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Results of an Experimental Study of the Thermoelectric Generator Integrated into a Plate Heat Exchanger

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Abstract- This paper examines the results of experimental studies of a prototype thermoelectric generator integrated into a plate heat exchanger (HX TEG). Such generators are designed to convert the energy of low-potential sources of heat and waste heat. The main objective was to validate the existing mathematical models of HX TEG in order to evaluate the reliability of the results of theoretical analysis. The results obtained confirm the accuracy of the calculations. The economic indicators are given, which allow expecting widespread use of the HX TEG for the operation of waste heat and low potential heat sources.

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Results of an Experimental Study of the Thermoelectric Generator Integrated into a Plate Heat Exchanger

Yuriy Lobunets [α] & Ilya Abdurakhmanov [σ]

Abstract- This paper examines the results of experimental studies of a prototype thermoelectric generator integrated into a plate heat exchanger (HX TEG). Such generators are designed to convert the energy of low-potential sources of heat and waste heat. The main objective was to validate the existing mathematical models of HX TEG in order to evaluate the reliability of the results of theoretical analysis. The results obtained confirm the accuracy of the calculations. The economic indicators are given, which allow expecting widespread use of the HX TEG for the operation of waste heat and low potential heat sources.

Keywords: thermoelectric generator, TEG, waste heat, LCOE of the TEG.

List of Symbols

Bi	Biot criterion
I	Electrical current (A)
j	Current density (A/cm^2)
J	Dimensionless current density
e	Seebeck coefficient (V/K)
E	Electromotive force (V)
λ	Thermal conductivity coefficient (W/cm-K)
r	Electrical conductivity coefficient [Ωcm]^1
h	Thermocouple leg length (cm)
n	Number of thermoelectric modules
nv	Number of thermoelectric elements in modules
s	Thermoelectric leg cross sectional area (cm^2)
To	Determining temperature (°C)
Th	Hot junction temperature (°C)
Tc	Cold junction temperature (°C)
dT	Junction temperature difference (°C)
th	Heat carrier temperature (°C)
tc	Coolant temperature (°C)
dt	Temperature difference of heat carriers (°C)
$\theta = T/To$	Dimensionless temperature
$\vartheta = t/To$	Dimensionless temperature of fluid
z	Thermoelectric figure-of-merit (K^{-1})
zTo	Dimensionless thermoelectric figure-of-merit
N	Electrical power (W)
Nx	Dimensionless power
Q	Heat power flow (W)
η	Efficiency
ηc	Carnot efficiency
α	Heat transfer coefficient (W/cm^2 K)
R	Electrical resistance (Ω)
RL	Electrical load resistance (Ω)
m = RL/R	Load factor
LCOE	Levelized cost of electricity ($/kWh)
V	The velocity of the heat carrier flow, (m/s)
Y = y/h	Dimensionless coordinate

