An Investigation into Heat Transfer Enhancement by Using Oscillating Fins

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ABSTRACT

The present work describes numerical and experimental investigation of the heat transfer characteristics in a plate-fin, having built-in piezoelectric actuator mounted on the base plate (substrate). The geometrical configuration considered in the present work is representative of a single element of the plate-fin and triple fins. Air is taken as the working fluid. A performance data for a single rectangular fin and triple fins are provided for different frequency levels (5, 30 and 50HZ) , different input power (5,10,20,30,40 and 50W) and different inlet velocity (0.5, 1, 2, 3, 4, 5 and 6m/s) for the single rectangular fin and triple fins with and without oscillation. The investigation was also performed with different geometrical fin heights (50mm and 35mm) and distance between the fins (3mm and 6mm). It is observed that the heat transfer increases with the increase in the frequency and Reynolds number. It is further observed that triple fins with (height=50mm and distance between the fins=3mm) gives better enhancement as compared to other cases, The study shows that the piezoelectric actuator when mounted on the rectangular fins gives great promise for enhancing the heat transfer rate.

Keywords: oscillating fins, forced convection, heat transfer enhancement, experimental and numerical study

دراسة لزيادة معدلات انتقال الحرارة باستخدام الزعانف المتذبذبة

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الملخص:

العمل الحالي يبحث عدديا وتجريبيا خصائص انتقال الحرارة في زعانف مدمجة مع (Piezoelectric Actuator) *ومثبتة على قاعدة الزعانف* (Substrate). واخذ بنظر الاعتبار الزعنفة المنفردة والزعانف الثلاثية. واستخدم الهواء كمائع عمل. اختبرت قيم الاداء للزعنفة المنفردة والزعانف الثلاثية لمستويات تردد مختلفة (5، 30، و50 هيرتز) ، قدرات ادخال مختلفة (5، 10، 20، 30، 40، و 50 واط) ، وسرع دخول مختلفة (0.5، 1، 2، 3، 4، 5 و 6 م/ثا) مع وبدون ذبذبة. وانجز البحث مع ارتفاعات زعانف مختلفة (35 ملم ، 50 ملم) ، ولمسافات بين الزعانف (3 ملم ، 6 ملم) . يلاحظ ان انتقال الحرارة يزداد مع زيادة التردد وعدد رينولد . كذلك يلاحظ ان الزعانف الثلاثية مع (الارتفاع=50 ملم والمسافة بين الزعانف=3 ملم) تعطي افضل

تحسن في انتقال الحرارة مقارنة مع الحالات الاخرى ، وتوضح الدراسة انه عند دمج ال (Piezoelectric Actuator) مع الزعانف المستطيلة يعطي تحسن كبير في معدل نقل الحرارة .

الكلمات الرئيسية: زعانف متذبذبة، حمل قسري، تحسين انتقال الحرارة، دراسة عددية وتجريبية

