October 31, 2012 – Microchannel, Nanofluid Boiling Reference List
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<u>Format</u>:

1. **Title**
    a. Author(s)
    b. Source/Journal
    c. Abstract

<u>References:</u>

1. **Formation mechanism and characteristics of a liquid microlayer in microchannel boiling system**
    a. Zhang, Yaohua; Utaka, Yoshio; Kashiwabara, Yuki
    b. *Journal of Heat Transfer*, v 132, n 12, 2010
    c. Experiments were performed using the laser extinction method to measure the thickness of the liquid film formed by growing flattened bubbles in a microchannel for gap sizes of 0.5 mm, 0.3 mm, and 0.15 mm. Water, ethanol, and toluene were used as test fluids. A high-speed camera was also used to simultaneously measure the bubble growth process. It was confirmed that the gap size and bubble forefront velocity determined the initial microlayer thickness. The variation trend of the microlayer thickness relative to the velocity of the interface was divided into two regions: region I, where the velocity is small and the thickness increases linearly with increasing velocity, and region II, where the thickness is almost constant or decreased slightly with increasing velocity. Furthermore, a nondimensional correlation for investigating the effects of test materials and gap sizes on microlayer thickness is presented. An analysis of the results showed that the boundaries of the two regions correspond to a Weber number of approximately 110, and in the region where the Weber number was smaller than 110, the thickness of the microlayer was thinner for the liquid whose value of ρ 0.62 0.42 σ-0.62 was relatively small. However, for the region where Weber number was larger than 110, the smaller the kinematic viscosity of the liquid, the thinner the microlayer became. © 2010 American Society of Mechanical Engineers

2. **Nanofluid stabilizes and enhances convective boiling heat transfer in a single microchannel**
    a. Xu, Li; Xu, Jinliang
    b. *International Journal of Heat and Mass Transfer*, v 55, n 21-22, p 5673-5686, October 2012

    c. The flow boiling heat transfer in a single microchannel was investigated with pure water and nanofluid as the working fluids. The microchannel had a size of 7500 × 100 × 250 μm, which was formed by two pyrex glasses and a silicon wafer. A platinum film with a length of 3500 μm and a width of 80 μm was deposited at the bottom channel surface, acting as the heater and temperature sensor. The nanofluid had a low weight concentration of 0.2%, consisting of de-ionized water and 40 nm Al_2O_3 nanoparticles. The nanoparticle deposition phenomenon was not observed. The boiling flow displays chaotic behavior due to the random bubble coalescence and breakup in the milliseconds timescale at moderate heat fluxes for pure water. The flow instability with large oscillation amplitudes and long cycle periods was observed with further increases in heat fluxes. The flow patterns are switched between the elongated bubbles and isolated miniature bubbles in the timescale of 100 s. It is found that nanofluid significantly mitigate the flow instability without nanoparticle deposition effect. The boiling flow is always stable or quasi-stable with significantly reduced pressure drop and enhanced heat transfer. Miniature bubbles are the major flow pattern in the microchannel. Elongated bubbles temporarily appear in the milliseconds timescale but isolated miniature bubbles will occupy the channel shortly. The decreased surface tension force acting on the bubble accounts for the smaller bubble size before the bubble departure. The inhibition of the dry patch development by the structural disjoining pressure, and the enlarged percentage of liquid film evaporation heat transfer region with nanoparticles, may account for the heat transfer enhancement compared to pure water.

3. **Critical heat flux (CHF) of subcooled flow boiling of alumina nanofluids in a horizontal microchannel**
    a. Vafaei, Saeid; Wen, Dongsheng
    b. *Journal of Heat Transfer*, v 132, n 10, p 1-7, October 2010
    c. his work investigates subcooled flow boiling of aqueous based alumina nanofluids in 510 µm single microchannels with a focus on the effect of nanoparticles on the critical heat flux. The surface temperature distribution along the pipe, the inlet and outlet pressures and temperatures are measured simultaneously for different concentrations of alumina nanofluids and de-ionized water. To minimize the effect of nanoparticle depositions, all nanofluid experiments are performed on fresh microchannels. The experiment shows an increase of ~51% in the critical heat flux under very low nanoparticle concentrations (0.1 vol %). Different burnout characteristics are observed between water and nanofluids, as well as different pressure and temperature fluctuations and flow pattern development during the stable boiling period. Detailed observations of the boiling surface show that nanoparticle deposition and a subsequent modification of the boiling surface are common features associated with nanofluids, which should be responsible for the different boiling behaviors of nanofluids.

