Introduction into thermoelectric power generation

Introduction

Operation of Thermoelectric Power Generating products is based on a phenomenon of direct conversion of heat flow into electromotive force. It was discovered in 1821 by Thomas Seebeck. The basic element of thermoelectric devices is thermocouple (fig.1). If temperature gradient arises across the junctions of dissimilar conductors (or semiconductors) electromotive force would be generated. If thermocouple would be connected to external electrical load electric current will flows through the circuit.

$E=\alpha\Delta T$

E – thermo electromotive force (TEMF), V;
α - TEMF coefficient, V/K;
Th – the hot side temperature, K;
Tc – the cold side temperature, K;
ΔT=Th-Tc – temperature difference, K;
Qh and Qc – heat-flow energy, W;
R_L - load resistance, Ohm;
I – electric current, A.

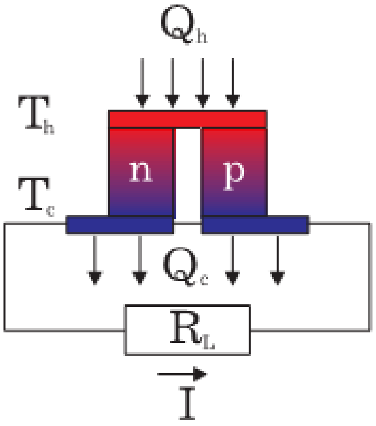

Fig.1. Thermocouple with semiconductor branches

To get visible power many thermocouples should be used. Normally they are connected in serial. To make solid and stable construction ceramic substrates with bonded wires are used (fig. 2). Up to several hundreds of thermocouples could be mounted between two ceramic substrates. This construction compose Thermoelectric Generating Module (TGM) with typical sizes from 20*20 mm (or less) up to 62*62mm.

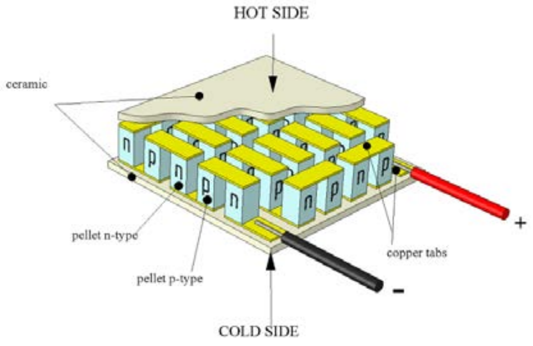

Fig. 2. Thermoelectric generating module structure

If two sides of TGM are maintained at different temperatures than thermocouples provide thermal electromotive force (TEMF) and TGM, being connected to electric circuit, generate current and therefore electric power. Presented construction provides best thermoelectric efficiency in conversion of a heat flow into TEMF.

To get the temperature difference between TGM sides, it is necessary to support heat flow (Qh) from hot side to cooled one. If Qh is incoming heat energy from heated side and Qc is thermal energy dissipated from cooled side, than due to the law of conservation of energy the electrical power available at the load could be determined from the equitation:

$$P = Qh - Qc = I^2 R \,,$$

$$P \sim \Delta T2$$

From this equitation it is obvious that the generated power is proportional to squared different of temperatures (ΔT). To achieve the maximum power the value of load resistance R_L should be equal to TGM internal resistance.

To carry out effective generation, it's important to concentrate thermal stream through the thermo electric module and minimize the losses on the way from the heat source to cold side heat sink through the module. To make it possible the heat source should have low thermal resistance and be thermo-insulated from the environment in order to provide the maximum heat flow through the TEM.

Another important point is effective heat removal from cooling side of TGM with a goal to provide lowest temperature on it. In the real life the engineer commonly is dealing with existing thermal power sources which have definite output parameters (sizes, surface material or it's thermal resistance, thermal flow dencity, temperature and it possible changes in time). Also engineer could be limited by the space in his construction of the cooling heat sink, it's weight, the type of heat removal in to ambient ((by air with natural or forced convection, by liquid, etc.). Another important point is the way of TGM mounting (the glue, thermal grease paste with tie bolts or soldering). On the way of heat flow from the source to environment there are several separate thermal resistance of the parts of construction. Most of them are connected sequentially and other in parallel (e.g. parasitic resistance of coupling bolts).

