CHAPTER 2

LITERATURE REVIEW

Chokri Mahmoudi et al., (2014) explain in the overview that, for propulsion, the Electric Vehicle (EV) employs high-capacity batteries and an electric motor. Because the battery is the only source of power, software-based power management solutions including such online Power Management Controllers, offline Power Management Controllers, Rule-based Power Management Controllers, and others are employed. Conductive and inductive charging, learning-based, GPS-based, low-level hardware-based. These Power Management Control solutions improve the performance of electric vehicles by making the best use of available battery power. (Chokri Mahmoudi et al., 2014)

Xing et al., (2011) have mentioned the different battery management strategies for lithium-ion batteries. Lithium–ion batteries are more suited than lead–acid batteries, according to a recent trend. Lithium-ion battery power management is also easy to control. Different tactics for improving and optimising the performance of the Battery Management System in Electric Vehicles should be used depending on the situation. The battery power profile can be used to analyse how driving habits affect an EV battery's performance and lifetime. (Xing et al., 2011)

Cell voltage measurement (CVM), Battery states estimate, Batteries uniform and equalize, and Fault diagnosis are the most significant components of lithium ion management in electric vehicles, according to Lu et al., (2012) in their review study (EVs). To address these concerns, various methodologies/techniques such as State of Charge (SOC) estimation, State of Health (SOH) estimation, and State of Function (SOF) estimation can be applied. (Lu et al., 2013)

Vidhi and Shrivastava (2018) have shown the electric vehicle lifecycle emissions. Although there are certain issues related to power management of electric vehicles but considering environmental health they can help to reduce the emission. NOx emissions from automobiles can be decreased by 7–25% depending on the charging energy source, while CO and CO2 emissions can be reduced by up to 85% if the charging energy is renewable. Therefore, even though Electric Vehicles are emission free but the source of electrical production may pollute the environment. As the number of electric vehicles grows, so does the demand for electricity, resulting in more electricity being generated. Whether the incremental power is generated from renewable resources such as solar and wind, or non-renewable resources such as coal and natural gas, will determine air pollution. For the year 2017, renewable energy generation in India accounts for 16.10% of India's energy mix. If successfully executed, it will be transformed with more than 25% by 2022. (Vidhi & Shrivastava, 2018)

According to Reddy et al., (2017) solar energy is considered one of the renewable energy sources for generating power, and it is used to charge batteries in cars. Although if compared with other vehicles which use electrical energy other than solar power, the performance of solar powered vehicle lags. This is evident from the performance of a solar powered electric auto-rickshaw were it is investigated by Reddy et al. for the sustainable road transport. The techniques used are MPPT- Max Power point Tracking controller, PMA 2144 pyrometers measuring global hemispherical radiation from 300-2800nm. The investigation has shown the results as optimal charging rate 2kW per day, Max speed- 21.69 Km/hr, Solar Irradiance- 325W/m^2. (Reddy et al., 2017)

The charging strategy might be either plug-in charging or regeneration from the vehicle's energy losses, according to McLaren et al., (2016). A conventional vehicle emits 200-250 g CO2/Km, while an electric vehicle emits 135.6 g CO2/Km and a plug-in hybrid electric vehicle (PHEV) emits 81.9 g CO2/Km. When the grid's CO2 intensity is high, it's evident that electric vehicles can only be a good solution if the batteries are charged using renewable energy. When the grid CO2 intensity is high, however, emissions savings for plug-in hybrid electric vehicles are greater than for electric vehicles. (McLaren et al., 2016)

Thomas et al., (2017) have tested fuel economy variability of hybrid and conventional vehicles on chassis roller dynamometer. The dispersion of miles per gallon figures for hybrid electric vehicles (HEVs) is higher than for normal gasoline vehicles, according to tests. As a result, Hybrid Electric Vehicles can meet the requirement for lower emissions and improved fuel economy. (Thomas et al., 2017)

Cubito et al. (2017) investigated the effect of driving cycle on hybrid electric vehicle performance. Hybrid cars use two or more technical principles to produce, store, and deliver energy. Series hybrid electric vehicles (engine charges battery and only electric motor drives wheels) and parallel hybrid electric cars (engine charges battery and only electric motor drives wheels) are the two forms of hybrid electric vehicles (both engine transmission and electric motor can drive the wheels simultaneously). When conventional vehicles' energy consumption and performance criteria are compared to plug-in hybrid electric vehicles and series hybrid electric vehicles, it is clear that plug-in hybrid electric vehicles and series hybrid electric vehicles outperform conventional vehicles in terms of fuel consumption, especially in urban drive cycles. Hybrid electric vehicles are thought to be the future. (Cubito et al., 2017)

Silvas et al., (2015) explained in the review that, the design of a Hybrid Electric Vehicle system must be optimised. Algorithms coupled on a multi-level can be used to determine the optimum design for given aims and limitations. The vehicle's available energy should be used as efficiently as possible. (Silvas et al., 2017)

Inverse reinforced learning was utilised by Vogel et al. (2012) to improve the performance of a hybrid electric car. Electric storage devices are used in hybrid electric vehicles (HEVs) to save a portion of the energy supplied by the engine and other regeneration mechanisms, lowering fuel usage. Fuel efficiency in hybrid vehicles is dependent on the efficient use of engine and battery power. A probabilistic driving route prediction system is taught using Inverse Reinforcement Learning (i.e. learning an agent's aims, values, or rewards by observing its behaviour) to improve the hybrid electric vehicle's fuel economy. Overall energy usage is reduced by 1.22 percent because to inverse reinforcement learning. (Vogel et al., 2012).

