Technical Review on Study of Compressed Air Vehicle (CAV)

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Abstract: Diesel and Petrol engine are frequently used by automobiles industries. Their impact on environment is disastrous and can't be neglected now. In view of above, the need of some alternative fuel has been arises which lead to the development of CAVs (Compressed Air Vehicle). It is an innovative concept of using a pressurized atmospheric air up to a desired pressure to run the engine of vehicles. Manufacturing of such vehicles would be environment friendly as well as put the favorable conditions for the cost. Applications of such compressed air driven engine are in small motor cars, bikes and can be used in the vehicles to be driven for shorter distances. This technology states that, if at 20 degree C, 300 liters tank filled with air at 300 bar carries 51MJ of energy, experimentally proved. Under ideal reversible isothermal conditions, this energy could be entirely converted to mechanical work which helps the piston and finally crankshaft to rotate at desired RPM (revolutions per minute).The result shows the comparison of different properties related to CAV and FE (Fuel Engines). For example emission of toxic gases, running cost, engine efficiency, maintenance, weight aspects etc.

Keywords: Compressed air vehicle. Fuel Engine, Compressed air technology

1. INTRODUCTION

Compressed air has been used since the 19th century to power mine locomotives and trams in cities such as Paris and was previously the basis of naval torpedo propulsion. Several researches & long term perseverance has put forward an idea of *Compressed Air Technology (CAT)* with the keen motto of reducing the pollution up to acceptable extent., it is said that the Frenchmen Andraud and Tessie of Motay ran a car powered by a pneumatic motor on a test track in Chaillot, France on July 9, 1840. *Motor Development International (MDI), France* is the first company who has worked on this future technology. Compressed air engine (CAE) is powered by compressed air which is stored in a tank at high pressure such as *30MPa (4500 Psi or 300 bar).* Instead of driving engine pistons with an ignited fuel air mixture, CAE uses the expansion of compressed air to provide a necessary *mechanical power to the crankshaft. Charles B. Hodges* is remembered as the father of CAT (Compressed Air Technology). He had not only driven a compressed air car but also achieved a considerable commercial success in it. His company initially sold a numerous such vehicle to the mining industries in U. S. In this work, the comparisons between CAV, FE and Battery Electric Vehicle has been done and on the basis of different parameters e.g.-: Required Primary Energy, Efficiency, Green house Gas Emission etc and on the basis of thermodynamic efficiencies.

2. TECHNOLOGY USED

Compressed air vehicle (CAV) is powered by engine fueled with compressed air, which is stored in a tank at high pressure such as 30 MPa (4500 psi or 300 bars). Rather than driving engine pistons with an ignited fuel-air mixture, CAV use the expansion of compressed air, in a similar manner to the expansion of steam in a steam engine. A CAE is the pneumatic actuator that creates useful work by expanding compressed air. Actually, the energy is primarily derived from electric grids to run an air compressor to compress the air as it is operated by electricity. So, we can divide the process into two stages: (1) Compression stage and (2) Power stage

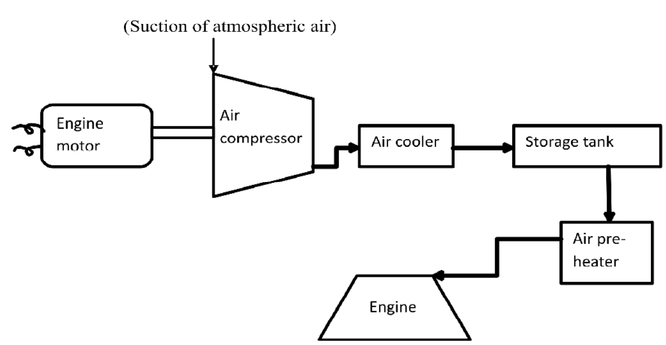


Figure 1: Block Diagram to Show the Working of CAV

2.1. Compression Stage

The fresh air is sucked by the compressor from the atmosphere which is then allowed to get filtered. After this operation, the air is compressed by the motor under certain pressure which is much greater than the atmospheric pressure i.e. 30 MPa or 4500 psi. After compression, air is delivered to storage tank. But during compression, the air gets heated which can be dangerous. So, we use air cooler before delivery. The storage tank often made up of carbon fiber or Kevlar for the deduction of weight while maintaining the strength.

