A Critical Review of Entropy Generation Analysis in Micro Channel Using Nano Fluids

Dr K Ashok Reddy

Professor, Dept. of Mechanical Engineering
MLR Institute of Technology, Dundegal , Hyderabad-43

Abstract : **A review of entropy generation performance evaluation was discussed for different micro channels with varying shape of the geometry used in conducting experimental and numerical solutions describe by various researchers have been presented in this paper. The analytical equations like Navier–Stokes, general equations of motions were given brief introduction in this context.**

Keywords: **micro channel, entropy, Nano fluids etc.**

Introduction:

Jie Li and Clement Kleinstreuer [1] presented in their technical paper a computer simulation model, entropy generation was analyzed in trapezoidal microchannels for steady laminar flow of pure water and CuO-water nanofluids. Focusing on microchannel heat sink applications, local and volumetric entropy rates caused by frictional and thermal effects are computed for different coolants, inlet temperatures, Reynolds numbers, and channel aspect ratios. It was found that there exists an optimal Reynolds number range to operate the system due to the characteristics of the two different entropy sources, both related to the inlet Reynolds number. Microchannels with high aspect ratios have a lower suitable operational Reynolds number range. The employment of nanofluids can further minimize entropy generation because of their superior thermal properties.Heat transfer induced entropy generation is dominant for typical microheating systems while frictional entropy generation becomes more and more important with the increase in fluid inlet velocity/Reynolds number

Waqar A. Khan, Richard J. Culham, and Michael M. Yovanovich[2] presented in their technical paper the numerical simulation of the three-dimensional incompressible steady and laminar fluid flow of a trapezoidal microchannel heat sink using nanofluids as a cooling fluid. Navier–Stokes equations with a conjugate energy equation are discretized by the finite-volume method. Numerical computations are performed for inlet velocity (W_{in} = 4 m/s, 6 m/s, and 10 m/s), hydraulic diameter D_h = 106.66 μm, and heat flux (q″ = 200 kW/m^2. Numerical optimization is demonstrated as a trapezoidal microchannel heat sink design which uses the combination of a full factorial design and the genetic algorithm method. Three optimal design variables represent the ratio of upper width and lower width of the microchannel ($1.2 \leq \alpha \leq 3.6$), the ratio of the height of the microchannel to the difference between the upper and lower width of the microchannel ($0.5 \leq \beta \leq 1.866$), and the volume fraction ($0 \leq \varphi \leq 4\%$). The dimensionless entropy generation rate of a trapezoidal microchannel is minimized for fixed heat flux and inlet velocity. Numerical results for the system dimensionless entropy generation rate show that the system dimensionless friction entropy generation rate increases with Reynolds number; on the contrary, the higher the Reynolds number, the lower the system dimensionless thermal entropy generation rate. The results below show that the two-phase model gives higher enhancement than the single-phase model assuming a steadily developing laminar flow.

Hooman, K. [3] presented in their technical paper forced convection in microducts of arbitrary cross-section, subject to H1 and H2 boundary condition, in the slip-flow regime with further complication of a temperature jump condition assumption. It is shown that applying an average slip velocity and temperature jump definition, one can still use the no-slip/no-jump results with some minor modifications. Present results for slip flow in microchannels of parallel plate, circular, and rectangular cross-sections are found to be in complete agreement with those in the literature. Application of this methodology to microchannels of triangular cross-section is also verified by comparing the present results with those obtained numerically by undertaking the commercially available software CFD-ACE

R.S.R. GORLA and B.J. GIREESHA[4] presented in their technical paper the transient velocity and steady state entropy generation in a microfluidic Couette flow influenced by electro-kinetic effect of charged nanoparticles. The equation for calculating the Couette flow velocity profile was derived for transient flow.

