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Design, development & performance evaluation of sustainable, hybrid air-conditioning system for automobiles

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Abstract

Performance of the vapor adsorption refrigeration system is based on controlling the pressure of refrigerant, multi fluid temperatures, ambient and cabin air temperatures, and humidity to maintain thermal equilibrium. A direct evaporative cooling (DEC) system combined with adsorption refrigeration technique is sustainable as it is driven by vehicle exhaust. The heat potential in the exhaust gases of a vehicle which otherwise is going to be wasted to the atmosphere, can be (HAC). The designed and fabricated HAC model is fitted in a small vehicle and vehicle exhaust is provided to this model for finding its COP and cooling potential with the help of a customized data acquisition and controlling system. This research describes the design development and testing of an innovative HAC system for small cabin volume cars. The theoretical and actual COP of HAC system is derived at maximum blower speed and two DEC fans working conditions. The theoretical COP of HAC system varies from 0.57 to 0.66 and the actual COP varies from 0.57 to 0.47 with vehicle speed. As velocity increases COP decreases. Increased COP of the HAC system promises its easy adaptability for automotives at reduced cost.

Keywords: sustainable cooling technologies, direct evaporative cooling, specific cooling power, cellulose grid, vehicle compartment's air cooling, vapor adsorption refrigeration, activated carbon granules.

1. Introduction

Since the previous four decades, human pain has been growing due to significant changes in the environment and atmospheric influences. As a result, the elective aspect of incorporating air conditioning in automobiles is today becoming a significant system of a vehicle and has become a need. These higher cooling requirements necessitate more air conditioning power and the consumption of additional hydrocarbon fuel. Vapor compression refrigeration is extensively employed in current vehicles propelled by internal combustion engines, with highly optimized and efficient components. To control engine power needs due to air conditioning system power, extra fuel is burned, increasing engine speed by 200 to 300 rpm (Johnson 2002). Hence, an engine exhibiting a thermal efficiency ranging from 25% to 30% incurs an extra 10% fuel consumption in both operational and non-operational states, increasing more combustion gases like carbon dioxide (CO2), carbon monoxide (CO), sulfur dioxide (SO2), nitrogen dioxide (NOx) emissions (Atan, 1998).

Regulations limiting the use of chlorofluorocarbon (CFC) and hydrofluorocarbons (HFC) to reduce ozone depletion and greenhouse gas emissions must also be severely enforced. As shown in **Figure 1**. below, a belt-driven mechanical nature of the compressor is utilized, which utilizes a designated portion of the power supplied by the engine.

Over the previous decade, efficiency enhancement and thermal load optimization have evolved, resulting in smaller total component sizes and more system flexibility in automobiles. These advancements facilitated the design of the complex space within the vehicle. The control of the compressor and crank pulley engagement is governed by an electronic control unit, which maps the temperature set requirement for the cabin's environment.

2. Literature Review

2.1 Development of adsorption air conditioning system

Engine operating at 30% thermal efficiency releases 70% of the waste heat through exhaust gases, coolant, and engine compartments by radiation (Johnson 2002). Atan et al. devoted their efforts to employing the waste energy in radiator water and exhaust gases for air conditioning purposes (Atan 1998). Johnson et al. illustrated two varieties of refrigeration systems: vapor absorption and other is solid adsorption, explaining the adsorption of refrigerant by porous media. Zeolite, gel of silica, activated carbon, and composites have porous structures that absorb or desorb the refrigerant gases on cooling or heating. The solid material is called an adsorbent while refrigerant gases are called adsorbate. The effectiveness of the adsorption system majorly depends on adsorbate uptake at working conditions (Johnson 2002).

2.2 Adsorbate and adsorbent working pair-sItre

The different working pairs of adsorbate-adsorbent have their unique adsorption equilibrium characteristics. Many researchers have found mathematical correlations to express various pair parameters for the formation of steady state equilibrium working conditions. **Figure 2**. shows the development of different adsorbent-adsorbate pairs till today. L. Wang et al. summarized the benefits and drawbacks of various working pairs. along with mathematical models (L. Wang, R. Wang, and Oliveira 2009). Many researchers put their efforts into adopting a variety of cooling techniques for different cooling applications nevertheless cooling performance improvement is the key focus area.

Extensive review work on air-conditioning of commercial vehicles focused on absorption refrigeration using engine exhaust and fuel cell exhaust. The yearly refrigerant leakage rate from presently used vapor compression system can be as high as 25% moreover, these refrigerants exhibit noteworthy Global Warming Potential (GWP). The review also found very scare contribution of absorption refrigeration to automobile air conditioning along with vehicle level experimentation (Venkataraman et al. 2020). Tiawri et al. developed the exhaust gas operated refrigeration system for trucks with 1kW capacity. The experimentation is done at a laboratory fitted engine with an Activated Carbon-ammonia working pair. It was possible to get a cooling power of 1 to 1.2 kW. The system's coefficient of performance (COP) falls within the spectrum of 0.40 to 0.45. the cooling effect requires around 10 minutes of heating time. The overall weight for a cooling capacity of 1kW is 3000g of Activated Carbon-ammonia (Tiwari and Parishwad 2012). Li Gang et al. experimentally analyzed the performance of the secondary loop refrigerant system for automobiles using R152a and HC-290. The experimental outputs are compared with those of single-loop R134a traditional system. The results have revealed an improvement in cooling performance by 15% with R152a while 60% with HC-290.The systematic uncertainty for the working range of instruments are also presented. The lower pressure of R134a is 3 bar while higher side pressure is about 14 bar for an ambient heat load of 35°C (G. Li et al. 2014).

2.3 Activated carbon (AC) as adsorbent

Activated carbon has graphite lattice that is very porous and amorphous. It's often made up of little pellets or powder or granules. Carbonization and activation or oxidation are the two steps in the manufacturing process. The carbonization process entails drying and heating in the range of 600-900°C in a nitrogen environment in order to remove by-products, such as tars and other hydrocarbons, from the source material, as well as expel any generated gases. In the activation or oxidation, the carbonized product is exposed to oxygen above 300°C. Further to improve porosity by opening its microstructure, chemical treatment is done with different hydroxides and chlorides.

