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Heat pipe embedded cold plate design with additive manufacturing technologies

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Abstract

Heat pipe embedded/integrated cold plates are mostly preferred to increase the thermal conductivity of the base material to have passive thermal management in reliable products. Thanks to Additive Manufacturing (AM) Technology, it became possible to find a high conductive product by simultaneously manufacturing the heat pipe in the cold plate. In this study, the heat pipe embedded cold plate design of an electronic chassis designed for a military product has been investigated in detail. Performing this study, it is seen that there are many outstanding advantages of using AM technology compared to the conventional heat pipe embedding techniques. Thermal analysis of a 6U size cold plate with a high thermal load is performed for aluminum & copper base material and groove type heat pipe embedded aluminum cold plate (HPECP). After that, the manufacturing constraints of both techniques are compared and outstanding design capabilities with AM technology are discussed in detail. It is seen that by using AM technology, it is possible to have a lighter cold plate with improved thermal conductivity in one piece and even lower cost.

Keywords: Cold Plate, Heat Pipe Embedded Cold Plate, Additive Manufacturing, Groove Type Heat Pipe, Electronic Cooling.

1. Introduction

In electronic cooling applications, depending on the requirement one can find many different packaging techniques. To have a low-cost and reliable product, mostly preferred cooling technique is the passive technique which does not require any control, energy, or rotating parts. A heat pipe is the most preferred technique to carry heat from the heated zone to the low-temperature locations to have effective cooling passively. Depending on the design approaches, heat pipe type, material, and filling fluid can be selected accordingly and the embedding processing can be performed after several stages to provide the requirement. It is known that many experienced companies are working in this field that can perform heat pipe embedding techniques to the base material. Till now, one can see that many different shapes have been used in many products both industrial and military applications. Since additive manufacturing technologies increases the flexibility, the point of view on product development has been steadily improving every day. Robinson et al. [1] studied the wicked heat pipe with AM to investigate the thermal performance of a novel cross-hatched porous wick structure and in each layer, the hatch distance is altered to have different wick properties. Characterizing the thermal performance in terms of thermal resistance, an effective two-phase cavity has been performed for different parameters. Recently, many studies have been published that cover heat pipe production with AM technology for space and earth applications [2-9]. In this study, AM technology is applied to have a highly conductive aluminum plate with an innovative heat pipe for a military product providing a lighter design.

1.1. Direct Metal Laser (Sintering DMLS) technique

There are many 3-D manufacturing techniques that serve different advantages depending on the requirement. DMLS is the most widely used 3D Printing process because of the multiple benefits it provides for many applications. DMSL enables metal AM by supporting a wide range of metals like titanium, steel, aluminum, stainless steel, nickel alloys, cobalt chrome, and precious metals. In addition, it can print metals or prototypes directly. The metal alloys make DMLS effective in producing functional parts that are both strong and durable. Nowadays, many engineers use DMLS for fully-functional parts and prototypes in their designs. It enables freedom in design without dealing with tooling and fixturing. One can also reuse unsintered metal powder after the printing process. Smooth surfaces can also be achieved with this technique.

1.2. Heat pipe application in electronic cooling

A heat pipe is a passive two-phase heat transporting technology used in many engineering applications. Its working principle is based on the enthalpy changes of fluid from liquid to vapor. It has basically three different regions called the evaporator, condenser, and adiabatic. It can be in many types and shapes depending on the application as far as working temperature range, thermal performances, and its medium (gravity assist or against-gravity) are considered. Its performance can be affected by many design parameters like, geometry, filling ratio, fluid types, enveloping metal, orientation, evaporator and condenser area, heat load, etc. Therefore, it is an interesting and promising technology to achieve a passive and compact design. It is an important issue to embed the heat pipe in a cold plate to spread the heat as well as possible to have a high conductive plate. The main issue to embed a heat pipe is to have minimum contact resistance between the base metal and heat pipe, a tight attachment, and a flat smooth surface.