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I. Introduction

Low-grade heat sources present a significant technical and economic potential: over 60 quadrillions BTU of energy were wasted yearly in the United States, mainly in the form of heat, [1], the huge renewable geothermal and solar thermal energy resources are also low- grade. Recovery even a small fraction of these heat resources can make a significant contribution to the energy balance. The main reason for limiting the use of these energy sources is the low-temperature potential - typically below 100°C. Not only does this substantially limit energy conversion efficiency (Carnot efficiency ηc does not exceed 20%), but it also determines the low energy flux density Q and the correspondingly high capital expenditure (CapEx) on the equipment. Two major energy conversion technologies are currently under consideration - the Organic Rankin Cycle (ORC) and the Thermoelectric Generator (TEG). ORC is the best-developed and commercialized technology - different range equipment available on the market, there are real estimates of Levelized Cost of Electricity (LCOE). At the same time, TEGs have potential benefits that can provide them with a niche in the market for low-grade heat sources. This is high reliability, low operating costs, compactness, and noiseless. Much research has been devoted to improving the economic efficiency of TEG. Reviews [2-3] provides statistics on existing devices and discuss possible ways to improve their performance. The modern paradigm of the development of thermoelectric devices is based on an increase in the thermoelectric figure of merit of thermoelectric materials *zT*, which determines the theoretical efficiency limit of TEG. However, no significant progress has been made recently in raising *zT*, and there is a reason to believe that there is a limit that has already been reached [4]. At the same time, large reserves remain for improving TEG economic performance by optimizing structures and regimes. First of all, it concerns the increase of heat exchange intensity. On the conditions of heat exchange depends on the useful temperature difference on thermocouples and their optimal height, which determine the density of heat fluxes and the specific power of TEG [5]. Most commonly, the sources of waste heat are liquid heat-carriers with a defined temperature. For these conditions, plate-type heat exchangers provide the best heat exchange intensity. In patents [6-8], several TEG designs integrated into plate heat exchangers (HX TEG) were proposed. The proposed TEG system provides for the high intensity of heat transfer, increase efficiency and specific power, simplify the system architecture, and reduce cost. This differs from the commonly accepted conventional TEG design, where the heat carriers are separated from the thermoelectric module by a separator plate or tube canals. The design concept consists of heat exchange plates integrated with an array of thermoelectric modules (Figure 1a), assembled into a modular stack (Figure 1b). Each plate is composed of the case in which thermoelectric modules are mounted and hermetically sealed. Gaskets are located between the plates, which form the transport channels for the heat carriers. The entire stack assembly is clamped between endplates that provide connections for the heat carriers. Electrical connections are made in parallel and series between individual thermoelectric modules and between plates, depending on the desired reliability, voltage, and current, with current collection terminals mounted into one of the stack endplates. A TEG based on this design concept can be comprised of a single stack or combine with multiple stacks into a rack-type structure for higher power output (Fig. 1c, 1d).

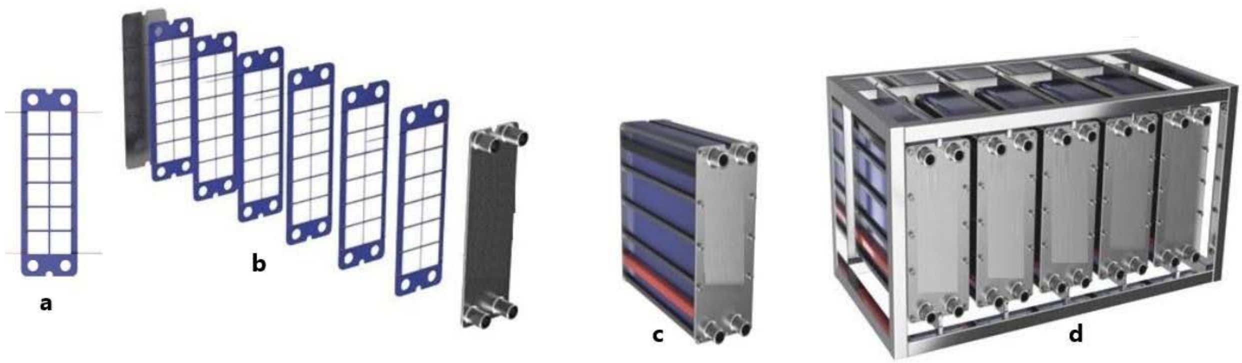

Figure 1: a-Thermoelectric plate; b - Stack Assembly; c, d -Modular Configuration

II. Theoretical Foundations

In general, the power of the TEG-HX is:

$$N = E^2 \frac{m}{(m+1)^2} \tag{1}$$

where $E = ne\Delta T$ – an electromotive force of the generator; m – load factor.

