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Experimental Investigation of Evaporative Air Cooling Potential For Passenger Mobiles

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Abstract — *In automobiles, even recent advances in vapor compression refrigeration using R134a refrigerant have still caused global warming potential, and environment-friendly ozone depletion is now no more hidden fact. In this paper, an innovative direct evaporative system is mathematical modeled, designed for 1kW, and developed for the passenger mobiles application of 2.8m3 cabin volume. Cellulose pad indirect evaporative cooling is used, and the system is installed in the vehicle for its performance evaluation. The research reveals the lower power consumption of blower motor by 8% if pad is just wetted by water spraying for 60seconds duration than keeping pump continues on condition. Model vehicle cabin air temperature and relative humidity are mapped for ambient air conditions of 39.6°C and 59.6% RH at 14 pm parked on sunny days. The cabin air temperature increases with ambient soaking, and after 38th min from the start of the test is found the stable meeting to 60°C and 54.1°C in front and rear of the cabin. This gives maximum rise of cabin air temperature by 19.2°C and 13.3°C at cabin front and rear. The cabin air humidity is dropped to 32.5% at the 40th minute of the test when ambient relative humidity was 38.7%. The average air grill temperature, cabin front, and rear air temperatures are mapped with the time duration of 10minutes in each of three blower speeds. After 10 minutes, the DEC is switched ON with fan speed 1, the cabin front and rear temperature dropped from 41.1 ˚C to 35.8 ˚C and 36.4 ˚C, respectively. The average drop at 1st speed was 36.1 ˚C. Subsequent to this at speeds 2 and 3 at the 30th and 40th minutes of the test cycle, cabin air temperature is dropped to 6.2 ˚C and 9.6 ˚C. As the speed of the DEC system increases, the cooling capacity also increases. The maximum cooling effect at speed 3 of the blower motor is 1042Watts with ambient air temperature drop from 41.9 ˚C to 32.4 ˚C. The developed cellulose direct evaporative system was found effective by reducing air temperature by 9.5 ˚C, giving better comfort to users. The COP of the system is achieved to 4.38 at maximum fan speed. The developed model is scalable as per the availability of space inside vehicle compartments.*

Keywords — *Alternative cooling technologies, Evaporative cooling system, Direct evaporative cooling, Cellulose pad, automobile cabin air cooling.*

I. INTRODUCTION

With the rapidly changing environment and atmospheric effects, the discomfort to the human being increasing day by day for the last four decades. Hence optional features of adopting air conditioning in vehicles are now turning to the important feature of a vehicle and become a necessity. This cooling demand increases power requirements and consumes additional fossil fuel. In current vehicles running with internal combustion engines, compression refrigeration is prominently used with highly optimized and efficient components. Still, to manage engine power requirements for air conditioning systems, power is increased by burning additional fuel, which raises engine revolution per minute by 200 to 300[4]. Thus engine running with 25% to 30% thermal efficiency consumes an additional 10% of fuel in air conditioning working and non-working conditions, thus raising CO2 emission [2][3]. Also, regulations to confined use of CFCs and HFCs for plummeting ozone depletion and greenhouse gases need to be followed strictly as current refrigerant R 134-a has GWP by 1430 times to CO2 [8]. At the lowest temperature setting of the current mobile air conditioning system, the higher cooling effect sometimes is uncomfortable, and the user needs a choice to move to a comfortable air temperature. In this process, hot air mixed in conditioned cold air loosing heat power resulting in higher compressor engagement time and thus needs an alternate air cooling technology. In consideration of this, one should follow curb usage of refrigerants and surge natural resources utilization. Over the last three decades, also a competent air conditioning system with compression refrigeration is not built for automobiles[10]. So the potential of researching new cooling technologies with increased effectiveness of system and subsystem is required. The system component sizing, material selection, heat transfer effectiveness, COP enhancement, and design considerations are significant to take away for researchers [1]. This paper focuses on the implementation of alternative cooling techniques in automobiles cabin air cooling. Considering the potential gap of literature review in design & development, integration and testing methodology are represented. The latent futures opportunities of employment of evaporative cooling systems are elucidated with the design considerations and vehicle layout.

Refer to Fig. 1, a belt-driven mechanical type of compressor is used, which consumes a defined portion of the power generated by the engine itself. Over the last decade, efficiency enhancement and optimization of the thermal load has developed, which reduced the overall size of components, making the system more flexible in an automobile. These advances helped in the utilization of available complex vehicle space for design. The engagement of compressor and crank pulley is controlled by means by electronics control unit by means mapping temperature set requirement of cabins environment. The compressor performance is the function of crank rotation controlling the refrigerant mass flow rate. Evaporative cooling consumes less power by 60-70% in comparison to the conventional compression cycle [11].