According to Millner et al., (2010), there are three improvements for plug-in hybrid electric vehicles that can increase their economy. An effort to improve plug-in hybrid electric vehicles includes predictive control based on location information, minimising demand charges when the car is parked, and maximising battery cycle life. According to this study, a practical strategy can improve the prediction and operating conditions of a hybrid electric car. (Millner et al., 2010)

The problems for hybrid electric vehicles were highlighted by Assadian et al., (2012). Hybrid Electric Vehicles are classed according to their hybridness, with Mild/ Micro hybrids falling under 20%, Full Hybrids falling under 50%, Plug-in Hybrids falling under 75%, and Electric Vehicles falling under 100%. For the mild hybrid electric car, both a belt-integrated starter generator and a crank-integrated starter generator have been modelled. A High Voltage Belt Integrated Starter Generator outperforms a Crank Integrated Stator Generator in terms of performance. Speed control tactics may be important in optimising hybrid electric vehicle performance. (Assadian et al., 2012)

Critical areas of hybrid electric vehicles, such as pollution and charging, have been mentioned by Fontaras et al., (2008). Various research are being conducted to estimate the gaseous pollutant emissions and fuel consumption of mild and full hybrid electric vehicles. A driving cycle test on a chassis roller dynamometer, as well as the Constant Volume Sampling (CVS) Technique for fuel efficiency and emission monitoring, were used in the experimental study. The Assessment and Reliability of Transport Emission Models and Inventory Systems (Artemis) measuring technique gives the real driving cycle when compared to the normal European type approval process. For accurate measurement of hybrid electric vehicle energy consumption and emissions, the battery's state of charge (SOC) at the end of the test should be the same as it was at the start. Several approaches to SOC correction have been proposed, including taking multiple measurements throughout each driving cycle to phase out SOC variations, extending the test until SOC is zero, and employing the graphical correction approach. Almost every cycle tested had CO2 emissions of less than 140 g/km. (Fontaras et al., 2008)

According to Hannan et al., various hybrid electric vehicle characteristics and technologies powered by alternate and renewable energies are extremely essential study interests of the researchers (2014). For hybrid electric vehicles, mathematical modelling and software simulations using MATLAB could be used as research tools. An ideal integrated system for controlling available power and energy is another alternative for hybrid electric vehicle applications. (Hannan et al., 2014)

In their study, Johri et al. (2017) proposed ways for improving the performance of hybrid electric vehicles. Similarly, research is being conducted to increase hybrid Electric Vehicle fuel efficiency and battery charge by adopting techniques such as continuous acceleration during engine starts and regenerative breaking, which uses energy losses during breaking and acceleration to recharge the battery. A regenerative brake is an appliance, method, or system that allows a vehicle to recapture and retain some of the kinetic energy lost to heat when braking. (Johri et al., 2017)

Regenerative braking was examined by Ketan Warake et al., (2018). The regenerative braking system on the automobiles achieves the purpose of recovering part of the energy lost during braking. It was determined during the test that regenerative braking recovers around 30% of the energy lost. Charging the battery in hybrid electric vehicles with readily available alternative energy sources is still a less-discussed problem. (Ketan Warake et al., 2018)

Donateo (2012) claims that an IC engine's intelligent energy use to convert heat directly into electricity using regenerative techniques has yet to be established. For the performance of an intelligent hybrid electric vehicle that can perceive its surroundings, the engine's efficient energy utilisation is crucial. (Donateo, 2012)

According to Jarman et al., (2013), One of the most effective ways to regenerate is to use waste heat from internal combustion engines to generate power. According to the literature, thermoelectric generating is a technology for recovering waste heat by converting it into electric power. The most appealing technologies to convert heat energy into electric power are thermoelectric, thermoonic, and magneto hydrodynamic. (Jarman et al., 2013)

According to Harold Schock et al., (2007), energy conversion employing thermoelectric generators (TEGs) and heat pipes are now used for automotive waste heat recovery systems. The Carnot efficiency thermodynamically restricts the maximum conversion efficiency of various techniques. A thermoelectric generator used for waste heat recovery in an IC engine has a conversion efficiency of 8-14.8 percent. Brake Specific Fuel Consumption is reduced by 6.2 percent with the thermoelectric generator. Bismuth telluride (Bi2Te3) is the most often used thermoelectric material, and it has a relatively high figure of merit. (Harold Schock et al., 2007)

Humphrey et al., (2005) have compared the thermionic and thermoelectric converters. Thermoelectric generators have a number of drawbacks, including limited temperature limits and low efficiency. In the ballistic transport regime, comparing the maximum achievable temperature difference for Bismuth telluride (Bi2Te3) as a function of length to the maximum possible difference in temperature for a device of the same size yields potential advantages of thermionic devices over thermoelectric devices. According to the data, thermoelectric devices perform significantly worse than thermionic devices. (Humphrey et al., 2005)

According to Kamarul Aizat Abdul Khalid, (2016), Thermoelectric generators have some advantages over thermionic energy converters. Vacuum Thermionic Energy Converters and Vapour Thermionic Energy Converters are the two forms of thermonic energy converters that are commonly used. Due to the lack of advanced fabrication techniques and technology development of thermionic energy converter is limited. By using advanced coating approaches, a low work function material, barium oxide (BaO), was deposited onto a polycrystalline-silicon carbide substrate, with a thin tungsten layer in between for adhesion purposes. The results demonstrate that a 1.7 eV work function was produced. (Kamarul Aizat Abdul Khalid, 2016)

Go et al., (2017) have shown the opportunities for thermionic converter. Thermionic Energy Conversion, or direct heat-to-electricity conversion, has a wide range of applications in space and on Earth. The creation of novel grid topologies to reduce the space charge effect has sparked researchers' interest in thermionic converter research. According to David et al., the best technique to build a nanostructure emitter is to manufacture nanotubes and nanowires. According to the findings, a thermionic converter can theoretically achieve Carnot efficiency. (Go et al., 2017)

