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Thermodynamic Analysis of Compressed Air Vehicle Propulsion

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Abstract

The fist compressed air vehicles were built by Andraud and Tessié du Motay in Paris between 1838 and 1840. Since then the idea has been tried again and again, but has never reached commercialization. In recent years the French developer MDI has demonstrated advanced compressed air vehicles. However, the claimed performance has been questioned by car manufacturers and automobile expert. Basically, when referred to ambient conditions, the relatively low energy content of the compressed air in a tank of acceptable volume is claimed to be insufficient to move even small cars over meaningful distances.

On the other hand, another air car developer claims to have driven 184 km on one 300 Liter filled with air at initially 300 bar pressure. Obviously, there are issues to be resolved, not by heated debates, but by an analysis of the thermodynamic processes involved. This is the aim of this study.

The results indicate that both sides are correct. At 20°C a 300 Liter tank filled with air at 300 bar carries 51 MJ of energy. Under ideal reversible isothermal conditions, this energy could be entirely converted to mechanical work. However, under isentropic conditions (no heat is exchanged with the environment) not more than 25 MJ become useful. By multi-stage expansion with inter-stage heating the expansion process is brought closer to the isothermal ideal.

The analysis is extended to the compression of air. Again, the ideal isothermal compression is approached by multi-stage processes with inter-cooling. By this approach energy demand for compression is reduced to acceptable levels and system pressure and temperature are kept within safe limits.

The results of this analysis seem to indicate that the efficiency of the four-stage expansion process is acceptable, while even a four-stage air compression with inter-cooling is associated with significant losses. However, the overall energy utilization could be increased if the waste heat generated during the air compression process would be used for domestic water and space heating.

It seems that there is some justification for continuing the development of compressed air cars. However, it would be useful to establish the performance

of such vehicles by an endurance race under controlled conditions in the presence of the general public.

1. Introduction

The air flow of a compressed air car is schematically shown in Figure 1. The following two questions need to be answered.

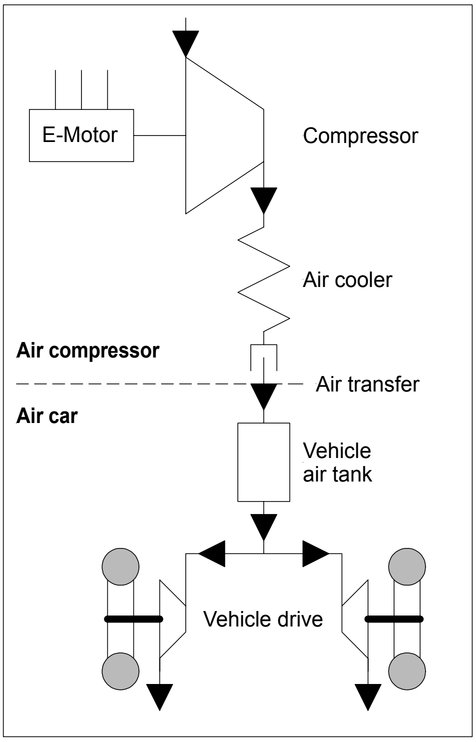

Figure 1 Schematic of air compression, compressed air transfer to car and the use of compressed air for vehicle propulsion

Question A

How much compression energy is needed to fill the tank with air at final pressure (300 bar = 30 MPa), but ambient temperature (20°C = 293.15K)?

The compression process is treated as polytropic change of state. The compression from the initial air volume V_1 to the final tank volume $V_2 = V_3$ is followed by heat removal at constant tank volume V_3 from (p_2,T_2) to (p_3,T_3=T_1), i.e. back to the original ambient temperature T_1. The final conditions (p_3,T_3=T_1) can also be reached by an ideal isothermal compression from (p_1,V_1). The technical work input by isothermal compression W_{t13} is equal to the final energy content of the tank irrespective of the chosen path of polytropic compression and isochoric cooling. The energy input is related to the thermodynamics of the compression process. The lower limit is obtained for isothermal, the upper for isentropic compression while polytropic case are located between the two.

Question B

How much mechanical energy can be recovered by expanding the compressed air in an air motor?

The expansion from (p_3,T_3=T_1) to (p_4=p_1, T_4<T_1) is also considered to be polytropic. For an ideal isothermal expansion the entire reversible isothermal technical work input W_{t13} could be recovered by a reversible process. However, in reality less energy is converted to technical work by the real expansion. Again, the polytropic process is worse than an isothermal, but better than an isentropic expansion.

