DOI: 10.63527/1607-8829-2024-3-64-73

A. Gurevich, *Cand.Sc. (Phys-Math)* [1*]
I. Steiner, [1]
Z. Dashevsky, *Dok.(Phys-Math)* [2]
S. Vitriuk [3]

[1]Double Check Ltd, Bnei Brak, (Israel)
[2]Ben-Gurion University of the Negev, Beer-Sheva, (Israel)
[3]Interm Ltd, Chernivtsi, (Ukraine)
[*]email: alex@dc-ts.com

DEVELOPMENT OF HIGH PERFORMANCE THERMOELECTRIC MODULES WITH SUBSTRATES MADE BY VAPOR CHAMBER TECHNOLOGY

Thermoelectric systems are widely used in different industrial applications. The main factor limiting rise of application range is relatively low Coefficient of Performance. Improvement performance of Thermoelectric modules (TEM) is a goal of multiple research projects during few decades. Main efforts are applied to development of new efficient materials but significant progress in performance of materials suitable for industrial use has not reached yet. Another way of performance improvement is optimization of modules structure elements, particularly substrates. It is known that performances of TEM are improved with increase of substrates thermal conductivity. The best candidate for highly conductive substrates is Vapor Chamber having effective thermal conductivity of more than 5.000 W/m/K which is about 30 times higher than the best ceramic substrates made from ALN. Optimized Vapor Chambers including copper envelope with sintered wick and aluminum with grooved wick were developed, manufactured and tested. Two different working fluids were used for the hot and cold copper Vapor Chamber substrates: water and methanol. Effective thermal conductivity of copper Vapor Chamber substrates was about 2.500 W/m/K. Computer simulations showed that Thermoelectric Modules with Vapor Chamber Substrates (TEVC) provides more even temperature distribution over the heat sink surface and reduces hot spot temperature on each leg. As a result, effective thermal resistance of heat sink for TEVC is lower than for regular TEM at the same module size, structure, power dissipation and heat sink parameters. For the studied example, thermoelectric system including TEVC assembled with heat sinks provides rise of COP relatively to regular TEM on about 40% at the same conditions. When used as power generator TEVC improves efficiency on more than 18%. Experimental samples of TEVC were manufactured and tested. Good correlation between theoretical and test data was proved. Bibl. 9, Fig. 12.
Key words: thermoelectric modules, thermal conductivity, thermoelectric cooling systems.

Introduction

Thermoelectric systems are used in many applications including military, medical, food transportations, avionics and others [1-3]. The main factor limiting further widening the application range is relatively low Coefficient of Performance. Despite substantial research efforts applied to the development of thermoelectric materials with higher Figure of Merit, the high performance thermoelectric modules are still not available for industrial applications.

A prospective approach for design of high performance thermoelectric systems including regular Thermoelectric Modules (TEM) is combination with other thermal technologies like Vapor Chambers [4-8].

Solution

An ovel approach for improvement efficiency of Thermoelectric Modules (TEM) is optimization of thermal structure elements - substrates [9]. It is known that performances of TEM are improved with increase of substrates thermal conductivity. Effect of substrates thermal conductivity on TEM performance is shown in the Fig. 1.

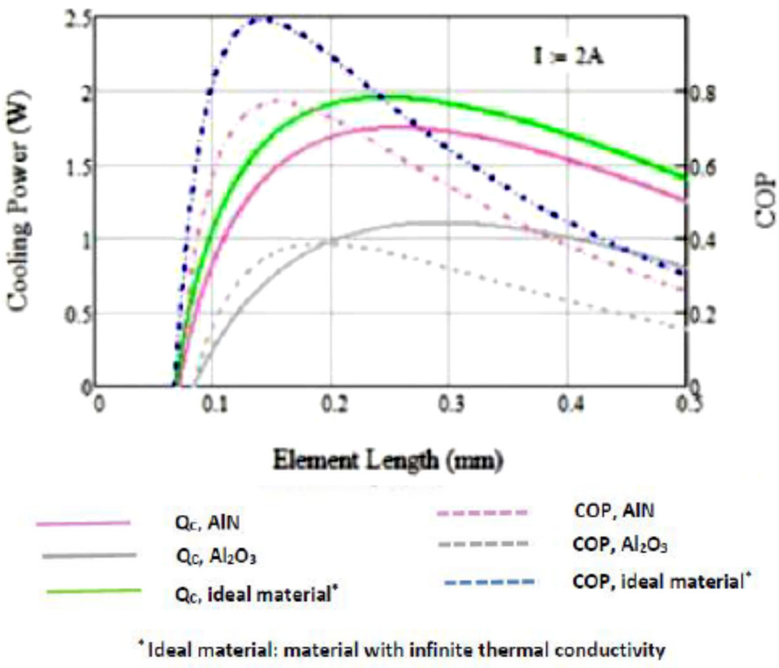


Fig. 1. Dependences of module cooling power and COP on thermoelement length for TEMs with various substrate thermal conductivity