That is, in order to determine the power of HX TEG, it is necessary to know the temperature difference on thermocouples ΔT and its distribution along the channel. The mathematical models presented in [5] allow the analysis and evaluation of the economic indicators of the HX TEG based on the initial data - material properties and sizes of thermoelectric modules, assembly geometry, initial temperatures and coolant flow rates. Figure 2, below, illustrates a basic conceptual design for an HX TEG device for the purpose of discussion. In this illustrative example, heating (t_h) and cooling (t_C) fluids pass through the canals between thermoelectric modules and flow over their surface, ensuring the maintenance of a temperature difference (ΔT) on the thermoelectric modules. Due to certain irreversible losses associated with heat exchange, as well as a result of changes in the temperatures of the fluids along the length of each channel, the actual working temperature difference across a thermoelectric module will always be less than the inlet temperature difference:

$$\Delta T < dt_o = t_{ho} - t_{co} \tag{2}$$

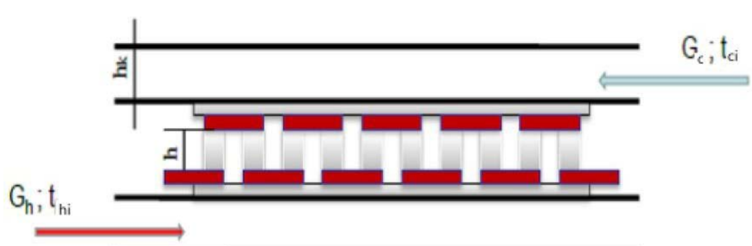

Figure 2: Conceptual design of the HX TEG

A mathematical model to determine this temperature difference contains [5]:

- The solution of the equations of heat and electricity transfer with third type boundary conditions:

$$\Theta(J,Y) = C_1 + C_2Y - Y2, \text{\`} \quad (3)$$

where,

$$C_1 = \frac{b2Bic\theta c - b1}{J - Bih + b2(J + Bic)};$$

$$C_2 = C_1\,(J + Bi_c) - Bi_c\theta_c;$$

$$b_1 = \frac{J2}{Io} - \frac{J2(J - Bih)}{2Io}\,Bi_h\theta_h;$$

$$b_2 = J\text{-}Bi_h\text{ -}1;$$

- criteria equations for determining the heat transfer coefficients:

$$Nu = 0.022Re^{0.8}Pr^{0.43} \quad (4)$$

The system of equations (1 - 4) allows the calculation of the temperature distribution in the thermoelectric elements and in the fluid and, respectively, to determine the characteristics of the HX TEG as a function of the operational and geometrical parameters, the properties of the thermoelectric materials, and the properties of the fluids. Since the properties of coolants depend on temperature, for the calculation of heat transfer coefficients is applied to the interpolation of tabular data of the thermo physical properties using cubic splines. The peculiarity of the calculations is that in the case of a counter-current flow pattern of the coolant, at least one of the required temperatures (the temperature at the outlet of the heat exchanger) is uncertain. The problem is solved by successive calculations of the temperature distribution in each thermocouple (or module) using the parameters of the coolant at the output of the module as input parameters for the next module. The solution is numerically finding the temperature $th(1)= thout$ that satisfies the initial conditions, i.e. $th(n)= tho$ and $tc(1)= tco$. Figure 3 illustrates the results of calculating the temperature distribution along HX TEG channels.

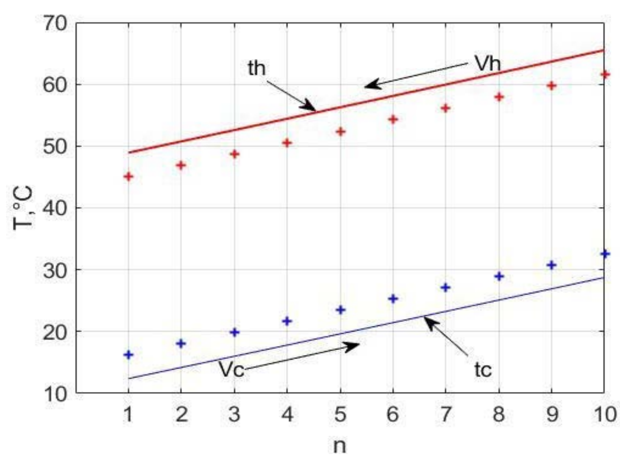

Figure 3: Temperature distribution in the HX TEG

(*markers - the temperature of modules T,* °C; *lines - temperatures of heat carriers, t,* °C).