Yeo et al., reviewed the adsorption refrigeration system using improved porosity of the adsorbent. The utilization of readily accessible commercial activated carbon without antecedent treatment has led to a diminished performance outcome. Oxidized activated carbon has a better adsorption property on hexavalent chromium (VI) as compared to the untreated activated

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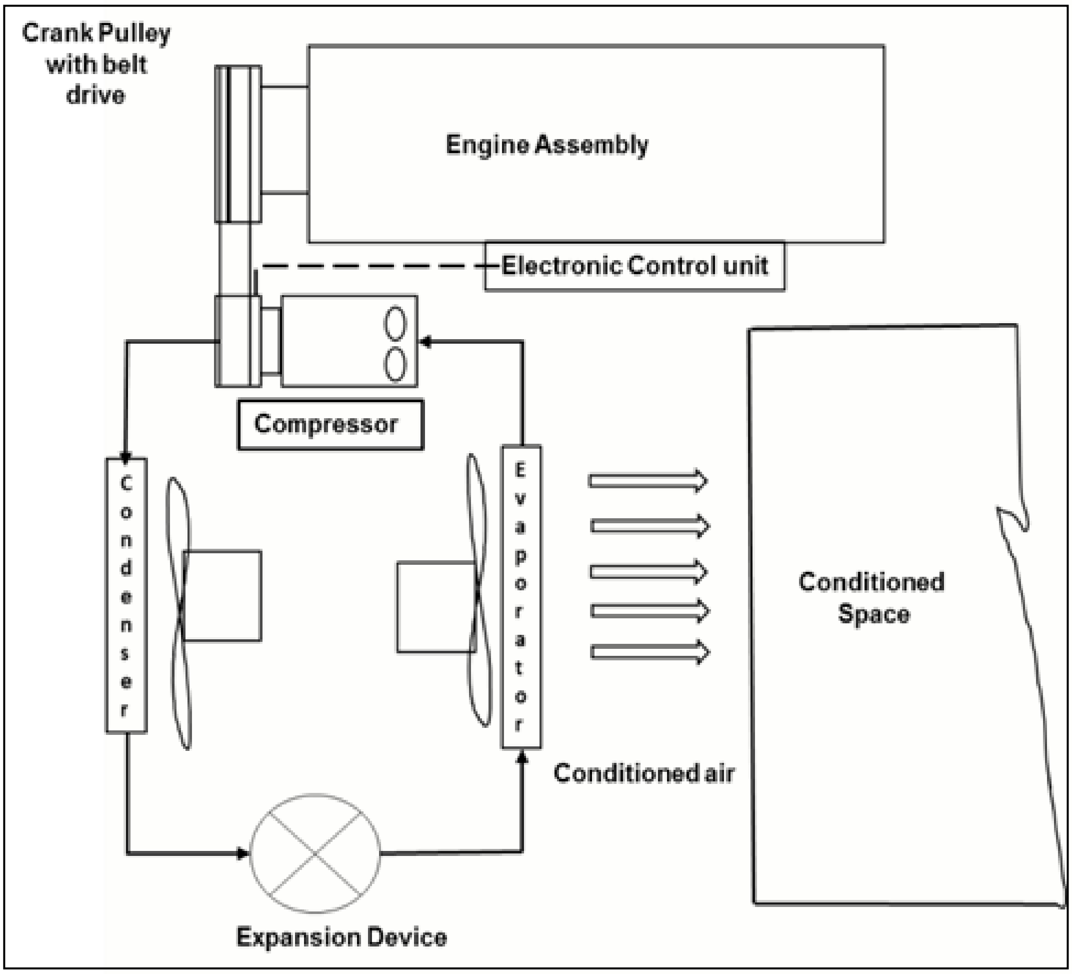

Fig 1. Conventional compression refrigeration

carbon. Oxidative treatment of activated carbon was highly effective in increasing metal ion uptakes. Generally, the thermal treatment of activated carbon proved effective in enhancing the adsorption capacity of organic components (Yeo, Tan, and Abdullah 2012). Ruzhu Wang et al. explained the microstructure of different types of activated carbon. Other adsorbents and adsorbates are also explained with their properties. Different working pairs with their performance parameters and thermodynamic properties of physical adsorption are also explained. Fig 3. (a) and Fig 3 (b) below show the pictorial and microscopic view of granular activated carbon (GAC) made of purified coconut shells (Ruzhu Wang, Liwei, and Jingy 2014).

Zeng et al., Investigated the impact of particle diameter on thermal conductivity. The thermal conductivity of the adsorbent is also affected by the refrigerant's thermal conduction coefficient and the number of voids present in the adsorbent layer. When the pressure drop in the adsorber is reduced. The mass transfer performance improves. As permeability increases, pressure drop reduces. The permeability experiment was carried out on adsorbent with diameters of 305μm, 390μm, 513μm, and 605μm, and it was discovered that the permeability increases as the adsorbent diameter and void ratio increase (Zeng et al. 2017).

The researcher designed a refrigeration system based on adsorption utilizing granular activated carbon as the adsorbent and refrigerant R134a as the adsorbate. The system uses solar thermal energy or waste heat in exhaust gases. The maximum temperature used for exhaust gases is 100°C. The calculated maximum value of the coefficient of performance is 0.36. The maximum specific cooling energy (SCE) of the system obtained from the test is 71 kJ/kg compared with the theoretical highest SCE of 82 kJ/kg (Askalany et al. 2013). The author analyzed the physical properties of granular activated carbon and R-134a refrigerant pair at temperatures from 21 ℃ to 61℃ and pressures up to 11 kgf /cm2. After 20 minutes of operation at 21˚C, the highest rate of adsorption was found equal to 1.90kg of R134a per kg of granular activated carbon. These outcomes as well

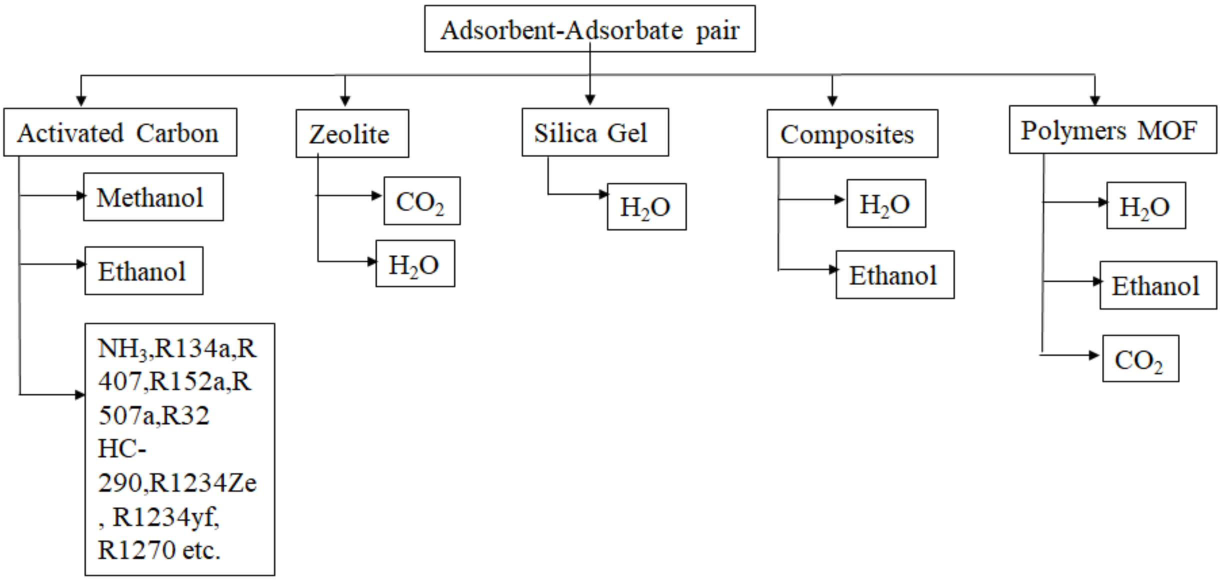

Fig 2. Development of different adsorbent-adsorbate pairs (Shabir et al. 2020).

