



RECENT ADVANCES IN PIN FIN APPLICATIONS FOR HEAT TRANSFER ENHANCEMENT - A REVIEW OF RECENT PROGRESS

S. O. Obayopo^{1,*}, S. Akintunde², A. Adewoyin³, E. Onojowho⁴, and M. Julius⁵

¹Department of Mechanical Engineering,
Obafemi Awolowo University, Ile-Ife, Nigeria.

^{2,3,4,5} Department of Mechanical Engineering.

*Email of Corresponding Author: sirajolanre@yahoo.com

ABSTRACT

Heat transfer enhancement has played a critical role in many industrial application to improve system performance and heat recovery processes. The quest for improved heat recovery in the industry and alternative energy systems has necessitated the need to explore more sophisticated heat transfer enhancement approaches towards optimal system. This review article presents a broad assessment and critical review of past researches on pin fin enhancement basically to provide a comprehensive understanding of pin fin as an important application tool in various areas in the thermal science field and industry including power generation, high power electronics cooling, refrigeration and air-conditioning, nuclear reactors, etc. Several heat transfer enhancement techniques have been reported in the literature in recent times with practical application challenges such as machinability, pressure drop concerns and identification of industrial cost towards implementation. The important achievements, inconsistencies and contradictions from the literature in these heat transfer area are identified and discussed. These provide basis for immediate research needs and identified area of future researches in pin fin application for enhanced heat transfer.

Keywords: Heat transfer; Enhancement; Pin fins; System performance; Heat recovery; Industrial applications

INTRODUCTION

Heat transfer enhancement has played a critical role in many industrial application to improve system performance and heat recovery processes. The quest for improved heat recovery in the industry and alternative energy systems has necessitated the need to explore more sophisticated heat transfer enhancement approaches towards optimal system. The quest is justifiable from the development of components, devices, system technologically which all come with their own side effects. Some of these devices could be domestic or industrial depending on it purpose. An example of such are electronic equipment has which become an integral part of modern life, its applications ranging from compact devices like video players to modern day super computers. These components require flow of electric current to perform their functions, and current flows through, it is always accompanied by heating of the component due to resistance. When operating at higher temperatures, the reliability and functionality of the components are greatly jeopardized. Therefore, thermal management of electronic equipment is very critical in ensuring smooth functioning of an electronic system without any breakdown. Jadhav, and Balaji (2016).

A pin fin array has been a popular method for improving a variety of thermal applications since they increase heat transfer area and enhance convective heat transfer coefficients. Examples of pin fins could be found in cooling turbine airfoils that experience extremely high temperature working conditions. In turbine airfoil cooling, the pin fin array augments convective heat transfer within the internal coolant passages of the airfoils, and provides

structural bridges between the two airfoil aerodynamic surfaces. More recently, the advent of micro fabrication technologies allowed shrinking the pin fin structures to the micro scale for cooling applications within compact spaces, such as electronics. Eren, *et al.* (2016). In pin fin array, many variables affect the heat transfer process, such as pin fin density, arrangement, pitch distances, etc. To decouple some of these parameters, previous efforts experimentally studied a more rudimentary configuration – flow and heat transfer over/downstream a single pin fin. It was found that increased fluid mixing and vortex shedding downstream the pin fin enhanced heat transfer Wang, *et al.* (2016).

Others which will be looked into are the geometry variations. Some of the example of works done in this are Sahiti, *et al.* (2007), Uzo and Camci (2005), Sara, *et al.* (2001), Li and Wu (2016), among others. Also recent studies shows that the heat enhancement of the pin fin does not depend solely on the properties of the fin applied but as well as the flow properties of the convecting fluid as reported by Jadhav and Balaji (2016), Ochende and Bejan (2004), Silva and Gosselin (2013), Liu, *et al.* (2015). Other studies also show that introduction of pin fins will cause a pressure drop in the flow, which is very important to be investigated not to completely obstruct the fluid flow as done by Jeng and Tzeng (2007), Metzger, *et al.* (1984), Chang (2016).



