L.I. Anatychuk

THE EFFECT OF HEAT-EXCHANGE SYSTEMS ON THE EFFICIENCY OF THERMOELECTRIC DEVICES

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

A.V. Prybyla

• *Generalized models of thermoelectric power converters are investigated in generation and cooling modes with regard to the effect of heat-exchange systems on their energy characteristics. It is shown that limited-quality and non- dedicated heat-exchange devices reduce the energy characteristics by 30 – 50%. Possibilities of improvement this situation are analyzed.*

Introduction

General characterization of the problem. The efforts aimed at improving the efficiency of thermoelectric devices [1] are primarily focused on thermoelectric power converters and are reduced to improving the figure of merit [2] of thermoelectric materials for such converters. However, the efficiency of thermoelectric devices depends not only on the quality of thermoelectric power converters. It depends quite as much on the heat-exchange devices and systems used to deliver and remove heat fluxes to and from thermoelectric power converters. In so doing, proper attention has not been given yet to quality enhancement of thermoelectric devices and systems. Preliminary analysis shows that the real values of efficiency, coefficient of performance and heating coefficient are much lower than the expected ones even at the attained values of material figure of merit. It is due to the fact that in the design and optimization of thermoelectric equipment one mostly employs simplified physical models [3 - 8] that do not take into account the quality of heat exchange systems, the thermal and electrical losses that may degrade considerably their energy characteristics.

Therefore, the purpose of this work is to study physical models of generators and cooling devices with regard to the effect of heat-exchange systems.

Electric power generation mode

A physical model of thermoelectric generator is shown in Fig.1. Electric power W is generated by thermoelectric module 7. Heat flux Q_h is obtained from the hot heat carrier 2 with temperature T_{ghc} and flow rate G through use of a heat exchanger composed of liquid-air radiator 3 and liquid heat exchanger 5. Liquid motion is assured by liquid pump 4 that consumes electric power W_2, and air motion is intensified by fan 1 that consumes electric power W_1. Located on both sides of thermoelectric module are heat-conducting layers 12, 13 that improve thermal contact between generator elements. Located on the hot side of thermoelectric module is metal element 6 used for flow-over of heat Q_h from heat exchanger 5 to thermoelectric module 7. Heat removal from the hot side of thermoelectric module is done by heat exchanger composed of liquid heat exchanger 8 and liquid-air radiator 10. Liquid motion is assured by liquid pump 9 that consumes electric power W_3, and air motion is intensified by fan 11 that consumes electric power W_4.

Thermoelectric generator module is characterized by such parameters as generated electric power W and efficiency η, determined by the ratio of obtained electric power W to spent thermal power Q. However, in operation, thermoelectric generator (TEG) spends electrical energy on its functioning, and, moreover, there are always temperature and thermal losses Q_l on its structural members. Therefore, the real electric power of TEG will be less: $W_r = W - W_1 - W_2 - W_3 - W_4$, hence, the real efficiency will be determined by the value W_r and the real heat flux Q_r that will take into account all losses on the structural members of TEG $\eta_{TEG} = W_r/Q_r$.

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

where η_{TEG} is TEG efficiency, W_u is useful electric power, Q_s is spent thermal power.

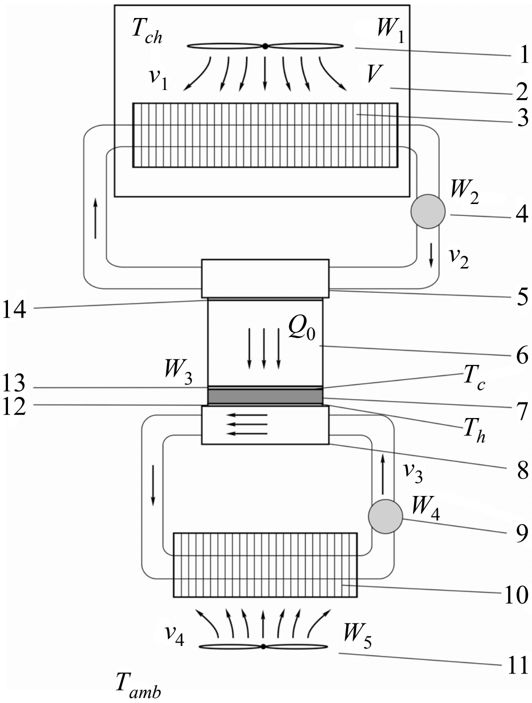

Fig. 1. A physical model of thermoelectric generator: 1, 11 – fans, 2 – volume filled with hot heat carrier, 3 – liquid-air radiator, 4, 9 – liquid pumps, 5 – liquid heat exchanger, 6 – element through which thermal flux flows, 7 – thermoelectric module, 8 – liquid heat exchanger, 10 – liquid-air radiator, 12 – 14 – thermal contact between structural members of TEG.

