THERMAL PERFORMANCE EVALUATION OF DIFFERENT PASSIVE DEVICES FOR ELECTRONICS COOLING

by

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The advent of modern electronic technology lead to miniaturization and high power density of electronic devices, then the existing electronic cooling techniques cannot be used, directly affecting the performance, cost, and reliability of electronic devices. Thus, the thermal management of electronic packaging has become a key technique in many products. Passive heat transfer devices can be a good alternative to the stabilization of electronic devices temperature. In this research, an experimental evaluation of the thermal performance of four different passive devices was accomplished. The considered devices were a rod, a thermosyphon, a heat pipe with a metal screen as the capillary structure, and a heat pipe with microgrooves. The heat pipe is a highly efficient device that carries large amounts of power with a small temperature difference. The heat pipe consists of the involucre, the working fluid, and the capillary structure. The thermosyphon is a kind of heat pipe assisted by gravity. In other words, it has no wick structure to return the working fluid. The devices were made of copper with a total length of 200 mm and an outer diameter of 9.45 mm. The thermosyphon and the heat pipes used deionized water as working fluid with a filling ratio of 60% of the evaporator volume. The devices were tested in vertical and horizontal positions under thermal loads between 5 W and 45 W. All the devices have operated satisfactorily when tested in accordance with the behavior of the thermal resistance. The heat pipes were the best among the tested devices and the best position was vertical.

Key words: *experimental thermal performance, passive devices, heat pipes, thermosyphons*

Introduction

Due to the advent of the modern electronic technology, electronic device miniaturization and higher switching speeds created a significant demand for achieving high heat dissipation rates [1]. The failure factor of the electronic devices resulting from electromigration and oxide breakdown, in general, increase almost exponentially with the working temperature that should not exceed a value between 85 °C and 100 °C [2]. Limiting the maximum operating temperature has resulted in an increase of packaging complexity, then the existing electronic cooling techniques cannot be used, directly affecting the performance, cost, and reliability of electronic devices [3]. Thus, the thermal management of electronic packaging has be-

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come a key technique in many applications [4]. The heat pipes and/or thermosyphons are heat exchangers with phase change, which can be a good technological solution alternative to the stabilization of microelectronic devices temperature [5].

Heat pipes and thermosyphons are passive heat transfer devices capable of transferring large amounts of heat with a small temperature difference. They became popular in recent decades because of their effectiveness and convenience [6]. These devices are used to improve heat transfer in many industrial fields such as electronics, telecommunications, aerospace, among others [7]. Heat pipes and thermosyphons are devices with very high thermal conductivity, 10-50 times greater than a solid rod with the same dimensions [8]. The heat transmitted through these devices is based on phase change. Major advantages of heat pipes include a very high thermal conductance, no pumping power requirements, no moving parts, and relatively low-pressure drops [9]. Furthermore, the heat pipes and thermosyphons are devices relatively simple to manufacture and, therefore, have low cost when their geometry is favorable. However, as their dimensions are reduced, the manufacturing complexity increases, resulting in a consequent increase in cost [10]. Therefore, new technologies, which improve the heat pipes' and thermosyphons' efficiency while reducing their cost, are very welcome [11].

The heat pipes and thermosyphons operate according to the following principle [12]: in the evaporator region, heat is transferred to the heat pipe or thermosyphon, vaporizing the working fluid contained inside this region. The steam generated is moved, due to the pressure and density differences, to the cooling regions of the heat pipe or thermosyphons (condenser region) where heat transported is rejected to the cold source. In the heat rejection process, the steam condenses, and the condensate returns back to the evaporator closing the cycle. The adiabatic region, which may have variable dimensions (in some cases it is absent) is located between the evaporator and the condenser being insulated from the external environment. In the heat pipes, the working fluid returns from the condenser to the evaporator due to capillary pumping effect. However, the return of the working fluid occurs because of the gravity in thermosyphons, once they do not have capillary structure. A schematic diagram of the operating principle of heat pipes is presented in fig. 1 [13]. More details on the principle of the heat pipes and thermosyphons can be found in [5-7, 9, 10].

