Potential Applications and Performance of Energy Recovery in Motor Vehicles: A Literature Review

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Abstract - *This paper reviews the research and thorough study of the capabilities and potential uses of the energy recovery system installed in motor vehicles. The article draws motivation from the ever increasing demand of fossil fuels and hence tries to investigate some futuristic solutions to diminish the fuel requirement and increase the performance simultaneously. This paper reviews the system converting waste heat energy to not only increase the engine efficiency but also used in various other systems like air conditioning. Some of the experiments conducted to find the constructive use of the waste thermal energy generated in an automobile engine and kinetic energy lost while decelerating are explored in this paper. It also attempts to present an overview of the hybrid technology employed in passenger vehicles and its advantage over a conventional gasoline powered vehicle. It presents the use of Vapor Absorption Refrigeration System (VARS) powered by waste exhaust heat instead of the conventional Vapor Compression Refrigeration System (VCRS) used in cars to make the air conditioning cost effective and energy efficient. A brief review on the innovative concept of regenerative braking is discussed which is used in most hybrid and electric vehicles helping to boost the efficiency and bring down costs. The paper also spotlights on the integration of Motor Generator Unit- Heat (MGU-H) in a commercial vehicle prototype, a concept used in Formula One to harvest waste thermal energy and its conversion into electrical energy. Energy generation by torsional springs while braking is also glanced over in this article.*

Key Words: **Regenerative Braking, Vapor Absorption Refrigeration System, Kinetic Energy Recovery System, Thermoelectric Generator, Hybrid Electric Vehicle, Turbocharging, MGU-H, MGU-K, Supercapacitor.**

1. INTRODUCTION

Ever since the first automobile was born in 1886, mankind has witnessed the burning of fossil fuels for decades. As time progressed, as population began increasing and as industrial revolution made the dream of having cars cheaper, the rate of fuel depletion has increased drastically day by day. Today, the practical alternative to gasoline in ships, aircrafts and rocket propulsion vehicles is out of picture as the energy requirement simply exceeds the capacity of battery packs and other renewable energy sources. But the birth of Tesla electric cars has definitely made the future look electric in the case of passenger vehicles. In the quest of ruling out gasoline cars, giving birth to electric cars and scraping gasoline vehicles simply doesn't look like the way out. Hence the goal cannot be making combustion vehicles 100% efficient but squeezing out the maximum performance from each drop of fuel. This research led to the introduction of hybrid cars boasting an internal combustion engine along with an electric motor. Hybrid cars act like an intermediate product between gasoline and electric cars. Conceptually, the engine powers the wheels as usual and an electric motor assists the engine and harvests energy when the gas pedal is released by reverse flow of current to the battery thereby recharging it and saving fuel. In a nutshell, this is Regenerative braking. While the research on running vehicles free of gasoline has been on since years, we have been equally keen on decreasing the fuel burn rate in gasoline cars and obtaining more range at the same time. Mechanics and electronics went hand in hand when hybrid cars were born. In an internal combustion engine, 70 to 85% of thermal energy generated is lost in exhaust emissions, frictional and pumping losses which makes a gasoline vehicle costly and not much efficient. The 20-25% power output can be further increased by converting this waste heat into useful work. This is achieved by some innovative techniques like regenerative braking, turbocharging, etc. The need for increasing engine efficiencies to reduce fossil fuel depletion has also led numerous motorsport events to research on developing technologies to burn less fuel and produce more power. In 2014, Formula One brought in new regulations which saw the introduction of a turbocharged V6 engine and an all new Energy Recovery System (ERS) making the power unit more than 30% efficient with just a third of fuel.

2. LITERATURE REVIEW

Albert Boretti [1] evaluated the performance of a passenger car engine after installing a Motor Generator Unit-Heat (MGU-H) based on the one used in F1 cars. 86 x 86 cm four-cylinder virtual square in-line engine was considered with a compression ratio 10. The engine was built using GT-SUITE, a software used worldwide by OEMS and suppliers in engine research and development. It was found that the efficiency η (Ratio of engine crankshaft power to fuel flow power) at minimum speeds with MGU-H increased up to 4%. At all operating conditions, power output of turbine can be greater, equal to or smaller than required compressor power. It was observed that at medium speeds, efficiency η^* (Ratio of engine crankshaft and turbocharger shaft power to fuel flow power) exceeds η up to 2% and lags η up to 2% at maximum speeds. The author commented that initially such system is suitable for luxury and sports cars with turbocharged engines. A gradual transition to economy hybrid electric sedans can be planned owing to the cost evolution of the motor generator components. It was concluded that installation of MGU-H would definitely benefit hybrid road vehicles by increasing low speed torques and vanishing the turbo lag while accelerating but these benefits are relatively much lesser when costs are considered.