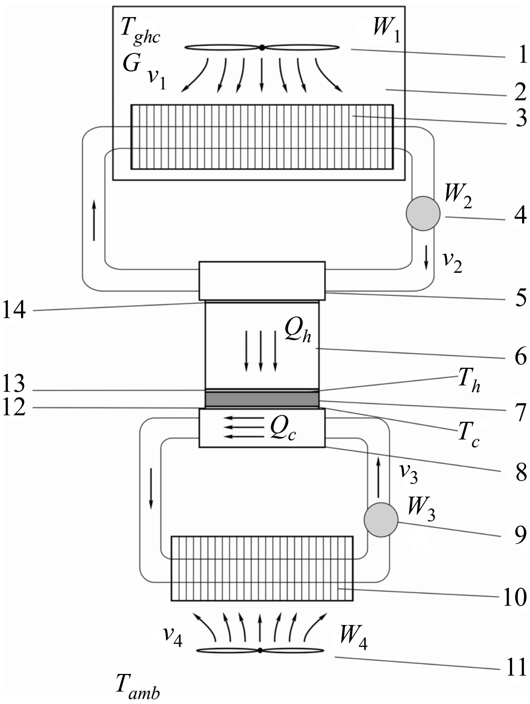

Fig. 2. A physical model of thermoelectric heat pump: 1, 11 – fans, 2 – cooling chamber, 3 – liquid-air radiator, 4, 9 – liquid pumps, 5 – liquid heat exchanger, 6 – element through which thermal flux flows, 7 – thermoelectric module, 8 – liquid heat exchanger, 10 – liquid-air radiator, 12 – 14 – thermal contact.

$$W_u = W_{TP} - W_{el.l}, \tag{2}$$

where W_{TP} is electric power of thermopile, $W_{el.l}$ is electric power spent for additional power supply to TEG (power supply to electric fans and electric liquid pumps).

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

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

In the formulae Q_h is thermal flux to thermoelectric module, Q_c is thermal flux after thermoelectric module, T_h is the hot side temperature of thermoelectric module, T_c is the cold side temperature of thermoelectric module, η_{TP} (T_h, T_c) is thermopile efficiency.

$$Q_s = C \cdot m \cdot (T_{ghc} - T_{amb}) = C \cdot G \cdot \rho \cdot (T_{ghc} - T_{amb}), \tag{5}$$

where C is heat carrier heat capacity, m is heat carrier mass, G is heat carrier flow rate, c is heat carrier density, T_{ghc} is temperature of gas heat carrier, T_{amb} is ambient temperature.

Thermal flux and the hot and cold side temperatures of thermoelectric module are determined from the heat balance equations:

$$Q_h = \alpha_1(v_1) \cdot S_1 \cdot (T_{ghc} - T_1), \quad (6)$$

where $\alpha_1(\nu_1)$ is heat exchange coefficient of the external surface of liquid-air radiator, S_1 is the area of external surface of liquid-air radiator that contacts the hot heat carrier, T_1 is the temperature of liquid-air radiator surface that contacts the hot heat carrier;

$$Q_h = \chi_1 \cdot (T_1 - T_2), \quad (7)$$

where χ_1 is thermal resistance of the hot liquid-air radiator, T_2 is the temperature of the internal surface of liquid-air radiator;

$$Q_h = \alpha_2(v_2) \cdot S_2 \cdot (T_2 - T_3), \quad (8)$$

where $\alpha_2(\nu_2)$ is heat exchange coefficient of the internal surface of liquid-air heat exchanger, S_2 is the area of the internal surface of liquid-air heat exchanger, T_3 is the average temperature of liquid between the inlet to and outlet of liquid-air heat exchanger;

