OPTIMIZATION OF THE MICROELECTROMECHANICAL PROPERTIES OF HEAT EXCHANGE SYSTEMS THROUGH MICROCHANNEL TECHNOLOGY

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Abstract: Performance of microchannel heat exchangers is highly dependent on their geometry and shape. Hence, the structural design is as equally important as the material components. This paper expounds the development and applications of microchannel technology thereby proposing an optimal applicability on the microelectromechanical properties of heat exchange systems.

Keywords: microelectromechanical properties, microchannel technology, heat exchangers, 3D circuits

1. INTRODUCTION

Heat is the display of all kinds of energy. Heat transfer by convection gives a way to transfer the thermal energy or heat from one surface to another and is governed by the equation q = h A (Ts −T f). In the past shell and tube type heat exchangers were used commonly in the industrial zone. Studies were done on the compact heat exchangers because of transportation issues. For gas applications, heat exchangers with plate fins were developed.

1.1. Channel classification

Channel classification is as follows (Figure 1):
- Micro-channels: 1 micrometer -100 microchannels;
- Meso-channels: 1 micrometer -1 mm;
- Compact Channels: 1mm - 6mm;
- Conventional Channels: greater than 6mm.

Conventional channels - $D_h > 3mm$
Minichannels – $3mm \geq D_h > 200\ \mu m$
Microchannels – $200\ \mu m \geq D_h > 10\ \mu m$
Transitional Channels- $10\ \mu m \geq D_h > 0.1\ \mu m$
Transitional Microchannels -$10\ \mu m \geq D_h > 1\ \mu m$
Transitional Nanochannels - $1\ \mu m \geq D_h > 0.1\ \mu m$
Molecular Nanochannels - $0.1\ \mu m \geq D_h$

Fig. 1. Classification of channels [1].

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The above criteria are made by taking into consideration about the characteristics of gas flow. However, they can be used for liquid as well [2-4].

1.2. Use of microchannels in heat transfer

Microchannels are now used in the application of processing. The space constraints in the aero industry are addressed by microchannels. Main use is in compact heat exchangers. They are of great use in microelectronics cooling applications.

Fullerenes, a new form of carbon, were discovered in 1985 [2] in graphite vaporization under inert gas at low pressure. Fullerenes have many properties different from either diamond or graphite. The arc discharge method developed by Kratschmer's group [3] in 1990 remains until now the major tool for synthesizing fullerenes. Several works has been done for the macroscopic production of the fullerenes by using other different techniques, laser ablation [2-4], electron beam evaporation, heat resistive method, diffusion flame and ion beam sputtering [5].

The electric arc is still one of the nest methods to produce fullerenes, which is why we decided to find the condition for an optimized production. The main aim of this work is to establish the values of the discharge current and of the gas pressure for maximum values of the fullerene yield (fullerene mass proportion in the soot) and of the productivity.

2. PERFORMANCE OF MICROCHANNELS

The relation between the hydraulic diameter with the transfer of heat and pressure drop is shown in Figure 2. Water and air are flowing in a channel square. The conditions are of constant heat flux and have laminar conditions. The coefficient of heat transfer is not dependent upon Reynold's Number.

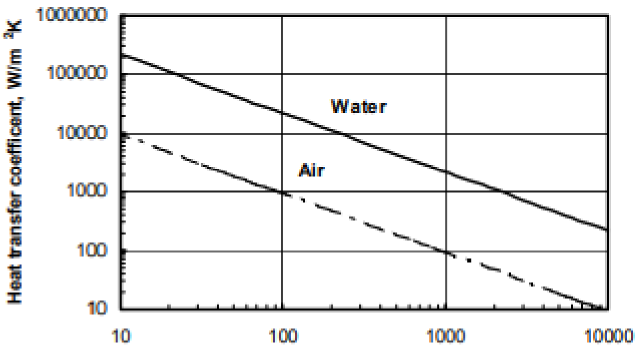

Fig. 2. Coefficient of heat transfer.

2.1. Microchannel condensation

Microchannels are used to enhance the condensation heat transfer. The constraints faced during condensation are not as severe as compared to hear flux removal.

2.2. Fabrication technique

The use of microchannel heat exchanger is greatly increased by the progress made in the microfabrication industry.

2.3. Semi-conductor

Much of the modern-day research about microsystems technology and microelectromechanical systems is focused around the micro fabrication technique in semiconductor sector, most of them are silicon-based variant.

