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EXHAUST HEAT UTILIZATION FOR COMFORTABLE CABIN CONDITIONS FOR CI ENGINE: A REVIEW

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ABSTRACT: With the advent of enhancing environmental and energy concerns, sustainability that can be done with the utilization of exhaust system energy that carries an ample amount of heat of combustion is of major concern. Improvement in the quality of environment and air conditioning of vehicle cabin adds to the merits of cogeneration. In this paper, recent research is reviewed and it illustrates the use of exhaust energy in both mobile and immobile diesel engines and discussed automobile cabin cooling application. This will lead to a dual advantage of cooling with a low grade energy of exhaust gas (which otherwise goes as waste) as well as greater environmental benefits with low use of Freon (like R12 or R22) which otherwise have been used in general AC systems. Use of low grade energy assisted cooling in compression ignition engine are a ready solution available to save Mother Earth from haunting environmental implications, however, with some limitations and with certain advantages as reported by many researchers. The aim of the paper is to discuss the potential of diesel engine exhaust heat in cooling and a comprehensive and critical review is presented pertaining to use of cogeneration/ trigeneration and various cabin cooling techniques in diesel engine.

I. INTRODUCTION

The world of today is toiling hard to solve energy related problems, such as energy shortage, energy supply security, emission control, economy and conservation of energy etc. A great potential lies in the hand of automotive engineers and scientists to fulfill inhabitants' insatiable energy need, comfort as well as protecting Mother Earth's atmosphere. Usually, diesel engines have efficiency in the range of about 35% and rest of the input energy goes as waste either with coolant or in exhaust gas [14][15][26]. So, we must ponder upon methods to utilize the energy from exhaust. One very prominent solution for sustainable development is to utilize waste heat in cabin cooling which is a form of Combined Cooling, Heating and Power (CCHP). Since then a lot of research is being done on the use of Combined Heat Power (CHP) [1][3][4][5][6]. It is an exponentially growing technology for enhancing energy efficiency, assured future availability of energy impartment and lowering down CO2 emission level, all of which are of paramount concern. In various developed and developing countries, manoeuvre utilization of energy is encouraged by deployment of microCHP system. Government of India through the Electricity Act 2003 highlighted upon the intense need of deregulated power sector [2]. Not only in India, are countries across the globe striving for energy security. The European Union, Germany Government emphasizes on the installation of microCHP systems so that it can meet the stringent international and domestic targets on carbon emissions. UK government has lowered VAT from 17.5% to 5% and it has been estimated that around 30-40% of the UK electricity needs will be fulfilled by microCHPs by the year 2050. The Dutch government is also paving a smooth way for micro CHP systems and making it accessible by public funding for companies developing mass market [1]. In Turkey, the total installed cogeneration capacity is around 6000MWe by 2005 (i.e., 20% of total electricity production capacity) [3].

II. CCHP and microCHPs

Combined cooling, heating and power (CCHP), is derived from combined heat and power (CHP, also called cogeneration);

- Produces power with the help of turbines or engines (using any thermodynamic cycle).
- Utilizes thermal energy (for cooling, steam for heating process water, hot gas for drying)

Both electrical (or mechanical) power and useful thermal energy are obtained from the same primary energy source. When cooling is amended in it, cogeneration which stands for power and thermal energy production gets converted into trigeneration [5][6].Cogeneration is a reliable technology with a history of more than 100 years, which was utilized mainly in large scale centralized power plants and industrial application. The conventional way to produce electricity and generate heat is to purchase electricity from the local grid and by burning fuel in a boiler respectively. Byproduct heat, which can be as much as 60-80% of total primary energy in combustion–based electricity generation is recycled for different uses [4][5].