4. **Flow boiling heat transfer of alumina nanofluids in single microchannels and the roles of nanoparticles**
    a. Vafaei, Saeid; Wen, Dongsheng
    b. *Journal of Nanoparticle Research*, v 13, n 3, p 1063-1073, March 2011
    c. This study investigates flow boiling heat transfer of aqueous alumina nanofluids in single microchannels with particular focuses on the critical heat flux (CHF) and the potential dual roles played by nanoparticles, i.e., (i) modification of the heating surface through particle deposition and (ii) modification of bubble dynamics through particles suspended in the liquid phase. Low concentrations of nanofluids (0.001-0.1 vol.%) are formulated by the two-step method and the average alumina particle size is ∼25 nm. Two sets of experiments are performed: (a) flow boiling of formed nanofluids in single microchannels where the effect of heating surface modification by nanoparticle deposition is apparent and (b) bubble formation in a quiescent pool of alumina

nanofluids under adiabatic conditions where the role of suspended nanoparticles in the liquid phase is revealed. The flow boiling experiments reveal a modest increase in CHF by nanofluids, being higher at higher nanoparticle concentrations and higher inlet subcoolings. The bubble formation experiments show that suspended nanoparticles in the liquid phase alone can significantly affect bubble dynamics. Further discussion reveals that both roles are likely co-existent in a typical boiling system. Properly surface-promoted nanoparticles could minimize particle deposition hence little modification of the heating surface, but could still contribute to the modification in heat transfer through the second mechanism, which is potentially promising for microchannel applications. © 2010 Springer Science+Business Media B.V.

5. **Two-phase microchannel heat sinks: Theory, applications, and limitations**
    a. Mudawar, Issam
    b. *Journal of Electronic Packaging, Transactions of the ASME*, v 133, n 4, 2011
    c. Boiling water in small channels that are formed along turbine blades has been examined since the 1970s as a means to dissipating large amounts of heat. Later, similar geometries could be found in cooling systems for computers, fusion reactors, rocket nozzles, avionics, hybrid vehicle power electronics, and space systems. This paper addresses (a) the implementation of two-phase microchannel heat sinks in these applications, (b) the fluid physics and limitations of boiling in small passages, and effective tools for predicting the thermal performance of heat sinks, and (c) means to enhance this performance. It is shown that despite many hundreds of publications attempting to predict the performance of two-phase microchannel heat sinks, there are only a handful of predictive tools that can tackle broad ranges of geometrical and operating parameters or different fluids. Development of these tools is complicated by a lack of reliable databases and the drastic differences in boiling behavior of different fluids in small passages. For example, flow boiling of certain fluids in very small diameter channels may be no different than in macrochannels. Conversely, other fluids may exhibit considerable confinement even in seemingly large diameter channels. It is shown that cutting-edge heat transfer enhancement techniques, such as the use of nanofluids and carbon nanotube coatings, with proven merits to single-phase macrosystems, may not offer similar advantages to microchannel heat sinks. Better performance may be achieved by careful optimization of the heat sink's geometrical parameters and by adapting a new class of hybrid cooling schemes that combine the benefits of microchannel flow with those of jet impingement. © 2011 American Society of Mechanical Engineers.

6. **Eulerian-Eulerian two-phase numerical simulation of nanofluid laminar forced convection in a microchannel**
    a. Kalteh, Mohammad; Abbassi, Abbas; Saffar-Avval, Majid; Harting, Jens
    b. *International Journal of Heat and Fluid Flow*, v 32, n 1, p 107-116, February 2011
    c. In this paper, laminar forced convection heat transfer of a copper-water nanofluid inside an isothermally heated microchannel is studied numerically. An Eulerian two-fluid model is considered to simulate the nanofluid flow inside the microchannel and the governing mass, momentum and energy equations for both phases are solved using the

finite volume method. For the first time, the detailed study of the relative velocity and temperature of the phases are presented and it has been observed that the relative velocity and temperature between the phases is very small and negligible and the nanoparticle concentration distribution is uniform. However, the two-phase modeling results show higher heat transfer enhancement in comparison to the homogeneous single-phase model. Also, the heat transfer enhancement increases with increase in Reynolds number and nanoparticle volume concentration as well as with decrease in the nanoparticle diameter, while the pressure drop increases only slightly.