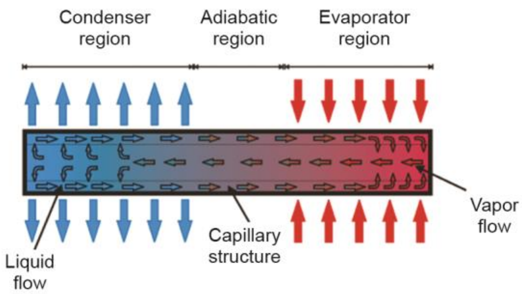


Figure 1. Schematic representation of the operating principle of heat pipes

The heat pipes basically consist of a metal tube sealed with capillary structure internally, which is embedded with a working fluid [14]. This capillary structure can be made of screen meshes, grooves, or sintered media [15]. The metal screen is the most commonly used capillary structure because of availability, ease of construction and good capillary pumping [16]. The grooves, as capillary structure, have a high thermal conductivity and good permeability [17]. As mentioned earlier, the thermosyphon is a heat pipe assisted by gravity, because it has no capillary structure to return the working fluid. Some papers available in the literature on heat transfer passive devices that include heat pipes and thermosyphons are presented in [2, 3, 5-7, 11, 14-26].

Therefore, in this research, the thermal performance of four heat transfer passive devices was investigated experimentally in horizontal and vertical positions. Due to their geometrical characteristics, they can be applied to electronics cooling. The considered devices were a rod, a thermosyphon, a heat pipe with a metal screen as capillary structure, and a heat pipe with microgrooves. The results compared the thermal performance, in order to evaluate the best passive heat transfer device.

Manufacturing of the passive devices

The methodology for manufacture (cleaning, assembly, tightness testing, evacuation procedure, and working fluid filling), test, and analysis of the passive devices of heat transfer was based on considerations of [27-29].

Characteristics of developed passive devices

Copper tubes ASTM B-75 Alloy 122 with an outer diameter of 9.45 mm, an inner diameter of 7.75 mm, and a length of 200 mm were used to fabricate the heat pipes and thermosyphon. The rod was obtained from a full copper bar ASTM B-75 Alloy 122 with the same dimensions of the developed heat pipes and thermosyphons. All the devices have an evaporator of 80 mm in length, an adiabatic region of 20 mm in length, and a condenser of 100 mm in length. The working fluid used was deionized water with a filling ratio of 60% of the evaporator volume. Table 1 shows the main characteristics of the heat transfer passive devices analyzed in this research.

Table 1. Main characteristics of passive devices

Characteristics	Rod	Thermosyphon [27]	Heat pipe with screen mesh [28]	Heat pipe with microgrooves [29]
Inner diameter [mm]	–	7.75	7.75	6.20
Outer diameter [mm]	9.45	9.45	9.45	9.45
Evaporator length [mm]	80.0	80.0	80.0	80.0
Adiabatic section length [mm]	20.0	20.0	20.0	20.0
Condenser length [mm]	100	100	100	100
Working fluid	–	Water	Water	Water
Volume of working fluid [mL]	–	2.26	2.19	1.73
Filling ratio [%]	–	60	60	60
Capillary structure	–	No capillary structure	Phosphor bronze screen mesh #100	Microgrooves by the wire-EDM

According to [28, 30], the best thermal behavior results were presented by the screen mesh #100. Thus, the heat pipe with screen mesh used one layer of phosphor bronze mesh #100 as capillary structure. A micro-scale image of screen mesh #100 is shown in fig. 2(a). The image was obtained by backscattered electron detector for SEM. More information about this heat pipe can be found in [28].

The grooved heat pipe had 32 microgrooves made by the wire electrical discharge machining (wire-EDM). The microgrooves details are shown by a micro-scale image in fig. 2(b). More details about this heat pipe can be found in [29].

Experimental analysis

Experimental apparatus

The experimental apparatus used for the experimental tests, shown in fig. 3, is composed of a power supply unit (Agilent^{TM} U8002A), a data logger (Agilent^{TM} 34970A with 20 channels), a Dell^{TM} laptop, a universal support, a uninterruptible power supply NHS^{TM}, and an Ultrar^{TM} fan.

