ECE309 Project: Compressed Air Car

Assigned date: June 20, 2016 Due date: July 21, 2016

INTRODUCTION

Air pollution and rising fuel prices have forced many automotive manufacturers to reexamine the use of the internal combustion engine as the predominant means of powering cars, trucks, and commercial vehicles. Some have promoted the idea of using the expansion of compressed air in a manner similar to using the expansion of steam to power a steam engine. The idea of using compressed air to power a vehicle isn't new. Early prototypes of air-powered vehicles date back to the middle of the 19th century, even before the invention of the internal combustion engine (http://www.aircaraccess.com/history.htm).

More recently, Tata Motors has developed the Airpod, a low cost, light weight urban vehicle powered by a 430cc 2-cylinder engine that develops 7kW at 1,500rpm enough for it to reach 70kph. The latest model comes with a 260-litre tank, with a maximum air pressure of 248 bar and a range between 120km and 150km. Total weight of the Airpod is around 200kg, with 24kg of that accounted for by the engine.

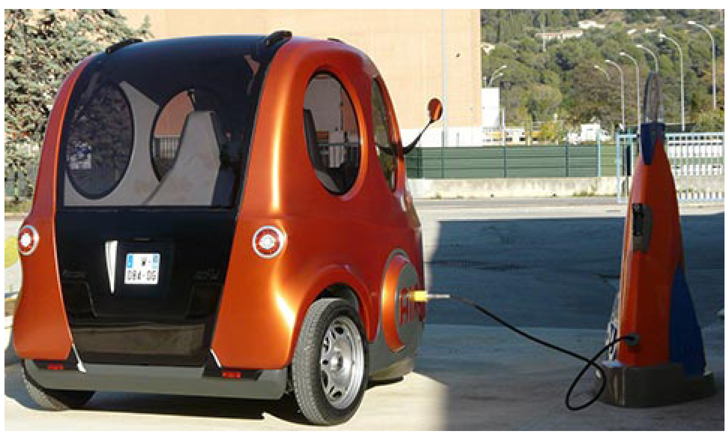

Figure 1: Tata Motors AirPod

THE AIR CAR

Our Air Car is powered by compressed air contained in a storage tank that drives air turbines located at each of the four wheels. Typically the tank is “refuelled” by connecting to a charging station with a maximum operating pressure of $30\ MPa$ ($4500\ psi$ or $300\ bar$). A schematic of the charging station and the Air Car is shown in Fig. 2.

Air is compressed from ambient conditions (state 1) under a polytropic process, $PV^n = const$ in the compressor [review Cengel: section 8-11 for polytropic compression]. The pressure ratio ($r_p = P_2/P_1$) of the compressor can vary from 50 to 300 and the ambient temperature can vary from $-20\ °C$ to $40\ °C$. The compressed air is then cooled in an air-cooler where the temperature of the air supplied to the storage tank can be regulated by extracting heat and discharging it to the environment. Depending on the effectiveness of the air cooler, the temperature of the air stored in the tank can vary as follows: $T_3 = [1 - \epsilon_{ac}](T_2 - T_1) + T_1$, where ϵ_{ac} is the effectiveness of the cooler with $\epsilon_{ac} = 0$ providing no cooling effect and $\epsilon_{ac} = 1$ providing maximum cooling effect. The pressurized air is then stored in the vehicle's air tank. The $500\ L$ air tank is thermally isolated from the surrounding environment. Once the air car is disconnected from the charging station, the compressed air is transferred to the turbines to produce work and then discharged to the atmosphere. The car stops moving when the air in the tank is in equilibrium with the surrounding atmosphere i.e. $P_4 = P_{atm}$ and $T_4 = T_{atm}$.

