APPLICATION OF METALLIC NANOPARTICLE SUSPENSIONS IN ADVANCED COOLING SYSTEMS*

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ABSTRACT

In the development of energy-efficient heat transfer fluids that are required in many cooling applications, low thermal conductivity is a primary limitation. However, it is well known that at room temperature, metals in solid form have orders-of-magnitude higher thermal conductivities than those of fluids. Therefore, the thermal conductivities of fluids that contain suspended solid metallic particles are expected to be significantly enhanced over those of conventional heat transfer fluids. In fact, numerous theoretical and experimental studies of the effective thermal conductivity of dispersions that contain solid particles have been conducted since Maxwell's theoretical work was published more than 100 years ago. However, all of the studies on thermal conductivity of suspensions have been confined to millimeter- or micrometer-sized particles.

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One of the authors has proposed that an innovative new class of energy-efficient heat transfer fluids can be engineered by suspending nanometer-sized metallic particles (nanoparticles) in conventional heat transfer fluids. The resulting "nanofluids" are expected to exhibit much higher thermal conductivities than those of currently used heat transfer fluids and represent the best hope for high-performance cooling in next-generation cooling systems.

Based on this concept of nanofluids, Argonne thermal scientists have developed an advanced cooling technology. The advanced cooling approach relies on many microchannels consisting of long narrow slits (only thousands of an inch wide) and coolants containing nanometer-sized metallic particles. In other words, the innovative process employs microchannels filled with metallic nanoparticle-laden coolant to extract heat faster than present technology. This advanced cooling approach provides more efficient cooling than any other cooling technologies because the microchannels increase the effective heat transfer area and the metallic nanoparticles increase the effective thermal conductivity of coolants.

The feasibility of the concept of high-thermal-conductivity nanofluids has been demonstrated by applying the Hamilton and Crosser model to copper nanoparticles in water, together with some experimental results for CuO and γ-Al_2O_3 particles in water. Therefore, it is expected that nanofluids with a thermal conductivity of ≈ 3 times that of a conventional fluid can be engineered.

This advanced nanofluid cooling technology may be used in engines, in superconducting magnets, and in supercomputers where densely packed chips generate much heat. It may also be useful in fiber-forming processes or in reducing the size of current industrial cooling equipment. In this study, the advanced cooling technology has been applied to cooling crystal silicon mirrors used in high-intensity X-ray sources such as Argonne's Advanced Photon Source. Because the X-ray beam creates tremendous heat as it strikes the mirror, cooling rates of 2000-3000 W/cm^2 must be achievable with the advanced technology.

Analysis has been carried out to estimate the performance of microchannel heat exchangers with water, liquid nitrogen and nanofluids as the working fluid. The design and optimization procedures for microchannel heat exchangers show the existence of an optimum channel width that minimizes the thermal resistance of a microchannel heat exchanger. For a pressure drop of 210 kPa (30 psi), the optimized channel width and depth are 56 μm and 360 μm for a water-cooled silicon heat sink and 39 μm and 1410 μm for a liquid-nitrogen-cooled silicon heat sink. For the optimized configuration, performance of the nanofluid-cooled microchannel heat exchanger has been compared with that of a water-cooled and liquid-nitrogen-cooled microchannel heat exchanger. The results show the superiority of a nanofluid-cooled microchannel heat exchanger. When nanofluids are used, the thermal resistances are reduced and the power densities are increased. Excellent thermal performance of a silicon microchannel heat exchanger is demonstrated using nanofluids as the room temperature coolant.

In this study, analysis demonstrates that a nanofluid-cooled microchannel heat exchanger can extract heat from the silicon crystal mirror to a working fluid faster than present cooling technology. The benefits of nanofluid cooling are clear, including dramatic enhancement of cooling rates while operating the advanced cooling system at room temperature. Furthermore, the possibility of thermal distortion and flow-induced vibration will be eliminated by passing the nanofluids through microchannels within the silicon mirror itself. Future experimental work on the nanofluid-cooled microchannel heat exchanger will advance the art of cooling high-heat-load X-ray monochromators. For the high aspect ratio microchannels, power densities of ≈ 3000 W/cm^2 should be achievable with the use of nanofluids.

