Journal of Sciences and Management Research 2600-738X

CONVECTIVE BOUNDARY LAYER FLOW IN A NANO FLUID

Muhammad Khairul Anuar Mohamed[1,2*], Norlianah Mohd Shah[1], Nurul Ainn Ismail[1], FadhilahChe Jamil[1], Norhamizah Hashim[1], Mohd Zuki Salleh[2], Hasmawani Hashim[3]

[1]Centre of Interdisciplinary Studies,
DRB-HICOM University of Automotive Malaysia,
Peramu Jaya Industrial Area, 26607 Pekan, Pahang, MALAYSIA.
[2]Applied & Industrial Mathematics Research Group,
Faculty of Industrial Sciences& Technology,
Universiti Malaysia Pahang,
26300 Kuantan, Pahang, MALAYSIA.
[3]Faculty of Information & Interactive Technology,
Widad University College,
Bandar Indera Mahkota, 25200 Kuantan, Pahang, MALAYSIA.
Corresponding author email*: khairul.anuar@dhu.edu.my

Introduction

The thermal transportation also known as heat transfer process occurs when there existed a temperature difference between matters. The thermal transportation basically exists in three conditions which are conduction, radiation and convection. Conduction is the transfer of energy through matter from one particle to another particle. Physically, the particle is static and vibrates in its place. It is the heat energy that is transfered and distributed from atom to atom within a medium. Radiation involves the heat transfer from electromagnetic waves when comes in contact with an object. Radiation may occur in the absence of a medium for example the sunlight which transferred in vacuum to the earth surface. Meanwhile, the convection is the transfer of heat by phsysically or actual movement of matter. According to Baehr and Stephen (2006) and Lienhard IV and Lienhard V (2011), heat transfer by conduction and radiation from a solid surface to a fluid is named as the convective heat transfer process. In this study, only the convection flow will be considered.

Convective Heat Transfer Process

The word convection refers to heat transfer that occurs between a surface with a moving fluid when both are at a different temperature (Incropera et al., 2006). Generally, convection is formed by two mechanisms, namely convection caused by the random motion of molecules (diffusion) and also the energy which is transferred by the movement of the fluid. The convection heat transfer is a complicated process which it is an actually a surface phenomenon. With that, the condition and geometry of surfaces will influence the convection heat transfer process (Darus, 1995).

Convection can be divided into two types which are the forced convection and the free convection (also known as natural convection) (Burmeister, 1983, Pop and Ingham, 2001, Bejan and Kraus, 2003, Kreith et al., 2010). The forced convection occurs when the fluid motion is generated mechanically through the use of a fan, blower, nozzle, jet, etc. Fluid motion relative to a surface can also be obtained by moving an object, such as a missile through a fluid. The applications of forced convection can be found in cooling fan of a central processor unit (CPU) in computer devices. The speed of cooling fan can be controlled and monitored hence to ensure the efficiency of the cooling system is employed.

On the other hand, the free convection occurs when the fluid motion is generated by gravitational field only. However, the presence of a gravitational field is not sufficient to set a fluid in motion. Changes in fluid density is also required for free convection to occur. In free convection, density variation is primarily due to temperature changes. Those configurations can be found in home theater unit, stereo hi-fi and television unit. The use of cooling fins to release the heat produced by the electronic component is sufficient, besides it produces no vibration and noise which may annoy the entertainment experience.

Furthermore, the combination of the free and forced convection is called the mixed convection. The buoyancy parameter $\lambda = \frac{Gr_x}{Re_x^n}$ takes part as scalar to measure an influence of forced and free convection in a flow with Re_x is the local Reynold number, Gr_x is the local Grashof number and n as a positive constant. The forced convection is dominant when $\lambda = \frac{Gr_x}{Re_x^n} \to 0,$ while free convection takes part as $\lambda = \frac{Gr_x}{Re_x^n} \to \infty$ (Pop and Ingham, 2001, Kreith et al., 2010). The applications of mixed convection are widely used in engineering and industrial outputs, for an example in engine and automatic transmission cooling system such as cooling fins in car radiator, nuclear reactant power plant, airconditioner, refrigerator and many more.

Boundary Layer Theory

Boundary layer theory was first introduced by Ludwig Prandtl (1875–1953) on 8th August 1904 in Heidelberg, Germany. The idea behind the theory is, there exist a thin layer (region) of sticks to a surface that are embedded in fluid motion field (Anderson, 2005). This region (thin layer) near the surface is called the boundary layer.

