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# Consequences of flow configuration and nanofluid transport on entropy generation in parallel microchannel cooling systems

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ABSTRACT

While known to be superior coolants in stand–alone conditions, some scepticism exists with respect to the hydrodynamic and thermodynamic performance of nanofluids in real life applications. The present work employs theoretical investigations (supported by simulation results) on the entropy generation characteristics in parallel microchannel cooling systems (PMCS) employing water and nanofluid as working fluids. Alumina-water nanofluid of different concentrations and PMCS of three different configurations, viz. U, I and Z have been employed for the present study. In order to shed more clarity onto the real thermodynamic performance of nanofluids, an Eulerian–Lagrangian discrete phase approach (DPM) has also been used to model nanofluids alongside the conventional effective property approach (EPM). The thermodynamic performance of twin component nanofluid model in PMCS over the base fluid and single component counterpart has been investigated in view of flow friction generated entropy and heat transfer generated entropy. To quantify thermodynamic irreversibility of nanofluids in PMCS due to heat transfer, the Bejan number has been employed. The entropy generation due to particle migration effects reveal that the effective property model overestimates the entropy generation in case of nanofluids and essentially nanofluids generate lesser degree of entropy than estimated by use of simplistic models. The Bejan number analysis reveals that although hydrodynamically inferior to water, nanofluids are thermodynamically superior fluids when employed as coolants in complex microscale flow systems. The article sheds insight onto the entropy generation behaviour of such dispersed system flows with respect to flow and heat transfer characteristics such as particle concentration, flow Reynolds number, and heat load for proper design of such systems.

## 1. Introduction

Rapid strides in microelectronic device technologies demands highly efficient cooling systems which are capable of ensuring thermal safety and reliability for such advanced miniaturized devices. Consequently, research on thermal management systems which are efficient in removal of high heat fluxes from micro devices took a leap forward in the last two decades. Examples of such devices are parallel microchannel heat sinks [1,2], miniaturized heat pipes [3,4], etc. However, it so happens that such devices still fall short of extracting the requisite amount of heat and hence research on optimizing the geometry of the parallel microchannel cooling systems (PMCS) has become important [5]. In addition to modifying the geometric parameters of the flow domains, trying to enhance thermal properties of the working fluids, such as phase change fluids [6] and nanofluids [7,8] The research has led to interesting results which show that nanofluids in PMCS hold tremendous potential in becoming the next generation micro device cooling platforms [9–11].

Though efficient in terms of cooling performance, it is necessary to clearly comprehend the hydrodynamic and thermodynamic efficiency in order to select the optimal fluid and PMCS configuration suitable for a given system. Having established these points, it is required to analyse the so called thermally efficient working fluids (nanofluids) in terms of hydrodynamic and thermodynamic performance over the corresponding base fluids. Prasher et al. [12] theoretically reported for first time the effectiveness of nanofluids from the point of hydrodynamic performance over base fluids and concluded that nanofluids are hydrodynamically and thermally efficient fluids only when the increment in viscosity is less than four times the increase in thermal conductivity. Similarly, the efficiency of nanofluids over base fluids has been reported by defining a fig-

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### Nomenclature

| | |
|---|---|
| $\mu$ | viscosity |
| $\rho$ | density |
| $Kn$ | Knudsen number |
| $T$ | temperature |
| $V$ | velocity |
| $C_p$ | specific heat |
| $P$ | pressure |
| $F$ | force |
| $p$ | particle (subscript) |
| $f$ | fluid (subscript) |
| $\lambda$ | mean free path |
| $k$ | thermal conductivity |
| $k_B$ | Boltzmann constant |
| $m$ | mass |
| $D$ | diffusion coefficient |
| $f$ | friction factor |
| $Re$ | Reynolds number |
| $D_h$ | hydraulic diameter |
| $Be$ | Bejan number |
| $S_{gen}$ | entropy generation |
| $\phi$ | concentration |
| $eff$ | effective (subscript) |
| $nf$ | nanofluid (subscript) |

ure of merit [13] concerned with increment in pumping power per unit enhancement of thermal performance. Even though the figure of merit approach is a necessary method to analyse overall performance, it is not a sufficient method to analyse the overall performance of nanofluids over base fluid. Any cooling system is said to be completely efficient system if it is efficient in all aspects i.e. hydrodynamically, thermally and thermodynamically. So it may be inferred from the survey of existing reports that analysis of pumping power or figure of merit may not be a strong approach to completely deduce the thermodynamic effectiveness of a fluid or flow domain.