Tsai and Lin (2010) published another paper that focuses on thermoelectric generator modelling. Formulae for thermal conduction, figure of merit, and output voltage are developed. The simulation revealed that a maximum power output of 19W could be achieved at 7.9A and 2.3V. The conversion efficiency of the thermoelectric convertor is around 4.5 percent. If used to recover waste heat in a hybrid electric vehicle, the conversion efficiency of this thermoelectric generator will be insufficient. (Tsai & Lin, 2010)

Because the thermoelectric generator's conversion efficiency is so poor, thermionic energy convertors (TEC) must be considered. Littau et al. (2013) explain how TEC is made up of thinly spaced plates. The thermionic emission of the cathode releases electrons, which go to the anode and produce a current, which generates electricity. Because currents above the related Child-Langmuir limit can occur at operating temperatures, simple structures are frequently space-charge limited. (Littau et al., 2013)

John Fairbanks (2013) in an article Automotive Thermoelectric Generators and HVAC have explained the research work on direct heat to electricity conversion devices installed in automotive vehicles. 9 projects on thermoelectric device development were funded by US in 2010-2013. Ford Lincoln MKT, BMW X6 & Chevy Suburban were presented with the thermoelectric regenerators. A cylindrical TEG is designed for installation in exhaust pipe. The GM TEG model have shown 10% conversion efficiency with $\Delta T=450K$, with max power output of 3 KW in simulation. The achieved conversion efficiency using thermoelectric device installed in vehicle is 5.7%. (Fairbanks, n.d.)

In a research paper, Fairchild et al. (2011) state that one of the challenges to thermionic energy conversion's acceptance has been its low efficiency of 10–15 percent. The efficiency of a heat engine working at 1200°C has a Carnot efficiency of 82 percent, according to theory. A thermionic convertor consists of two parallel plates, one of which (the cathode) is heated in order to thermionically transmit electrons to the other electrode via a small vacuum gap (the anode). The limiting component is the space-charge effect, which is the electric field formed by the liberated electrons. (Fairchild et al., 2011)

Belbachir, et al. (2014), have demonstrated a micro-gap of 10m between the emitter and collector electrodes allowed a thermionic generator to operate at a low temperature of 830^0 C. An 11.5 mW/cm2 output power density is attained. To improve the effectiveness of a thermionic generator, the inter-electrode spacing must be kept in microns, according to the findings of the above study. (Belbachir et al., 2014)

Yuan Wang, et.al. (2013), have developed mathematical expressions for specifying optimum design criteria for irreversible vacuum thermionic generator. There is a mentioned phenomenon of space charge as electron travel across the vacuum gap. It's a negative electrostatic charge that prevents more emission. For effective energy-conversion devices, overcoming the space-charge effect is a fundamental goal. Energy balancing equations are used to determine design criteria that improve conversion efficiency in the given model. This criteria includes lower work function materials with micro interelectrode gap & lower operating temperatures. (Wang et al., 2013)

Lo, et.al (2014) have done modelling of thermionic convertor to improve the performance. At 1500k emitter temperature, a 0.3V output voltage is recorded for a 2.2eV and 1.6eV work function emitter and collector. The analysis of numerical model is done by liner interpolation and plasma simulation program. The thermionic energy converter is modelled and simulated using finite-difference time domain particle-in-cell. The child’s law extension is used for verifying the accuracy of numerical model. The numerical model and simulation method is useful for understanding the space charge effect. (Lo et al., 2014)

Olawole,et al. (2016) have developed a three-dimensional model of graphene and carbon nanotube thermionic emission. The electron mass of graphene or carbon nanotube is reevaluated in light of its significance in the Fermi energy and Fermi velocity equations. A three-dimensional model is created based on these relationships and existing models to fit experimental thermionic emission data for graphene and carbon nanotubes. The determined work functions by the model are equivalent with the individual experimental results. (Olawole & De, 2016)

In their research, N. M. Cook and J. P. Edelen (2018) built a model employing warp code. Warp is a particle-in-cell (PIC) structure that simulates electron transport. An external circuit model is also used to establish a constant current value in steady state. Power formulas, external circuit effect, and steady - state condition four phase simulation are some of the modelling and simulation techniques used. Lui et al. (2004) reviewed thermionic energy converters. This report investigated the potential applications of TECs based on current research and technology. The recent works are done in modelling of thermionic energy conversion. (Cook et al., 2018) (Liu et al., 2008)

The modelling results indicate that space charge is a major restraint for TEC operation. Lee et al. (2012) established approaches to limit space charge in a research paper, such as neutralisation by introducing an easily ionic gas into to the vacuum space, or suppression besides trying to make the inter- electrode vacuum space extremely small, with optimised separation usually characterised by the wavelength of thermal radiation of the hot emitter (0.9–10 m). (J.-H. Lee et al., 2012)

The methods for maximising TEC efficiency have been presented in a research work by Moyzhes and Geballe, (2005) Meir et al (2013). In a more recent work from the Max Planck Institute for solid state thermionic emission research, Moyzhes and Geballe (2005) suggested an inter-electrode grid or circumferential ring to produce electric field and utilises a right angles magnetic flux to achieve helical or focused electron paths to reduce current loss to the grid electrode. A magnetic field is not required with the suggested inter-electrode grid design. According to Meir et al. (2013), the space-charge problem can be overcome by customising the converter's electrostatic current distribution such that the static charged particle space-charge clouds are converted into an output current. (Moyzhes & Geballe, 2005) (Meir et al., 2013)

Regan et al. (2012) developed an electrical polarisation of a thin film collector for the development of novel field-effect photovoltaic devices that could be used in TEC designs. The goal of these designs is to transfer electrons with as little power loss as possible. An accelerated pace electric field can be combined with a magnetic field to increase current or prevent power loss to any extra electrodes. (Regan et al., 2012)

