L.I. Anatychuk

THE EFFECT OF HEAT EXCHANGE SYSTEM ON THERMOELECTRIC GENERATOR EFFICIENCY

L.I. Anatychuk, A.V. Prybyla
(Institute of Thermoelectricity, 1, Nauky Str., Chernivtsi, 58029, Ukraine)

A.V. Prybyla

• *The results of calculation of thermoelectric generator efficiency with regard to the effect of heat exchange system are given. Optimal parameters of heat exchange system for achieving the highest efficiency are determined.*

Introduction

General characterization of the problem. In the majority of cases, efficiency improvement of thermoelectric power generators (TEG) [1] consists in the increase of figure of merit [2] of thermoelectric materials. However, the efficiency of such generators is governed not only by the quality of thermoelectric power converters. To no less extent it depends on the heat exchange devices and systems taking heat fluxes to and from the thermoelectric power converters. In so doing, no due attention has been given so far to quality improvement of heat exchange devices and systems. Preliminary analysis shows that real values of thermoelectric generator efficiency are much lower than those expected even with the achieved material figure of merit. It is due to the fact that in the design and optimization of thermoelectric equipment, simplified physical models are mostly used [3 - 5] that do not take into account the quality of heat exchange systems, the thermal and electrical losses that can degrade their energy characteristics considerably.

In Ref. [6], procedure for calculating the efficiency of TEG for generalized physical models of thermoelectric power converters is considered. *The present work aims* at analyzing the effect of a real heat exchange system on the efficiency of thermoelectric generator. For this purpose, the efficiency of TEG with regard to experimentally determined structural and energy characteristics of heat exchange system was calculated, the optimal parameters of heat exchange system to achieve the best TEG efficiency were determined.

Physical models of TEG

Physical models of TEG are shown in Figs. 1 and 2. The electric power W is generated by thermoelectric generator modules 4. As a source of heat Q_s, a gasoline burner of power 2.3 kW is used, which provides the exhaust gas temperature $T_{h.t.} = 800$ °C at the flow rate $G = 165.4$ g/h. A chamber of gasoline burner 1 accommodates air heat sink 2 assuring abstraction of heat Q_h from the exhaust gases and its transfer to thermoelectric modules. Removal of heat Q_c from the cold side of thermoelectric modules is done by liquid-air heat exchanger (Fig. 1) that consists of liquid heat exchangers 5 and liquid-air heat sink 7. Liquid motion is assured by liquid pump 6 consuming electric power W_1, and air motion is intensified by air fans 8 consuming electric power W_2, W_3. Moreover, the model takes into account losses due to the presence of thermal contact resistances between thermoelectric generator structural elements 9, 10, 11.

In the case represented in Fig. 2 heat removal is done by air heat exchanger 5 and intensified by fans 6 consuming power W_1, W_2.

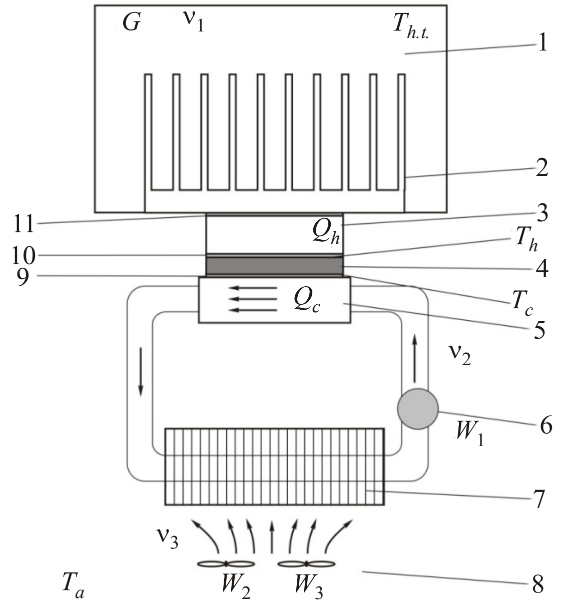

Fig. 1. Physical model of thermoelectric generator with heat removal by water-air heat exchanger: 1– chamber of gasoline burner of power 2.3 kW, 2 – air heat exchanger, 3 – heat spreader between the air heat sink and thermoelectric modules, 4 – thermoelectric generator modules, 5 – liquid heat exchangers, 6 – water pump, 7 – liquid-air heat exchanger, 8 – electric fans, 9 – 11 – thermal contact between thermoelectric generator structural elements.