2. Material and methods

Both HPECP and bare 6U size cold plate has been analyzed using Ansys 2022 Fluent® tool to have temperature distribution with fixed side wall temperature boundary conditions. An aluminum cold plate with a groove heat pipe is manufactured in one piece. Since the heat pipe is already manufactured with the cold plate using AM technology, there is no need for the bonding or flattening process of the materials. After filling the pipes in the cold plate with a proper liquid, it is ready for use. For 3D AM, aluminum material is used as AlSi10Mg powder and the thermal conductivity of the material is assumed to reach k=170W/mK with the heat treatment process. In the analysis, heat pipe conductivity is taken to be a variable between k=500 to 5000 W/mK to investigate thermal behavior depending on the possible gravitational effects and use of different fluids. In the manufacturing stage, one of the most important parameters is to have the groove size as planned. In heat pipe application, it is crucial to provide the necessary pumping power in the evaporator section and to allow the condensed liquid to come back from the condenser to the evaporator section with the aid of gravity and capillary effect through the grooves. Depending on the required pumping power, this groove shape can be adapted to have an efficient cooling design. Mostly tapered and omega-shaped grooves are preferred depending on the required force. Heat pipe orientation in the plate and groove details are given in Fig. 1. Cold plate has 233.4 mm length, 164.0 mm height and 25.0 mm width.

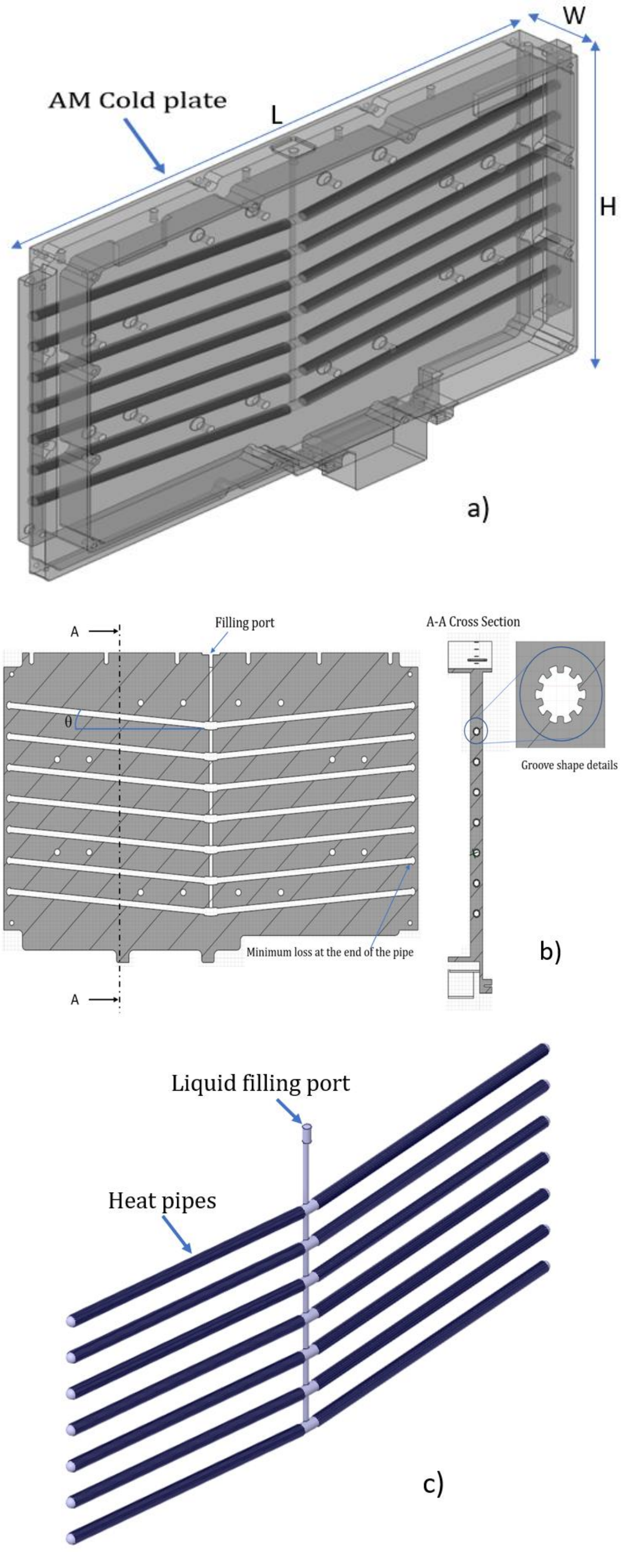

Fig 1. a) 3D transparent modal of the 6U cold plate, b) Cut view of the plate c) AM Modal of Cold plate with heat pipes and liquid filling port only.