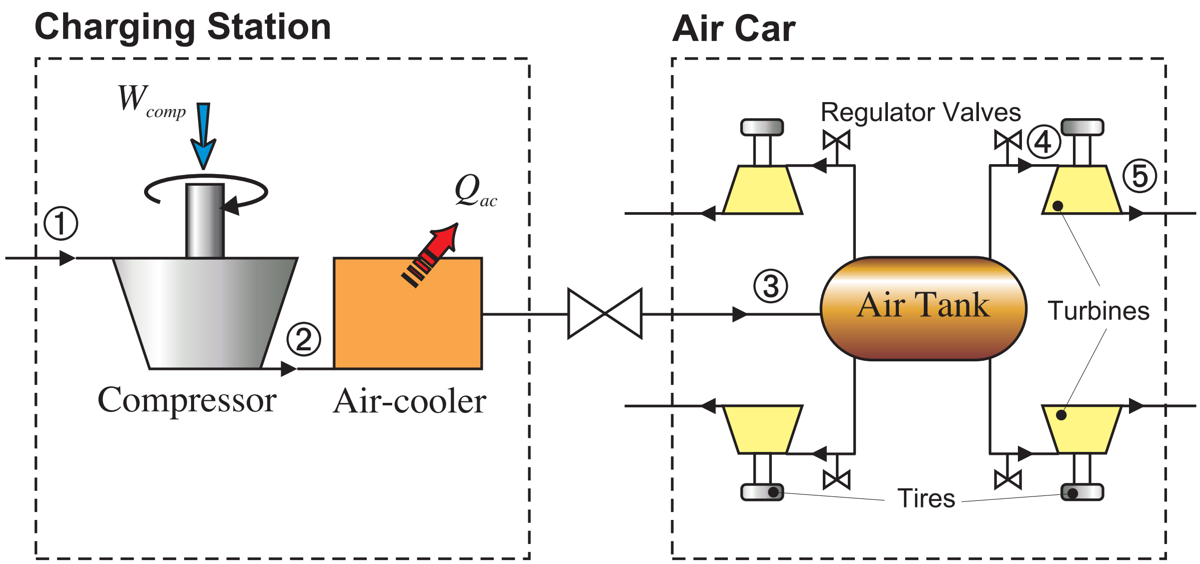

Figure 2: Schematic of the Air Car and Air Compression Process

ASSIGNMENT

1. **Thermodynamics Analysis:** The default scenario is specified as having a constant ambient temperature of $T_1 = 20\ °C$, an ambient pressure of $P_1 = 100\ kPa$, a pressure ratio, $r_p = 300$ and a polytropic coefficient of $n = 1.3$. Determine:
   (a) the amount of work needed to fill the $500\ L$ air tank, $W_{comp}\ [kJ]$,
   (b) the heat transfer from the air-cooler, $Q_{ac}\ [kJ]$, where $T_3 = [1 - \epsilon_{ac}](T_2 - T_1) + T_1]$, with $\epsilon_{ac} = 0.5$,
   (c) the amount of work produced in the turbines to move the car, $W_{turb}\ [kJ]$,
   (d) the mass of air stored in the tank when it is full, m_{full},
   (e) the mass ratio, defined as $m_{ratio} = m_{full}/m_{empty}$, and
   (f) the total efficiency of the Air Car, η.

2. **Mechanics Analysis:** The maximum speed of our car is $V_{max} = 70\ km/hr$ (along a flat road) and it requires $12\ seconds$ to reach the maximum speed under constant acceleration

conditions. Assume a constant friction coefficient, $f = 0.3$ for the friction resistance between the tires and the road. If the mass of the car is $m_{car} = 180\ kg$ (not including the mass of the air tank) and the mass of the driver is $m_{driver} = 75\ kg$, find:

(a) the distance travelled during the initial acceleration period, ΔX_{acc}, the distance travelled during the constant velocity period, ΔX_{cv}, and the total distance travelled, ΔX_{max} on one tank of air with only the driver

(b) the distance travelled during the initial acceleration period, ΔX_{acc}, the distance travelled during the constant velocity period, ΔX_{cv}, and the total distance travelled, ΔX_{max} on one tank of air with the driver plus a passenger with a mass of $m_{passenger} = 75\ kg$

Hint: You can consider an average mass of $(m_{full} + m_{empty})/2$ for the air tank over the duration of ΔX_{max}.

3. **Variable Ambient Temperature:** With just the driver in the vehicle let the ambient temperature vary from $-20\ °C$ to $40\ °C$, in increments of $10\ °C$ while the ambient pressure, $P_1 = 100\ kPa$, $r_p = 300$, and $\epsilon_{ac} = 0.5$ are held constant. Show the effect that ambient temperature has on W_{comp}, Q_{ac}, W_{turb}, η and ΔX_{max}. Summarize your results in tabular and graphical form.