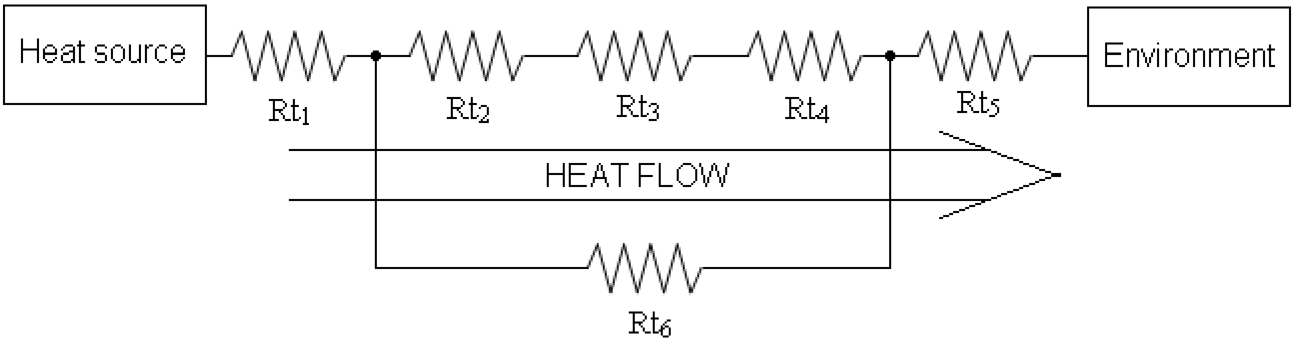

Fig.4. Block-scheme of thermoelectric generating device

Rt_1-thermal resistance of heat source;
Rt_2 and Rt_4- thermal resistance of thermo-conductive paste, glue or mounting solder;
Rt_3 - thermal resistance of TGM construction (ceramics, thermo electric elements, assembly solder etc);
Rt_5- thermal resistance of cooling heatsink;
Rt_6 - parasitic thermal resistance of construction.

As one can see from the presented scheme, in case of value Rt_1 is set and Rt_5 limited for example by heatsink weight/size, the constructor should choose TGM from the set conditions of optimal thermal resistance.

At the KRYOTHERM website one can find exhaustive information about wide range of different types of TGM covering most popular applications. They are designed for different heat power density and could be used with different types of heat sinks (convection air flow, forced air flow and liquid type). Properly they have different sizes and different heat resistance.

For the same thermoelectric material and square size of TGM there is direct relation between output electric power, thermal and electrical resistance of TGM. Lower electrical internal resistance allows to generate higher power but result in necessity to have cold side heat sink with lower thermal resistance.

Most popular TGM for liquid heat remove is TGM-199-1.4-0.8 with square sizes 40*40 mm. It allow to generate up to 12 W of electric power at temperature difference 170K (fig. 5).   .

