Journal of Energy Research and Environmental Technology (JERET)
p-ISSN: 2394-1561; e-ISSN: 2394-157X; Volume 3, Issue 1; January-March, 2016; pp. 38-41

http://www.krishisanskriti.org/Publication.html

Review of Power Generation from Exhaust Heat using Thermoelectric Generators and Heat Pipes

Deepak Monga[1] and Anuj Sharma[2]

[1,2]Dept. of Mechanical Engineering THE NORTHCAP University, Gurgaon
E-mail: [1]monga.d1189@gmail.com, [2]simple.anuj@gmail.com

Abstract—*The increasing environmental and energy issues have attracted the application of waste heat recovery techniques in the IC engines. Waste heat recovery system has a great potential to recover large amount of energy from exhaust gases which further contribute to the work output of engine. A significant increase in the efficiency of the engine can be achieved by proper recovery of ICE waste heat. Thermoelectric generators (TEGs) being one of the promising device for waste heat recovery, TEGs coupled with heat pipes have also brought the attention with in recent years. Both TEGs and heat pipe are solid state, passive, silent, scalable and durable. Heat pipes as one of the best devices for the heat recovery application has an extensive range of operating temperature and a high thermal conductivity. The use of heat pipes can potentially reduce the thermal resistance and pressure losses in the system as well as temperature regulation of the TEGs and increased design flexibility. In this study, the focus is to review the recent advancements on the waste heat recovery of the exhaust gases in internal combustion engines using thermoelectric generators (TEGs) and heat pipes. When used in conjunction, these technologies have the potential to create a completely solid state and passive waste heat recovery system. Further the study also presented the potential saving in the energy and performance of the technologies.*

Keywords*: Exhaust heat recovery; TEGs; Heat Pipes.*

1. INTRODUCTION

During combustion of fuel inside the IC engines produces high temperatures which can damage the engine block and its components. To achieve safe operating conditions, thermal management of internal combustion engines is required and it is essential to have a heat removal process. Only the 12-25% of the total energy generated by the fuel is converted into useful work, whereas rest of the fuel energy is discharged to the surrounding through exhaust gases, the cooling system and the intake air [1]. Exhaust gases carries most significant fraction of the waste heat discharged to the ambient which is accounted as the one third of the total energy generated from the fuel. The conversion of the fuel energy into useful work is limited by number of irreversible processes occurring in the engine cylinder. The rapid expansion of gases produces high temperature differences, turbulent fluid motions and large heat transfers from the fluid to the cylinder walls. These rapid successions occurring inside the engine cylinder leads to expansion of exhaust gases with pressure higher than atmospheric and large amount of heat is carried by the gases during their outflow from the exhaust manifold. The work output of the engine can be increased by recovering the waste heat from the engine exhaust [2,3]. The waste heat recovery system is significant for increasing the overall efficiency and to reduce the fuel consumption of the engine. Increased efficiency and lower fuel consumption by improving the fuel economy leads to the production of fewer emission from the exhaust which further leads to the reduction of greenhouse gas emissions.

2. THERMOELECTRIC ENERGY CONVERSION TECHNOLOGY

A waste heat recovery system has the potential to convert the waste heat into electrical energy and consequently reduce the fuel consumption of the vehicle. Thermoelectric energy conversion presents a promising technology which can use this waste heat [4,5]. For this system, thermoelectric generator is the outstanding device that can convert the heat energy into the electrical energy when a temperature difference is created across it and energy conversion efficiency of TEG is about 5% [5,6]. The efficiency is limited by the Carnot efficiency and operates at about 20%of the Carnot efficiency over a varying range of temperature [5]. The thermoelectric Fig. of merit (ZT) can be used to compare the efficiencies of different TEGs operating at same temperatures. Higher the ZT value, better the performance of TEG [7]. Thermoelectric generator works on the principle of ‘Seebeck effect’. A TEG is made up of many elements of N type and P type semiconductor material which are connected electrically in series but thermally in parallel as shown in Fig. 1.