depict "The adsorption capacity per kilogram of adsorber rises with an increase in heat transfer area.". This has given rise to a tube heat exchanger with fins which can be used as an adsorber. For capacities ranging from 0.21 to 1.82 kg of adsorbate/kg of adsorbent, The isosteric heat of adsorption spans from 120 to 340 kJ/kg. The Author analyzed the refrigeration system with R134a. Isotherms of the adsorption process are obtained for Maxsorb III in the temperature spans of 6°C – 70 °C and pressures reaching 12 bars during desorption. In current testing data, the isosteric adsorption heat is predicted for the working pair (Askalany et al. 2013). Shmroukh et al., designed adsorption chillers of 5 kW capacity. A tube and fin exchanger were used at the adsorber center. The surface was sealed with adhesive material. Powder activated carbon/R-134a, Powder activated carbon /R-407c, Powder activated carbon /R-507A, Granular activated carbon/R-507A, Granular activated carbon /R-407c, and Granular activated carbon /R-134a were all tested at varied adsorption temperatures ranging from 26°C to 52°C. At 25°C, PAC/R-134a had a highest adsorption capacity of 0.8352 kg/kg, whereas at 50°C, it had a peak adsorption capacity of 0.3207 kg/kg. The Powder activated carbon /R-134a pair is strongly suggested as a working pair due to its extraordinary adsorption capability in the tested working pairs (Shmroukh et al., 2015). Habib et al., depicted the kinematic characteristics of R134a and R507A for adsorption on pitch type Activated Carbon for various temperatures ranging from 21°C to 61°C using a variable pressure at constant volume. The adsorbent can adsorb the refrigerant R134a 1.6 kg/kg in 1200s at 25°C. As the ad-sorption temperature rises to 60°C, equilibrium absorption decreases to 1.0 kg/kg.

The equilibrium position, on the other hand, takes only 600 seconds to attain (Habib et al., 2010). The effectiveness of an adsorption chiller which has our adsorbent beds using Maxsorb III activated carbon was examined by Jribi et al., with 81 kg of Maxsorb and produced from solar energy at 85°C or waste heat. The system is able to generate 2 kW cooling power. The adsorption cooling performance of R1234ze is found to be virtually equal to that of R134a. Both R134a and R1234ze refrigerants have well-formulated mathematical models for adsorption cooling systems (Jribi et al., 2013).

Astina et al. in his experimentation used AC-R32 working pair. The adsorption capacity is increased using nitric acid and sulfuric acid and compared with pure activated carbon. The obtained COPs are in the range of 0.14 to 0.22 and SCP ranged between 4.0 and 6.3 W/kg of Activated Carbon. The OMB-DAQ-2461

data logger is used to map the temperature after 5 seconds interval and pressure is measured manually. The Clausius-Clapeyron equation stating the linkage between the evaporator pressure, the condenser pressure,

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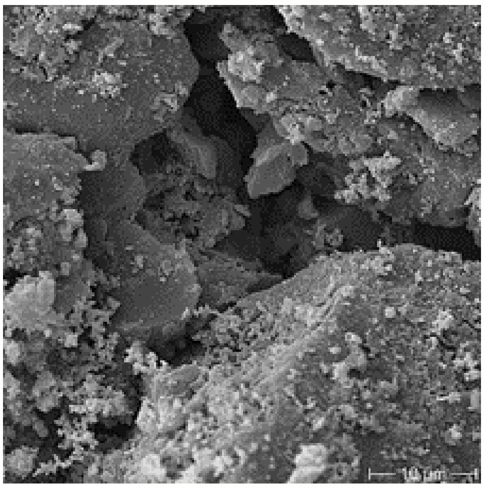
and system temperatures is described. The evaporator cooling capacity is dependent on a specific cooling power, cycle time, and mass of activated carbon in the bed. Thus, an increase in the number of adsorber bed than one and an optimum mass-accommodated design with a higher heat transfer coefficient enhances the cooling capacity. The adsorber bed leakage testing and evacuation is also mentioned before charging refrigerants into the adsorption system (Astina et al., 2018).

(a)



(b)

Fig 3. (a) Pictorial view of GAC; (b) Microscopic view of GAC

2.4 Activated Carbon-R134a working pair

Ahmed et al., explained the physical, chemical and composite adsorption future working pairs. In his work a review of many new and current work is covered: out of that AC/R134a pair is found much effective implementable working pair for automobiles applications. An adsorption isotherm at a pressure of 0.8 MPa, 30°C temperature, R134a -AC had a maximum capacity of adsorption uptake as 2 g/g. The adsorption time at 25°C was calculated to be 1200 seconds (Ahmed and Shehata 2017). Ahmed N. Shmroukh et al. reviewed the current advancements in the utilization of adsorption working pairs and revealed that the Maxsorb III/R134 combination stands out with the peak adsorption capacity. Activated carbon /Methanol has max. the adsorption capacity of 0.259kg/kg and Activated carbon/R134a has a maximum adsorption capacity of 2kg/kg at 30°C of bed temperature (Shmroukh et al., 2015).

Ojha et al., in their review, described different working pairs and recent progress in adsorption refrigeration along with different working pairs and applications. In his review, the maximum operating temperature is 250°C. It is observed that the use of activated charcoal is very frequent due to its highly porous volume. This sets activated carbon apart from typical adsorbents. In adsorption refrigeration systems, to maintain the continuity of the cooling effect produced, a minimum of two adsorber beds is a requisite (Ojha et al., 2021).

The system parameters of the GAC/R134a pair were reviewed by Askalany et al., The studies were carried out using a laboratory-scale test rig that was conceived and manufactured. At various temperatures, the GAC's adsorption ability was investigated. During the experiments, pressure and time were monitored. After 1000 seconds, The maximum capacity measured was to be 1.68 kg of refrigerant /kg of adsorbent at a temperature of 25°C (Askalany et al., 2013). Shmroukh et al., tested experimentally the adsorption properties of the granular activated carbon/R-134a pair in the temperatures 20°C to 60°C and at maximum pressures of 10 bars. At the end of 1200 seconds at 20°C, the highest adsorping capacity was obtained equal to 1.92 kg/kg. The test results show that as the thermal exchange surface area escalates the adsorping capacity /kg of adsorber also increases, based on which an adsorption heat exchanger with fins is developed. For adsorbing powers between 0.2 to 1.8 kg/kg, the isosteric heat of adsorption was estimated to be 120 to 340 kJ/kg (Shmroukh et al., 2015). S.A.Wani et al. reviewed experimental evaluation of adsorption refrigeration unit driven by exhaust gasses heat of automobiles. With a source temperature of 350°C to 450°C, the cooling power achieved was 5KW, COP was 0.25 and SCP of 165 W/kg to 202 W/kg of activated carbon (S.A.Wani et al., 2015).

