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Cryogenic Liquid Nitrogen Vehicles (ZEV'S)

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Abstract- As a result of widely increasing air pollution throughout the world & vehicle emissions having a major contribution towards the same, it makes its very essential to engineer or design an alternative to the present traditional gasoline vehicles. Liquid nitrogen fueled vehicles can act as an excellent alternative for the same. Liquefied N2 at cryogenic temperatures can replace conventional fuels in cryogenic heat engines used as a propellant. The ambient temperature of the surrounding vaporizes the liquid form of N2 under pressure & leads to the formation of compressed N2 gas. This gas actuates a pneumatic motor. A combination of multiple reheat open Rankine cycle & closed Brayton cycle are involved in the process to make use of liquid N2 as a non-polluting fuel. A system of such a kind will also be able to refuel itself in a matter of time comparable to that of traditional engines, unlike the electrically charged ones.

Index Terms- Cryogenic temperature, Liquid nitrogen vehicle, Zero Emissive vehicles, Brayton cycle.

I. Introduction

As the name itself suggests, a liquid nitrogen vehicle works on the basis of liquid nitrogen contained in a storage tank. Generally the engine is designed in such a way that the liquid nitrogen is heated in a heat exchanger, wherein ambient air is used to heat the medium which results in the formation of pressurized gas which further actuates a piston or a rotary motor. The vehicles operating on this principle has been demonstrated many a times in the past but never commercialized. Recently in June 2016 trials had been carried in London on supermarket J Sainsbury's fleet of food delivery automobile which implemented Dearman nitrogen engine providing cooling for the food in cases when the vehicle used to being stationary positions. Nowadays even second smaller diesel engines are used as an substitute. A typical heat engine developed which employs a sub atmospheric temperature thermal reservoir such as liquid nitrogen as a heat sink is said to be a "cryogenic heat engine". This concept of a cryogenic heat engine is designed in order of developing non polluting automobiles. The way of bringing cryogenic heat engines using liquid nitrogen as heat sink & atmospheric air as a heat source is studied here.

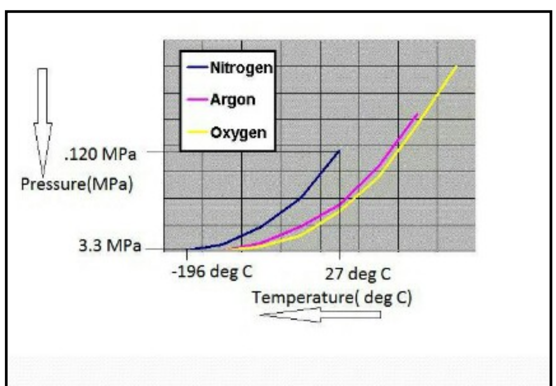
Transportations have increased drastically in these years in the urban areas leading to the emission of greenhouse gases that heavily effect the air purity. Thereby in order to bring in an alternative for it an efficient vehicle system has to be designed having zero emission, a lower tag price, an efficiency that could be compared with that of the conventional automobiles, one that can be charged or fueled quickly, etc. Only if all these major drawbacks are been engineered upon, it results in customer satisfaction gaining popularity. Currently the only commercially available zero emission vehicle (ZEV) meeting it's standards are the electrically recharged ones, however these vehicles are also not a great success in the society due to its own limitations like initial cost, slow recharge, speeds etc. Lead acid & Ni-Cd batteries are the past of major technologies in the electric vehicles. They exhibit specific energy in the range of 30-40 W-hr/kg. Lead- acid batteries take hours to recharge & the major drawback of the batteries in all the cases is their replacement periodically. This directly/indirectly increases the operating cost when studied carefully & thereby not 100% acceptable.

Recent studies make it clear that the vehicles using liquid nitrogen as their means provide an excellent alternative before the battery driven ones. The ambient air warms & vaporizes the liquid nitrogen generating compressed/pressurized air actuating the motor. Carlos A Ordonez with his colleagues demonstrated the concept through a prototyped vehicle named CooLN2Car (fig. is shown) at the University of North Texas, Denton.