AM-Manufacturing has been done at the facilities of ALUTEAM® Company located in İstanbul. EOS M 290 machine is used with the DMLS (Direct Metal Laser Sintering) technique with a layer thickness of 30mm.

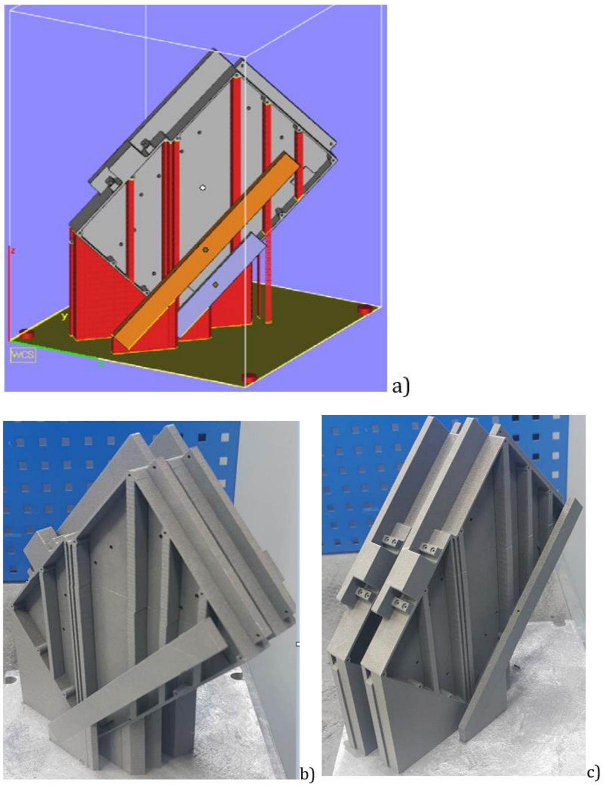

Fig 2. a) Materialize magics ® software view, b-c) A view of finished product with supports, (at ALUTEAM Facilities).

The production is carried out with two samples at the same powder bath with different groove shapes and a small section including only the heat pipe details has been also manufactured during the process for detail examination. In Fig. 2, Materialize magics® software view and finished product without post-processing are illustrated to follow the process closely.

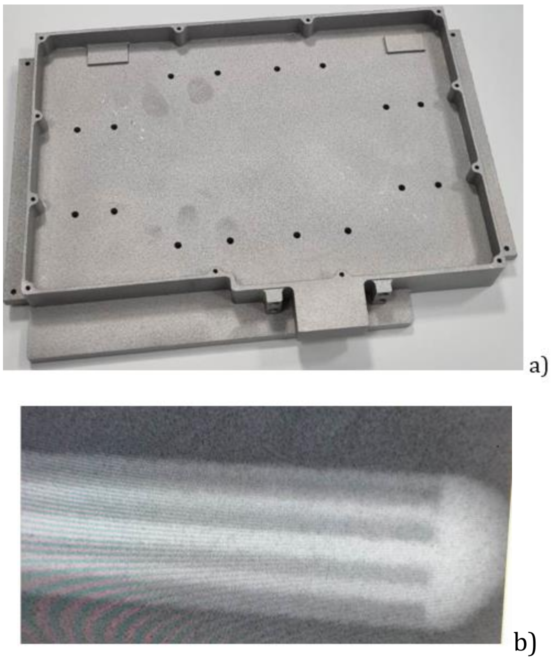

Fig 3. a) Final product picture after supports are removed b) X-Ray view of the groove HP, (at ASELSAN INC. Facilities) with inner diameter of 4 mm and 6 mm cold plate thickness.

In Fig. 3a the final product after removing the supports and applying shot blasting is given. In Fig. 3b an X-ray view of a small part of the heat pipe is illustrated. Additional thickness of 0.5 mm is left on both faces of the plate and wedge lock contact surfaces. The surfaces will be smoothed after a milling operation to have minimal contact resistance between the parts to have low thermal resistance on the conduction path. The holes on the plate are left for the mounting inserts.