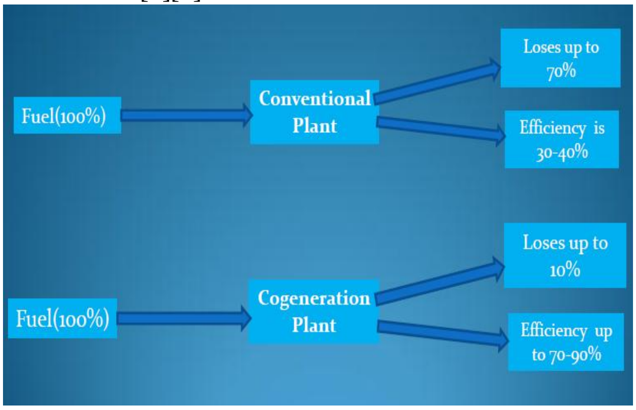

Figure 1: Conventional and Cogeneration Plant

The term "micro" is used under 20kW'. When power is produced using small sized reciprocating Internal

Combustion engine, it is also categorized under MicroCHPs.

III. RECIPROCATING IC ENGINES

Internal combustion engines are mainly of two types: spark ignition engine, which are operated mainly with natural gas and compression ignition engines, which can use diesel fuel, as well as heavy fuel oil or biodiesel. Reciprocating engines are a proven technology with a variable range of size and the least initial capital cost of all CCHP systems [1][5][9]. It also has advantages like quick start-ups, high operating reliability, and high efficiency at part load condition providing end users a flexible power source, which also makes it suitable for emergency or standby power supplies. It is the most prominent power generation equipment under 1 MW. A typical reciprocating engine (diesel, gas, multiple fuel) and a generator linked to the engine are quite efficient in producing electricity, have a large power range and choice of fuels. The applicability of gas engines is best in back-up systems. Diesel engines are recommended for continuous power generation conditions.

A. Drawbacks

Although they are a mature technology, reciprocating engines have some drawbacks. Relatively high vibrations are produced that prerequisites shock absorber and shielding measures to reduce acoustic noise. A large number of moving parts leads to frequent maintenance interval, increase maintenance costs. Utilization of various heat sources with diverse temperature levels in CCHP application is difficult. Produces high emissions – particularly nitrogen oxides – are the reducing the growth pace of this technology, which need improvement. Manufacturers around the world continuously thriving for development of new engines with lower emissions along with emission control options, such as selective catalytic reduction (SCR), have been utilized to reduce emissions.

Diesel engines can have two applications:

- Mobile as in vehicles/automobiles
- Immobile as employed in hospitals [22][52], industries, Gujarat International Finance Tec-City (GIFT) [28]

In the conventional system, Internal combustion engine consuming a substantial amount of diesel fuel produces direct current then it needs to be altered into alternating current to be used in the present VCRS operated air conditioning system with the aid of an inverter which is again a complex-structured, less reliable and expensive device. COP of the system is also low and refrigerant (R12 or R22) leaks, which when rescued from the system into the atmosphere, deplete the ozone layer and Render conducive role to the greenhouse effect.

Substance	Lifetime (years)	Global Warming Potential		
		20 years	100 years	500 years
Ca bon dioxide	Uncertain	1	1	1
Methane	12.0	62	23	7
R-12 (CFC)	100	10200	10600	5200
R-22 (HCFC)	11.9	4800	1700	540
R-32 (HFC)	5.0	1800	550	170
R-125 (HFC)	29	5900	3400	1100
R-134a (HFC)	13.8	3300	1300	400
R-407C (HFC)	15.6 *	3605 *	1653 *	522 *
R-410A (HFC)	17 *	3850 *	1975 *	635 *

Table 1: GWP of refrigerants [30]

This paper discusses various exhaust heat assisted cooling techniques incorporated in stationary and movable diesel engine and their advantages and shortcomings. The ever-growing need of energy resources, global warming and blackouts have intensified the search for more efficient energy conservation techniques, reducing GHG emissions and ameliorating comfortable human conditions [3]-[6],[8]-[10].