Shabir et al., in his review work mentioned isotherm model for different adsorbate and adsorbent working pairs. For activated carbon/R134a working pair Dubinine Astakhov (D-A) model is used which gives fundamental equations for finding adsorption uptake isotherm at different pressures. Granular Activated carbon (GAC) with different heat treatment and oxidation processes improves the refrigerant uptake capacity. The granular activated carbon has a total pore volume of 0.878 cm^3/g and a surface area of 899 m^2/g. At 32°C saturation conditions, the equilibrium adsorption uptake is 1.639 kg/kg. It is evident that extensive research is underway to pioneer energy-efficient adsorption systems as a substitute for traditional air conditioning technology (Shabir et al., 2020).

Banker et al., in their performance analysis, used the AC-R134a pair along with thermal compression addition to existing conventional air conditioning systems. It showed an energy saving of 40% in hybrid compression over conventional compressors. Such a type of system is suitable for large cooling capacity requirements and where heat source at low temp. is available in abundant form like in industrial applications (Banker et al., 2008).

Kılıç et al., in his work, uses the 4 adsorber beds filled with activated carbon and R134a working pair. D-A equation model is used and parameters for creating the isotherm model are given. The mathematical equations for adsorber bed's parameters like length, diameter and inner diameter, coolant pipe diameters, mass of adsorbent, and adsorbate based on driving temperature are presented. The Saturation pressure at evaporator is 4.23 bar while and condenser is 8.68 bar. For evaporator, the temperature achieved is 10.6℃, and the cycle time considered is 960 seconds. The experimentation compared activated carbon granules-R134a or R404a paired with activated carbon pallets and isotherms are plotted at different pressures and temperatures with governing equation models for these pairs. The process of plotting the adsorption isotherm is mentioned with the procedure of vacuuming at 0.05kPa and desorbing residual gases. To prevent condensation within the adsorption tank during refrigerant charging, measures were taken to ensure that the pressure during the filling process was retained below the saturation pressure of the adsorbate fluid. Computed adsorption capacity and isosteric heat are presented compared with experimental data (Kılıç and Gönül 2018).

Pinto et al., reviewed details of Activated Carbon/R134a pair with four beds system had compared simulation and experimental results. Heated water at 84.9°C while cold water at 29.9°C is flown in the circuit. The ID of bed is 36.4 mm, 4.499 kg of R134a is filled. Optimized cycle time is found as 40 mins (10 mins to each process). At no load on evaporator condition, the lowest cooling of 14.5°C with a refrigeration capacity of 430±13W with COP 0.5 (Pinto et al. 2019). Dakkama et al. explore the use of Simulink/MATLAB software for testing the performance of several adsorbent/refrigerant working pairs in cascaded adsorption refrigeration. Activated carbon with an alkali activation process (Maxsorb) is used with R134a, R152a, Propane and Ethanol. Amongst all refrigerants R134a and propane paired with Maxsorb found the highest cooling capacity at 350s of cycle time with a COP of 0.088 (Dakkama et al., 2015).

X.H. Li et al. studied and reviewed the various methods for maximizing the Performance of an adsorption refrigeration system which depends basically on the size and shape of the adsorber bed. One approach involves reducing resistance to the heat transfer of the bed, achievable by increasing the heat transfer area. Options to achieve this include utilizing a plate-finned bed, a spiral plate bed, or a pin-fin bed, all of which effectively enhance the transfer area. The cycling time is reduced and the COP is improved when the heat pipe technology is introduced into the bed. It has been discovered that lowering the thermal contact resistance between the wall and the adsorbent and also reducing the heat resistance of the adsorbent itself can improve heat transfer performance. By adding new advances in the heat transfer process, adsorption cycles can be reduced (X. H. Li et al. 2015). Sharafian et al. studied different adsorber bed designs. Tubular adsorber beds with fins and extensions are developed as implementing practical solutions to augment heat and mass transfer rates within the bed for the required SCP of 350W/kg of dry adsorbent after optimizing fin parameters like fin pitch and fin length and improved adsorbent material's thermal conductivity. The metal wool is added to activated carbon to improve thermal conductivity for enhanced heat transfer rate (Sharafian and Bahrami 2014).

3. Procedure for design of Hybrid Air Conditioning System (HAC)

Hybrid air conditioning systems incorporate various cooling methods or cooling machines which have an energy-saving potential. Kojok et al. extensively reviewed a variety of hybrid systems. The evaporative cooling when compared with vapor compression cycle showed an increase in saving of energy from 20% to 49%. The use of cooling pads for liquid cooled vapor compression condenser improves system performance. The reduction in temperature of condenser even by 1℃ leads to 2-4% COP improvement. Hybrid systems utilizing adsorption cooling offer advantages primarily in scenarios with modest air conditioning loads and where discontinuous cooling is acceptable. This is particularly applicable in applications such as cold storage, air conditioning for vehicles, and similar use cases (Kojok et al., 2016). Kilic et al., in his experimentation, combine vapor adsorption and vapor compression refrigeration cycle. The refrigeration system uses silica gel- water pair. The flow of the mathematical model is given. Adsorption and desorption time is considered as 500s while cooling and heating time is 50s. The vapor compression cycle tested with different refrigerants found with highest COP and energy-saving ratio of 8.8 (Kilic and Anjrini 2020). Sultan et al., focus on desiccant dehumidification for air conditioning applications. Desiccant refrigeration combines desiccant dehumidification and evaporative cooling to manage humidity and temperature. The Desiccant air-conditioning (DAC) is appealing since it is devoid of harmful refrigerants, and regeneration is feasible using lower-grade heat. Silica gel, synthetic zeolite, activated alumina, polymer desiccant are the materials used for DAC system whose COP values found from 0.35 to 0.44. The desiccant efficiently bears the latent load of AC, lowering energy consumption and increasing system COP. The higher COP requires higher regenerated temperatures and humidity, so the system is mostly useful in highly humid and hot ambient regions (Sultan et al. 2015).

3.1 Heat load in modelled vehicle

The necessary cooling load for cooling of the vehicle compartments is determined through the conventional way of calculating various heat load scenarios. This includes considerations for solar radiation on vehicle rooftops, vehicle walls, the number of individuals within the cabin and windows, air heat load, utility equipment loads, as well as sensible and latent heat loads. For load assessment, a model vehicle with cabin dimensions of (2.23 x 1 x 1.4) m3 is used. According to environmental statistics from West India's local region, the maximum atmospheric temperature is 40°C (Verde et al., 2016). The DEC system is developed with a critical condition of 40°C and 40% RH. Considering the fluctuating load throughout the year, a specified comfort target temperature which is 25°C desired.