A solution for substrates with extremely high thermal conductivity close to the "ideal material" is use of Vapor Chamber Technology. Vapor Chamber is a heat transfer device operating by fluid evaporation-condensation cycle similar to heat pipes and characterized by effective thermal conductivity of more than 5000 W/(mK). General scheme of Vapor Chamber operation is shown in the Fig. 2.

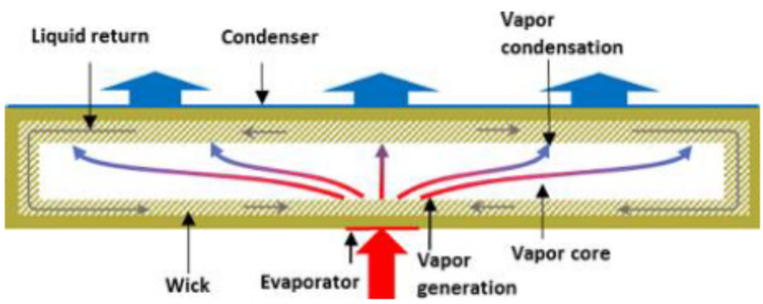


Fig. 2. Schematic of Vapor Chamber operation

As a solution for Thermoelectric Modules performance improvement, we developed patented Thermoelectric Modules with Substrates made by Vapor Chamber Technology (TEVC). Scheme of TEVC structure is shown in the Fig. 3.

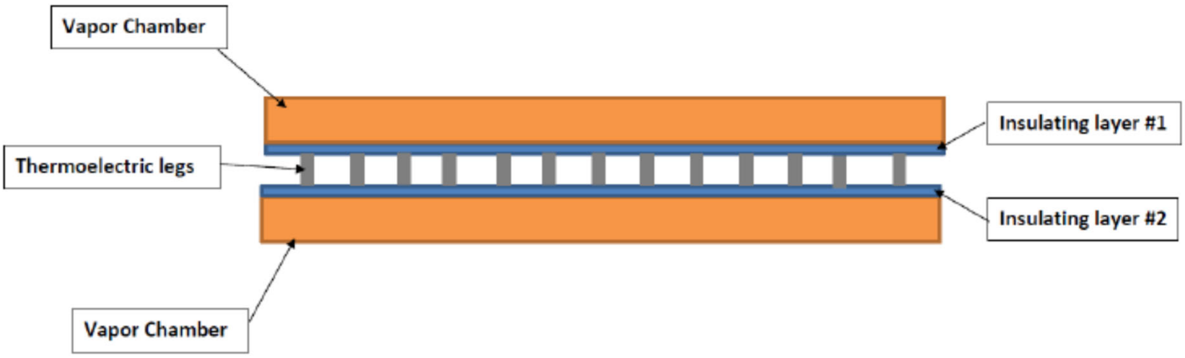


Fig. 3. Schematic of of TEVC structure

Substrates of TEVC is multilayer and consists of the following layers: Vapor Chamber, electrically insulating layer and a pattern of copper conductors.

Technical approach

Vapor Chambers

Two optional materials for Vapor Chamber case were used for TEVC: copper and aluminum. These materials have high thermal conductivities and are widely used for manufacturing of Vapor Chambers.

For copper Vapor Chambers two types of working fluid were used: water for the hot side of TEVC and methanol – for the cold side.

Working fluid for aluminum Vapor Chambers – freon.

Electrical insulating layers

We are evaluating several technological solutions for the insulating layers: DBC/AMB ceramic substrates, thin film ceramics, coatings.

At the present stage DBC *AlN* substrates was used.

Other options will be evaluated during the next stage of development.

Assembly

Special technology including several steps of soldering was developed for assembly of TEVC.

Copper Vapor Chambers have sintered powder wick. Working fluids are water for the hot side substrate and methanol for the cold side substrates. Pictures of the copper Vapor Chamber are shown in the Fig. 4.