IV. IMMOBILE DIESEL-ENGINE COOLING TECHNIQUES

In immobile diesel engine cooling techniques, any low grade heat operated system can be utilized as even if the cooling system is robust, heavy, it doesn't create any hindrance as it is not required to be transported. Recent development of CCHP systems led to the emergence of DER (distributed/ decentralized energy resources) which is a novel technical concept in energy supply in state-of-the-art. DER is defined as an electricity-generating system located at or near user facilities, which provides electrical and thermal energy simultaneously to meet local users reducing significant transmission losses [22]. In deploying CCHP system with a stationary internal combustion engine, the cooling technique mostly used is absorption chillers. Adsorption cooling technique is also used and many studies [16][32][45] have been carried out with adsorption cooling in stationary unit but absorption is mostly used for its higher COPs. When cooling is required for refrigeration that is mostly achieved by ammonia-water VARS [35] [36][39][44][45][53].

A. Absorption Cooling

A typical CCHP system is showed in fig. 2. It comprises of a gas engine (which produces mechanical power and thermal heat due to incomplete combustion), a generator (converts mechanical power to electrical power) and absorption chiller (produces cooling effect depending upon the weather conditions utilizing exhaust gas and jacket water derived from the engine), thus trigeneration system is attained-power, heat and cold generation simultaneously. If waste heat from engine is insatiable as per demand requirement, a combustor in absorption chiller can burn natural gas as a supplement source [11].

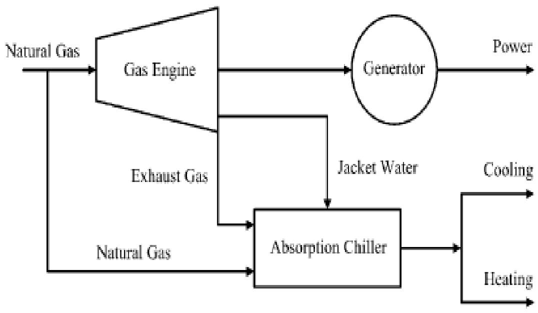

Figure 2: Typical CCHP system.

B. Absorbent-Refrigerant Pair

Commercial refrigerant-absorbent pairs used in the absorption cycle are water-lithium bromide (H2O-LiBr) and ammonia-water (NH3-H2O). The operation of the former is limited in the evaporating and the absorbent temperature, so it is mostly used in air conditioning applications whereas the operation of the latter cycle is not limited in either the evaporating or absorption temperature, so they can be used for refrigeration applications like in ice-refrigeration plants, food storage plants. For the fact that ammonia is toxic in nature, hard to detect in case of leakages, its usage is limited to the large capacity system and not used in household applications. Typical cooling COPs of the single-effect, double-effect, and triple-effect absorption cycles are 0.7, 1.2, and 1.7, respectively [7].

C. Various experiments and simulation results

A micro-trigeneration set-up has been deployed for research purpose at the Laboratory of Seconda Università degli Studi di Napoli,(Italy) operated on natural gas fuelled reciprocating internal combustion engine that is coupled with a thermal-chemical absorption system (triple state water-LiCl) and air cooled water chiller and conducted experimental investigations under real operating conditions. Thermal energy is recovered from exhaust and coolant jacket by a water-glycol mixture as coolant. Thermal power recovered from MCHP system improves at incrementing the electric power (varied from 0.9Kw to 11.3kW) supplied to the end-user. Best results are obtained when the power el is 5.4kW and results achieved are poor when the end user power requirement is 0.9kW or below it. MCHP also reduces GHG emission to a significant amount; it is around 26% if compared to the Conventional System and around 22% at electric power supply of 5.4kW. if compared to the Best Available Technology, the CO2 reduction ranges between 6% and 30%; MCHP allows for an operating cost reduction up to 26% while the supplied electric power is around 5.4 kW; no significant differences between MCHP system and BAT can be highlighted at around 0.9 kW as electric power. However performed tests showed that MCHP system efficiency is strongly affected by the user load profile and benefited when operated at high load; therefore MCHP performances should be investigated in a wider range of operating conditions and its application in conjunction with the domestic households thermal and electrical demand profiles should be also assessed [23]. A system has been modeled where power is produced in IC engine, waste heat is recovered from coolant and exhaust gas with heat exchanger and satisfy both summer and winter demand, the system is also provided with accumulator and batteries for better control and to meet the irregular thermal demands [24].