TYPE OF PINS USED IN FINS:

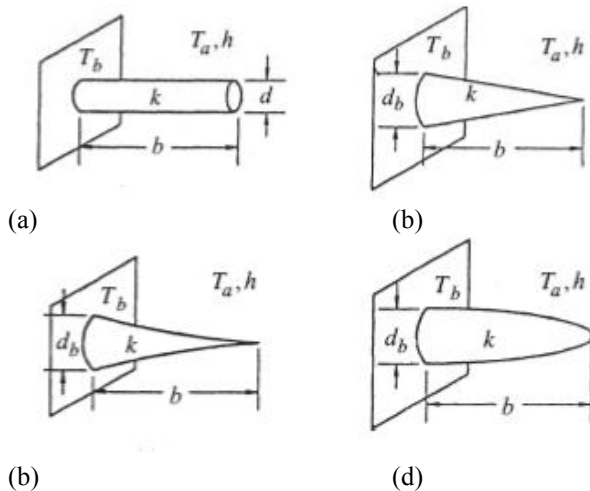


Figure 1: Types of pins (a) Cylindrical pin (b) Conical pin (c) Concave parabolic (d) Convex parabolic

GENERAL REVIEW

Pin fin is a heat transfer application that obeys the convective principle of heat transfer according to the Newton's law cooling which states that the rate of heat transfer $[Q]$ between a solid and a fluid is proportional to the temperature difference $[\Delta T]$ between the solid and the fluid and the surface area $[A]$ perpendicular to the direction of the heat flow and the constant of proportionality is the heat transfer coefficient $[h]$.

$$Q = hA\Delta T \quad (1)$$

In view of this proportionality, the heat transfer rate can be improved only by influencing the surface area and the heat transfer coefficient. The mechanism which leads to high heat transfer coefficients of such fins is the periodic interruption of the boundary layer around the fins and also by achieving better mixing of fluid streams at different temperatures. Otherwise the heat transfer surface area increase is achieved by a dense population of the bare surface with such fins and by selecting thin and long fin forms. Similar effects can be expected also in pin fin arrays of either in line or staggered. Hence they may be considered as a special kind of interrupted fins. The main objective of this work is the review previous works in the application pin fins in the enhancement of heat transfer considering the various parameters that influences this purpose and how to improve these parameters to improve heat transfer rate. Also this work will open the eyes of researchers to other areas which are yet to be considered in order to improve heat transfer rate in pin fin application. The parameters that are considered in the researches on pin fins can be categorized into two; (1) parameters that are related to the fin itself and (2) parameters related to the convecting fluid around the fin.

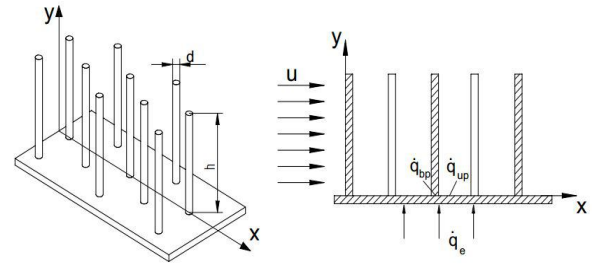


Figure 2A 3-dimensional view and sectional view of a cylindrical Pin fin heat sink.

FIN PARAMETERS

Generally, the performance of heat sinks depends on so many factors including geometry of the cooling fins, the form of the heat sources [location and concentration], the fluid flow, and aggregately the thermal resistance. To design a heat that will very affective in heat dissipation, there must be adequate consideration for criteria such as the type of pin-fin arrangement and the spacing of the pins in the array, the pin size and shape have a strong impact on the heat transfer in the heat sink. In a pin-fin array heat is transferred from both the smooth channel end wall and the numerous pins. Flow around the pins in the array is comparable to flow around a single cylinder. As the coolant flows past the pin, the flow separates and wakes are shed downstream of the pin. In addition to this wake formation, a horseshoe vortex forms just upstream of the base of the pin, and the vortex wraps around the pins. This horseshoe vortex creates additional mixing, and thus enhanced heat transfer. In the design of pin fins, there two major types of arrangements; inline and staggered arrangement. Each of these arrangement has it best form of geometry for optimum performance.