In introducing the concept of the boundary layer theory, the fluid flows on a flat plate is considered as shown in Figure 1. Boundary layer is a thin layer near the flat surface where its viscosity cannot be neglected. Also, in the boundary layer, the frictional force must be considered, while outside the boundary layer (inviscid flow), the frictional force is too small and can be neglected (Schlichting, 1979).

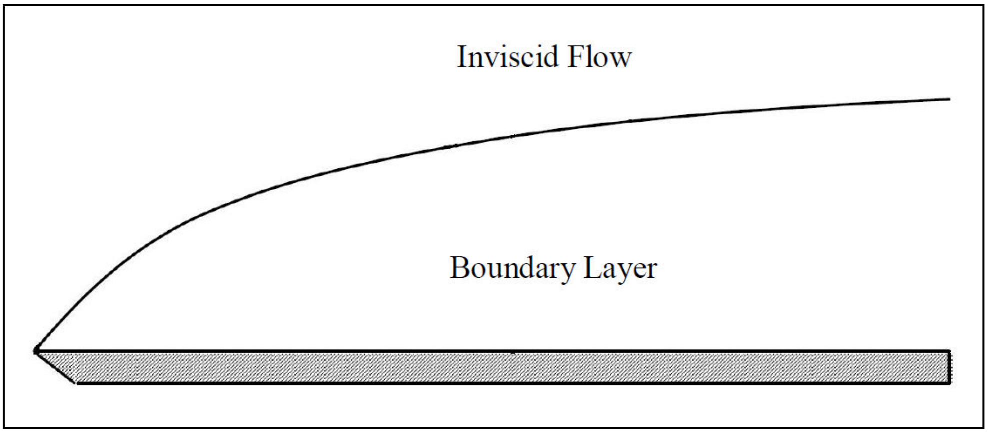

Figure 1: Inviscid flow and boundary layer

Basically, the boundary layer for viscous fluid can be divided into two, which are the velocity boundary layer and thermal boundary layer. By referring to Figure 2, when the fluid molecule is attached to the flat surface, it is assumed that the velocity of the molecule is zero. This zero velocity molecule then delays the movement of other fluid molecule in layer next to it. This process continues until the distance $y = \delta_h$ from the flat surface and after that, this effect can be neglected. By increasing the distance from surface in y, fluid velocity in x component also increases, tends the free stream velocity U_∞ outside the boundary layer. This quantity δ_h is called the velocity boundary layer thickness, and usually it is defined by y with $u = 0.99U_\infty$. Besides, the velocity profile is changed with respect to the boundary layer (Incropera et al., 2006, Kreith et al., 2010).

Thermal boundary layer is formed when the temperature of the free flow is different with the plate surface temperature. Also, from Figure 2, it is found that there is an existence of a region where the temperature changes from $T(y)$ at $y = 0$ to T_∞ which is at a free flow outside the boundary layer. The quantity δ_T is represented the thermal boundary layer thickness. Also, this region can be characterized by the temperature of gradient and heat transfer (Incropera et al., 2006, Kreith et al., 2010).