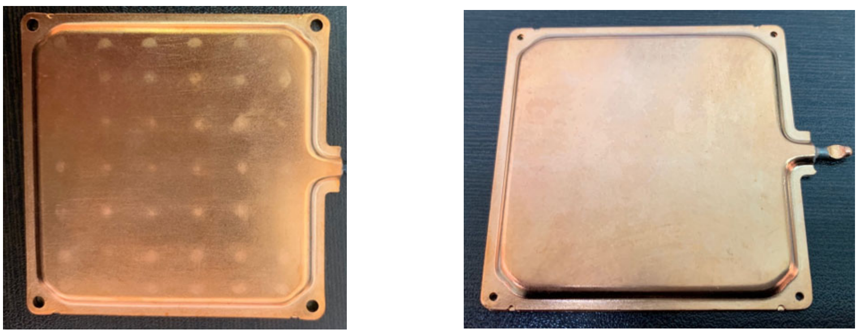
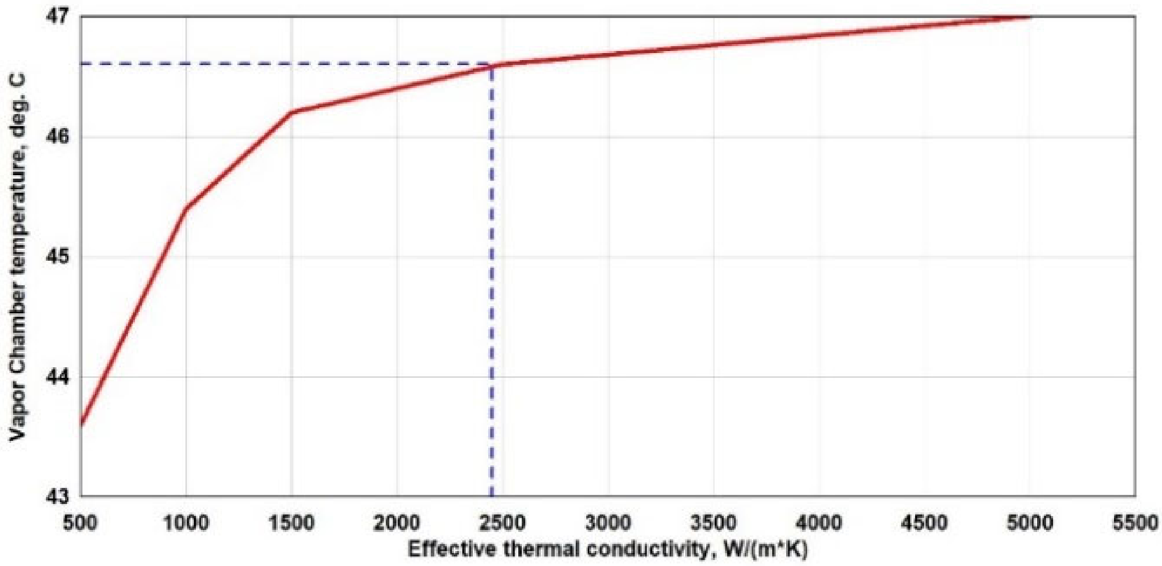
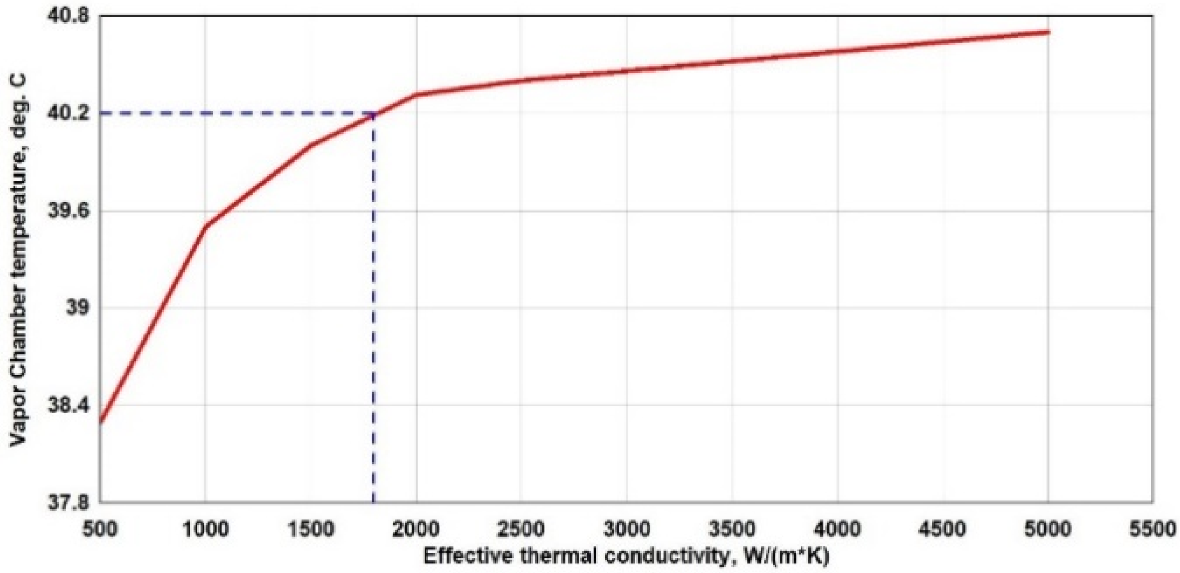