INTRODUCTION

Heat transfer enhancement has become popular recently in the development of high performance thermal systems. A wide variety of industrial processes involve the transfer of heat energy. These processes provide a source for energy recovery and process fluid heating or cooling. Enhanced heat transfer surfaces can be designed through a combination of factors that include increasing fluid turbulence, generating secondary fluid flow patterns, reducing the thermal boundary layer thickness and increasing heat transfer surface area (David 2010).Electronic portable devices, especially desktop PCs and CPUs, have become challenging and popular. Today's rapid IT development like the Internet PC is capable of processing more data at a tremendous speeds. This leads to higher heat density and increased heat dissipation, making the CPU temperature rise and causing a shortened life, malfunction, and failure of CPU, (R. Mohan 2011). Heat transfer under the influence of vibration and flow oscillation (also sound) has been the subject of many researches since the early 1950's. Enhancement of heat transfer for a circular cylinder by using oscillations was studied by (H.M.Blackburn 1993), (Chin 1997), (C.Gau 2001), (H.G.Park 2001), Fu [2002],(Tait 2006), (Yue-Tzu 2008), (Osama 2009) and (Jalal 2009). In addition to numerous methods have been proposed to enhance heat transfer rate by using block moving back and forth on a heated surface in a channel flow, this phenomena causes the heat transfer rate of the heat surface to be enhanced because it destroys and suppresses the velocity and thermal boundary layers on the heat surface periodically studied by (Wu-Shung 2000) , (Wu-Shung 2001),(Wu-Shung 2001) and (Wu-Shung2010).(Hiroshi 1971)studied analytically the time –mean heat transfer of the Incompressible laminar boundary layer on a flat plate under the influence of oscillation. The results show that, when the oscillation is of high frequency, the time –mean heat flux to the wall can be several times as large as that without oscillation.(Wu-Shung 2001) proposed a method for enhancing heat transfer of a finned heat sink for electronic device cooling. They used extremely thin fins swinging back and forth in a flow. The Galerkin finite element method with moving meshes was used to solve the differential governing equations. They studied the effects of Reynolds number (ranged between 500 to 1500), swinging speed and amplitude of the fins. The results show that: as the fins swing with a small speed, the variations of the flow and thermal fields are slight and similar to the fluid flowing over a flat plate. (Subhrajit 2009) Carried out a numerical investigation using finite volume method for a 3D oscillating fin to disturb the thermal boundary layer to enhance forced convection heat transfer from conventional heat sink. The fin dimensions were (0.5" *1"*0.01") and substrate was (1"*1"). The power supplied to the substrate was 20W. It was found that such oscillations lead to tip-leakage vortices from the fins. Most of the reviewed literatures deal with flow oscillation and study the effect of this oscillation on heat transfer and fluid flow. Also they focus on study the effect of wall oscillation, body moving, heated surface and oscillation of the cylinder to destroy the thermal boundary layer developed on the heated surface. Up to our knowledge, very rare previous work focus on heat transfer rate from an oscillating fin (by using a piezoelectric actuator) attached to a hot substrate in a flowing fluid. The experimental and theoretical parts of the present work are concerned with the effect of fin height, fin spacing, power supplied to the hot substrate, fins number (single or triple), frequency of oscillations, and inlet velocity of the flowing fluid. The present study is involved with the enhancement of convective heat transfer by utilizing fixed or oscillating fins from a hot plate to a longitudinal flowing fluid. The investigation is carried out for different parameters, namely; number of fins (single or triple), height of fins, distance between the fins, power supply to the hot plate, frequency of the oscillated fins and velocity of flowing fluid. In the present study a combine substrate and oscillated fins model is design and instrumented. Fig. (1) Shows isometric view of the model

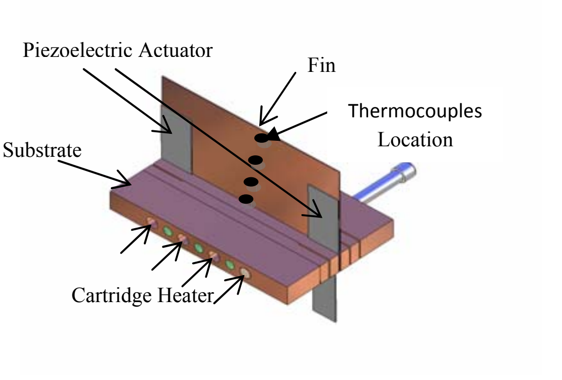


Fig. (1): The Structure of Oscillating Fin

NUMERICAL SIMULATION

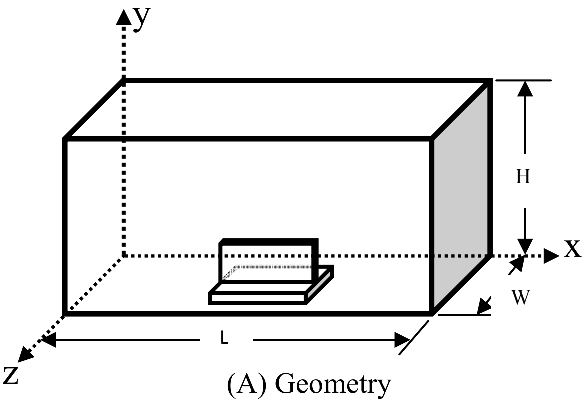
In order to analyze the flow field over plate fin with and without oscillation, a solution of Navier-stokes equations is required. Conservation equations for continuity and momentum for laminar model of the plate fins are presented in FLUENT built-in solver. For air flows involving additional heat transfer (added or removed) an additional equation for energy conservation is solved. In the present work, the mathematical model of the fixed and oscillating fins are solved numerically using a CFD Code FLUENT 6.3.26 after describing the mesh model using the Gambit 2.2.30.