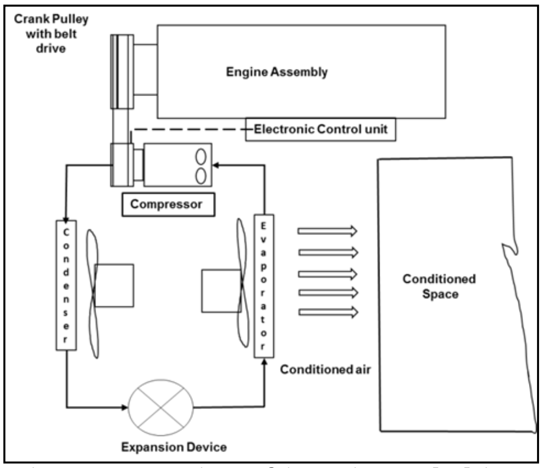

Fig 1. Compression refrigeration- Belt driven

An evaporative cooling cycle consists of Direct Evaporative Cooling (DEC) or Indirect Evaporative cooling (IEC) heat exchanger and pumped water for latent or sensible heat transfer for pre-cooling of air which will then space to be cooled. To control humidity, sometimes both the systems are combined as per conditioned air requirements [13]. The use of latent heat of evaporation of water for evaporative cooling is extensively used for cooling of air for the past several decades in domestic and industrial applications. Though the higher humidity from direct evaporative cooling is due to direct air mixing with water can be treated under indirect evaporative cooling. Comparative performance of desert coolers employing six different pads wood wool, khus, coconut coir fiber, ceramic materials tubes, stainless steel, galvanized metal sheets as pads in are considered for investigation gives temperature drop of 6°C to 11°C at 42°C test conditions[6][9]. From the comparative study, vertically aligned galvanized metal sheets(0.3mm thin) with pad thickness of 0.450m could withstand the cooling efficiency is nearly 85% above all the performance indicators. The effect of airflow and temperature variation on humidity was found with a cellulose pad for evaporation cooling [23]. The saturation efficiency of DEC varies in the range of 98.3% to 71.9% [25]. It will be suitable for climatic conditions of 39°C to 46°C DBT and 37% to 46% RH. The different evaporative cooling technologies for occupant's thermal comfort is 22.5°C to 27°C in hot and cold condition with favorable humidity conditions are 30% to 72% are noted[22]. The regenerative evaporative cooling increases COP of DEC by 20-25% as compared with DEC results[26]. The ceramic porous material [27] used as wet media give effectiveness greater than unity for hot and dry climatic conditions. The nocturnal cooling combined with DEC has been experimented and effectiveness more than 100% is feasible [36]. Double stage evaporative cooling used for vegetables and fruits storage helps in maintaining the cabin temperature between 8°C to 16 °C. For the domestic application of air cooling, cotton and khus materials are used with vertical duct type design for reducing the water consumption, effectiveness of cotton material are found 79.7% and humidity 52.7% [38]. The evaporatively cooled condenser is also an option to reduce the air conditioning power consumption by 20% and COP enhancement by 50%[39]. The thickness of the evaporative pad plays an important in air cooling and reaching humidity requirements. The effect of air cooling and water cooling is experimented with at varies pad thicknesses and found that air temperature at the top of the evaporative pad is less than at the bottom side of the pad. With 150mm pad thickness, air cooling of 10.57 ºC is achieved [40].

In indirect evaporative refrigeration, the water channels are provided to cool the air and separated by efficient channels which exchange heat by vaporizing the water. The vertical and horizontal channels are designed in such a way that it allows the least resistance to flow. In the experimentation work Poly Carbonate (PC) material sheet, 0.2mm thick with (5x5)mm cross-section slots, is considered for experimentation with two cases of recirculation and combined with DEC. The results of combined DEC were found superior [24]. Adopting a PC heat exchanger can give 800W cooling capacity, and 50% ventilation load is reduced [36]. The combined evaporative cooling with vapor compression cycle in which cabin cooled air is extracted and used to cool the condenser. Evaporative cooled condenser with metallic twisted tubes, circular tubes, and elliptical tubes were used for heat exchangers [32]. The maximum and minimum savings of (64.19%) and (27.36%) are found in lower (34ºC) and higher ambient temperature (38ºC), respectively. Different materials like Steel packs, aluminum foil packs, the fiber of plants packs, the glass fiber packs, and filler of polymer packs were compared and found steel packing effective at increasing airflow [32]. Material conductivity and porosity are found less key factors than shape, water holding capacity, and compatibility for waterproof coating are important factors [33].

Two stages DEC/IEC cooler with cooling different media and alternative shapes have experimented with plate type and wet aspen media. The effectiveness of the combined system varies from 108% to 111%[12]. The combined air cooling to 22.5 ºC to 25 ºC was found in 39.9 ºC ambient temperature [14][35]. The use of CFD and MATLAB for IEC effectiveness is found by changing the flow of air-water. The counter-current flow direction relative humidity found up to 70% in 50ºC temperature [19]. In a tube-fin-based IEC system, dry bulb temperature reduction of 9°C to 14°C was achieved [5]. In the combined IEC and mechanical cooling system, when clubbed together, 75% of the cooling load is reduced[7]. The sub wet evaporative system effectiveness of 1.36 is achieved with a combined parallel regenerative cooling technique [28]. Based on climatic conditions cooling load is varying throughout the year. The system adaptability can be considered for a change of the wetted surface to ascend the system to either DEC or IEC. Thus it can be used for regenerative cooling load reduction in Automobile air cooling.

