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International Journal of Innovations in Science & Technology

Design and Fabrication of Novel Air Conditioning System in CNG Fitted Vehicles

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Citation | Ullah. S, Ullah. Haseeb. A, Adnan. M, Munib. S, Asif. M, Bukhari. M. Z, "Design and Fabrication of Novel Air Conditioning System in CNG Fitted Vehicles", IJIST, Vol. 7 Issue. 4 pp 3211-3226, December 2025

Received | November 20, 2025 **Revised |** December 15, 2025 **Accepted |** December 18, 2025 **Published |** December 21,2025.

This paper presents a novel air conditioning system for Compressed Natural Gas (CNG)-fitted vehicles that overcomes the high fuel consumption of conventional belt-driven compressors. The system utilizes the Joule–Thomson effect of CNG expansion to generate cooling, captured through a heat exchanger and circulated via a blower, without adding engine load. CNG consumption was measured by recording the initial and final tank pressures and calculating the consumed gas mass based on tank volume and CNG density. Emissions were measured using a gas flow analyzer, with sensors placed in the vehicle's silencer. Tests were conducted under identical conditions for both the conventional and the proposed air conditioning systems. The main objective of this project was to get a fuel-free air conditioning system in CNG-fitted vehicles. Experimental results show a significant cabin temperature drop to 11°C (284.15K) in 14 minutes (readings were noted by using digital multi meter having temperature sensor), improved fuel economy up to 25% as compared to conventional air conditioning system, and reduced emissions of CO_2 about 55% and CO about 30% (emissions reading were noted by using kane-458s gas flow analyzer). Car Consumption has been calculated by an indirect gravimetric (pressure-density-based) method used to estimate CNG fuel consumption. The findings confirm that the system is a technically feasible, low-cost, and sustainable alternative to conventional AC units for CNG vehicles, especially in hot climates.

Keywords: Traditional Air Conditioning, Novel Air Conditioning, Compressed Natural Gas (CNG), Joule-Thomson effect, Fuel Consumption.

Introduction:

Air conditioning is a key feature of modern transportation, especially when it comes to the hot and humid climatic conditions of South Asian countries like Pakistan, India, and Bangladesh. Air conditioning holds primary importance in both public and private transportation as it has effects on the travel quality and the health issues [1].

In traditional systems, air conditioning in transportation is managed by belted compressor, driven by the internal combustion engine. The belted compressor phenomenon puts load on the vehicle's engine and contradicts the cost-effective and sustainability advantages. Cleaner types of fuel are a key factor in reducing emissions [2]. To solve the above-mentioned issues, a new system has been designed that is sustainable, cost-free, and durable [3]. The design is based on a well-known thermodynamic principle called the Joule-Thomson effect. As CNG flows through the regulator or expansion valve, there is a significant drop in temperature [4]. The proposed system utilizes this change in the structure; the evaporator coil is integrated into the gas line. The blower fan disperses the cool air in the cabin. The proposed system provides several notable benefits, such as it does not impose any additional mechanical load on the engine. It operates independently of the engine power and eliminates the need for a belt-driven compressor, thereby improving the vehicle's fuel economy. Furthermore, the lack of use of traditional refrigerants such as hydrochlorofluorocarbons (HFCs) [5], which is a major cause of greenhouse gas emissions, is a sustainable system that promotes green technologies [6].

CNG is a productive and compact form of energy that is both sustainable and cost-effective. It is produced by compressing naturally occurring gas to a range between 180 and 270 bar as compared to the volume at normal atmospheric pressure. Liquefied natural gas (LNG) is another form of energy from natural gas. LNG is obtained by cooling the organic gas to a cryogenic temperature that is typically around -162°C (111.15 K). At such a low temperature, it changes to liquid form, and its volume is reduced, making it a lot easier to store and transport over long distances [7]. LNG is composed of 75% methane and 5% nitrogen content or less. Methane is one of the main components of LNG and CNG [8].

Travelling often causes anxiety to the passengers, and the absence of an adequate cooling resource, it could cause potential stress and health issues induced by excessive heat. This system replaces the traditional structure with something more sustainable, which is also functional and does not induce load on the engine. Previous researchers have shown that operating an internal combustion engine on natural gas can significantly improve energy efficiency and lower emissions compared to gasoline [9]. This system is driving the development of an alternative method that is cost-effective and sustainable. According to the previous analysis, CNG is a better alternative to traditional fuels. It is a cost-effective fuel as well as reducing the negative ecological impacts. CNG also reduces the state's dependence on the import of fuel, resulting in fuel independence.

In order for CNG be used effectively, it is passed through 2 different stages. As CNG is stored at a very high pressure of 200 bar, to provide adequate fuel capacity, safety cannot be compromised. To ensure the safety and effectiveness of the fuel. In the 1st stage, the high pressure of CNG is reduced to 20 bar. This is achieved by subjecting the high-pressure CNG to a primary force regulator. Similarly, in the next stage, the pressure is further reduced to 7 bar. Now the fuel is at a state where it is suitable for combustion within the engine cylinders and injection. This pressure drop is achieved by a secondary pressure regulator. These pressure drop takes place in every CNG fitted vehicles but that pressure drop occurs in only one pressure regulator which produces cooling but that effect is wasting, in our proposed system we make primary pressure drop of high pressure CNG just before passing through evaporator due to which it causes cooling effect in the evaporator coil and we use that cooling effect for the interior cabin of the car which makes our system Novel.

Natural Gas Vehicles (NGVs) have gained widespread recognition for being a more suitable fuel option as it emits a lower percentage of harmful nitrogen oxides (NOx) and particulate matter (PM) [10]. Their widespread use has a constructive effect on the vapor standard of the environment, specifically in urban areas where, due to excessive transportation and other destructive activities, the air pollution is alarming. This positive impact also reduces the health challenges linked to the respiratory and cardiovascular systems. It reduces social costs linked to the damaging effects of air pollution, such as medical expenses generated due to excessive air pollution like asthma and tuberculosis, loss of productivity, and effectivity of the environment. NGVs are a better option for the population as they are more sustainable as well as cost-effective in densely populated areas. NGVs emit less greenhouse gas (GHG) as compared to traditional fuel vehicles. CNG have higher content of hydrogen and carbon ratio. This results in a cleaner burn and lower CO_2 emission, about 10-13%. CNG-fueled flicker ignition engines were detected to produce approximately 15–30% less CO than gasoline [11]. This reduction is due to the cleaner burning environment of methane, the main component of CNG, which encourages complete combustion due to its simple chemical structure and higher hydrogen/carbon ratio. The high-octane content of compressed natural gas increases its ability to withstand engine knocking, and thus it can be safely used at higher compression ratios. This feature allows a deeper and more effective combustion, which leads to higher thermal efficiency and engine performance in general. Moreover, CNG has stable combustion characteristics that minimize the pre-ignition or explosion risk, and as such, improve the safety of engines in operation and reliability [12].