7. **Study on the thermal behavior and cooling performance of a nanofluid-cooled microchannel heat sink**
    a. Chen, Chien-Hsin; Ding, Chang-Yi
    b. *International Journal of Thermal Sciences*, v 50, n 3, p 378-384, March 2011
    c. This paper presents an analysis of the heat transfer characteristics and cooling performance of a microchannel heat sink with water-γAl 2O3 nanofluids having different nanoparticle volume fraction. In view of the small dimensions of the microstructures, the microchannel heat sink is modeled as a fluid-saturated porous medium for problem solving. The Forchheimer-Brinkman-extended Darcy equation is used to describe the fluid flow and the two-equation model with thermal dispersion is utilized for heat transfer. Typical results for the temperature distributions of the fluid phase and the channel wall are presented for various values of nanoparticle volume fraction and the inertial force parameter. It is found that the temperature distribution of the channel wall is practically not sensitive to the inertial effect, while the fluid temperature distribution and the total thermal resistance change significantly due to the inertial force effect. In general, the effect of fluid inertia is to reduce the total thermal resistance and the temperature difference between the channel wall and the fluid phase. The total thermal resistances obtained from the present model with inertial effect match well with the existing experimental results, whereas the thermal resistance is overestimated as the inertial effect is neglected.

8. **Experimental and numerical investigation of nanofluid forced convection inside a wide microchannel heat sink**
    a. Kalteh, Mohammad; Abbassi, Abbas; Saffar-Avval, Majid; Frijns, Arjan; Darhuber, Anton; Harting, Jens
    b. *Applied Thermal Engineering*, v 36, n 1, p 260-268, April 2012
    c. This paper aims to study the laminar convective heat transfer of an alumina-water nanofluid flow inside a wide rectangular microchannel heat sink (94.3 mm, 28.1 mm and 580 μm; length, width and height, respectively) both numerically and experimentally. For experimental study, a microchannel is made using a silicon wafer with glass layers. For the numerical study, a two-phase Eulerian-Eulerian method using the finite volume approach is adopted in this study. Comparing the experimental and numerical results show that two-phase results are in better agreement with experimental results than the homogeneous (single-phase) modeling. The maximum deviation from experimental

results is 12.61% and 7.42% for homogeneous and two-phase methods, respectively. This findings show that the two-phase method is more appropriate than the homogeneous method to simulate the nanofluid heat transfer. Also, the two-phase results show that the velocity and temperature difference between the phases is very small and negligible. Moreover, the average Nusselt number increases with an increase in Reynolds number and volume concentration as well as with a decrease in the nanoparticle size.

9. **Modeling and simulation on the mass flow distribution in microchannel heat sinks with non-uniform heat flux conditions**
    a. Cho, Eun Seok; Choi, Jong Won; Yoon, Jae Sung; Kim, Min Soo
    b. *International Journal of Heat and Mass Transfer*, v 53, n 7-8, p 1341-1348, March 2010
    c. This paper describes modeling and numerical simulation on the mass flow distribution in microchannel heat sink, which is a promising device for cooling miniature electronic systems. The microchannel heat sinks in this study consist of headers, multiple fluidic channels and port holes, all of which influence flow distribution in the multiple channels. This study focuses on design of the header with non-uniform heating conditions over the channel area. To investigate the effect of non-uniform heat flux, three different non-uniform heat flux conditions were applied. The simulation work has been carried out to find optimal header geometry for two-phase flow in the microchannel heat sinks. The header geometry was expressed in mathematical terms by defining a geometric parameter of header shape, n. For the optimal design of microchannel heat sinks, absolute average deviation and root mean squared deviation of the flow distribution under various header shapes have been calculated as well as pressure drop. The results show that mass flow rate distribution tends to be less changed among microchannels over a certain value of n.