Henry Hadi et al. [2] designed and simulated electrical Kinetic Energy Recovery System (KERS) prototype using an electric motor to rotate the wheels installed on a motorcycle. Mathematical model of generator and motor was made on MATLAB 2012a. Due to generation of varying voltage while braking, a voltage stabilizer was used to keep it stable while charging the battery. Three modes namely EV (Electric Vehicle), engine-driven and split e-CVT (Electronically Controlled Continuously Variable Transmission) were tested to evaluate their performances and improvements over the conventional IC (Internal Combustion) engine mode. Performance evaluation was done by comparing 6 electric and conventional IC engine motorcycles by taking them on two Lisbon routes. In optimum engine state, fluctuating output voltage of 67.96 volts was generated but it was stabilized to 24 volts before storing in the battery using a stabilizer. 36% increase in trip time for electric bikes was reported but 61% less TTW (Tank to Wheel) energy was consumed. Overall, up to 32% improvement in fuel economy was observed. While simulating the model on Simulink, input torque of 7.84 Nm at 6000 RPM was fed. Four European driving cycles were generated and the electrical energy generated by the KERS was plotted against the total time while braking. On an average, 1012 watts power was generated in the first 0.12 seconds while braking and then it linearly decreased to 0 over a span of 10 seconds.

Steven Anton et al. researched on waste heat energy harvesting of motorcycle using 1995 Kawasaki Ninja 250R having a two-cylinder 248cc IC engine with an aim to replace the alternator for battery charging and reducing engine load [3]. A TEG (Thermoelectric generator) was used to convert the waste thermal energy into electrical energy from the temperature gradient. The employed module Melcor HT3-12-30 with max operating temperature of 200°C having dimensions 1.18in x 1.34in x 0.13in was reported to produce an average of 0.47 watts from average temperature gradient of 48°C. The temperature of the headers reached around 280°C when the motorcycle was taken for various rides around town and on highway which is more than the maximum operating temperature of commercially available thermoelectric modules around 220°C. The module was thus placed farther from the header just before the muffler which helped in getting a lower cold side temperature too as it was more exposed to the air flow of ambient air. It was clamped on the exhaust pipe with a hose clamp. A Pace Scientific model data logger was placed beneath the seat which recorded the temperature deltas and a RadioShack switch was used to easily switch it on or off as per required. On running five trials of different riding conditions, an average power output of 0.4694 watts with average Seeback coefficient of 0.03V/°C was recorded. But to match the alternator's output of 14 volts and 17 ampere, 570 modules (10 in series and 57 in parallel) wrapped completely on a 5m exhaust pipe would be required to match the voltage and current respectively. Hence it was concluded that further work on this topic is necessary before knowing if this system is advantageous or not. With the use of more advanced modules and an optimized heat sink, the power output can be greater and perhaps enough to achieve the aim.

Abhilash Pathania et al. proposed a Vapor Absorption Refrigeration System (VARS) model without a compressor using hot radiator water acting as a generator to produce high pressure ammonia vapors [4]. The system comprised of four heat exchangers namely evaporators, condensers, absorbers and expansion valves. The experimental investigation by building the mathematical model of the study and its analysis is planned to be done in part two of the research.

Harus L. G. et al. [5]. designed a mechanical electrical KERS system using a flywheel to turn a 12 volts generator with a transmission belt. Flywheel was utilized to charge the motor and also run the car alternator. A VSD (Variable Speed Driver) was employed to run the flywheel at four frequencies of 10, 15, 20 and 25 Hz to evaluate the charging capacity of the motor. An efficiency of 119% at 1197 rpm and 10Hz was found while simulating a city drive. The graphs of the four frequencies vs the angular speeds were plotted. The KERS was capable of producing an average electrical power of 71.3 watts.

In [6] Mohamed Mourad demonstrated effectiveness of regenerative braking in a parallel hybrid vehicle using *Advisor*, a software package developed for simulating vehicle prototypes and testing their performance. Hybrid electric powertrain was simulated by MATLAB/SIMULINK and the emissions and fuel economies were analyzed. Vehicle testing was done in Germany at an emissions test facility equipped with roller dynamometers to create real driving cycles. It was discovered that the energy consumed from the engine and battery was 0.17 kWh and 0.05 kWh respectively. The driving cycles lasted 1084 seconds over 4.32 km at an average speed of 53.7 km/h. From the plots it could be observed that an average power of 1.3 kWh was produced with regenerative braking. The dip in the battery state was linear from 0.7 to 0.67 after which there was sudden rise indicating the recharge process had commenced. The emissions reported were dramatically lower than gasoline vehicles almost reduced to half.

Nader Javani et al. thermodynamically analyzed the waste heat recovery for cabin cooling systems in hybrid electric vehicles (HEVs) used to power the boiler and generator [7]. Shell and Tube type heat exchanger was used to heat the generator. Lithium Bromide (LiBr) was used as refrigerant having strong affinity towards water. Energy analysis for ejector and absorber was conducted and LiBr concentrations were determined from MATLAB. For 85% of exhaust heat and 15.47kW of available heat, the cooling capacity was found to be 7.3 kW sufficient enough for heat transfer which can cool the cabin to 15°C. However, the waste heat produced by battery in electric vehicle (EV) was not sufficient for the refrigerating effect with a mere cooling capacity of 2 kW. Absorption refrigeration in hybrid vehicle turned out to be more efficient having cooling capacity of 7.9kW for same available heat quantity.