Fig. 4. Pictures of copper Vapor Chamber

Effective thermal conductivity of the Vapor Chamber substrates was measured using special procedure based on comparison between experimental data and results of computer simulations. Results of the evaluations are shown in the Fig. 5.



a)



b)

Fig. 5. Results of effective thermal conductivity evaluation.
a) copper-water Vapor Chamber, b) copper- methanol Vapor Chamber.

As we can see from the Fig. 5a effective thermal conductivity of copper-water Vapor Chamber is equal to 2450 W/m/K. Effective thermal conductivity of copper- methanol Vapor Chamber is 1800 W/m/K (Fig. 5b).

Theoretical background

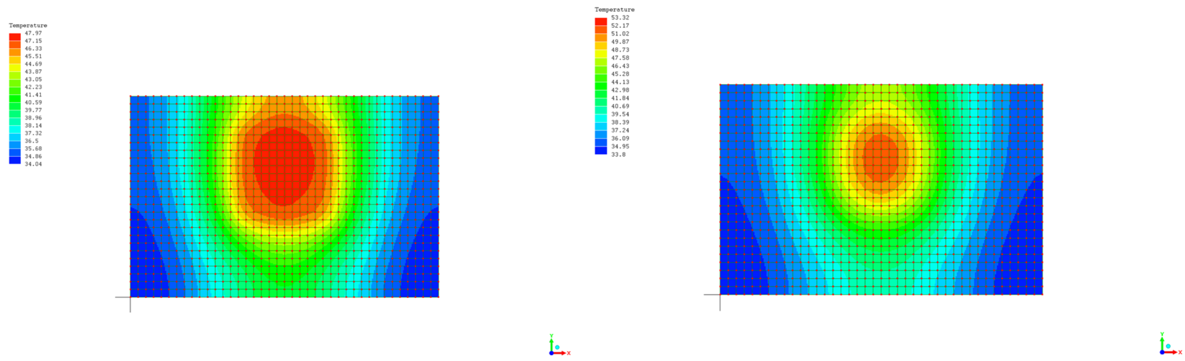
Computer simulations was performed to study performance improvement mechanism for TEVC relatively to regular TEM.

Simulations were made for the TEM/TEVC with dimensions 62x62 mm assembled on aluminium extruded heat sink with fan.

Module parameters: Heat sink parameters:

I_{max} = 7.5 A	Base plate dimensions:	200 × 130 mm
V_{max} = 15.4 V	Base plate thickness:	5 mm
R = 1.1 Ω	Fins height:	19 mm
ΔT_{max} = 70 °C	Air flow rate:	0.9 CMM

Temperature distributions over the heat sink surface for TEVC and regular TEM with alumina substrates were estimated at the same power dissipation of 100 Won the substrate. The results are shown in the Fig.6*a* (TEVC) and Fig. 6*b* (TEM). The maximum heat sink temperature for TEVC is 48.0 °C, and for regular TEM - 53.3 °C.