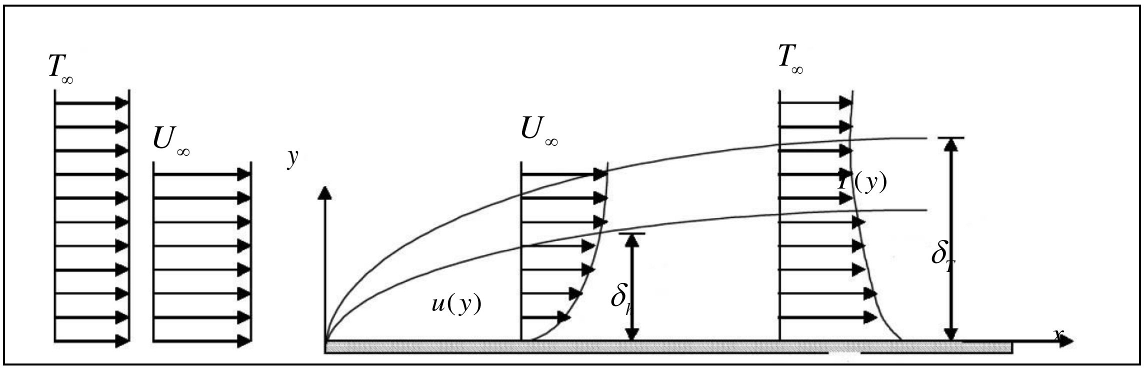

Figure 2: Velocity and thermal boundary layer

In addition, the flow of nanofluid, considers another partition of boundary layer. It is known as the concentration boundary layer as shown in Figure 3. The thickness of concentration boundary layer is denoted as δ_c, formed while C_∞ and C_w are the ambient and surface nanoparticle volume fraction, respectively.

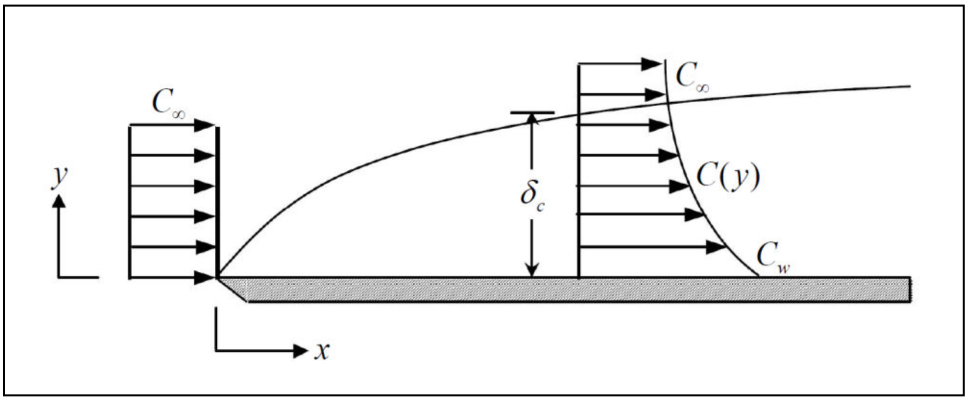

Figure 3: Concentration boundary layer

Nanofluid

Nanofluid is a fluid containing nanometer-sized particles, called nanoparticles. It was first coined by Choi (1995). These fluids are engineered colloidal suspensions of ultrafine particles (nanoparticles) which the diameter is smaller than 50 nanometer size in a base fluid (Taylor et al., 2013).The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes by physical and chemical synthesis processes. Typical physical methods include the high energy pulsed process, mechanical grinding method and the inert-gas-condensation technique (Granquist and Buhrman, 1976). The examples of nanoparticles are aluminium trioxide, copper oxide, silicates and titanium oxide. Common base fluids include water, ethylene glycoland oil.

Nanofluid Characteristics

Nanofluid is experimentally proven in enhancing the thermal conductivity, viscosity, thermal diffusivity and convective heat transfer compared to those base fluids like water and oil (Kakaç and Pramuanjaroenkij, 2009). Experimental studies by Eastman et al. (1997) has shown that the nanofluid is made from water as a base fluid with 5% volume of CuO increases aproximately 60% of thermal conductivity compared to base fluid itself. Further, Choi et al. (2001) concluded that the thermal conductivity increased until two times when small amounts (less than 1%) of nanoparticles are added into concentrated heat transfer liquid.

In considering the stability of the nanofluid, the small amount of nanoparticles physically means less weight which denotes less chances of sedimentation. The reduction in sedimentation overcomes major drawbacks of suspension as a results it makes the nanofluid more stable. Further, less sedimentation from nanofluid makes it the best fluid for cooling microchannel applications without clogging. Other advantages the used of nanofluid is the reduction in erosion onto wall or surface. Since the nanoparticles are very small, the momentum input to wall or surface is minimum. Therefore, this situation reduces chances of erosion (less or no damaged) onto heat transfer components such as the heat exchanger, ball bearings, pipelines and pump (Lee et al., 1999, Das et al., 2006). Besides extending life-time of the components, according to Das et al. (2006), this type of fluid maintains the Newtonian behavior of the fluid where the viscosity slightly increases as well as pressure rises marginally.