II. Major Physical Properties of Liquid Nitrogen

Table 1: Liquid Nitrogen Physical and Chemical Properties

Chemical Formula	N_2
Molecular Weight	28.01
Boiling Point @ 1 atm	−320.5°F (−195.8°C)
Freezing Point @ 1 atm	−346.0°F (−210.0°C)
Critical Temperature	−232.5°F (−146.9°C)
Critical Pressure	492.3 psia (33.5 atm)
Density, Liquid @ BP, 1 atm	50.47 lb/scf (808.5 Kg/m^3)
Density, Gas @ 68°F (20°C), 1 atm	0.0725 lb/scf (1.16 Kg/m^3)
Specific Gravity, Gas (air=1) @ 68°F (20°C), 1 atm	0.967
Specific Gravity, Liquid (water=1) @ 68°F (20°C), 1 atm	0.808
Specific Volume @ 68°F (20°C), 1 atm	13.80 scf/lb (0.861 m^3/kg)
Latent Heat of Vaporization	856 Btu/lb (199.1 kJ/kg)
Expansion Ratio, Liquid to Gas, BP to 68°F (20°C)	1 to 694



P-T Chart showing Nitrogen Liquification

III. HOW DANGEROUS IS THE LIQUID NITROGEN EXPANSION?

Fig: Liquid N_2 being transferred into Dewar Flask

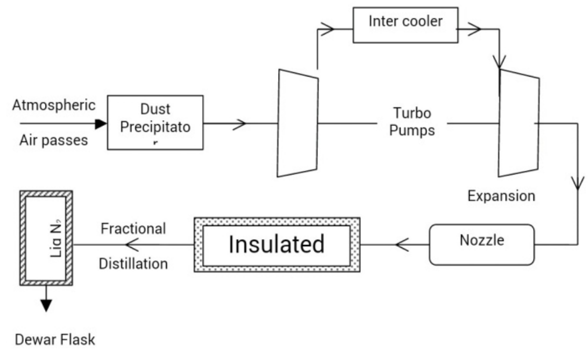
The liquid to gas expansion ratio of nitrogen being 1:649 at 20^{o} C i.e 68^{o}F, a tremendous amount of force is generated as it vaporizes rapidly in an enclosed space. The extent upto which this can be dangerous can be well illustrated using an example from the past that happened in Jan 12 2006 at the Texas, A&M university. The pressure relief valve of a liquid nitrogen tank malfunctioning & sealed later on. As a result of subsequent pressure buildup, the tank catastrophically failed. The force of explosion was high as of immediately propelling the tank through the ceiling right above it & shatter a concrete beam below it, blowing the walls of the laboratory out of its foundation!

As a result of extremely low temperature & careless handling of the liquid nitrogen, objects cooled by it may result in cold burns. Thereby special gloves should be used while handling it. However a small splash will not burn the skin immediately as the evaporating gas thermally insulates to some extent. Nitrogen is odorless, colourless, tasteless & may produce asphyxia(deficient supply of oxygen to the body) without any sensation or an advance warning.

IV. LIQUID NITROGEN & CRYOGENIC HEAT ENGINE

Liquid nitrogen is the cheapest, widely produced & most commonly used cryogenic liquid, mass produced in air liquefaction plants. During the process, atmospheric air is passed through the dust precipitator & pre-cooled using refrigeration techniques. Later on it is compressed inside large turbo-pumps to about 100 atmospheric pressure. Once the air reaches 100 atmospheric pressure & has been cooled to the room temperature it is allowed to expand rapidly through a nozzle into an insulated chamber. By running of several cycles the temperate of chambers reaches low enough temperatures & the air entering starts to liquefy. Liquid nitrogen is separated by fractional distillation & is stored inside well insulated Dewar flasks.

Liquid nitrogen is used in association with cryogenic heat engines. It is an engine that uses very cold substances to produce useful energy. A unique feature of an cryogenic heat engine is that it operates in an environment at the peak temperature of the power cycle, & thereby there is always an heat input to the working fluid during the expansion process.