The solutions for momentum and energy equations are used to get the exact solution for the dimensionless velocity ratio and dimensionless entropy generation number. The effects of the dimensionless entropy generation number, Bejan number, irreversibility ratio, entropy generation due to fluid friction and due to heat transfer on dimensionless time, relative channel height, Brinkman number, dimensionless temperature ratio, nanoparticle volume fraction are analyzed.

Amir Shalchi-Tabrizi , Hamid Reza Seyf[5] presented in their technical paper the effect of using Al2O3–water nanofluids with different volume fractions and particle diameters on generated entropy, hydrodynamic performance and heat transfer characteristics of a tangential micro-heat sink (TMHS) was numerically investigated in this research. Results indicated that considerable heat transfer enhancement is possible when using Al2O3–water nanofluids as coolant and clearly the enhancement improves with increasing particles concentration and decreasing particles size. However, using nanofluid has also induced drastic effects on the pumping power that increases with particles volume fraction and Reynolds number. Finally, it was found that generated total entropy decreases with increasing volume fraction and Reynolds number and decreasing particles size.

R. Sohel et al [6] presented in their technical paper different types of entropy generations in the circular shaped microchannel and minichannel was discussed analytically using different types of nanoparticles and base fluids. In this analysis, Copper (Cu), alumina (Al_2O_3) as the nanoparticle and H_2O, ethylene glycol (EG) as the base fluids were used. The volume fractions of the nanoparticles were varied from 2% to 6%. In this paper, the irreversibility or entropy generation analysis as the function of entropy generation ratio, thermal entropy generation rate and fluid friction entropy generation rate for these types of nanofluids in turbulent flow condition have been analyzed using available correlations. Cu–H_2O nanofluid showed the highest decreasing entropy generation rate ratio (36%) compared to these nanofluids flow through the microchannel at 6 vol.%. The higher thermal conductivity of H_2O causes to generate much lower thermal entropy generation rate compared to the EG base fluid. The fluid friction entropy generation rate decreases fruitfully by the increasing of volume fraction of the nanoparticles. Cu–H_2O and Cu–EG nanofluid gave the maximum decreasing rates of the fluid friction entropy generation rate are 38% and 35% respectively at 6% volume fraction of the nanoparticles. Smaller diameter showed less entropy generation in case of all nanofluids.

Jurij Avsec et al [7] presented in their technical paper was developed a formulation of fluid motion and entropy production in microchannels. We have developed the formulations for pressure driven flow, flow under electric forces and flow under ferromagnetic forces. Friction, thermal and electromagnetic irreversibilities have significance in energy efficiency of microfluid systems. The results indicate that entropy and the Second Law have practical significance in electrokinetic liquid transport through microchannels.

Hamid Reza Seyf et al [8] presented in their technical paper a three-dimensional model describing thermal and hydrodynamic characteristics of a Microtube heat sink with tangential impingement with nanoencapsulated phase change materials (NEPCM)slurry as coolant. In this study, octadecane for NEPCM and polyalphaolefin (PAO) is used as a basefluid. The continuity, momentum, and energy equations are solved using a finite volume method. The model is validated by comparing results with available data in the literature. The effects of dominant parameters including mass concentration and melting range of NEPCM as well as Reynolds number on temperature uniformity, thermal resistance, Nusselt number, pressure drop and generated entropies in the system are investigated. Results indicated that adding NEPCM to base fluid leads to considerable heat transfer enhancement. However, using NEPCM slurry as coolant has also induced drastic effects on the pressure drop that increases with mass concentration and Reynolds number. It was found that that an increase in nanoparticles mass concentration, inlet Reynolds number and melting range of NEPCM, results in a higher Nusselt number, better temperature uniformity and lower thermal resistance. Furthermore, the effects of different parameters on slurry entropy production are demonstrated. It is found that generated total entropy decreases with increasing mass concentration and Reynolds number.