An adsorption system has been simulated and tested to know the system's optimum matching and operation of adsorption chiller in MBCHP system correctly, this paper dealt with the performance of adsorption chiller under varying heating conditions. Experimental results show that the COP and heating power significantly rises in the operation mode of varying hot water inlet temperature and high hot water mass flow rate. The COP is as high as 0.40 in VTNH modes. When electricity output conditions ranges from 6.0 to 8.3 kW, VTNH mode is especially preferred when cooling demand is high [25].

D. Experimental setup and results installed in MNIT

A practical experimental set-up is also developed in IC engine lab of MNIT premises where already number of tests has been conducted to evaluate the system performance and investigate the challenges facing the practical application of the system. Experiment is conducted on the developed cogeneration system set up at MNIT Jaipur Laboratory and the results are compared with the single generation system (when the thermal energy is not recovered). The results show that the total efficiency (electrical & thermal) of Cogeneration system reaches to 86.2% at full load however for mono power generator it is only 33.7% at the same load. The CO2 emission from cogeneration system is 0.1211 kg CO2/kWh compared to that of 0.308 kg CO2/kWh from single generation at the engine full load and sfc also reduces in cogeneration whereas there is no alteration in BSFC and BTE when the generator set is running alone or in Cogeneration system [18].

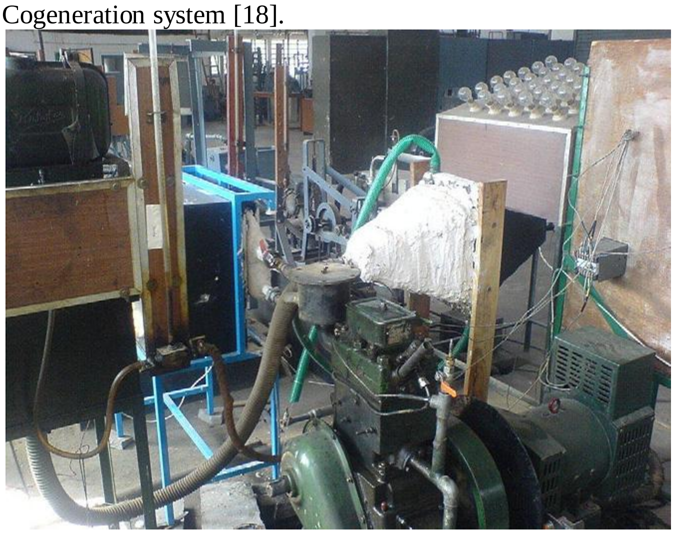

Figure 3: Cogeneration set up (MNIT, Jaipur)

Installed Cogeneration system in MNIT Jaipur has been added up with an Electrolux vapor absorption (VA) chiller s for space cooling of a small sized cabin 3'X5'X6' and temperature drop of 5oC has been achieved after 6hours of

DI diesel engine operation and BSFC, BTE and emission level (all parameters) have been observed favourable [33].

Figure 4: cabin incorporated with VARS (Trigeneration)