A potential difference is generated when one side of TEG is maintained at higher temperature than the other side. The device offers the conversion of thermal energy into electric current in a simple and reliable way. The thermoelectric generators are used in recovery system as the device has no moving parts, little maintenance required due to wear and corrosion as no chemical reaction take place in the device. The key advantages of TEGs over other heat recovery technologies are because of their small size, scalability, durability and silent operation. Bismuth Telluride is most popular thermoelectric material in generators. The thermoelectric generators made of this material has limited use because their maximum hot side operating temperature is relatively low. To improve the power generation and efficiency of TEGs, Lead Telluride and Calcium Manganese have been used as materials due to their ability to handle high temperatures. More power can be produced by using Lead Telluride on hot side and Bismuth Telluride on cold side as compared to TEG made of Lead Telluride [7].

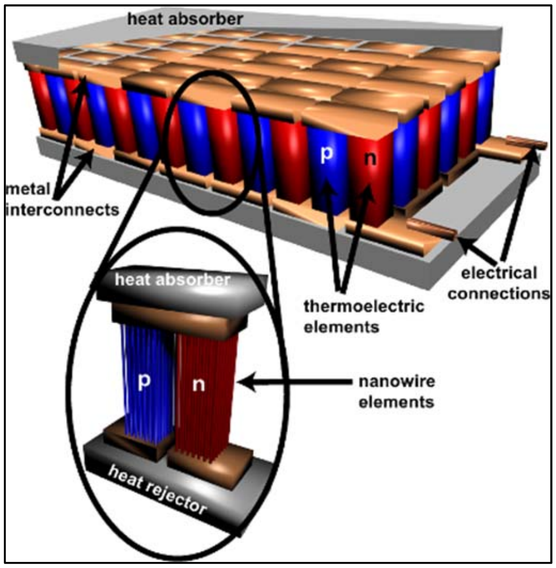

Fig. 1: Schematic of a thermoelectric device

Within recent years, thermoelectric generators coupled with heat pipes have been widely used to recover waste heat. Heat pipes are metallic pipes and very good conductor of heat are used to transfer heat at relatively long distances with minimum thermal resistance [8,9]. Heat pipe consists of an evaporator section, an adiabatic section and a condenser section. It is filled with the working fluid at vacuum pressure and sealed at both ends. Water is generally used as working medium but other fluids can be used for different operating temperatures [10]. Fig. 2 shows the cross-sectional view of heat pipe and the phenomenon of heat transfer by the transportation of working fluid.

Variable conductance heat pipes can also be used to vary TEG temperatures. The heat pipes used in conjunction with thermoelectric generators offers more flexible designs as heat pipes are solid state and passive heat transfer devices. Both thermoelectric generator and heat pipes have very promising attributes for their use in exhaust heat recovery systems to recover the heat of exhaust gases that can be utilize to generate power and to increase the engine performance.

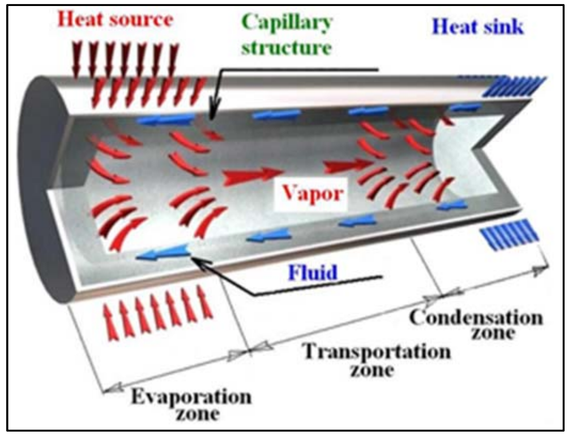

Fig. 2: Working of a heat pipe

3. LITERATURE REVIEW

Remeli et al. [11, 12] developed a theoretical model to study the electrical performance of thermoelectric generators using waste heat from the exhaust gases. A cogeneration system consisting of heat pipes and thermoelectric generators (HP-TEG) incorporates a TEG which was sandwiched between two finned heat pipes to develop a temperature gradient across the TEG for power generation. The experimental results showed that 8 rows of TEG modules can generate 10.39 W of power by recovering 1.35 kW of heat energy. Thermal and electrical characteristics of TEG were studied which were further used in mathematical model to predict the optimum settings of full scale HP-TEG system. Further experiments were conducted to study the effect of air face velocity on the heat transfer rate of HP-TEG system. The effectiveness of the system increases from 35% to 41% when the air face velocity was reduced to its minimum value as a result the power output of system increases. The mathematical model and the HP-TEG system proposed can be efficiently employed for recovering the waste heat energy.