Bello-Ochende, *et al.* (2010) numerically investigated to determine the optimal configuration of rows of pin-fins that will maximizes the total heat transfer from the fins and the hot surfaces, subjecting the set-up to constraints of fixed total volume of system and fixed volume of pin-fin material. He was aimed at striking a balance between convective resistance and conductive resistance of pin-fin array under a laminar forced convective heat transfer with the application of constructal theory. In his findings show that pin-fins flow structure performs best when the pin-fin diameters and heights are non-uniform".

In inline arrangement as investigated by Yang, *et al.* (2007) circular cross-section of the fins has the best performance. This is so because the circular pin fins shows an appreciable influence on the fin density, which is proportional to the heat transfer coefficient. In the staggered arrangement, Jonsson and Palm evaluated from their experiment at high velocities, elliptical fins possess the lowest thermal resistance and as well as at low-mid range velocities the circular fins possesses the optimum thermal resistance as such, the velocity of the flowing fluid as to be considered in the choice of the geometry for optimum performance.

Younghwan, and Sung J. (2015), had a two objective functions in the comparison of plate-fin and pin-fin heat: the total heat dissipation and the heat dissipation per

unit mass for a given base-to-ambient temperature difference. They proposed a new correlation of heat transfer coefficient for pin fin heat sink; the asymptotic method proposed by Chur-chill and Usagi is used to propose a new correlation of the heat transfer coefficient for pin-fin heat sinks. And they came out with a final correlation of the heat transfer coefficient for pin fin as;

$$h_{fin} = \left[\left(h_{fin,1}^{-1.3} + h_{fin,2}^{-1.3} + h_{fin,3}^{-1.3} \right)^{-\frac{0.8}{1.3}} + h_{fin,4}^{-0.8} \right]^{-\frac{1}{0.8}} \quad (2)$$

Their correlation was numerically and experimentally on a comparison between the plate and pin fins. Their results were; when the objective function is the total heat dissipation, the optimized plate-fin heat sinks perform better than do the optimized pin-fin heat sinks in most practical applications and when the objective function is the heat dissipation per unit mass, on the other hand, the optimized pin-fin heat sinks perform also better than the optimized plate-fin heat sinks in most practical applications. Yang, K. S., *et al.* (2007)

FLOW PARAMETERS

The basic forms of fluid initiated in pin fin application is either by natural convection. The natural depends on the buoyancy force that acts within the molecules of the fluid due the density changes by virtue of temperature gradient. It is known generally that the application of pin fins will lead to pressure drop in the fluid flow. Such pressure must not be too large as it will obstruct the fluid flow and the purpose of the heat exchange by convection may completely change to conduction as a result.

The parameter that improves these mostly is the heat surface area to volume ratio γ . This will directly imply that the best performance of pin fins application can be found in micro pin fins as evidenced by Kumar, *et al.* (2016). Another parameter which is used to determine the performance of a pin fin arrangement is a dimensionless parameter called the Nusselt number Nu which is proportional to the heat transfer coefficient. It was observed the Nusselt number increases monotonically with the number of pin perforations while the pressure drop and the pumping power required to overcome the pressure drop all reduce monotonically. This as a result of the increase in the heat surface area and also as the formation of localized jet around the perforation. This can only be achieved by maximum alignment of the perforations to the dominant flow direction as discovered by Al-Damook, *et al.* (2015).