Thermodynamic efficiency of any heat transfer device using nanofluid as working fluid can be understood by analysing entropy generation rate within system [14]. The total entropy generation rate within a system is essentially the net irreversibility caused by flow friction, heat transfer, chemical reactions, field effects, etc. Bejan et al. [15] derived expressions for entropy generation due to forced convection heat transfer in various geometries. Several reports have concentrated towards minimizing entropy generation in case of flow and heat transfer devices, process devices, etc. [16,17]. There are studies along with theories on minimizing entropy generation in macroscale devices using single phase fluids. There are reports concentrated on entropy generation analysis in parallel microchannel heat sinks using single phase working fluids like water [18,19]. Singh et al. [20] Studied entropy generation for convection in nanofluids flowing in single micro tube and reported thermodynamic efficiency of nanofluids over based fluids at different working conditions through scaling analysis. From detailed survey of literature, studies concentrated on thermodynamic analysis of PMCS when nanofluids are employed as working fluid are naught. Furthermore, studies involving nanofluids consider the effective property approach which has been reported to predict incorrect properties for nanofluids [10]. Also, the effects of flow distribution geometry as well as contribution of the particle migration in nanofluids to the entropy generation rate are yet to be studied. The present paper thus comprehensively quantifies the entropy generation characteristics of realistically modelled nanofluids (using the discrete phase approach) during thermal management of micro devices employing PMCS of variant manifold–channel distribution geometries and associated flow and heat transfer parameters employing relevant thermodynamic parameters. The paper discusses the theoretical formulation employed in the present analysis and discusses the effects of configuration, nanofluid flow parameters, thermal aspects and nanofluid properties on the entropy generation characteristics. Further, the thermodynamic performance of nanofluids with respect to water has been discussed based upon Bejan number analysis as well as the behaviour of entropy generation due to flow friction and heat transfer are segregated and the behaviour for nanofluids studied. Finally, the entropy generation contribution due to the various particle transport mechanisms has been put forward.

## 2. Theoretical formulation

The governing equations for EPM and continuous phase of the DPM are equations of mass, momentum and energy conservation, expressed as

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\vec{V}) = 0 \tag{1}$$

$$\frac{\partial \rho\vec{V}}{\partial t} + \nabla.(\rho\vec{V}\vec{V}) = -\nabla P + \nabla.(\mu(\nabla\vec{V} + \nabla V^{T})) + S_m \tag{2}$$

$$\rho C_p\left[\frac{\partial T}{\partial t} + \vec{V}.\nabla T\right] = \nabla.[k_f\nabla T] + S_e \tag{3}$$

In the above equations, $\rho$ is density of liquid, V is velocity of the liquid, $\mu$ is viscosity of liquid phase, t is time, P is pressure, g is the acceleration due to gravity, C is the specific heat of fluid, $k_f$ is thermal conductivity of fluid and T is fluid temperature. $S_m$ and $S_e$ are source terms representing exchange of momentum and energy between the continuous and discrete phase (nanoparticles). The effects of viscous dissipation and compressibility have been neglected in the energy equation. The governing equation for the motion of the nanoparticles in Lagrangian frame can be expressed based on Newton's second law as

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g(\rho_p - \rho)}{\rho_p} + F \tag{4}$$

$$F = F_G + F_B + F_T + F_L + F_P + F_V \tag{5}$$

u and $u_p$ are fluid phase velocity and particle velocity respectively, $\rho_p$ is particle density, g is acceleration due to gravity and F is the total specific force experienced by the particle. Terms $F_D$, $F_G$, $F_B$, $F_T$, $F_L$, $F_P$ and $F_V$ represent the forces resulting out of fluidic drag, gravity, Brownian motion, thermophoretic drift, Saffman lift, contribution of pressure gradient and contribution of virtual mass respectively. The expression for the forces is as [21,22]

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D Re}{24} \tag{6}$$

For nanoparticles, the classical Stokesian drag is modified to take care of the non–continuum slip effects (important for high Knudsen number systems, like flow over nanoparticles) at the particle–fluid interface and is expressed as