II. PROPOSED EVAPORATIVE COOLING SYSTEM

Fig 2. Shows component layout of direct evaporative cooling system where water is sprayed on water absorbent media pumped from the sump to replace evaporated water with cooling the air to adiabatic saturation temperature. In DEC, the heat convection between water and air decreases the air-dry bulb temperature (DBT), and humidity increases, keeping constant enthalpy (adiabatic cooling) as an epitome process. The attainable lowest temperature can be a thermodynamic wet-bulb temperature (Twbt) of the incoming ambient air. The effectiveness of this DEC process is defined as the rate of real decreases of DBT of air to the maximum theoretical decreases that DBT. The 100% efficient process could result in saturated outlet air. Wet porous material or pad provides hefty wetted surfaces area in which the air moisture exchange is achieved. In the offered experimentation work, 150mm thickness of cellulose pad is used for attaining effective cooling for the selected vehicle. For commercial vehicle applications pointing comfort to the low cost cannot be excluded in adopting evaporative cooling in hot and dry climatic conditions where driving comfort and safety are regulatory required to meet interim comfort standards. Even though the direct evaporative cooling effectiveness reached 98% in cellulose pads, more focus to be emphasized on alternative and durable materials. The challenges of water flow management and storage, improved air quality need to be addressed in evaporative cooling.

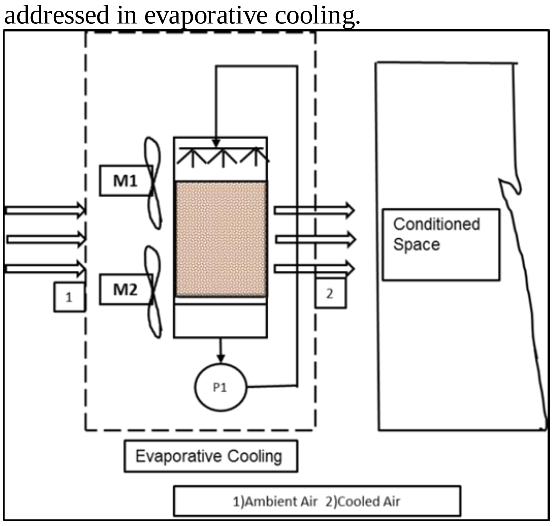

Fig 2: Direct Evaporative refrigeration.

Fig. 3 shows the proposed location on the roof side (outside of cabin) and below the dashboard (inside of cabin) for integration of evaporative refrigeration circuit for a commercial truck application. When the system is placed inside the cabin, evaporative cooling pad material should be sufficiently maintained wet, ensuring that water dripping should not create annoying noise to the passengers. To avoid this, the roof position can provide the added advantage of using water flow for wetting the pads with gravity.

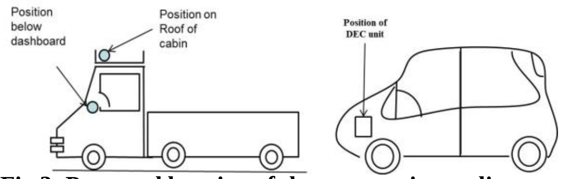

Fig 3: Proposed location of the evaporative cooling system in commercial trucks and passenger vehicles.

Based on the literature review on alternative refrigeration techniques, important information on technique maturity, effectiveness, and integration adaptability are mapped in Table II as per the rating scale given[17] and suggested the locations of placing the evaporative DEC unit [18]. In this paper customized DEC system is mathematically modeled, designed, and developed for the passenger mobiles application. For the selected vehicle model, space is identified, and the unit is installed. Finally, performance evaluation is done with rigorous experimentations at various conditions.

III. MATHEMATICAL MODELING

The cooling load required for cabin cooling is calculated by using the standard method of savior heat load cases. The various factors of heat load like solar radiation of roofs, walls, glasses, air infiltration load, utility loads, and the number of persons in the cabin, sensible heat load, and latent heat load are considered. A model vehicle is considered for cooling load estimation with cabin dimensions (2.23 x 1x 1.4) m3. The maximum atmospheric temperature is considered as 40ºC by referring to environment data of West India's local region [41]. The DEC system is designed at an ambient temperature of 40 ºC and 40 %RH as a critical condition. Considering the varying load throughout the year, a comfort condition of 25 ºC is targeted.

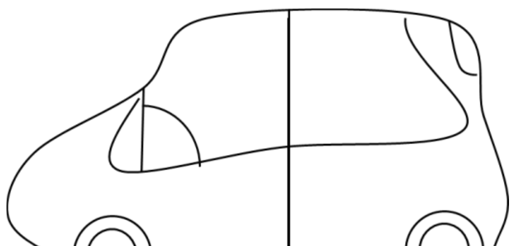

Fig 4: Model vehicle for evaluation [18]

The total heat load required for a model vehicle is calculated as 2.8 kW for space cooling; therefore, a cooling system of 0.8 TR is considered sufficient to maintain cabin temperature at 25 ºC. The refrigerating effect required varies through the year based on ambient conditions, and system usage is considered as per average cooling load per year to 1kW. This total heat load is shared by evaporative air cooling combined with a lower capacity of the vapor compression cycle in extreme weather conditions. The theoretical engine power consumption can be reduced by 41% by air pre-cooling in the DEC system of 1kW capacity.