INTRODUCTION

Despite considerable previous research and development efforts on heat transfer enhancement, major improvements in cooling capabilities have been constrained because of the low thermal conductivity of conventional heat transfer fluids. With an increasing global competition, industries have a strong need to develop advanced heat transfer fluids with significantly higher thermal conductivities than are presently available.

It is well known that, at room temperature, metals in solid form have orders-of-magnitude larger thermal conductivities than fluids. For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil. Therefore, fluids containing suspended solid metallic particles are expected to possess significantly enhanced thermal conductivities compared to conventional heat transfer fluids. In fact, numerous theoretical and experimental studies of the effective thermal conductivity of dispersions containing particles have been conducted since Maxwell's theoretical work was published more than 100 years ago (Maxwell, 1881). However, all of the studies on the thermal conductivity of suspensions have been confined to mm- or micron-sized particles.

Choi has proposed that metallic particles having nanometer dimensions can be suspended in industrial heat transfer fluids such as water, ethylene glycol, or engine oil, resulting in the production of a new class of engineered fluids with extremely high thermal conductivity (Choi, 1995). He has coined the term nanofluids (NFs) for this new class of engineered heat transfer fluids. It should be noted taht metallic particles with average particle sizes of about 10 nanometers can be produced by current nanophase technology.

NFs are expected to have superior properties compared to conventional heat transfer fluids, as well as fluids containing micron-sized metallic particles. Since heat transfer takes place at the surface of the particle, it is desirable to use a substance with a large surface area. Nanoparticles have extremely high surface areas and therefore have a great potential for application in heat transfer enhancement. The much larger relative surface areas of nanophase powders compared to conventional micron-sized powders should result in markedly improved heat transfer capabilities and the stability of the suspensions.

The feasibility of the concept of high-thermal-conductivity nanofluids has been demonstrated by applying the Hamilton and Crosser model to copper nanoparticles in water, together with some experimental results for CuO and γ-Al$_2$O$_3$ particles in water (Choi, 1995). Therefore, it is expected that nanofluids with a thermal conductivity of ≈ 3 times that of a conventional fluid can be engineered.

The advent of computer systems employing high-speed, high-density very large scale integrated circuits implies the requirements for effective and compact heat removal. The microchannel cooling technology for silicon integrated circuits has been improved during the last decade. Tuckerman has developed the design and optimization procedures for microchannel heat exchangers (Tuckerman and Pease, 1981; Tuckerman, 1984). The analysis of Tuckerman, confirmed by later experiments, showed that, with water cooling, water/silicon thermal resistance could be reduced to $< 0.1°C/W/cm^2$ by using cooling channels with a characteristic width of 40 μm and an aspect ratio of $\approx 10{:}1$ (Tuckerman and Pease, 1981; Tuckerman, 1984). Analysis has been carried out to demonstrate that a liquid-nitrogen-cooled microchannel heat exchanger can be designed to maximize heat transfer from silicon to a working fluid (Choi et al., 1992). The results show that the performance of the liquid-nitrogen-cooled microchannel heat exchanger is enhanced approximately three times over that of flowing water through microchannels.

Based on this concept of NFs and microchannel heat exchanger, Argonne thermal scientists have developed an advanced cooling technology. The advanced cooling approach relies on many microchannels consisting of long narrow slits (only thousands of an inch wide) and coolants containing nanometer-sized metallic particles. In other words, the innovative process employs microchannels filled with metallic nanoparticle-laden coolant to extract heat faster than present technology. This advanced cooling approach provides more efficient cooling than any other cooling technologies because the microchannels increase the effective heat transfer area and the metallic nanoparticles increase the effective thermal conductivity of coolants.