Bo Yu et al. [8] researched on the strategy of braking energy recovery of an EV considering ideal braking energy curve (I-curve) and Economic Commission of Europe (ECE) regulations. Simulink and Cruise were employed in simulating the vehicle model. Coefficient of adhesion was taken as 0.8 and three braking conditions, mild, moderate and severe at 74% of initial battery state were simulated. An increase of 22km compared to vehicle with no braking energy recovery was found. The braking energy recovery rates were observed to be 27.4%, 43.4% and 42.41% respectively to the three braking conditions mentioned before. The cruising range was reportedly increased to 136.64km on implementing the braking control strategy.

Rohan Thosar et al. proposed a theoretical electrically assisted turbocharger in an automobile with an inbuilt motor generator unit with the aim of reducing fuel consumption, meeting electrical energy demands and increasing the power output [9]. Heat balance sheet was produced and various types of electrical loads were investigated. The total loads associated with intermittent, prolonged and continuous loads were calculated to be 1.7kW, 180W and 260W respectively. The MGU-H was connected to the turbocharger unlike the MGU-K connected to the drive shaft which spins it to reduce turbo lag when sudden increase in power is required during acceleration post idling.

In [10] Ataur Rahman et al. did an innovative approach on power generation from waste thermal energy of IC engines based on coolant and exhaust. A constant intake temperature of 70°C was maintained using fuzzy intelligent controlled micro faucet exhaust gas recirculation (MiF-EGR) and a TEG was used to produce electric power from exhaust gas temperature gradient. The hot coolant heated the ramming air from supercharger in the range 60-70°C for complete fuel vaporization. Finned type TEG was attached along the exhaust pipe to produce electricity by Seeback effect. The waste heat recovery system performance was tested using GT Suite software at 4000 rpm. Specific fuel consumption was improved by 3% due to less hydrocarbons in cylinder and 7% increase in brake power was reported. A total of 200W could be recovered from TEG which roughly equals 20% of alternator output.

Mohm. Quasim Khan et al. [11] experimented the use of TEG to harvest vehicle exhaust for electrical energy generation. The TEG was tested between engine speeds 2500 and 4000rpm. Three different TEG positions were examined and maximum power was generated between muffler and catalytic converter due to low pressure drop. At 150kW engine power, 1.4kW of electricity production was recorded. A linear increase in power production was observed with increase in engine speed till 112.7 km/h and 3500 rpm. An average TEG efficiency of 4% was found. Also cost of TEG materials was discussed which concluded that Bismuth Telluride (Be2Te3) is very economic costing around 100$ per kg.

C Śliwiński proposed a kinetic energy recovery concept using tortional springs during braking [12]. Four torsional springs connected to five clutches and two locking mechanisms on the rear axle was proposed, a system similar to propulsion system in pull back toy cars. A combination of gears was used in the concept to produce the required torques during acceleration and produce the twisting motion of spring.

In [13] I. Pielecha et al. researched on the possibility of voltage gain from regenerative braking in parallel hybrid vehicles. Two full hybrid models, Lenux NX 300h and Toyota RAV4 Hybrid were tested on the same city route in Warsaw, Poland in urban conditions for the voltage analysis. It was noted that the voltage value generated depended on engine speeds and not on the torques produced by the transmission. The driving cycles lasted about 2250 seconds over an average distance of 15km at 24kmph. Results showed that energy recovery happened at about 15% and 20% of the cycle in case of Toyota and Lexus respectively and no regenerative braking was recorded below 7kmph. Also 22% more energy was recovered by the Lexus although being 7% heavier. Further work on the impact of braking energy recovery on exhaust emissions and fuel consumption is planned in the second stage of the research.

Emiliano Pipitone [14] evaluated an electrical kinetic energy recovery system using a supercapacitor for energy storage on Volkswagen Golf 1.4TSI, a vehicle prototype having an internal combustion engine. The model performance based on fuel economics and energy savings was tested based on the standard driving cycles, ECE-15 and Artemis Urban simulated on MATLAB Simulink. For the two cycles, different values for sufficient KERS model power were found, 13kW and 15kW for ECE and Artemis respectively. For accurate results, same supercapacitor was coupled with four different motors with different power ratings in the order 11, 14, 24 and 30kW respectively. The fourth combination proved to be the most efficient with energy savings in the range 16-19% for ECE and 20-24% Artemis Urban respectively.

3. CONCLUSIONS

Various methodologies involved in the recovery of waste thermal and kinetic energy generated in motor vehicles were briefly reviewed. All the subsystems or domains where this recovered energy could be reused were investigated. It was concluded that next to ZEV (Zero Emission Vehicle), hybrid electric vehicle is the key to the reduction in the hazardous vehicle exhausts and fossil fuel depletion. Even though many of the ideologies are still in the initial research stages, they still have tremendous potential to shape the next generation green automobile future in the coming era.

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