Smith J. (2013), Littau. K, et al. (2013) discussed various approaches for reducing the space charge effect in order to improve thermionic conversion performance. Smith J. created a model to characterise the output characteristics of a TEC that employs a negative electron affinity collector. The results show that by massively reducing the collector barrier height, a device of reasonable size can achieve an output power of around 1 kW at 20% efficiency (0.1 m2 emission area). Littau, K., et al. (2013) demonstrated vacuum thermionic energy converters comprised of barium dispenser cathodes and thin film tungsten anodes separated by size-specific alumina microbeads, allowing for simple device fabrication and control of the inter-electrode gap. The experiment depicts a TEC design that employs a dual electrically charged grid to solve the space charge problem and improve efficiency. (Ryan Smith, 2013)

By combining magnetic and electrical fields, Ian Bickerton and Neil A. (2017) propose a method to reduce the space charge effect in thermionic devices. This setup employs three electrode layouts, with just a collector and emitter on same plane and a grid electrode just above them. This produces a perpendicular electric field, which when combined with a longitudinal magnetic field accelerates transfer of electrons from a hot emitter to a collector. As a result, the findings imply that a dual electric field can improve conversion efficiency by increasing electron transport speed. Whereas, Wanke et al., (2016) have proposed a magnetic field free thermionic conversion. Possibility of high conversion rate is explored from low mass graphene & similar 2 dimensional materials. From both research work it is understood that the thermionic energy converter design must satisfy the requirements of space charge reduction. (Bickerton & Fox, 2017) (Wanke et al., 2016)

Lee, J. H.et al. (2012) are developing a new solid-state energy conversion technology based on micro fabricated heterostructure semiconductor cathodes with appropriate band engineering and photon-enhanced thermionic energy converters (PETECs). Micro fabrication enables very small emitter and collector gaps (10–100 m), resulting in a significant reduction in the space-charge effect. PETECs are expected to increase total system efficiencies by more than 50%. However, a practical device has yet to be developed. Zavadil et al. (2004), on the other hand, developed and tested a microminiature thermionic converter (MTC) with inter-electrode spacings on the order of microns in a Sandia study. To obtain optimal performance, the research indicates that improved theoretical, modelling, and fabrication capabilities are necessary (J. H. Lee et al., 2012) (Zavadil et al., 2004)

Tianjun Liao created the prototype of a photon enhanced thermionic energy converter (2019). In this design, the two electrode materials are boron doped diamond and p-type silicon semiconductor covered negative electron affinity material. Traditional metal-based VTEC performs worse than silicon-based VTEC. So far, the addition of cesium and rare earth oxides has decreased the work function of thermionic metal emitters. This study suggests that low-work-function emitter and collector materials be used to improve TEC performance. (T. Liao, 2019)

Graphene work functions can be created, according to Olukunle C. Olawole and Dilip kumar De. (2018). The temperature dependent work function is used to calculate conversion efficiencies precisely. The solar TEC power equation is devised. The nanomaterials Richardson-Dushman equation will be modified and applied to the model. The modelling results reveal a 63 percent efficiency at emitter temperature of 3180 K. (Assuming no space charge effect). (Olawole & De, 2018)

According to Tiwari, A. et al., low electron affinity coatings reduce the material's work function, permitting emitters at lower temperatures (2014). As a result, it is an essential component of thermionic devices. This can also be achieved by enclosing a Cs or Ba source in a high vacuum that also evaporates at the operating temperature and coats the emitter. This increases the size, complexity, and cost of the device. (Tiwari et al., 2014)

Trucchi, D., and Melosh, N., (2017) discuss how signature 1D materials including such carbon nanotubes show lower electrical resistivity and significant field electron emission at low applied fields in a review. Many new advancements have been made in the development of emission-specific materials, with a focus not only on reducing work function but also on increasing emission through other processes. (Trucchi & Melosh, 2017b)

Chou et al. (2014) created graphene in a vacuum that can withstand high temperatures (4600 K). Graphene's work function is regulated and can be as low as 1 eV. Graphene has a high electronic conductivity due to the lack of flaws in its crystallography. Because of these properties, graphene is an excellent thermionic emission for use in a TEC. Because graphene's work function is modifiable, it can also be used as a collector with appropriate work function engineering. TEC with a graphene collector and emitter shows great promise for large-scale power generation. (Chou et al., n.d.)

Graphene:

Zabek and Morini (2019), reviewed direct energy conversion advances in techniques and materials. The comparison shows the power efficiency and electric energy output of different direct energy converters. Thermionic energy conversion has higher experimental efficiency of 14.7% with electrical output of maximum $10W/cm^2$. (Zabek & Morini, 2019)

In a report, King et al. (2001) discusses the modelling and fabrication procedures used to produce cathodes for thermoelectric conversion. At 900 K, electron emission begins in a tri-layered thin film made of tungsten and barium-strontium-calcium oxide (BaSrCaO). The structure has uniform 2.0 eV work function. Though the layer microstructure is complex and difficult for fabrication. Also the tungstate formation is a limitation observed. (King et al., 2001)

Zebarjadi (2017), has done analysis in nonlinear regime using analytical method for solid state thermionic energy conversion. The mathematical expressions are derived for optimum power and optimum efficiency conditions. The efficiency of solid state thermionic power producers can be higher than that of state-of-the-art thermoelectric modules. The research establishes an appropriate thermal and electrical resistance threshold for solid state thermionic converters, above or below which performance is unaffected (Zebarjadi, 2017)

Schwede and Hess (2019) developed a method and system for decreasing work function and thermionic energy conversion. For photo voltage-based work function regulation, anodes and cathodes have one or more semiconductor layers manufactured with 2D materials. The current emission out ranges from 0.1 A/cm^2 to 10 A/cm^2. This model describes the need for low work function materials and use of 2D structures to do so. (Schwede & Hess, 2019)

Trucchi and Melosh (2017), has discussed nanowires, nanotubes, graphene and electron emission models. The materials are specifically being studied for thermionic emission properties. The study also highlights that the innovation in low dimensional material is significant in electron emission. Thermionic emission studies are focused towards 2D materials such as graphene. (Trucchi & Melosh, 2017a)

