

INNOVATIONS

Numerical assessment with Nusselt number and Reynolds number based on experimental outcomes of cooling in high dense network-on-chip

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Abstract:

The effect of tremendous temperature in high dense Network-on-Chip (NoC) plays a vital role in the performance of the application and it is great need to cool down such densely packed integrated circuit within a single chip. In this paper, the metrics like temperature, heat transfer rate, velocity, Reynolds number and Nusselt number are studied based on experimental outcomes derived from the cooling of NoC. Out of the four modes of coolant flow, employing the strategies of multichannel and turbulent provides high heat dissipating feature with high velocity air as coolant. It is found that the heat transfer rate of multichannel laminar flow, single channel turbulent flow and multi channel turbulent flow are 14%, 18% and 24% higher than the conventional single channel laminar flow of coolant. Also, Nusselt number of the above cases increases by 21%, 58% and 94% than the single laminar flow. Thus, the experimental results of the proposed methodology exhibit a profound behavior in terms of Nusselt number and Reynolds number.

Keywords: 1. Network-on-Chip 2. Reynolds number 3. Nusselt number 4. Multichannel turbulent flow 5. High dense Network-on-Chip 6. Numerical assessment

Highlights

- Innovative methodology with four modes was examined and exemplary results were shown in turbulent and multi-channel mode in contrast to conventional cooling methods.
- Heat transfer coefficient of multi channel turbulent flow is 24% higher than the single channel laminar flow.
- The derived Nusselt number from the experimental outcomes shows 21%, 58% and 94% higher than the conventional cooling method.
- Reynolds number of multichannel laminar flow, single channel turbulent flow and multi channel turbulent flow are 50%, 149% and 250% higher than conventional single Channel laminar flow of coolant.
- Easy to implement and/or modify the existing design of most of the electronic device

Introduction

Recent days, electronic components with high functionality are favored for compact size and high end applications. The compactness could be achieved by integrating mostly entire functional units in a single chip. This evolution gives rise to the magnificent use of System-on-Chip (SoC) in most of the electronic devices ranging from mobile phones, satellites, radar system sand even in tele health instrumentation. The major bottleneck in the SoC is the intent heat that produced at the ends of the device due to the highly dense systems within a slim area [1]. Various mechanisms have been employing by the recent researchers to reduce the heat and save the device from mal-functionality and even system crash [2, 3]. The Proposed methodology provides a novel pilot work for the rmal management in the high dense systems than the conventional cooling methods that are discussed in [4-6]. The metrics stated in [7] used as base for the examination of experimental values and numerical outcomes. The governing equations for the forced convection in the proposed system lies on Newton’s Law of cooling, which could provide deliberate solution to verify the heat transfer characteristics as in [8]. This methodology was equated with the governing equations and the results were validated with valid metrics. Will et.al in [9] show that very important and significant method of examining the fluid flow mode is by the way of using Reynolds number (Re)and Nusselt Number (Nu). The conventional method of employing laminar flow and manifold arrangements were explored in [10-12].The proposed system uses turbulent flow, multiple channel flow and the combination of both to examine the thermal character is ticso fair as coolant.

1. Methodology

1.1 Experimental Unit

The proposed model consists of a customized working unit which is attached with temperature sensor to monitor the temperature of the heating element which is fed with external power supply. The input power is utilized to heat up the working unit over time and the heat generated is examine dusing the attached temperature sensor. The other parameters like voltage, current of the model are examined by the voltage and current sensor at the controlling unit. The modeling module consists of a controlling unit where the various sensors are controlled using the controller kit. The system works in DC environment as in most of the electronic equipment, in which the power dissipated of the systemis directly proporti on alto in put voltage applied to the system from the below equation(1). The power applied to the system is dissipated in the form of external heat that was generated from the device.

$$P=V_{in} * I \text{ ----- (1)}$$

The dimensions of the customized heating element with ceramic material to simulate silicon chip, which is densely occupied with high functionality units. The schematic view of the architecture of the working model with arrangement of sensors attached with it in order to collect, display in the I/O Device and recorded in cloud is exhibited in Fig.2. After the working model entered into the heating phase, it has to be cooled with the coolant that is blown using the external blower. Various modes of coolant flow are shown in Fig.1. The air is taken as coolant and the properties are shown intheTable1.