However, due to possible errors in determining the initial data (first of all, the conditions of heat exchange), these models require verification by comparing the calculated and experimental data.

III. Study of the HX TEG at the Thermoelectric Test Rig

In order to verify the mathematical model (1- 4), an experimental study of the characteristics of a laboratory prototype HX-TEG was conducted. The flows diagram of the test apparatus is shown in Fig. 4. The experimental TEG consisted of thermoelectric plates designed in accordance with the patent [10]. The dimensions of the thermoelectric plate is similar to the Alfa Laval plate of heat exchanger type T2–BFG (380 mm x 140 mm). Each thermoelectric module pack in the plate consists of 10 thermoelectric modules type MT2.6-0.8-263. The first value in the specification of the module indicates the area of the cross-section of the thermocouples (s=2.6 mm^2), the second value is the legs length of the thermocouples (h=0.8 mm), and the third value is the number of thermocouples (nv=263). The size of the module is 50 mm x 50 mm x 4 mm and the total number of modules in the HX TEG was n=40 pieces. The thermoelectric material is Bi_2Te_3, whose properties (α, σ, λ) are described as polynomials of degree 2 with sufficient accuracy. Hot and cold heat-carriers (potable water) flowed through channels with a cross-section of F=2 cm^2 (100 mm x 2 mm). The temperatures of the heat- carriers at the inlets and outlets and the electromotive force (EMF) of the HX TEG were measured. The flow rates of the heat carriers were measured with rotameters (varied between 0 – 1.0 kg/sec). The temperature of input coolants varied between t_{co}=3.5°C – 7°C and t_{ho}=40°C -70°C. The entire TEG assembly was constructed in an aluminum chassis. The dependences of the power output of the HX TEG on the velocity and temperature of the heat-carrier were investigated and the experimental data were compared with the results of calculations. Using the experimental data for t_h, t_c, G_h, and G_c, together with the mathematical model (1 – 4), all HX TEG parameters were calculated:

- The distribution of temperature of the heat carriers t_h, t_c;
- The distribution of temperature difference on thermoelectric modules ΔT, °C;
- An electromotive force EMF, V, and
- Power *N*, W.

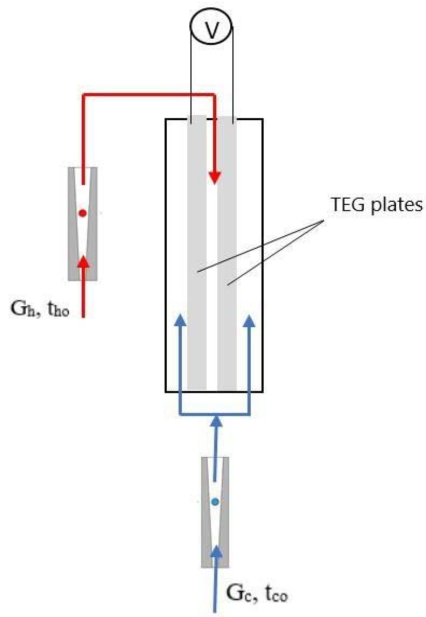

Figure 4: Flows diagram of the test rig

Since the basis for calculations is primary data (initial temperature and mass flow of coolants), the accuracy of the mathematical model was estimated by comparing the experimental data of the EMF of HX TEG with the calculation by to same conditions. The correlation between the calculated and experimental data is presented in Figure 5, below, which presents the EMF, as calculated (*Calc*) compared with actual EMF measurements (*Exp*) for the same conditions.