The model solved a finite volume formulation using an implicit solver approach. The Navier-Stokes momentum equations were discretized For time-dependent calculations, conservation equations are solved using an explicit time marching scheme. Pressure velocity coupling of the continuity equation was achieved using the SIMPLE algorithm that is valid for small time steps used in the simulation. The system geometry in the present work basically consists of a box (which represents the flow tunnel) and this box contains the substrate combined with fins (three fins).

The geometry was designed using basic five geometries (cuboids) for flow duct, substrate and three fins. Also it is good to say here that three regions are interconnected with split function so the analysis of the results are continuum and interchangeable in between of them.

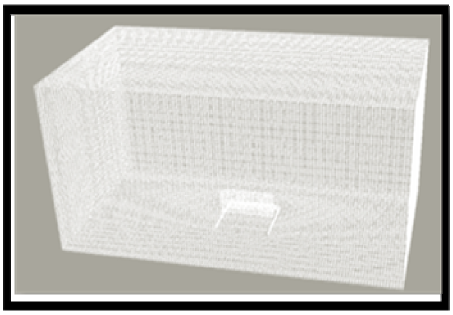
MODELLING AND MESHING

The exact geometry and the corresponding mesh of the oscillating fin are shown in fig. (2). The computational region dimension is 600mm in length, 340 in width, 340mm in height. In the present work, a higher order element type tetrahedral / hybrid is used for mesh generation to approximate precisely the geometry interfaces. Grid refinement tests for residual coefficients indicated that a grid size of approximately (2 million cell) provide sufficient accuracy and resolution to be adopted as the standard for fin wall junction with upstream substrate and (400,000 cells) for fin wall junction only. In our case study the UDFs used here play the rules of substituting the effect of the sinusoidal behavior of the fins during the transient time change in dissipating of heat from substrate to the flow. A UDF is a function (programmed by the user) written in C language which can be dynamically linked with the FLUENT solver.



(A) Geometry

Fig. (2): (A)Geometry and (B)Model Mesheing



(B) Model Meshing

at the wall; u=v=w=0

at the inlet ; T=T∞ and u=u_{in}.

at the outlet; p=patm.

Fig. (2): Continued

EXPERIMENTAL WORK

A schematic drawing of the experimental set-up is shown in Fig. (3). The experiments were carred out in the Energy lab at Cardiff University of School of Engineering U.K.The experimental set-up of the wind tunnel consists mainly of a filter, a nozzle with flow straighteners, the test section, a damping chamber, a diffuser, and an AC fan. The main duct which supplies air to the test section contains the impeller fan. a flow straightener (screen) at the air inlet side of the wind tunnel, honeycombs to reduce the swirl motion of the air stream and to break up occasional large eddies that may reach the working section. The air flow is induced by means of a fan driven by variable speed electric motor at the side of the tunnel. Air enters the base of the tunnel by way of a muslin strainer and is led through a contraction cone to the working section. The test section consists of rectangular duct (340mm ×340 mm and 600mm length). The tested model consists of square base plate, tested fins, and heating unit. The base plate is made from copper plate, of 100 mm long, 100 mm wide and 11 mm thickness. The tested fins are made from the pure copper plate of (t) thickness 0.075mm, (H) height 35 and 50mm and (L) long 100mm.

Four copper–constantan thermocouples were distributed uniformly along fin height at mid plane. During the experiments, the effect of the fin height (H), fins spacing (W) and the fins number (N) were investigated. The heating unit mainly consists of the four cartridge electric heater and the thermal insulation. The total heater output power is 1200 W at 250 V and current of 4.8A. The electrical power input to the heaters was controlled by a PID controller and power transformer variac to obtain constant heat flux along the base plate over the range of the tested conditions and measured by an in-line digital plug-in power and energy monitor. The cartridge heaters were isolated thermally by using Isofrax paper (k = 0.073W/m.K) also insulated from the bottom surface by Insulfrax Blanket (k = 0.07 W/m. K) with 80 mm thickness. The experiments of the fluid flow and heat transfer were carried out for each tested model for seven values of Reynolds number depend on hydraulic diameter of test section (10885.88 to 130630.61). Inside the test section, there is substrate with fins. The first fin is fixed at middle of the substrate and another two fins fixed on both sides of first fin. The finned substrate is fixed at bottom surface of test section.