After the extraction of expansion work the air is exhausted at low temperatures. In an overall energy balance the heat taken from the ambient to restore initial air temperatures is less than the heat released during air compression because of the non-ideal processes involved.

There are technical options for compression and expansion. The following analysis will suggest useful clues for the design of a compression-expansion system for air cars with acceptable driving performance that make good use of the electric energy needed to compress the air.

2. Reference Conditions

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	ρ_1	= 1.1883 kg/m^3		
Original air volume	V_1	= V_3 * p_3/p_1	= 90 m^3 (before compression)	
Mass of air	m_1	= V_1 * ρ_1	= 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	ρ_3	= 356.49 kg/m^3		
Mass of compressed air	m_3	= V_3 * ρ_3	= 106.95 kg	= m_1 (check)

Final conditions after expansion ("4"):

Air pressure	p_4	= 1 bar	= 0.1 MPa	

3. Air Compression

Three compression processes are illustrated in a pressure-volume diagram (Figures 2) and a temperature-entropy diagram (Figure 3). Both presentations are commonly used for thermodynamic analyses.

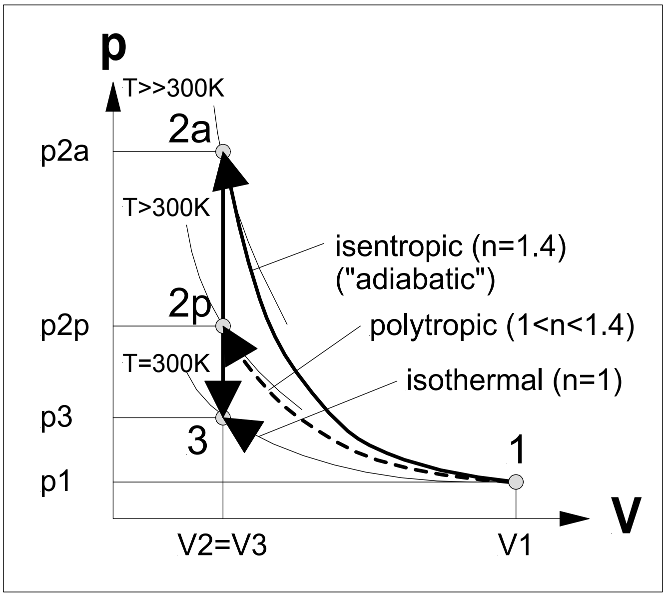

Figure 2 P-V Diagram of single-stage air compression

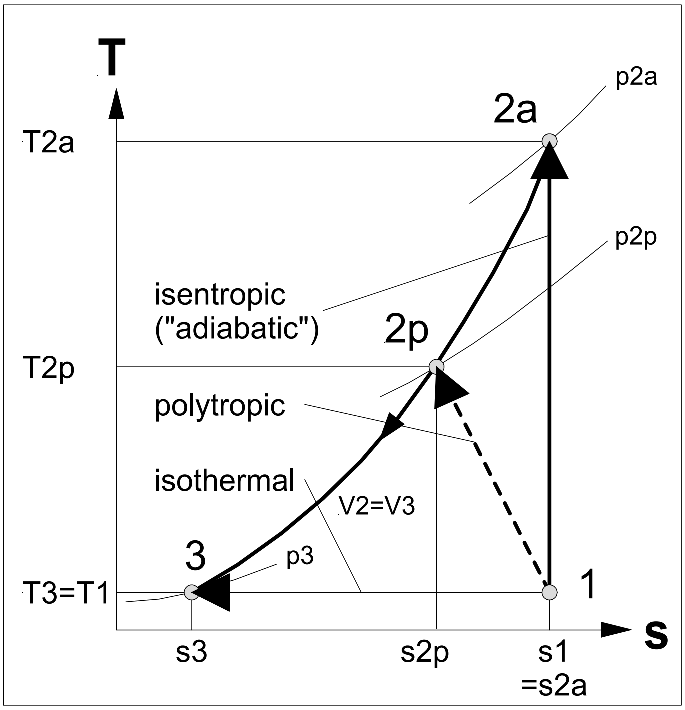

Figure 3 T-s Diagram of single-stage air compression

3. Isothermal Compression

During the idealized reversible isothermal compression process the temperature is considered to remain unchanged. The initial temperature T_1 is also the final temperature T_3. All compression heat must be removed during the compression process by heat exchange with the environment (e.g. by transfer to a colder medium). In reality this is impossible for practical system designs.