For the evaluation of the thermal performance of the different heat transfer passive devices, K-type thermocouples Omega^{TM} were used. They were fixed on the outer surface of the devices by a thermosensitive adhesive strip Kapton^{TM}. As shown in fig. 4, there were three thermocouples in the evaporator ($T_{evap,1}$, $T_{evap,2}$, and $T_{evap,3}$), one thermocouple in the adiabatic section (T_{adiab}), and four thermocouples in the condenser ($T_{cond,1}$, $T_{cond,2}$, $T_{cond,3}$, and $T_{cond,4}$) for the heat pipes and thermosyphon. For the rod, two thermocouples were fixed in the evaporator ($T_{evap,1}$ and $T_{evap,2}$), one thermocouple in the adiabatic section (T_{adiab}) and three thermocouples in the condenser ($T_{cond,1}$, $T_{cond,2}$, and $T_{cond,3}$).

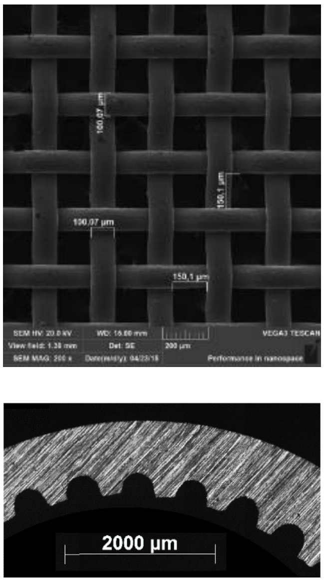
(a)
(b)


Figure 2. Micro-scale image of different capillary structures; (a) screen mesh #100, (b) microgrooves

Figure 3. Experimental apparatus

The heating system of the evaporator was conducted by power dissipation from the passage of an electric current in a nickel-chromium alloy power strip resistor Omega^{TM} with 0.1 mm in thickness and 3.5 mm in width. To ensure that the generated heat by Joule effect was transmitted to the evaporator, an aeronautic thermal insulation and a layer of polyethylene were installed in this region. A fiberglass tape was used in adiabatic section as heat insulation between the support and the passive device. The cooling system using air forced convection consisted of a fan in the condenser region.

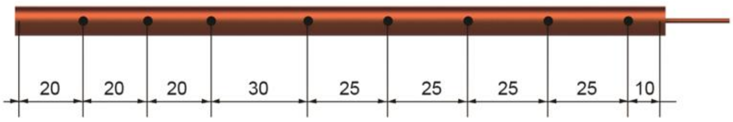


Figure 4. Thermocouple positions [mm]

Experimental procedure

To ensure the best results and the repeatability of experimental tests, the ambient temperature was maintained at 20 °C ± 1 °C by the thermal conditioning system York^{TM}. A detailed check of the equipment and the passive device (fixing thermocouples, thermal insulation, resistor connection, among others) was made before each experimental test. The passive device was carefully fixed to the universal support with a bracket in the adiabatic region at the desired position. The fan was turned on, positioned correctly in the condenser region of the passive device and set at a speed of 5 m/s with a combined error of ±0.2 m/s. The data acquisition system was turned on, collecting the temperatures measured by the K-type thermocouples. The temperatures were verified according to the ambient temperature, and if these were stable and approximately at 20 °C, finally, the power supply was turned on and adjusted to the desired dissipation power. The initial load was 5 W and if the thermocouples showed stationary values after approximately 15 minutes, the thermal load was increased by 5 W. The load increment was made until the maximum temperature of the passive device reached the critical temperature (150 °C), where the melting of the materials could happen. Data was acquired every 5 seconds, recorded in the laptop by the software Agilent^{TM} Benchlink Data Logger 3.

Data reduction

The performance of the passive devices was analyzed and compared by the thermal resistance and the effective thermal conductivity. The total thermal resistance, R_{th}, of a heat pipe and of a thermosyphon can be defined as the difficulty of the device to carry heat. The higher the thermal resistance, the greater the difficulty is in transporting heat from the system. The total thermal resistance can be calculated by:

$$R_{th} = \frac{\Delta T}{q} = \frac{T_{evap} - T_{cond}}{q} \tag{1}$$

where q is the heat transfer capability of the device, T_{evap} and T_{cond} – the average temperature of the evaporator and the condenser, respectively.