Yu et al. [13] presented a numerical model and studied the behaviour of thermoelectric generator under different start up modes and the influence of these operating modes on the performance of TEG. The analysis was carried for various start up modes viz constant current, constant voltage, maximum power and constant power with lower and higher currents. The analysis showed that the current is the key factor for calculation of heat flow and power generation in different modes of start-up. The TEG performance was significantly affected by vehicle speed as compared to the ambient temperature.

Orr et al. [14-16] employed heat pipe and thermoelectric generator to recover heat from the exhaust gases and the heat was utilised to generate electricity. The system consisted of 8 thermoelectric cells and 6.03 W of power was generated leading to electricity conversion efficiency of 1.43% which is 1/15 of the Carnot efficiency. Further investigations were conducted to develop the design of the system to handle higher exhaust temperatures. To increase the capability of the heat pipes thick walled copper pipes were used and higher temperature rated TEGs were employed. To prevent the heat pipes from overheating, a Naphthalene heat pipe pre exchanger was proposed. Naphthalene heat pipes have a working temperature range between 250 °C to 450 °C which works when the exhaust gases have temperature between the mentioned temperature ranges.

Niu et al. and Bai et al. conducted the numerical analysis of exhaust system of internal combustion engine for recovery of waste heat using thermoelectric generators. The study was made to investigate the effect of bafflers on heat transfer rate and pressure drop along the channel and on the performance of TEGs. Niu et al. [17] investigated that larger baffle angle increases the pressure drop and to improve the performance baffle angle should be adjusted according to different engine operating conditions. Bai et al. [18] carried out simulations for 6 exhaust heat exchangers taking different plate structures viz. The results showed that CFD models with solid, liquid and fluid domain were developed to simulate the temperature field, velocity field and to investigate the maximum heat transfer rate for all structures with pressure drop along the flow.

Du et al. [19] analysed the effect of coolant, flow arrangement, flow rate and bafflers location on the performance of thermoelectric generator coupled with exhaust. The results showed that for high power output, liquid cooling with low flow velocity can be used than air cooling. The performance of TEGs can be further enhanced by bafflers in front of a TEG module which guide the cooling medium and develop sufficient temperature difference. Air cooling can be significant when cooling air flow is free to use but using air cooling with bafflers leads to power losses.

Rahman et al. [20] developed a harvesting system for waste heat recovery using Micro-Facet emission gas recirculation (MiF-EGR) integrated with thermoelectric generators. MiF-EGR, a fuzzy intelligent control system was used to control the intake temperature. A temperature of 70 C was kept by flow of exhaust gases to engine cylinder which increases the volumetric efficiency. TEGs were used to generate electrical power which reduces the alternator load by conversion of heat energy into electrical energy. The investigated results showed that by using MiF-EGR coupled with thermoelectric generator leads to reduction of engine emission, less fuel consumption and enhanced brake power. The developed system was able to recover 15% of the waste heat energy and 200 W of power was developed with 20% of alternator output.

Liang et al. [21] implemented the concept of thermoelectric generator for exhaust heat recovery of internal combustion engines. Two stage thermoelectric model was developed and the performance comparison was made with single stage thermoelectric generator. The results showed that the power output and conversion efficiency of two-stage TEG was higher than single-stage TEG for a heat source when source temperature varies from 600 K to 800 K. The heat transfer coefficient of the two sides have a significant effect on performance of TEG when working under a certain value of heat transfer coefficient. In two stage TEG, ratio of pairs of thermocouples at the top and bottom stage showed a significant effect. For peak power output ratio should vary between 0.8 and 0.9.

Kim et al. [22] has designed and investigated a thermoelectric power generation system with heat pipes for waste heat recovery of an exhaust system. Heat pipe which act as highly efficient heat transfer device and provide a large heating area were used to increase the performance of TEGs. The designed HPTEG system generated a maximum of 350 W using 112 TEGs.

Baatar and Kim [23] presented a low temperature thermoelectric power generation system for a vehicle. The proposed system uses the waste heat carried by engine coolant and has air cooling structure composed of heat pipes and heat sink. The system composed of 72 Bi_2Te_3 thermoelectric modules (4.0 mm x 4.0 mm) were mounted on a test engine of about 2 litres and experiment was performed under idle and driving conditions of the vehicle. The results showed that maximum power output generated by the system was 75 W with overall conversion efficiency of 0.4% in driving mode of 80 km/h.