V. NITROGEN POWERED CAR

When related to a nitrogen powered car (ZEV), heat from the atmosphere vaporizes liquid nitrogen under pressure & produces compressed nitrogen gas. This compressed gas in turn runs a pneumatic motor with nitrogen gas as exhaust.

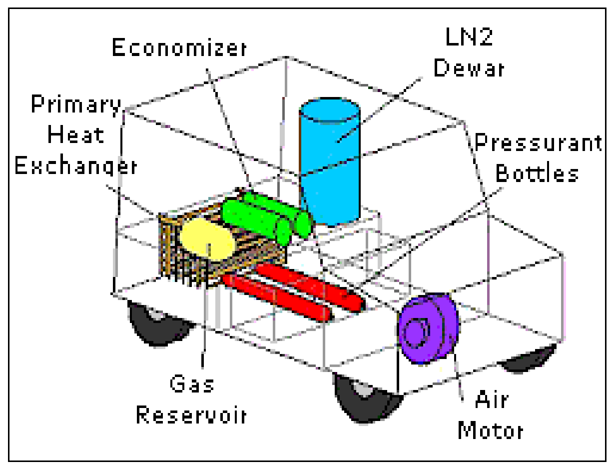


Fig: Components involved in a N_2 powered car

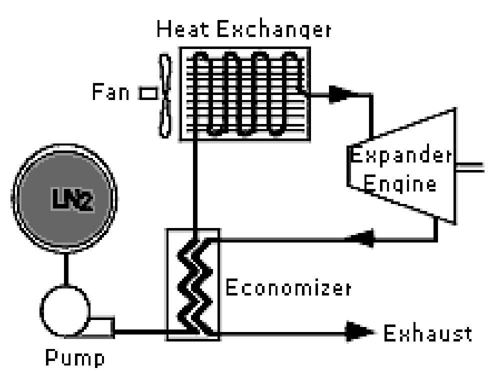


Fig: Working path of the car engine (N_2 fuel)

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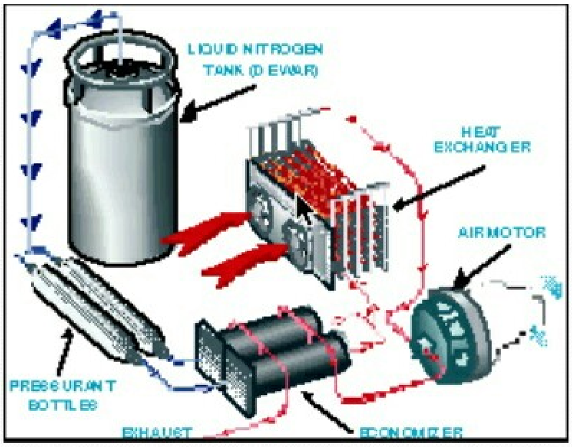
VI. MAIN COMPONENTS OF THE ENGINE

- A pressurized tank to store liquid nitrogen
- A heat exchanger that heats (using atmospheric heat) liquid nitrogen to form nitrogen gas, then heats gas under pressure to near atmospheric temperature.
- A pneumatic motor (along with a Volkswagen transmission) that runs the car.



Major components of the Nitrogen powered car

VII. PRINCIPLE OF OPERATION

The principle of running the LN2000Car is similar to that of a steam engine, except for the fact that there is no combustion process involved. Instead pressurized liquid nitrogen at –320^{o}F (-196^{o}C) is used and then vaporized in a heat exchanger by ambient air. This heat exchanger is like the radiator of a car but instead of using air to cool water, it uses air to heat and boil liquid nitrogen. The resulting high pressure nitrogen gas is fed to an engine that operates like a reciprocating steam engine, converting pressure to mechanical power. The only exhaust is nitrogen, which is major constituent of our atmosphere. The efficiency of LN2 car : It can travel 15 miles on a full (48 gallons) of liquid nitrogen going 20 MPH. Its maximum speed is about 35 MPH.