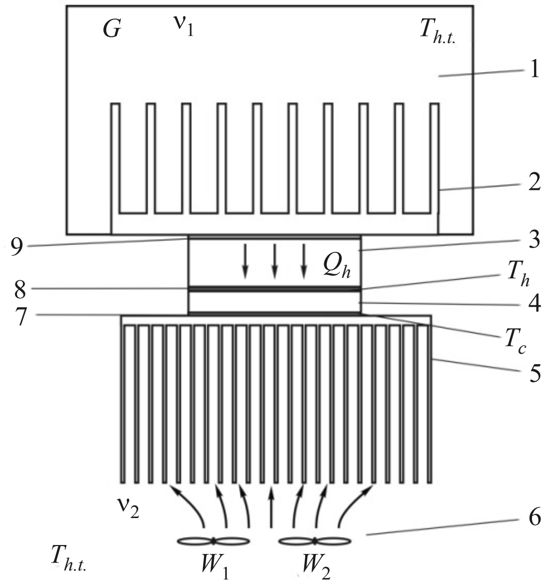

Fig. 2. Physical model of thermoelectric generator with heat removal by air heat exchanger: 1– chamber of gasoline burner of power 2.3 kW, 2 – air heat exchanger, 3 – heat spreader between the air heat sink and thermoelectric modules, 4 – thermoelectric generator modules, 5 – cold air heat exchanger, 6 – electric fans, 7 – 9 – thermal contact between thermoelectric generator structural elements.

Calculation of thermoelectric generator efficiency

Efficiency calculation for two physical models of thermoelectric generator was done according to procedure described in [9]:

$$\eta_{TEG} = \frac{W_u}{Q_{con}}, \tag{1}$$

where η_{TEG} is TEG efficiency, W_u is useful electric power, Q_{con} is consumed thermal power.

$$W_u = W_{Thb} - W_l, \tag{2}$$

where W_{Thb} is thermopile electric power, W_l is electric power used for additional electric supply to TEG (electric supply to electric fans and electric water pump).

$$W_{Thb}(T_h, T_c) = Q_h \cdot \eta_{Thb}(T_h, T_c), \tag{3}$$

$$Q_h = Q_c + W_{Thb}(T_h, T_c), \tag{4}$$

where Q_h is heat flux upstream of thermoelectric module, Q_c is heat flux downstream of thermoelectric module, T_h is hot side temperature of thermoelectric module, T_c is cold side temperature of thermoelectric module, $\eta_{Thb}(T_h, T_c)$ is thermopile efficiency.

Calculation of thermal power consumption was done according to known fuel flow rate in gasoline burner G = 165.4 g/h and fuel calorific power λ = 10.4 kcal/g and makes Q_c = 2.3 kW.

$$Q_c = G \cdot \lambda, \tag{5}$$

The temperature of exhaust gases at the outlet of thermoelectric generator is found from the relation:

$$Q_h = C \cdot m \cdot (T_{ht}^{in} - T_{ht}^{out}) = C \cdot G \cdot \rho \cdot (T_{ht}^{in} - T_{ht}^{out}), \tag{6}$$

where C is heat carrier heat capacity, m is heat carrier mass, G is heat carrier flow rate, ρ is heat carrier density, T_{ht}^{in} is inlet temperature of gas heat carrier, T_{ht}^{out} is gas heat carrier temperature at the outlet of thermoelectric generator.

In the design of TEG, experimental dependences of the efficiency of thermoelectric generator modules Altec-1061 were used (Fig. 3).

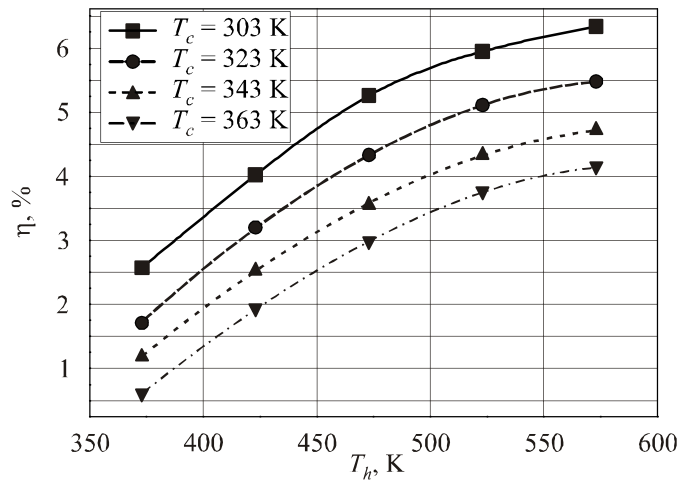

Fig. 3. Efficiency of thermoelectric modules Altec-1061.