The cumulative heat load required for space cooling in the model car is assessed to be 1.7 kW, hence a refrigeration system of 0.5 TR is considered adequate to keep the vehicle compartment temperature at 25°C (Waghchore, Jumde and Somwanshi . 2013).

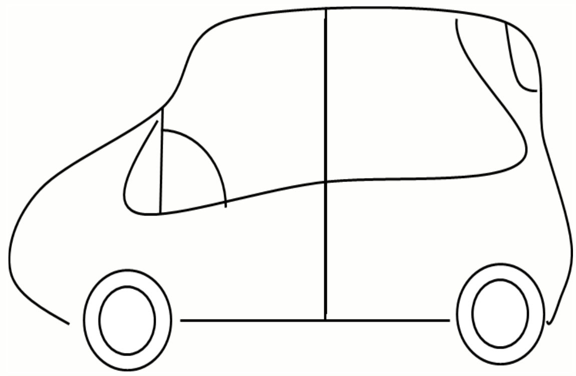


Fig 4. Outline of model vehicle for evaluation

3.2 Working of hybrid air conditioning system

Figure 5 above illustrates a schematic representation of the recently devised hybrid air conditioning system (HAC). using adsorption refrigeration combined with evaporative cooling.

The Direct Evaporative Cooling system (DEC) makes use of pads of cellulose material and takes latent enthalpy of vaporization of moisture, from air, lowering the temperature of the air. This cooled air from DEC system is then passed over the surface of finned evaporator tubes which is also a part adsorption refrigeration circuit. So, the air is further cooled over the evaporator tubes and then passed to the passenger compartment space for cooling. Thus HAC System consists of different circuits viz Flow of refrigerant through a circuit, Flow of exhaust gas circuit, and Flow of coolant circuit. As shown in Fig 5 above, the refrigerant circuit consists of two adsorber beds (B1 and B2) which work alternately in adsorption and desorption modes. In bed B1 when the adsorption of refrigerant is going on, bed B2 is involved in the desorption of the refrigerant process. The heat required for pressurization and desorption is taken from the waste heat of exhaust gases. The cooling of adsorber beds is done by passing coolant from the coolant circuit. Bed B1 is connected to the condenser through valve V3 through high-pressure line of refrigerant. Condenser outlet is connected by high-pressure line to the throttling valve and evaporator. The evaporator outlet is connected to bed B1 through valve V5 by low-pressure lines. Similarly, adsorber bed B2 is connected to the condenser through valve V4 by a high-pressure line. Condenser outlet is connected by a high-pressure line to the throttling valve and evaporator. Outlet of evaporator is connected to bed B2 through valve V6 by low-pressure lines.