$$Q_h = \alpha_3(v_2) \cdot S_3 \cdot (T_3 - T_4), \quad (9)$$

where $\alpha_3(\nu_2)$ is heat exchange coefficient of liquid heat exchanger, S_3 is the area of the internal surface of liquid heat exchanger, T_4 is the temperature of liquid heat exchanger surface that contacts the liquid;

$$Q_h = \chi_2 \cdot (T_4 - T_5), \quad (10)$$

where χ_2 is thermal resistance of the hot liquid heat exchanger, T_5 is the temperature of the hot liquid heat exchanger surface that contacts the metal heat-conducting element;

$$Q_h = \chi_3 \cdot (T_5 - T_6), \quad (11)$$

where χ_3 is thermal contact resistance between the hot liquid heat exchanger and the metal heat-conducting element, T_6 is the temperature of the metal heat-conducting element surface that contacts the hot liquid heat exchanger;

$$Q_h = \chi_4 \cdot (T_6 - T_7), \quad (12)$$

where χ_4 is thermal resistance of the metal heat-conducting element, T_7 is the temperature of surface of the metal heat-conducting element that contacts thermoelectric module;

$$Q_h = \chi_5 \cdot (T_7 - T_h), \quad (13)$$

where χ_5 is thermal contact resistance between the metal heat-conducting element and thermoelectric module;

$$Q_h = \chi_6 \cdot (T_h - T_c) + W_{TP}(T_h, T_c), \quad (14)$$

where χ_6 is thermal resistance of thermoelectric module;

$$Q_c = \chi_7 \cdot (T_c - T_8), \quad (15)$$

where χ_7 is thermal contact resistance between the thermoelectric module and liquid heat exchanger, T_8 is the temperature of liquid heat exchanger surface that contacts the thermoelectric module;

$$Q_c = \chi_8 \cdot (T_8 - T_9), \quad (16)$$

where χ_8 is thermal resistance of water heat exchanger, T_9 is the temperature of cold liquid heat exchanger surface that contacts the liquid;

$$Q_c = \alpha_4(v_3) \cdot S_4 \cdot (T_9 - T_{10}), \quad (17)$$

where $\alpha_4(\nu_3)$ is heat exchange coefficient of liquid heat exchanger, S_3 is the area of liquid heat exchanger surface, T_{10} is the average liquid temperature between the inlet to and outlet of the cold liquid heat exchanger;

$$Q_c = \alpha_5(v_3) \cdot S_5 \cdot (T_{10} - T_{11}), \quad (18)$$

where $\alpha_5(\nu_3)$ is heat exchange coefficient of the internal surface of liquid-air heat exchanger, S_5 is the area of the internal surface of liquid-air heat exchanger, T_{11} is the average liquid temperature between the inlet to and outlet of the cold liquid-air heat exchanger;

$$Q_c = \chi_9 \cdot (T_{11} - T_{12}), \tag{19}$$

where χ_9 is thermal resistance of liquid-air heat exchanger, T_{12} is the temperature of liquid-air heat exchanger surface that contacts the ambient medium;

$$Q_c = \alpha_6(\nu_4) \cdot S_6 \cdot (T_{12} - T_{amb}), \tag{20}$$

where $\alpha_6(\nu_4)$ is heat exchange coefficient of the external surface of liquid-air heat exchanger, S_6 is the area of liquid-air heat exchanger surface that contacts the ambient medium.

Substituting (2 – 5) into (1) gives:

$$\eta_{TEG} = \frac{W_u}{Q_s} = \frac{W_{TP} - W_{el.l}}{C \cdot G \cdot \rho \cdot (T_{ghc} - T_{amb})} = \frac{Q_h \cdot \eta_{TP}(T_h, T_c) - W_{el.l}}{C \cdot G \cdot \rho \cdot (T_{ghc} - T_{amb})}. \tag{21}$$

Using in (21) the heat balance equations (6) – (20), we get

$$\eta_{TEG} = \frac{\dfrac{\alpha_1 \cdot S_1 \cdot (T_{ghc} - T_{amb}) \cdot \eta_{TP}(T_h, T_c)}{1 + \alpha_1 \cdot S_1 \cdot \left[N_1 + N_2 \cdot \left(1 - \eta_{TP}(T_h, T_c)\right) \right]} - W_{el.l}}{C \cdot G \cdot \rho \cdot (T_{ghc} - T_{amb})}, \tag{22}$$

where

$$N_1 = \frac{1}{\chi_1} + \frac{1}{\alpha_2 \cdot S_2} + \frac{1}{\alpha_3 \cdot S_3} + \frac{1}{\chi_2} + \frac{1}{\chi_3} + \frac{1}{\chi_4} + \frac{1}{\chi_5} + \frac{1}{\chi_6},$$
$$N_2 = \frac{1}{\chi_7} + \frac{1}{\chi_8} + \frac{1}{\alpha_4 \cdot S_4} + \frac{1}{\alpha_5 \cdot S_5} + \frac{1}{\chi_9} + \frac{1}{\alpha_6 \cdot S_6}. \tag{23}$$