These techniques can be divided into 2 groups. In bulk mode, the finished part is made by removing the parts of starting material. Due to this it has great strength and stress is less. On the other hand surface technique forms a product by pattern deposition and other steps.

The main problem in the first technique is the etch process. It can be done in wet a chemical or dry format.

2.4. Microchannel taxonomy

The major division is between miniaturized and modern technologies. Their characteristics of modern technologies cannot be described easily but are based on the progress made in the twentieth century. Miniaturized techniques are direct approach to create micro features. They use the conventional techniques and tools to work. It includes molding and electroforming. The modern technique can be distinguished as either serial or batch [5].

2.5. Molecular and transitional channels fabrication

The characteristics of the flow to heat transfer in transitional and molecular nanochannels lies in the range of 10-0.1 micrometer. The range of 10-1 micrometer is a transition between MEMS and semiconductor fabrication.

3. FABRICATION OF MICROCHANNELS INTEGRATED WITH PRESSURE AND TEMPERATURE SENSORS

The development channels are very important for the research purposes and also for heat transfer most of the microchannels used do not provide the detailed data and information but general information at the inlet and outlet. For the study of heat transfer heat loss and other considerations are very important. Most of the MEMS techniques that are developed use silicon water which is an excellent thermal conductor and has high value of thermal conductivity. This causes a great amount of heat loss.

The current progress is being done to develop microchannel system that is used to obtain heat transfer coefficient. Insulation can be done on all sides of the channel and one side can be uniformly heated. Temperature and pressure sensors are used to take measurements from the heated wall so that local study of heat transfer along the channel is done.

3.1. Microchannel heat transfer

Heat Transfer integrated with microchannel technology is used for cooling microchips that are used in a computer system. It is also used in systems that need effective cooling. It reduces the weight but also increases then performance to exclude the heat from the system. Nusselt's Number which is associated with heat transfer formula is hD/k, in this formula, h is the heat transfer coefficient being the diameter of the channel. There is an inverse relation between the size of the channel and convective coefficient h. When the size of the channel is extremely reduced, h becomes much higher so that Nu number remains constant.

3.2. Microchannel heat exchanger

In Heat Ventilation and air conditioning systems, heat exchangers with high performance have always been a key focus. In recent times due to the increase in prices of copper, there is a demand for lightweight heat exchanger. This can be done by using the micro-channel heat exchanger. In this way the cost of manufacturing heat exchangers can also be reduced. As the technology is progressing micro-channel technology is now constantly used in HVAC systems. This concept was introduced by Tuckerman and Pease in 1981 [6].

Microchannel Heat Exchanger is defined as the kind of heat exchanger where the diameter of heat exchanger is less than 1 mm. As the progress is being done on the study of microchannel and its application in HVAC systems, its advantages are quite high as compared to traditional heat exchangers. Nowadays, they are being used in automobile industry [7].

As compared to other heat exchangers, micro-channel heat exchangers have different characteristics of flow because their structures are quite different, the scale is reduced to enhance compressibility of fluid effect [8]. This causes the increase in coefficient of drag.

In 2003, Purdue university made a model that consists of annular flow. They also collected the data of coefficient of heat transferring microchannel heat sink and concluded that coefficient of heat transfer has an inverse relation with vapor quality. In 2004, Re'mi Revellion made studies on the flow characteristics (2 phase) with R-134a refrigerant [9-11].

4. OPTIMIZATION OF MICROCHANNEL HEAT EXCHANGE PERFORMANCE

The performance of microchannel heat exchanger is highly dependent upon their geometry and shape. So, the structure design is an important aspect. Efforts were made to optimize the structural aspects of micro channel heat exchanger by RW Knight [12]. This was done by reducing thermal resistance on the condition of drop in pressure. After that, a method was designed in order to reduce the thermal resistance by Sun Jim Kim.

4.1. Benefits of microchannel heat exchangers (MCHE)

Compact design. MCHE has a smart design which can be compared with conventional coil. They are nearly 35% less in size which helps in logistics and transportation.

Lower holdup volume. This technology has increased the heat transfer by the use of less refrigerant. Holdup volume is 77% less.

Weight. They are much lighter and smaller with great performance. They are cheap to transport and have high efficiency.

Material. They are made up of aluminum which is a metal having low density to prevent the corrosion. They can easily be recycled.

Efficiency. They give higher air side efficiency which was one of the limiting factors of coil performance.