Kalinin, and Yarkho (1966) used different fluids in the range $1500 \leq Re \leq 400,000$ and $7 \leq Pr \leq 50$ to investigate the effect of Reynolds and Prandtl numbers on the effectiveness of heat transfer enhancement in smoothly outlined internally grooved tubes. The ranges

of the transverse groove heights tested were $0.983 \leq d/D \leq 0.875$, (where d is the fin tip diameter and D is the inner diameter) with maximum groove spacing equal to the pipe nominal diameter. They reported that fin spacing equal to half the pipe diameter for a grooved tube, has the maximum increase in the heat transfer coefficient of up to 2.2 times the minimum measured value. The authors also observed that the behavior of the Nusselt number for the tested range of Prandtl numbers is independent of the Prandtl number.

Copetti, *et al.* (2004) tested a single internally microfinned tube of 9.52mm diameter using water as the test fluid. Under the same conditions, comparative experiments with an internally smooth tube were also conducted. They noted that the microfin tube provides higher heat transfer performance than the smooth tube although the pressure drop increase is also substantial. The finned tube performance efficiency index as defined by Brognaux, *et al.* (1997) were also determined which showed that the heat transfer increase was always superior to the pressure drop penalty. The experimentally obtained Nusselt numbers were empirically correlated separately as a Dittus-Boelter, a Sieder-Tate, and a Gnielinski type correlation. These correlations predicted their data reasonably well.

CFD APPLICATIONS IN PIN FIN STUDIES

A reasonable comparison of various pin-fin geometries has been attempted. A three dimensional conjugate problem has been studied with a 3-dimensional CFD model. These were greatly simplified by assuming 1-column in-line pin-fins with axes perpendicular to the flow and isothermal heat transfer surfaces. It was discovered that lower values of pressure drop and pumping power, drop shaped fins work best. At higher values, drop-shaped fins and Circular fins offer highest performance. For high Reynolds numbers, the fins thermal efficiency and effectiveness show same behavior, but drop-shaped fins configuration always stand a little bit upper. Also its variation in different flow regimes is smoother. Sharma, *et al.* (2013), in the optimization of pin fin shapes in automobile application, using Ansys fluent® (Version 6.3.26). This numerical study led to the outcome that the drop molded pin fins show enhanced results on the premise of heat transfer and pressure drop by comparing different fins.

NOTABLE AREAS OF PIN FIN APPLICATION

TURBINE BLADE COOLING

Gas turbine blades are cooled internally and externally. Internal cooling is achieved by passing the coolant through several enhanced serpentine passages inside the blades and extracting the heat from the outside of the blades. Jet impingement cooling and pin fin cooling are also utilized as a method of internal cooling. External cooling is also called film cooling. Internal coolant air is ejected out through discrete holes or slots to provide a

coolant film to protect the outside surface of the blade from hot combustion gases. Han, *et al.* (2001).

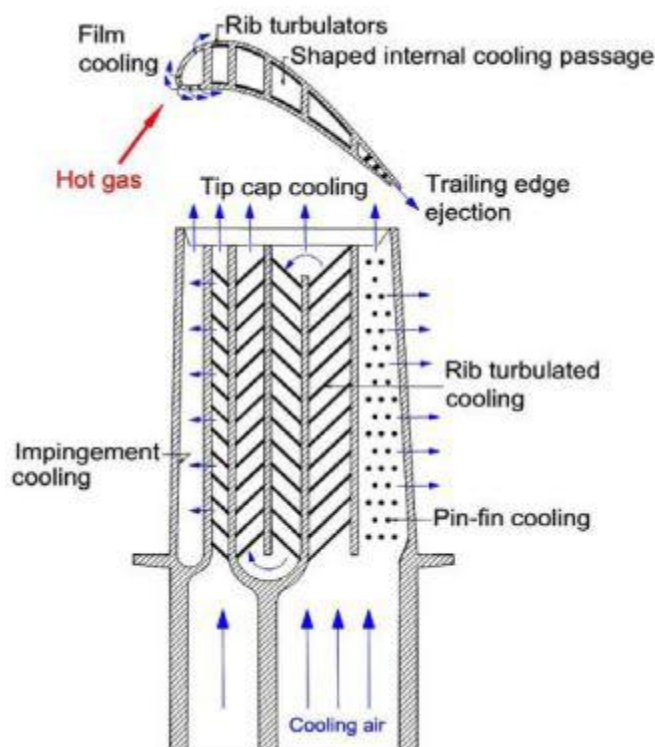


Figure 3A Typical Internal Blade Cooling. Han, *et al.* (2001)