The technical work required for filling the tank with air from (p_1,T_1) to (p_3,T_3=T_1) under isothermal conditions is

$$W_{t13} = W_{13} = p_1 * V_1 * \ln(p_3/p_1)$$
$$= p_1 * V_1 * \ln(V_1/V_3) \qquad (1)$$

4. Polytropic Compression Followed by Isochoric Cooling

The polytropic change of state follows the isentropic laws. However, the isentropic coefficient (γ = 1.4 for air) is replaced by a polytropic coefficient n. The value of the coefficient n may vary between 1.4 for isentropic and 1.0 for isothermal expansions. Air is treated as an ideal gas.

In the isentropic case, no heat is neither exchanged with the environment nor generated internally by friction or poor aerodynamics, while in the polytropic case some heat is exchanged with the environment or available form internal friction losses. The isothermal case is the second idealized limit for real compression or expansion processes. However, a polytropic compression process is always associated with an increase of entropy as seen in the T-s-Diagram (Figure 3).

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 the following equation:

$$W_{t12} = m * c_p * (T_2 – T_1)$$
$$= p_1 * V_1 * n/(n-1) * [(V_1/V_3)\text{^}(n -1) – 1] \qquad (2)$$

The intermediate pressure p_2 and temperature T_2 are obtained from

$$p_2 = p_1 *(V_1/V_3)\text{^}n \qquad (3)$$
and $$T_2 = T_1 * (V_1/V_3)\text{^}[(n-1)/n] \qquad (4)$$

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.

$$\eta_{th} = W_{t13} / W_{t12} \qquad (5)$$

The following significant results are obtained for different polytropic coefficients:

Single-stage compression	iso-thermal	poly-tropic	poly-tropic	poly-tropic	isen-tropic	units
Polytropic coefficient n	1.0	1.1	1.2	1.3	1.4	-
Technical Work W_{t12}	51	76	115	177	277	MJ
Energy in tank Wt_{13}	51	51	51	51	51	MJ
Efficiency Wt_{13}/W_{t12}	100	67	45	29	19	%
Final temperature T_2	20	219	485	820	1,223	°C

The results clearly indicate that the compression has to proceed close to the isothermal limit. Low energy input, reasonable temperatures and acceptable efficiencies cannot be obtained under isentropic conditions. The problems are solved with multi-stage compression and air cooling between stages. The analysis does not include real gas effects and mechanical or electrical losses.

5. Four-Stage Compression

A four-stage compression process is now analyzed. Heat is removed by three intercoolers between stages 1 to 4 and between the final stage and the tank. The polytropic compression process is started with air under normal conditions (p_1 = 1bar, T_1 = 20°C). For all following stages the inlet air temperature is assumed to be cooled to 20°C. In practice, this can only be accomplished by heat transfer to a cold medium.

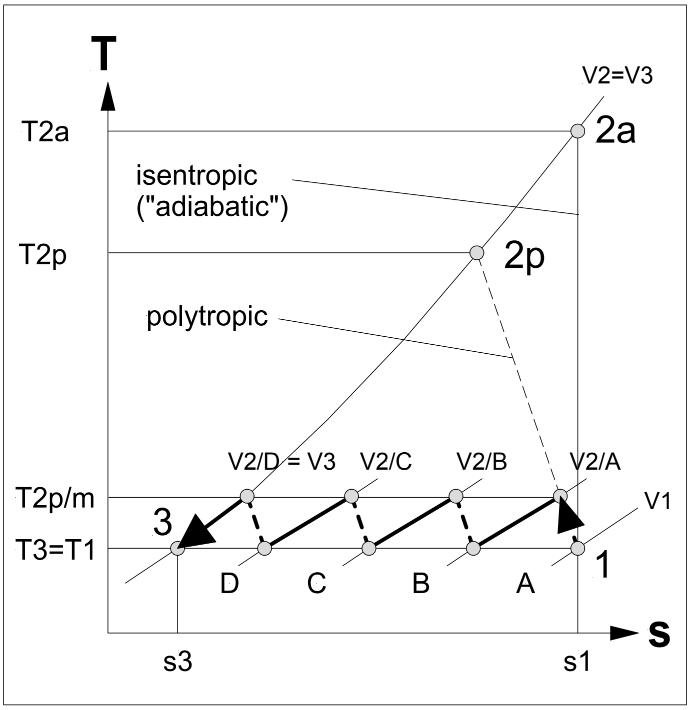

Figure 4 T-s-presentation of a four-stage compression compared to a single-stage compression

The four-stage compression process is sketched in the temperature-entropy presentation of Figure 4. Compared to the single-stage polytropic process (point

2p) excessive air temperatures are avoided by multi-stage compression. Also, the compression work needed is reduced significantly as shown by the table below.