In this study, the advanced cooling technology has been applied to cooling crystal silicon mirrors used in high-intensity X-ray sources such as Argonne's Advanced Photon Source. Because the X-ray beam creates tremendous heat as it strikes the mirror, cooling rates of 2000-3000 W/cm^2 must be achievable with the advanced technology. The purpose of this study is to estimate the performance of microchannel heat exchangers with water, liquid nitrogen and nanofluids as the working fluid and show that the performance of the nanofluid-cooled microchannel heat exchanger is equal to or better than that of a water-cooled or liquid-nitrogen-cooled microchannel heat exchanger.

DESIGN

The performance of a heat sink is measured by its thermal resistance $R = \Delta T / \dot{q}$, where ΔT is the difference between the silicon substrate temperature and the coolant inlet temperature and $\dot{q}$ is the dissipated power. When the maximum temperature difference ΔT_{max} is given, thermal resistance determines the maximum power at which a silicon optical element can operate. In general, R is the sum of three components: R_{cond}, due to conduction from the top surface of the crystal to the heat sink interface; R_{conv}, due to convection from the heat sink to the coolant fluid; and R_{cal}, due to heating of the fluid as it absorbs energy passing through the heat exchanger.

Figure 1 is a diagram of a high-performance IC heat sink proposed by Tuckerman (1984), where the front surface of the substrate contains a planar heat source (the circuits), and the back surface contains deep rectangular channels of width W_c and depth H which carry the coolant, separated by walls of width W_w.

If we assume simple parallel channel flow and one dimensional heat flow in the wall, it is possible to get the analytical expressions for these three components of thermal resistance.

As a first approximation, we will neglect R_{cond} in this discussion, because R_{cond} can be made very small independently of R_{conv} and R_{cal} by locating the heat exchanger very near to the heat source.

R_{conv} can be expressed as follows;

$$R_{conv} = \frac{2}{k_f Nu_\infty LW} W_c \alpha^{-1} \eta^{-1} \tag{1}$$

where the α is surface area multiplication factor and for high aspect ratio rectangular channels, it can be presented as;

$$\alpha = \frac{2H}{W_c + W_w} \tag{2}$$

η is correction factor used to accounting for a finite wall conductivity and it is known as the "fin efficiency." The analytical approximation for η can be obtained by assuming a constant heat transfer coefficient up the walls and modeling the heat flow in the wall as one-dimensional:

$$\eta = \frac{\tanh N}{N} \tag{3}$$

where

$$N = \left(2h/k_w W_w\right)^{1/2} H \tag{4}$$

R_{cal} can be obtained as:

$$R_{cal} = \frac{24\mu L}{\rho C_p PW}\left(W_c^{-3}\alpha^{-1}\right) \tag{5}$$

With the above three equations, we can calculate the thermal resistances (1), (5) by using the channel geometry (W_c, W_w, H) and equations (2), (3), (4). Moreover, it is possible to show that there exists an optimum channel width that minimizes total thermal resistance R. For a fixed pressure drop, the optimized channel width W_c is

$$W_c = 2.29\sqrt[4]{\mu k_f L^2 Nu_\infty/\rho C_p P} \tag{6}$$

for which

$$R = \frac{8.01}{WL^{1/2}}\sqrt[4]{\mu/k_f k_w^2 \rho C_p P Nu_\infty} \tag{7}$$

where μ is the viscosity of the coolant fluid, k_f is the thermal conductivity of the coolant fluid, k_w is the thermal conductivity of substrate wall, ρ is the density of the coolant fluid, C_p is the coolant heat capacity at constant pressure, P is the overall pressure drop across the channel, Nu_∞ is the Nusselt number for a fully developed temperature profile, and L and W are the length and width of the heated area, respectively.