Table: 1 Properties of Coolant

| PROPERTIES OF AIR AS COOLANT | | |
|-------------------------------|---|---|
| Attribute | At 25°C | At 30°C |
| Density (ρ) | 1.1845 kg/m ³ | 1.1649 kg/m ³ |
| Dynamic Viscosity (μ) | 1.844 x 10 ⁻⁵ kg/m.s | 1.8680 x 10 ⁻⁵ kg/m.s |
| Kinematic Viscosity (ν) | 1.5571 x 10 ⁻⁵ m ² /s | 1.6036 x 10 ⁻⁵ m ² /s |
| Specific Heat Capacity (cp) | 1.0063 x 10 ³ J/kg.K | 1.6036 x 10 ³ J/kg.K |
| Thermal Conductivity (k) | 0.025969 W/m.K | 0.026341 W/m.K |
| Prandtl Number (Pr) | 0.71465 | 0.71375 |

(Courtesy: Content from “Fundamentals of Engineering Thermodynamics” book in [7])

During the cooling phase, the working unit is exposed to the coolant through four modes of fluid flow (i.e.) Single Channel Laminar Flow, Multi-Channel Laminar Flow, Single Channel Turbulent Flow and Multi-Channel Turbulent Flow as shown in Fig.1. The coolant flow is catalyzed by the externally connected blower, which corresponds to the fan which is present in electronic equipment. The Coolant flow system is characterized by various parameters and is shown clearly in Table.2. The flow rate of the blown coolant is monitored by the flow rate sensor attached in the controlling module. The experimental setup with all sensors shown in Fig.2