Brito et al., Martins et al., Gonclaves et al. [24-27] designed a waste heat recovery system which uses heat pipe to recover heat from the exhaust gases and acts as heat source to hot side of thermoelectric modules and on the other side for cooling effect water sink was used. For steady operating temperature, a variable conductance heat pipe was used instead of a standard heat pipe. A VCHP assisted thermos electric module for power generation contains non condensable gases inside the pipe. The investigation presented the potential use of heat pipes as an efficient device for transferring heat from hot exhaust gases to TEGs. The operating temperature of the heat pipe was kept steady because TEGs can fail when operated over their rated maximum temperature.

Jang et al. [28] presented an alternative exhaust heat recovery design using heat pipes and TEGs. The system composed of loop thermosiphons instead of traditional heat pipes.

4. CONCLUSION

The presented study shows that the waste heat recovery system has a great potential to recover low grade energy from the exhaust gases of the internal combustion engines which can be used for generating electrical work and to contribute in work output of the IC engine. There are numerous waste heat recovery technologies. The conclusion can be made that the thermoelectric generator is a promising energy conversion device for harvesting waste heat. TEG has a relatively low conversion efficiency and to maximize the energy conversion efficiency, TEG can be incorporated with heat pipe. Further, more power would be produced by using material with high ZT at higher temperatures on hot side and a material with high ZT at low temperatures on cold side. The HP-TEG (heat pipe thermoelectric generator) technology has advantages over TEG system because heat pipes can reduce the thermal resistance between the TEG and exhaust gases. Heat pipes can regulate the temperature of TEGs and can also reduce the pressure losses in the gas stream due to reduced fin surface area. The use of heat pipes allows more flexible design. A completely passive and solid state exhaust recovery system can be developed using both TEGs and heat pipes and a significant increase in efficiency of the engine can be achieved.

REFERENCES

[1] Heywood, J. B., *Internal Combustion Engine Fundamentals*, McGraw Hill; 1988.

[2] Saidur, R., Rezai, M., Muzammil, W. K., Hassan M. H., Paria, S., and Hasanuzzaman, “Technologies to recover exhaust heat from internal combustion engines”, *Renewable and Sustainable Energy Reviews*, 16, August 2012, pp. 5649-5659.

[3] Stobart, R. K., “An availability approach to thermal energy recovery in vehicles”, *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 221, 2007.

[4] Law, R., Harvey, A., and Reay, D., “Opportunities for low-grade heat recovery in the UK food processing industry”, Applied Thermal Engineering, 53, 2012, pp. 188-196.

[5] Karri, M. A., Thacher, E. F., and Helenbrook, B. T., “Exhaust energy conversion by thermoelectric generator: Two case studies”, *Energy Conversion and Management*, 52, 2011, pp. 1596-1611.

[6] Kim, S., Park, S., Kim, S., and Rhi, S. H., “A thermoelectric generator using engine coolant for light-duty internal combustion engine-powered vehicles”, *Journal of Electronic Materials*, 40, 2011, pp. 812-816.

[7] Goldsmid, H., “Bismuth Telluride and its alloys as materials for thermoelectric generation”, Materials, 7, 2014, pp. 2577-2592.

[8] Incropera, F. P., *Introduction to heat transfer*, 3rd ed. International, United states, McGraw hill: 1996.

[9] Cengel, Y. A., *Heat Transfer: a practical approach*, 2nd ed. McGraw hill, Series in Mechanical Engineeering: 2006.

[10] Yang, X., Yan, Y. Y., and Mullen, D., “Recent developments of lightweight, high performance heat pipes”, *Applied Thermal Engineering*, 33, 2012, pp. 1-14.

[11] Remeli, F. Z., Lippong Tan, L., Date, A., Singh, B., and Akbarzadeh, A., “Simultaneous power generation and heat recovery using a heat pipe assisted thermoelectric generator system”, *Energy Conversion and Management*, 91, 2015, pp. 110-119.

[12] Remeli, F. Z., Date, A., Orr, B., Ding, C. L., Singh, B., Affandi, N. D. N., and Akbarzadeh, A., “Experimental investigation of combined heat recovery and power generation using a heat pipe assisted thermoelectric generator system”, *Energy Conversion and Management*, 111, 2016, pp. 147-157.