PIN-FIN INTERNAL COOLING

As the coolant flows past the pin, the flow separates and wakes are shed downstream of the pin. In addition to this wake formation, a horseshoe vortex forms just upstream of the base of the pin, and the vortex wraps around the pins. This horseshoe vortex creates additional mixing, and thus enhanced heat transfer. Many factors must be considered when investigating pin fin cooling. The type of pin-fin array and the spacing of the pins in the array, the pin size and shape have a profound impact on the heat transfer in the cooling passage. Because pin-fins are commonly coupled with trailing edge ejection, the effect of this coolant extraction must also be considered.

PIN ARRAY/ARRANGEMENT

There are two array structures commonly used. One is the inline array and the other is the staggered array. Figure 3 shows a typical experimental test model with a staggered array of pin-fins. Metzger, *et al.* used staggered arrays of circular pins with 1.5 to 5 pin diameter spacing in a rectangular channel. Han, *et al.* (2000). A closer spaced array (smaller x/D) shows a higher heat transfer coefficient. Chyu, *et al.* showed that the heat transfer coefficient on the pin surface for both arrays is consistently higher than that of the channel end wall. Metzger, *et al.* (1982). The pin surface heat transfer is observed to be 10 to 20% higher for the presented case. Arora and Abdel - Messeh studied the effects of partial length pins in a rectangular channel. Chyu, *et al.* (1998). The surface containing pins is not

affected by the pin tip clearance. Whereas the opposite surface, that does not have pins, shows a decrease in heat transfer. The friction factor is lower for partial pins compared to full-length pins.

PIN-FIN COOLING WITH EJECTION

Kumran, *et al.* (1991) investigated the effects of the length of coolant ejection holes on the heat transfer coefficient in pin fins. More coolant ejection reduces the Nusselt number significantly from no ejection. Hwang, and Lu, (2000) investigated a converging channel with ejection and found that increasing the ejection degrades the end wall heat transfer near the tall wall and the heat transfer on the channel endwall surface near the ejection holes is increased. They also concluded that square, diamond, and circular pin-fin arrays enhance the heat transfer equally in channels with large ejection flows.

As for the effect of pin shape, the square pin performs a better end wall heat transfer than the diamond pin, and subsequently than the circular pin for a flow rate, $\varepsilon=0.8$. As compared to the fully developed smooth duct results, the heat transfer enhancement for the square, diamond, and circular pins are about 170–260, 160–260, and 130–210 percent, respectively. In addition, the square pins yield the highest pressure drop, while the circular pin has the lowest pressure drop in the trapezoidal duct under a fixed Reynolds number and lateral-flow rate. Correlations for end-wall averaged heat transfer in the trapezoidal duct with different pin shapes are developed in terms of the lateral-flow rate and the flow Reynolds number for the first time. Hwang, and Lu (2000)

APPLICATION IN (Proton Exchange Membrane) PEM FUEL CELL

Investigation of the effect of pin fins transversely arranged along the flow channel on the reactant gas distribution and pressure drop characteristics of the fuel cell reactant gas channel was done by Obayopo, *et al.* (2012) using pin fins of small hydraulic diameter, in order to reduce the additional pressure drop. Pin fins are employed and the effect on PEM performance was investigated. In addition, a mathematical optimization tool was used to choose the best pin fin geometric configuration that improves the fuel cell performance at a reduced pumping power requirement penalty in the PEM fuel cell flow channel. This work presents a novel approach at enhancing the oxygen mass transfer through the fuel cell (Gas diffusion layer) GDL at reduced pressure drop. The fuel cell performance was evaluated using the pumping power requirement at varying clearance ratio of the pin fins. Some of the outcomes obtain form the work are;

1. The reactant gas flow field and its diffusion through gas diffusion layer (GDL) are significantly affected positively as the flow Reynolds number increases.
2. The friction factor also increases with increasing clearance ratio of pin fin and channel.