Mishra et al., (2017), has done a mathematical modelling to evaluate thermionic flux from multilayer graphene. This is done by using analytical expression derived from Fermi Dirac law. The numerical expressions were developed for ABA and ABC stacking of graphene and simulated. The graphene based cathode at 900 K and cesium coated Ag/Pt have shown 55% conversion efficiency. (Mishra et al., 2017)

The performance of a graphene emitter for solar thermionic conversion was studied by Olawole et al., (2016). A graphene on silicon carbide model is created. The energy dynamics of solar thermos electronic power conversion are investigated in this paper. The work functions of graphene may be adjusted from 4.5 eV to 1.5 eV. For graphene structures the work function gets affected due to emitter temperature. (Olawole et al., 2016)

Coating materials:

Cesium;

Cesium is being studied since century for effective thermionic emission and conversion. Therefore it was necessary to study cesium as a part of thermionic energy conversion and their findings;

The behaviour of cesium oxide as a low work function coating was examined by Uebbing and James (1970). Cesium oxide was used to cover GaSb and n-type semiconductors, as well as silver. The coating is carried out in an ultrahigh vacuum atmosphere, with the surface exposed to Cesium vapour until the maximum photo yield is achieved. The work functions of silver and GaSb covered with cesium oxide were 1 eV and 1.04 eV, respectively, according to the experimental data. (Uebbing & James, 1970)

Huang et al. (2007) used thermally produced cesium carbonate nanolayers to create a low work function surface. Cesium carbonate is used to the cathodes of aluminium (Al) and gold (Au). The experimental results show that the few surface layers of aluminium get oxidized and forms Al–O–Cs structure, this reduces the metal work function to 2.1 eV. Similarly gold work function reduced to 3.4 eV. (Huang et al., 2007)

Koeck et al. (2009) had to use a relatively low work function phosphorus doped diamond coating to improve thermionic emission. They created phosphorus-doped polycrystalline diamond plates on metallic substrates using plasma aided chemical vapour deposition. According to the experiments, the coating reduced the work function to 0.9 eV and stabilised the thermionic emission current below 765^0C. (Koeck et al., 2009)

Sun et al. (2011) used nitrogen doped diamond sheets as a photon and thermionic emission material with a low work function. The thermionic emission current is detected at temperatures below 500^0C using molybdenum as the base metal. The work function on the surface was reduced to 1.5 eV. (Sun et al., 2011)

Naghdi and Sanchez-Arriaga (2019) tested a new method for making tethers with a low work function and loosely connected electrons. Graphene oxide doped with cesium was used to cover aluminium and copper. X-ray spectroscopy (EDS), Field Emission Scanning Electron Microscopy (FE-SEM), and ultraviolet photoelectron spectroscopy were used to obtain information about the coating (UPS). By doping graphene oxide (GO) with cesium (Cs), the work function can be reduced by 1.5 eV, from 4.6 eV to 3.09 eV. (Naghdi & Sanchez-Arriaga, 2019)

Machining;

The raw material for tungsten and molybdenum is available in cylindrical rod form. Therefore machining is needed as per the design requirement. It is difficult to machine tungsten and molybdenum by conventional turning or milling machines. The literature on advanced electro discharge machining is studied and mentioned below;

The state of the art in wire electrical discharge machining was described by Ho et al. (2004). (WEDM). WEDM is a fast and accurate machining method for exceptionally hard materials like tungsten and molybdenum. WEDM outperforms traditional machining in terms of precision and critical shape machining. (Ho et al., 2004)

Wire EDM for fine surface polishing was examined by Y. S. Liao et al., (2004). The study looks at how variables like ignition power and machining affect surface finish. With the help of taguchi quality design, the traditional circuit for low power ignition is adjusted. (Y. S. Liao et al., 2004)

Non-conventional electrochemical and electro discharge machining (EDM) methods were explored by Rajurkar et al., (2013). Advances in electro-discharge machining are also discussed, as well as the state of the art in these processes. These techniques can readily machine macro, micro, and complicated shape items. Wire EDM may create profiles in circular and non-circular holes drilled with EDM. (Rajurkar et al., 2013)

Exhaust system design

Xin and Qianfan (2013), in an article “Durability and reliability in diesel engine system design” discussed an idea about exhaust manifold design considerations. To express durability, discussions on system-level loading and durability design constraints are used. The hypothesis and assessment methods of durability in diesel engine system design are presented using a FEA methodology. On system durability and dependability, an integrated analytical technique is applied. According to the findings, exhaust pressure is a significant design parameter for manifolds that influences their durability. It is determined by the exhaust gas flow rate, exhaust manifold volume, and exhaust manifold cross sectional area. When it comes to engine durability, the engine delta P and exhaust pressure should not exceed the limit. These data will aid in determining the durability of a thermionic regeneration system that has been retrofitted to an exhaust system. (Xin, 2013a)

In a separate chapter titled "Diesel engine air system design," Xin and Qianfan (2013) gives a complete analysis process of the second law of thermodynamics for modern turbocharged EGR diesel engines. The air system design philosophy of a diesel engine is explained, along with engine cycle simulations. The exhaust manifold design analysis is performed using one-dimensional gas wave dynamics simulation software in conjunction with engine cycle simulation. The effect of exhaust pressure pulses on volumetric efficiency, Engine delta P, transient corrected turbine flow rate, and turbine efficiency is investigated. The difference between total peak of the exhaust pressure pulse and the allowed design limit reveals a link among pressure head and EGR driving capabilities. This article summarises the effects of the engine's intake and exhaust systems on its durability. The discussions are important to consider when developing system level models for engine exhaust. (Xin, 2013b)