10. **Flow boiling of R134a in circular microtubes - Part II: Study of critical heat flux condition**
    a. Basu, Saptarshi; Ndao, Sidy; Michna, Gregory J.; Peles, Yoav; Jensen, Michael K.
    b. *Journal of Heat Transfer*, v 133, n 5, 2011
    c. A detailed experimental study was carried out on the critical heat flux (CHF) condition for flow boiling of R134a in single circular microtubes. The test sections had inner diameters (ID) of 0.50 mm, 0.96 mm, and 1.60 mm. Experiments were conducted over a large range of mass flux, inlet subcooling, saturation pressure, and vapor quality. CHF occurred under saturated conditions at high qualities and increased with increasing mass fluxes, tube diameters, and inlet subcoolings. CHF generally, but not always, decreases with increasing saturation pressures and vapor qualities. The experimental data were mapped to the flow pattern maps developed by Hasan [2005, "Two-Phase Flow Regime Transitions in Microchannels: A Comparative Experimental Study," Nanoscale Microscale Thermophys. Eng., 9, pp. 165-182] and Revellin and Thome [2007, "A New Type of Diabatic Flow Pattern Map for Boiling Heat Transfer in Microchannels," J. Micromech. Microeng., 17, pp. 788-796]. Based on these maps, CHF mainly occurred in the annular flow regime in the larger tubes. The flow pattern for the 0.50 mm ID tube was not conclusively identified. Four correlations-the Bowring correlation, the Katto-

Ohno correlation, the Thome correlation, and the Zhang correlation-were used to predict the experimental data. The correlations predicted the correct experimental trend, but the mean absolute error (MAE) was high (>15%) A new correlation was developed to fit the experimental data with a MAE of 10%.

11. **Flow boiling of water in a minichannel: The effects of surface wettability on two-phase pressure drop**
    a. Phan, Hai Trieu; Caney, Nadia; Marty, Philippe; Colasson, Stéphane; Gavillet, Jérôme
    b. *Applied Thermal Engineering*, v 31, n 11-12, p 1894-1905, August 2011
    c. Experiments were performed to study the effects of surface wettability on two-phase pressure drop of flow boiling of water at atmospheric pressure. The test channel is a single rectangular channel 0.5 mm high, 5 mm wide and 180 mm long. The mass flux was set at 100 kg/m^2 s and 120 kg/m^2 s, respectively. The base heat flux varied from 30 to 80 kW/m^2. Water enters the test channel under subcooled conditions. The study has been performed at low exit vapour quality (less than 0.1). The samples are either hydrophilic like Polydimethylsiloxane (SiOx), Titanium (Ti), Diamond-Like Carbon (DLC) or hydrophobic like Polydimethylsiloxane (SiOC). These surfaces have static contact angles of 26°, 49°, 63° and 103°, respectively. It was observed that the total two-phase pressure drop significantly increases with the static contact angle. In particular, the average deviation between the highly-wetted and the unwetted surfaces is about 170%. To explain this observation, the "wetting pressure drop" notion caused by the surface tension forces generated at the triple contact lines is introduced. Afterwards, a model is proposed to predict the wetting pressure drop as a function of the static contact angle. This model shows a good agreement with the experimental data with 86% of the data included within the lines of 20% error.

12. **The performance evaluation of Al2O3/water nanofluid flow and heat transfer in microchannel heat sink**
    a. Lelea, Dorin
    b. *International Journal of Heat and Mass Transfer*, v 54, n 17-18, p 3891-3899, August 2011
    c. The numerical modeling of the conjugate heat transfer and fluid flow of Al2O3/water nanofluid through the microchannel heat sink is presented in the paper. The laminar flow regime was considered along with viscous dissipation effect. The microchannel heat sink with square microchannels and Dh = 50 µm is considered. The heat flux was fixed to q = 35 W/m^2 with heating and cooling cases. The water based Al 2O3 nanofluid was encountered with various volume concentrations of Al2O3 particles ϕ=1-9% and three diameters of the particle dp = 13, 28 and 47 nm. The analysis is performed on the results obtained for the local heat transfer coefficients based on a fixed pumping power. The results reveal a different local heat transfer behavior compared to the analysis made on a basis of the constant Re.