Nader Pourmahmoud et al [9] presented in their technical paper with fluid flow, heat transfer and entropy generation in an internally ribbed microchannel. Mass, momentum and energy equations for constant heat flux boundary condition are solved using the finite volume method. Average Nusselt number and Fanning friction factor are reported as a function of rib height at different Reynolds numbers. The effects of non-dimensional rib height, wall heat flux and the Reynolds number on the entropy generation attributed to friction, heat transfer and total entropy generation are explored. The first law indicates that rib height has the great effect on the flow filed and heat transfer.

The second law analysis reveals that for any values of Reynolds number and wall heat flux, as rib height grows; the frictional irreversibility increases while, there is a rib height which provides the minimum heat transfer irreversibility . It is found that the optimum rib height with the minimum total entropy generation rate depends on Reynolds number and wall heat flux.

Mohammadreza Hassan et al [10] presented in their technical paper theoretical research on entropy generation influences due to heat transfer and flow in nanofluid suspensions. A conventional nanofluid of alumina-water (Al_2O_3-H_2O) was considered as the fluid model. Due to the sensitivity of entropy to duct diameter, mini- and microchannels with diameters of 3 mm and 0.05 mm were considered, and a laminar flow regime was assumed. The conductivity and viscosity of two different nanofluid models were examined with the help of theoretical and experimentally determined parameter values. It was shown that order of the magnitude analysis can be used for estimating entropy generation characteristics of nanofluids in mini- and microchannels. It was found that using highly viscous alumina-water nanofluid under laminar flow regime in microchannels was not desirable. Thus, there is a need for the development of low viscosity alumina-water (Al_2O_3-H_2O) nanofluids for use in microchannels under laminar flow condition. On the other hand, Al_2O_3-H_2O nanofluid was a superior coolant under laminar flow regime in minichannels.

Jorge Mario Cruz-Duarte et al [11] presented in their technical paper the design of an optimal rectangular microchannel made of a high thermal conductive graphite (HTCG). For simulating the proposed microchannel heat sink, the total resistance model and the entropy generation minimization criterion were used. For solving the optimization problem, the unifi ed particle swarm optimization algorithm (UPSO), was used. Results showed a marked effect of using this high thermal conductor when compared to traditional materials, such as aluminum, and while using air and ammonia gas as the working fl uids. It is also reported the relative effect of the constriction, convective and fl uid thermal resistances on the overall equivalent thermal resistance. As a demonstrative example when changing the nature of the coolant, a titanium dioxide nanofl uid was selected. It was found that the Nusselt number is perceptibly lower, when the coolant is a nanofl uid and the material for the making of the microchannel is an HTCG.

N. Sher Akbar and Z. H. Khan[12] presented in their technical paper the entropy generation analysis for the peristaltic flow of Cu-water nanofluid with magnetic field in a lopsided channel. The mathematical formulation was presented. The resulting equations are solved exactly. The obtained expressions for pressure gradient, pressure rise, temperature and velocity phenomenon are described through graphs for various pertinent parameters. The streamlines are drawn for some physical quantities to discuss the trapping phenomenon.

Amit Agnihotri, Aashish Sharma [13] presented in their technical paper numerical simulation of three dimensional heat transfers in a silicon based microchannel heat sink has been conducted using nanofluid (TiO2-H2O) by SIMPLE method. Model of microchannel consists of trapezoidal channel. Dimensions of trapezoidal microchannel are 10 mm length, 280 μm channel top width, 225 μm channel bottom width, 431 μm channel hypotenuse and 430 μm channel height. Influence of properties of nanofluid on the heat transfer was investigated. Different parameters like heat transfer coefficient, Nusselt number, heat flux, outlet temperature are studied for different pressure drop. Pumping power depends upon pressure difference. So power consumption can be optimized by this study. Result shows that heat transfer coefficient was high in comparison to the water as a coolant in microchannel heat sink. Because of boundary layer, variation of Nusselt number decreases along the flow direction.