V. MOBILE DIESEL ENGINE COOLING TECHNIQUES

When a vehicle is operated at high speed, turbulent air produced by the operating condition can be injurious to the people's sitting in the vehicle as turbulent air is a threat to a person's eardrums and so vehicle's windows needs to be closed. We know air turbulence, solar and engine radiation generates ample heat inside the cabin and it is approximately 100C higher than the atmospheric temperature [14] which enhances fatigue condition of the vehicle occupants when running at peak speed. In locomotives the cooling components emits considerable noise and consumes a major part of energy [19]. It has been analyzed in an investigation in France that in torrid working conditions which is uncomfortable for drivers ameliorates the probability for accident to about 40% especially in locomotive cabins. Transportation sector in India consumes alone 11% (study in 2005) of primary which is likely to be doubled to 20% by 2030 [60]. Thus, there is an urgent need of a system that is able to recover waste heat at low temperature levels: can be an interesting alternative for wiser energy conservation and management and which alleviates the existing dangers of conventional locomotive systems. The concept of automobile waste heat-driven cooling seems to be very attractive and wide studies have already been conducted [14] [15] [19]. However, until now, paltry experimental results have been reported. In movable engines, different cooling techniques can be used but adsorption chillers are more felicitous as the system is simple and requires zero or no maintenance because of its unavailability of any moving parts or machined surface. It is also emancipated from rectificer-analyser assembly used in ammonia-water absorption system as in adsorption, there is no recrystallization or rectification problem. So, the latter system is easily used in movables like locomotives, buses, cars etc. For vehicles moving at extremely high speed as in case of locomotive, adsorption operated air conditioning is the appropriate solution as this is suitable for vibration, incline and rotation occasions. Various research personnel has been conducting studies on implementation of adsorption air conditioning [17][25] Adsorption-cooling technology is a novel, environmentally friendly and effective means of using low-grade heat sources. An adsorption refrigeration system is similar to vapor compression systems except that heat—instead of work—provides the energy needed for compression. Unlike conventional vapor compression systems which require a mechanical compressor assembly, this new technology uses a thermally driven static sorption bed, saving as much as 90% of the required input power typically used to drive a mechanical compressor [17]. Based on these merits of the adsorption system, active research in China, Europe, Japan and the US has resulted in the breakthrough of this technology. Adsorption cooling has been widely used for ice production since last many decades.

A. Cooling load requirement of locomotive cabin:

In ordinary conditions (torrid seasons), the cooling load is 4.2kW and the refrigeration capacity is to be designed for more than 5kW. Even though the cabin size is small, the load is higher due to lack of air tightness and insulation, even the solar radiation through the glass adds up to the increment of temperature inside the cabin [14]-[15].

B. Adsorbent-adsorbate (refrigerant) working pairs: Activated carbon and methanol; (2) CaCl2 and ammonia; (3) compound adsorbent (80% CaCl2 + 20% activated carbon) and ammonia 4) zeolite and water, 5) zeolite and ammonia, and 6) silica gel and water. Researches have been conducted [20] and applications and suitability of various pairs have been discussed. The zeolite-water combination is superior when the temperature (adsorption-evaporating temperature) exceeds 458oC [14] and it is also the most suitable pair for air conditioning [15]. Zeolite-water can also withstand high regenerating temperatures as like in exhaust gas of an engine, where the temperature is relatively high (>500oC) [12].

Adsorbent	Adsorbate	Heat of adsorption	Toxicity	Vacuum Level
Silica gel	H_2O	2500kJ/kg	No	High
	CH_3OH	1000kJ/kg	Yes	High
Zeolite	H_2O	4000kJ/kg	No	High
	NH_3	5000kJ/kg	Yes	Low
Activated charcoal	C_2H_5OH	1300kJ/kg	No	Med
	CH_3OH	1900kJ/kg	Yes	High
$CaCl_2$	NH_3	kJ/kg	Yes	Low
	CH_3OH	kJ/kg	Yes	Low

Table 2: Characteristics of adsorption working pairs

An experimental set up has been installed at the laboratory of Institute of refrigeration and cryogenics, Shanghai(China) to study the practical outlook of the exhaust assisted cooling aspects of single adsorber with regenerator in DF-4B no. 2369 locomotive and 16 240 ZB locomotive. Regenerator installed can sustain variable exhaust heat condition and provide cooling effect during the desorption period.