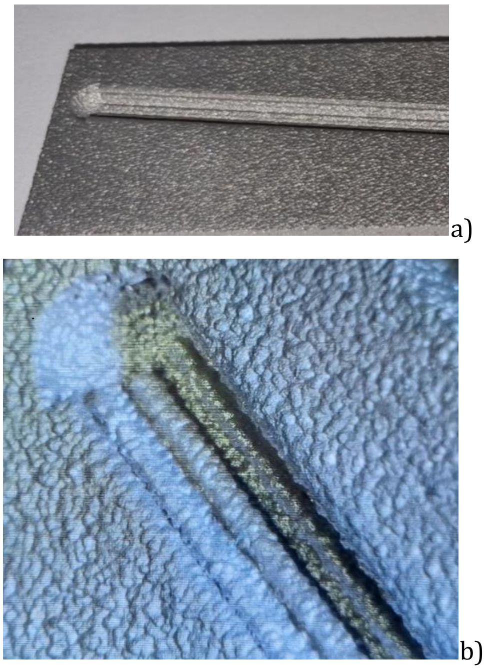

Fig 4. a) Picture of the half-detailed groove HP with AM manufacturing, b) microscopic view of a small part of it.

In Fig. 4, views of the single groove heat pipe details are illustrated with a microscopic picture.

3. Thermal modelling with FVM

Finite Volume Method (FVM) is a suitable method for especially fluid flow problems to study the problem numerically. In the solving and evaluation part, Fluent 2022® has been used with sufficient element numbers to compare the cases. In Fig. 5, thermal modal, a cold plate with heat pipes and boundary conditions are given to define the problem well. The thermal performance and weight comparison of each case are illustrated in the result part. In order to compare the thermal performance of each case, temperature difference equation (1) is used.

$$\Delta T= T_{hot\_spot}-T_{wall} \tag{1}$$

Where, T_{hot_spot} and T_{wall} refers to the average temperature of any heat source given and side wall boundary condition 71°C respectively illustrated in Fig. 5b. The cold plate is cooled through the side walls and to make a reasonable comparison. They are kept at constant temperature and therefore all thermal resistance is calculated as given in equation (2).

$$R_{th}= R_{cond}+R_{contact} \tag{2}$$

Where R_{th} refers to the total thermal resistance including conduction (R_{cond}=kA/L) and contact resistance ($R_{contact}$) between the cold plate and chassis wall including wedge lock. R_{cond} is directly related to the thermal conductivity of the material, length, and cross-sectional area of the plate. While contact resistance involves pressure applied by the wedge lock mechanism and surface roughness of both the cold plate and chassis wall. Using the traditional wedge lock, the thermal resistance can be defined differently for each contact surface as shown in Fig. 5b. For the present case, there are two big size heat loads with 40W each and there are also smaller heat sources with 10 W each. The structure is symmetric with respect to the vertical axis as shown in Fig. 5a. Total heat load is 100W and the calculated resultant contact resistance ($R_{contact}$) is 0.1428°C/W which gives rise to a 7.1°C temperature increment at the card edge. Heat pipe thermal conductivity is defined as k_{eff} and it is altered in the analysis to evaluate the performance of the heat pipe effect.

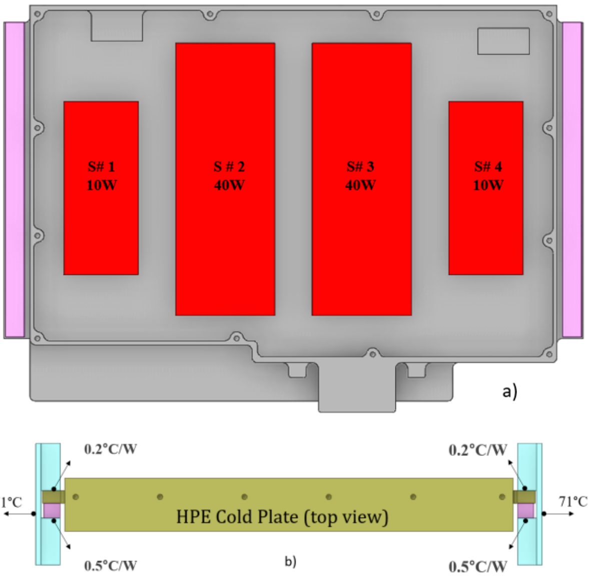

Fig 5. a) Thermal modal and heat sources, b) boundary conditions of the cold plate with wedge lock thermal resistance.