3. Optimal clearance ratio and pitch for the considered fuel cell channel decreases with an increase in fuel channel friction.
 4. The channel friction and pressure drop significantly reduces as GDL porosity increases due to decrease of friction factor.
- An optimal pin fin clearance ratio can be reached with a minimum pumping power.

HOT SPOT COOLING IN ELECTRONICS

Ravi, and Je-Young (2008) had a work on the cooling of electronic chips with micro-pin fin creating a special interest on hot spot. Eason, C., *et al.* (2007) in thermal evaluations of hot spot impact on Flip-Chip Ball Grid Array (FCBGA) design. A special characteristic of hot spot is their localization based around the heat generation components either CPU, high powered electronic appliance or other interested areas. Hence their temperature distribution die is always non-uniform as shown below. Eason, C., *et al.* (2007), Abas, A., *et al.* (2015).

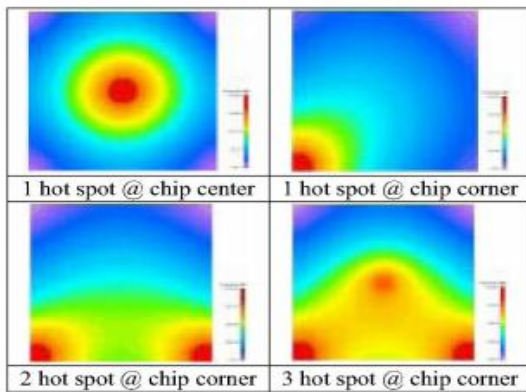
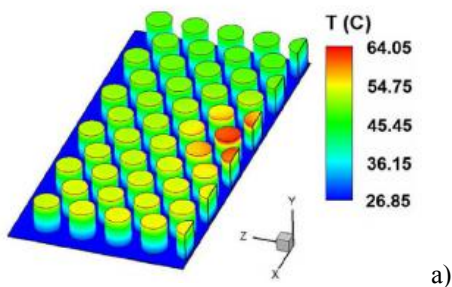


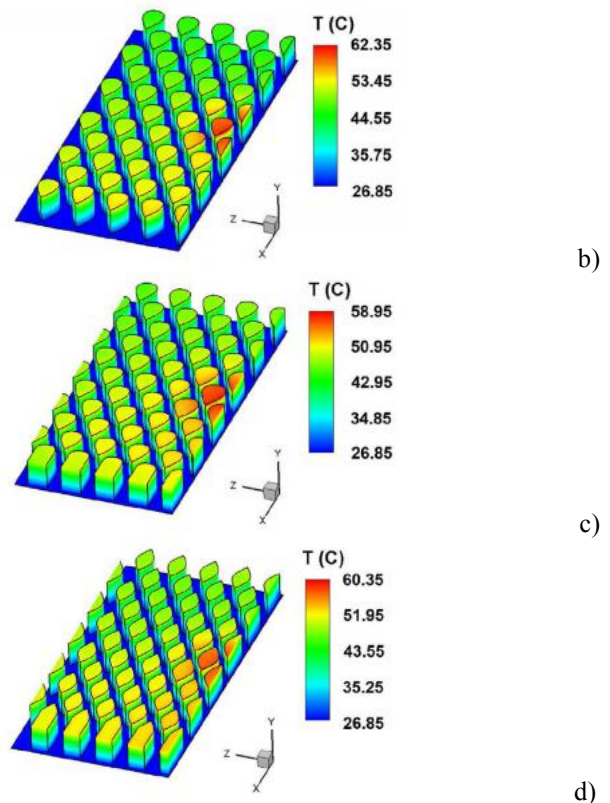
Figure 4 (c) Temperature distribution die result of a hot spot. Eason, C., *et al.* (2007).