In our study we assumed that the
1. Flow in the microchannels is laminar and fully developed.
2. Thermal boundary layer is fully developed in the microchannels.
3. Maximum temperature difference $\Delta T_{max} = 60°C$.
4. Properties of silicon and coolants are constant.
5. Microchannels are embedded in a 1 x 1 cm silicon substrate.
6. Heat flux is uniform over a 1-cm^2 area of the silicon crystal.

First, using water and liquid nitrogen as two reference coolants, we have determined the optimized geometry of a microchannel heat exchanger which is a silicon heat sink on a 1 x 1 cm substrate. A cross-sectional view of the modeled microchannel configuration is given in Fig. 1. Next, analysis has been carried out to estimate the performance of microchannel heat exchangers with water, liquid nitrogen and nanofluids as the working fluid.
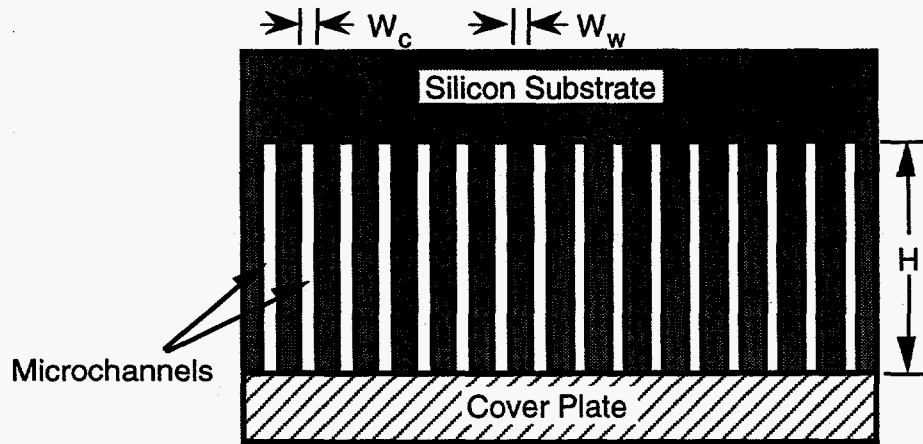
Fig.1 Cross-sectional view of silicon optical element with microchannels

RESULTS AND DISCUSSION

Optimized Microchannels   Fig. 2 shows that, for the two reference coolants, the optimized microchannel width is on the order of tens of micrometers and decreases with pressure. The use of liquid nitrogen has reduced the channel width by $\approx 30\%$ and improved the aspect ratio by a factor of ≈ 6. For example, for a water-cooled silicon heat sink at a pressure drop of $P = 210$ kPa (30 psi), the optimization procedures give $W_c = W_w = 56$ μm; $H = 360$ μm; $R = 0.084°C/W$, and $\dot{q}=710W/cm^2$. For a liquid-nitrogen-cooled silicon heat sink, the optimization procedures give the designed optimum: $W_c = W_w = 39$ μm, $H = 1410$ μm, $R = 0.033°C/W$, and $\dot{q}=1800W/cm^2$.
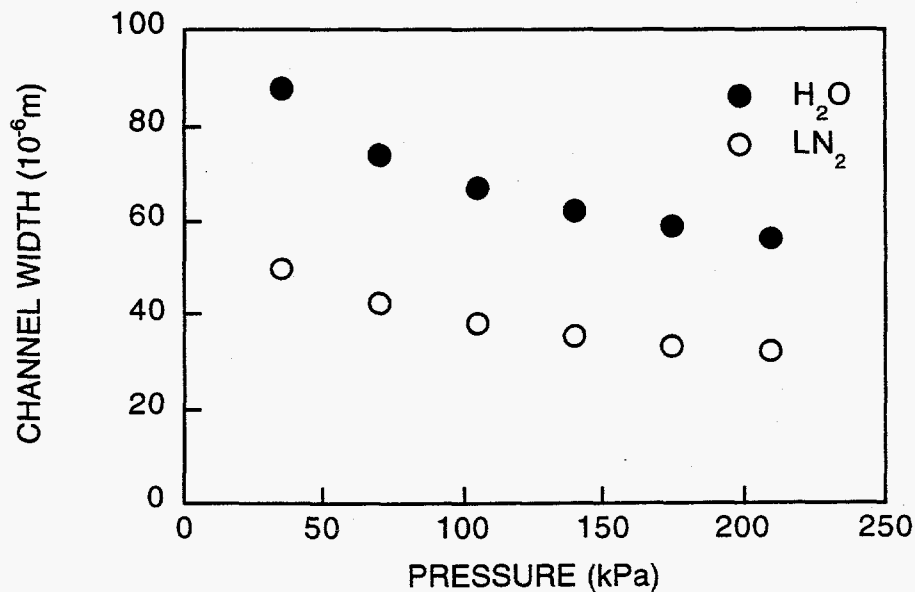