A basic thermodynamic process used universally in refrigeration and air-conditioning systems is called the ideal vapor-compression refrigeration cycle. It consists of four major steps: isentropic compression, during which the refrigerant is adiabatically compressed and its pressure and temperature rise; constant-pressure heat rejection in the condenser, where the low-pressure refrigerant expels heat into the environment and condenses into a liquid; throttling, where the pressure and temperature of the refrigerant are decreased by an expansion valve to an isenthalpic process; and constant-pressure heat absorption, during which the low-pressure refrigerant cools down the surroundings and condenses into a liquid [13].

With increasing awareness of climate change, people search for fuel alternatives that are as effective as conventional fuels, sustainable, and cost-effective. CNG is one of the eco-friendlier alternatives, and it is also one of the cheaper fuel options in developing countries like Pakistan. CNG has lower carbon emissions, and it has a cleaner burn. Despite its ecological advantages, CNG-fitted engines are less efficient and produce less engine power, which results in lower engine life. Furthermore, equipping the vehicle with a conventional (belted compressor) air conditioning system reduces the engine's life. When fuel burns in the engine cylinder, it creates pressure that pushes the cylinder piston down. This pressure determines the engine power. At an engine speed of 4500 rpm, gasoline has a maximum pressure of 40 bar, while CNG only has 32 bar. These results show that CNG has less energy per volume, so each combustion releases less heat energy, and less fuel flows into the cylinder compared to gasoline [14]. Due to the mentioned reasons, the piston does not get a strong push as in gasoline engines. Due to which the engine produces less torque and power. To maintain good engine state and performance, engineers usually adjust the ignition timings and optimum combustion settings.

During engine running, there is heat exchange from the burning of gases to the engine walls. 27 KW for gasoline, while there is a 20 KW heat exchange. This is a 26% drop from conventional engines. CNG runs at a low temperature, making CNG engines more sustainable as there is less load on the engine, induced by high temperatures. But despite that, the efficiency is still lower than that of gasoline-fitted engines. The escalating environmental and energy issues have also caused the quest for finding alternative fuels that can reduce the emissions of vehicles without compromising the engine's performance to satisfactory levels [15]. Compressed natural gas (CNG) has been one of these alternatives and has been made eminent by its clean-burning nature, high octane number, and the fact that it is available in high quantities. In comparative emission studies on CNG and other conventional fuels like gasoline and diesel, there are huge benefits of CNG in the minimization of major pollutants [16]. Also, there are some safety concerns which are associated with the expansion of high-pressure CNG.

The primary safety concern associated with high-pressure CNG is the risk of leakage, which can create a flammability hazard near the passenger cabin. To mitigate this risk, the cooling box is positioned outside the cabin to isolate high-pressure components. Insulated pipelines and automotive-grade CNG fittings are used to minimize leakage [17]. A gas detection sensor coupled with an automated shut-off valve at the CNG tank ensures immediate system isolation in the event of a leak. Additionally, tank pressure is monitored via a gauge prior to vehicle operation to detect abnormal pressure loss indicative of potential leakage.

The emissions of carbon monoxide (CO), which result from incomplete combustion, are significantly lower when CNG is used; experiment results show that a 70 percent decrease in carbon monoxide emissions, which occur with pure gasoline, occurs to 1.23 percent when a CNG-gasoline mixture is used. On the same note, CNG has lower carbon dioxide (CO_2) emissions owing to its reduced carbon-to-hydrogen ratio, hence reducing the contribution to greenhouse gas formation. Biofuels like ethanol and biodiesel can also reduce CO_2 generation, but their life cycle emission is different according to production processes; CNG has relatively the same low-level of exhaust. Nitrogen oxides (NOx), which normally form at high temperatures of combustion, can be slightly enhanced by high CNG ratios due to lean combustion and high temperature of methane, but this disadvantage can be reduced by using emission control methods of exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) [18].

In addition, CNG operation also leads to significantly reduced unburned hydrocarbon (HC) emissions, reducing the figure of 99 ppm in the case of gasoline to 44 ppm, which is a result of its uniform air-fuel mixing and full combustion behavior. Moreover, CNG can reduce the formation of soot and smoke because of its gaseous nature and the non-presence of heavy hydrocarbons in its composition, unlike diesel, which leads to the formation of high levels of soot and PM. On the whole, CNG has the best environmental performance, recording significant CO, CO_2, HC, and PM emissions when compared to all major emission categories, with the levels of NOx being manageable due to modern methods of emission control, making it a clean and sustainable fuel option in spark ignition engines [19].

The gas pressure regulator is a very important part in compressed natural gas (CNG) systems that will retain a constant outlet pressure even when there is a change in the inlet pressure to prevent an increase or decrease in the outlet pressure of the gas, and it is provided to power the engine or the auxiliary systems. It functions by using three main components: a restricting valve, which regulates gas flow, a loading system that maintains the balance of forces like a spring or a diaphragm, and a measuring component that detects outlet pressure and adjusts the valve motion [20]. The process of regulation has a high-pressure gas flowing into an orifice, and the diaphragm and valve continuously vary in order to keep a constant downstream pressure in response to changes in demand. To be more accurate, CNG systems typically use a two-step regulation process, which first brings high storage pressure down to a medium level, and then brings it down to a range that can be used (which is usually 0.021-0.3 bar) [11], thus making the process safer and more controlled. As part of the air-conditioning systems of CNG-powered buses, the evaporator is an inseparable part of the vapor compression cycle of refrigeration, and it captures heat in the air of the cabin and exchanges it with the refrigerant that is circulated.

