# Numerical Investigation of Heat Transfer Characteristics in a Pin Fin Dimple Channel with Various Inclinations

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***Abstract-****A numerical study was conducted to investigate the effects of pin fin inclinations on the flow and heat transfer characteristics in a pin fin-dimple channel, where dimples are located span wisely between the pin fins. The study aimed at promoting the understanding of the underlying convective heat transfer mechanisms in the pin fin-dimple channels and improving the cooling design for the gas turbine components. The friction factor and heat transfer performance of the pin fin-dimple channels with various pin fin inclinations in the direction of flow have been obtained and compared with each other for the Reynolds number range of 10,000–50,000. The study showed that, compared to the pin fin dimple channel, the pin fin dimple channels with inclined fins in the flow direction have further improved convective heat transfer performance.*

***Keywords****-*Pin fin dimple channel, secondary flow, friction factor, overall thermal performance.

## I. INTRODUCTION

The science and engineering of air-side heat transfer plays a critical role in the design of compact heat exchangers. Typically, air-side thermal resistance constitutes about 80% of the total thermal resistance to heat flow. Commonly, densely packed fins are used to increase the air-side surface area and also play the dual role of increasing the heat transfer coefficient. This is accomplished by using various topologies such that the thermal boundary layer is constantly regenerated either by interrupted surfaces and/or inducing self sustained flow oscillations. Fins can be broadly categorized into continuous surfaces, e.g. wavy fins and ribbed channels, and interrupted fins, e.g. strip fins and louvered fins. An additional aspect which any design has to be sensitive to is the friction penalty of achieving enhanced heat transfer. Hence, surface topologies which maximize heat transfer augmentation with minimal friction penalty are sought

## II. LITERATURE REVIEW

Recently surfaces imprinted with dimples or concave indentations have been researched extensively. One of the early investigations was conducted by Afansayev et al.[1], who investigated the effect of applying shallow dimples ($\delta/D$ =0.067) on flat plates on the overall heat transfer and pressure drop for turbulent flow. Significant heat transfer augmentation (30-40%) at negligible pressure drop augmentation was reported. Since then a number of experimental investigations have been conducted for different dimple geometries yielding heat transfer augmentation factors of about 2-2.5 with low frictional losses compared to other surfaces with flow turbulators [2].

Most experimental studies were conducted in the fully turbulent flow regime; the few lowReynolds number studies conducted were mainly concerned with flow visualization, which showed periodic and continuous shedding of a primary vortex pair from the central portion of the dimple, in addition to a secondary vortex pair shed from the span-wise edges of the dimple (Mahmood et al.[3], Ligrani et al[4] and Ligrani et al[5]). Heat transfer distribution and local Nusselt number variation on the dimpled surface showed the existence of a low heat transfer region in the upstream half of the dimple cavity followed by a high heat transfer region in the downstream half. Additional regions of high heat transfer were identified at the downstream rim of the dimple. A number of studies have reported significant heat transfer augmentation at low pressure drop penalty (Mahmood et al.[3], Ligrani et al[5], Chyu et al.[6], Moon et al.[7], Burgess and Ligrani [8] and Ekkad and Nasir [9]).

The use of two dimpled surfaces on opposite walls was studied by Borisov et al.[10], where highest heat transfer enhancement was reported at Re = 2500. The use of dimples on rotating channel surfaces has been studied by Griffith et al[11] who reported a heat transfer augmentation of 2.0. The effect of using spherical dimples and protrusions on opposite walls of the channel was studied by Ligrani et al[12] and Mahmood et al[13], where only the dimpled side of the channel was heated. Intensified secondary flow structures, flow unsteadiness and heat transfer augmentation were reported. Moon et al.[14] studied the effect of gap clearance in a channel with protrusions only on one side of the channel, where heat distribution showed high heat transfer augmentation at the front of the protrusion and in the passage between protrusions.

Numerical study of the problem of dimpled channel flow was conducted by a number of researchers. Wang et al.[15], using laminar flow simulation, identified a symmetric 3D horseshoe vortex inside a single dimple. Lin et al.[16], Isaev and Leont'ev[17], Park et al.[18], Won and Ligrani [19] and Park and Ligrani [20] used steady state Reynolds Averaged Navier Stokes (RANS) modeling to study flow and heat transfer in dimpled channel in the turbulent regime. All of the RANS calculations were done in the fully turbulent flow regime. Patrick and Tafti[21] used Direct Numerical Simulations (DNS) and Large-Eddy Simulations (LES) to predict the heat transfer and friction coefficient augmentation in a channel with onedimpled wall at low Reynolds numbers (ReH = 50 to 2000). Elyyan et al.[22] used LES to predict heat transfer and flow structure in a channel with dimples and protrusions on opposite sides for a fully turbulent flow of ReH = 15000. Recently, Wang et al.[23] used DNS to study turbulent flows over dimpled surfaces in a channel for different dimple depths, diameter and densities.