13. **Nanofluid stabilizes and enhances convective boiling heat transfer in a single microchannel**

a. Xu, Li; Xu, Jinliang
b. *International Journal of Heat and Mass Transfer*, v 55, n 21-22, p 5673-5686, October 2012
c. The flow boiling heat transfer in a single microchannel was investigated with pure water and nanofluid as the working fluids. The microchannel had a size of 7500 × 100 × 250 μm, which was formed by two pyrex glasses and a silicon wafer. A platinum film with a length of 3500 μm and a width of 80 μm was deposited at the bottom channel surface, acting as the heater and temperature sensor. The nanofluid had a low weight concentration of 0.2%, consisting of de-ionized water and 40 nm Al_2O_3 nanoparticles. The nanoparticle deposition phenomenon was not observed. The boiling flow displays chaotic behavior due to the random bubble coalescence and breakup in the milliseconds timescale at moderate heat fluxes for pure water. The flow instability with large oscillation amplitudes and long cycle periods was observed with further increases in heat fluxes. The flow patterns are switched between the elongated bubbles and isolated miniature bubbles in the timescale of 100 s. It is found that nanofluid significantly mitigate the flow instability without nanoparticle deposition effect. The boiling flow is always stable or quasi-stable with significantly reduced pressure drop and enhanced heat transfer. Miniature bubbles are the major flow pattern in the microchannel. Elongated bubbles temporarily appear in the milliseconds timescale but isolated miniature bubbles will occupy the channel shortly. The decreased surface tension force acting on the bubble accounts for the smaller bubble size before the bubble departure. The inhibition of the dry patch development by the structural disjoining pressure, and the enlarged percentage of liquid film evaporation heat transfer region with nanoparticles, may account for the heat transfer enhancement compared to pure water.

14. Influence of various base nanofluids and substrate materials on heat transfer in trapezoidal microchannel heat sinks

a. Mohammed, H.A.; Gunnasegaran, P.; Shuaib, N.H.
b. *International Communications in Heat and Mass Transfer*, v 38, n 2, p 194-201, February 2011
c. Numerical investigations are performed to investigate the laminar flow and heat transfer characteristics of trapezoidal MCHS using various types of base nanofluids and various MCHS substrate materials on MCHS performance. This study considered four types of base fluids including water, ethylene glycol (EG), oil, and glycerin with 2% volume fraction of diamond nanoparticle, and four types of MCHS substrate materials including copper, aluminium, steel, and titanium. The three-dimensional steady, laminar flow and heat transfer governing equations are solved using the finite volume method. It is found that the best uniformities in heat transfer coefficient and temperature among the four mixture flows can be obtained using glycerin-base nanofluid followed by oil-base nanofluid, EG-base nanofluid, and water-base nanofluid heat sinks. However, the heat transfer performance of water-base nanofluid can be greatly enhanced in steel made substrate heat sink.

15. **Investigation of the Velocity Field and Nanoparticle Concentration Distribution of Nanofluid Using Lagrangian-Eulerian Approach**
    a. Aminfar, Habib; Motallebzadeh, Roghayyeh
    b. *Journal of Dispersion Science and Technology*, v 33, n 1, p 155-163, January 2012
    c. In this study, we use the Lagrangian-Eulerian approach to determine the concentration distribution and velocity of nanoparticles are investigated in nanofluid. Furthermore, the velocity of the fluid phase affected by the particle movement is examined. Moreover, the effects of Brownian, thermophoretic, gravitational,, and drag forces on particles and fluid velocity and nanoparticle distribution are studied, as are the effects of Reynolds number on the concentration distribution.According to the results of this study, particles are not uniformly distributed, rather, they areconcentrated more in the vicinity of the centerline of the pipe than the wall; the cause of this lack of uniform distribution is due to Brownian and thermophoretic forces. In addition, the results of this study show that the effects of Brownian forces on nanoparticle distribution and velocity field is stronger than that of other forces including thermophoretic ones.