The evaporator, located between the expansion valve and the compressor, receives low-pressure refrigerant, which absorbs heat in the cabin air passing over its coils, and is changed into vapor. This is done at low temperature and pressure and cools the passenger compartment with minimal increase in refrigerant temperature. To ensure the reliability of the system, the refrigerant can be superheated before leaving the evaporator to avoid liquid intrusion into the compressor. Nevertheless, other conditions like variable engine speed may affect the efficiency of the evaporator because when the engine speed is intensive, it decreases the circulation of the refrigerant and airflow, restricting the transmission of heat. To deal with these difficulties, contemporary designs like multi-flow and microchannel evaporators are being established with an aim of improving the heat exchange, reducing the weight of the system, and also increasing energy efficiency. In turn, streamlined evaporator and regulator designs in the CNG-based air conditioning systems are added to a stable thermal operation, low fuel use, and environmental sustainability in the public transportation sector.

The advantages of compressed natural gas (CNG), including its high storage pressure, clean combustion characteristics, and lower exhaust emissions, are particularly relevant to the present study because they provide a unique opportunity for energy recovery through gas expansion [21]. In CNG-fitted vehicles, the pressure reduction process inherently generates a cooling effect due to the Joule–Thomson phenomenon. However, in conventional systems, this cooling potential is largely dissipated without practical utilization. The proposed JT-based air-conditioning system exploits this unused expansion cooling to provide cabin thermal comfort while simultaneously eliminating the mechanical load associated with conventional compressors. Therefore, the inherent properties of CNG not only contribute to environmental sustainability but also directly motivate the development of the present compressor-free cooling system, establishing a clear link between fuel characteristics, system design, and research objectives.

Material and Methods:

Design Calculations:

Heat Load Calculation:

The calculation of the heat load of an air-fuel-based system, in which combustion is made up of some basic thermodynamic equations, can be calculated. The objective of this calculation is to calculate the thermal energy produced through combustion, and it is allocated to air conditioning in the customized CNG vehicle system.

$$Q = \dot{m}_f \times C_p \times \Delta T \quad (1)$$

Were

$\dot{m}_f$ = the mass flow rate of fuel(kg/s),

C_p = specific heat constant pressure (J/kgK),

ΔT = the change in temperature (K).

To obtain $\dot{m}_f$, the mass flow rate of air, $\dot{m}_a$, and air-fuel ratio (AFR) must be evaluated first. The correlation is such that:

$$AF = \dot{m}_a / \dot{m}_f \Rightarrow \dot{m}_f = \dot{m}_a / AF \quad (2)$$

The ideal gas law of flowing gases is used to find the mass flow rate of air:

$$\dot{m}_a = (P/T) \times V \times (1/R) \quad (3)$$

Were,

P = 110300Pa (absolute pressure),

T = 366.3K (air temperature),

V = 0.188 m^3/s (volumetric flow rate of air),

R = 287 J/kg K (specific gas constant of air).

Replacing these values in equation (3),

$$\dot{m}_a = (110300/366.3) \times 0.188 \times (1/287)$$

$\Rightarrow \dot{m}_a = 0.197$ kg/s

With a ratio of air and fuel of 16.9, the rate of flow is:

$\dot{m}_f = 0.197 / 16.9 = 0.012$ kg/s

To identify the temperature change on expansion, the isenthalpic relation is utilized:

$$(T_2 / T_1) = (P_2 / P_1)^{((k-1)/k)} \quad (4)$$

Where:

$P_1 = 220$ bar, $P_2 = 18$ bar, $T_1 = 300$ K, $k = 1.299$

Substituting into equation (4):

$$T_2 = 300\,(18/220)^{(1.299-1)/1.299} = 168.7 \text{ K}$$

This is equivalent to a temperature of -104.5 °C. At the temperature of 300k, the known specific heat at constant pressure, Cp = 2.253 kj/kg.

The heat load was calculated as shown in equation (1)

$$Q = 0.012 \times 2253 \times (25-(-104))$$

$$\Rightarrow Q = 3.4 \text{ kW}$$

The estimated thermal energy that can be used in the cooling system is around 3.4 kilowatts. This finding shows that it is possible to use the heat energy generated during combustion to power the air conditioning process, which can be added to the overall energy-efficient design of the system to be developed in CNG-powered cars.

Identification of Surface Area of Evaporator:

The fundamental heat transfer equation that can be used to obtain the heat transfer through the evaporator is as follows:

$$Q = U \times A \times \Delta T$$

Repositioning to get surface area A, we obtain:

$$A = (Q / U \times \Delta T) \ \ldots\ldots\ (5)$$

To find ΔT, the Log Mean Temperature Difference will be found by calculating:

$LMTD = \Delta Tm = \{(Thin - Tcout) - (Thout - Tcin)) / (\ln (Thin - Tcout) / (Thout - Tcin))\}$

$\Delta Tm = \{(25 - 12) - (-104 - 45) / (\ln (25 - 12) / (-104 - 45))\}$

$\Delta Tm = 67.5$ degrees

$U = 50\ W/m^2.k$

Put values in equation (5)

$A = (Q/U \times \Delta T)$

$A = (3487.6\ W) / (50\ W/m^2.k \times 67.5°)$

$A = 1.03\ m^2$

Thus, the area of the evaporator that was calculated to be needed to get the required rate of heat transfer is 1.03 m^2.

Determination of Pressure Drop:

The difference in pressure (ΔP) in a tube as a result of fluid flow is calculated according to the equation of Darcy-Weisbach:

$$\Delta P = f \times (L/D) \times \rho \times (V^2/2)$$

The multiple circular tubes area is determined as:

$$A = n \times (\pi/4) \times B^2$$

$$A = 4 \times (\pi/4) \times (0.074)^2$$

$$A = 0.0171\ m^2$$

Calculation of Velocity

$$V = \dot{m} / (\rho \times A)$$

$$V = 0.012\ kg/s / (313\ kg/m^3 \times 0.0171\ m^2)$$

$$V = 0.00242\ m/s$$

Calculation of Reynolds Number

$$Re = (\rho \times V \times D) / \mu$$

$$Re = (313 \times 0.00242 \times 0.005)/0.000038 = 99.66$$

Friction Factor

For laminar flow ($Re < 2000$), $f = 64/Re$

$$f = 64 / 99.66 = 0.6423$$

Now the pressure drop will be equal to

$$\Delta P = f \times (L/D) \times \rho \times (V^2/2)$$
$$\Delta P = 0.6423 \times (5.34/0.005) \times (313 \times (0.00242)^2/2)$$
$$\Delta P = 0.6287\ kg/m \cdot s^2$$
$$\Delta P = 0.6287\ Pa$$
$$\Delta P = 6.287e\text{-}6\ bar$$

Therefore, the pressure drops across the tube is determined to be about 6.287e-6 bar.