VIII. ANALYSIS OF COOLN2 CAR PERFORMANCE

A single-cylinder reciprocating expander running on compressed nitrogen gas releasing exhaust gas into the atmosphere was considered. As compressed gas was allowed to flow into the expanders cylinder, isobaric work was done on the moving piston by the nitrogen gas.

The net isobaric expansion work done during a single cycle is gauge pressure of the gas multiplied by the volume of the gas that flows into the cylinder.

The isobaric specific energy is given by,
$W_i = (P_h - P_i)V = P_h(1-P^{-1})V$
$P_h - P_i$ is the difference in absolute pressure between inlet and exhaust (outlet) gas.

If P_i is atmospheric pressure, $P_h - P_i$ is the gauge pressure of compressed gas.
V is the volume occupied by the compressed gas / unit mass of gas.
$P = P_h / P_i$ is inlet to exhaust pressure ratio.
The isobaric specific energy is given by,
$W_i = RT_h (1-P^{-1}) /A$.
Here T_h refers to the temperature of the high pressure inlet gas.

The COOLN2Car which a converted 1973 Volkswagen and runs on liquid nitrogen is an illustrative to the use of isobaric expansion equation.

IX. LN2000

Fig: The LN2000

The vehicle works similar to that of a steam engine, except for using vaporized cold liquid nitrogen instead of steam from boiling water. Vapour of the nitrogen actuates the air motor to propel the car & then escapes out through the tail pipe. As the atmosphere consists of about 78% of nitrogen, the environmental effects of driving LN2000 vehicles would be negligible virtually. The heat exchanger of the vehicle pulls liquid nitrogen from an insulated fuel tank(cryogenic) through a series of aluminium tubing coils & specially designed pipes. The heat exchanger is like the radiator of the car, instead of using air to cool water, here the air is used to boil liquid nitrogen to nitrogen gas for the further processings.

X. OPEN RANKINE CYCLE

The processes considered are the expansion of nitrogen gas at 300K and 3.3 MPA to near atmospheric pressure. Initially the process considered is isothermal expansion, i.e from 3.3 MPA to 120KPA and the work can be calculated as,
$W_{isothermal} = rT \ln (P_2/P_1)$
r = 0.2968 (KJ/KgK) for nitrogen gas and T = 300K.

The result for Nitrogen is 291.59 KJ/Kg. Another limiting process is the simple adiabatic expansion of the gas in which no heat is admitted during the expansion process. The work done is calculated as,
$W_{adiabatic} = KrT [1-(P_2 / P_1)^{K-1/K]} (k-1)$
Where T = 300K and K = 1.4, the specific heat ratio for nitrogen.

The resulting $W_{adiabatic}$ is 180KJ/Kg of Nitrogen exhausted at 150KPA.

XI. CLOSED BRAYTON CYCLE

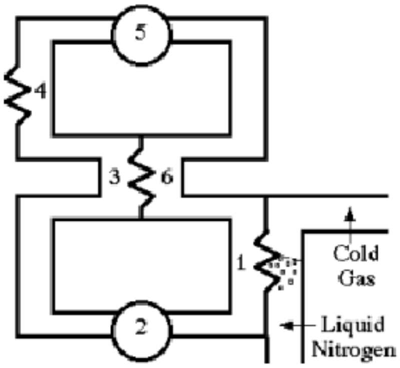


Figure 1 Closed Brayton-cycle cryogenic heat engine

Operation of liquid-nitrogen fueled, regenerative, closed Brayton cycle, cryogenic heat engine is illustrated. Taking into consideration the adiabatic expander and compressor, the specific energy provided by the system is given by,

$W = e_g \mu (e_e w_e - w_c/e_c)$ ……………….(1)

Here,

$\mu = A\varepsilon L/Rt_{cold}(p^{\varepsilon}-1)]$ ……………….(2) is the ratio of the working fluid mass flow rate to the liquid nitrogen vaporization rate.

T_{cold} is the temperature of the heat single.

P is the ratio of the absolute pressures on the high and low pressure sides.

L = liquid nitrogen's latent heat of vaporization.