Price. As the size is very compact, so the material used is less. Material is small portion of the cost. So, they are not prone to price fluctuation.

Noise. The airflow is undisturbed. As a result, noise level is low. So, it is very helpful is residential areas. The airflow gives less drop in pressure and fan power require is less.

Flexible design. They are quite flexible in both size as well as mounting. They have variety of sizes and can be adjusted with every type of installation.

Transport Refrigeration. Using microchannel heat exchanger in you air conditioning system for refrigerated transport can help you to increase the capacity of product. Also, you can increase the heat transfer to make smaller, much compact in size AC system. The also reduces the fuel costs.

Precision Cooling. MCHE have precise control of temperature which can help you to create the cooling system the help in safeguarding the technologies like data center server rooms etc. they also help to free up space and reduce the cost of electricity.

Cold Rooms. MCHE are quite useful for the cold storage. For example, in restaurants, markets and plants. They are easy to place and to ensure the hygiene that is required for food business. As compared to standard coils microchannel heat exchangers provide 10% better coefficient of performance. The main advantage is its less size and weight without any compromise on its performance and effects. So, they can be used to make clean and efficient systems that can be used to keep cold rooms at required temperatures.

5. APPLICATIONS OF MICROCHANNEL REACTORS

The advantages of a micro reactor are that it has much greater performance and high transfer of mass because of small channels. Reaction Takes place in these channels. It is far more reactive than the conventional methods. Application of Micro channel Reactor in medicine is imperative because of they are sizable and scalable. Their channels are of small diameters which increases the performance of heat transfer and mass transfer. They are used for high value products whose production amount is in small quantities.

5.1. Features of microchannel reactors

By reducing the diameter of channels high heat transfer is achieved as shown in Figure 3.

The fluid that flows through small diameter channels is affected by the surface of the wall, but effect of gravity is minimal.

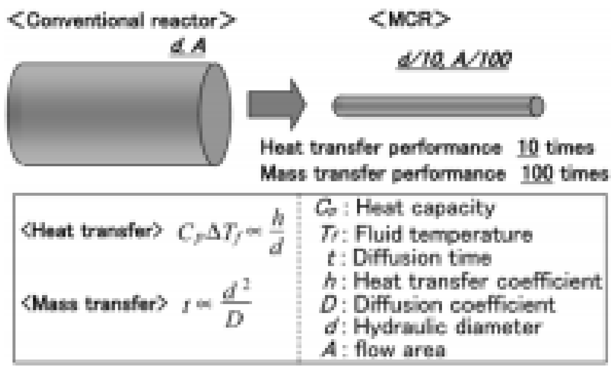

Fig. 3. Comparison between MCR and conventional reactor.

Sometimes MCR's are known as micro-reactors because of their small sizes. That is the reason that they are used to produce small number of products. The reason behind is the large capital cost that is required to make equipment which includes he amount to make the channels. It is not used for large industrial applications.

5.1.1. Stacked microchannel reactors

They contain plate fin heat exchangers that are made up of aluminum alloy which gives great heat transfer performance (Figure 4). It was developed for equipment whose functions are to convert air into oxygen and nitrogen at minute temperatures. In some equipment, SMCR has heat transfer rate that goes up to 1000 m^2/m^3 which is higher than the heat exchangers that are employed conventionally.

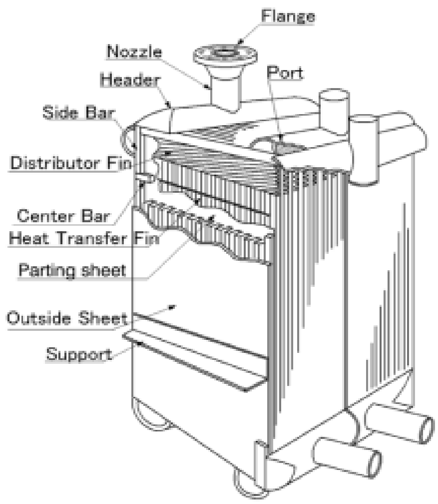

Fig. 4. Stacked MCR.

It offers the following technologies:
- Joining and fabrication of channels.
- Design to calculate the performance and for pressure loss calculations.
- Reduction of maldistribution between layers.

5.1.2. SMCR Applications

For making a certain chemical product requires various steps which includes extraction. Extraction solvent is used for removing the desired or undesired material. The application of SMCR in extraction process can provide certain benefits:
- Time of extraction is reduced.
- The dimensional size of the equipment that is being used for extraction is reduced.

