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THEORY AND DESIGN OF THERMOELECTRIC GENERATORS USING WASTE HEAT ON VEHICLES

The paper presents the results of the analysis of theoretical works concerning the use of thermoelectric generators for vehicles in order to obtain additional electricity and, accordingly, fuel saving. The trends and current state of development of such generators are considered. Bibl. 21.

Key words: thermoelectric generator, internal combustion engine, heat recovery.

Introduction

General characterization of the problem. The use of thermoelectric generators (TEGs) for heat recovery of internal combustion engines to generate electricity over the past three decades remains a subject of increased interest from the automotive industry and specialists in thermoelectricity.

The purpose of the work is to analyze the existing achievements in the design and construction of thermoelectric generators for vehicles and to determine the prospects in the development and design of such generators.

Basic theories of TEG design for vehicles

The number of publications containing information on the theory of design and optimization of thermoelectric generators for vehicles is a small part of the total number of works on thermoelectric generators for vehicles. Below are the main results of theoretical research.

U.S. Department of Energy's National Renewable Energy Laboratory [1, 2]

A study by Hendricks and Lustbader for different classes of trucks. Model assumptions: one-dimensional TEG model is considered; temperature of hot exhaust gases is 700 °C. An attempt is made to optimize the components of the system by taking into account the contact thermal and electrical resistances in the TEG elements. The unit cost of the heat generator depending on its electric power is analyzed. It is shown that it decreases with increasing TEG output power due to the reduction of the unit cost of the heat removal system and in the considered model it tends to the value of $ 10/W.

A.A. Baikov Institute, Russia [3]

A number of theoretical works have been carried out, where the reasons for the inefficiency of a thermoelectric generator (TEG) for an internal combustion engine are analyzed. The conflict of the "engine-TEG" system is considered. Conclusions are made about the zero efficiency of the TEG, in particular, due to the presence of additional back pressure in the system, additional mass and the need for an additional cooling system of TEG. In the model under consideration, the economic efficiency of the TEG is zero due to a decrease in the efficiency of the engine during the installation of the TEG.

Chalmers University of Technology, Sweden [4]

A computer three-dimensional non-stationary model of a thermoelectric generator for a diesel engine is considered. The model calculates in detail the exhaust gas flows in the generator and the heat carrier flows. It is proposed to use this model to optimize the design of heat exchangers, select the optimal thermoelectric materials and determine the impact of the generator on the engine. In this paper, no conclusions are made about the economic efficiency of TEG.

Department of Mechanical Engineering, Stevens Institute of Technology, Hoboken, NJ, USA [5]

The purpose of the work was to determine the influence of the following parameters on the efficiency of TEG: the length of thermoelement legs, the size of heat carrier channels, the ratio of electrical conductivity and thermal conductivity of materials; the Reynolds, Nusselt and Prandtl numbers *Re*, *Nu*, *Pr*; the dimensionless thermoelectric figure of merit of thermoelement materials *ZT*.

Theoretical approximations used. The model is one-dimensional. Heat fluxes along the direction of heat carriers motion were not taken into account, the physical properties of the materials were assumed to be independent of temperature. Heat losses in structural elements, in connections, on transitional thermal resistances were not taken into account. Losses in electrical connections were also disregarded. The mass flow rate of both heat carriers was assumed to be equal.

The model was not confirmed, as it gave a discrepancy between theoretical calculations and experimental measurements by 40-50%.

North China Electric Power University, China [6]

The multi-parameter model includes hot and cold heat exchangers and thermoelectric modules. In fact, the source of heat of exhaust gases and water cooling of the radiator are modeled. Emphasis is placed on the non-uniformity of temperature differences on thermoelectric units along the gas flow.

Conclusions are made about the possibility of reducing the volume of thermoelectric material when optimizing the design of TEG.

Due to significant assumptions and simplifications, the results obtained are not very suitable for the design of generators. The model does not make it possible to draw conclusions about the economic feasibility of the generator.

Department of Mechanical Engineering, University of Maryland, College Park, USA [7]

In the work of Crane and Jackson, the TEG scheme with perpendicular directions of heat carrier flows in the hot air and cold liquid circuits of the heat exchanger is considered. The fluid circuit uses the fluid of the car's engine cooling system.

The purpose of the work was the simultaneous optimization of the geometry of the heat exchanger and thermoelectric modules. The optimization procedure included: theoretical modeling based on well-known theories of convective heat transfer and thermoelectric energy conversion; numerical analysis, experimental verification and final optimization at the level of the whole system at the cost of a unit of electric power.

The following assumptions are used. The planes in the middle of the partitions between adjacent channels are adiabatic boundaries for heat flows. This allowed the analysis of the entire heat exchanger based on the consideration of one channel. Thomson's heat, as in the Betancourt model, is assumed to be negligibly small. The physical properties of materials are temperature independent. Only convective heat exchange of heat carriers with the heat exchanger was taken into account. The energy balance of the TEG takes into account the power of the fan, air circuit and liquid pump. It was assumed that Bi_2Te_3 material was used in thermoelectric modules.

The main results of the work. The one-dimensional Betancourt model generalized to the case of non-parallel heat carrier flows. The possibility of obtaining a specific power of 40 W / liter of hot water and a maximum cost of 1.1 kW / $ 10000 is demonstrated.

Clarkson University, Potsdam, NY, USA [8].

Karri developed and researched a TEG model that uses the heat of the exhaust gas. The model is based on the use of Hi-Z 20 modules. Hot heat carrier - exhaust gases, cold - water from the car's radiator circuit.

Mathematically, the model is described by a system of four nonlinear equations solved by computer means. The obtained results are quite accurate, but do not provide information on the optimization of TEG. Simulation is reduced to obtaining values that can be more accurately found experimentally. The model does not yield results of economic efficiency of the generator.