Mohamed M Awad [14] presented in their technical paper thermodynamic optimum of microchannels based on entropy generation analysis was presented. Using entropy generation analysis as evaluation parameter of microchannels has been reported by many studies in the literature. In these studies, different working fluids such as nanofluids, air, water, engine oil, aniline, ethylene glycol, and non-Newtonian fluids have been used. For the case of nanofluids, ‘‘nanoparticles’’ has been used in various kinds such as Al2O3 and Cu, and ‘‘base fluid’’ has been used in various kinds such as water and ethylene glycol. Furthermore, studies on thermodynamic optimum of microchannels based on entropy generation analysis are summarized in a table. At the end, recommendations of future work for thermodynamic optimum of microchannels based on entropy generation analysis are given. As a result, this article can not only be used as the starting point for the researcher interested in entropy generation in microchannels, but it also includes recommendations for future studies on entropy generation in microchannels.

Ali Kianifar et al [15] presented in their technical paper the development and use of nanofluids, i.e., dilute suspensions of nanoparticles in liquids, have found a wide range of applications in consumer products, nanomedicine, energy conversion, and microsystem cooling. Of special interest is the use of nanofluid flow for enhanced convection heat transfer to achieve rapid cooling of high heat-flux devices. However, for proper optimization of such thermal engineering systems in terms of design and operation, not only the heat transfer has to be maximized but the entropy generation has to be minimized as well. First, a variety of models used to calculate the thermophysical properties of nanofluids are presented. Then, the effects of thermal nanofluid flow on the rate of entropy generation for different applications are discussed. Finally, some suggestions for future work are presented. The aim of this review paper is to motivate the researchers to pay more attention to the entropy generation analysis of heat and fluid flow of nanofluids to improve the system performance.

Behzad Fani , Abbas Abbassi , Mohammad Kalteh[16] presented in their technical paper spherical nanoparticles size effects on thermal performance and pressure drop of a nanofluid in a trapezoidal microchannel-heat-sink (MCHS). Eulerian–Eulerian two-phase numerical approach is utilized for forced convection laminar, incompressible and steady three dimensional flow of copper-oxide nanoparticles with water as base fluid at 100 to 200 nm diameter and 1% to 4% volume concentration range. Continuity, momentum, energy and volume conservation equations are solved at whole of the computational domain via finite volume method. Obtained results signify that pressure drop increases 15% at Re = 500 and 1% volume concentration while nanoparticles diameter increases from 100 to 200 nm. By increasing volume concentration, nanoparticles size effect becomes more prominent and it is observed that increment rate of pressure drop is intensified for above 150 nm particles diameter. Unlike the pressure drop, heat transfer decreases with an increase in nanoparticles diameter. Also, it is observed that with an increase in nanoparticles diameter, average Nusselt number of base fluid decreases more than that of the nanoparticles and this signifies that base fluid has more efficacy on thermal performance of copper-oxide nanofluid.

Mohammadreza Hassan et al [17] presented in their technical paper theoretical research on entropy generation influences due to heat transfer and flow in nanofluid suspensions. A conventional nanofluid of alumina-water (Al2O3-H2O) was considered as the fluid model. Due to the sensitivity of entropy to duct diameter, mini- and microchannels with diameters of 3 mm and 0.05 mm were considered, and a laminar flow regime was assumed. The conductivity and viscosity of two different nanofluid models were examined with the help of theoretical and
experimentally determined parameter values. It was shown that order of the magnitude analysis can be used for estimating entropy generation characteristics of nanofluids in mini- and microchannels. It was found that using highly viscous alumina-water nanofluid under laminar flow regime in microchannels was not desirable. Thus, there is a need for the development of low viscosity alumina-water (Al2O3-H2O) nanofluids for use in microchannels under laminar flow condition. On the other hand, Al2O3-H2O nanofluid was a superior coolant under laminar flow regime in minichannels. The presented results also indicate that flow friction and thermal irreversibility are, respectively, more significant at lower and higher tube diameters.