For the simplified analysis each of the four stages was assumed to operate at the same compression ratio of 4.162, equal to the 4th root of the total pressure ratio of 300. For a polytropic exponent n = 1.40 the following results are obtained:

Stage identification	A	B	C	D	Units
Inlet pressure	0.1	0.42	1.73	7.21	MPa
Outlet pressure	0.42	1.73	7.21	30.00	MPa
Inlet temperature	20	20	20	20	°C
Outlet temperature	168	148	128	110	°C
Inlet air volume (20°C)	90	21.63	5.20	1.25	m^3
Outlet air volume	21.63	5.20	1.25	0.30	m^3
Inlet air density	1.19	4.95	20.58	85.66	kg/m^3
Outlet air density	5.82	20.20	70.12	243.35	kg/m^3

The equations (1) to (5) derived for a single stage air compression are used for each stage of the four subsequent processes. The overall results are obtained by summing the technical work input or the heat released from each stage. The results strongly depend on the polytropic coefficient n, i.e. on the polytropic efficiency or the aerodynamic quality of the compressor and the intercooler heat exchangers.

Four-stage compression	iso-thermal	poly-tropic	poly-tropic	poly-tropic	isen-tropic	units
Polytropic coefficient n	1.0	1.1	1.2	1.3	1.4	-
Technical Work W_{t12}	51	61	71	83	97	MJ
Energy in tank Wt_{13}	51	51	51	51	51	MJ
Efficiency Wt_{13}/W_{t12}	100	87	81	78	77	%
Final temperature T_2	20	60	90	107	110	°C

Obviously, significant energetic and thermodynamic advantages can be obtained when the compression process is spread over many stages with integrated inter-cooling. Even for an isentropic compression process the overall thermodynamic efficiency is increased from 42% to 53% by staging. Realistic may be a polytropic four-stage compression with n = 1.30 yielding an thermodynamic efficiency of 78%. Even higher values may be obtained by adding compression stages or by improved air cooling between stages. However, such solutions are complex and expensive. They may not be suited for onboard applications in vehicles.

6. Technical Work Derived from the Stored Pressurized Air

Technical work is recovered by expanding the compressed air in suitable expansion engines from tank conditions (p_3 = 30 MPa, T_3 = 20°C = 293K) to ambient pressure (p_4 = 0.1 MPa = 1 bar). The temperature of the expanding air will drop to depending on the pressure ratio and the thermodynamic quality of the expansion. The lowest temperatures are reached for an isentropic expansion when no heat can flow from the environment to the cooler air. The other extreme is the isothermal expansion at constant temperature.