Nanofluid Applications

The special characteristics of nanofluid make them potentially useful in many important applications which involve fluid as a cooling medium in industrial outputs. Nanofluid has replaced water as a cooling medium, due to water capability to remove heat is limited. This can be found in industrial cooling applications, for example in the tire production at Michelin North America tire plants. Further, the nuclear reactor and the extraction of geothermal power under earth surface is the best example of nanofluid capability as a cooling medium, where the temperature may rise around 500° to 1000ºC. In addition, Wong and De Leon (2010) stated that nanofluid is also used in biomedical applications. In cancer theraupetics treatment, the iron-based nanoparticles act as a vehicle for drugs in cancer patients. Magnetic nanofluidis used to guide the particles up the bloodstream to reach the tumor with magnets. By this, it will allow doctors to deliver high local doses of drugs without damaging nearby healthy tissues. Other biomedical treatments considered where nanofluid applications are use, include nanodrug delivery, nanocryosurgery, cryopreservation, sensing and imaging treatment.

Liquid Cooling Electronic Devices

Futures electronic devices for example the computer central processor unit (CPU) and power supply unit (PSU) are interpret will no longer use the blower fan to cooling down the cylindrical capacitors, spherical transistors and other electronic components like flat circuit. The used of nanofluid is the alternative way as nanofluid is efficient and quietly operational.

The central processing unit (CPU) technology has moving forward. The presence of multicore CPU and hyper-threading technology has increased the CPU performance (Marr et al., 2002, Phatak, 2014, Tegtmeier, 2015). Therefore, the classical method which using fan to cooling down the CPU is now becomes less efficient due to the increasing of heat produced proportionally with the increase in performance. Technically, CPU in computer devices is cooled by CPU fan which attached closely to CPU surface with the aid of heatsink. The speed of CPU fan is directly controlled by the CPU itself. As the temperature rise, the CPU will automatically increase the CPU fan speed. This cause an excessive noise and vibration in computer devices. In handling this, some manufacturers offered passive cooling system which oriented from free convection concept. The cooling device is builds as cooling fin where it can release heat from CPU without the use of fan. The advantages of this configuration are there will no more noise and vibration produced. This application can be found in home theater personal computer (HTPC), radio and television.

However, this passive cooling system is not suitable for high performance computer especially for those used a computer for a gaming purpose and overclocking activity. Gaming computer produced large amount of heat compared to stock computer. It is due to the heavy multitasking which promoted CPU to its maximum thermal design power. The presence of graphic card or video card also contributed to the excessive heat. Therefore, the used of liquid cooling system seems to be the best solution. It is due to the advantages of fluid like water has higher specific heat capacity and thermal conductivity than air. The idea of this system is similar with engine car cooling system. Simple liquid cooling system consists of pump, radiator, liquid tube and conductor plate. Usually the radiator is mounted at the back of the computer casing and it is cooled with the used of huge blower fan. Large diameter blower fan which revs at a lower speed with a lower noise have more cooling power compared to smaller fan.

Liquid Submerged Cooling

In computer power supply unit, there are many components which in a shape of circular cylinder like capacitor. Capacitor is used to store electrical charges temporarily in a form of electrostatic fields and also to block direct current while allowing alternating current to pass in electronic circuit (Poh, 2004, Bird, 2010). Apart from knowing the specification on operated voltage and capacitance, capacitor has its temperature rating which is usually at 85°C or 105°C (Gerow, 2013). To extend the life of capacitor, it must be operated below the temperature rating. Since capacitor played an important role in electronic circuit, then it is exposed to produce a large amount of heat.

The alternative way to cooling down the capacitor and other electronic component is by liquid submersion cooling system. The basic idea of this arrangement is the electronic components are immersed totally in the container of cooling liquid hence the heat produced by the components are spread away by convection into a cooling liquid. The heated cooling liquid then are cooling down by blower fan usually located at the rear side of container. The liquid submersion cooling system has been used usually to cooling down components such as transformers. Liquid submersion cooling system is still in study but it is realistic to be applied on computer in future (Volkel, 2006). Besides improve the efficiency of heat removal, liquid submersion cooling system promise low vibration and noise which enhanced the computing experience.