The previous experimental research work [24] has showed that a combined structure of pin fins and dimples in a channel can produce greater heat transfer performance at an even reduced pressure drop penalty compared with the channel with only pin fins, and the pin fin-dimple combined structure is believed to be able to maintain reasonable structural integrity and stiffness. Of interest in the present paper is to numerically investigate the effects of dimple depth on the flow friction and heat transfer characteristics in the pin fin-dimple channels, where dimples are located span wisely between the pin fins. Details of the flow structure in the pin fin-dimple channels with various dimple depths have also been reported, which revealed the underlying mechanisms for the associated flow friction reduction and heat transfer enhancement phenomenon in the pin fin-dimple channels.

## III. PROBLEM DESCRIPTION AND BOUNDARY CONDITIONS

Figure 1 shows a schematic of the geometrical configurations of a periodic pin fin-dimple channel segment, which are identical to those in the experimental work [24]. The periodic pin fin dimple channel segment contains a two-row staggered array of pin fin-dimples hybrid structure.

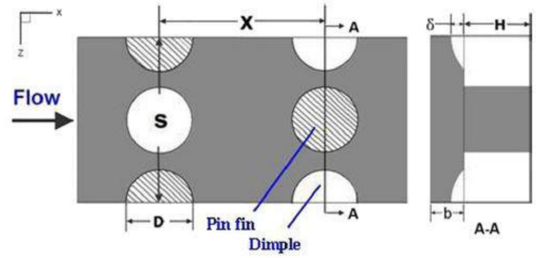


Fig 1: Geometry of the pin fin dimple channel

The pin fins and dimples are mounted on a base plate with a thickness of 5 mm. The material for the pin fins and the base plate is stainless steel. The pin fin diameter D = 10 mm, the span wise spacing to diameter ratio S/D = 2:5, the stream wise spacing to diameter ratio X/D = 2:5, the pin fin height-to-diameter ratio H/D = 1:0, and the hydraulic diameter-to-pin fin diameter ratio $D_h/D$ = 2:0. The dimples also have a print diameter of D = 10 mm and dimple depth to print diameter ratio δ/D = 0.2. The dimples are arranged span wisely in between the pin fins of the same row. The arrangement of the pin fin array with X/D = 2.5 and S/D = 2.5 in the test channels is considered to be one of the optimal array arrangements for turbine airfoil cooling [25-29]. Further inclinations has been given to the pin fins in the direction of flow i.e., Ø = 3°,6°,9°,12° as shown in Fig. 2

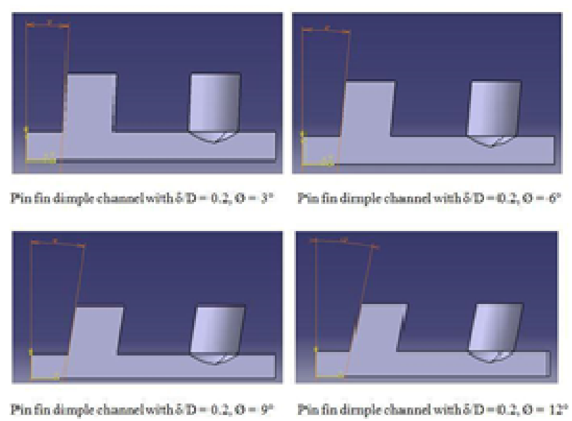


Fig 2: Pin fin dimple channel with fin inclinations

A schematic of the boundary conditions for the conjugate computations for the flow and heat transfer in the pin fin-dimple channels with various dimple depths, and the boundary conditions are identical to those in the experimental work [24] is shown in Fig 3. The computation model includes the heat transfer in the solid wall and in the fluid. The channels are uniformly heated from bottom, whereas the top wall of the channel is insulated. The channel, pin fin, and dimple surfaces are treated as no-slip boundaries. At the inlet and outlet of the channels, a pair of periodic boundary conditions was employed stream wisely for the velocities, pressure, and temperature. Transversely, on both sides of the periodic channel segment, symmetry conditions are employed.