The effective thermal conductivity, k_{eff}, is the property of a certain material to conduct heat, defined by:

$$k_{eff} = \frac{qL_{eff}}{A_C \Delta T} = \frac{qL_{eff}}{A_C (T_{evap} - T_{cond})} \tag{2}$$

where L_{eff} is the effective length and A_C – the heat transfer cross-sectional area, which is defined by $A_C = (\pi D_o^2)/4$ for a rod and by $A_C = (\pi D_i^2)/4$ for heat pipes and thermosyphons. The effective length of the passive device, L_{eff}, can be defined by:

$$L_{eff} = \frac{L_{evap}}{2} + L_{adiab} + \frac{L_{cond}}{2} \tag{3}$$

where L_{evap} is the evaporator length, L_{adiab} – the adiabatic section length, and L_{cond} – the condenser length.

The experimental uncertainties are associated to the K-type thermocouples, the data logger, and the power supply. The experimental temperature uncertainty is estimated to be approximately ±1.0 °C and a thermal load was ±1%. They are shown in the obtained results. For the uncertainties determination, the error propagation method described by [31] was used.

Results and discussion

The experimental results show the thermal behavior of different heat transfer passive devices (rod, thermosyphon, heat pipe with a metal screen, and grooved heat pipe) operating in two positions: vertical and horizontal. The experimental tests were repeated three times and the errors were compared taking into account that the difference between the mean values were less than 0.5 °C. The tests were performed at increasing heat loads of 5 W, ranging from 5 W to 45 W for both positions.

Vertical position

Figure 5 shows the temperature distributions as a function of time in the vertical position for the four heat transfer passive devices: (a) rod, (b) thermosyphon, (c) heat pipe with a screen mesh, and (d) heat pipe with grooves. For the rod, the maximum dissipated power was 15 W. For thermosyphon, the maximum power was 30 W while for the heat pipes the maximum dissipated power was 45 W.

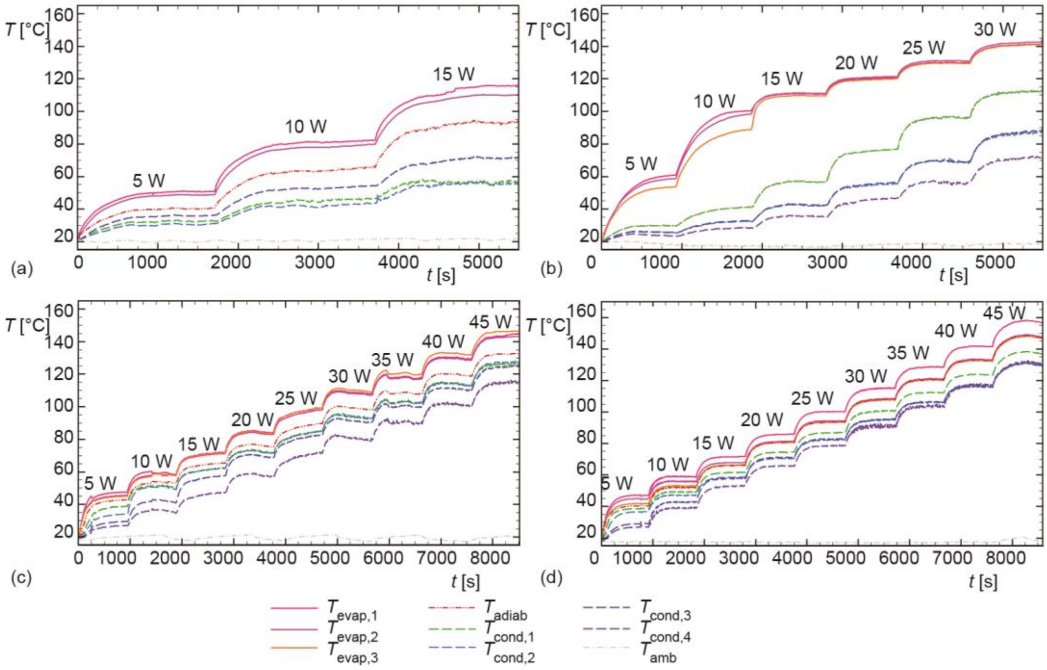


Figure 5. Temperature distribution *vs.* time in the vertical position;
(a) rod, (b) thermosyphon, (c) heat pipe with a screen mesh #100, (d) heat pipe with microgrooves
(*for colour image see journal web site*)

Horizontal position

The temperature distributions as a function of time in the horizontal position for the four heat transfer passive devices are presented in fig. 6. For the rod and the thermosyphon, the maximum dissipated power was 15 W. For the heat pipe with microgrooves, the maximum power was 40 W and the heat pipe with a screen mesh #100 showed a maximum dissipation of 45 W.