To determine the effect of TEG heat exchange system and temperature losses on its elements, heat balance equations were written:

$$Q_h = \alpha_1(v_1) \cdot S_1 \cdot (T_{ht} - T_1), \tag{7}$$

where $\alpha_1(\nu_1)$ is coefficient of heat transfer of air heat sink external surface which is a function of hot heat carrier velocity ν_1, S_1 is external surface area of liquid-air heat sink that contacts the hot heat carrier, T_{ht} is gas heat carrier temperature, T_1 is temperature of air heat sink surface that contacts the hot heat carrier.

Construction of air heat exchanger used in the calculations has overall dimensions 120 × 100 × 20 mm and is composed of 10 sections with a variable fin height to assure equal temperature on thermoelectric modules. At heat carrier velocity ν_1 = 7.5 m/s and inlet gas temperature $Q_h = \alpha_1(v_1) \cdot S_1 \cdot (T_{ht} - T_1) = 1073$ K and outlet temperature $T_{ht}^{out} = 615$ K the average temperature of heat exchange surface is T_1 = 590 K.

Knowing the temperature resistance of heat exchange material and its geometry, we find the temperature of heat exchanger base T_2:

$$Q_h = \chi_2 \cdot (T_2 - T_1), \tag{8}$$

where χ_2 is thermal resistance of air heat exchanger, T_2 is temperature of air heat exchanger base

$$Q_h = \chi_3 \cdot (T_3 - T_2), \tag{9}$$

where χ_3 is thermal resistance of metal heat conducting element, T_3 is temperature of air heat exchanger that contacts the electrically insulating mica plate.

As is shown in Fig. 1, at points of contact of thermoelectric generator structural elements there is thermal contact resistance whose value from the experimental data is $\chi_c = 0.035$ K/W. The presence of contact thermal resistance with a known heat flux density leads to temperature drop $\Delta T = 4.5$ K.

$$Q_h = \chi_c \cdot (T_h - T_3), \tag{10}$$

where χ_c is thermal contact resistance.

Heat flux and temperatures on 10 thermoelectric modules are: $T_h = 563$ K, $T_c = 323$ K, respectively, at heat flux $Q_h = 1430$ W.

$$Q_h = \chi_m \cdot (T_h - T_c) + W_{Thb}(T_h, T_c), \tag{11}$$

where χ_m is thermal resistance of thermoelectric module.

Calculation of losses on the cold side of thermoelectric generator is done similarly.

$$Q_c = \chi_c \cdot (T_c - T_4), \tag{12}$$

where χ_4 is thermal contact resistance between thermoelectric module and liquid heat exchanger, T_4 is surface temperature of liquid heat exchanger that contacts the thermoelectric module.

Ten water heat exchangers of overall dimensions 45 × 42 × 6 mm were used where liquid motion is assured by water pump of power 8 W.

$$Q_c = \chi_4 \cdot (T_4 - T_5), \tag{13}$$

where χ_4 is thermal resistance of water heat exchangers, T_5 is surface temperature of cold liquid heat exchanger that contacts the liquid,

$$Q_c = \alpha_2(\nu_2) \cdot S_2 \cdot (T_5 - T_6), \tag{14}$$

where $\alpha_2(\nu_2)$ is heat transfer coefficient of liquid heat exchanger which is a function of liquid velocity ν_2, S_2 is surface area of liquid heat exchanger, T_6 is average liquid temperature between the inlet to and outlet of the cold liquid heat exchanger

$$Q_c = \alpha_3(\nu_3) \cdot S_3 \cdot (T_6 - T_7), \tag{15}$$

where $\alpha_3(\nu_3)$ is heat transfer coefficient of the internal surface of liquid-air heat exchanger that is a function of liquid velocity ν_3, S_3 is the internal surface area of liquid-air heat exchanger, T_{11} is average liquid temperature between the inlet to and outlet of the cold liquid-air heat exchanger,

$$Q_c = \chi_5 \cdot (T_7 - T_8), \tag{16}$$

where χ_5 is thermal resistance of liquid-air heat exchanger, T_8 is surface temperature of liquid-air heat exchanger that contacts the environment,

$$Q_c = \alpha_4(\nu_4) \cdot S_4 \cdot (T_8 - T_a), \tag{17}$$

where $\alpha_4(\nu_4)$ is heat transfer coefficient of the external surface of liquid-air heat exchanger that is a function of air velocity ν_4, T_a is ambient temperature, S_4 is surface area of liquid-air heat exchanger that contacts the environment.