4. Results and discussion

Analysis results of all solutions are given in the following figures. Accordingly, depending on the fluid, filling ratio, gravitational effect and condenser area the thermal performance of HPECP changes. In Fig. 6, the thermal contour of HPECP is given for k_{eff} = 3000W/mK. This value gives the same thermal performance as that of a copper cold plate. The side wall of the plate is around 79°C due to the addition of the wedge lock mechanism and contact resistance. The hot spot is located at the center of the cold plate as it is expected due to the symmetry boundary condition.

In Fig. 7, the thermal performance (ΔT) of the cold plate depending on the k_{eff} is plotted. Therefore, instead of using copper, there is a possibility that an Aluminum HPECP can serve satisfactory thermal and mechanical results with a much lighter weight.

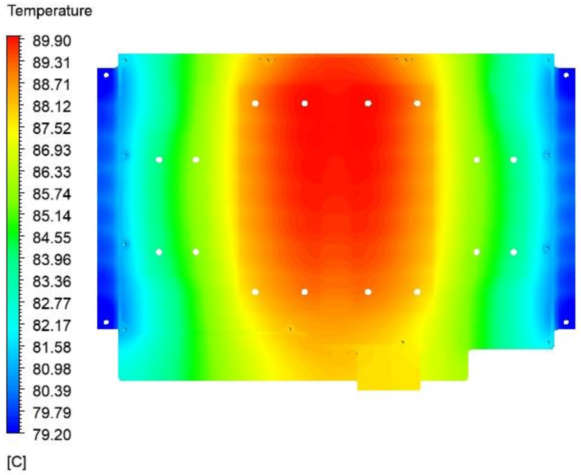

Fig 6. Temperature contour of HPECP with k_{eff}=3000 W/mK which is equal to the pure copper performance.

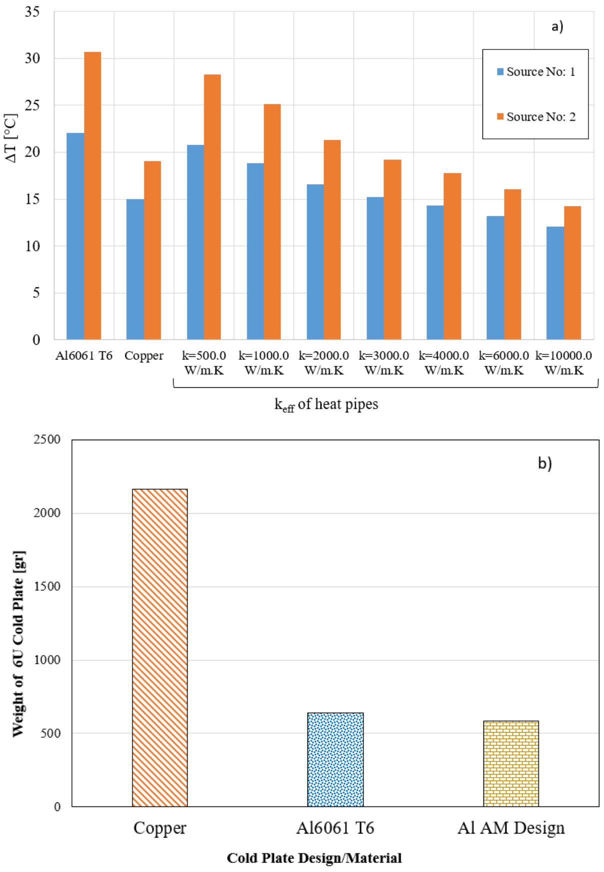

Fig 7. Illustration of a) Thermal performance and b) weight comparation of different cold plates.

Using AM technology, many advantages have been gained and this makes it possible to find more design versatility to have better thermal results. Table 1 is given to compare the pros & cons of using 3-D AM technology instead of the conventional embedding approach. In conventional methods, bonding of heat pipe to base material brings about many problems in terms of both mechanical and thermal respects. It is aimed that AM can solve many problems and result in a higher thermal performance of the cold plate. For the time being, it is thought that AM technology will let the designer design more challenging parts to have a lighter, reliable, and thermally well product in the near future. Most probably, some powder with a negligible amount will be trapped in the AM cold plate. However, this may not create a problem. On the contrary, it may add some additional thermal conductivity to the fluid behaving like a nanoparticle. And it is known that there are many studies in the literature investigating the effect of nanoparticles on thermal performance for single-phase liquid cooling and heat pipe applications.