The air can be compressed by two technologies:

(a) Single stage compression

(b) Multi stage compression

(a) Suction stroke (b) Compression stroke

Figure 2: Basic Operations

Multi stage compression is more efficient than single stage compression but it requires more space. The basic operation of both is same i.e. suction and compression as shown in fig. 2 (a) & 2 (b) but in multi stage this phenomenon is repeated.

2.2. Power Stage

A desired volume of compressed air is allowed to enter in the piston cylinder arrangement which on after expansion provides the mechanical work to the piston and hence, desired torque to the crankshaft. All the working hierarchy is very similar to the normal engines but uses special crankshaft and piston. The piston is allowed to be held at top dead center (TDC) for about 70 degree of the cycle. In this way, we can get a better torque on the crankshaft. The atmospheric temperature is used to reheat the engine and increase the road coverage. To expel the cold air, the air conditioning system is used.

3. THERMODYNAMIC ANALYSIS

Thermodynamically, there are two processes, compression and expansion which need to be study throughout the working cycle of engine.

3.1. Compression

The compression process is treated as polytropic change of state. The compression to initial air volume V_1 to the final tank volume V, is followed by heat removal at constant tank volume $V_3 = V_2$ from P_2, T_2 to P_3, T_3 ($T_3 = T_1$, T_1 is initial ambient temperature).

Reference Conditions

Normal pressure P_0 = 760 mmHg = 1.01325 bar = 0.101325 MPa

Normal temperature T_0 = 0°C = 273.15 K

Air density at NTP ρ_0 = 1.2922 kg/m^3

Initial conditions ("1")

Ambient temperature T_1 = 20°C = 293.15K

Ambient pressure P_1 = 1 bar = 0.1 MPa

Air density ρ1 = 1.1883 kg/m3

Original air volume $V_1 = V_3 * P_3/P_1$ = 90 m^3 (before compression)

Mass of air M_1 = V1 * ρ1 = 106.95 kg

Final conditions inside filled tank ("3")

Tank volume V_3 = 300 Liter = 0.3 m^3

Air temperature $T_3 = T_1$ = 20°C = 293.15 K

Pressure in air tank P_3 = 300 bar = 30 MPa

Air density ρ3 = 356.49 kg/m^3

Mass of compressed air $M_3 = V_3$ * ρ3 = 106.95 kg = M_1 (check)

Final conditions after expansion ("4")

Air pressure p_4 = 1 bar = 0.1 MPa

Three compression processes are illustrated in a pressure-volume diagram (Figures 3) and a temperature-entropy diagram (Figure 4). In single

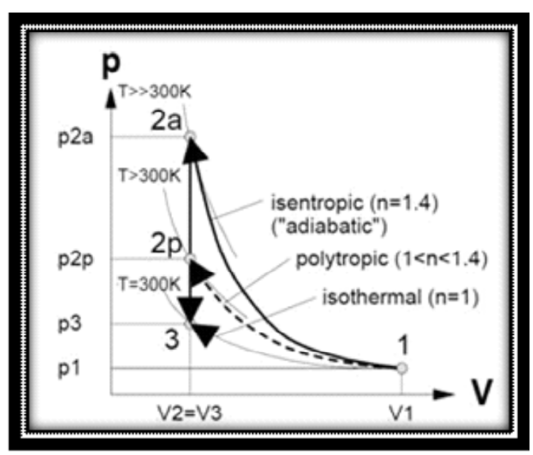


Figure 3

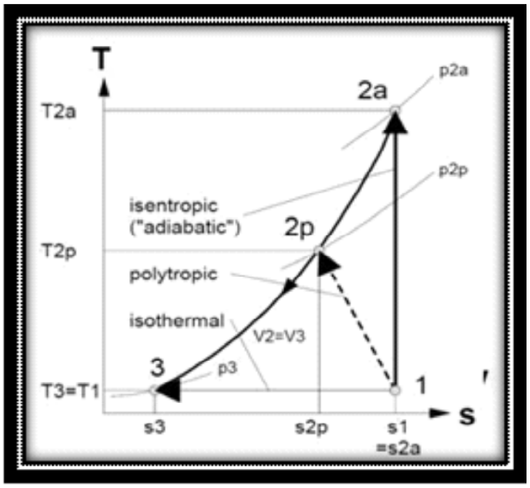


Figure 4

stage compression, several processes can be followed according to the environment provided.