- Consumption of the unit is reduced.
- Continuous processing is ensured.

5.2. Microchannel coil technology
The design of this technology is derived from the technology in automobile industry. It is made from the aluminum tubes with flow that is parallel and are brazed to increase the heat transfer (Figure 5). The coils are corrosion resistant.

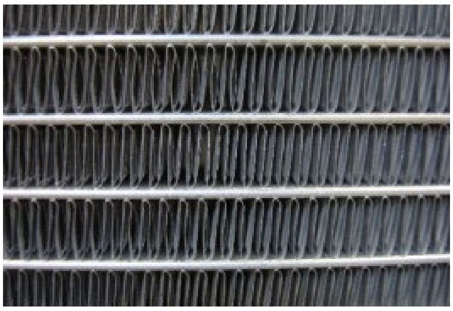

Fig. 5. Microchannel coil.

5.3. Comparison with other coils
Most of the conventional coils use copper tubes with aluminum fins or spiny coils. These two designs make the coil large in size which can cause damages and need much greater amount of refrigerant. The aluminum fins that are used are very weak and delicate.

5.3.1. Advantages
Microchannel coils are much smaller and much more efficient and uses less amount of refrigerant than standard coils.

They are much hard and less prone to damage. In coastal environment their life is 7 times longer.

They can be easily cleaned. You can even use a high-pressure sprayer without causing damage to fins. In this way you can change your maintenance contract and add condenser oil cleaning in it. You can easily clean it in 10 minutes.

Conventional coils are easily damaged in transportation and handling. Microchannel coils the not prone to damage but they are damage resistant. They also have a steel coil and diamond mesh guard.

They can easily be repaired by using propane or MAP gas torch. They can easily be repaired in few minutes.

6. INTEGRATION OF MICROCHANNEL COOLING METHOD WITH THREE DIMENSIONAL CIRCUITS

The removal of heat through conventional cooling methods does not allow the engineers to stack more components together on smaller chips to increase the processing speeds and reduce the overall size of the central processing units. Large computers require efficient thermal systems. They generate more heat energy and require immediate removal of heat from the processing units otherwise there is a chance of burning out the sensitive components present in the processing units. Mostly, the heat load of processors depends on their processing power. This can be experienced in everyday life. When your personal computer is rendering some video or you are playing some game with good graphics, your computer tends to heat up. This is also the case with supercomputers which keep running 24 hours a day to compute critical scientific calculations on huge amounts of data. This problem can be solved by integrating the microchannel technology with the circuits located in the processing units of these heavy-duty computers. Now this microchannel cooling system has two benefits. It reduces the heat load generated by the processing components significantly and it can also remove the generated heat at greater rate than the conventional cooling systems. As the name suggests, microchannel describes a system of many small channels in its structure in which liquid circulates to remove the heat. As the diameter of these channels is reduced to the micro-level or even nano level, the heat transfer coefficient increases many folds. By decreasing the diameter of the microchannel tubes, we increase the surface area. As the surface area increases, space to dissipate heat also increases. This helps in increasing the heat dissipating capability of the microchannels [13].

6.1. Printed Circuit Heat Exchangers

A research conducted by university of Sydney in the 1980s on the microchannel heat exchanger technology resulted in the formation of a company called Heatric Company. This company made microchannel heat exchangers for printed circuit boards. The channel size was as less as 200 micrometers [14]. These microchannels were fabricated by the direct milling process on the plates. Then these plates were joined together or stacked together by the process of diffusion bonding [15]. These printed circuit boards have the capability to bear the temperatures as high as 900 degree Celsius and pressures of 500 bar to 1000 bar. Figure shows the microchannel integrated printed circuit heat exchangers [13].

Three-dimensional circuitry is introduced to increase the processing speeds of modern processors. In this type of circuits, many components such as optoelectronic devices, RF devices etc. can be incorporated on a single chip. An advantage to this type of configuration is that it speeds up the processing speeds. However, there is a drawback to this type of circuits. They tend to produce a lot of heat because of a large number of components mounted on a small space. In addition to this, due to more space is covered by components mounted on the chip, this leaves less space for heat removal. As the chip surface exposed to the atmosphere is reduced, the heat generation per unit surface area is increased. This problem can be solved by integrating three-dimensional circuits with microchannel network.