Heat pump mode

A physical model of thermoelectric heat pump is shown in Fig. 2. Thermoelectric cooling and heating is done by thermoelectric module 7 that consumes electric power W_3. Heat transfer from cooling (heating) chamber 2 of volume V and temperature T_{ch} is done by heat exchanger composed of liquid-air radiator 3 and liquid heat exchanger 5. Liquid motion is assured by liquid pump 4 that consumes electric power W_2, and air motion is intensified by fan 1 that consumes electric power W_1. Located on both sides of thermoelectric module are heat-conducting layers 12, 13 that improve thermal contact with heat pump components. Located on the cold side of thermoelectric module is metal component 6 for overflow of heat Q_0 from heat exchanger 5 to thermoelectric module 7. Heat removal from the hot side of thermoelectric module is done by heat exchanger composed of liquid heat exchanger 8 and liquid-air radiator 10. Liquid motion is assured by liquid pump 9 that consumes electric power W_4, and air motion is intensified by fan 11 that consumes electric power W_5. There is inleak of heat Q_1 from the ambient medium to cooling (heating) chamber.

Thermoelectric cooling module is characterized by refrigerating capacity (heating productivity) Q_0, that is, by the amount of heat that overflows from cooling (heating) chamber through thermoelectric module, as well as by coefficient of performance (heating coefficient) of thermoelectric module ε_1, that is, the ratio of refrigerating capacity (heating productivity) Q_0 to spent electric power W_3. However, important in practical work are the real values of refrigerating capacity (heating productivity) that will be reduced due to thermal losses on structural members, as well as due to heat inleak from the ambient medium, Q_{amb}. Coefficient of performance and heating coefficient of heat pump will be determined by the ratio of real refrigerating capacity (heating productivity) Q_r to total spent electric power $W_r = W_1 + W_2 + W_3 + W_4 + W_5$.

$$\varepsilon_{HP} = \frac{Q_r}{W_r}, \qquad (24)$$

where ε_{HP} is coefficient of performance, W_r is spent electric power, Q_r is refrigerating capacity of heat pump.

$$Q_r = Q_{TP}(T_h, T_c) - Q_1, \qquad (25)$$

where Q_{TP} is refrigerating capacity of thermopile.

Heat flux and the hot and cold side temperatures of thermoelectric module are found from the heat balance equations with regard to all thermal losses on structural members, as described in the previous paragraph.

Thus,

$$\varepsilon_{HP} = \frac{Q_{TP}(T_h, T_c) - Q_{amb}}{W_1 + W_2 + W_3 + W_4 + W_5}, \qquad (26)$$

Analysis of the results

The obtained relations for the efficiency and coefficient of performance make it possible to analyze the effect of heat exchange systems produced on them. The values of really existing heat exchange systems were employed in the analysis. It was established that the use of non-dedicated heat exchange systems reduces TEG efficiency by 30 to 50 % and the coefficient of performance of heat pumps by 55%.

Such results testify to the necessity of creating high-efficient dedicated for thermoelectricity liquid, air and air-liquid heat exchangers. There is also a need to optimize the powers of fans and liquid pumps in the design of thermoelectric devices, including up-to-date computer calculation methods.

Estimates show that in this way the efficiency of thermoelectric generators and coolers can be improved by a factor of 1.2 to 1.5.

Conclusions

1. The relations for efficiency and coefficient of performance of thermoelectric devices have been obtained with regard to the effect of heat exchange systems.
2. It has been established that the use of non-dedicated heat exchange systems reduces TEG efficiency by 30 to 50 % and the coefficient of performance by 55%.
3. It has been calculated that the use of dedicated heat exchange systems will improve the efficiency of thermoelectric generators and coolers by a factor of 1.2 to 1.5.

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