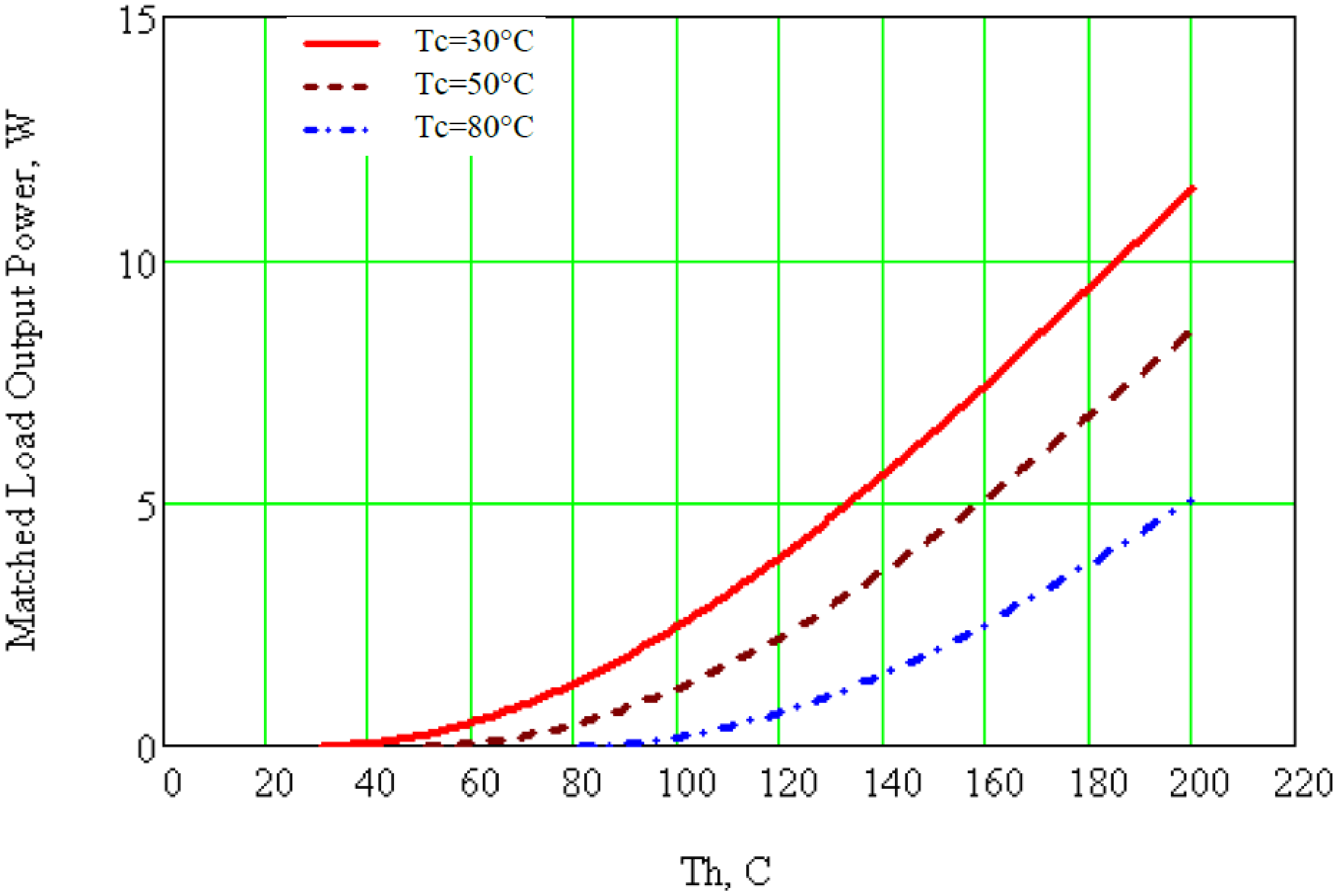

Fig.5. Output power of TGM-199-1.4-0.8 depending on hot and cold sides temperature.

The thermal resistance Rt of this TGM is 0,57 K/W and fit to liquid heat sink thermal resistance value.. Calculations of TGM Rt are provided with taking into account the heat loss in the TGM ceramic substrates of 96% aluminum oxide (Al_2O_3 with thermal conductivity of 26 W/(m * K) and thermal paste applied for TGM installation in the generator construction. The nominal (rated) power of standard TGM-199-1.4-0.8 with cold side temperature of 50 °C and 150 °C at hot side is 4.3 Watts.

For maximum power generation of the TEG the TGM should be chosen taking into account features of other elements of construction including the heat-sinks and thermal interface materials.

Heat resistance of TGM is one of the most important parameters. Heat resistance of heat-sinks on the cold and hot sides is determined by the following ratio:

Rt~k·(Rc+Rh),

were:

k – numerical coefficient equal to 1,0…1,5;
Rc – heat resistance between the cold side of TGM and the ambient (the heat resistance of the heat-sink and thermal transfer compound interface);
Rh – heat resistance between the hot side of TGM and the heat-source with specified temperature.

Some facility test results are presented below compared with the calculated data (fig.5). The graph shows test results of TGM-199-1.4-0.8 (dependence of power output from the load resistance), conducted by KRYOTHERM facility. The results obtained for the mentioned above TGM with standard version (blue graph) at maximum extremum point (4,91W) are 14% better than calculated data given on the website.