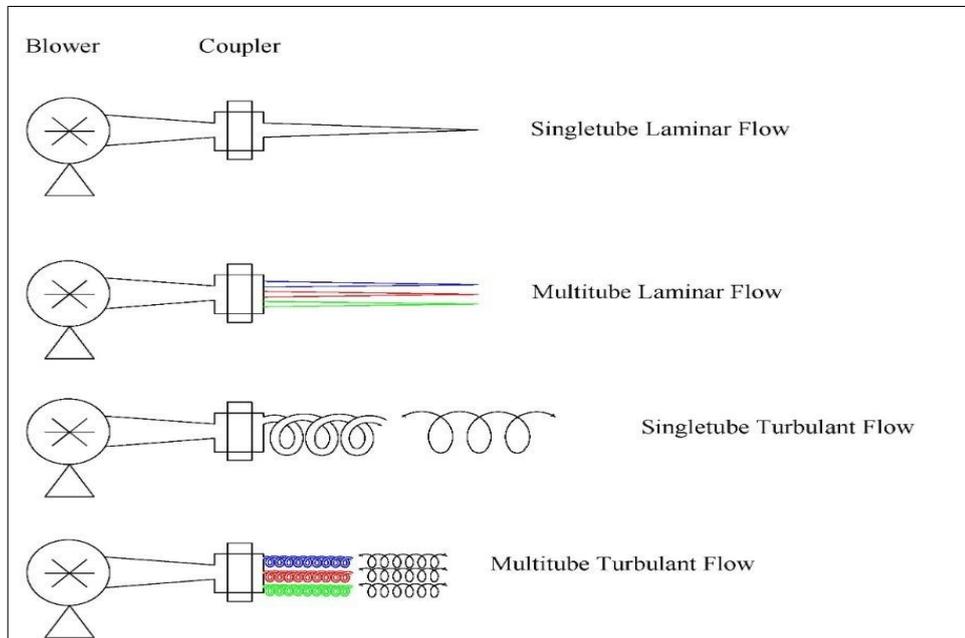


Fig.1 Modes of coolant Flow

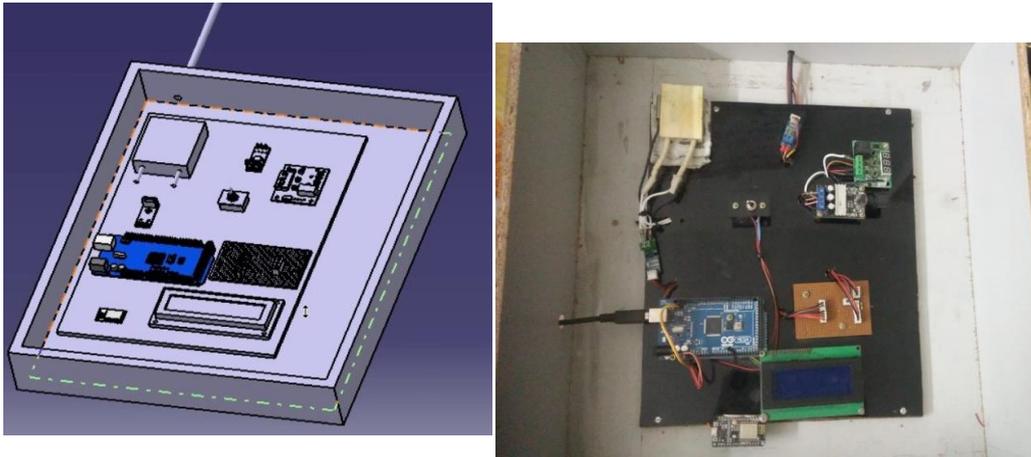


Fig.2 Schematic View and photographic view of experimental setup

Table: 2 Characteristics of Cooling Module

| Working environment of fluid flow | |
|-----------------------------------|------------|
| Parameter | Value |
| Diameter of fluid flow duct | 7mm |
| Length of fluid flow duct | 170mm |
| Maximum Flow rate of Blower | 35Lit./min |
| Maximum Pressure of Blower | 0.024 MPa |

All the above mentioned four cases have been tested and based on the results obtained from the model. The model leads to the applauding results in multi-channel and turbulent methods of coolant flow in conformance with the thermal efficiency. Upon the four cases, the heat mitigation is more prevailed in the case of turbulent flow and the usage of multiple channels as shown in Table 3 and Fig.3

Table.3: Examination on four modes of cooling methodology

| Methodology | Average Drop in temperature per minute (°C) |
|-------------------------------|---|
| Single channel Laminar flow | 2.3 |
| Single channel Turbulent flow | 7.6 |
| Multi channel Laminar Flow | 8.5 |
| Multi channel Turbulent Flow | 10.1 |