Jiangzhou et al. suggested the ratio between the desorption period and the adsorption period can be optimized to improve the overall performance of the system. It is beneficial to the system if the adsorption time is more than desorption as desorption and adsorption temperatures have significant influence on the COP and experiments revealed that there is no significant role of condensing temperature of a zeolite-water adsorption system unlike activated carbon–methanol adsorption system. An air-cooled condenser may be employed in the actual system as mass transfer inside the adsorber can enhance the performance of the system, even evaporator design should also be checked for increasing the refrigeration capacity output. Similar results have been obtained in both the IC engine studies [14]-[15]. Vicatos et al (29) tested the theoretical design of cabin cooling on a prototype in road condition as well as in laboratory incorporating VARS in it (with ammonia-water pair) and considering cooling load as 2kW in NISSAN 1400 truck, laboratory test has been performed by simulating the exhaust gas condition by burning propane and the results obtained have been found in accord to those of road test-data. They validated the feasibility of exhaust gas to cool the cabin of the above mentioned specimen and when ammonia is used as refrigerant carbon made materials should be replaced with steel or mild-steel. An experimental investigation with adsorption cooling technique has been carried out on 14 passenger occupancy cabin (full load) of a commercial minibus with an air cooled, 4 cylinder DI engine for comfort heating through a water stream heated by the hot exhaust gas and testified under various ambient conditions: temperature ranging from -3,0,5 & 10oC and it has been observed that when engine speed is above 2500rpm and at ambient temperature above 0OC, the system had comfortable condition without any surplus expenditure of fuel. Tests have been performed at various loads and validation of the heating system is calculated, it has been concluded that the system is very economic with one-third cost of conventional system and saves 110l of fuel [31]. An experimental intermittent adsorption cooling system driven by the exhaust gas of a four stroke, non-turbocharged, direct injection diesel engine is designed and tested. The adsorber is a double-tube pipe packed with Zeolite 13x pallets inside and to enhance heat transfer, 12 radial fins are welded to the inner tube, controlled and instrumentation facilities of the test rig are also developed to intensify the performance (COP of the system is 0.38, and the SCP is 25.7 w/kg). Experimental results indicated that this prototype can be successfully used for waste heat driven air conditioning. These parameters may be very encouraging. However, for a practical automobile (mobile system) waste heat adsorption cooling system WCOP is satisfactory, but for relatively low SCP (concerning bulk and cost) further research is needed [13]. The vehicles more suitable for this kind of air conditioner are buses and locomotives as this requires significant amount of mass and volume.

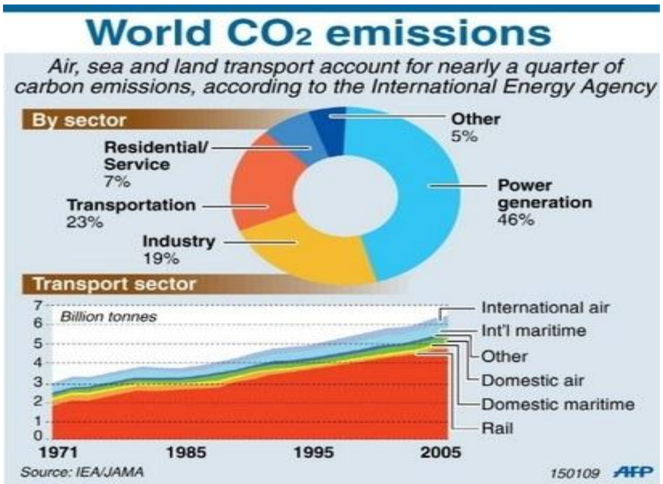

Figure 5: Transportation sector and its CO2 production

Transportation sector with the conventional system generates 23% CO2 and around 20-40% Freons are generated per year, so implementing adsorption cooling in vehicles should be considered as the demand of cooling and supply of exhaust heat are in phase, so does not matter whatever the COP is, it should be deployed and the installation difficulties that are paving the way should be flushed out.
There can be two ways to solve this problem:

- Efforts should be made to raise the efficiency so that even with small size the desired cooling can be achieved or
- Improvement in Heat transferability by incorporating fins to reduce the size and weight.