3.1.1. Isothermal Compression

During the idealized reversible isothermal compression process the temperature is considered to remain unchanged. The technical work required for filling the tank with air from P_1, T_1 to P_3, T_3=T_1 under isothermal condition is-

$$Wt_{13} = W_{13} = P_1 * V_1 * \ln (P_3/P_1)$$
$$= P_1 * V_1 * \ln(V_1/V_3) \quad (1)$$

3.1.2. Polytropic Compression Followed By Isochoric Cooling

The polytropic change of state follows the isentropic laws. However, the isentropic coefficient (√ = 1.4 for air) is replaced by polytropic coefficient i.e. 1.4 for isentropic and 1.0 for isothermal process.The technical work required for polytropic air compression from initial (P_1, V_1) to final (P_2, V_2) with V_2=V_3 is given by:

$$Wt_{12} = m * cp * (T_2 - T_1)$$
$$= P_1 * V_1 * n/ (n\text{-}1) * [(V_1/V_3) \wedge (n\text{-}1) - 1] \quad (2)$$

The intermediate pressure P_2 and temperature T_2 are obtained from

$$P2 = P1 * (V1/V3) \wedge n \quad (3)$$
$$T_2 = T_1 * (V_1/V_3) \wedge [(n\text{-}1)/n] \quad (4)$$

Finally, a thermodynamic efficiency of compression can be defined as the ratio of useful energy in the tank to the total technical work required to fill the tank with compressed air.

$$\eta th = Wt_{13} / Wt_{12} \quad (5)$$

The following significant results are obtained for different polytropic coefficient (Table 1)

Table 1

Single stage compression	*Isothermal*	*polytropic*	*Polytropic*	*polytropic*	*isentropic*	*units*
Polytropic coefficient n	1.0	1.1	1.2	1.3	1.4	-
Technical Work W_{t34}	51	76	115	177	277	MJ
Energy in tank Wt_{13}	51	51	51	51	51	MJ
Efficiency Wt_{34}/W_{t13}	100	67	45	29	19	%
Final temperature T_4	20	219	485	820	1,223	°C

3.2. Expansion Process

The thermodynamic equations presented above for air compression are also valid for air expansion. Again, the expansion process follows some polytropic dependence between the isentropic (n = 1.40) and isothermal (n = 1.00) limit. While in the case of compression the thermodynamic change of state was related to the change of volume, it is related to the change of pressure for the case of expansion. For a generalized polytropic expansion from the initial conditions (P_3 = 30 MPa and T_3 = 20°C = 293K) to P_4 = 0.1 MPa = 1 bar with ($P_3V_3 = P_1V_1$) the technical work recovered is given by:

$$Wt_{34} = m * cp * (T_4 - T_3)$$
$$= P_1 * V_1 * n/ (n\text{-}1) * [(P_4/P_3)\wedge(n/(n\text{-}1)) - 1] \quad (6)$$

The final temperature T4 is obtained from

$$T_4 = T_3 * (P_4/P_3) \wedge [(n\text{-}1)/n] \quad (7)$$

Finally, the overall thermodynamic efficiency is of interest. The useful technical work output of the expansion engine Wt34 is related to the technical work input for compression Wt12:

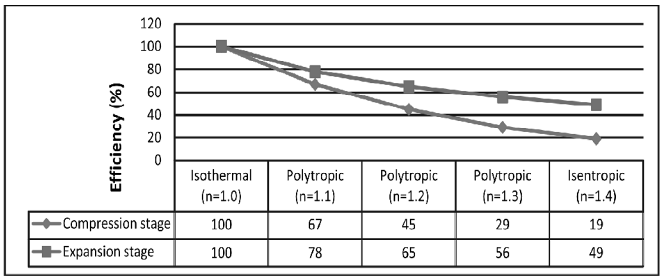
$$\eta th = Wt_{34} / Wt_{12} \quad (8)$$

The following results represent a single-stage polytropic expansion of air from tank conditions P_3 = 30 MPa and T_3 = 20°C. All equation for work or energy yield negative results as work is extracted from the system. (Table 2).

Table 2

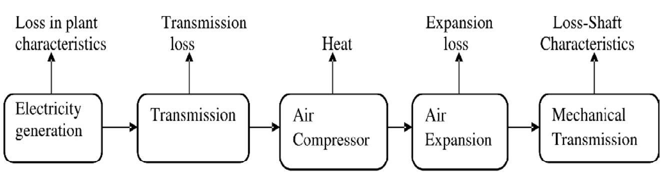
Single stage expansion	*Isother-mal*	*polytro-pic*	*Polytro-pic*	*polytro-pic*	*isentro-pic*	*units*
Polytropic coefficient n	1.0	1.1	1.2	1.3	1.4	-
Technical Work W_{t34}	51	51	33	29	25	MJ
Energy in tank Wt_{13}	51	51	51	51	51	MJ
Efficiency Wt_{34}/W_{t13}	100	78	65	56	49	%
Final temperature T_4	20	-99	-160	-194	-216	ºC

The above efficiencies are depicted in graph 1



(Graph 1)

The different stages of efficiency loss for transportation with the compressed air car are shown as a flow chart (1):



Flowchart 1

4. COMPARISONS WITH FUEL AND BATTERY ENGINES (FE AND BE)

How does compressed car perform compare to the conventional FE and BE?

In this particular, we compare different technologies with respect to:

1. Required energy per kilometer.
2. Efficiency for propellant.
3. Fuel storage weight and volume.
4. Primary energy required
5. Green house gas emission per kilometer.
6. Cost analysis.

4.1. Required Energy per Kilometer

Battery Electric Vehicle (BEVs) and Compressed Air Vehicle (CAVs) are commonly classified as electric cars as both types of car obtain their energy from the grid. To achieve ambitious climate change mitigation goals, not only must fuel economy must be improved but also total energy requirements (and travel demand) must be reduced. The improved fuel economy is achieved mainly by weight reduction, as well as other feasible technological improvements, and reduced motor power.

Table 3

Type of Vehicle	*Energy Require Per 100km. (Kwh)*	*Weight (Kg)*	*Speed (km/Hr)*
CAV	5.21	900	145
BEV	13.7	1000	100

4.2. Efficiency for Propellant

In order to compare the total efficiencies with respect to total energy requirement, we must consider the mechanical, flow and grid transmission losses which take place in between the stages from where the primary energy is obtained to the power transmitted on the wheel.

Table 4

Efficiency of propellant	*FEs*	*CAVs*	*BEVs*
Coal to wheel (%)	17.7	11.7	28.3
Wind to wheel (%)	17.7	29.2	70.8
Grid to wheel (%)	21.2	26.7	77.5
Propellant to wheel (κ) (%)	21.2	34.6	90

4.3. Fuel Storage Weight And Volume

The propellant weight is not significant as a fraction of total weight for conventional cars as their weight is much more than propellant but in case of BEVs and CAVs, it is mandatory to consider fuel weight and weight of batteries. Because the weight of propellant needed is a function of range (distance to be travelled) required. The relationship between fuel weight and vehicle properties can be stated as follows.

$$w_f e_f = (w_v + a w_f)\, r\, E_{wr}\, k^{-1}$$

Where w_f is the propellant weight, e_f the energy per weight fuel (gasoline: 45 MJ kg^{-1}, CAC:

1.94 MJ kg^{-1}, BEV: 0.40 MJ kg^{-1}) and κ the fuel-to-wheel efficiency. Defining the range-specific energy required per weight as, $E_{rs/w} \equiv rEwr^{k-1}$ the required propellant weight is

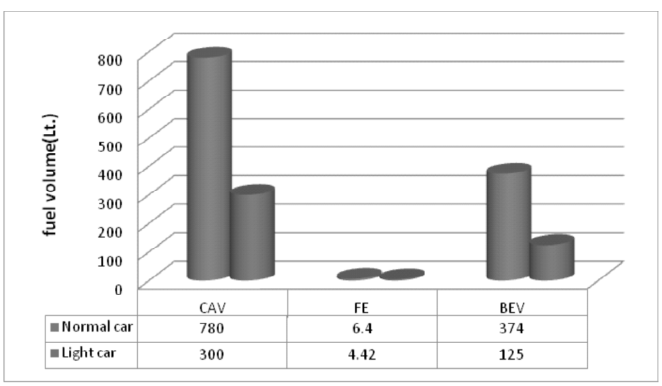
$$w_f = \frac{w_v E_{rs/w}}{e_f - aE_{rs/w}}.$$

The fuel weight for different storage technologies and car sizes is summarized in (table 5). Compressed-air weighs ten times more than gasoline with similar energy content, but three times less than batteries with similar energy content.

Table 5

Car weight (kg)	*Gasoline (kg)*	*CAC (kg)*	*BEV (kg)*
900	4.8	53.0	140.3
300	1.6	17.7	46.8

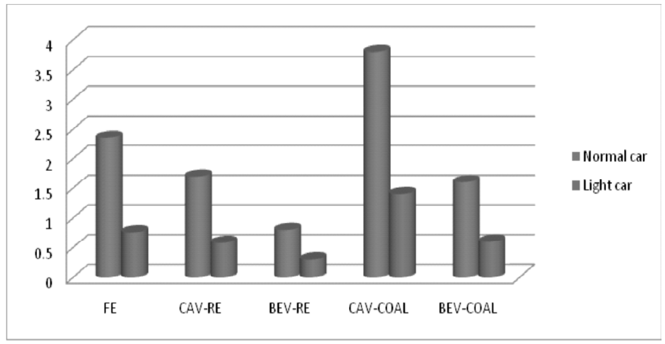
Cover a large distance, CAV requires a significant amount of compressed air. However, it is really the biggest issue that it has low energy density (energy stored per unit volume) and to do so a large storage tank is required. For 900 kg CAV to have a 150 km range, 780 l storage is required which is more than the double of trunk volume of small Internal Combustion Engine and BEVs, but the weight of it three times less than BEVs. All data has been illustrated in graph 2.



Graph 2: Fuel Volume in Liters for 150 km Range

4.4. Primary Energy Required

The primary energy requirement is crucially dependent on the power plant. If electric cars are powered by renewable energies, less primary energy is required than for the gasoline car. If electric cars are powered by coal power plants, more primary energy is required for CAVs but still less for BEVs. From the overall efficiency perspective battery cars are much more efficient.



Graph 3: Primary Energy Required in MJ /Km

4.5. Green House Gas Emissions Per Kilometre

Environmental performance as *zero local emissions* is one of the primary arguments for the compressed-air car. Indeed, noxious matter is not emitted locally when driving; thereby one of the main contributors to urban air pollution is eliminated. This benefit is shared by battery cars. However, compressed-air tanks can be disposed of or recycled with less toxic waste pollution than batteries, depending on the precise recycling requirements. One important environmental concern relating to car use is the impact of cars on climate change. Greenhouse gas emissions themselves depend critically on the source of electricity used for charging batteries or running the CAV compressor. Whereas a compressed-air car or the BEV does not emit greenhouse gases (GHG) when operated, emissions are shifted to power plants. Emission levels then depend on the power plant characteristics i.e. primary energy is obtaining from whether coal power plant, hydro power plant, solar energy, water energy, geothermal energy etc. Different power plants have different levels of CO2 emission which affects the ultimate GHG emission.