16. **Heat transfer enhancement in microchannel heat sinks using nanofluids**
    a. Hung, Tu-Chieh; Yan, Wei-Mon; Wang, Xiao-Dong; Chang, Chun-Yen
    b. *International Journal of Heat and Mass Transfer*, v 55, n 9-10, p 2559-2570, April 2012
    c. Heat transfer enhancement in a 3-D microchannel heat sink (MCHS) using nanofluids is investigated by a numerical study. The addition of nanoparticles to the coolant fluid changes its thermophysical properties in ways that are closely related to the type of nanoparticle, base fluid, particle volume fraction, particle size, and pumping power. The calculations in this work suggest that the best heat transfer enhancement can be obtained by using a system with an Al2O3-water nanofluid-cooled MCHS. Moreover, using base fluids with lower dynamic viscosity (such as water) and substrate materials with high thermal conductivity enhance the thermal performance of the MCHS. The results also show that as the particle volume fraction of the nanofluid increases, the thermal resistance first decreases and then increases. The lowest thermal resistance can be obtained by properly adjusting the volume fraction and pumping power under given geometric conditions. For a moderate range of particle sizes, the MCHS yields better performance when nanofluids with smaller nanoparticles are used. Furthermore, the overall thermal resistance of the MCHS is reduced significantly by increasing the pumping power. The heat transfer performance of Al 2O3-water and diamond-water nanofluids was 21.6% better than that of pure water. The results reported here may facilitate improvements in the thermal performance of MCHSs.

17. **Experimental and numerical investigation into the heat transfer study of nanofluids in microchannel**
    a. Singh, Pawan K.; Harikrishna, P.V.; Sundararajan, T.; Das, Sarit K.
    b. *Journal of Heat Transfer*, v 133, n 12, 2011
    c. There are very few detailed experimental investigations about the heat transfer behavior of nanofluids in microchannel. The heat transfer behavior of nanofluids in

microchannel is investigated. Two microchannels with hydraulic diameters 218 and 303 m are fabricated by wet etching process on silicon wafer. An experimental set-up having provision of flow in the channel and temperature measurement along with bottom wall temperature is built-up. Alumina nanofluids with concentrations of 0.25 vol. % , 0.5 vol. % , and 1 vol. with 45 nm are prepared, stabilized, and characterized by standard methods. The thermal conductivity and viscosity used in the study were measured and analyzed. The base fluids used are water and ethylene glycol. The effect of volume fraction, channel size, particle size, and base fluids are presented and analyzed. An important phenomenon of dispersion is observed. In addition, numerical modeling is carried out by using discrete phase approach. Shear induced particle migration is identified to be the reason of difference for dispersion of particles. The Brownian and thermophoretic forces are responsible for major changes in particle concentration and their movement. Also, it was found that better heat transfer characteristics can be obtained by higher concentration of nanofluids and by low viscous base fluids.

18. **Local convective boiling heat transfer and pressure drop of nanofluid in narrow rectangular channels**
    a. Boudouh, Mounir; Gualous, Hasna Louahlia; De Labachelerie, Michel
    b. *Applied Thermal Engineering*, v 30, n 17-18, p 2619-2631, December 2010
    c. This paper reports an experimental study on convective boiling heat transfer of nanofluids and de-ionized water flowing in a multichannel. The test copper plate contains 50 parallel rectangular minichannels of hydraulic diameter 800 µm. Experiments were performed to characterize the local heat transfer coefficients and surface temperature using copper-water nanofluids with very small nanoparticles concentration. Axial distribution of local heat transfer is estimated using a non-intrusive method. Only responses of thermocouples located inside the wall are used to solve inverse heat conduction problem. It is shown that the distribution of the local heat flux, surface temperature, and local heat transfer coefficient is dependent on the axial location and nanoparticles concentration. The local heat transfer coefficients estimated inversely are close to those determined from the correlation of Kandlikar and Balasubramanian [An extension of the flow boiling correlation to transition, laminar and deep laminar flows in minichannels and microchannels, Heat Transfer Eng. 25 (3) (2004) 86-93.] for boiling water. It is shown that the local heat flux, local vapor quality, and local heat transfer coefficient increase with copper nanoparticles concentration. The surface temperature is high for de-ionized water and it decreases with copper nanoparticles concentration.