Block Diagram:

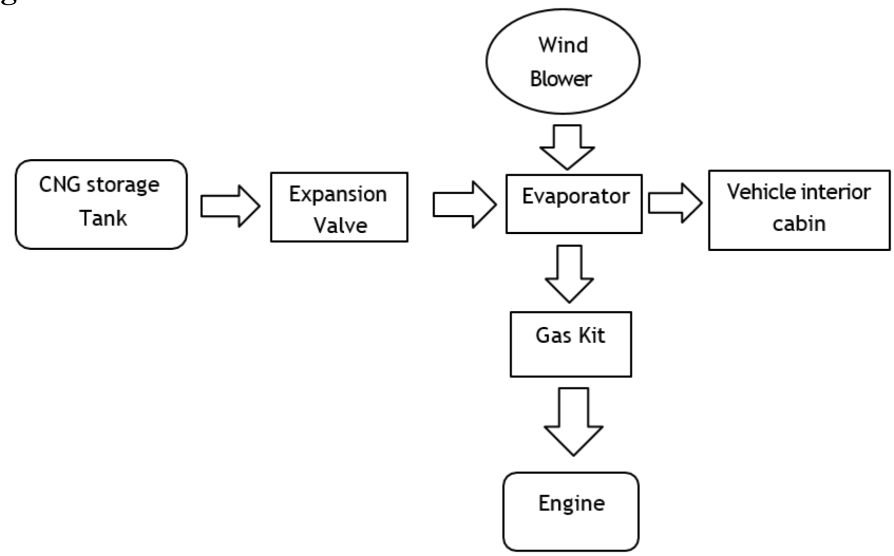

Figure 1. Block Diagram

Methodology and CAD Model:

CNG Storage Tank:

CNG is stored in an onboard cylinder next to a compressor, typically ranging from 200 to 250 bars. This high-pressure gas is intended to be used to fuel the engine, but in our design, before reaching the gas kit, it is diverted by means of a custom-made expansion circuit to obtain useful cooling.

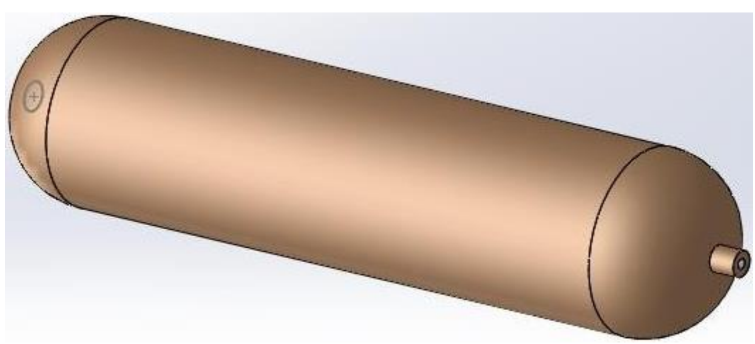

Figure 2. CNG Storage Tank

Expansion Valve and Pressure Regulator:

A specially designed expansion valve shall be used when CNG leaves the storage cylinder, as shown in Figure 2. The present valve constitutes an essential component for the control of the stress drop. Their stress falls dramatically when the gas expands abruptly through the existing vent. As a result of the Joule- Thomson effect, the current pressure causes the gas to cool, supplying the inversion temperature of CNG, which is usually higher than the ambient temperature.

The cooling results in this area are significant and can be exploited to support the cooling load of a vehicle cabin that does not have any external energy feedback.

Figure 3. Pressure Regulator

Evaporator:

The evaporator coil will then pass the expanded cold CNG. Alternatively, a cooling chamber may be provided with an air handling unit (AHU). When the warm ambient air blows through the current coil, which engages the blower fan, the heat is transferred from the air to the cold gas inside the coil. This causes the gas inside to absorb heat, so it functions as the usual refrigerant in a vapor compression structure.

The chilled gas will then flow directly into the second inner cabin of the vehicle, providing passengers with effective thermal comfort.

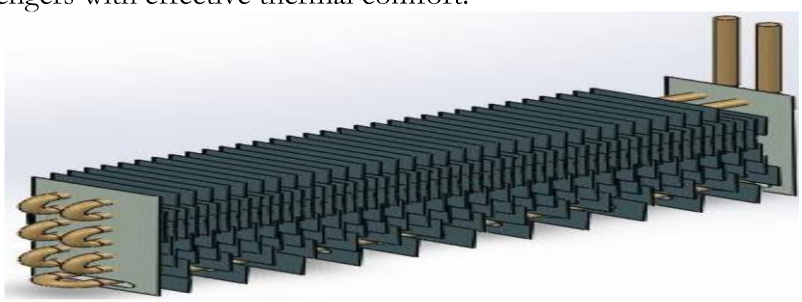

Figure 4. Evaporator

The CNG then moves onwards to the engine via the evaporator and absorber. It enters the gas kit whenever it is mixed with the air in the appropriate proportion. The current mixture will then be transmitted to the combustion chamber of the engine. Despite its expansion and cooling, the gas energy content is adequate for the operation of the motor since it affects only sensible heat, not chemical energy.

That system is green since it uses the cool power of CNG, which would otherwise be wasteful while being strained by regulation. Traditional regulators allow CNG to extend and cool without using this lower temperature. In contrast, at this stage, our design integrates a heat extraction mechanism. Thus, CNG performs a dual function; one acts as a refrigerant during expansion, and the second acts as a fuel for engine operation.

