank is enormous. The volume of air stored in the tank also increases with an increase in these same influencable aspects. Meanwhile, the amount of energy stored increases as the permissible pressure in the tank increases. Also, the discharge time of the same tank is high with a high storage pressure and a small number of expansion stages. In contrast, the tank discharges too early. The next logical step in this work is to study an air motor and/or a biodiesel engine paired with a compressed air tank fed by a CPVTA in order to raise awareness of the key parameters affecting the performance of the system studied.

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