Jie Li [18] presented in their technical paper dilute suspensions of nanoparticles in liquids, may exhibit quite different thermal properties than the pure carrier fluids. For example, numerous experiments with nanofluids have shown that the effective thermal conductivities for such mixtures are measurably elevated, and hence beneficial applications to (micro-scale) cooling are obvious.A very different application of nanofluids could be in modern medicine, where for example, nanodrugs are mixed in microchannels for controlled delivery with bio-MEMS. In general, to optimize nanofluid flow in microchannels, best possible conduit geometries, mixing units, and device operational conditions have to be found for specific applications.Specifically, a suitable model of common nanofluids, performance as well as cost effective mixers, and entropy minimizing channel designs are the prerequisites for achieving these project objectives. Two effective thermal conductivity models for nanofluids were compared in detail, where the new KKL (Koo-Kleinstreuer-Li) model, based on Brownian-motion induced micro-mixing, achieved good agreements with the currently available experimental data sets. The thermal performance of nanofluid flow in a trapezoidal microchannel was analyzed using pure water as well as a nanofluid, i.e., CuO-water, with volume fractions of 1% and 4% CuO-particles with . It was found that nanofluids do measurably enhance the thermal performance of microchannel mixture flow with a small increase in pumping power. Specifically, the thermal performance increases with volume fraction; but, the extra pressure drop, or pumping power, will somewhat decrease the beneficial effects. Microchannel heat sinks with nanofluids are expected to be good candidates for the next generation of cooling devices. Microcooling device design aspects in light of minimization of entropy generation were investigated numerically. The influence of the Reynolds number (inlet velocity), fluid inlet temperature, and channel geometry on frictional and heat transfer entropy generation $d\,p = 28.6nm$ was investigated.

It was found that the employment of nanofluids can help achieving entropy minimization due to their high thermal properties. The heat transfer induced entropy generation is dominant for the micro-cooling device. The frictional entropy generation becomes more important for high aspect ratio geometries. A bio-MEMS application in terms of nanofluid flow in microchannels was presented. Specifically, the transient 3-D problem of controlled nanodrug delivery in a heated microchannel has been numerically solved to gain new physical insight and to determine suitable geometric and operational system parameters. Computer model accuracy was verified via numerical tests and comparisons with benchmark experimental data sets. The overall design goals of near-uniform nanodrug concentration at the microchannel exit plane and desired mixture fluid temperature were achieved with computer experiments considering different microchannel lengths, nanoparticle diameters, channel flow rates, wall heat flux areas, and nanofluid supply rates. Such micro-systems,

featuring controlled transport processes for optimal nanodrug delivery, are important in laboratory-testing of predecessors of implantable smart devices as well as in the development of pharmaceuticals and for performing biomedical precision tasks.As a sample application, the microfluidics of controlled nanodrug delivery to living cells in a representative, partially heated microchannel has been analyzed. The objective was to achieve uniform nanoparticle exit concentrations at a minimum microchannel length with the aid of simple static mixers, e.g., a multi-baffle-slit or perforated injection micro-mixer. A variable wall heat flux, which influences the local nanofluid properties and carrier fluid velocities, was added to ensure that mixture delivery to the living cells occurs at the required (body) temperature of . The results show that both the baffle-slit micro-mixer and the perforated injection micro-mixer aid in decreasing the microchannel length while achieving uniform nanoparticle exit concentrations. The injection micro-mixer not only decreases best the system's dimension, but also reduces the system power requirement. The baffle-slit micro-mixer also decreases the microchannel length; however, it may add to the power requirement. The imposed wall heat flux aids in enhanced nanoparticle and base-fluid mixing as well.

Lokesh Chandra Joshi et al [19] presented in their technical paper heat transfer in micro-channel heat exchanger. In this study we have demonstrated research based result and outcomes without any assumptions. In this paper we have discussed slip flow effect on micro-channel, role of Knudsen number in heat transfer, influence of channel geometry, effect of entropy generation, effect of frosting and nano-fluids. With increasing applications of microchannel, it is important to cover all above factors. By considering these points we can increase the performance of microchannel and design an efficient microchannel heat exchanger.