GEOMETRICAL DESIGN OF FIN

Abas A., *et al.* (2015) reported a 3-D CFD analysis of thermo fluid with micro pin-fins for four different cross sectional geometry: circular shape, hydrofoil shape, modified hydrofoil shape and symmetric convex lens shape. All the fins were subjected to cooling, with water set as the coolant at an inlet temperature, velocity and pressure of 26.85°C, 2.0ms⁻¹ and 20KPa respectively in staggered arrays. The temperature distribution results of the four shapes is as presented



a)



b)

c)

d)

Figure 6 Temperature distribution on half micro pin fin of (a) circular shape (b) hydrofoil shape (c) modified hydrofoil shape (d) symmetric convex lens shape. Abas, A., *et al.* (2015).

The conventional circular geometry pin fin possess a setback of flow separation with the flow stream, which increases the required inlet pressure and at the same time decreases convective coefficient. Hence, a different geometry similar to NACA0060 symmetric airfoil was needed to proffer a solution instead of the circular cylindrical pin. The hydrodynamic created with the cross section shape provided better hydrothermal efficiency needed and the temperature distribution result reflected the hot spot and micro pin fin maximum temperature of 77.15°C and 62.35°C that was about 1.80°C and 1.70°C respectively less than the circular shape as shown in b). This yielded a desired significant reduction in the pressure drop by 23.5% of 1.7KPa with a) to 1.3KPa of b) Abas, A., *et al.* (2015). With shape c) the maximum pressure in this case was 11.8% lower than in shape a) and 13.3% higher than in shape b). The increase in maximum pressure was as a result of the larger fluid contact area. As for shape d) of convex lens from the above figure, the maximum temperature of the micro pin fin case was 60.35°C which was 1.4°C higher than in the modified hydrofoil shape. The maximum inlet pressure as applied with convex lens shape was 41.2% lower than that of circular cylinder shape, 23.1% lower than with hydrofoil shape and 33.3% lower than modified hydrofoil shape. Abas A., *et al.* (2015)

COMPOSITION OF PIN

In hot spot cases, pin fin are most time given special setup composition of fin, substrate, chips etc. as the case maybe. Some may call it “thermal package”

consisting of integrated heat spreader (IHS) - copper, heat sink (which are the pin fin or other forms) and thermal interface material (TIM) which most times are two in number. Ravi, P., *et al.* (2008), Sohail Reddy, R. (2015). The thermal interface material may be between the chip and the IHS and between the IHS and fin (heat sink) as shown below. Thereafter suitable mathematical correlation are applied depending on the desired interest.

AUTOMOBILE

Internal combustion engine work on efficiency about 50 percent, Fengming Wang, *et al.* (2012), even the world's largest diesel based engine has efficiency of 51.7 percent. The remaining 50 percent energy is going to convert into heat. This heat produced in engine is going to damage it. So it must be radiated out. Pin fins have been applied in automobile as a means of cooling the engines by convection. Many researchers investigated the performance parameters of pin-fin and compared it with profiles of other fins and suggested that, pin-fin elements are best suited for enhancement of heat transfer.

Sahiti, N., *et al.* (2006), suggested that, best suitable pin fin arrays with highest heat transfer rate. The results of the simulation of six different pin cross-sections in both arrangement of inline and staggered arrays showed that the staggered arrangement with elliptic profile performs better than all other pin cross sections. One can conclude that for practical application of pin fins as heat transfer enhancement elements, the elliptic profile offers the highest heat transfer rate for a given base area and for the same energy input. In case of perforated fins there is higher contact area with fluid in comparison with solid fins result in average friction drag force for perforated fins compare to solid fins and also increase by adding perforations. There is drop in temperature from fin base to fin top surface increases with number of perforations. Increasing perforations, weight reduction is remarkable and this economic benefit is along with more enhancement heat transfer rate. Ravi, *et al.* (2016).