A. Design of Evaporative cooling unit:

Considering the flow of humid air close to a wet surface, according to Fig.6 and Fig.7, the heat transfer will occur if the surface temperature Twbt is different from the draft temperature Tin.

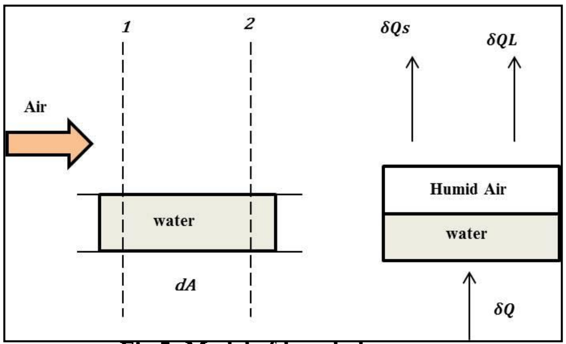

Fig 5: Model of heat balance

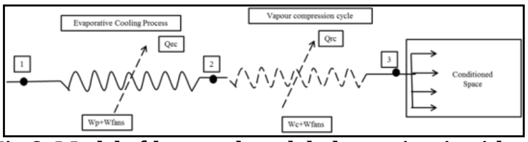

Fig 6: Model of heat and work balance circuit with DEC and VCC.

If the absolute humidity (concentration) of the air close to wet surface h_s is different from the humidity of the draft air, then the mass transfer will also occur.

The sensible heat is driven by the equation for the elementary part of the cellulose pad,

$$dQs = hc.dA(Twbt - Tin) \quad (1)$$

The latent heat is driven by the equation for the elementary part of the cellulose pad.

$$dQl = hm.\rho a.dA(hs - h1) \quad (2)$$

The total heat flow is governed by the energy conservation equation.

$$dQ = dQs + dQl \quad (3)$$

Design ambient conditions are: (DBT40℃, RH 40%)

From the weather data, the specific volume (Vs) is calculated by using a psychometric chart is given by Vs=0.913 m^3/kg,

$$\rho = \frac{1}{Vs} \quad (4)$$

B. Saturation efficiency (η_{sat}):

Saturation efficiency is the index used to assess the performance of the direct evaporative cooler is given by

$$\eta_{sat} = \frac{Tin - Tout}{Tin - Twbt} \quad (5)$$

C. Temperature drop:

The saturation efficiency of the aspen pad obtained for 150mm thickness is 94%, the temperature drop is given by [20]

$$Tin - Tout = \eta_{sat} \times (Tin - Twbt) \quad (6)$$

D. Cooling Capacity and mass flow rate of air:

According to the requirement, we considered the cooling load as 1 kW, so we know that,

$$m_a = \frac{Qc}{Cp(Tin - Tout)} \quad (7)$$

E. Water consumption rate:

At hot and dry climatic conditions, evaporation of water is more. Extreme weather conditions of 43ºC, 20% RH, and airflow 2388 m3/hr., the water consumption was 58.7%[34]. The water consumption rate is important because it indicates the amount of water needed to operate the system. The water consumption of the evaporative cooler Qw is given by [21],

$$Qw = m_a \times (\omega 1 - \omega 2) \quad (8)$$

The designed DEC specifications are marked below the table, which is taken for proto development.

TABLE I

SPECIFICATION OF DEC SYSTEM

Parameters	Variable	Values
Wetted surface area (m^2)	A_w	3.736
Power consumption (W)	W_p	37.5
Maximum current (A)	I_m	8.5
The mass flow rate of air (kg/s)	M_a	0.065 at Speed 1
		0.084 at Speed 2
		0.109 at Speed 3
Theoretical Temperature drop (ºC)	T_{max}	9.8

IV. DESIGN AND DEVELOPMENT OF EVAPORATIVE COOLING UNIT

The model is prepared with two axial fans diverting outside ambient air from outside to cabin inside. The air then passed from housing which is filled with cellulose pad and submersible pump located at the bottom side of cooling unit, keeping the pads wet with regular intervals of time which lets the air achieve the WBT temperature. The cooled air was then transferred via ducts and outlets inside the cabin. The unit is placed outside the cabin separating sheet metal wall marked with the blue line in below Figure 7. When the vehicle is running fans, power consumption can be optimized by taking the benefit of draft air.

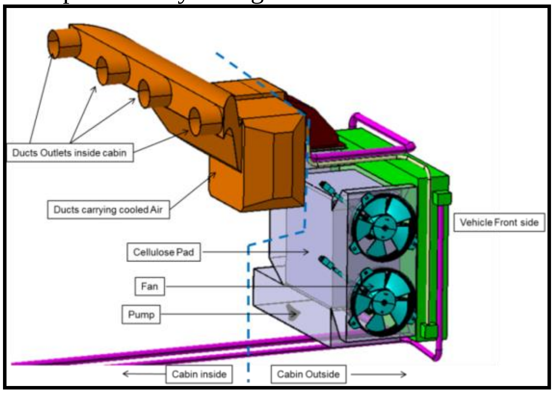

Fig 7: Design of Evaporator cooling unit

A. The housing of evaporative cooling system:

The slope of housing is designed in such a way that the water should not be transferred inside the cabin airflow path due to water gravity and directing back to the bottom storage tank called a sump. The housing is made of an aluminum sheet of 2mm thickness is used to precisely cut as per the design requirement by using a laser beam machine and then welded together to avoid water leakage the as mentioned in Fig.8.