This design is not used in academic writing, only to simplify the gas condition framework by removing the compressor, condenser, and refrigerant. However, it furthermore reduces energy consumption, mechanical load on the engine, and costs.

The developed cooling system utilizes the pressure drop of compressed natural gas (CNG) to produce a cooling effect based on the Joule-Thomson phenomenon. The fabrication and functional sequence of the system is described below.

CNG Storage Tank:

The process begins with the CNG stored in a high-pressure storage tank, typically at a pressure range of 200–220 bar. This tank is securely mounted in the vehicle and equipped with safety valves to regulate outflow. The gas remains highly compressed within this tank.

High Pressure Gas-line:

From the storage tank, the CNG goes through a high-pressure gas line. This pipeline is constructed using steel or reinforced copper tubing capable of withstanding high pressure without leakage or deformation. Special attention is given to sealing and vibration resistance to ensure safe gas delivery.

Expansion Valve:

The high-pressure gas is then passed through a custom-fabricated expansion valve made of brass. Brass is selected for its corrosion resistance, ease of machining, and durability under varying pressure and temperature conditions. The expansion valve is a critical component that reduces the gas pressure, resulting in a significant drop in temperature as the gas expands. This pressure drop occurs through a narrow orifice in the valve, allowing only a small amount of gas to expand at a time, thus generating a cooling effect in line with the Joule-Thomson effect.

Silver-Evaporator Coil:

At this stage, low-pressure CNG flows into a specially fabricated evaporator coil made from silver. Silver is chosen due to its highest thermal conductivity among metals, ensuring rapid and efficient heat absorption from the surrounding air.

The silver coil is designed in a serpentine pattern and includes thin silver fins attached throughout the tubing to maximize surface area for heat exchange. The gas flowing through this coil remains at a low temperature and absorbs heat from the surrounding air passing over the fins. Silver was used for the evaporator coil in the experimental prototype due to its high thermal conductivity, allowing effective evaluation of the cooling performance. However, due to its high cost and limited practicality for mass production, aluminum or copper is recommended for large-scale automotive applications. The evaporator was enclosed in an insulated cooling box to ensure safe operation. There is a very small pressure drop across the evaporator due to U-bends in the evaporator, but it does not affect the engine operations and its combustion.

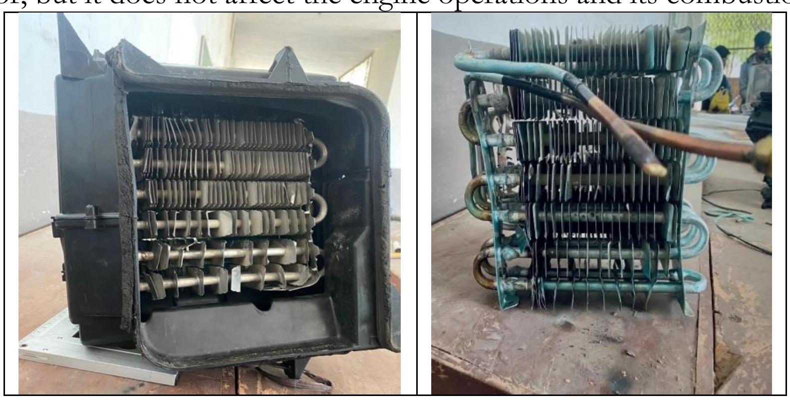

Figure 5. Fabricated Evaporator

Figure 6. Final Fabricated Model

Practical Feasibilities:

Cost: This system can be installed in a car that is already operating through CNG for just the cost of a gas flow regulator (if the car has its own traditional air conditioning system), evaporator, and alteration in the CNG fitting. Currently, by installing the proposed air conditioning system, the cost is 10000-12000 Pakistani Rupees.

Durability: The proposed fuel-free air conditioning system is inherently durable due to its simple construction and minimal moving parts. Unlike conventional automotive air-conditioning systems, which rely on compressors, belts, refrigerants, and lubricants, the present system operates using the pressure drop of CNG through a regulator, eliminating major wear-prone components.

Maintenance: Compared to a traditional air conditioning system, the proposed system has low maintenance because replacing refrigerant gas with CNG can minimize maintenance costs, as it is cheaper than refrigerant. Also, we remove the compressor of traditional Air conditioning, due to which maintenance is also minimized (compressor, driving belt, engine load).

Legal Scale Vehicle Integration: The proposed system can be easily integrated into CNG vehicles because it uses existing CNG components and does not require major engine modifications. Its compact and modular design allows simple retrofitting or installation during vehicle manufacturing. Since it operates without compressors or extra engine load, it is suitable for large-scale adoption in CNG vehicles.

Result and Discussion:

Experiment No. 1:

Test 1. Car Emission Test without Air Conditioning:

The first test was conducted under normal operating conditions with the air conditioning system switched off to assess the emission characteristics of the test vehicle, as shown in Table 1. The exhaust emissions were measured using a laboratory gas analyzer commonly employed for automotive exhaust analysis. The analyzer was pre-calibrated by the laboratory using standard calibration gases before testing. The typical measurement accuracies reported for such analyzers are approximately ±1–2% of full scale for CO_2 and ±5–10 ppm for CO, which are consistent with standard automotive emission testing practices.

Temperature measurements were obtained using contact-type temperature sensors (thermocouple-based) installed at the evaporator coil and relevant system locations. These sensors were laboratory-calibrated before testing, with a typical accuracy of ±1 °C.