M.R. Sohel, et al [20] presented in their technical paper the thermal performance of a circular shaped copper microchannel heat sink using three types of nanofluids is discussed analytically. Al_2O_3–Water, TiO_2–water and CuO–water nanofluids were used in this analysis and the comparative thermal performance of these three nanofluids is also discussed. The hydraulic diameter of the circular channel is 400 μm and the total block dimension is 10 mm×10 mm×4 mm. A steady laminar and incompressible flow with constant heat flux is assumed in the circular channel. The analyses are done at various volume fractions ranging from 0.5 vol.% to 4 vol.% and at a constant inlet velocity of 1.5 m/s. The results showed that the thermal performance can be increased significantly by using CuO–water nanofluid as a coolant for cooling of electronic heat sink when Al_2O_3–water and TiO_2–water nanofluids showed less improvement. Compared to pure water, the highest improvement (13.15%) in the heat flux occurred for 4 vol.% CuO–water nanofluid when Al_2O_3–water and TiO_2–water nanofluids showed 6.80% and 6.20% improvements respectively. This improvement in heat flux is calculated without considering the additional required pumping power due to the increased viscosity of nanofluids. Therefore, CuO–water nanofluid can be recommended to obtain maximum heat transfer performance in a circular microchannel heat sink.

Arash Karimipour et al [21] presented in their technical paper laminar forced convection heat transfer of water–Cu nanofluids in a microchannel was studied utilizing the lattice Boltzmann method (LBM). The entering flow was at a lower temperature compared to the microchannel walls. Simulations were performed for nanoparticle volume fractions of 0.00 to 0.04 and slip coefficient from 0.005 to 0.02. The model predictions were found to be in good agreement with earlier studies. The effects of wall slip velocity and temperature jump of the nanofluid were studied for the first time by using lattice Boltzmann method. Streamlines, isotherms, longitudinal variations of Nusselt number, slip velocity and temperature jump as well as velocity and temperature profiles for different cross sections were presented. The results indicate that LBM can be used to simulate forced convection for the nanofluid micro flows. Moreover, the effect of the temperature jump on the heat transfer rate is significant. Also, the results showed that decreasing the values of slip coefficient enhances the convective heat transfer coefficient and consequently the Nusselt number (Nu) but increases the wall slip velocity and temperature jump values

Tiew Wei Ting et al [22] presented in their technical paper based on the first-law and second-law of thermodynamics, we investigate thermal performance and entropy generation of water–alumina nanofluid flows in porous media embedded in a microchannel under local thermal non-equilibrium condition. Analytical closed-form solutions of two-dimensional temperature distributions are obtained for the cases with and without the viscous dissipation term in the energy equation. The thermal non-equilibrium entropy generation function is derived using the differential method. Due to the embedment of the porous medium in the microchannel and the suspension of the nanoparticle in the working fluid, the viscous dissipation effect is magnified significantly, altering thermal characteristics and entropy generation of the system. For the case where the viscous dissipation effect was neglected, total entropy generation and fluid friction irreversibility are overrated while heat transfer irreversibility was remarkably underestimated. In a low-aspect-ratio microchannel, the suspension of nanoparticles in the fluid decreases the thermodynamic efficiency from the second-law point of view. Utilization of nanofluids in a high-aspect-ratio microchannel enhances exergetic effectiveness in low-Reynolds-number flow regime. By reducing the nanoparticle size, entropy generation can be decreased by as much as 73%. The optimum Reynolds number associated with minimum entropy generation for nanofluid