4. **Variable Pressure Ratio:** With just the driver in the vehicle let the pressure ratio vary from 50 to 300, in increments of 50 while the ambient temperature, $T_1 = 20\ °C$, ambient pressure $P_1 = 100\ kPa$, and air cooler effectiveness $\epsilon_{ac} = 0.5$ are held constant. Show the effect that pressure ratio has on W_{comp}, Q_{ac}, W_{turb}, η and ΔX_{max}. Summarize your results in tabular and graphical form.

5. **Variable Effectiveness of the Air Cooler:** Maintain the ambient temperature and pressure constant at $T_1 = 25\ °C$ and $P_1 = 100\ kPa$ respectively and hold the pressure ratio constant at $r_p = 300$. Allow the effectiveness of the air cooler to vary from $0 \leq \epsilon_{ac} \leq 1$ in increments of 0.25. Show the effect of air cooler effectiveness on the mass of air in the tank (m_{tank}), the temperature of the air stored in the tank (T_3), the work of the compressor, W_{comp}, the heat transfer from the air cooler, Q_{ac}, the work of the turbine, W_{turb} and the total efficiency of the Air Car, η. Summarize your results in tabular and graphical form.

6. **Results and Discussion:** Elaborate on your results; make recommendations based on your observations and draw conclusions. What would be the optimum working condition for the Air Car? For parts (3.), (4.) and (5.) you should write a program to extract data and plot the results. You can use any of the popular software tools, such as Maple, Mathematica, Excel, Matlab, C++, Java, etc.

Notes:

1. Do not assume constant specific heat for the above analyses. You must determine specific heat calculations based on local temperature.

2. if any of the above cases are not feasible for any reason, clearly indicate which cases are not feasible and offer an explanation why they are not feasible.

REPORTING STRUCTURE

This is an engineering report and should adhere the following structure:

Introduction:

- A brief description of how the Air Car works.
- A summary listing advantages and disadvantages of the Air Car.

Analysis:

- Justify the assumptions and simplifications.
- Control volumes and calculations.
- Plots and tables.
- Discussions of the results.
- Recommendations and suggestions.

Conclusions and Summary:

A bound hard copy of the report (not exceeding 15 pages, appendices extra if needed) should be submitted on the due date. A copy of the computer program used in parts 3, 4 and 5 should be submitted to the Learn Drop box provided.

USEFUL EQUATIONS

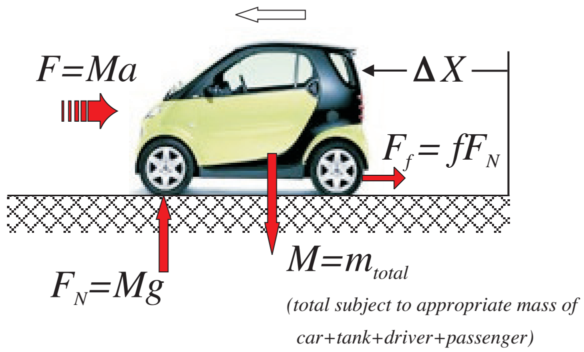

Figure 3: Force Balance

Mass of Air

$$\begin{aligned} m_{start} &= \frac{P_1 V}{R T_1} = m_{empty} \\ m_{in} &= m_{full} - m_{start} \\ m_{ratio} &= m_{full}/m_{start} \end{aligned}$$

Work

Polytropic Compression

$$w_{comp} = \frac{n\,R\,T_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right] = \frac{n\,R(T_2 - T_1)}{n-1}$$

Efficiency

$$\eta = \frac{\textbf{Benefit}}{\textbf{Cost}} = \frac{W_{turb}}{W_{comp}}$$

Acceleration

$$a = \Delta V/\Delta t$$

Maximum Distance

$$W_{turb} = (F + F_f)\Delta X_{max}$$

Note (1): When cruising, acceleration is zero, $a = 0$.

Note (2): Neglect the final deceleration in ΔX_{max} calculation.

Note (3): See Cengel section 6-5: Energy Analysis of Unsteady-Flow Processes for charging and discharging of a rigid tank

ASSUMPTIONS

- negligible mechanical losses.
- air is an ideal gas.
- negligible pressure losses in pipes, joints and the air-cooler.
- specific heat is a function of temperature. If you use Table A-2, assume correlations valid over full range of temperature.
- time to reach maximum velocity is independent of the total mass
- when the air tank reaches atmospheric pressure the vehicle stops immediately i.e. no deceleration

SUGGESTED CONTROL VOLUMES