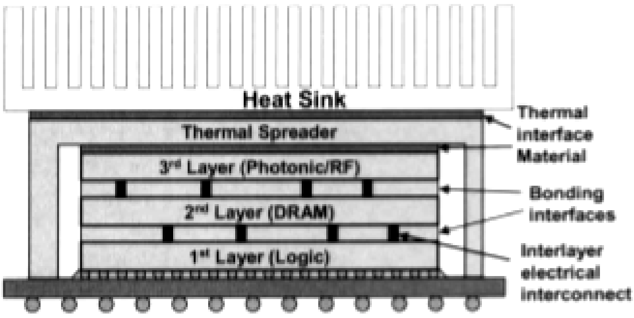

Fig. 6. Heat sink technology used in 3D circuits [1].

In the past, heat sink technology was used as shown in Figure 6. Figure 6 shows the integration of 3d circuit with heat sink cooling system. In this article, an alternative is presented to this cooling system. Figure 7 shows the proposed structure of integrating microchannel technology in the cooling of 3d circuitry. Layers of components are stacked with adjacent layers of microchannel tubes of relatively low thermal resistance. This technique allows to have a uniform temperature profile. It also makes the use of latent heat of coolant and effectively minimizes the need for pumping. In this article heat simulations are performed for 3d circuitry with integrated microchannel cooling systems.

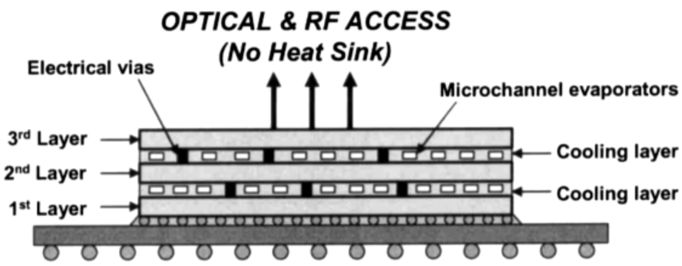

Fig. 7. Microchannel cooling system.

6.2. Fabrication methods of 3D-circuits

Our primary concern is to discuss the heat removal from 3D circuits, but it will be good to understand the basic fabrication mechanisms of making 3D circuits. There are various methods to fabricate 3D circuits. Which

methods are used depends on the availability of that manufacturing equipment, requirements of the usage and compatibility of components which will be mounted on the chip with the chip itself? Some of the techniques are:
- Wafer bonding.
- Polysilicon recrystallization method.
- Growth of epitaxial silicon.

There are also several techniques to manufacture microchannels inside three dimensional circuits. Some of the techniques are:
- Plasma etching;
- Chemical etching.

Previously, work has been done on the two-dimensional heat removal using microchannel by Tuckerman and Pease [16]. In their paper, they showed that microchannel technology can remove up to 790 W of heat energy from an area of 1 cm^2. After that paper, their research began on the optimization of heat removal using two-phase flow in this technology. In the past, the works on double phase microchannel heat removal process from two-dimensional circuits was mostly based on the removal of heat, such studies did not take into account the effects of flow distribution of coolant in the microchannels. There is also a problem faced in two-phase microchannel flow that arises due to the formations of voids which causes instability in the flow. This also creates problems of larger magnitude in three-dimensional circuits integrated with microchannel cooling.

3D circuits with integrated microchannels are analyzed to measure their cooling performances and generate their heat profiles. Microchannels were embedded inside the three-dimensional circuits using deep etching technique and wafer bonding. Different stacking methods were used to test the cooling performance. These stacking techniques are shown in the figure. One thing should be kept in mind that different components produce heat differently. For example, logical ICs generate 90% of the heat and memory ICs generate up to 10% of total heat. So, to simulate this phenomenon two areas are created; one represents Logic (L) and one represents Memory (M). Four different configurations are used to mimic this complete situation.

Case 1. Memory and logic are located on two different device layers. Water passes in between them (Figure 8).

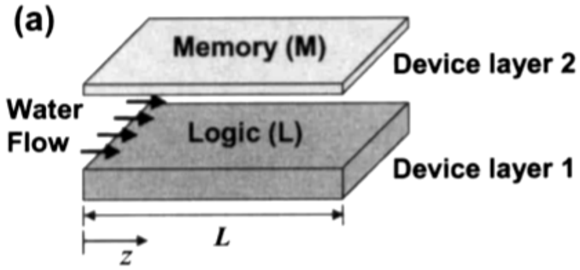

Fig 8. Case 1 - configuration [1].