Multiphysics applications in automotive engineering have been demonstrated by Q. Zhang and Cen (2016). The goal of the research is to perform a weak coupling fluid–solid–thermal analysis of an exhaust manifold. We built and simulated models for steady-state thermal fluid flow and steady-state thermal stress analysis. The velocity, pressure, temperature, and stress distributions within the exhaust manifold are depicted and described. The maximum gas flow velocity through the exhaust manifold is around 8 m/s. The fluid temperature varies dramatically near the coupling surface, with the average temperature at the entrance and outlet being very close. This is due to the short path and high flow velocity of the exhaust manifold. This study's design considerations can be applied to the development of a thermionic regeneration system. (Q. Zhang & Cen, 2016)

Based on engine cycle simulation, Kanazaki et al. (2003) created an exhaust for a car engine. At 1,500 rpm, the goal is to optimise the gas temperature at the exhaust pipe's tip, and at 6,000 rpm, the goal is to maximise charging efficiency, which indicates engine power. To analyse the three-dimensional manifold shapes, the unorganised, unstable Euler code is merged with the observational engine cycle simulation code. The Divided Range Multiobjective Genetic Algorithm (DRMOGA) was used to develop a multiobjective design optimization system for exhaust manifold morphologies for an automobile engine, with the goal of increasing engine power while minimising environmental impact. As a result, the variable pipe radius definition appears to be a significant design parameter for achieving both design goals. (Kanazaki et al., 2003)

Park et al. (2006) investigated the modelling work and layout of an exhaust manifold subjected to thermomechanical loading. In this paper, a thermal stress index is proposed as a practical implementation to the initial stages of exhaust manifold design. The thermal index can be used to predict the durability of the exhaust manifold (TSI). The TSI exhibits approximately quadratic behaviour in terms of pipe diameter and thickness. (Park et al., 2006)

Tong et al. (2014) demonstrated the interoperability of an automotive exhaust thermoelectric generation system (TEG), catalytic converter (CC), and muffler. TEG's position is altered in three different scenarios. In case 1, TEG is located at the end of the exhaust system; in case 2, it is located between the CC and the muffler; and in case 3, it is located upstream of the CC and the muffler. Thermal uniformity and pressure drop are compared using simulations and testing. Case 2's heat exchanger achieved a reasonably high surface temperature and perfect temperature uniformity to increase the TEG's efficiency. The pressure loss of the CC, muffler, and heat exchanger was relatively low, meeting the requirements of the exhaust gas system. In example 2, the CC and muffler can both function normally at the same time. As a result, case 2 is the best. (Tong et al., 2014)

Thermionic conversion improvement

X. Zhang et al. (2017) created a model for a graphene-based thermionic converter and an aluminum-32 gallium-48 arsenide-based thermoradiative cell in order to improve the conversion efficiency of a solar cell using a thermionic-thermoradiative approach and to create a model for a graphene-based thermionic converter and an aluminum-32 gallium-48 arsenide-based thermoradiative cell. Electron and photon fluxes are used in tandem to efficiently convert solar radiation to electricity. In mathematical modelling, energy equations are used. The model takes into account thermal coupling between absorbers, the space-charge effect, non-radiative recombination, and numerous irreversible energy losses. The results show a solar-to-electricity efficiency of 22.5 percent. Temperatures for the cathode were 2687 K and the anode was 803 K. The thermionic converter's voltage output is 1.88V. The absorber is supposed to have a constant temperature TC, however in practise, temperature fluctuates for solar. The effect of emitter temperature on voltage output has not been investigated. The interelectrode gap is not taken into account in the equation. (X. Zhang et al., 2017)

By deriving mathematical formulas for power output density and efficiency, X. Zhang, Ang, Du, Chen, & Ang (2017) constructed a graphene-based thermionic energy converter. Numerical calculations are done using energy balance equations and the Richardson equation is modified for graphene. Max efficiency of 30% and power density of 0.575 Wcm^2 at emitter 1500 K and collector 300 K. Study is limited to numerical analysis. Graphene layer is not described and coating thickness effects are not considered. Vacuum gap consideration is just as Nano scale, not specific.(“Parametric Optimum Design of a Graphene-Based Thermionic Energy Converter,” 2017)

Jensen et al. (2019) used thorough charge and thermal transport modelling to develop submicron-gap thermionic power generation. The goal is to develop a theoretical model for sub - micron thermionic power generation and to conduct an energy balance study for thermionic power generation. Energy balance analysis is done by charge transport process using current density equations. Methodology used is numerical study based on Nano scale charge and thermal transport. The optimum energy conversion efficiency is around 25-30% when the device is functioned at 1575 K with a vacuum gap range of 300 nm to 1 m. The fabrication methods and complexity are not explored, and no experimentation is carried out. (Jensen et al., 2019)

Heat transfer modeling for engines

Spitsov (2013) developed a model for internal combustion engine heat transport and compared it to experimental data. A one dimensional single zone model is implemented in MATLAB to simulate and obtain heat flux at different locations of engine block. Whereas, the heat flux is physically measured by means of Gradient Heat Flux Sensors. Maximum heat flux of 160 KW/m^2 was obtained varying in range of 40-160 KW/m^2 with crank angle.(Spitsov, 2013)

Yuan et al.(2020) investigated transient thermal processes in a vehicle's under-bonnet region throughout natural soak conditions using computer-aided engineering (CAE). In this study, a merged transient 3D computational fluids dynamics (CFD) – heat transfer modelling approach in a passenger car was investigated. Flow fields are modelled using the Lattice-Boltzmann method. To solve the thermal modelling, PowerTHERM®, a heat exchange algorithm iterates that predicts surface temperatures and heat fluxes caused by thermal radiation, conduction, and convection, was used. (Yuan et al., 2020)