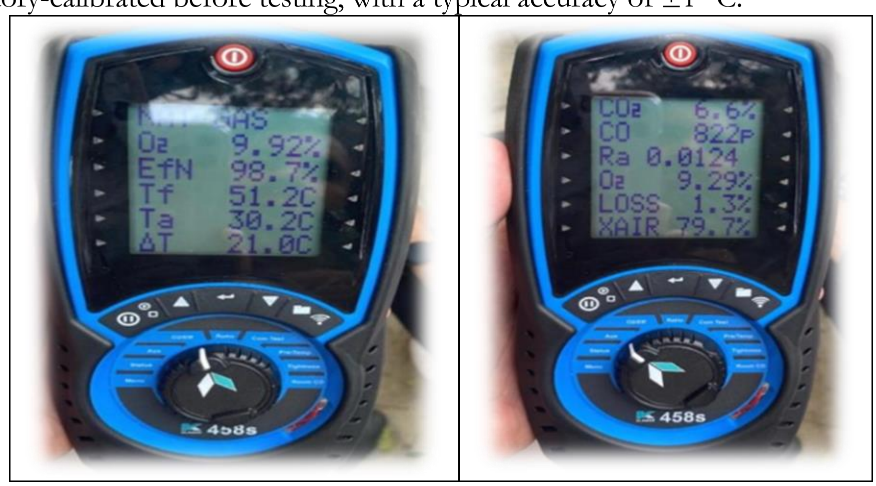

Figure 7. Emission Test (without AC)

Note: EfN (%) represents the exhaust normalization factor reported by the gas analyzer, which is an internal diagnostic indicator related to exhaust gas dilution and analyzer operating conditions rather than a regulated emission parameter. Similarly, XAIR (%) indicates the excess air factor or relative air content in the exhaust, providing qualitative information about combustion air-fuel conditions

Table 1. Emission Values (Without Air Conditioning)

No's	Parameter	Value
1	CO_2 (%)	6.6
2	CO (ppm)	822
3	Ra	0.0124
4	O_2 (%)	9.29
5	LOSS (%)	1.3
6	XAIR (%)	79.7
7	EfN (%)	98.7
8	Tf (°C)	51.2
9	Ta (°C)	30.2
10	ΔT (°C)	21.0

.Test 2. Car Emission Test with Traditional Air Conditioning:

The second test was conducted under comparable ambient conditions under traditional air conditioning to assess the vehicle emissions and thermal behavior.

Figure 8. Emission Test (with Traditional AC)

Table 2. Emission Values (with Traditional Air Conditioning)

No's	Parameter	Value
1	CO_2 (%)	8.3
2	CO (ppm)	791
3	Ra	0.0095
4	O_2 (%)	6.35
5	LOSS (%)	1.4
6	XAIR (%)	43.5
7	EfN (%)	98.4
8	Tf (°C)	65.3
9	Ta (°C)	32.7
10	ΔT (°C)	32.7

Test 3. Car Emission Test with Novel Air Conditioning:

The third test under normal conditions alongside the existing air conditioning system was carried out to assess the effectiveness and ecological impact of the newly designed air conditioning system. The current trial aims to assess whether the system achieves its own objective of reducing fuel and emissions load compared to the traditional AC apparatus. The recorded consequences are interpreted as lower.

Figure 9. Emission Test (with Novel AC)

Table 3. Emission Values (with Novel Air Conditioning)

No's	Parameter	Value
1	CO_2 (%)	3.7
2	CO (ppm)	554
3	Ra	0.0150
4	O_2 (%)	14.43
5	LOSS (%)	1.2
6	XAIR (%)	200
7	EfN (%)	02++
8	Tf (°C)	38.0
9	Ta (°C)	27.1
10	ΔT (°C)	11.0

Comparative Analysis of Emission Tests:

To assess the performance of the proposed novel air conditioning framework in comparison with the traditional air conditioning, a complete analysis of the three test scenarios was performed: test 1 (without AC), test 2 (with conventional AC), and test 3 (with novel AC). Their results are shown below in Figure 10.

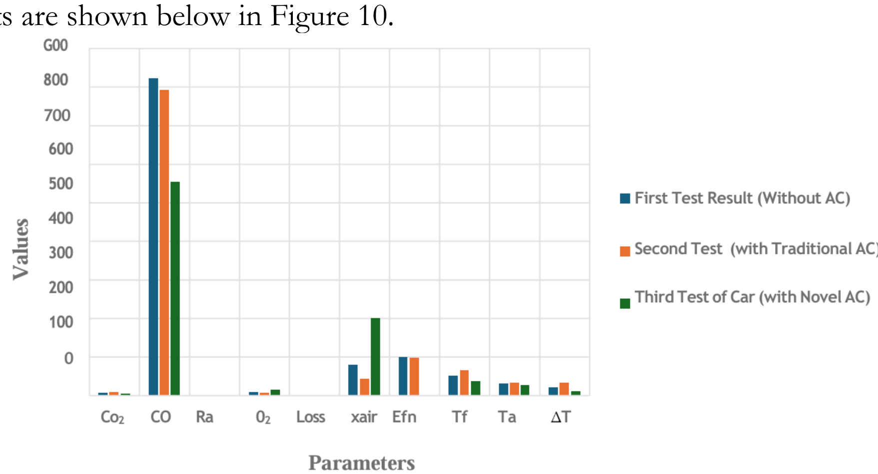

Figure 10. Comparative Emission tests Analysis

Experiment Number. 2:

Experimental Analysis of CNG consumption under varying Air Conditioning Systems

Test 1. CNG Consumption without AC:

The initial test was carried out when both the AC systems were switched off. This study was intended to establish a baseline for CNG consumption without any additional thermal load on the engine.

Initial Cylinder Pressure: 195 bar
Final Cylinder Pressure: 100 bar
Total Gas Consumed: 4.08 kg
Distance Travelled: 57 km
Average CNG Consumption: 0.06175 kg/km

Table 4. Vehicle Speed VS CNG consumption (Test without AC)

Distance (Km/h)	CNG consumption (Kg)
17	1.21
27	1.93
37	2.65
47	3.37
57	4.08

Test 2. CNG Consumption with Traditional AC:

In the second test, the vehicle was tested with a conventional belt-driven AC system in operation. The refrigerant compression in such systems is mechanically powered by the engine, increasing its load and resulting in higher fuel consumption.

Initial Cylinder Pressure: 222 bar
Final Cylinder Pressure: 100 bar
Total Gas Consumed: 5.964 kg
Distance Travelled: 61 km
Average CNG Consumption: 0.084 kg/km

Table 5. Vehicle Speed VS CNG consumption (Test with Traditional AC)

Distance (Km/h)	CNG consumption (Kg)
21	1.764
31	2.604
41	3.444
51	4.284
61	5.124

Test 3. CNG Consumption with Novel AC:

The third test uses a newly designed AC structure, which was designed to reduce the mechanical load on the engine while still delivering adequate cabin cooling. Incorporating changes to the existing structure aims at improving thermal efficiency and reducing energy consumption.