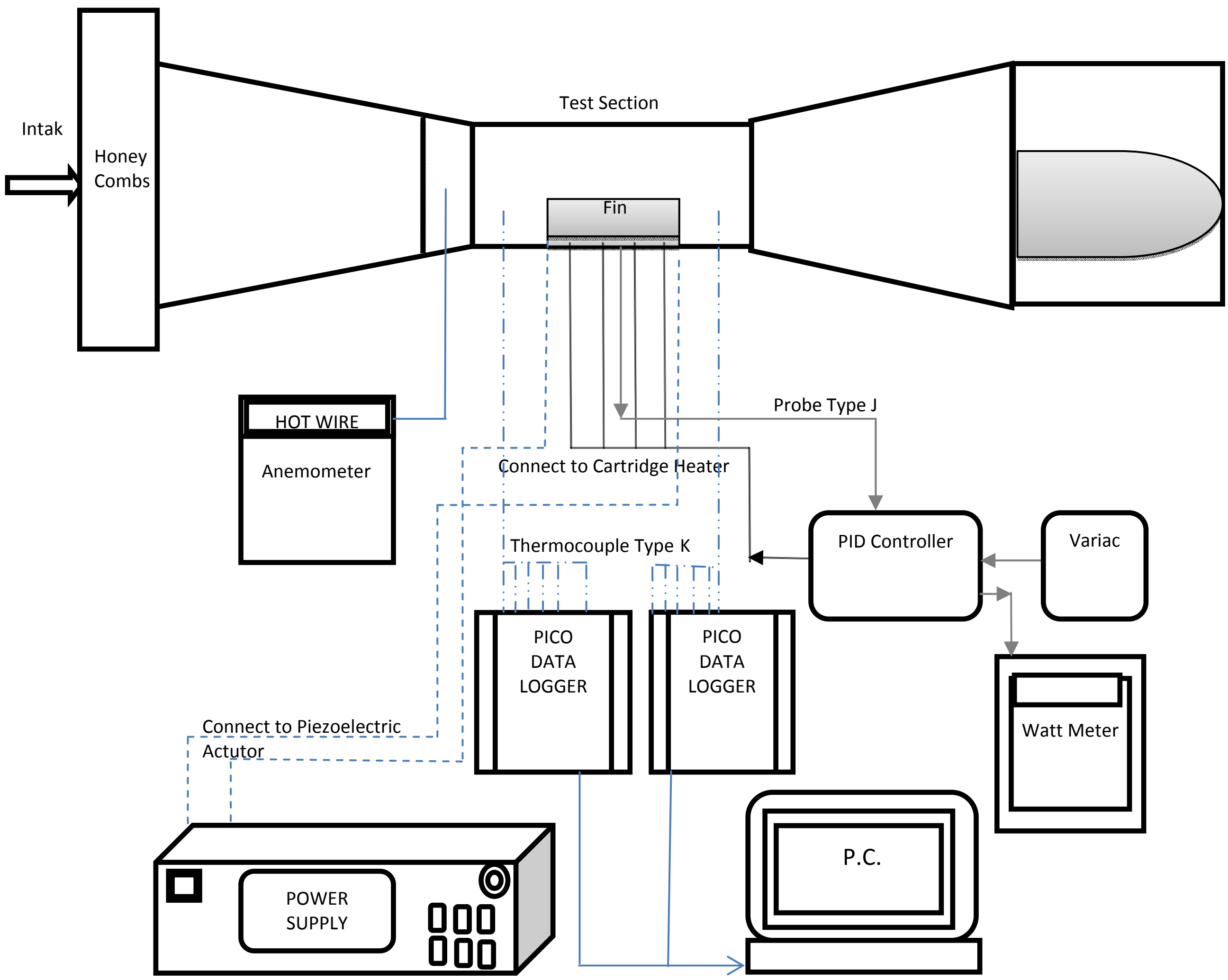


Fig.(3) A Schematic Drawing of the Experimental Set-Up

RESULTS AND DISCUSSION

1) Experimental results

Fig. (4) shows the steady state temperature distribution through the middle fin for case of fixed and oscillated fins with 50HZ. The temperature begins to drop with increase in the frequency. The cooling effect appears at the tip, that means the effect of oscillation increases with the height of fin and be more effective at tip of the fin. The top curve represents (T1) at root of the middle fin, and the lower curve is (T4) at the tip, the other two curves are between the root and tip. The best performance is with case of triple fins (height=50mm and the inter-fin space =3mm).