Graphene Coating

Piao et al. (2019) improved this same dynamic response of twisted and coiled soft actuators using graphene coating (TCA). The study demonstrates 3 separate strategies for coating graphene layer on the surface of TCA. Low-pressure chemical vapour deposition was used to make large-area monolayer graphene, whereas atmospheric pressure chemical vapour deposition was used to make graphene foam, and sonication was used to exfoliate graphite nanoplatelets to make graphene flakes. To coat nylon TCA surfaces, graphene materials with high heat conductivity thermal mass were used. The TCA's dynamic reactions were improved, resulting in a 30.9 percent reduction in cycle time. These basic coating processes can boost dynamic performance. (Piao et al., 2019)

Pham et al. (2010) indicated that spray-coating can be used to quickly and easily create a large transparent chemically-converted graphene layer. Sonication is used to create a dispersion of graphene oxide (GO) and hydrazine monohydrate. The GO–hydrazine fraction was spritzed onto a 2 * 2 cm2 preheated quartz substrate using an airbrush device and N2 as a carrier gas. Chemically converted graphene on metal surfaces can be successfully synthesised using this process. (Pham et al., 2010)

Different coating processes for graphene-based materials and composites were reviewed by Yao tong et al. (2013). Mechanical emulsification, decrease from graphene oxide, and chemical vapour deposition are promising methods for producing graphene (CVD). Graphene reduction from graphene oxide has been widely used to investigate the usage of graphene-based materials in a variety of applications. The coating methods used by researchers for synthesising graphene surfaces include chemical vapour deposition, dip coating, spin coating, layer by layer self-assembling, sol-gel approach, direct apply and curing, spray drying, spray coating, in-situ polymerization coating, and electrophoretic deposition. (Yao Tong et al., n.d.)

Fu et al. (2019) examined the production processes, accuracies, and problems associated with several characterisation approaches in graphene-related materials for heat management. Heat spreaders made of graphene, fibres, laminates, 3D structures, and nanofluids are all being researched and produced. Molecular Dynamics is used to model graphene thermal transfer. It is a force-field-based classical description of atomic motion. Liquid phase exfoliation (LPE) and chemical vapour deposition (CVD) are two processes for preparing graphene surfaces that are gaining popularity. (Fu et al., 2019)

HEV Modelling on MATLAB

Janevska et al. (2019) provided a multi-physics approach hybrid electric vehicle model. Using system level models, a series-parallel hybrid electric vehicle model is created. The simulation is run using the input of a step function for vehicle speed. The step reaction is explored for several scenarios of vehicle acceleration and deceleration. The systems are integrated into the whole vehicle model, and the vehicle's performance is simulated and analysed. System level modelling is used to represent a hybrid electric vehicle at full scale. (Janevska et al., 2019)

A parallel HEV model was built using ADVISOR (a MATLAB/ Simulink based software) by Mohammadi et al. (2019). Technical aspects are investigated in order to minimise mechanical and electrical power losses while also maximising energy absorption from the braking system. The simulation findings aid in identifying crucial areas that need to be changed in order to increase overall efficiency. (Mohammadi et al., 2019)

Ahmed et al. (2020) demonstrated a waste heat recovery system based on thermoelectric generating for hybrid electric vehicles. The goal is to create a TEG array model for a Hybrid Electric Vehicle (HEV) system using MATLAB. To investigate the system performance, simulations are run using the MATLAB/Simulink software suite.

Modeling the TEG module using math equations and implementing the module in a HEV system are part of the methodology. At 300^0 C, the voltage and current outputs are 11.4 V and 19 A, respectively. The paper does not go through the design specifications. TEG's cold side temperature is also used as the ambient temperature. (Ahmed et al., 2020)

Bellucci et al., (2020) created photovoltaic anodes to improve thermionic energy conversion. The goal was to demonstrate a hybrid thermionic-photovoltaic device in an experimental setting. Both electrons and photons released by the cathode are used in thermionic conversion. Thermionic electrons have been implanted into the valence band of a gallium arsenide semiconducting anode, photovoltaically pumped to the conduction band, and then extracted from the conduction band to provide usable energy before being injected back into the cathode. Optimized near-field TIPV products have the ability to accomplish thermal-to-electric conversion efficiencies of more than 30% and power densities of more than 100 W/cm2 (at 2000 K). (Bellucci et al., 2020)

Deheeger et al., (2009) investigated heat stresses in a bonded joint experimentally. The goal is to determine the distribution of heat stress in a composite/aluminum bonded joint. An infrared camera and a CCD camera are used to measure the temperature and displacement fields of an aluminium specimen that has been symmetrically reinforced with two composite patches. The grid approach is used to obtain the displacement fields in the composite patch. Finally, the shear stress high point in the sealant along the patch's free edge is computed. (Deheeger et al., 2009)

Serpente et al. (2020) used ultra-thin barium fluoride films with low work function to explore the impact of film structural rigidity and chemical properties on the work function of the eventually results heterostructure in thermionic-thermo photovoltaic applications. Electron beam evaporation was used to deposit thin and ultra-thin barium fluoride films on gallium arsenide substrates. The work function falls to 2.1 eV for a layer thickness of 2.0 nm. A test thermionic converter operating at 1385 °C cathode temperature confirms a significant reduction in the work function to at least 3.0 eV. (Serpente et al., 2020)

Borges et al., (2019) tested an indirectly heated cathode ion source at different temperatures for thermionic emission. Comparison of temperature and thermionic emission measurements for cathode ion sources. Reduction in thermal losses are achieved by introducing thermal barrier in Cathode design. The thermal barrier is made up of a number of closely spaced concentric foils. The new universal cathode had a better temperature profile on the cathode surface, increasing the surface temperature by (100°C) and lowering thermionic emission by 25%. (Borges et al., 2019)

O. C. Olawole et al. (2020) assessed the current state of solar energy thermionic conversion. TEC is mainly concerned with two scientific issues: low-work-function electrode materials capable of withstanding high temperatures, and a space-charge obstruction that reduces current density, power output, and efficiency. The maximum theoretical conversion efficiency is claimed to be 55%. The maximum experimental conversion efficiency for TEC and hybrid TEC was found to be 15.1 percent and 30 percent, respectively. (O. C.Olawole et al., 2020)