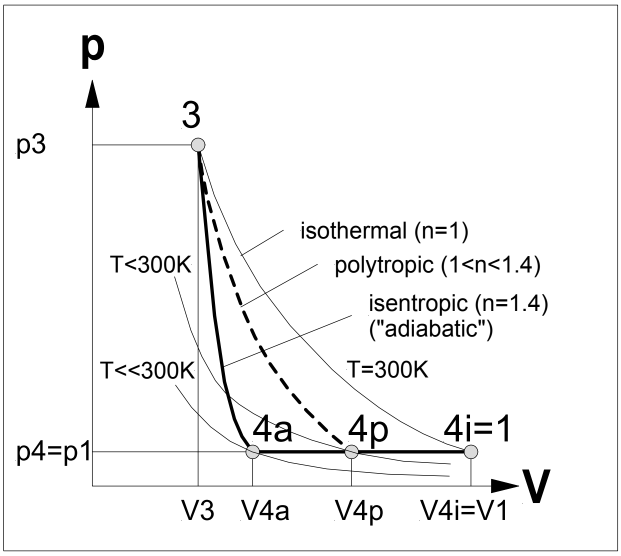

Figure 5 p-V-diagram of single-stage expansion processes

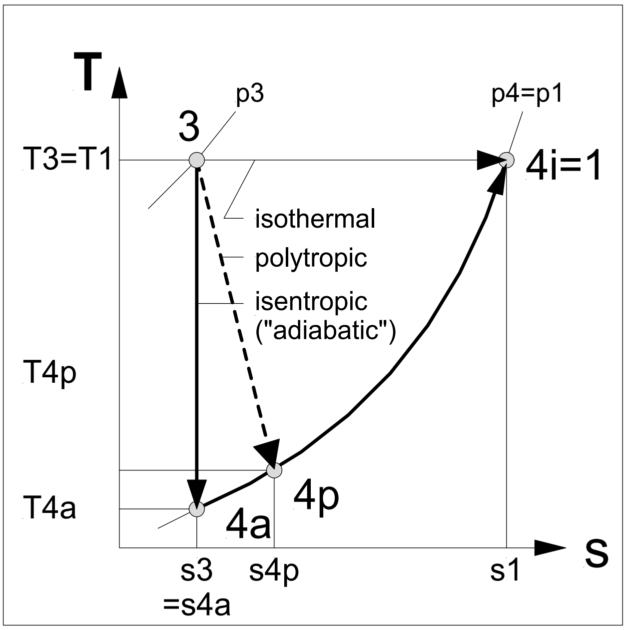

Figure 6 T-s-diagram of single-stage expansion processes

With respect to ambient temperature T_1 = 20°C the energy content of the tank is equal to the isothermal technical work W_{t13}. This energy can be recovered only partially by an isentropic or polytropic expansions as indicated by the p*dV diagram (Figure 5).

7. Single-Stage Expansion

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) limits. 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

$$W_{t34} = m * c_p * (T_4 - T_3)$$
$$= p_1 * V_1 * n/(n-1) * [(p_4/p_3)^\wedge(n/(n-1)) - 1] \qquad (6)$$

The final temperature T_4 is obtained from

$$T_4 = T_3 * (p_4/p_3)^\wedge[(n-1)/n] \qquad (7)$$

Finally, the overall thermodynamic efficiency is of interest. The useful technical work output of the expansion engine W_{t34} is related to the technical work input for compression W_{t12}:

$$\eta_{th} = W_{t34} / W_{t12} \qquad (8)$$

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. However, minus signs are omitted from the tabulated numbers.

Single-stage expansion	iso-thermal	poly-tropic	poly-tropic	poly-tropic	isen-tropic	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	°C

In the isentropic case the theoretical final temperature of the expanded air drops to minus 216°C, i.e. well below the temperature of liquid air at atmospheric pressure. Needless to say, this does not represent reality. However, it indicates that technical problems may limit the extraction of mechanical work from compressed air by expansion engines.

8. Four-Stage Expansion

The lowest technical work W_{t34} is recovered from an isentropic expansion. For polytropic expansions the temperature of the air is raised by heat generated during the process as a result of friction or non-ideal aerodynamics, or heat is accepted from the environment by heat exchange. As expected, the highest efficiency is obtained when the expansion process proceeds close to the isothermal limit. From an energetic standpoint, the best results may be obtained by using a multistage expansion motor with heating between stages.

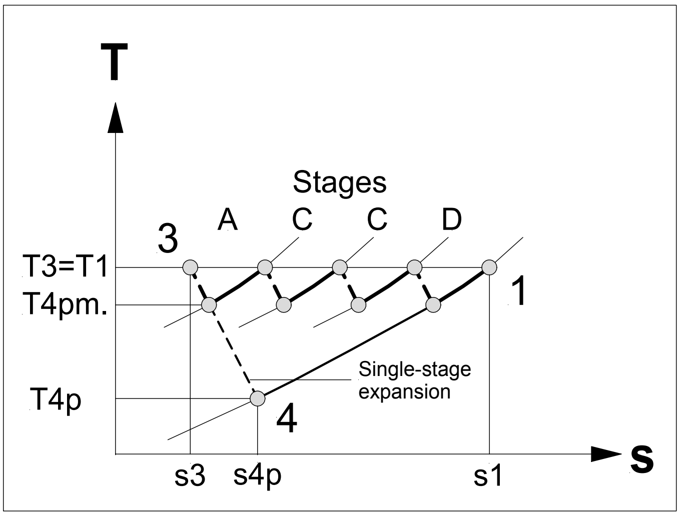

Figure 7 T-s-diagram of a four-stage expansion compared to a single-stage expansion (point 4)

The analysis is for a four-stage expansion with three heat exchangers between the first three stages. As the cold exhaust is released into the atmosphere, nature will take care of the final heat exchange to restore the original ambient conditions of 20°C. It is assumed that all heat exchangers are sized to raise the temperature of the air exhaust of all but the last stage to 20°C. This is not easily accomplished even on hot summer days. For all three expansion stages the pressure ratio of 4.16 is assumed corresponding to the 4th root of the overall expansion ratio of 300

The following results are obtained for the "ideal" isentropic coefficient n = 1.40..