The temperature at the tip of the middle fin is decrease by (45 %) by using oscillating frequency of 50HZ w.r.t. case with fixed fins. For case (height =35mm and the inter-fin space =3mm), the influence of oscillation with this height is not effective. For case (height =50mm and the inter-fin space =6mm), where the cooling with this distance between the fins is good, the drop occurs in the temperature distribution from the root fin to the tip of the fin, but the effect of oscillation in this case is low. The temperature at the tip of the middle fin is decrease by (10 %) by using oscillating frequency of 50HZ w.r.t. case with fixed fins.

For the case (height =35mm and the inter-fin space =6mm), the cooling is good for substrate and fins with this height and distance between the fin, but the effect of oscillation is weak. For single fin case (height =50mm), where there is drop in the temperature distribution of the fin with increasing oscillation but with low effect. The temperature at the tip of the middle fin is decrease by (7 %) by using oscillating frequency of 50HZ w.r.t. case with fixed fins.

Fig. (5) shows the transient temperature distribution through the middle fixed and oscillated fin. The temperature is decreasing with increasing (Re) due to increasing the flow velocity around the fin and decreasing (B.L) thickness. The figure shows the change of temperature from the root of the fin (T1) to tip (T4), also the change with time until the steady state for all inlet velocity and input power. The temperature decreased with increasing the momentum of flow passes the fin. But, the high velocity affects the performance of oscillation or reduces the effect of oscillation, because the air works as damping to the oscillation. The result shows that the effect of oscillation on the tip of the fin is more than that in the root of the fin. So, the cooling of the fins with oscillation is better than the case without oscillation. The effect of frequency 50HZ on the temperature distribution through the middle fin indicates the best performance in transferring the heat from the substrate and dissipating through the fins, where the oscillation with this frequency helps the fin to deliver the heat quickly, this is especially observed at the tip of the fin.

Fig. (6) manifests the variation of the temperature at the tip of the middle fin with time for different inlet velocities and frequencies. The top curve case, no oscillations, displays higher temperature along the height of the fin until the near neighbourhood of the fin tip. There is a clear enhancement of the oscillations even for the moderate frequency of 5HZ, case (B). Then, the enhancement increases markedly along the fin height. With increasing frequency of oscillation, cases (C) and cases (D), even greater enhancements are attained. The temperature at the tip of the fin affects strongly with increasing the frequency, especially with 50HZ. This frequency produced a big drop in the temperature at the tip of the fin. This enhancement occurs for all inlet velocities in case (height=50mm and the inter-fin space =3mm). Also the best perform at low inlet velocity such as 0.5,1 and 2m/s.

Fig. (7) shows the variation of the temperature at the tip of the middle fin with time for different input powers. The improvement in the performance of enhancement of heat transfer with oscillation is observed, that is clear at high input power only from 20Watt to 50Watt and low velocity (0.5m/s, 1m/s and 2m/s). The temperature at the tip of the fin with oscillation begins in drop quickly from the first and uniformly after that.

Fig. (8) exhibits the effect of height of the fin (H) on the local Nusselt number for all inlet velocities and for fixed and oscillating fins at 50HZ, for case (height =50mm and the inter-fin space =3mm). The results display that local Nusselt number is higher at the tip of the fin, and it increases with increasing the inlet velocity, that means increasing the flow capacity for convective heat transfer. It is clear that (Nu) increases toward fins tip due to the convection of large heat from the tip of the fins. Local Nusselt number increases with frequency of 50HZ compare to fixed fins, and the relative improvement is better at lower Re than at higher values for fin oscillation. The local up wash on the lateral surfaces of the fin leads to an overall enhancement in heat transfer through the rest of the fin surface when compared with a conventional static fin. The variation in flow at the fin tip indicated strong flow fluctuations near the fin. At an oscillation frequency of 50HZ, the enhancement was large enough to give rise to surface heat transfer coefficients. Since the oscillation of the fins in the same direction and with large oscillation space, can generate larger airflow. for case (height =35mm and the inter-fin space =3mm or the inter-fin space =6mm), the increase of the frequency gave no significant effect on the local Nusselt number, because the height of piezoelectric is not suitable with this height of the fin; that means the height of the fin must be larger than height of the piezoelectric actuator. for case (height =50mm and the inter-fin space =6mm). The results show decrease in local Nusselt number compared to case (height=50mm and inter-fin space=3mm) especially at high velocity.

Fig. (9) illustrates the effect of height of the fin (H) on local heat transfer (Nusselt number) for all inlet velocities and for fixed and oscillated single fins with 50HZ, for case (height =50mm) and input power = 50Watt. The results display that (Nu) is higher at the tip of the fin also, the (Nu) increases with increasing inlet velocity, that means increasing the flow capacity for convective heat transfer. The comparison between the figures clarified the increase of the frequency with no significant effect on the local Nusselt number.