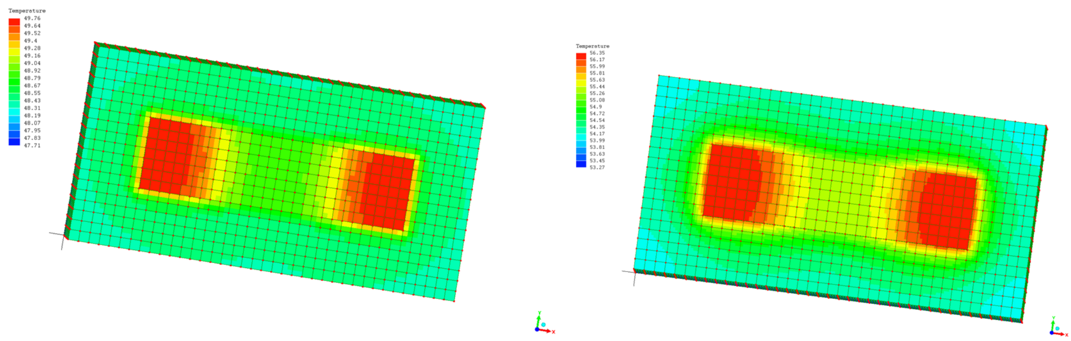


a) *b)*

Fig. 6. Temperature distributions over the heat sink surface for TEVC (a) and regular TEM (b) with alumina substrates.

So, TEVC reduces the maximum heat sink temperature on 5.3 °C relatively to regular TEM at the same operating conditions.

Results of simulations temperatures near the thermoelectric leg are shown in the Fig.7(a - TEVC, b - regular TEM):



a) *b)*

Fig. 7. Temperature distribution near the thermoelectric leg for TEVC (a) and regular TEM (b) with alumina substrates.

The maximum temperature on the leg is 49.7°C for TEVC and 56.7°C for regular TEM showing the total temperature reduction of 7.0°C. Additional reduction of 1.7°C caused by Vapor Chamber ability to spread efficiently hot spot near the thermoelectric leg.

So, for the analyzed case the temperature of thermoelectric leg for TEVC is lower on 7°C relatively to regular TEM. This temperature reduction is caused by two thermal effects:

- More even temperature distribution over the heat sink surface.
- Spreading of the hot spot near each thermoelectric leg.

For thermal design of thermoelectric cooling/heating systems the mentioned temperature reduction can be translated to reduction in effective thermal resistance of heat sink. In other words, TEVC operates like regular TEM with the same structure but assembled with the heat sink having lower thermal resistance. In the present case reduction of effective thermal resistance for TEVC is 0.07 °C/W. It is important to note that this value is not constant and dependent on heat sink characteristics and TEVC dimensions.

Comparison of COP for the thermoelectric cooling systems including regular TEM and TEVC assembled with the heat sinks having thermal resistances Rh=0.2°C/W (hot heat sink) and Rc= 0.3°C/W (cold heat sink) and ambient air temperatures: 25°C (hot side), 2°C (cold side)is shown in the Fig. 8:

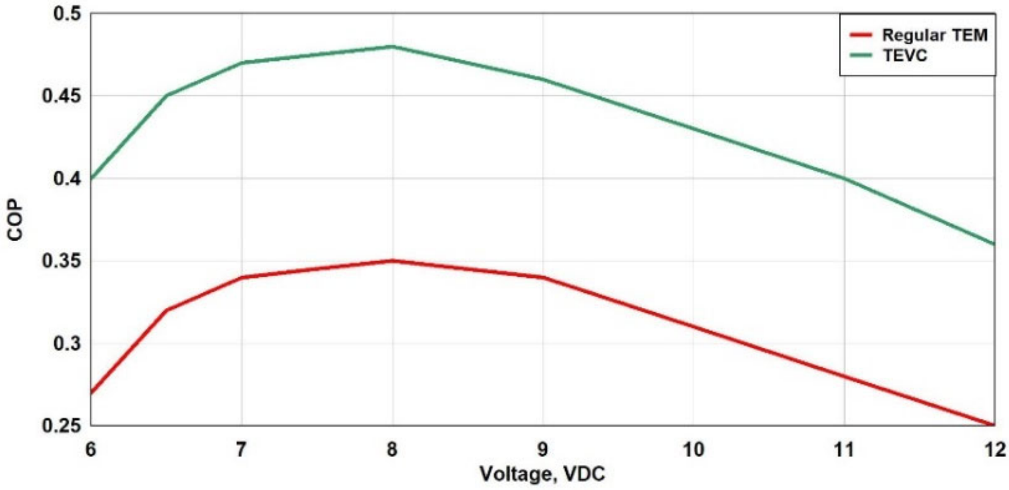


Fig.8. Dependences of COP on voltage for thermoelectric cooling systems

As we can see TEVC provides improvement in COP relatively to regular TEM of about 40% at the same conditions.

Another prospective application of TEVC technology is power generation. The results of power generation assembly simulations are shown in Fig.9.