For solar energy conversion, De et al. (2019) presented a greatly improved Thermionic Energy Converter. The methodology employs modelling and simulation of conversion efficiency as a function of collector and emitter temperatures. To maintain the temperature differential, controlled heat extraction from collector systems have been established. The values of the work functions of the emitter and collector should be as low as feasible while the difference is more than 0.5 eV for high efficiency thermionic power conversion. (De et al., 2019)

De and Olawole (2019) provided a three-dimensional model for graphene and carbon nanotube thermionic emission. Firstly 2D models are considered and then a 3D model is developed. The Modifying Richardson Dushman Equation (MRDE) is used for temperature dependent Work function of CNT and graphene. The mathematical model is then simulated for current density and work function. A 3D model gives more accurate results in comparison with existing 1D and 2D models. MRDE considers the varying work function with temperature giving better results. The model is expected to aid in the correct simulation of thermionic energy converter performance. (De & Olawole, 2019)

Szanto and Sziki (2020) looked at current car powertrains using MATLAB/Simulink modelling and simulation. Electric motors, hybrid drives/ powertrains, batteries, fuel cells, and IC engines are all explained using mathematical models. This study examines MATLAB-based hybrid and electric car systems and models. As a result, it will be easier to create new models and simulation programmes that will aid in doing system-level simulations and comparing the performance, dynamic, and energetic properties of this system and vehicle components. (Szántó & Szíki, 2020)

Panagiotidis et al., (2000) built a regenerative braking model for parallel hybrid vehicles using ADVISOR, a MATLAB/SIMULINK-based simulation. ADVISOR allows you to quickly compare the performance, emissions, and fuel efficiency of conventional, electric, and hybrid vehicles. ADVISOR's component models are empirical, based on lab-evaluated input/output relationships, and quasi-static, based on data acquired in steady-state tests and corrected for transient factors such as drivetrain component rotational inertia. When it comes to modifying several of the models, ADVISOR gives the designer a lot of leeway. In the Federal Urban Driving Schedule (FUDS) cycle, regenerative braking improves fuel economy by 4 percent to 19 percent. (Panagiotidis et al., 2000)

Berjoza et al. (2020) especially in comparison the fuel usage of a hybrid vehicle to that of a conventional vehicle. The primary objective was always to make comparisons the performance and energy usage of an electric hybrid car as well as its conventional internal combustion Engine in a laboratory setting. The IM-240 Cycle and Jelgava Cycle were used to test the chassis roller dynamometer for conventional and HEV vehicles. The results suggest that the Toyota Yaris Hybrid is better suited to urban driving, with a 21.3 percent lower fuel usage than the Toyota Yaris conventional gasoline vehicle, with 7.29L and 8.84 L per 100 km, respectively. (Berjoza et al., 2020)

Datas and Vaillon (2019) pioneered thermoionic-enhanced near-field thermophotovoltaics. The concurrently emission of photoelectrons via nanoscale vacuum gaps is used to model a device. Particle trajectories are subjected to the Langmuir theory. The emitter is made of tungsten coated with a thin (10 nm) layer of LaB6, while the collector is made of a very thin (1-3 nm) layer of BaF2. It is calculated the total net flow of photons and electrons through the vacuum gap between the emitter and the detector. Efficiencies and electrical energy densities of 30% and 70 W/cm2 are possible at 2000 K and a practical gap distance of 100 nm. (Datas & Vaillon, 2019)

Nojeh, (2019) explained fundamentals and recent progress in thermionic energy conversion enabled by nanotechnology. Space charge elimination, low interelectrode gap, low work function materials, negative electron affinity collectors are the significant approaches to achieve higher conversion efficiencies. With advanced Nano materials and methods the thermionic conversion efficiency up to 30 % can be achieved. (Nojeh, 2019)

This literature review firstly gives a brief idea about hybrid electric vehicles. The HEV has a potential electric demand as the electrical systems are more. Waste heat recovery methods are also studied. Understanding the higher conversion rate of a thermionic energy conversion, the literature showcasing materials, methods and design criteria for improving thermionic conversion are considered. Manufacturing methods are mentioned in the literature for specific thermionic materials. The studies on exhaust system design considerations and heat transfer analysis are highlighted. The significant methods for full vehicle simulation using MATLAB are also shown.

The thermionic energy conversion (TEC) technology has not yet been researched for specific automotive applications, according to this study. Thermionic regeneration systems come into play here by repurposing waste heat to charge the battery, thereby enhancing a vehicle's overall efficiency. It's difficult to design a gadget that works on the thermionic emission concept.

2.1 Research Problem

The comprehensive study on existing research work mentioned in earlier section have highlighted following statements as a research problem;

1. Potential for alternate source of energy for producing electric power in hybrid electric vehicles is more.
2. Existing regenerative systems used in HEV are less efficient.
3. The devices which are based on the principle of thermoelectric conversion for direct conversion of heat to electricity are less efficient.
4. Thermionic energy conversion is not yet considered for automotive applications.

2.2 Thesis Contribution

1. Design of a thermionic regenerator applying reverse engineering.
2. Development of a thermionic regeneration system (TRS)
3. Integration of the TRS with hybrid electric vehicle for improving fuel economy and drive range i.e. vehicle's overall efficiency.

2.3 Objectives of the Study

1. To study and evaluate the effectiveness of different thermionic and thermoelectric converters for regeneration of waste heat of an engine to electricity.
2. To design and develop a regeneration method for direct conversion of engine's waste heat to electricity in hybrid electric vehicle based on principle of thermionic conversion.
3. To conduct an experimental analysis for assessing conversion efficiency of thermionic conversion method for hybrid electric vehicles.