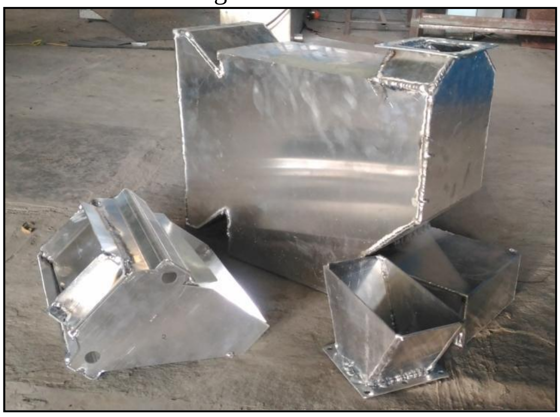

Fig 8: Development of evaporator cooling unit

Other design considerations include thermal insulation of DEC unit body with PE insulation 5mm thick to avoid heat transfer from other heat exchangers of vehicle. The main body is designed with a water flow separation section to avoid water escape in the airflow path. The water pipe layout is considered to cover water spray uniformly on the evaporative pad. The dripped water from evaporator pads will be drained back to the bottom tank, for which the evaporative pad is located on a perforated plate. The bottom tank is provided with a drain outlet for replacing complete water at regular intervals. The annoying water noise generation areas should be avoided. The water-sealed fan motor assembly is required to be used. The evaporative cooling pad should be easily serviceable to flush the dust and consumed water at regular intervals.

B. Water pump, cooling pad, and axial fan:

The sump is located at the base of the cooler. The water is circulated with the help of flexible pipes mounted on the body of the evaporator unit. The water will wet the cellulose pad and forms the wetted surface. The atmospheric air gives latent heat of evaporation to water. The operating voltage of the pump is 12V, discharges 3.33lit/min of water. The head of the pump is 0.4 to 1.5 m, and discharge is 200LPH. Refer Fig. 9(a).

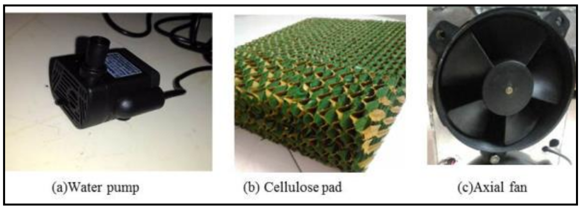

Fig 9: Components of evaporative cooling system

In general evaporative cooling system uses a wetted pad through which air passed at a uniform rate to make it saturated. In the proposed design cellulose pad is recommended due to its highest saturation efficiency of more than 90%. It is more efficient than other materials like aspen pad and coconut coir. A pad is shown in Fig.9 (b) is wetted by spraying water on the upper side with the help of a recirculating pump. The outside ambient air is sucked by an axial fan, and the air is blown axially in a horizontal direction passed across as a wetted cellulose pad. In axial fan, the airflow in Axial Fan with fan RPM of 2500 with 12V is proposed as per Fig. 9(c).

V. INSTRUMENTATION AND EXPERIMENTAL SETUP

The Omni make GL840 data logger is used to mapping required data of temperature and humidity placed, and sensors are located as per the parameters mapping list for finding the temperature inside the cabin after system implementation, and experimentally values are mapped for air at the outlet of a subsystem as below [30][31].

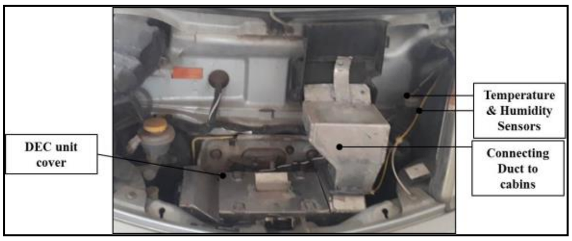

Fig 10: Experimental Setup of Direct Evaporative System in vehicle

The DEC unit is placed at the front side of the vehicle with connecting duct attaching to the cabin inlet as per Fig. 10. Air temperature of inlet and outlet conditions of the DEC unit are mapped using K-type class-2 temperature sensors and humidity sensor of 12V, 4 to 20mA output is connected to the data logger. An experimental uncertainty of anemometer, humidity sensor, and temperature sensor needs accountability in air properties measurement for DBT, WBT, RH, and airflow [19]. Resolution of measuring instruments is limited to K type 0.5ºC and 1.5% accuracy for temperature and humidity measurement.

The DEC unit is placed at available space on the front side of the vehicle. The connecting duct transfers the cooled air into the cabin. The cover on DEC units allows water top-up and servicing at regular intervals. Cooled air from the DEC unit enters the cabin through the air grills, where it is kept fully open and directing air towards the passenger's face. Four temperature sensors are installed at the center of each air grill without touching its body. Refer Fig. 11. for thermo sensors installations at grills.