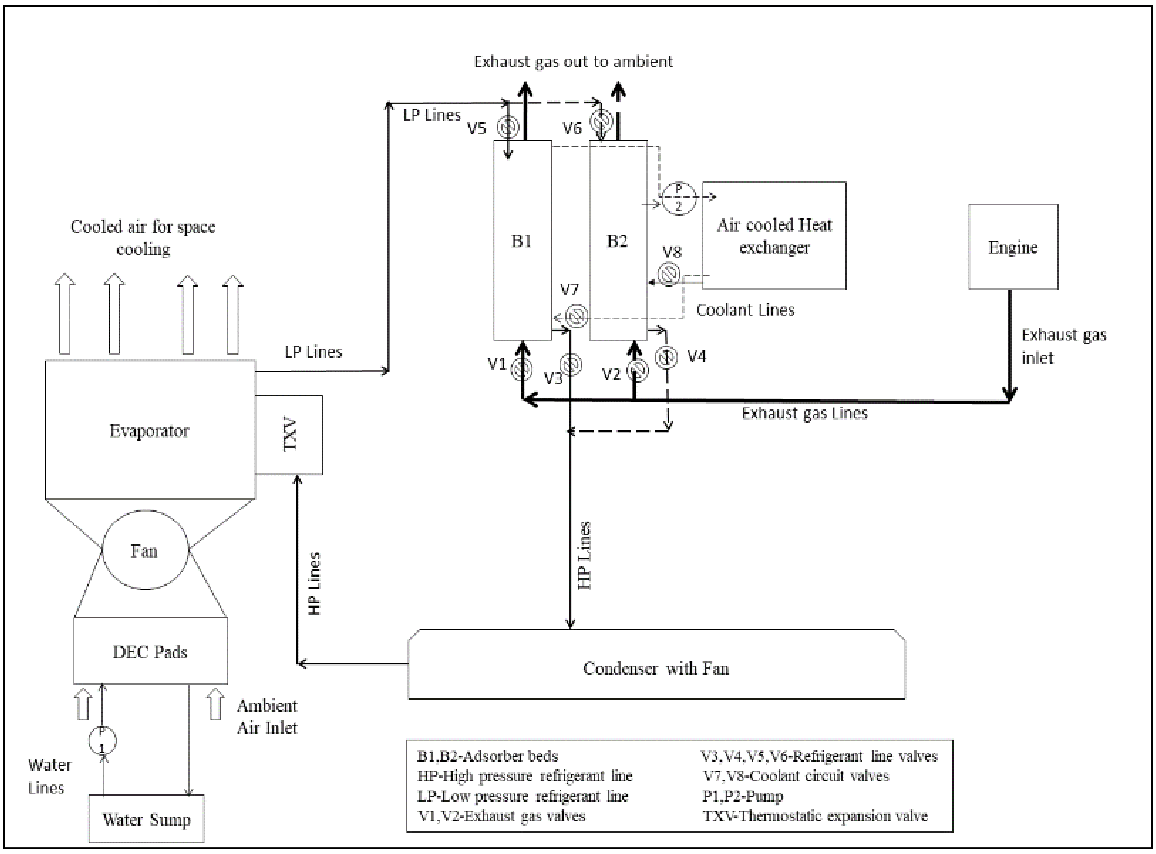


Fig 5. Hybrid Air Conditioning System

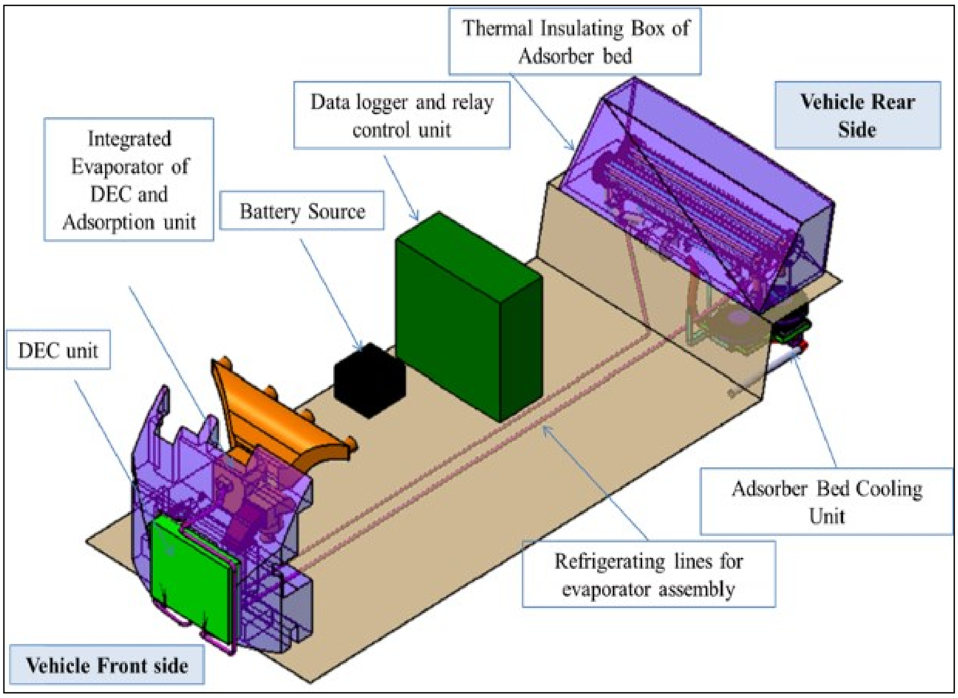
The exhaust gases from the engine are supplied alternately to bed B1 and B2 through valves V1 and V2 respectively. A water-glycol (50:50) mixture is used as a coolant to cool the adsorbed bed. The coolant absorbs heat from bed B1 and B2 and rejects it to air-cooled heat exchangers through alternate operation of valves V7 and V8 respectively. Pump P1 is used in DEC system to take water from the sump, pressurize it and spray over to DEC pads. Pump P2 sucks the heated coolant from bed B1 and B2 and forces it through air cooled heat exchangers.

3.3 Experimental setup in modelled vehicle

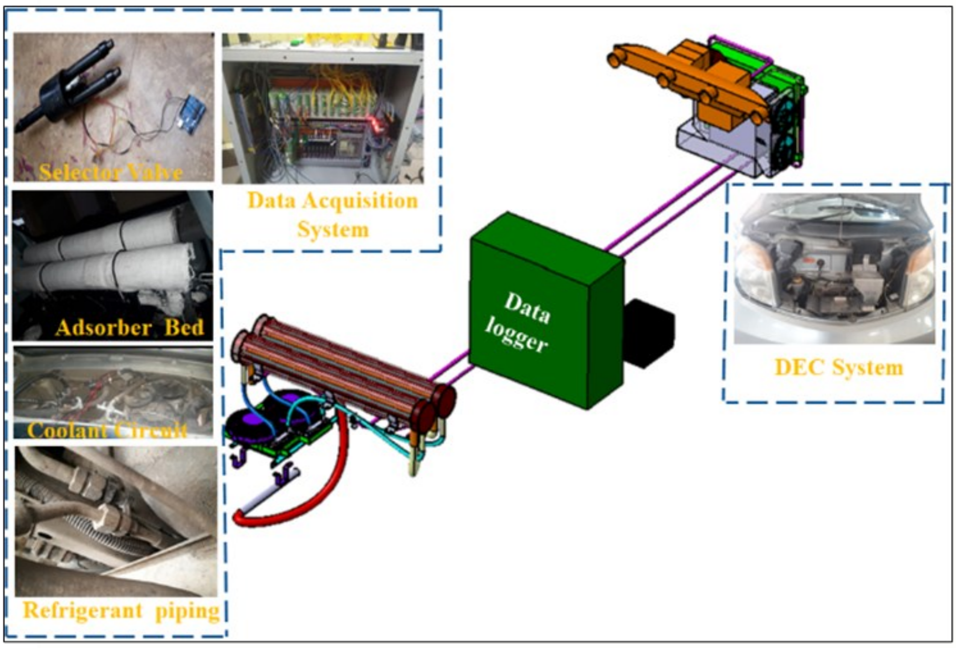
Refer to **Figure 6** (a) below which shows the proposed and developed HAC system integrated in selected passenger vehicles. The components are installed as proposed layout. DEC system is at the vehicle front side which transfers cooled air to cabin through a common evaporator assembly of the Vapor Adsorption System (VAS). The refrigerating line for evaporator cooling in VAS is routed form bottom of cabin floor from which refrigerant R134a is charged by vacuuming the circuit. Adsorber beds of VAS are installed at the vehicle rear side and are placed inside an insulated laminated box to avoid heat ingress to the cabin. The Data Acquistion System (DAS) is installed at the rear side of the vehicle and the battery at the center.

3.3 Vacuuming and determination of capacity of adsorption uptake

The capacity of adsorption uptake of an adsorbing material is determined by plotting an isotherm for the selected working pair. An isotherm is a graph that illustrates the correlation among pressure and adsorption uptake capacity for an activated carbon-R134a pair at a constant temperature. The concentration ratio for Vapor Adsorption Refrigeration System (VAS) is expressed as the ratio of adsorbed refrigerant mass to the activated carbon mass. The higher the concentration ratio, the higher will be the cooling effect. The pressure rise during the adsorption process is dependent on the adsorber bed design geometry hence this graph must be analyzed before experimentation of the HAC system. Before charging of gas, vacuuming is an important step where any minor leakage from any joints or component gets caught which may help in achieving stable performance system.



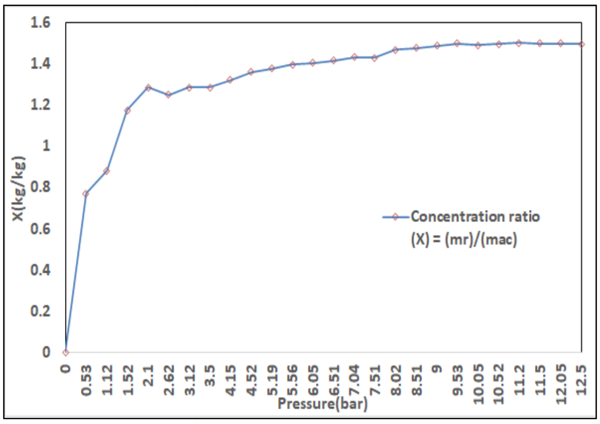
(a)



(b)

Fig 6 (a) Proposed integration of HAC system inside vehicle; (b) Proposed and developed HAC system components.

The vacuum pump is employed to establish a vacuum within the adsorber bed, removing all gases and moisture until reaching the vacuum pump's limit, approximately 0.2 bar (absolute) (Jribi et al., 2013). In this process, any minor leakage in the refrigerating circuit leads to an increase in the vacuuming time and is critically overlooked to avoid gas leakage. In the process of vacuuming, the dust particles from the adsorber bed will dilute the vacuum pump oil and require to be changed after the vacuuming process.