Case 2. Memory and logic are located on both device layers with an equal amount of area occupied by them. Logic is facing the side on which water flow occurs first. On the other hand, the memory area makes contact with the water after it passes over the logic area (Figure 9).

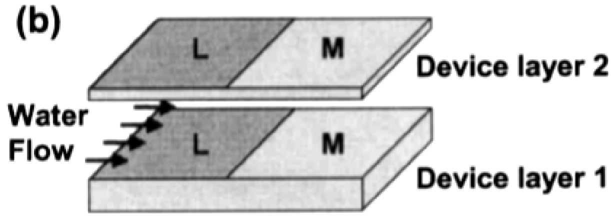

Fig. 9. Case 2 - configuration [1].

Case 3. Memory and logic are located on both device layers with an equal amount of area occupied by them. The memory is facing the side on which water flow occurs first. On the other hand, the Logic area makes contact with the water after it passes over the logic area (Figure 10).

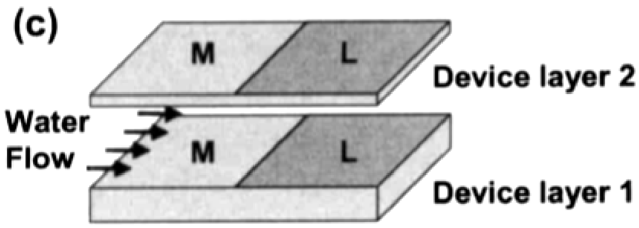

Fig. 10. Case 3 - configuration [1].

Case 4. Memory and logic are located on both device layers with an equal amount of area occupied by them. But they have alternative places on the adjacent device layers. On the bottom layer, logic makes contact with the water first and then memory makes it contact. However, on the top device layer memory makes contact with the water first and then logic makes it contact (Figure 11).

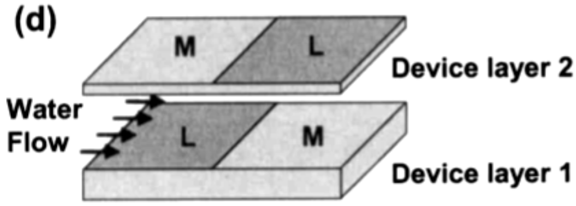

Fig. 11. Case 4 - configuration [1].

This configuration and geometry are mentioned in the Table 1.

Table 1. Configuration and geometry of 3D circuit architecture [1].

3D circuit architecture	
Chip size	14.14 mm x 14.14 mm
Power dissipation	150 W (Logic 90%, Memory: 10%)
Device Layer1	
Silicon layer thickness	500 μm
Oxide layer thickness	10 μm
Device layer	
Silicon thickness	20 μm
Oxide layer thickness	10 μm
Microchannels	
Channels layer thickness	400 μm
Number of channels	18
Channel geometry	
Liquid water flow rate	700 μm (width) X 300 μm (depth) 15 mL/min
Inlet fluid temperature	70 degree Celsius
Exit fluid pressure	0.3 bar
Conventional fin heat with a copper spreader	
Heat sink resistance	0.25 K/W
Thermal interface material	1X10E-5 K/W
Copper spreader size	28 mm X 28 mm X 2 8mm

The inlet temperature of the water is fixed at 70 degree Celsius and the outlet pressure is fixed at 0.3 bar. Now as we all know that the water boils at 100 degrees Celsius. This is the saturation temperature of the water which is used as coolant liquid. On the other hand, one thing must be kept in mind that devices can operate at a maximum of 90 degree Celsius. So, if water gets saturated on 100 degrees, devices will be burnt at that temperature. To solve this problem, we can reduce the outlet pressure to lower the boiling temperature of the water and mimic the sub-atmospheric conditions. So, the pressure at the outlet is adjusted to 0.3 bar [1] to reduce the saturation temperature of the water.

Heat profiles generated on these four configurations for microchannel integrated three-dimensional cooling technique and conventional cooling method.