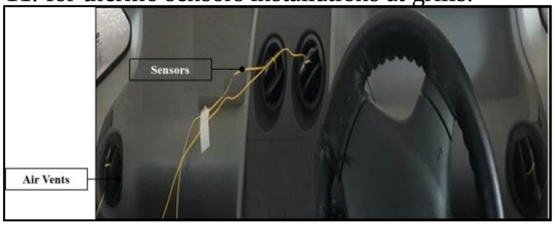

Fig 11: Instrumentation of thermosensors at cabin air grills

Temperature sensors are installed at the roof of the cabin, two at the front side positioning to driver's and co-drivers nose level. In a similar way, another two sensors are placed on the rear side of the cabin, positioning at passenger nose level. The average temperatures of the cabin air front and the rear side are mapped. Refer position of temperature sensor installation in Fig.12.

Fig 12: Instrumentation of Direct Evaporative System in vehicle

VI. TESTING AND RESULTS

The experimentation was carried out for three days from 2nd April 2020 to 4th April 2020 to find the effect of the performance of the DEC system against ambient air conditions. Refer to Fig. 13, the current consumption versus voltage data is mapped for fans motors with cooling pad dry run, wet cooling pad (1min pump on in one hour's intervals till evaporator cooling pad wet completely and wet pad with continuous pump ON. The motor's current consumes 2.31A in the wet pad (Pump ON) versus the 2.12A in the wet pad.

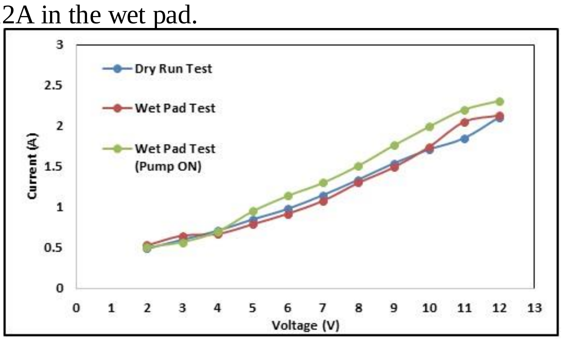

Fig 13: Current Consumption of DEC unit Vs. Supplied

This resulted in power consumption of fans with continuous pump ON at 12V supply is 27.7W while with Pump ON with 1 min till evaporator cooling pad wet completely is 25.4 which is 8% less. Thus every one hour, the fan will be kept on for 1mins, and readings were taken for the temperature inside the cabin. Refer to Fig. 14.

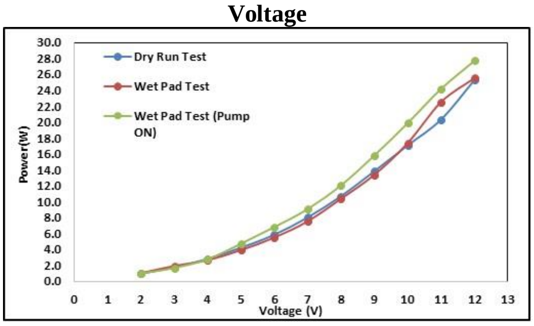

Fig 14: Power of DEC system Vs. Supplied Voltage

Refer to Figure 15, and Figure 16 represents front and rear cabin air temperature which was averaged with two thermocouples readings for 02nd and 03rd April 2020. On April 02nd, the vehicle was parked at the desired parking space at 7 AM, and readings for each hour were recorded for daytime 8.00 am to 18.00 pm[30]. During the experiments, the vehicle was parked with all windows up, and the DEC system turned on for 10min duration, contributing to air exchange across the vehicle cabin. While on 03rd of April 2020, the same vehicle was parked in the same parking space at 7 AM, and hourly readings were taken as before but with the DEC system off.

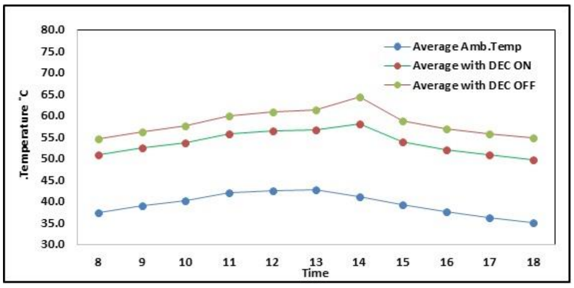

Fig 15: Cabin Front side average air temperature mapping

Refer to figure 15; the maximum of 64.4°C air temperature was recorded at 14 hours when the vehicle was parked with DEC off condition, while the two days average ambient temperature at the 14 hours was 41.2 °C. Interestingly, when the vehicle was parked with DEC ON, the air temperature reduced to 58.2 °C at the end of the DEC running cycle. Since the vehicle windshield allows a large amount of solar radiation to penetrate through it and blocks the reflected ones, this contributes to rising air temperature as the materials of dashboards and seats present in the front cabin absorb the radiation's heat and release to the cabin air. Refer to Fig.16, the Cabin rear air maximum temperature of found 57.4°C was recorded at 14 hours when the vehicle was parked with DEC Off condition, while the two days average ambient temperature was recorded as 41.2 °C at 14 pm. Also, when the vehicle was parked with DEC ON, the air temperature was reduced to 52.4 °C. The 5.8°C and 5°C air temperature drops are found at the front and rear side cabin area.