Fig. (10) present four cases which are respectively correspond to the four investigated cases: (A) no oscillation, (B) 5HZ oscillations, (C) 30HZ oscillations and (D) 50HZ oscillations. All cases are with input power 50Watt. The heat transfer is high and increases with increasing (y/h) until (y/h=1) due to the convection of large heat from the tip of the fins.

The results show that the best case is with frequency 50HZ, where a higher local Nusselt number determined, especially at the tip of the fin. Also the best performance is for oscillation with a range of velocity from 0.5m/s to 2m/s. After that, the increase of the velocity of the air gives no good performance, because the air at high velocity works as damping for oscillation.

Fig. (11) reveals the effect of height of the fin (H) on local heat transfer (Nusselt number) with a triple oscillated fin for frequency 50HZ. This case is with input power 10, 30 and 50Watt. The heat transfer is high and increases with increasing (y/h) until (y/h=1) due to the convection of large heat from the tip of the fin.

2) numerical results and comparison

Figure (12 to 15) present the numerical results of the present work compared to the experimental ones. Good agreement can be observed from the figures with maximum deviation of 5% for all investigated cases. The maximum deviation occurred at the tip of the fin.

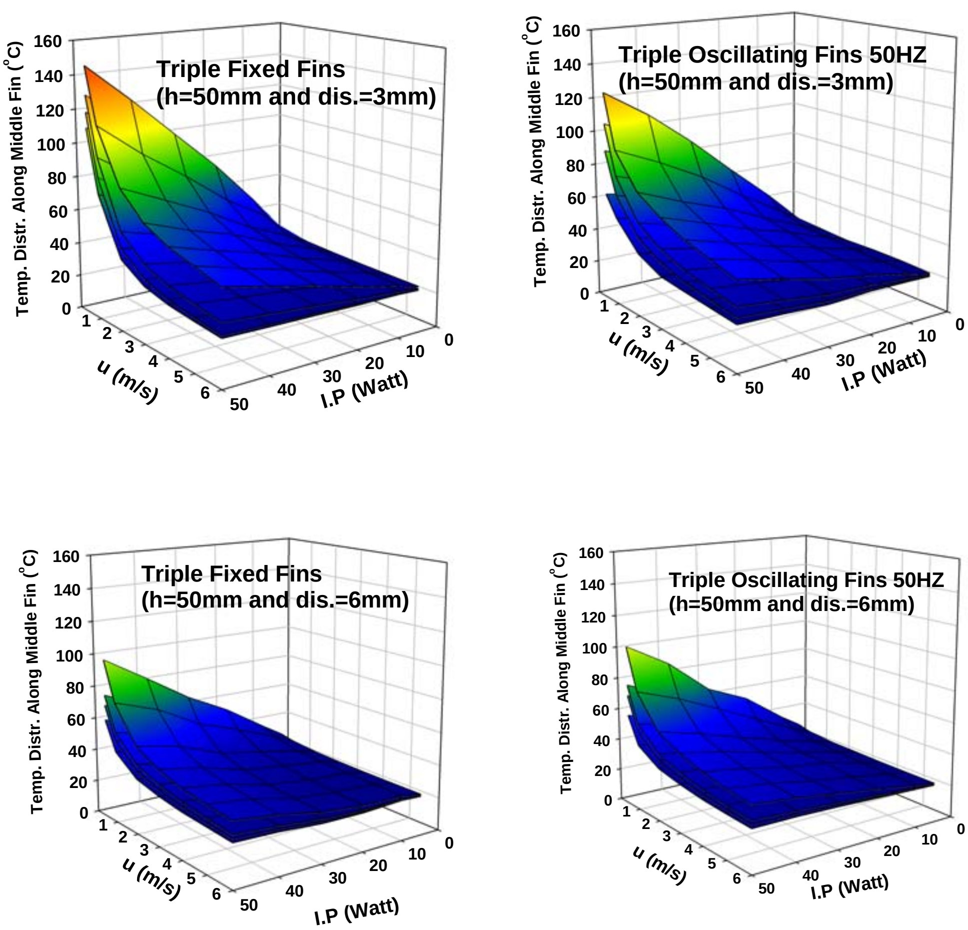


Fig. (4): Variations of the Temperature Distribution along the Height of Middle Fin with Inlet Velocity and Input Power. Single and Triple Fins