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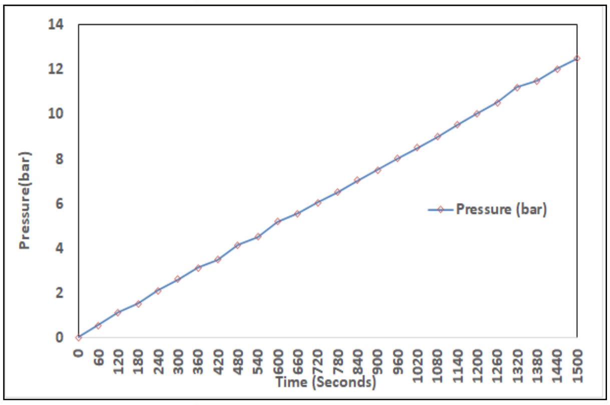


(b)

Fig 7. (a) Adsorption bed uptake during R134a charging; (b) Adsorption bed R134a pressure rises with time.

The purity of refrigerant is important in achieving better performance. The adsorption bed can be heated during the vacuuming operation by keeping the exhaust gas input port open, allowing trapped gases from activated carbon to be released and increased adsorption uptake to be attained. This creates pressure difference in vacuuming leading to refrigerant flow from the refrigerating cylinder to the refrigerant circuit. Value make VES50B model of automatic charging machine is used to charge the refrigerant. The charging machine possesses two ports inlet and outlet ports. The Inlet port is connected to the refrigerant gas cylinder and the outlet port is connected to the vacuumed refrigerant circuit at the inlet refrigerant port of the adsorber bed. The outlet refrigerant ports of adsorbed beds are closed manually by turning off the solenoid valves by giving an electrical power supply. An adsorber bed coolant circuit is kept working to cool the adsorber. The gas cylinder is placed on the weighing platform of the automatic charging machine and the initial weight of the gas cylinder is noted. Now the outlet port of the gas charging machine is slowly opened. After 60s of refrigerant flow hold and wait for equilibrium to be achieved. Take the reading of the weight of the cylinder. The reduction in the weight of the cylinder is equal to the mass of the refrigerant transferred to the adsorber bed refrigerant circuit. As the refrigerant enters into the refrigerating circuit and adsorber beds its pressure increases. This pressure is also measured. Accordingly, the charging time, mass of R134a adsorbed, and pressure is tabulated. Based on this concentration equilibrium is calculated and the graph is plotted for adsorption concentration and pressure built as mentioned in Fig 7 (a) below concentration equilibrium is achieved after 1080 seconds and the total adsorbed refrigerant is 1.49kg. We decided the adsorption time is 600 seconds, hence at 600 seconds refrigerant uptake was 1.38kg/kg of activated carbon.

The adsorption and desorption process is pressure-dependent in the system, Fig 7. (b) shows the graph of pressure attained by refrigerant during charging with respect to time. At 600 seconds the adsorber bed pressure was 5.19 bar during the adsorption process while during the desorption process at 1200 seconds, it was 10.05 bar. So, our system will operate in this two-pressure range. There will be changes in the enthalpy of the refrigerant at these pressures which will give the desired cooling effect in the evaporator. These are the condenser and evaporator working pressures, Pc = 10.1 bar and Pe = 5.2 bar.

4. Dynamic testing for evaluating the performance of HAC: procedure, results, and discussion

Figure 8. (a) below represents the integration of the adsorption bed connected with the selector valve, solenoid valves, and DAS with a laptop. It has been discussed about the integration of DECS in **Figure 6**. (a) of the above section. The required thermosensors are instrumented as per **Figure 8.** (a) for measurement of temperatures of the ambient air, cabin air, refrigerant temperatures at adsorber bed inlet and outlet, exhaust gas inlets and

Fig 8. (Instrumentation of HAC System in Automobiles

in refrigeration circuits are placed for pressure measurement in adsorber bed inlet and outlets. Humidity sensors are located inside and outside the cabin for humidity measurements.

The vehicle along with HAC system fitted inside was run for a long distance in scarce area on dates 30th and 31st January 2023 on National Highway for dynamic testing. The testing of the vehicle HAC system started when thermal equilibrium temperature was achieved. The atmospheric conditions changed from 29ºC DBT, 54% RH to 31.5 ºC, 58% RH during testing.

Figure 8. (b) shows the time needed for heating the bed to raise the refrigerant pressure to the required working pressure, keeping the volume constant. With the escalation of vehicle speed, the triggering pressure also rises and it is achieved after 781 seconds at 72 kmph speed. The engine exhaust waste heat of 2.52kW to 3.14 kW is utilized for HAC system.

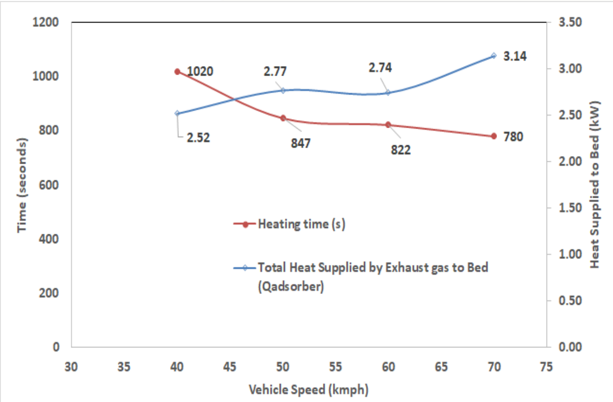
Figure 9. (a) below illustrates the theoretical and actual COP of the HAC system at maximum blower speed with two DEC fans in operation. The theoretical COP ranges from 0.57 to 0.66, while the actual COP is recorded as 0.57 and 0.47, exhibiting a decrease with increasing vehicle speed. This decline is attributed to the uncontrolled variations in gear change ratios, ambient air temperature, fluctuations in relative humidity, and variations in engine exhaust gas temperatures, which deviate from the ideal conditions.

From experimentation, it is observed that the minimum heat utilized at 40 kmph vehicle speed is 2.52kW and it is 3.14kW at a vehicle speed of 70kmph. The percentage utilization at lower vehicle speed is more 76.21% and reduces to 37.16% as vehicle speed increases. This is due to the reduction in heating time to attain the required refrigerant pressures of triggering for achieving cooling effects when the vehicle is running at higher speeds.

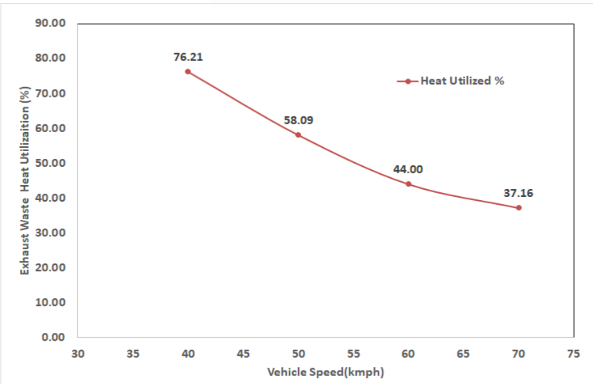
5. Payback period of HAC system in passenger and commercial vehicles

The implementation of any new technology products requires the overall system's cost consideration and its payback period. The payback period of HAC system in passenger and commercial vehicles as compared to presently used Vapor Compression Refrigeration system is explained below based on following assumptions:

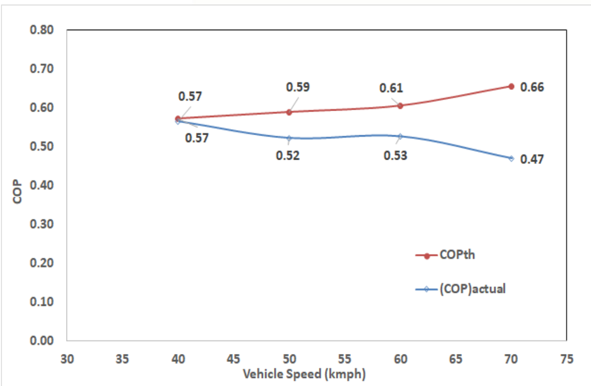
- Daily driving of passenger and commercial vehicle is considered as 250km, 30 days and 12 months of vehicle running.