VI. ECONOMICS

Research scientists studied and evaluated the economic profitability of the micro-cogeneration system [27], it is profitable in most of the cases and profitability greatly varies with the variance in government's rules (country conditions), as feed-in tariffs, bonus payment, market mechanism and even tax rebates. As a result, estimating the accurate economic benefits is very complex by the large number of parameters involved and by the fact that incentives are often assigned according to multiple schemes. Initially higher investment is required for the user as compared to the conventional separate production of heating and electricity. The economic feasibility calculation also involves the knowledge of natural gas and electricity prices in the domestic sector and this price varies largely across Europe and all over the world. After the EU released directives on the promotion of energy efficiency and renewable energy, different incentive schemes have been implemented by member states in order to attain momentum in the uptake of efficient and green energy technologies. The authors [22] analysed the economics of trigeneration system installed in Slovenia's biggest hospital, the trigeneration needed additional to compression chiller along with absorption chiller to meet the energy need, and they carried out the economic analysis and found it is profitable, has low payback period (PBP) and high Net Present Value (NPV).

VII. FUTURE ASPECTS

Research can be conducted for higher heat transferability (exergy) and improved COP of low grade cooling system. The stationary system can be coupled with solar energy in high insolation zone [47][49][56] and change in power production can be analyzed, efficient accumulator or thermal energy storage [34][38] can be developed for intermittent period and desorption phase in adsorption cooling system, when energy source is unavailable during need. The trigenration efficiency improvement can also be analysed using other fuel blends and fuels as achieved by researchers using LPG [36], biomass [46][51], hydrogen [48],biofuel [55][56] and the optimum sizing and cost of trigenerator according to the need should be simulated before installation of the system as per various simulation techniques illustrated [41][42][50][52][54].

VIII. CONCLUSION

This analysis shows that the idea of aspiring for Micro-Trigeneration is a judicious way for small remote home, vehicles, and locomotives of a developing country as well as congruous way to fit in the stringent environmental norms. Such exhaust heat assisted cooling techniques also helps in adhering to the Kyoto protocol targets (1987) set for domestic and international [29] and this technique also has a major role in controlling global warming of earth as it reduces CO2 to a significant amount [40][59] and the correlation of CO2 and global temperature is well established [58].The feasibility in implementation of exhaust gas as the source of input energy for air conditioning is well-proven [57]. But the vehicle cooling effect gets started only after the exhaust produces enough heat to warm up, which is a major set-back and there are norms for the limit of energy extraction from exhaust gas. Ning et al. [21] investigated the effect on diesel particulate when exhaust gas is cooled and their experiments revealed that there is considerable increase in particulate matter when the exhaust gas was cooled to 150oC or below. On the contrary, when exhaust gas temperature was cooled above 200oC, there was a slight increase in the diesel particulate, which makes it a pre-requisite that exhaust gas temperature must be kept above a certain value for environmental and ecological concerns. But the extracted heat is enough for satisfying the cabin cooling load and saves around 50% of fuel and reduces CO and NOx production by nearly 70% and 80% respectively as comparison to conventional vehicle ACs [31]. So this way, implementation of trigeneration in automobiles can lead to sustainable development and assist to shape the earth technically and economically viable in an effective manner.

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DEFINITIONS, ABBREVIATIONS

Term: Cogeneration, Trigeneration, Micro CHP, Adsorber, Adsorbate, Absorber, NPV, PBP

AC	Air Conditioning
BAT	Best Available Technology
BCHP	Building Cooling, Heating and Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CCHP	Combined Cooling, Heating and Power
COP	Coefficient of Performance
DER	Distributed/Decentralized Energy Resources
GHG	Greenhouse Gas
GWP	Global Warming Potential
MCHP	Micro Combined Heating and Power
NPV	Net Positive Value
PBP	Pay Back Period
VAT	Value Added Tax
VARS	Vapour Absorption Refrigeration System
VCRS	Vapour Compression Refrigeration System
WCOP	Coefficient of Waste heat cooling
SCP	Specific Cooling Power (W/kg of adsorbent)
SCR	Selective Catalytic Reduction