This analysis as shown by Koo (Figure 12):

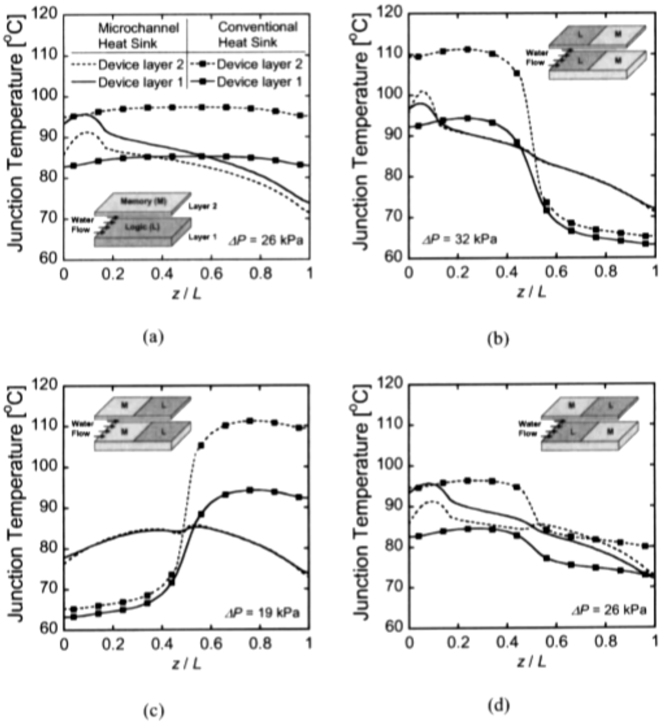

Fig. 12. Junction temperature profiles for conventional method of cooling and microchannel integrated cooling [1].

Case 1. For conventional heat cooling method, heat profile along the device layers is almost identical. The junction temperature is almost the same at inlet and outlet. So, in conclusion, the conventional method does not perform any cooling effect. On the other hand, in microchannel configuration, junction temperature first rises and then drops considerably while moving towards the outlet region. The reason for the increase in temperature is that when the water is in liquid phase it goes towards its boiling temperature, so the temperature increases. When it boils it changes its phase and now it is in its two-phase state. Now its temperature decreases due to the drop in pressure towards the outlet. In microchannel technology, the temperature difference between inlet and outlet is 10 degrees centigrade. While in the conventional cooling system its inlet and outlet temperature difference were almost negligible.

Case 2. For case two, there is a significant difference between inlet and outlet temperatures for both the conventional cooling technique and the microchannel integrated cooling system. One of the reasons is that the memory region is located towards the outlet. One thing should be kept in mind that the memory region generates lower heat energy than logical region. So, the junction temperature falls drastically after it passes from the logical region to the memory region.

Case 3. For case three, the temperature profile of the junction temperature is almost opposite to the profile obtained in case 2. The differences between the inlet and the outlet junction temperatures for both the conventional method of cooling and the microchannel cooling is significant. This is due to the very same reason that logical region generates more heat energy than the memory region. So, when the water passes from the memory region to the logical region its temperature rises significantly.

Case 4. In case 4, the junction temperature profile of the conventional method of cooling is more uniform and smoother than the microchannel integrated way of cooling. One thing should be noted that, in all of the cases mentioned above, for the conventional method of cooling, device layer 1 temperature is always less than the device layer 2 because in the conventional method environment is present between the two layers and the thermal resistance of gases is normally higher than solids and liquids.

7. CONCLUSIONS

This research shows the optimization of the cooling performance of 3D circuits and other applications via microchannel technology.

As shown in this paper, the earliest research on microchannel integrated cooling systems was at Stanford University by Tuckerman and Pease [6]. After that Babin [15] and his group also worked on the heat pipes having the diameter in micrometer. However, recently these results are being converted into useful applications. Some of the applications are: printed circuit heat exchangers, micro level cooling devices, cooling for gas turbines, cooling for nuclear reactors working at high temperatures, micro heat exchangers etc.

These microchannels make heat exchange in many industrial applications faster and more efficient. They are mostly implemented where compactness is desired such as circuit boards and modern refrigerators. They are also used in some critical applications such as in heat exchangers of high temperature nuclear power reactors [16]. More new methods describing the industrial applications and geometrical properties of the microchannel technology have been discussed in detail by Kim et al, Tuckerman et al and Schubert et al. [17-19].

In addition, we have shown that microchannel integration for heat removal in 3D circuits is essential for building electronic components and has a broad range of applications in information technology, biomedical engineering etc. However, a great deal of challenges arises when optimizing the geometrical properties of the microelectromechanical components of heat exchange systems such as unsteadiness of operating conditions and inefficiency of shapes. More research is needed in figuring out ways of stabilizing the operating conditions (such as temperature and pressure) of microchannel heat exchange systems in circuits.

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