In the calculation, we used a standard liquid-air heat exchanger with the overall dimensions 270 × 160 × 40 mm whose parameters were studied experimentally. Attached to such heat exchanger are two air fans of power 6 W that intensify heat between the heat exchanger surface and the environment of temperature T_a = 290 K.

Substituting (2 – 5) into (1), we obtain:

$$\eta_{TEG} = \frac{W_u}{Q_{con}} = \frac{W_{Thb} - W_l}{G \cdot \lambda} = \frac{Q_h \cdot \eta_{Thb}(T_h, T_c) - W_l}{G \cdot \lambda}. \quad (18)$$

Using in (18) the heat balance equations (7) – (17):

$$\eta_{TEG} = \frac{\dfrac{\alpha_1(\nu_1) \cdot S_1 \cdot (T_{ht} - T_{ct}) \cdot \eta_{Thb}(T_h, T_c)}{1 + \alpha_1(\nu_1) \cdot S_1 \cdot (N_1 + N_2 \cdot (1 - \eta_{Thb}(T_h, T_c)))} - W_l}{G \cdot \lambda}, \quad (19)$$

where

$$N_1 = \frac{1}{\chi_1} + \frac{1}{\chi_2} + \frac{1}{\chi_3} + \frac{1}{\chi_c} + \frac{1}{\chi_m}, \quad (20)$$

$$N_2 = \frac{1}{\chi_4} + \frac{1}{\chi_c} + \frac{1}{\alpha_2 \cdot S_2} + \frac{1}{\alpha_3 \cdot S_3} + \frac{1}{\chi_5} + \frac{1}{\alpha_4 \cdot S_4}. \quad (21)$$

Thus, the efficiency of thermoelectric generator with water-air heat removal system (Fig. 1) of power W = 67 W with regard to the effect of heat exchange system is $\eta_{TEГ}$ = 2.7%.

Similar calculations for TEG with a system of heat removal only by air heat exchangers (Fig. 2) yield the following results: the electric power is W = 48 W, η_{TEG} = 1.9%.

Selection of optimal heat exchange system

Electric power output of TEG and its efficiency depend on the temperature and thermal conditions on thermoelectric modules that are assured by heat input and output system. In its turn, the efficiency of heat exchange system is improved due to forced air cooling by electric fans, and heat exchange with liquid heat carrier is improved with the aid of a liquid pump.

Fig. 3 shows the electric power output of TEG as a function of power consumed by heat exchange system. As is evident from the figure, the optimal electric power of heat exchange system Q_{el} = 25 W has been found that assures the highest TEG efficiency.

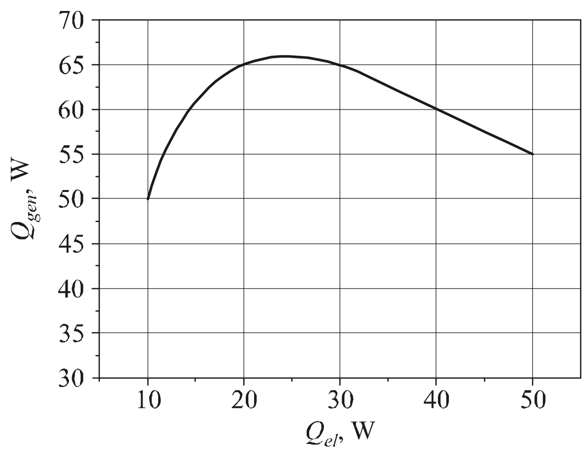

Fig. 3. Electric power output of TEG as a function of power consumed by heat exchange system.

Conclusions

1. The efficiency of thermoelectric generator has been calculated with regard to the effect of heat exchange system and makes 2.7% for a generator with a combined water-air heat exchange system and 1.9% for that with an air heat exchange system.
2. The optimal parameters of heat exchange system for achieving the highest efficiency have been determined.
3. It has been established that a system of heat exchange of total power Q_{el} = 25 W must be used to achieve the highest electric power output of TEG.

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