Engine Downsizing

In automotive segment, the manufacturers faced a challenge to build the high performance engines while durability and economical consumption being a subject that cannot be ignored. Then, the idea comes by using the small form engine fitted with turbocharged unit. It is proven the used of turbocharged unit has increased the engine output. Some manufacturers has declared their 1.0 litre turbocharged engine produce more power and torque than 1.5 normally aspirated engine (Ford, 2015). Further, the 2.0 litre turbocharged engine fitted in new Audi A4 have the equivalent output with the previous version 3.0 litre normally aspirated engine (Audi, 2000, Tan, 2008). This situation contributed to the economy fuel consumption and also less in engine friction which prolong the engine durability.

Since the engine output has increased, hence the heat produced by the engine also greatly increased. The heat will flow through the turbocharged unit before it is released by exhaust unit to the air. The temperature rise up to 1050°C which may harm and corrosive the turbocharged component (Simon et al., 2000). Hence, the oil pump is employed to lubricated and also cooling down the turbocharged component especially the sphere ball bearing and turbocharged gasket. It is known that the used of oil pump with the presence of gravitational field is the mixed convection process. The efficiency of lubricating and heat removes process (convection) will definitely depends on design of the turbocharged itself, the flow, conductivity, viscosity and the characteristic of the fluid used. In considering the fluid used, the nanofluid seems to be the suitable fluid to employed. It is due to its stability, less sedimentation which prevents clogging, highly in thermal diffusivity and conductivity compared its based fluid and less erosion which prolong the components surface.

Mathematical Models of Nanofluid

Modelling the boundary layer flow and heat transfer in a nanofluid poses a challenge (Tiwari and Das, 2007). There are two main approaches that have been adopted which are known as single-phase model and two-phase model. The two-phase model takes the based fluid and nanoparticles role in the heat transfer process separately. Meanwhile, single-phase model takes both, based fluid and nanoparticles in thermal equilibrium state and it flows in the same local velocity.

There are several issues involved and must be taken into account in modeling the nanofluid boundary layer flow. Buongiorno (2006) listed seven slip mechanisms that may produce a relative velocity between the nanoparticles and the based fluid which are inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage and gravity. Further, other phenomena like sedimentation and dispersion may exist in the main flow. Therefore, two phase single is not applicable to describe the behaviour of nanofluid because nanofluid characteristic behave more like fluid rather than solid-fluid mixture. Tiwari and Das (2007) stated that the modified single-phase model which accounts for some above mechanism is more effective than two-phase model to study the heat transfer process.

Considering pioneer papers by Buongiorno (2006), Tiwari and Das (2007), Oztop and Abu-Nada (2008), Kakaç and Pramuanjaroenkij (2009), Khan and Pop (2010), Bachok et al. (2010, 2011), Yacob et al. (2011), Arifin et al. (2011), Ahmad et al. (2011), Nazar et al. (2011a, 2011b), Vajravelu et al. (2011), Noghrehabadi et al. (2012), Rohni et al. (2013), Tham et al. (2013, 2014), Roşca and Pop (2014), Zaimi et al. (2014) and recently by Sulochana and Sandeep (2015), Tham et al. (2015), Hamid et al. (2016) and Pal et al. (2016), it is concluded that there are two convenient mathematical nanofluid models which are known as Buongiorno-Darcy model and Tiwari and Das model.

Tiwari and Das model is a single-phase model with a specific case of nanofluid. It is suitable to study the flow and heat transfer characteristic of specific nanofluid. The coefficient physical properties like thermal conductivity, density and specific heat of nanofluid are involved in computation, since difference in materials of nanometers possess unique physical and chemical properties (Das et al., 2007). Meanwhile, Buongiorno-Darcy model is two-component four-equation non-homogeneous equilibrium model for continuity, mass, momentum and heat transfer in nanofluid. It was first introduced by Buongiorno (2006) who analysed that from seven slip mechanisms in the nanofluid, only Brownian diffusion and thermophoresis diffusion were important to be considered while other mechanisms were too small and can be ignored.

Conclusion

Present paper has briefly described the basic concept of convective boundary layer flow in a nanofluid. Nanofluid is applied to replace water and other base fluid in handling thermal solution because of its special characteristics in viscosity, diffusivity, thermal conductivity, heat transfer capabilities as well as its stability. The nanofluid employment in engineering and industries may improve the manufacturing processes, the medical segment, automotive, as well as electronic andgeothermal field thus, required further studies to be done either by mathematical model or by experimental approach.

Acknowledgements

Authors thanks DRB-HICOM University of Automotive Malaysia and Universiti Malaysia Pahang for the financial and facilities supports.

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