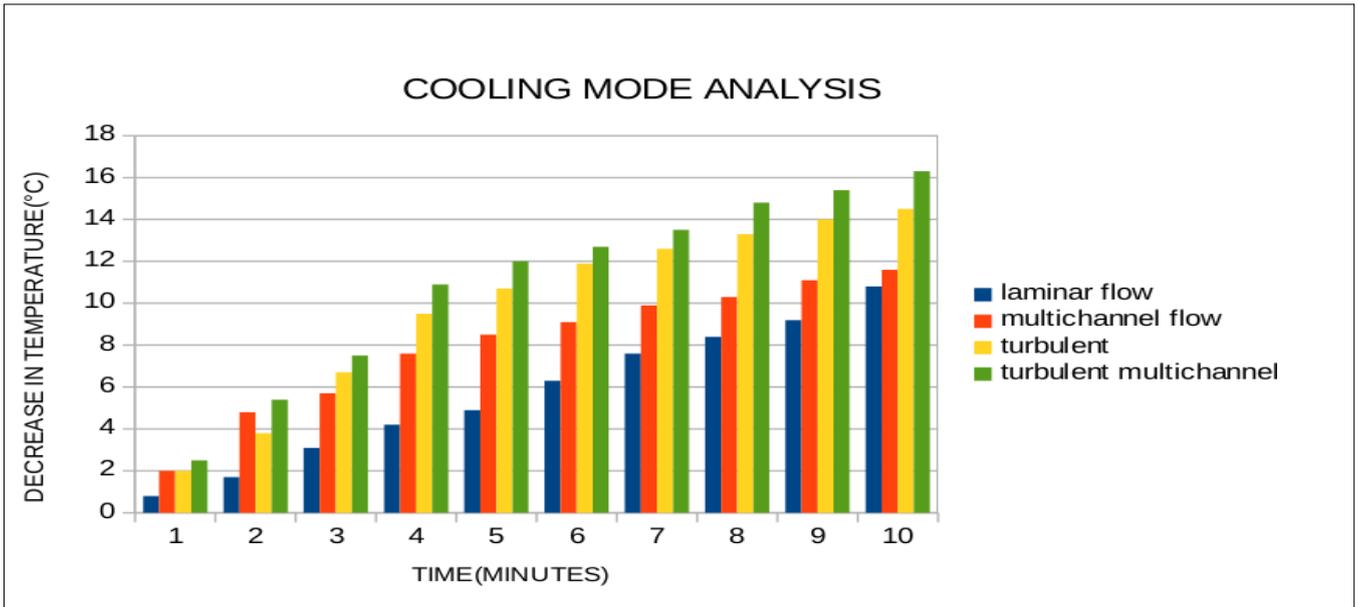


Fig.3 Comparison of results in four modeling Cases

Mathematical Modeling

The modeling unit is intended to verify with the basic governing equations like Newton' slaw of cooling. The transfer characteristics due to natural convection and radiation may be of less or nosignificanceintheworkingmodelandhencetheheattransfercharacteristicsarederivedhereisbasedontheasumptionofforcedconvectionfactorignoringtheradiationandnaturalconvection. The mathematical modeling of proposed system has been used to solve the momentum equations in terms of velocity and flow rate. In this numerical investigation, high velocity air is used as the coolant. The governing mass, momentum, and energy equations (2), (3), (4) and (5) are written as follows for the laminar and steady-state fluid flow [13]:

Continuity equation:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0. \quad \text{---(2)}$$

Momentum equation:

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \rho g_x - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad \text{--- (3)}$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \rho g_y - \frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad \text{---(4)}$$

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = \rho g_z - \frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad \text{---(5)}$$

The average heat transfer coefficient 'h' by convection and Reynolds number is given by equations (6) and (7)

$$Q = h * A * (\Delta T) \quad \text{---(6)}$$

$$Re = V * L * D / \text{viscosity} \quad \text{---(7)}$$

Equation (7) derives the relationship between the geometric dimensions and viscous force of the system.

The another parameter used for heat transfer analysis is the derivation of Nusselt Number, Nu which is the function of Reynolds Number (Re) and Prantl Number (Pr) which is shown in equations (8) and (9)

$$Nu = \{Re, Pr\} \quad \text{---(8)}$$

Nusselt Number is given by,

$$Nu = 0.683 Re^{0.466} Pr^{1/3} \quad \text{---(9)}$$

Results and discussion

The proposed model used high velocity air as coolant in both experimental and numerical analysis. The results are obtained for different velocities of coolant is considered for estimation of heat transfer coefficient, Reynolds number, Nusselt number and the relationship between Reynolds and nusselt number as follows.

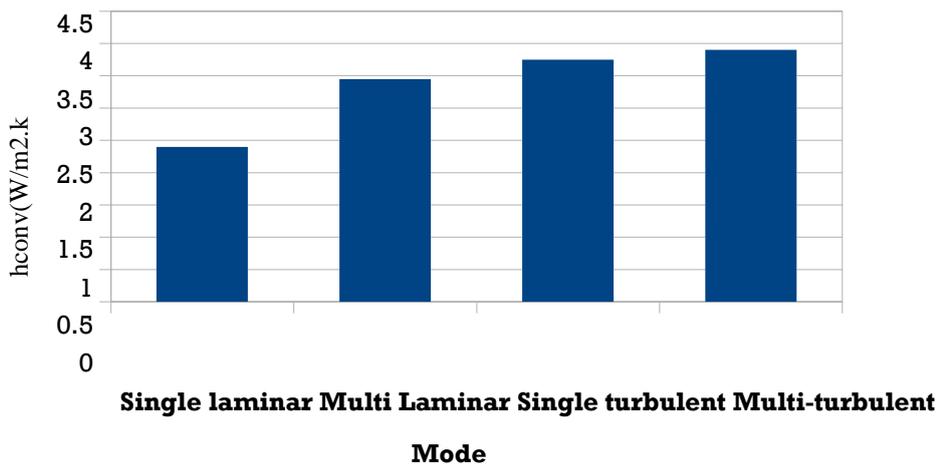


Fig.4 Heat Transfer Coefficient (h_{conv} in W/m².k) for the four modes of operation