Fig.2 Channel width vs. pressure drop for water- and liquid-nitrogen-cooled microchannels

Performance Analysis In estimating the performance of microchannel heat exchangers, the two optimized microchannels for water and liquid nitrogen were used for nanofluids in order to show the impact of nanofluids on performance. NF_2 and NF_3 are nanofluids whose thermal conductivities are two and three times greater than that of water, respectively.

Figure 3 shows the variation of thermal resistance with pressure for room temperature water and nanofluid cooled microchannels. It can be seen that when NF_3 are used the thermal resistances are reduced by a factor of 2. Figure 4 shows that the power density increases with pressure. It also shows that the use of NF_3 can make approximately three-fold improvement in heat transfer performance compared with water. Thermal resistance as low as $0.04°C/W$ are predicted from $1cm^2$ crystals: thus power densities of $1500W/cm^2$ should be achievable with the use of nanofluids in microchannel heat exchangers.

Figure 5 shows the variation of thermal resistance with pressure for the coolants of liquid nitrogen at cryogenic temperatures and nanofluids at room temperature. Again, it should be noted that the geometry optimized for liquid nitrogen is also used in the performance estimation of nanofluids. It can be seen that the thermal resistance of an NF_3-cooled microchannel heat exchanger can be reduced to that of a liquid nitrogen-cooled heat exchanger. Figure 6 is a comparison of power density for liquid nitrogen-cooled and nanofluids-cooled microchannel heat exchangers. It shows that the use of NF_3 at room temperature can increase the heat removal rate to that of liquid nitrogen at cryogenic temperatures.
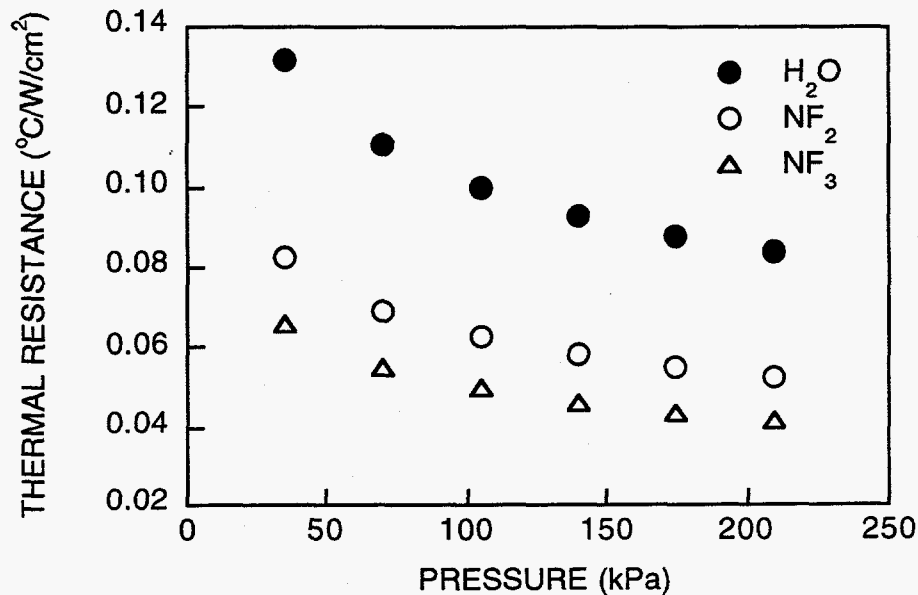