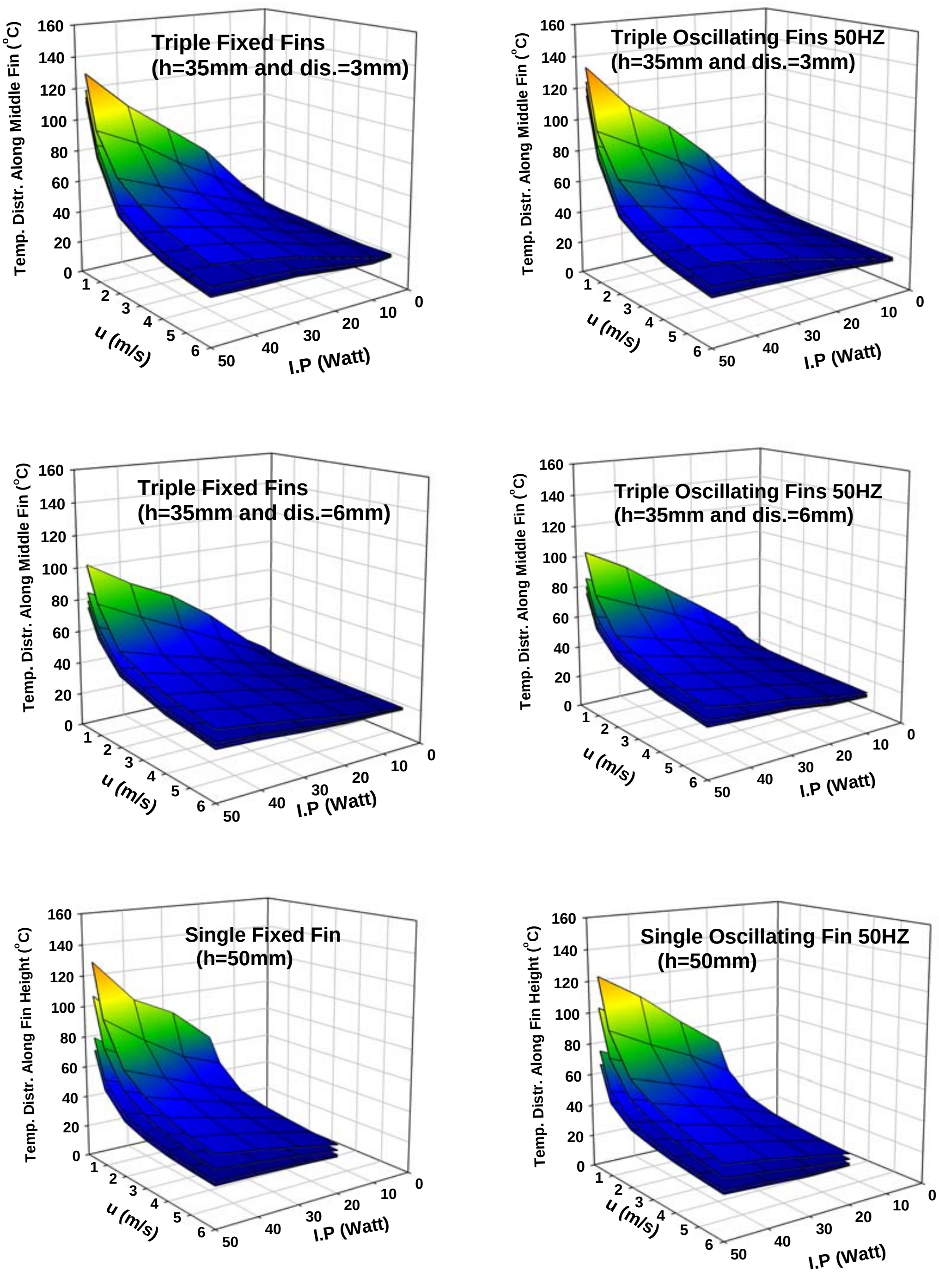
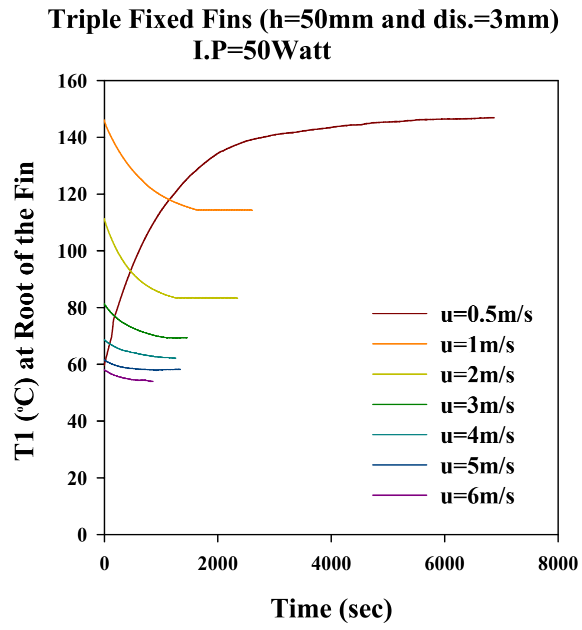
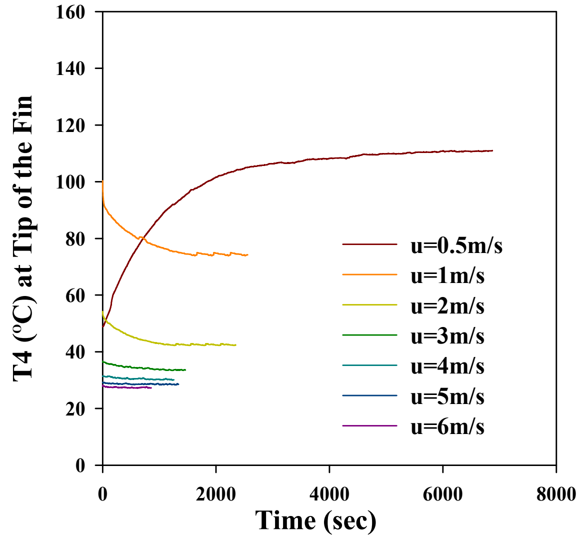