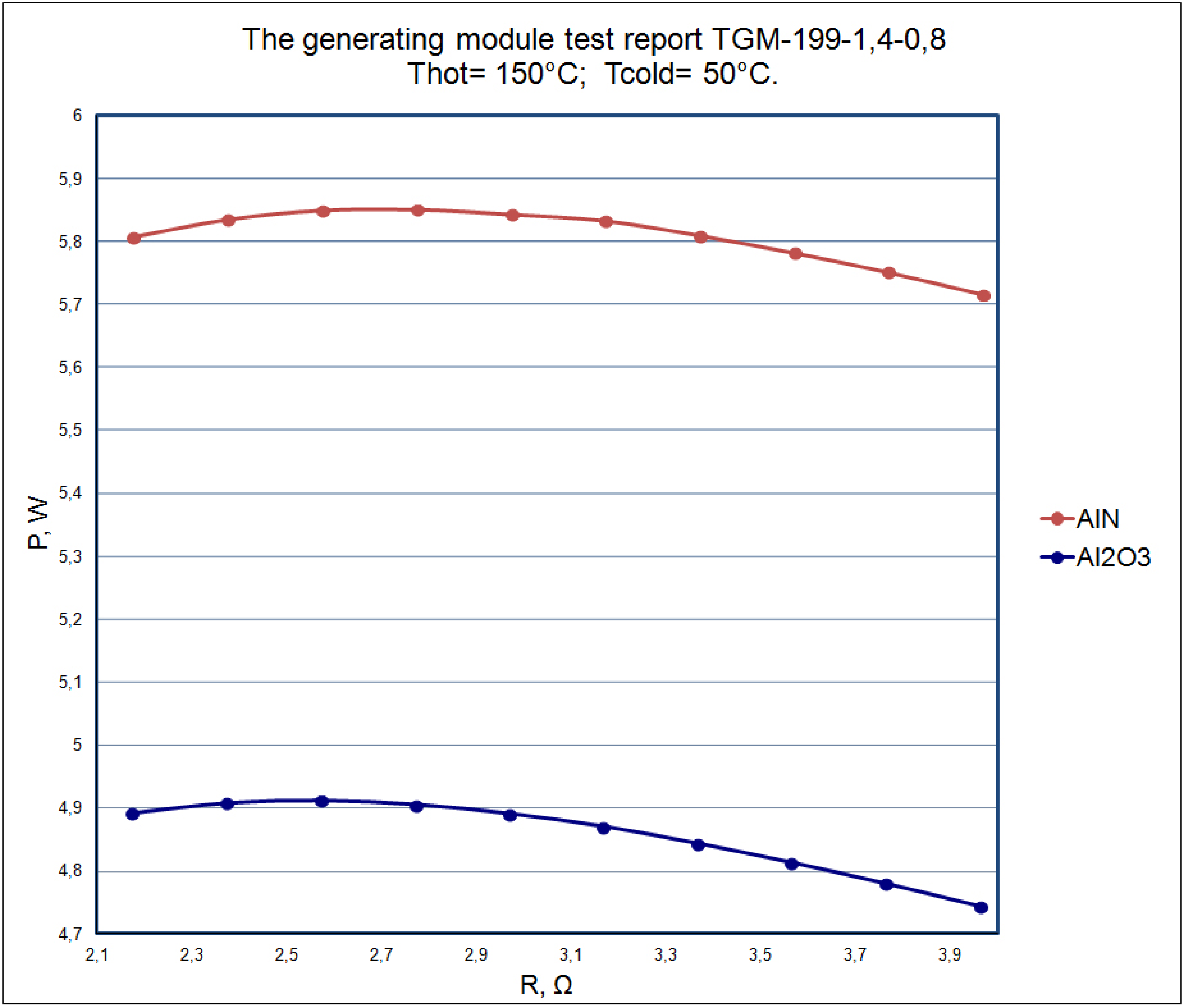

Fig. 6. Facility test results of TGM-199-1.4-0.8.

The red graph reflects test results of the same generator module, but assembled with an AlN ceramic substrate made of high thermal conductivity (AlN - aluminum nitride, thermal conductivity of 200 W /(m * K). As one can see from the graphs, the power generated under similar conditions exceed standard version at 20% due to the reduction of losses of the heat flow on ceramics.

Conclusion №1: The above online information about power generated by standard version of TGM corresponds to the worst conditions, and can be increased e.g. by reducing the thickness of the layer of thermal paste, surface finish of heat exchangers in general, and thoroughness of the assembly of the generator;

Conclusion №2: The application of ceramic substrates with high thermal conductivity on the basis of AlN (aluminum nitride), under the same thermal conditions allows to increase the power output by 20% (in our case from 4,91W to 5,85W).

Conclusion №3: Received results could be extended to calculate the power generated by modules in the wider temperature range. For this one can multiply received power value by the square relationship of the temperature range of 100°C (150°C - 50°C). Thus, for the temperature range 30°C on cold side to 200°C on hot side generated by the module power would be:

14.2 W for TGM-199-1,4-0,8 with ceramics Al_2O_3;

16.9 W for TGM-199-1,4-0,8 with ceramics AlN.