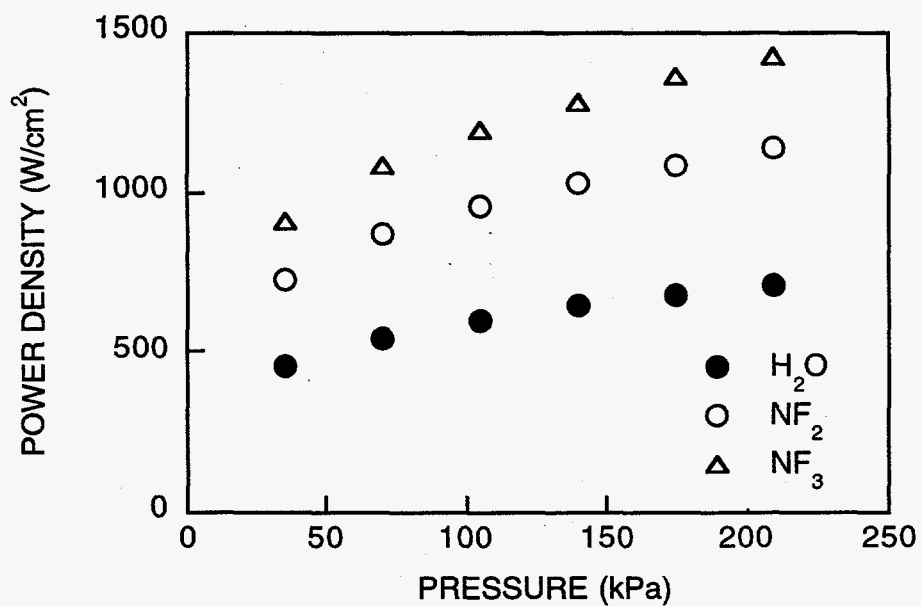Fig.3 Thermal resistance vs. pressure for water- and nanofluid-cooled microchannels

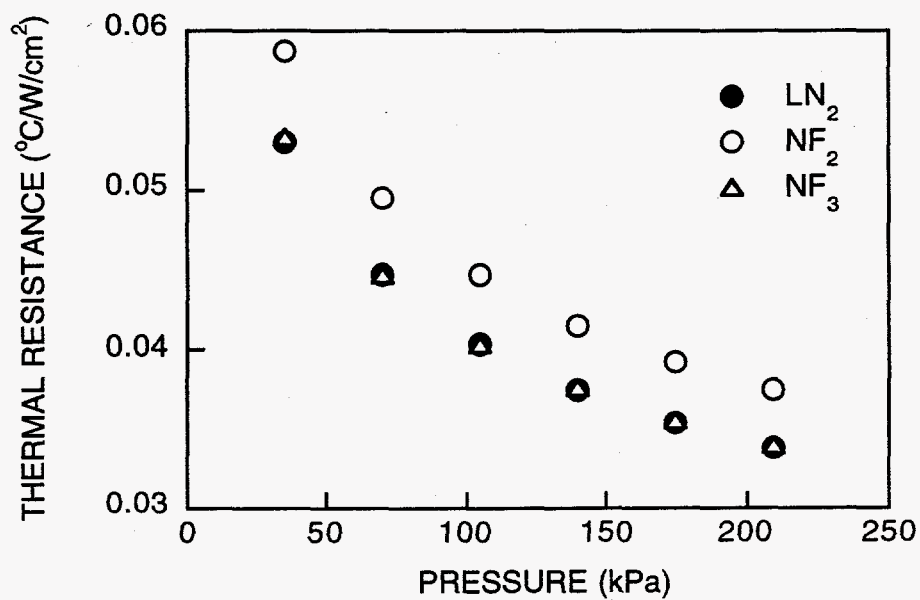Fig.4 Power density vs. pressure for water- and nanofluid-cooled microchannels