4.6. Cost Analysis

One of the dominant concerns for consumers is fluctuating high fuel prices and road maintenance costs. Initial cost or the purchasing price of CAV is slightly more as compared to BEVs, which does not make much difference. But the fuel and maintenance prices are much lesser than BEVs as we need to replace the electric batteries every successive year as they get exhausted or cannot be recycled again and again. For fuelling the CAVs and BEVs, both required electricity. So their fuel prices are same and much lesser than combustion engine. In case of BEVs, recharging is required very frequently i.e. under less range of driving but in case of CAVs, this range is double of that.

5.1. Pneumatic-Combustion Hybrid

In this concept, we can use two engines on the same crankshaft to provide power. To get the intial torque, FE is used and after achieving good speed, the engine is switched over to compressed air engine (CAE). Hence, this technology is used with the aim of reducing the emission of polluting gases up to certain limit. One theoretical study found that optimizing a hybrid air tank to 16 kPa and 80 l with combined engine downsizing can improve fuel efficiency by 31%. Fuel economy improvements of 64% in the city and of 12% on the highway have been reported in another model. Work demonstrated the feasibility of this concept, recovering up to half of the energy content of the compressed air; the expansion efficiency is > 48%.

5.2. Air-Engine Hybrid

The other hybrid concept is focused on the air engine. Here, a combustion engine would be used to recharge the air tank. Here the internal combustion engine can constantly work in the maximum efficiency regime. Energy is lost in the compression and expansion stages, comparably to section. However, waste heat of the combustion engine can be used to heat up the expanded air and, hence, increase expansion efficiency. Modeling studies claim that such an air engine hybrid can reach total vehicle efficiency > 33% compared to vehicle efficiency of 20% of the conventional car in our study.

6. POSITIVE ASPECTS OF CAV

One major advan-tage of using compressed air to power a car's engine is that a pure compressed air vehicle produces no pollution at the tailpipe. More specifically, the compressed air cars we're likely to see in the near future won't pollute at all until they reach speeds exceeding 35 miles per hour. That's when the car's internal air compressor will kick in to achieve extra speed. The motor that runs this air compressor will require fuel that'll produce a small amount of air pollution. Some fuel (you can use eco-friendly biofuels or fossil fuels) will also be used to heat the air as it emerges from the tank. The newest compressed air engines also offer drivers the option of using fossil fuels or biofuels to heat the air as it enters the engine. Nonetheless, this technology represents a marked improvement over cars powered by internal combustion engines that produce significant amounts of pollution at any speed. Air cars are also designed to be lighter than conventional cars. The aluminum construction of these vehicles will keep their weight under 2,000 pounds (907 kilograms), which is essential to making these vehicles fuel efficient and will help them go faster for longer periods of time.Another advantage of air cars is that the fuel should be remarkably cheap, an important consideration in this era of volatile gas prices. Some estimates say that the cars will get the equivalent of 106 miles (171 kilometers) per gallon, although compressed air will probably not be sold by the gallon. A more meaningful estimate is that it may take as little as $2 worth of electricity to fill the compressed air tank, though you'll also need gasoline to power the electric motor that compresses air while driving.

7. FURTHER IMPROVEMENT REQUIRED

When air expands in the engine it cools dramatically (Charles law) and must be heated to ambient temperature using a heat exchanger. The heating is necessary in order to obtain a significant fraction of the theoretical energy output. The heat exchanger can be problematic: while it performs a similar task to an *intercooler* for an internal combustion engine, the temperature difference between the incoming air and the working gas is smaller. In heating the stored air, the device gets very cold and may ice up in cool, moist climates.We can also use regenerative brakes to recharge the battery etc.

8. CONCLUSION

With the study of all the data, it is proved that both CAVs and BEVs are much more efficient and eco-friendly than gasoline engines i.e. FE.Moreover, CAVs and BEVs have a good fight for their existence on the platform of non conventional vehicles. But, where the power is more important, CAVs always dominate the BEVs as it can be hybrid with conventional engines. In addition to this, efficiency of CAVs can easily be increased more than that of BEVs with the implications of certain technologies.

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