19. **Analytical study on forced convection of nanofluids with viscous dissipation in microchannels**
    a. Hung, Yew Mun
    b. *Heat Transfer Engineering*, v 31, n 14, p 1184-1192, 2010
    c. This article presents an analytical study on forced convection of laminar fully developed flow of incompressible, constant-property nanofluids in microchannels. Closed-form solutions for the temperature distributions in the radial direction with the incorporation

of viscous dissipation are obtained under isoflux boundary condition. The effects of the governing parameters, including modified Brinkman number, thermal conductivity ratio, and nanoparticle volume fraction of the nanofluids, on the temperature distributions are investigated and analyzed for both heating and cooling processes. The heat transfer performance characterized by the Nusselt number is investigated based on the effects induced by these parameters. In the comparison between the models with and without viscous dissipation, it is found that the thermal performance of a microchannel is overrated when viscous dissipation is excluded in the analysis. It is concluded that these governing parameters are intimately interrelated in the flow and thermal analyses of nanofluids in microchannels. The interrelationship of the viscous dissipation effect and the nanoparticle volume fraction is examined in a contour deviation map of Nusselt numbers between the model with and without considering the viscous dissipation. Copyright © Taylor and Francis Group, LLC.

20. Entropy generation due to flow and heat transfer in nanofluids

a. Singh, Pawan K.; Anoop, K.B.; Sundararajan, T.; Das, Sarit K.
b. *International Journal of Heat and Mass Transfer*, v 53, n 21-22, p 4757-4767, 2010
c. Present study provides a theoretical investigation of the entropy generation analysis due to flow and heat transfer in nanofluids. For this purpose, the most common alumina-water nanofluids are considered as the model fluid. Since entropy is sensitive to diameter, three different diameters of tube in their different regimes have been taken. Those are microchannel (0.1 mm), minichannel (1 mm) and conventional channel (10 mm). To consider the effect of conductivity and viscosity, two different models have been used to represent theoretical and experimental values. It has been found that the reduced equation with the help of order of magnitude analysis predicts microchannel and conventional channel entropy generation behaviour of nanofluids very well. The alumina-water with high viscosity nanofluids are better coolant for use in minichannels and conventional channels with laminar flow and microchannels and minichannel with turbulent flow. It is not advisable to use alumina-water nanofluids with high viscosity in microchannels with laminar flow or minichannels and conventional channels with turbulent flow. Also there is need to develop low viscosity alumina-water nanofluids for use in microchannel with laminar flow. It is observed that at lower tube diameter, flow friction irreversibility is more significant and at higher tube diameter thermal irreversibility is more. Finally, for both laminar and turbulent flow, there is an optimum diameter at which the entropy generation rate is the minimum for a given nanofluid. © 2010 Elsevier Ltd.(23 refs)

21. A critical review on convective heat transfer correlations of nanofluids

a. Sarkar, Jahar
b. *Renewable and Sustainable Energy Reviews*, v 15, n 6, p 3271-3277, August 2011
c. Nanofluids are engineered colloids made of a base fluid and nanoparticles, which become potential candidate for next generation heat transfer medium. Nanofluids have higher thermal conductivity and single-phase heat transfer coefficients than their base fluids. The heat transfer coefficient increases appear to go beyond the mere thermal conductivity effect, and cannot be predicted by traditional pure fluid correlations. This review summarizes the correlations development for fluid flow and heat transfer

characteristics of nanofluids in forced and free convection flows. The review shows that most of the investigations recommended conventional friction factor correlation of base fluid for pressure drop prediction of the nanofluids for both laminar and turbulent flows in minichannel as well as in microchannel. However, the conventional correlation is not suitable for heat transfer coefficient of nanofluid and hence various correlations have been suggested for the Nusselt number for both laminar and turbulent flow. However, the large deviation of predicted values for proposed correlations has been observed may be due to strong influence of particle properties and nanofluid composition on flow and heat transfer characteristics, lack of common understanding on basic mechanism of nanofluid flow and insufficient experimental data on nanofluid heat transfer. Hence, a general framework for heat transfer correlation needs to be developed. © 2011 Elsevier Ltd. All rights reserved.(27 refs)