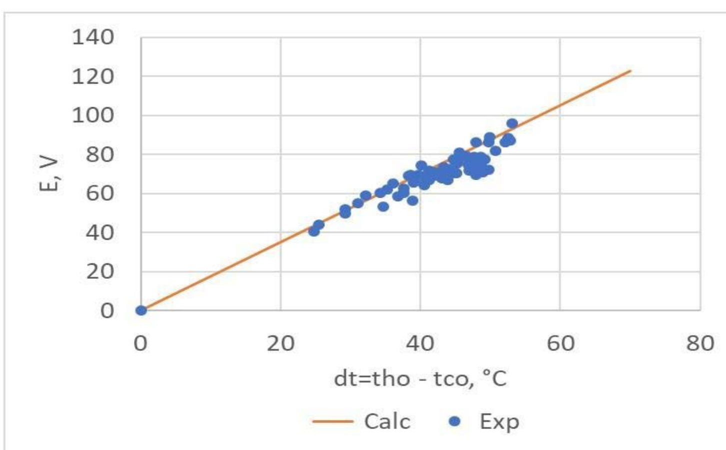

Figure 5: Comparison of calculation (Calc) and experimental (Exp) data

IV. Results and Discussion

The correlation between the calculated and experimental data is presented in Fig. 6. The results obtained confirm the high accuracy of the developed mathematical model. The error estimate in the form *Delta = (Eexp - Ecalc) / Eexp* * 100% shows that the

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difference between the experimental and calculated data does not exceed *Delta*≈7%, which is equal to about half of the scattering corridor of the experimental data (Fig. 7). That's quite acceptable and due primarily to the errors in the measurement of the heat carrier flows and the standard errors of the equation for the calculation of heat exchange intensity. The character of the scattering shows that the deviations are random and relate primarily to the results of the measurement, and not to the accuracy of the mathematical model.

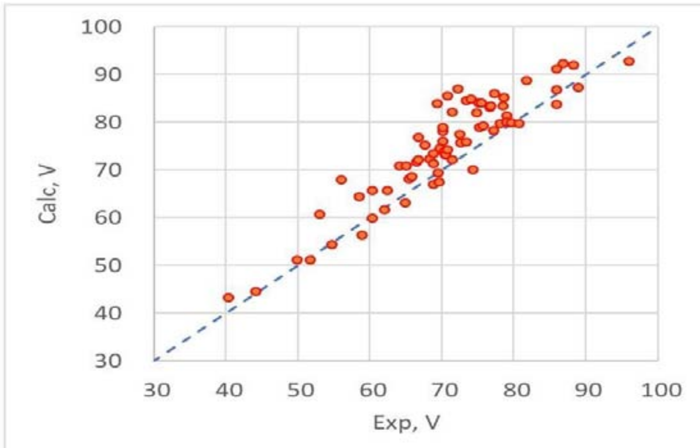

Figure 6: The correlation between the calculated (Calc) and experimental (Exp) data

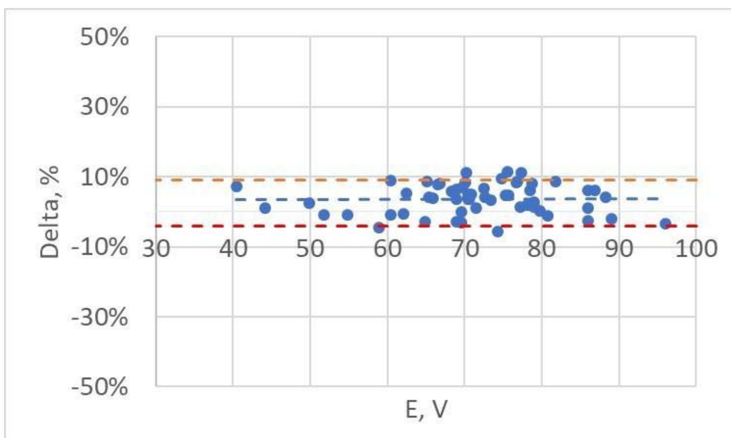

Figure 7: Deviation of experimental data compared with mathematical model for different dt