MICRO REACTOR

A micro reactor or micro structured reactor or micro-channel reactor is a device in which chemical reactions take place in a confinement with typical lateral dimensions below 1 mm; the most typical form of such confinement are micro channels. Watts, P., and Wiles, C., (2007).

Qian, M., *et al.* (2016) researched on how to improve the flow and heat transfer performance of micro-reactors with micro-pin-fin arrays (MPFAR), a micro-reactor with non-uniform micro-pin-fin arrays (NMPFAR) was proposed. To investigate its flow and heat transfer characteristic at low Reynolds number. Simulated results indicated that the NMPFAR has the better heat transfer performance than MPFAR. Also, the heat transfer performance of three different NMPFARs with two, four and eight kinds of pin diameter was investigated by numerical simulation. Results showed the Nusselt number is larger when the change of pin diameter in NMPFAR is less, which means the

NMPFAR with two kinds of pin diameter has the better heat transfer performance. The research result shows that the NMPFAR does have the merit for enhancing flow and heat transfer performance of the micro-reactor as with the MPFAR. Qian M., *et al.* (2016).

Mei, D., *et al.* (2014) In their investigation, the MPFAR with different tip clearances was studied to investigate the effect of tip clearance on the heat transfer and pressure drop performance at low Reynolds numbers. A computational model of the MPFAR with or without tip clearance was developed, and the thermal and hydrodynamic performance was studied by numerical analysis. The heat transfer performance decreased with increasing tip clearance, while the pressure drop performance was improved. The heat transfer performance in the MPFAR with a tip clearance of $h_c/h_f = 1.1$ or 1.2 was much better than that without tip clearance when the Reynolds number ranged from 33 to 350. The terms $(h_c/h_f)_{1.41}$ and $(h_c/h_f)_{1.64}$, accounting for the effect of tip clearance, were introduced into the new heat transfer and friction factor correlations, respectively. The new correlations indicated a strong dependence of the average Nusselt number and friction factor on the tip clearance. Finally the numerical analysis was validated experimentally.

According to Mei, D., (2012), to enhance the compactness of the micro-reactors for hydrogen production via methanol steam reforming (SMR) for fuel cell, a novel micro-reactor with micro-pin-fin arrays (MPFAR) is designed and fabricated based on the micro thixo-forming technology. A three-dimensional model is adopted in the numerical analysis to investigate the heat and mass transfer in the micro-reactor. The results show that the methanol conversion in the MPFAR is higher than that in a micro-channel reactor, the velocity and temperature distribution is uniform in the catalyst support. Higher reaction temperature and contact time result in higher methanol conversion and CO molar fraction at the outlet, while a higher steam to methanol (S C-1) molar ratio results in a lower CO molar fraction. Finally, experiments are conducted to test the performance of the MPFAR for hydrogen production. The experimental results agree well with the simulated ones, which validate the accuracy of the simulation model. When the S C-1 molar ratio and the contact time are 1.2 and 0.12 s, respectively, the methanol conversion of the MPFAR reaches to 87.5% with the hydrogen molar fraction of about 75% at the outlet, which is suitable for the application in the fuel cell system.

CONCLUSION AND POTENTIAL RESEARCH AREAS ON PIN FIN

This work provides an overview of the recent researches performed in the field of pin fin heat transfer enhancement. This will be a guide into areas to which research can be furthered in this field. The following were the future research areas as related to multi-objective analysis and optimization in the application of pin fins.

1 Optimization of two-floor configurations can be performed. It was shown that the temperature on the bottom surface remains relatively high and would require two-floor configuration in electronics applications.

2 There is need to investigate how the two arrays of in line and staggered arrangement can be best combined in a single heat sink in order to obtain the optimum performance with the optimum pressure drop.

3 There could also be need for the combination of different geometries best applicable to each arrangement.

4 There is need to investigate into application of other nano-fluids fluids due to the observation that liquids dissipates heat better than gases. There is need to investigate into the changes into the fluid properties as the temperature changes and as it may influence the performance of the pin fin.

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