[13] Yu, S., Du, Q., Diao, H., Shu, G., and Jiao, K., “Start-up modes of thermoelectric generator based on vehicle exhaust waste heat recovery”, *Applied Energy*, 138, 2015, pp. 276-290.

[14] Orr, B., Singh, B., Tan, L., and Akbarzadeh, A., “Electricity generation from exhaust heat recovery system utilising thermoelectric cells and heat pipes”, *Applied Thermal Engineering*, 73, July 2014, pp. 588-597.

[15] Orr, B., Akbarzadeh, A., and Lappas, P., “Predicting the performance of a car exhaust heat recovery system that utilises thermoelectric generators and heat pipes, in *SOLAR*, Melbourne, Australia, 2014.

[16] Orr, B., Akbarzadeh, A., and Lappas,P., “Reducing Automobile Co_2 Emissions with an Exhaust Heat Recovery System Utilising Thermoelectric Generators and Heat Pipes”, presented at *APAC18*, Melbourne, Australia, 2015.

[17] Niu, Z., Diao, H., Yu, S., Jio, K., Du, Q., and Shu, G., “Investigation and design optimization of exhaust-based thermoelectric generator system for internal combustion engine”, *Energy Conversion and Management*, 85, June 2014, pp. 85-101.

[18] Bai, S., Lu, H., Wu, T., Yin, X., Shi, X., and Chen, L., “Numerical and experimental analysis for exhaust heat exchangers in automobile thermoelectric generators”, *Case Studies in Thermal Engineering*, 4, July 2014, pp. 99-112.

[19] Du, Q., Diao, H., Niu, Z., Zhang, G., Shu, G., and Jiao, K., “Effect of cooling design on the characteristics and performance of thermoelectric generator used for internal combustion engine”, *Energy Conversion and Management*, 101, May 2015, pp. 9-18.

[20] Rahman, A., Razzak, F., Afroz, R., AKM, M., and Hawlader, M., “Power generation from waste of IC engine”, *Renewable and Sustainable Energy Reviews*, 51, June 2015, pp. 382-395.

[21] Liang, X., Sun, X., Tian, H., Shu, G., Wang, Y., and Wang, X., “Comparison and parameter optimization of a two-stage thermoelectric generator using high temperature exhaust of internal combustion engine”, *Applied Energy*, 130, June 2014, pp. 190-199.

[22] Kim, S., Won, B., Rhi, S., Kim, S., Yoo, J., and Jang, J., “Thermoelectric Power Generation System for Future Hybrid Vehicles using hot exhaust gas”, *Journal of Electronic Materials*, 40, 5, March 2011.

[23] Baatar, N., and Kim, S., “A thermoelectric generator replacing radiator for internal combustion vehicles”, *TELKOMNIKA*, 9, 3, December 2011, pp. 523-530.

[24] Brito, F. P., Martins, J., Hancer, E., Antunes, N., and Gonclaves, L. M., “Thermoelectric exhaust heat recovery with heat-pipe based thermal control”, *Journal of Electronics Material*, 44, 6, February 2015, pp. 1984-1997.

[25] Brito, F. P., Gonclaves, L. M., Martins, J., Antunes, N., and Sousa, D., “Influence of heat pipe operating temperature on exhaust heat thermoelectric generation”, *SAE Int. J. Passeng. Cars-Mech*, 6, 2, 2013, pp. 652-664.

[26] Martins, J., Gonclaves, L. M., Antunes, J., and Brito, F. P., “Thermoelectric exhaust energy recovery with temperature control through heat pipes”, *SAE Int*., 2011.

[27] Goncalves, L. M., Martins, J., Antunes, J., Rocha, R., and Brito, F.P., “Heat-pipe assisted thermoelectric generators for exhaust gas applications”, *ASME 2010 International Mechanical Engineering Congress & Exposition*, 2010, pp. 1387-1396.

[28] Jang, J. C., Chi, R. G., Rhi, S. H., Lee, K. B., Hwang, H. C., and Lee, J. S., “ Heat pipe assisted thermoelectric power generation technology for waste heat recovery”, *Journal of Electronic Materials*, 44, 6, June 2015, pp. 2039-2047.