Initial Cylinder Pressure: 250 bar
Final Cylinder Pressure: 140 bar
Total Gas Consumed: 4.62 kg
Distance Travelled: 61 km
Average CNG Consumption: 0.0650 kg/km

Table 6. Vehicle Speed VS CNG consumption (Test with Novel AC)

Distance (Km/h)	CNG consumption (Kg)
21	1.36
31	2.01
41	2.66
51	3.31
61	3.96

Comparative Analysis of CNG Consumption Tests:

The CNG consumption between the novel AC system and the conventional AC system is shown below in Table 7. The values are taken and calculated from the experimental tests performed under the same driving conditions.

Table 7. Comparative Analysis of Traditional AC System VS Novel AC System

Distance (km)	Traditional AC (kg)	Novel AC (kg)	Difference (kg)	% Reduction with Novel AC
21	1.764	1.36	0.404	22.9%
31	2.604	2.01	0.594	22.8%
41	3.444	2.66	0.784	22.8%
51	4.284	3.31	0.974	22.7%
61	5.124	3.96	1.164	22.7%
71	5.964	4.62	1.344	22.5%

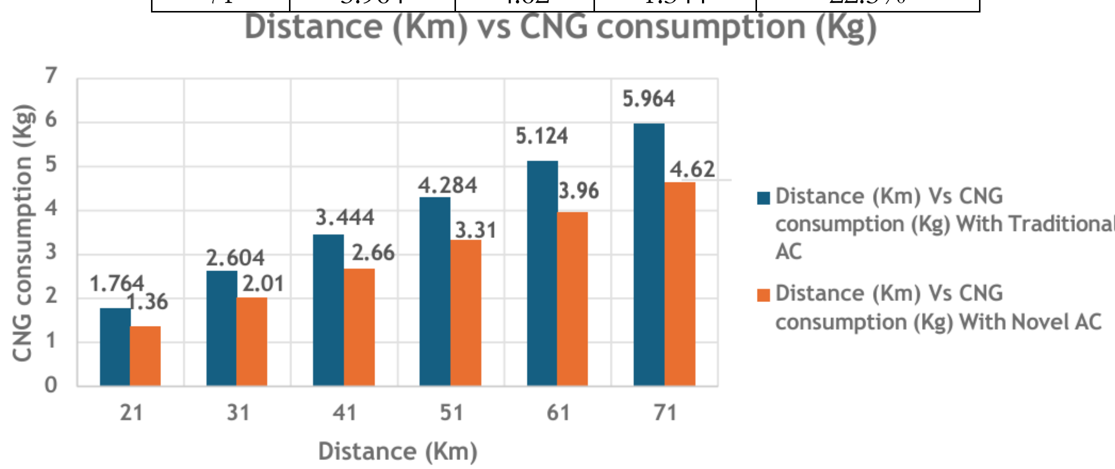

Figure 11. Comparative CNG consumption analysis between Traditional and Novel AC

From the above all results we it has been proved that our system has shown good temperature drop and best fuel economy, according to the calculations when vehicle is operating its traditional air conditioning system then the fuel average is 12 km/kg while operating novel air conditioning system (proposed system) the fuel average is 15km/kg which is almost 22.8% increase in fuel economy.

The observed performance improvements can be explained by the underlying thermodynamic and engine-operating mechanisms of the proposed system. The significant cabin temperature reduction is primarily attributed to the enhanced cooling effect generated by the Joule-Thomson expansion of CNG during pressure regulation, which produces low-temperature gas that effectively absorbs heat in the evaporator. Furthermore, the elimination of the belt-driven compressor reduces the mechanical load on the engine, leading to improved fuel economy and more efficient power utilization. This reduction in auxiliary power demand also contributes to improved combustion stability and reduced thermal stress on engine components. Consequently, exhaust emissions, including CO and CO_2, are reduced due to lower engine loading and more favorable air–fuel mixing conditions. These combined effects demonstrate that the reported numerical improvements are directly linked to the physical operation of the proposed JT-based air-conditioning system.

Limitations and Future Work:

The present study is limited to experimental testing on a single vehicle under controlled conditions, and system performance is influenced by CNG pressure variations. A potential limitation is the safety risk associated with high-pressure CNG leakage near the vehicle cabin, which requires further validation through improved sealing, leak detection, and long-term testing. Future work will focus on evaporator design optimization, integration of a control mechanism for regulated cooling, incorporation of a bypass valve to enable warm air supply during winter operation, and integration of an automated storage tank valve with the gas leak detection sensor to ensure safety in case of an incident.

Conclusion:

The comparison of experimental data proves that the suggested CNG-based air conditioning (AC) system has better cooling properties than traditional arrangements in terms of cooling rate, thermal stability, and efficiency of the system. The new design has a constant low cabin temperature during prolonged operation, whilst thermal load to the components is reduced. Meaning it has a high heat transfer efficiency through maximized gas expansion and better use of pressure. Inspired by the CNG-powered vehicles that are used in high-temperature areas like Pakistan, the proposed system uses the Joule-Thomson effect in which the CNG expands under pressure regulator to induce a cooling in the gas, which is then transferred to a specially designed evaporator coil. This removes the use of engine-driven compressors and chemical-based refrigerants, which results in less mechanical load and therefore the economy of fuel is saved, which is one of the main benefits of CNG propulsion.

Experimental findings verify a reduction rate of about 22.5 to 22.9 percent of refrigerant mass flow and subsequent reduction of compressor workload, which translates to an almost 10 percent reduction in CNG use when the system is under variable speed operation. Analysis of emissions indicated a decrease in CO and CO_2 levels, lower exhaust gas temperatures, and a higher excess air ratio, which is an indication of the higher efficiency of the combustion and the reduction of engine load. The system thermally improved the drop in cabin temperature between 21°C (294.15 K) and 11°C (284.15 K) in 14 minutes, which is better than traditional AC systems, which have a maximum drop of 14°C (287.15 K) in 14 minutes.