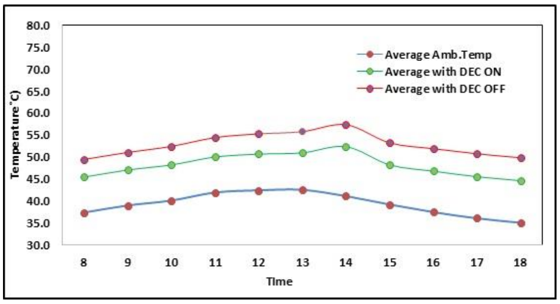

Fig. 16: Cabin Rear side average air temperature mapping

Refer to figure 17 and figure 18, on day 4th April, the effect of ambient soaking on cabin air quality has experimented for 45min test duration. The cabin air temperature and relative humidity are mapped for ambient air conditions of 39.6°C and 59.6% RH at 14 pm.

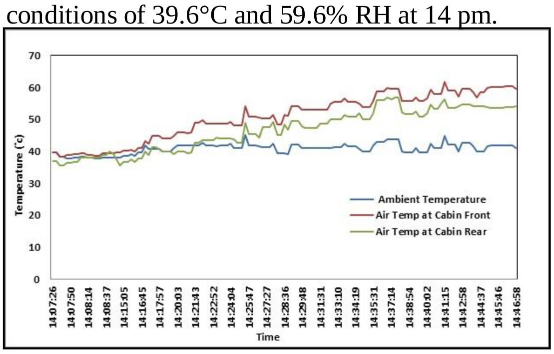

Fig 17: Effect of Ambient Soaking on Cabin air dry bulb temperature

The cabin air temperature increases with ambient soaking, and after 38th min from the start of the test is found stable at 60°C and 54.1°C in front and rear. This gives maximum rise of cabin air temperature by 19.2°C at 13.3°C at cabin front and rear. Refer to the Fig. 18, cabin humidity is mapped against ambient relative humidity to analyze the effect of ambient soaking on cabin air conditioning. It is observed that at the start of the test cabin, relative humidity was more by 1.5% and reduced with the soaking effect.

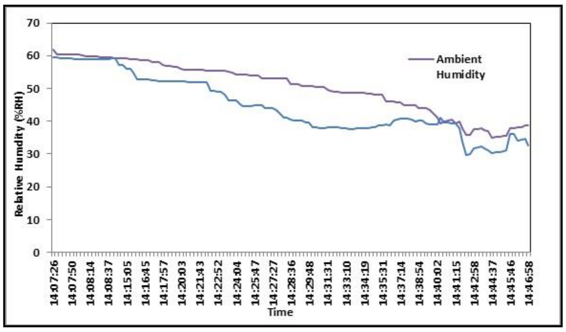

Fig 18: Effect of ambient soaking on cabin air relative humidity

The cabin air humidity is dropped to 32.5% at the 40th minute of the test when ambient relative humidity was 38.7%. This drop of relative humidity of cabin air is due to cabin air heat up. These parameters of increased dry air temperature and reduced cabin air relative humidity lead to uncomfortable climatic conditions for passengers as saturation efficiency decreases airflow increases [15]. Therefore the developed direct evaporative cooling with 3-speed airflow is experimented as per Figure 19. After soaking the cabin for 40 minutes, the only fan is kept ON for 10minutes, followed by direct evaporative cooling for 10mintes at each blower speed. The average air grill temperature, cabin front, and rear air temperatures are mapped with the time duration of 10minutes in each fan speed.

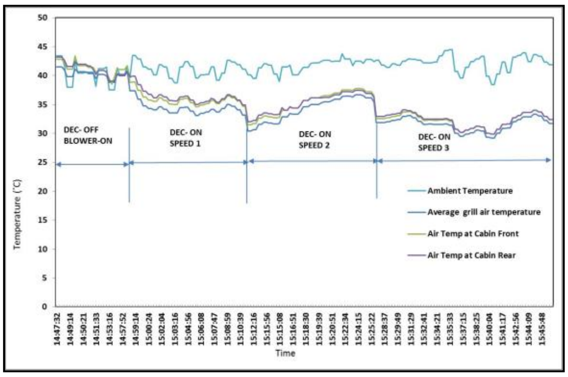

Fig 19: Effect of ambient soaking on cabin air relative humidity

. The average ambient air temperature during the first 10 minutes was noted at 40.5 ˚ C. When only the blower is ON, the average grill air temperature is reduced to 40.3 ˚C the affecting the cabin front, and rear temperatures are 42.2 ˚C and 44.2 ˚C, significantly not changed due to Soaked cabin thermal inertia. After 10 minutes, the DEC is switched ON with fan speed 1, the cabin front and rear temperature dropped from 41.1 ˚C to 35.8 ˚C and 36.4 ˚C, respectively. The average drop at 1st speed was 36.1 ˚C. Subsequent to this at speeds 2 and 3 at the 30th and 40th minutes of the test cycle, cabin air temperature is dropped to 6.2 ˚C and 9.6 ˚C.