Stage identification	A	B	C	D	Units
Inlet pressure	30	7.21	1.73	0.42	MPa
Outlet pressure	7.21	1.73	0.41	0.10	MPa
Inlet temperature	20	20	20	20	°C
Outlet temperature	- 78	- 78	- 78	- 78	°C
Inlet air volume (20°C)	0.30	1.25	5.20	21.63	m^3
Outlet air volume	1.25	5.20	21.63	90.00	m^3
Inlet air density	356.49	85.66	20.58	4.95	kg/m^3
Outlet air density	128,74	30.93	7.43	1.79	kg/m^3

Similar parameters can be obtained for other polytropic expansion coefficients

For five different polytropic coefficients the results are presented in the following table for the stated assumptions. The listed numbers are obtained by summing the technical work output of all four stages. The results strongly depend on the choice of polytropic coefficient n as shown. Again, the minus signs are omitted for the extracted work.

Four-stage expansion	iso-thermal	poly-tropic	poly-tropic	poly-tropic	isen-tropic	units
Polytropic coefficient n	1.0	1.1	1.2	1.3	1.4	-
Technical Work W_{t34}	51	12.04	11.42	10.94	10.54	MJ
Energy in tank Wt_{13}	51	51	51	51	51	MJ
Efficiency Wt_{34} / W_{t13}	1.000	0.938	0.890	0.852	0.821	-
	100	94	89	85	82	%
Final temperature T_4	20	-16	-42	-62	-78	°C

7. Overall Efficiency

The overall thermodynamic efficiency of an air car cycle is defined as the useful technical work W_{t34} obtained by expanding the compressed air compared to the compression energy W_{t12} needed to fill the tank.

$$\eta_{tot} = W_{t34} / W_{t12} \tag{9}$$

Assuming isentropic conditions (n = 1.40) for compression and expansion the following is obtained:

Single stage system:

$$\eta_{tot} = W_{t34} / W_{t12} = 25.33 \text{ MJ} / 276.93 \text{ MJ} = 0.0915 = 9.15\%$$

Four-stage system:

$$\eta_{tot} = W_{t34} / W_{t12} = 42.16 \text{ MJ} / 66.92 \text{ MJ} = 0.6101 = 61.01\%$$

For single-stage compression and expansion the overall efficiency is unacceptably low. But it is remarkably high for the four-stage solution.

It could be further improved by technical measures. A polytropic coefficient of 1.3 could be obtained by advanced compressor cooling. Also, heating the expansion engines could improve the process. Such effects can be recognized by using a polytropic coefficient of n = 1.35 for the expansion process. For these two more realistic numbers the overall efficiency becomes

$$\eta_{tot} = W_{t34} / W_{t12} = 42.91 \text{ MJ} / 65.87 \text{ MJ} = 0.6515 = 65.15\%$$

This efficiency does not include electrical and mechanical losses of the air compressor, mechanical losses of the expansion engine and all parasitic power consumption related to the operation of the vehicle.

It becomes apparent that major improvements will only be possible if the air compression and expansion can be accomplished closer to the isothermal limit. This is a task for creative engineers.

8. Conclusions

For the operation of a compressed air car the overall "plug-to-road" efficiency is one of the key criteria. The optimum is obtained when maximum technical work W_{t34} becomes available at a minimum of technical work W_{t12} input for air compression. It becomes clear from the foregoing analysis that both compression and expansion must proceed close to the isothermal limit. This can only be accomplished with multi-stage compression and expansion processes and heat exchangers for removal from or addition of heat to the process air.

The foregoing analysis may not be the first of its kind and certainly needs refinements. In particular, the thermodynamics of heat exchange, mechanical and aerodynamic losses, electrical efficiencies etc. need to be considered. All these effects may reduce the overall efficiency to 40% or less. However, such efficiencies may still be attractive in a sustainable energy future when renewable energy is harvested as electricity and transportation needs must be satisfied from available energy sources. With respect to overall efficiency, battery-electric vehicles may be better than air cars, but hydrogen fuel cell systems may be worse. However, with respect to system and operating costs, air cars may offer many advantages such as simplicity, operating and life cycle cost, independence, zero pollution and environmental friendliness of all system components.

All in all, the compressed air car seems to be a viable option for clean and efficient local transportation. Further analyses, additional research and development are most welcome to fully identify the potentials of this unconventional source of transportation energy.