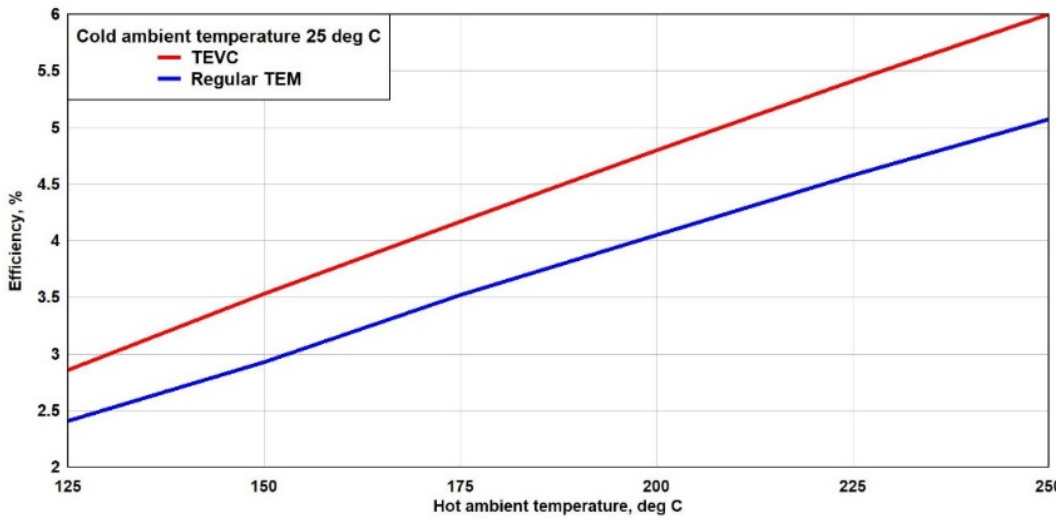
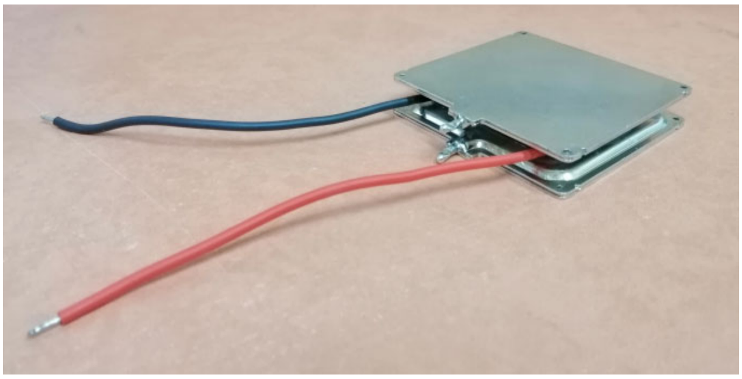


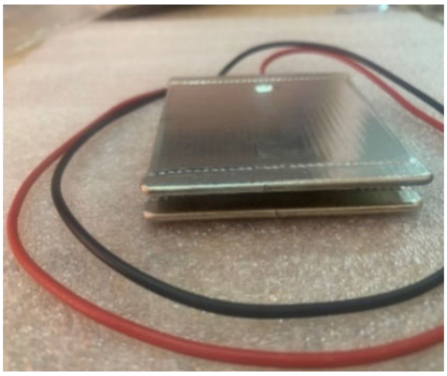
Fig.9. Dependences of efficiency on hot ambient temperature for thermoelectric generating systems

As we can see for the tested case TEVC provides rise in power generation efficiency on more than 18% at the same conditions.

Manufacturing and testing of TEVC samples.

Experimental samples of TEVC with copper and aluminum Vapor Chamber substrates were manufactured and evaluated. Pictures of TEVC are shown in the Fig.10*a* (copper) and Fig.10*b* (aluminum):





a) *b)*

Fig.10. Pictures of copper (a) and aluminium (b) TEVC

Performance tests were made to compare simulations result with experimental data.