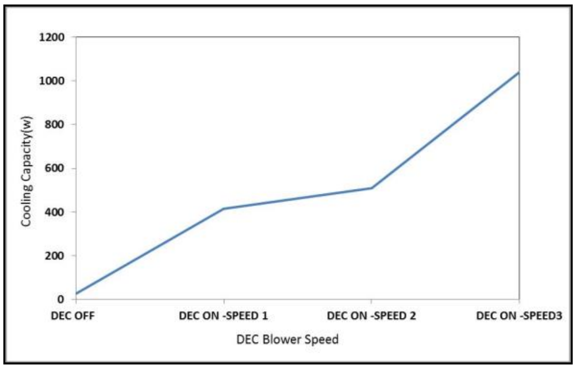

Fig 20: Cooling capacity of DEC system

Figure 20 represents the cooling capacity of the DEC system at the end of each blower speed. It is noticed that the effect at DEC OFF is to 19W; this is mainly due to the circulation of ambient air inside the cabin. As the speed of the DEC system increases, the cooling capacity also increases. The maximum cooling effect at speed-3 of the blower motor is 1042Watts with ambient air temperature drop from 41.9 ˚C to 32.4 ˚C. The developed cellulose direct evaporative system was found effective by reducing air temperature by 9.5 ˚C, giving better comfort to users.

The developed model is scalable as per the availability of space inside vehicle compartments.

The coefficient of performance (COP) of the DEC system is plotted as per blower power consumption at each speed. COP is the ratio of cooling capacity delivered by wet material by the electrical power consumed by fans and pumps.

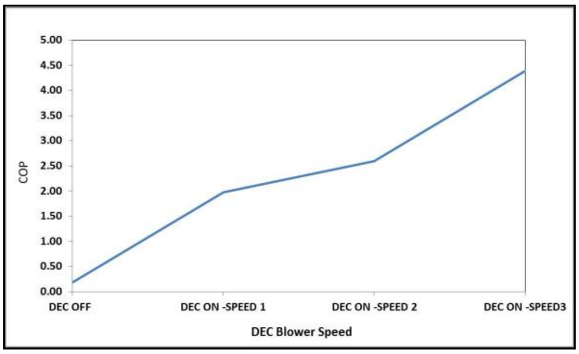

Fig 21: COP of DEC system at different blower speed

Figure 21 represents the COP of the system captured at each fan speed. The only blower on case COP achieved is 0.18 at the power consumption of 108W. The maximum power consumed by electrical components is 238W at a blower of speed 3.Subsequently, the COP of the DEC system achieved as 1.97, 2.66, and 4.38 is achieved at speed 1, speed 2, and speed 3, respectively. This increased COP of the system gives a better position for air cooling in automobiles at DEC at lower cost and component sizing.

VII. CONCLUSION

An alternate air cooling method using the cellulose pad-based direct evaporative cooling system developed for a 2.8m3 passenger cabin is installed and experimentally evaluated for its performance. The critical body design is required to avoid water leakage and noise management. The blower power consumption is found lower by 8% if the pad is just wetted by water spraying for a 60seconds duration than keeping the pump continues on condition. When the vehicle is parked under ambient solar load, the cabin air temperature and relative humidity have risen. The average cabin air temperature increases by 17.6°C with ambient, and the cabin air humidity is dropped by 27% at the 40th minute of the test. The test results are found stable after 38th min from the start of the test. The average air grill temperature, cabin front, and rear air temperatures are mapped with DEC system ON for 10minutes time in the duration of three blower speeds. After 10 minutes, the DEC is switched ON with fan speed 1, the cabin front and rear temperature dropped from 41.1 ˚C to 35.8 ˚C and 36.4 ˚C, respectively. The average drop at 1st speed was 36.1 ˚C. Subsequent to this at speeds 2 and 3 at the 30th and 40th minutes of the test cycle, cabin air temperature is dropped to 6.2 ˚C and 9.6 ˚C. The cooling capacity increases as the speed of the DEC system increases. The maximum cooling effect at speed 3 of the blower motor is 1042Watts with ambient air temperature drop from 41.9 ˚C to 32.4 ˚C. The developed cellulose direct evaporative system was found effective by reducing air temperature by 9.5 ˚C, giving better comfort to users. The COP of the system is achieved varying from 1.97 to 4.38 with DEC ON from Speed 1 to Speed 3 by the maximum power consumption of electrical components at 238W. This increased COP of the system gives easy adaptability at lower cost and component sizing.

The developed model is scalable as per the availability of space inside vehicle compartments. When the DEC system is assisted with the current vapor compression cycle, overall system size optimization and effectiveness can be enhanced, raising potential adaptability in the current automobile space.

NOMENCLATURE

ω1	-	Sp. humidity at inlet kg/kg of dry air
ω2	-	Sp. humidity at outlet kg/kg of dry air
ρ	-	The density of air kg/m^3
Vs	-	Specific volume m^3/kg
Tin	-	Inlet air temperature in ℃,
Tout	-	Outlet air temperature in ℃,
Tweet	-	Wet Bulb Temperature in ℃
Qc	-	Cooling load in kW
m_a	-	The mass flow rate of air kg/sec
Cp	-	Specific heat of air kJ/kg k
Ƞsat	-	Saturation efficiency
DEC	-	Direct Evaporative Cooling
IEC	-	Indirect Evaporative Cooling
COP	-	Coefficient of performance
Qw	-	Water consumption

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