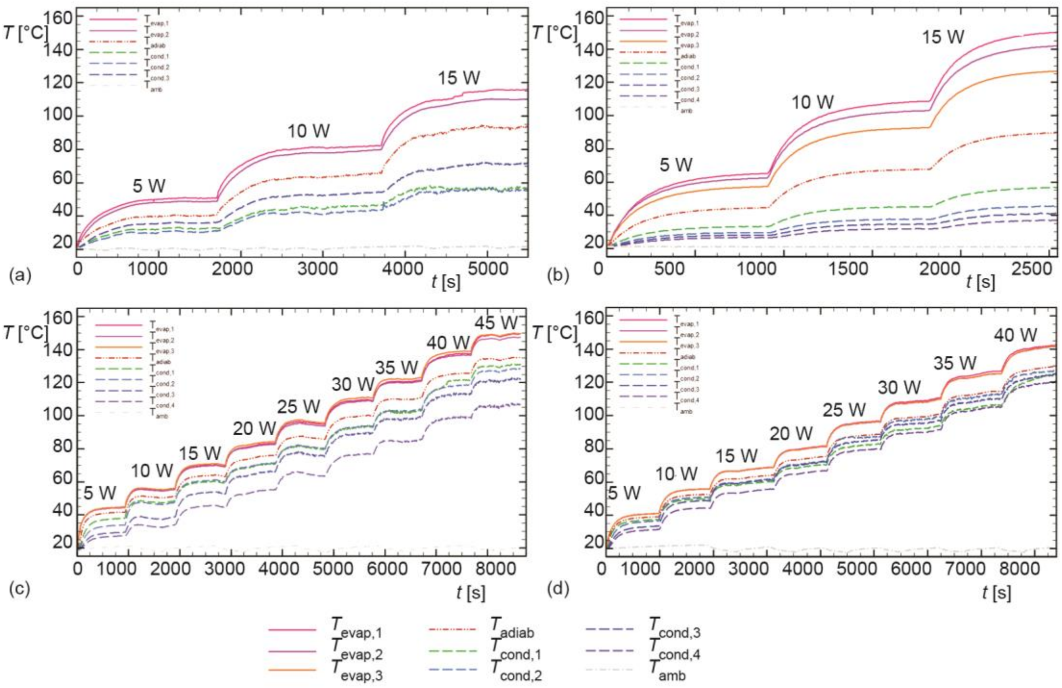


Figure 6. Temperature distribution *vs.* time in the horizontal position;
(a) rod, (b) thermosyphon, (c) heat pipe with a screen mesh #100, (d) heat pipe with microgrooves
(*for colour image see journal web site*)

Comparison

Figure 7 illustrates the behavior of the thermal resistance as a function of power dissipation considering the different heat transfer passive devices comparing the two positions. With the exception of the rod, which has a nearly constant thermal resistance, the heat pipes' and of the thermosyphon's thermal resistance decrease with the increasing heat dissipation in the evaporator in the vertical position. In the horizontal, the heat pipes and the rod remain with the same trend of behavior, however, the thermosyphon has changed dramatically. That happens due to the necessity of the gravity for the fluid return in the thermosyphon.

In fig. 8, the behavior of the effective thermal conductivity of the passive heat transfer devices is shown as a function of the power dissipated for vertical (a) and horizontal (b) positions. As expected, it can be seen that the passive devices that use phase change (heat pipes and thermosyphon) have a higher effective thermal conductivity and that this parameter increases with increasing power dissipation.