Table 1. Comparison of two different manufacturing techniques in a heat pipe embedded cold plate production.

	Conventional Manufacturing Methods	Additive Manufacturing Technology
Use of filler (bonding) material	+	-
Inconsistent different materials	+	-
Additional thermal contact resistance	+	-
Post-processing	+	+
Difficulties in bending or fitting	+	-
Difficulties in the manufacturing of heat pipe	+	-
Loss of performance due to flattening process	+	-
Need to use a thick plate to embed the heat pipe	+	-
Using adhesive material can shorten the effective length	+	-
Powder removal	-	+
Surface finishing	+	+

5. Conclusions

In this study, we have shown that a 6U size cold plate for a PCB can be manufactured with AM technology including groove heat pipes details to increase the conductivity of the aluminum cold plate. Theoretically, it is seen that HPECP can satisfy the thermal requirement as far as the filling is done accordingly. With the proper design, it is possible to change the fluid and its ratio without damaging the base material to perform series tests with a single sample without wasting materials.

As a future work; after the filling operation is completed, a thermal test will be conducted for a reliable comparison with different fluids like acetone and pentane including CNT (carbon nanotubes) nanoparticles to have the desired thermal performance.

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Author's statement

Conflict of interest: The authors are associated with ASELSAN Inc. REHIS-Engineering Division, Ankara, Turkey. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: n/a.

References

1. Robinson, A.J, J. Colenbrander, T. Deaville, J. Durfee, R. Kempers, *A wicked heat pipe fabricated using metal additive manufacturing*, International Journal of Thermofluids, https://doi.org/10.1016/j.ijft.2021.100117
2. Scott M. T, Z. S. Aspin, N. Shamsaei, A. Elwany, L. Bian, *Additive manufacturing of heat exchangers, A case study on a multi-layered Ti–6Al–4V oscillating heat pipe*, Additive Manufacturing, Volume 8, 2015,Pages 163-174,ISSN 2214-8604, https://doi.org/10.1016/j.addma.2015.09.003.
3. Ryan J. M, *An introduction to additive manufactured heat pipe technology and advanced thermal management products*, Thermal Science and Engineering Progress, Volume 25, 2021,100941, ISSN 2451-9049, https://doi.org/10.1016/j.tsep.2021.100941.
4. Wu. F and A. M. EL-Refaie, *Investigation of an Addtively-Manufactured Modular Permanent Magnet Machine for High Specific Power Design*, 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 777-784, DOI: 10.1109/ECCE.2019.8912763.
5. Phull, G.S, S. Kumar, R.S. Walia, *Conformal Cooling for Molds Produced by Additive Manufacturing*; *A Review*, International Journal of Mechanical Engineering and Technology 9(1),2018, pp. 1162–1172. http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=1
6. Richard, B. , W. G. Anderson and J. Crawmer, *Development of a 3D Printed Loop Heat Pipe*, 2019 35th Semiconductor, Thermal Measurement, Modeling and Management Symposium (SEMI-THERM), 2019, pp. 58-60.
7. Richard, B., B. Anderson and D. Pellicone, *Loop Heat Pipe Wick Fabrication via Additive Manufacturing*, 47th International Conference on Environmental Systems ICES-2017-12 Advanced Cooling Technologies, Inc., Lancaster, PA, 17601, 16-20 July 2017, Charleston, South Carolina.
8. Belfi, F., F. Iorizzo, C. Galbiati, and Lepore, F., *Space Structures with Embedded Flat Plate Pulsating Heat Pipe Built by Additive Manufacturing Technology: Development, Test and Performance Analysis*, ASME. J. Heat Transfer. September 2019; 141(9): 095001. https://doi.org/10.1115/1.4042082
9. *Yan, B.H., C. Wang, L.G. Li, The technology of micro heat pipe cooled reactor: A review, Annals of Nuclear Energy, Volume 135,2020,106948, ISSN 0306-4549, https://doi.org/10.1016/j.anucene.2019.106948.*