flow in a porous microchannel is identified. The optimum range of porous medium permeability was characterized by Da P 10_1. It is observed that effectiveness of the interstitial heat transfer between the solid and fluid phases of the porous medium induces a pronounced effect on the entropy generation,signifying the importance to consider the thermal non-equilibrium condition in the second-law performance analysis of porous-medium flow.
Tiew Wei et al [23] presented in their technical paper the effects of viscous dissipation on the entropy generation of water–alumina nanofluid convection in circular microchannels subjected to exponential wall heat flux are investigated.Closed-form solutions of the temperature distributions in the streamwise direction are obtained for the models with and without viscous dissipation term in the energy equation. The two models are compared by analyzing their relative deviations in entropy generation for different Reynolds numbers and nanoparticle volume fractions. The incorporation of viscous dissipation prominently affects the temperature distribution and consequently the entropy generation. When the viscous dissipation effect was neglected, the total entropy generation and the fluid friction irreversibility are nearly twofold overrated while the heat transfer irreversibility was underestimated significantly. By considering the viscous dissipation effect, the exergetic effectiveness for forced convection of nanofluid in microchannels attenuates with the increasing nanoparticle volume fraction and nanoparticle diameter. The increase in the entropy generation of nanofluid was mainly attributed to the intensification of fluid friction irreversibility. From the aspect of the second-law of thermodynamics, the widespread conjecture that nanofluids possess advantage over pure fluid associated with higher overall effectiveness was invalidated.

References:

1.Jie Li and Clement Kleinstreuer Entropy Generation Analysis for Nanofluid Flow in Microchannels Journal of Heat Transfer V 132(12)

2.Waqar A. Khan, Richard J. Culham, and Michael M. Yovanovich. "Optimal Design of Tube Banks in Crossflow Using Entropy Generation Minimization Method", Journal of Thermophysics and Heat Transfer, Vol. 21, No. 2 (2007), pp. 372-378.
3. Hooman, K. (2008) A superposition approach to study slip-flow forced convection in straight microchannels of uniform but arbitrary cross-section. International Journal of Heat and Mass Transfer, 51 15-16: 3753-3762.
4.R.S.R. GORLA and B.J. GIREESHA Transient Velocity And Steady State Entropy Generation In A Microfluidic Couette Flow Containing Charged Nano Particles Int. J. of Applied Mechanics and Engineering, 2015, vol.20, No.4, pp.787-804
5.Amir Shalchi-Tabrizi , Hamid Reza Seyf Analysis of entropy generation and convective heat transfer of Al2O3 nanofluid flow in a tangential micro heat sink International Journal of Heat and Mass Transfer 55 (2012) 4366–4375
6.R. Sohel, R. Saidur, N.H. Hassan, M.M. Elias, S.S. Khaleduzzaman, I.M. Mahbubul Analysis of entropy generation using nanofluid flow through the circular microchannel and minichannel heat sink International Communications in Heat and Mass Transfer 46 2013 85–91
7.Jurij Avsec, Peter Virtič, Greg Naterer Nanofluid And Ferrofluid Slip Flow In Rectangular And Circular Microchannels And Minichannels Przegląd Elektrotechniczny ,Electrical Review, R. 87 NR 3/2011 5-9
8.Hamid Reza Seyf, Zhou Zhou, H.B. Ma, Yuwen Zhang Three dimensional numerical study of heat-transfer enhancement by nano-encapsulated phase change material slurry in microtube heat sinks with tangential impingement International Journal of Heat and Mass Transfer 56 (2013) 561–573
9.Nader Pourmahmoud, Hosseinali Soltanipour, , Iraj Mirzaee The Effects Of Longitudinal Ribs On Entropy Generation For Laminar Forced Convection In A Microchannel Department of Mechanical Engineering, Faculty of Engineering, Urmia University, Urmia, Iran 1-12
10.Mohammadreza Hassan , Rad Sadri , Goodarz Ahmadi , Mahidzal B. Dahari , Salim N. Kazi , Mohammad R. Safaei and Emad Sadeghinezhad
Numerical Study of Entropy Generation in a Flowing Nanofluid Used in Micro- and Minichannels Entropy 2013, 15, 144-155
11.Jorge Mario Cruz-Duarte, Iván Mauricio Amaya-Contreras, Carlos Rodrigo Correa-Cely An optimal high thermal conductive graphite microchannel for electronic device cooling Revista Facultad de Ingeniería, Universidad de Antioquia, No. 77, pp. 143-152, 2015
12.N. Sher Akbar and Z. H. Khan Entropy Generation Analysis for the Peristaltic Flow of Cu-water Nanofluid with Magnetic Field in a Lopsided Channel Journal of Applied Fluid Mechanics, Vol. 9, No. 2, pp. 605-613, 2016.
13.Amit Agnihotri, Aashish Sharma Three-Dimensional Heat Transfer Analysis Of Microchannel Heat Sink Using Nanofluid International Journal of Science, Technology & Management Volume No 04, Special Issue No. 01, March 2015 1199 -1200
14.Mohamed M Awad A reviewof entropy generation in microchannels Advances in Mechanical Engineering 2015, Vol. 7(12) 1–32
15.Ali Kianifar , Clement Kleinstreuer , Moh'd A. Al-Nimr , Ioan Pop ,Ahmet Z. Sahin, Somchai Wongwises A review of entropy generation in nanofluid flow Omid Mahian, International Journal of Heat and Mass Transfer 65 (2013) 514–532
16.Behzad Fani , Abbas Abbassi , Mohammad Kalteh Effect of nanoparticles size on thermal performance of nanofluid in a trapezoidal microchannel-heat-sink International Communications in Heat and Mass Transfer 45 (2013) 155–161
17.Mohammadreza Hassan , Rad Sadri , Goodarz Ahmadi , Mahidzal B. Dahari , Salim N. Kazi , Mohammad R. Safaei and Emad Sadeghinezhad Numerical Study of Entropy Generation in a Flowing Nanofluid Used in Micro- and Minichannels Entropy 2013, 15, 144-155
18.Computational Analysis of Nanofluid Flow in Microchannels with Applications to Micro-heat Sinks and Bio-MEMS By Jie Li A dissertation submitted to the Graduate Faculty of North Carolina State University Doctor of Philosophy Mechanical Engineering Raleigh, North Carolina 2008 1-221