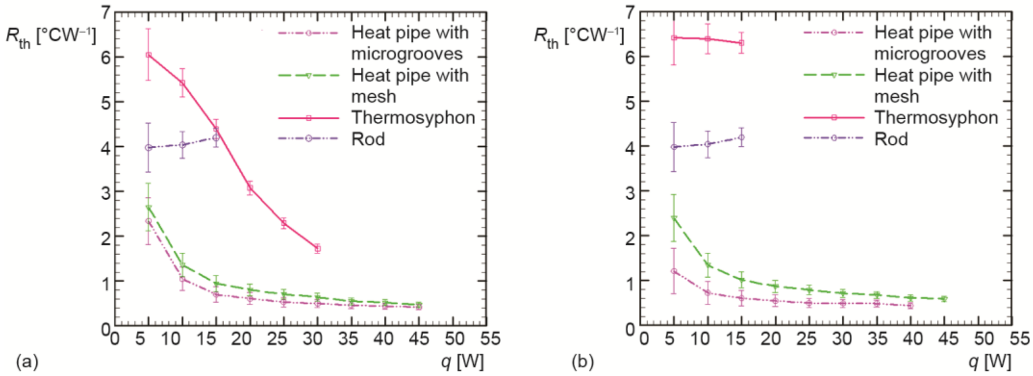


Figure 7. Thermal resistance *vs.* power dissipation; (a) vertical, (b) horzontal

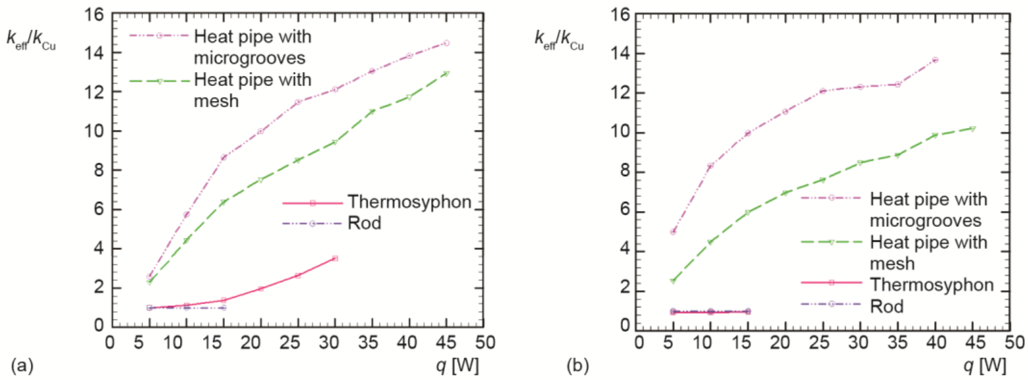


Figure 8. Relative effective thermal conductivity of the passive devices *vs.* power dissipation; (a) vertical, (b) horzontal

From the evaluated heat transfer passive devices, the heat pipe with a metal screen and the grooved heat pipe showed the best thermal behaviors. However, the heat pipe with a metal screen mesh #100 as capillary structure showed the best thermal performance in both positions, due to lower heat resistance or a higher effective thermal conductivity than the heat pipe with microgrooves. The reasons why the heat pipes present the best performance is that they use the vaporization heat of the working fluid concurrently with the capillary structure, which facilitates the flow of the working fluid from the condenser to the evaporator, especially in the horizontal position. The thermosyphon showed a satisfactory thermal performance in the vertical position. However, in the horizontal, its behavior was worse than a rod. This result is a consequence of the absence of the wick to return the working fluid.

Conclusion

In this research, an experimental investigation of the thermal performance of different heat transfer passive devices (solid rod, thermosyphon, heat pipe with a metal screen, and heat pipe with microgrooves) was performed. Due to the shape and size, they can be used in electronics cooling. These passive heat transfer devices were tested in vertical and horizontal positions under thermal loads between 5 W and 45 W and worked satisfactorily. The vertical position showed better results than the horizontal due to the gravity. The heat pipes were the devices with the best thermal performance, with a very similar behavior. However, the heat pipe with screen mesh #100 had a better thermal performance than the heat pipe with micro-grooves. The results showed that heat transfer passive devices with phase change can be an alternative to stabilize microelectronic devices temperature, on the other hand, solid rod cannot be used.

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Nomenclature

A_C – cross-sectional area, [m^2]
D – diameter, [m]
k – thermal conductivity, [Wm^{-1}K^{-1}]
L – length, [m]
q – heat transfer rate, [W]
R_{th} – total thermal resistance, [°CW^{-1}]
T – temperature [°C]

Subscripts

adiab – adiabatic section
cond – condenser
eff – effective
evap – evaporator
i – inner
o – outer

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