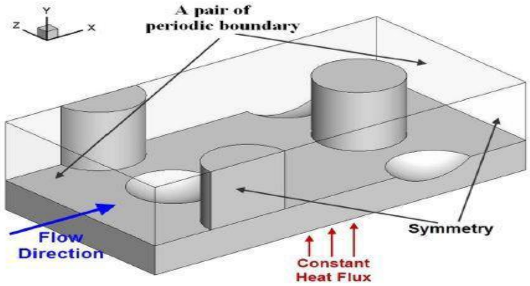


Fig. 3: Pin fin dimple channel with boundary conditions

## IV. METHODOLOGY

The computations for the flow and heat transfer in the pin fin-dimple channels were performed using the commercial solver ANSYSFLUENT 14.5. The computations were done by using a realizable k-ε turbulence model combined with an enhanced wall treatment. The realizable k-ε turbulence model is believed to have improved the predictive capability for complex turbulent flows with flow swirling and separation compared to the standard k - ε model and was also used to simulate the flow and heat transfer in the dimpled channel. Throughout the study, the fluid is considered to be incompressible, and hence the flow field and the energy equation were uncoupled. To reduce the numerical errors, a second order volume discretization scheme was used, and the SIMPLE algorithm was used for pressure-velocity coupling in the computations. All predicted quantities were steady state. The minimum convergence criterion for the continuity equation, velocity, and turbulence quantities is $10^{-4}$ and $10^{-7}$ for the energy equation. For all computation cases, model was generated by using software CATIA VSR 19 and an unstructured hybrid mesh was generated using the commercial software ANSYS14.5.

## V. SOLUTION

**Friction factor:** Fig 4 shows the comparison of thenumerical values of the friction factors of the pin fin-dimple channels with various pin fin inclinations in the direction of flow over the Reynolds number range of 10,000 – 50,000. It can be seen that, in the Reynolds number range of 10,000 – 50,000, depending on the pin fin inclinations in the pin fin-dimple channels show different flow friction characteristics. Over the studied Reynolds number range, the pin fin-dimple channel with Ǿ = 12° shows the lowest friction factors, which are slightly lower than the pin fin dimple channel with Ø = 0° by about 10.0% at Re = 50,000. However, the pin fin-dimple channels with lesser pin fin inclinations (Ø = 3°, 6° and 9°) show relatively higher flow friction factors than the pin fin dimple channel with straight fins. Therefore, it is interesting to know that the flow friction in thepin fin dimple channel can be reduced by tilting the pin fin in the direction of flow.

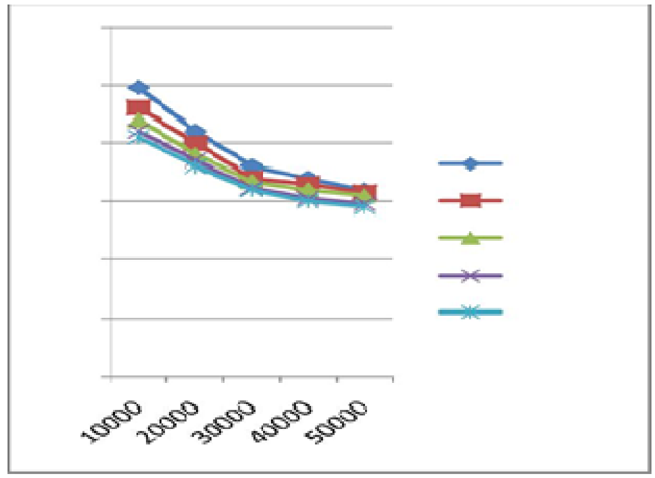


Fig 4: Comparison of friction factor with various pin fin inclinations

This phenomenon is due to the following facts. Since the tilting of pin fins in the flow direction cause the gradual contact of air on to the pin fins, the velocity and the blockage of the flow is thereby reduced, and the turbulent mixing level in the mainstream flow region is also reduced which contributes to reducing the pressure loss in the flow in the pin fin-dimple channels. However, as the inclination becomes larger, flow separation takes, which actually leads to additional pressure loss in the flow.

**Heat transfer:** Fig 5 shows a comparison of thenumerical values of the average Nusselt numbers of the pin fin dimple channels with various pin fin inclinations over the Reynolds number range of 10,000 – 50,000. It can be seen that, within the studied Reynolds number range, the Nusselt numbers of the pin fin dimple channels increase with the Reynolds number and also increase with the pin fin inclinations in the flow direction. The pin fin-dimple channel with Ø = 12° shows slightly higher Nu values than the pin fin dimple channel with straight pin fins. . For the pin fin-dimple channels with Ø = 12° has the Nusselt number 22% higher than the Nusselt number of pin fin dimple channel with straight pin fins at Re = 50,000.