The derived Reynolds number is estimated based on the calculated flow rate of the experimental and based on the velocity

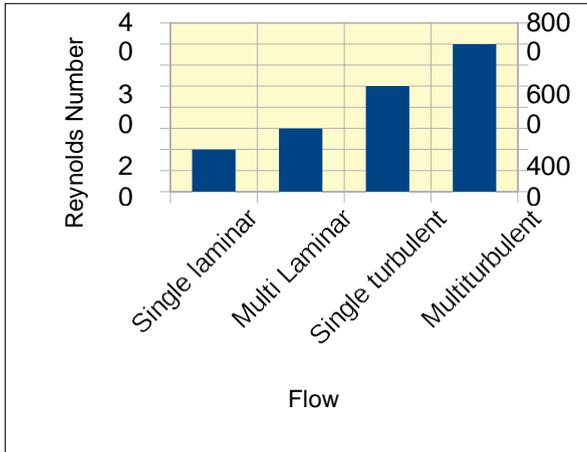


Fig.5 correlation between Flow rate and Re

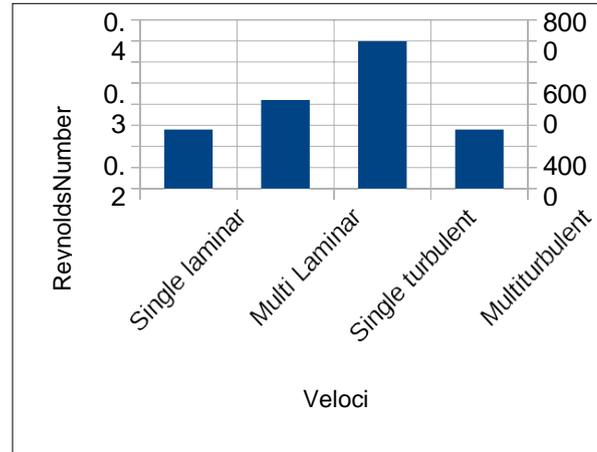


Fig.6 correlation between Velocity and Re

Wanget.alinpaper[11]examinedtheheattransfercharacteristicsoflongitudinalrowssoftubes with different dimensions,(which could be compared with multichannel flow of proposed methodology) with Reynolds numbers of 100 and 300 and a Prandtl number of 0.71.Anurag dahiyaet.al in paper[12] examined heat sinks with manifolds and derived Reynolds number for turbulent flow in the range of 342–857. The proposed work and inference could be depicted inFig.7

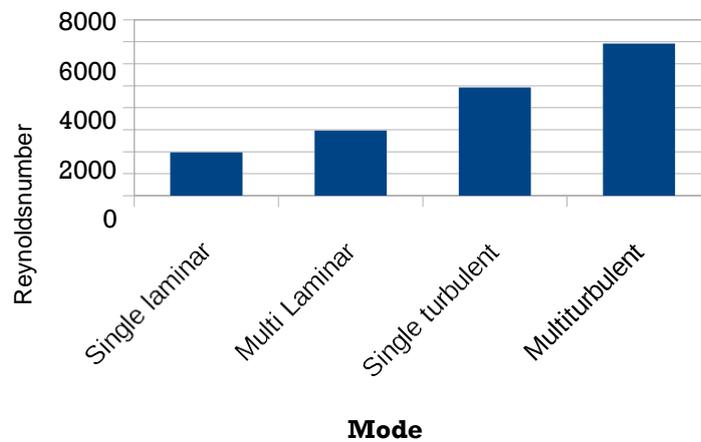


Fig.7 Comparison of results for the forced convection heat transfer based on Reynolds number, Re