Special jig was designed for this purpose(Fig.11):

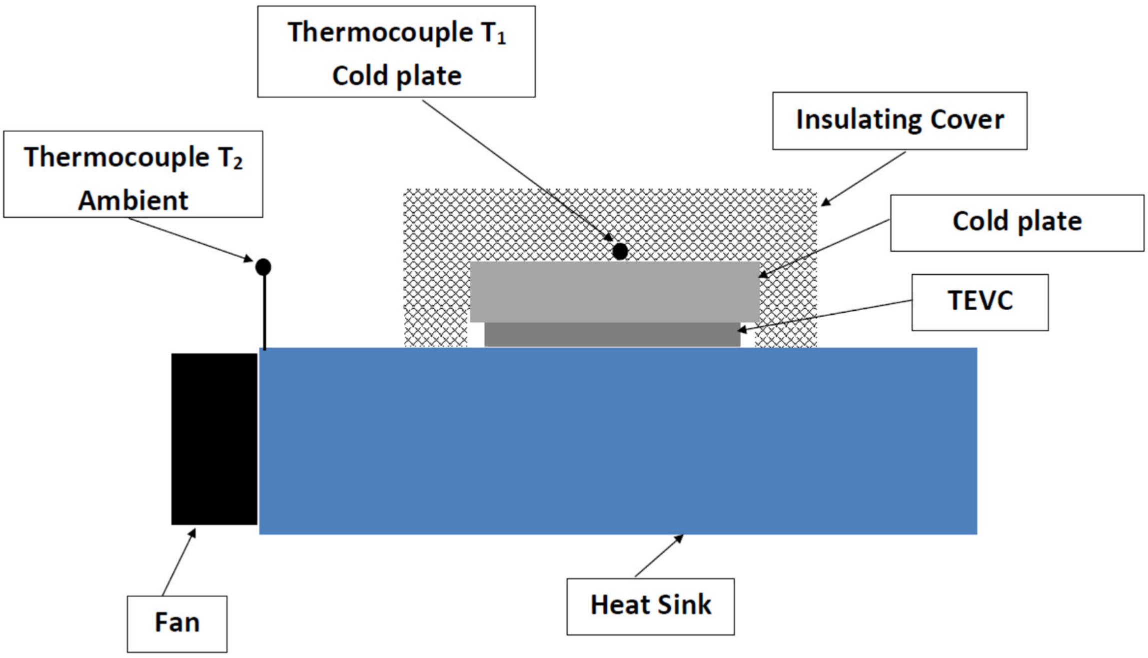


Fig. 11. Schematic of special jig designed for TEVC testing

Comparison of experimental data and theoretical estimations made using "effective thermal resistance", are shown in the Fig.12.

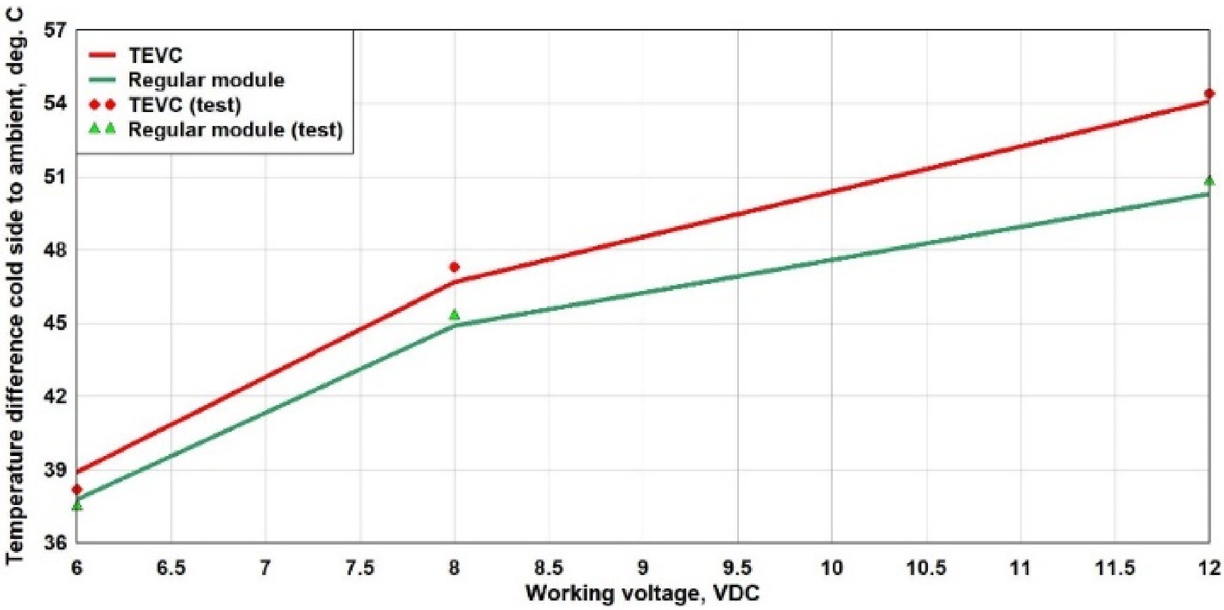


Fig.12. Dependences of temperature drop on working voltage for thermoelectric cooling systems

Good correlation between theoretical and experimental data is found. The maximum relative deviation is 2.6%.