R = 8314 J/mol-K universal gas constant

$\varepsilon = 1\text{-}1/r$; r = working fluid's ratio of specific heat capacities at constant pressure and constant volume.

The ideal specific energy provided by an adiabatic expander is

$We = RT_{hot} (1-p^{-\varepsilon})/[A.\varepsilon]$ ……….(3)

That = temperature of heat source

The ideal work done by an adiabatic compressor per unit mass of gas is

$Wc = RT_{cold} (P^{\varepsilon}-1)(A.\varepsilon)$ ……..(4)

By combining equations we get

$W = e_g L [e_e p^{-\varepsilon} (T_{hot} / T_{cold}) - (1/e_c)]$ ……..(5)

The equation (5) considers the energy available from using liquid nitrogen as a heat sink. The cold nitrogen gas that is produced by vaporizing liquid nitrogen can be used a heat sink as well.

XII. ADVANTAGES OF LIQUID NITROGEN VEHICLES

- Being different from the electrically charged vehicles, ZEV use liquid nitrogen as an energy source to instead of batteries as earlier mentioned. Some of its advantages over the other vehicles are,
- Much like the electrically powered vehicles, the liquid nitrogen vehicles are ultimately powered through electrical grid making it easier to focus on reducing pollution from one source, as opposed to the millions of vehicles on road.
- Transportation of the fuel would not be required due to drawing power off the electrical grid. This presents significant cost benefits. Pollution caused during fuel transportation eliminated.
- Disposing/recycling of Liquid Nitrogen tanks can be done with lesser pollution than the batteries.
- The tank can be refilled/refueled in a less interval time than the batteries can be recharged with the refueling rates comparable to the liquid fuels.
- They are unconstrained by the degradation problems associated with the battery systems.
- It can work as a part of combined cycle power train in association with a petrol/diesel engine, using the waste heat from one to run either of the turbo compound system.
- Low maintenance costs.

XIII. DISADVANTAGES OF LIQUID NITROGEN VEHICLES

- The primary disadvantage of the system is the inefficient use of its main energy. Energy from another is used to liquefy nitrogen, which in turn provides energy to run the motor. We already know that any conversion of energy is associated with losses. In liquid nitrogen cars, electrical energy is lost during the liquefaction process.
- Liquid Nitrogen not being available in the public stations at appropriate locations also poses a major concern. However liquid nitrogen can be abundantly obtained during the liquid oxygen production, being it's by-product.

XIV. CONCLUSION

If more & more of such kinds of vehicles (ZEV) are put into use, the cleaner the air will becomes marching the society towards an healthier environment, provided the liquefaction is driven by a non polluting energy source such as solar, wind, tidal energy. In addition to the environmental impact of these vehicles, refueling using current technology takes only a few minutes. As there is always a scope of improvement in all the fields, the safety of the vehicle needs to be improved from many points of view. Pressure relief valves need to be incorporated in all apparatus subjected to cryogenic temperatures. Over-pressurization may arise due to vaporization of nitrogen & the danger it poses to the surrounding is already explained, making safety issues a major concern to focus upon. More information regarding the safety concerns are given in various books on cryogenics.

REFERENCES

[1] Research paper on **"Liquid Nitrogen as a Non-Polluting Vehicle Fuel"** by Mitty C. Plummer, Carlos A. Ordonez and Richard F. Reidy, university of

North Texas. The University of Washington's Liquid Nitrogen Propelled Automobile

[2] "Automotive Propulsion using Liquid Nitrogen", Knowlen, C., Hertzberg, A., Mattick, A.T AIAA 94-3349, 1994.

[3] "Quasi Iso-thermal Expansion Engines for Liquid Nitrogen Automotive Propulsion", Knowlen, C., Williams, J.,Mattick, A.T. Deparis, H., Hertzberg, A., SAE 972649, 1997

[4] www.washington.edu/alumni/columns/dec97/car1.html

[5] www.ilt.kharkov.ua/

[6] www.wikipedia.org/wiki/Liquid nitrogen vehicle

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