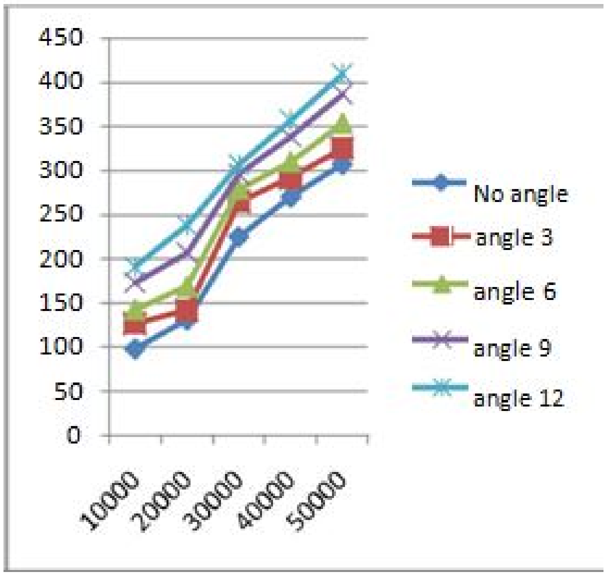


Fig 5: Comparison of Nusselt numbers with various pin fin inclinations.

Based on the above findings on the flow characteristics in the pin fin-dimple channels it can also be understood that in a pin fin dimple channel, the convective heat transfer increases and flow friction decreases with the increase in the pin fin inclination with the vertical in the direction of flow as the flow blockage reduces and pressure loss penalty decreases with slant pin fins.

**Overall thermal performance:** To properlyevaluate the thermal performance of the heat exchanger, the heat transfer performance of the pin fin-dimple channels can only be assessed after including the penalty effects related to the friction losses. Gee and Webb suggested the overall thermal performance parameter to evaluate the thermal performance of different heat transfer enhancement elements. The overall thermal performance parameter represents the quantity of heat transfer per unit pumping power.

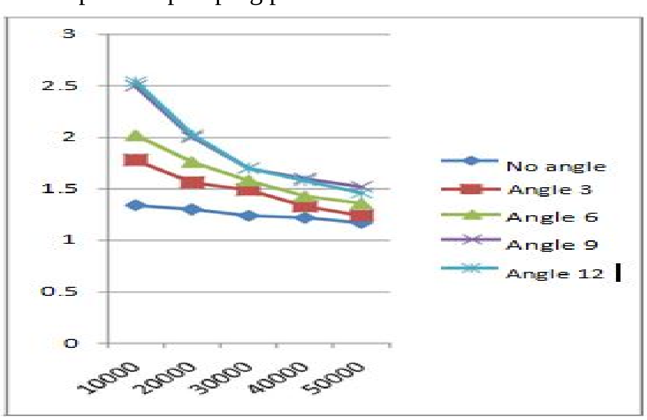


Fig 6: Comparison of Overall thermal performance with various pin fin inclinations.

Fig 6 shows the comparison of the numerical results of the overall thermal performance parameters of the pin fin-dimple channels with various pin fin inclinations versus the Reynolds number. According to the plot, within the Reynolds number range of 10,000 – 50,000 the overall thermal performance parameters of the pin fin-dimple channels all decrease with the Reynolds number

As the Reynolds number increases from 10,000 to 50,000, the overall thermal performance of the pin fin-dimple channels with the dimple depths of Ø = 9° and 12° shows approximately the same variation versus the Reynolds number, and both channels show the highest values of the overall thermal performance, but as the Reynolds number increases the overall thermal performance of the pin fin dimple channel with 12° inclination slightly starts decreasing over the other.

## VI. CONCLUSION

In this paper, comparative numerical studies have been conducted on the flow and heat transfer in the pin fin-dimple channels with various inclinations to the pin fins with the vertical in the direction of flow. The friction factor and the heat transfer performance of the pin fin-dimple channels with various pin fin inclinations have been obtained and compared with each other for the Reynolds number range of 10,000–50,000.

The comparisons showed that, compared to the pin fin channel, the pin fin-dimple channels with all four studied pin fin inclinations have further improved average Nusselt number, the channel with highest inclination increase theNusselt number by 22% over the pin fin dimple channel with vertical pin fins at higher Reynolds number. The comparisons still showed the pin fin-dimple channel with slant pin fins shows relatively lower friction factors by up to 10% at higher Reynolds numbers. But the overall thermal performance slightly starts decreasing with the increase in Reynolds number for the largest inclination of the studied inclinations. Finally it was concluded that the pin fin with Ø = 9° has the highest thermal performance.

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