19.Lokesh Chandra Joshi, Dr. Satyendra Singh, Shailesh Ranjan Kumar A review on enhancement of heat transfer in microchannel heat exchanger International Journal of Innovative Science, Engineering & Technology, Vol. 1 Issue 9, November 2014. 529-236
20.M.R. Sohel, R. Saidur, Mohd Faizul Mohd Sabri, M. Kamalisarvestani , M.M. Elias, Ali Ijam Investigating the heat transfer performance and thermophysical properties of nanofluids in a circular micro-channel International Communications in Heat and Mass Transfer 42 (2013) 75–81
21.Arash Karimipour , Alireza Hossein Nezhad, Annunziata D'Orazio ,Mohammad Hemmat Esfe , Mohammad Reza Safaei , Ebrahim Shirani Simulation of copper–water nanofluid in a microchannel in slip flow regime using the lattice Boltzmann method European Journal of Mechanics B/Fluids 49 (2015) 89–99
22.Tiew Wei Ting, Yew Mun Hung, Ningqun Guo Entropy generation of viscous dissipative nanofluid flow in thermal non-equilibrium porous media embedded in microchannels International Journal of Heat and Mass Transfer 81 (2015) 862–877
23.Tiew Wei TingYew Mun HungNingqun Guo Viscous Dissipation Effect on Streamwise EntropyGeneration of Nanofluid Flowin Microchannel Heat Sinks Journal of Energy Resources Technology Copyright VC 2016 by ASME SEPTEMBER 2016, Vol. 138 / 052002-1 1-9