Department of Mechanical Engineering Rochester Institute of Technology Rochester, NY, USA [9]

The Betancourt, Karri, Crane and Jackson models were used and refined in Smith's work.

Smith analyzed a more complex sectional TEG circuit. The hot heat carrier flow creates temperature differences in thermoelectric modules of three sections. The model assumes that each section has a different number of modules. Such sectional TEGs have been investigated with Hi-Z and Melcor modules by computer simulation and optimization.

32 combinations of the number of sections (from 1 to 3) and the number of modules in the section are considered. The temperature dependences of the module parameters given by the empirical linear functions of the average module temperature were taken into account.

The simulation results were tested experimentally on a TEG model.

The experiments differed from the results of computer simulations by 30-40%, which reduces the value of such simulations. The cost of the generator in this model is estimated around $ 10 / W.

Institute of Thermoelectricity, Ukraine [10 – 21]

A number of comprehensive studies of thermoelectric generators for vehicles have been carried out, which follow from the description of the physics of a thermoelectric generator and yield the main thing, i.e. information for determining the optimal models of thermoelectric generators

The first calculations were carried out on a TEG model with lumped parameters. It allows you to identify the most general patterns of TEG. This model contains a local heat exchanger of infinite thermal conductivity and an infinite heat transfer coefficient. Under this condition, the gas enters the heat exchanger and leaves it at a temperature equal to that of the heat exchanger. From the heat exchanger the heat is transferred to a thermoelectric converter, the hot temperature of which is equal to the temperature of the gas. This means that the model does not take into account heat loss during its transfer from the heat exchanger to the thermoelectric converter and during heat transfer from the gas to the heat exchanger. In a thermoelectric converter, thermal energy is partially converted into electrical energy, and the rest is transferred to the thermostat. An important conclusion is that the maximum value of the efficiency of the TEG is achieved at a certain optimal value of the temperature of the heat exchanger, which is half the difference between the temperatures of hot gas and cold thermostat. This is the main conclusion that allows the optimal design of the thermoelectric generator for the car. Based on the exhaust gas temperatures for different types of engines, it is possible to estimate the temperature of the thermoelectric converter. After analyzing the average exhaust temperatures for petrol and diesel engines, it was concluded that the most acceptable temperature for a petrol engine on the hot side of the thermoelectric module is only 300-350 ° C, and for a diesel engine as low as 200-250 °C.

Such results are understandable, since they are a consequence of two competing factors, namely an improvement in the efficiency of modules with a rise in the hot temperature and a decrease in efficiency with an increase in the thermal power passing through the TEG due to a drop in the hot temperature.

The obtained results refute the generally accepted opinion that high-temperature materials should be used in automotive thermoelectric generators, and also limit the list of currently known materials suitable for use in automotive thermoelectric generators.

The next important step is to analyze sectional generators. In this model, the sections sequentially collect heat from the exhaust gas. The sections are optimized for temperature conditions and the specific materials used in the sections. The following important information was obtained from the analysis of such a model: it is reasonable to use no more than three sections; the use of sections can increase the efficiency of TEG by a factor of 1.3 - 1.4. Therefore, the use of sections should be the subject of analysis in each specific case, since a sectional generator is much more complex in design, and, accordingly, more expensive.

The above results refer to the steady-state mode of TEG operation, when the exhaust gas is stable in temperature and thermal power. In fact, in cars in real operating modes, these conditions are not met. Another important result obtained at the Institute of Thermoelectricity is the analysis of the TEG operation in the transient oprerating modes. Computer simulation of real thermal conditions shows that the average power of the generators is approximately 4 times lower in relation to the maximum.

Conclusions

1. The design of automotive thermoelectric generators is in most cases empirical. Design is based on sorting out various options of the model components in order to find the best one. However, such approaches do not reveal the general regularities that describe the TEG, reducing the possibility of finding optimal constructions.
2. All theoretical models for calculating the power of TEGs for vehicles give an error of about 30-40%, which forces us to look for new approaches to the design of such TEGs.
3. The unit cost of TEG for vehicles is still high. Hope for their implementation remains only if they are significantly reduced in price.
4. A comprehensive approach to the design of a thermoelectric generator is needed, which will take into account the interaction of the TEG and the internal combustion engine.

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Submitted 01.04.2020

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ТЕОРІЯ ТА ПРОЕКТУВАННЯ ТЕРМОЕЛЕКТРИЧНИХ ГЕНЕРАТОРІВ, ЩО ВИКОРИСТОВУЮТЬ ВІДХОДИ ТЕПЛА НА ТРАНСПОРТНИХ ЗАСОБАХ

У роботі наводяться результати аналізу теоретичних робіт, що стосуються використання термоелектричних генераторів для транспортних засобів з метою отримання додаткової електричної енергії і, відповідно, економії палива. Розглянуто тенденції розвитку і сучасний стан розробки таких генераторів. Бібл. 21.

Ключові слова: термоелектричний генератор, двигун внутрішнього згорання, утилізація тепла.

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ТЕОРИЯ И ПРОЕКТИРОВАНИЕ ТЕРМОЭЛЕКТРИЧЕСКИХ ГЕНЕРАТОРОВ, ИСПОЛЬЗУЮЩИХ ОТХОДЫ ТЕПЛА НА ТРАНСПОРТНЫХ СРЕДСТВАХ

В работе приводятся результаты анализа теоретических работ, касающихся использования термоэлектрических генераторов для транспортных средств с целью получения дополнительной электрической энергии и, соответственно, экономии топлива. Рассмотрены тенденции развития и современное состояние разработки таких генераторов. Библ. 21.

Ключевые слова: термоэлектрический генератор, двигатель внутреннего сгорания, утилизация тепла.

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Submitted 01.04.2020