Moreover, the simplified design of the system discards an extra component compressor, a condenser, and R134a refrigerant, which reduces maintenance requirements and environmental effects. The proposed system is a cost-effective, reliable, and environmentally friendly solution. In general, the research confirms a dual-purpose air-conditioning system with increased cooling and fuel efficiency to provide the way for future developments of solar-assisted power integration, advanced heat exchangers, and automated control systems to make the most of energy use and flexibility in CNG-based transportation.

References:

[1] S. Vashisht and D. Rakshit, "Recent advances and sustainable solutions in automobile air conditioning systems," *J. Clean. Prod.*, vol. 329, p. 129754, 2021, [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0959652621039305

[2] Rui Hu, Xinyi Chen, "Exhaust emissions and energy conversion of hybrid and conventional CNG buses," *Transp. Res. Part D Transp. Environ.*, vol. 134, p. 1044055, 2024, [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1361920924003626

[3] G. A. Daria Sachelarie, "Air Conditioning Systems in Vehicles: Approaches and Challenges," *Sustainability*, vol. 17, no. 12, p. 5257, 2025, doi: https://doi.org/10.3390/su17125257.

[4] A. N. Sina Nabati Shoghl, "Thermodynamic analysis and process optimization of a natural gas liquid recovery unit based on the Joule – Thomson process," *J. Nat. Gas Sci. Eng.*, vol. 96, p. 104265, 2021, doi: https://doi.org/10.1016/j.jngse.2021.104265.

[5] N. Zhang and Y. Dai, "Performance evaluation of alternative refrigerants for R134a in automotive air conditioning system," *Asia-Pacific J. Chem. Eng.*, vol. 17, no. 1, Jan. 2022, doi: 10.1002/APJ.2732.

[6] S. A. R. Han-Seop Song, "Innovative Pathways for Sustainable Automotive Air Conditioning Systems: A Comprehensive Review," *ResearchGate*, 2025, doi: 10.20944/preprints202502.0728.v1.

[7] "- IEA." Accessed: Jan. 08, 2026. [Online]. Available: https://www.iea.org/data-and-statistics/data-product/natural-gas-information, Licence: Terms of Use for Non-CC Material

[8] X. Yang *et al.*, "Measurement report: Insight into greenhouse gas emission characteristics of light-duty vehicles in China in the context of technological innovation," *Atmos. Chem. Phys.*,

vol. 25, no. 14, pp. 7669–7682, Jul. 2025, doi: 10.5194/ACP-25-7669-2025.

[9] Marek Ja´skiewiczja´skiewicz, Zbigniew Matuszak, "Experimental Investigation of Performance and Emissions for a Hybrid Electric Vehicle Operating on Gasoline, CNG, and Dual Fuel over the WLTC," *Appl. Sci*, vol. 15, no. 23, p. 12541, 2025, [Online]. Available: https://www.mdpi.com/2076-3417/15/23/12541

[10] T. S. Roberto Gioria, "Regulated and unregulated emissions from Euro VI Diesel and CNG heavy-duty vehicles," *Transp. Res. Part D Transp. Environ.*, vol. 134, p. 104349, 2024, doi: https://doi.org/10.1016/j.trd.2024.104349.

[11] J. N. Johannes Fichtner, "Simultaneous Reductions in NOx Emissions, Combustion Instability, and Efficiency Loss in a Lean-Burn CHP Engine via Hydrogen-Enriched Natural Gas," *Energies*, vol. 18, no. 16, p. 4339, 2025, doi: https://doi.org/10.3390/en18164339.

[12] M. K. Fatih Özcan, "Dynamic Modeling of a Compressed Natural Gas Refueling Station and Multi-Objective Optimization via Gray Relational Analysis Method," *Appl. Sci.*, vol. 15, no. 9, p. 4908, 2025, doi: https://doi.org/10.3390/app15094908.

[13] Paolo Blecich, Laszlo Garbai, "Analysis of Thermodynamic Processes in Thermal Energy Storage Vessels," *Thermo*, vol. 6, no. 1, p. 5, 2026, [Online]. Available: https://www.mdpi.com/2673-7264/6/1/5

[14] S. A. Pradeep Vishnuram, "A critical review on alternative fuels for road transportation: Pollution mitigation, environment and economic perspective," *Energy Strateg. Rev.*, vol. 61, p. 101894, 2025, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211467X25002573

[15] Beatrice Pulvirenti, Giacomo Puccetti, "Dynamic Energy Consumption Modeling for HVAC Systems in Electric Vehicles," *Appl. Sci.*, vol. 15, no. 7, p. 3514, 20251, [Online]. Available: https://www.mdpi.com/2076-3417/15/7/3514

[16] N. G. Mohamed Hofny, "The Impact of Alternative Fuels on the Performance and Emissions of Petrol Engines: A Review," *J. Adv. Res. Fluid Mech. Therm. Sci.*, 2024, [Online]. Available: https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/article/view/9600

[17] Yousaf Ali, Ahsan Younus, "Compressed Natural Gas (CNG) as a fuel and the associated risks: A quantitative analysis in the scenario of a developing country," *J. Saf. Sci. Resil.*, vol. 5, no. 3, pp. 306–316, 2024, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666449624000380

[18] S. H. Medhat Elkelawy, M.M. Bassuoni, Hagar Alm ElDin Mohamad, "Effect of Dual-fuelled CNG and Gasoline on Spark Ignition engine performance and Emissions behaviors at different loads," *J. Eng. Res.*, 2024, doi: 10.70259/ENGJER.2024.861810.

[19] Y. Liang, "A Review of the Effect of Compressed Natural Gas (CNG) on Combustion and Emission Performance of Internal Combustion Engines," *Trends Renew. Energy*, vol. 8, no. 2, pp. 119–129, 2022, doi: 10.17737/tre.2022.8.2.00144.

[20] V. S. Dmitry Stadnik, "Study on Stability of Gas Pressure Regulator with a Built-In Silencer," *Energies*, vol. 16, no. 1, p. 372, 2023, [Online]. Available: https://www.mdpi.com/1996-1073/16/1/372

[21] Bi Yu Chen, Qi Liu, "Evaluation of energy-environmental-economic benefits of CNG taxi policy using multi-task deep-learning-based microscopic models and big trajectory data," *Travel Behav. Soc.*, vol. 34, p. 100680, 2024, [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S2214367X2300131X