Conclusions

1. A new generation of patented high performance Thermoelectric Modules with Substrates made by Vapor Chamber Technology was developed.
2. Computer simulations show that TEVC provides more even temperature distribution over the heat sink surface and reduces hot spot temperature on each leg. As a result, effective thermal resistance of heat sink for TEVC is reduced relatively to regular TEM at the same module dimensions, internal structure, power dissipation and heat sink parameters.
3. For the studied example, thermoelectric system including TEVC assembled with heat sinks provides improvement of about 40% in COP relatively to regular TEM at the same conditions.
4. Power generation is another prospective application for TEVC because of its ability to provide higher effective temperature difference on the leg relatively to regular TEM at the same conditions of operation. For the tested case TEVC shows rise in power generation efficiency on more than 18% at the same conditions.
5. Prototype of TEVC modules including optimized Vapor Chambers were fabricated and tested using special jig. Good correlation between data calculated based on the effective thermal conductivity and result of experiments was proved.

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Submitted: 10.07.2024.

А. Гуревич, *канд. фіз.-мат. наук* [1*]
І. Штайнер, [1]
З. Дашевський, *доктор фіз.-мат. наук* [2]
С. Вітрюк [3]

[1]Double Check Ltd, Bnei Brak, (Israel)
[2]Ben-Gurion University of the Negev, Beer-Sheva, (Israel)
[3]Interm Ltd, Chernivtsi, (Ukraine)
[*]E-mail of the corresponding author:alex@dc-ts.com

РОЗРОБКА ВИСОКОЕФЕКТИВНИХ ТЕРМОЕЛЕКТРИЧНИХ МОДУЛІВ З ПІДКЛАДКАМИ, ВИГОТОВЛЕНИМИ ЗА ТЕХНОЛОГІЄЮ ВИПАРНОЇ КАМЕРИ

Термоелектричні системи широко використовуються в різних галузях промисловості. Основним фактором, що обмежує розширення діапазону застосування, є відносно низький холодильний коефіцієнт (COP). Покращення продуктивності термоелектричних модулів (ТЕМ) є метою багатьох дослідницьких проектів протягом кількох десятиліть. Основні зусилля спрямовані на розробку нових ефективних матеріалів, але значного прогресу в характеристиках матеріалів, придатних для промислового використання, ще не досягнуто. Іншим способом підвищення продуктивності є оптимізація елементів структури модулів, зокрема підкладок. Відомо, що характеристики ТЕМ покращуються зі збільшенням теплопровідності підкладок. Найкращим кандидатом на високопровідні підкладки є випарна камера з ефективною теплопровідністю понад 5000 Вт/м/К, що приблизно в 30 разів вище, ніж у найкращих керамічних підкладок, виготовлених з ALN. Було розроблено, виготовлено та випробувано оптимізовані випарні камери, включаючи мідну оболонку з спеченим ґнотом і алюмінієву з рифленим ґнотом. Для підкладок *гарячої та холодної мідної випарної камери використовувалися дві різні робочі рідини: вода та метанол. Ефективна теплопровідність мідних підкладок випарної камери становила близько 2500 Вт/м/К. Комп'ютерне моделювання показало, що ТЕМ з підкладками за технологією випарної камери (ТЕМВК) забезпечують більш рівномірний розподіл температури по поверхні тепловідводу та знижують температуру гарячих точок на кожній гілці. Як наслідок, ефективний термічний опір тепловідводу для ТЕМВК нижчий, ніж для звичайного ТЕМ при тому ж розмірі модуля, структурі, розсіюваній потужності та параметрах тепловідводу. Для досліджуваного прикладу термоелектрична система, що включає ТЕМВК у зборі з тепловідводами, забезпечує підвищення COP відносно до звичайного ТЕМ приблизно на 40% за тих же умов. При використанні в якості генератора електроенергії ТЕМВК підвищує ККД більш ніж на 18%. Виготовлено та випробувано дослідні зразки ТЕМВК. Доведено хорошу кореляцію між теоретичними та тестовими даними. Бібл. 9, рис. 12.*

Ключові слова: термоелектричні модулі, теплопровідність, термоелектричні системи охолодження.

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Надійшла до редакції: 10.07.2024.