(a)



(b)



(c)

Fig 9. (a) Heating time and heat supplied;
(b) Theoretical and experimental COP of HAC;
(c) Heat utilized by HAC system.

- Operating cost is 12 % of diesel consumption cost considered in vapour compression refrigeration system.
- Servicing cost is 10% of diesel consumption cost is considered for air filters change, cleaning of ducts, refrigerant charging, component failures if any for vapour compression refrigeration system and HAC system.

The AC operating cost of vapour compression refrigeration system in commercial trucks prominently affect the fuel consumptions over passenger vehicles due to very less fuel mileage. For passenger car's vapour compression refrigeration system the payback period worked out is 35.8 days and for commercial truck payback period is just 10days. But the air conditioning operating cost in commercial truck is 340% higher than that for passenger vehicles. Even though the initial cost of HAC system in passenger and commercial vehicles is 2.86 times higher than vapour compression refrigeration system but the yearly air conditioning operating cost for HAC system is 1.2 times lower than that of vapour compression refrigeration system.

Payback period for HAC system is 226 days for passenger vehicles and 87days for commercial vehicle which is significantly lower as compared to the human thermal comfort. The Indian scenarios of buying the commercial vehicles fitted with air conditioning system are significantly very less to 15% only due to higher AC operating cost. Hence the developed HAC system significantly plays very important role of highly comfort to the cost. Also, as per required cooling load of various Indian climates the HAC system provides flexibility to use either DEC system or HAC system whichever is beneficial.

6. Conclusion

DEC system making use of cellulose material pads was innovated for cooling the occupant's compartment of a small vehicle and was evaluated for its performance. The critical design parameters considered are the prevention of water leakage and noise. The electric power input to the blower can be reduced by 7.99% if the pads are just wetted by spraying water for only 60 seconds rather than keeping the pump on continuously. When the car is exposed to sun radiation in static conditions, the mean compartment air temperature rises by 17.5°C above atmospheric temperature, and inside air relative humidity is reduced by 27% at the 40th minute pertaining to the static test. The experimental outcomes became stable after 38th minutes from the beginning of the experiment. The temperatures at various locations in the system are measured after keeping the DEC system on for 10minutes time at three different fan speeds. At the lowest fan speed, the compartment front and rear temperatures got reduced from 41.2˚C to 35.9˚C and 36.3˚C respectively. After this at the medium and high fan speeds, after 30th and 40th minutes from the start of the test, compartment air temperature is dropped by 6.3˚C and 9.5˚C respectively. The refrigerating capacity ascends with the augmentation of the fan speed. The highest refrigeration is obtained at the highest speed of the fan and is 1043W with ambient air temperature drop from 41.8˚C to 32.3˚C. The DEC system is effective for reducing air temperature by approximately 9.55˚C providing enhanced comfort for users. The coefficient of performance of DEC system obtained is 1.97 at blower speed 1 and 4.38 with blower speed 3. The maximum electric power consumed by electrical components is 238W. This increase in coefficient of performance of the system renders ease in adoptability at reduced cost and allows usage of smaller size automotive components. The theoretical and actual COP of HAC system was derived at maximum blower speed and two DEC fans working conditions. The theoretical COP of HAC system varies from 0.57 to 0.66 while actual COP is found 0.57 and 0.47 and COP decreases with a rise in vehicle speed. This is due to uncontrolled variation of gear change ratios, ambient air temperature, relative humidity change, and engine exhaust gas temperature variations that are not idealistic to those derived in numerical analysis. The HAC System model can be scaled up based on the space available in the compartment of the vehicle.

- **Uncertainty Analysis**

The error of sensors, instruments, and calibration needs to be mapped at the primary stage of experimentation to ensure the acceptable variation range of measured output. Also, as required accuracy increases, the cost associated with the sensors and instrument also increases. Hence a careful selection of the instruments needs to be done as per the required accuracy only. Uncertainty can be computed using the equation:

$$\%\ \text{uncertainty} = \frac{\text{Least count}}{\text{Minium value of output measured}}$$

Uncertainties in experiments can occur from selected instruments, their conditions and calibration, as well as the environment and test sampling. The temperature, pressure, humidity, mass flow, weight, and equipment current consumption are measured using the Data Acquisition System (DAS).

DAS comprises of 32 K-type thermocouples. These sensors have an operating range of about 0-600˚C having an accuracy of $\pm$1.5˚C. Temperature mapping is done using DVP-04TC modules. During the experiment, the lowest temperature observed was 22°C. Temperature uncertainty is derived as per the equation above is 6.81%. DAS consists of 2 humidity transducers of 947series and six Baumer make CTX pressure sensors. The pressure and humidity are mapped with DVP-04AD modules. The CPU used here is a Delta DVP-12SA2, which uses DVP16 SP I/O connections to handle acquired data. Uncertainties in airflow, weight, and current measurement are calculated using equation (a) and are mentioned in Table 1. given above which gives detailed insight into instruments, their make, operating range along with their experimental uncertainties

Instrument Name	Operating Range	Accuracy	Measurement Minimum value	%Uncertainty
K-type Thermosensors	0- 600°C	± 1.5 ℃	22 ℃	6.81%
Humidity sensors	0-100% RH	± 3% RH	32%RH	3%
Pressure sensors	1-40 bar	± 0.5% bar	0.53bar	0.5%
Anemometer Mextech AM-4208	0-9999 (m^3 per minute)	±(2%+1m^3 /min)	0.833 m^3/min	1.22%
Weight and charging machines VES 50B	0.002 to 50 kg	±0.05%	5.383	0.05%
Clamp Meter RX266	20A-1000A	± (2.0%)	0.44A	2%

Table 1. Uncertainties in Experimentation

Notes

- https://www.datasheetarchive.com/DVP-04AD-datasheet.html
- https://www.datasheetarchive.com/DVP-04TC-datasheet.html
- https://www.meanwell.com/Upload/PDF/LRS-100/LRS-100-SPEC.PDF
- https://www.datasheetarchive.com/DELTA+dvp+16sp-datasheet.html
- http://www.weatheronline.in/weather/maps/city

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