The specific power of TEG depends largely on the intensity of heat transfer, which for a fixed design is determined by the flow rate of the heat carriers. The above data were obtained for a heat carrier velocity of 1.1 m/s, which corresponds to heat transfer coefficients of about 0.22 W/cm^{2}K. Increasing the velocity of heat carriers leads to a significant increase in power of HX TEG and, consequently, to a decrease in capital expenditure (CapEx) per Watt. According to the presented in Fig.8 data, increasing the heat transfer coefficient to 1.0 W/cm^{2}K provides a double increase in power and a corresponding decrease in CapEx. For the considered design with smooth channels, such heat transfer coefficient corresponds to a speed of 8 m/s, which is not acceptable. But usually, the heat exchanger plates have a turbulent relief, thereby achieving α up to 2 W/cm^{2}K at reasonable heat carriers velocitie of V≈1 m/s. That is, existing methods allow to increase the intensity of heat transfer to the required level. The Levelized Cost Of Electricity (LCOE) estimates for the HX TEG is presented in Fig. 9. The real cost of components was taken into account in the CapEx calculations; the TEG resource is 10 years; the cost of the heat source (waste heat) and operating costs were not taken into account. Thus, the weighted price of electricity, given in Fig. 9 can be considered as a first approximation to reality.

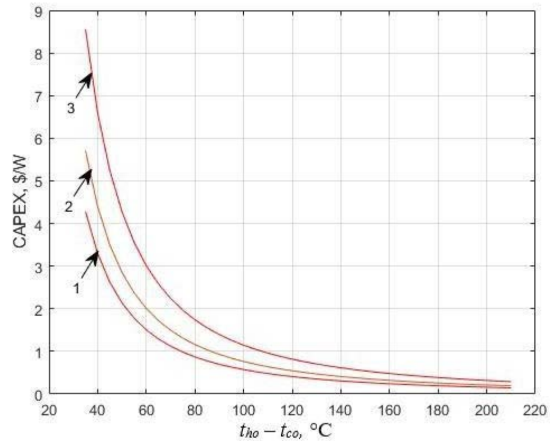

Figure 8: The dependence of CapEx on the initial temperature difference of the heat carriers. (1 – α = 1.0 W/cm^{2}K; 2 – α = 0.5 W/cm^{2}K; 3 – α = 0.22 W/cm^{2}K)

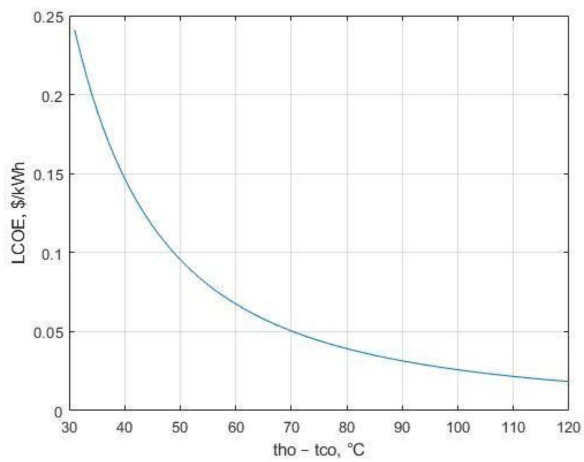

Figure 9: Levelized cost of electricity for the low-grade heat HX TEG (α = 1.0 W/cm^{2}K).

V. Conclusions

The results of the experimental study of the thermoelectric generator for utilizing low-grade heat are considered. The studies were carried out in order to verify the developed mathematical models of TEG, integrated into the plate heat exchanger (HX TEG). The results obtained confirm the accuracy of the calculations (the error is about 7%). The economic indicators of HX TEG are given. Possibility to reach the specific values of Cap Ex< 1 $/W and LCOE=3- 5 cents/kWh is demonstrated. Such technical and economic indicators allow us to expect a wide application of HX TEG for the exploitation of the waste heat and low-potential heat sources.

Acknowledgments

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