Fig.5 Thermal resistance vs. pressure for liquid nitrogen-and nanofluid-cooled microchannels
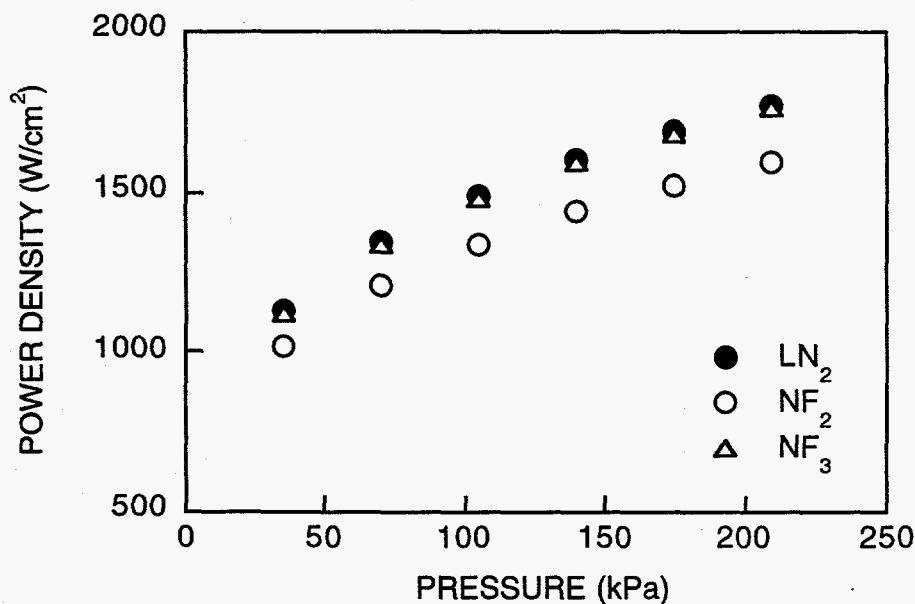
Fig.6 Power density vs. pressure for liquid nitrogen- and nanofluid-cooled microchannels

CONCLUSION

Analysis has been carried out to estimate the performance of microchannel heat exchangers with water, liquid nitrogen and nanofluids as the working fluid. The design and optimization procedures for microchannel heat exchangers show the existence of an optimum channel width that minimizes the thermal resistance of a microchannel heat exchanger. For the optimized configuration, performance of the nanofluid-cooled microchannel heat exchanger has been compared with that of a water-cooled and liquid-nitrogen-cooled microchannel heat exchanger. When nanofluids are used, the thermal resistances are reduced and the power densities are increased. The use of nanofluid whose thermal conductivity is three times that of water allows almost three-fold increases in power density compared with water and can reach the power density of liquid nitrogen-cooled microchannel heat exchanger.

When used as a new coolant in microchannel heat exchangers, nanofluids offer significant benefits, including dramatic enhancement of cooling rates while operating the advanced cooling system at room temperature. For applications where the overall cooling system cost must be kept low, nanofluids can be used as a very attractive coolant. Furthermore, the possibility of thermal distortion and flow-induced vibration will be eliminated by passing the nanofluids through microchannels within the silicon mirror itself. Future experimental work on the nanofluid-cooled microchannel heat exchanger will advance the art of cooling high-heat-load X-ray monochromators. For the high aspect ratio microchannels, power densities of ≈ 3000 W/cm^2 should be achievable with the use of nanofluids.

This advanced nanofluid cooling technology may be used in engines, in superconducting magnets, and in supercomputers where densely packed chips generate much heat. It may also be useful in fiber-forming processes or in reducing the size of current industrial cooling equipment.

ACKNOWLEDGMENTS

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