The impact of the nusselt number Nu for the four modes of the proposed methodology is depicted in Fig.8 and Fig.9

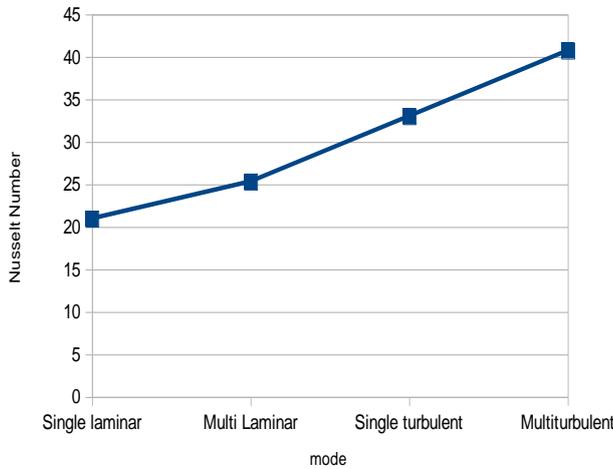


Fig.8 Comparison of Nu for four modes

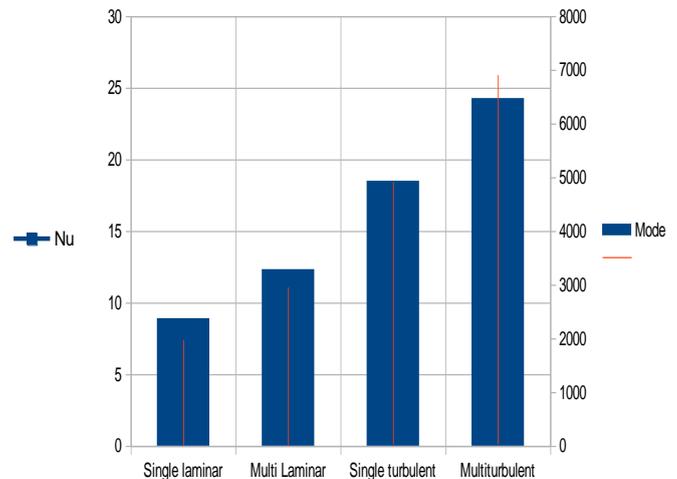


Fig.9 Relating Re and Nu for proposed methods

3.1.Failure Rate Estimation

The Life time of any electronic circuits is based on the values of failure estimation. Mean Timeto Failure (MTTF) based on Arrhenius equation is used for the derivation of life time. The failure ofelectronic circuits is mostly due to thermal problems like overheating and even circuit burning. It isderived from the Arrhenius equation which is stated in equation(9) that 10 degrees temperature risewill reduce the life of circuit by half. The inference of the same may be applied that 10 degreesdecrease in temperature may doubles the life of the circuit. The proposed methodology provides 10degrees temperature dip in experimental and mathematical estimation. The probability of double thelifetimeof thecircuitis higher than the conventional cool in gmethods.

$$K=A.e^{-(Ea/RT)} \quad \text{--- (9)}$$

Conclusion

The proposed work evaluates the metrics like temperature, heat transfer rate, velocity, Reynolds number and nusselt number based on experimental outcomes derived from the heat mitigation modes of NoC. It is found that the heat transfer rate of multichannel laminar flow, single channel turbulent flow and multichannel turbulent flow are 14%, 18%and 24% higher than the conventional single channel laminar flow of coolant which resembles fan mounted on chip. Also, Nusselt number of the above cases increases by 21%, 58% and 94% than the single laminar flow. The derived value is very much higher than values in [11] and [12]. Next, the active contribution of turbulent flow is exhibited from the Nusselt number in multi-channel turbulent flow. The proposed work exhibits the excellent heat mitigation effects by verifying the results with heat transfer metrics in forced convection fluid flow. The Life time of the electronic circuits in NoC could be doubled when the temperature decrease of 10 degrees as derived in experimental and mathematical analysis could be used in practical applications.

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