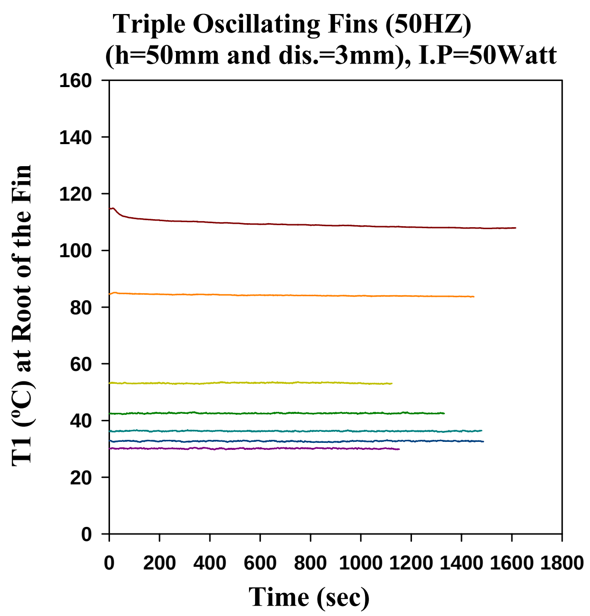
Fig. (4): Continued



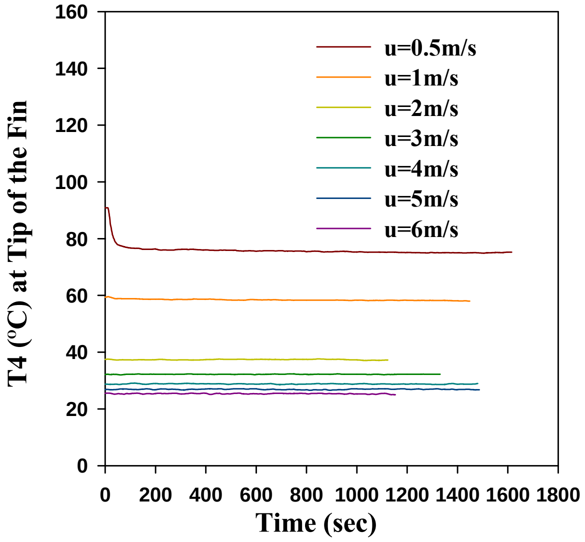
(A)



(B)



(C)



(D)

Fig. (5): Variations of the Temperature Distribution along the Middle Fin with Time for Various Inlet Velocities. (A, B); Triple Fixed Fins, (C, D) Triple Oscillating Fins Of (H=50mm and dis. =3mm).

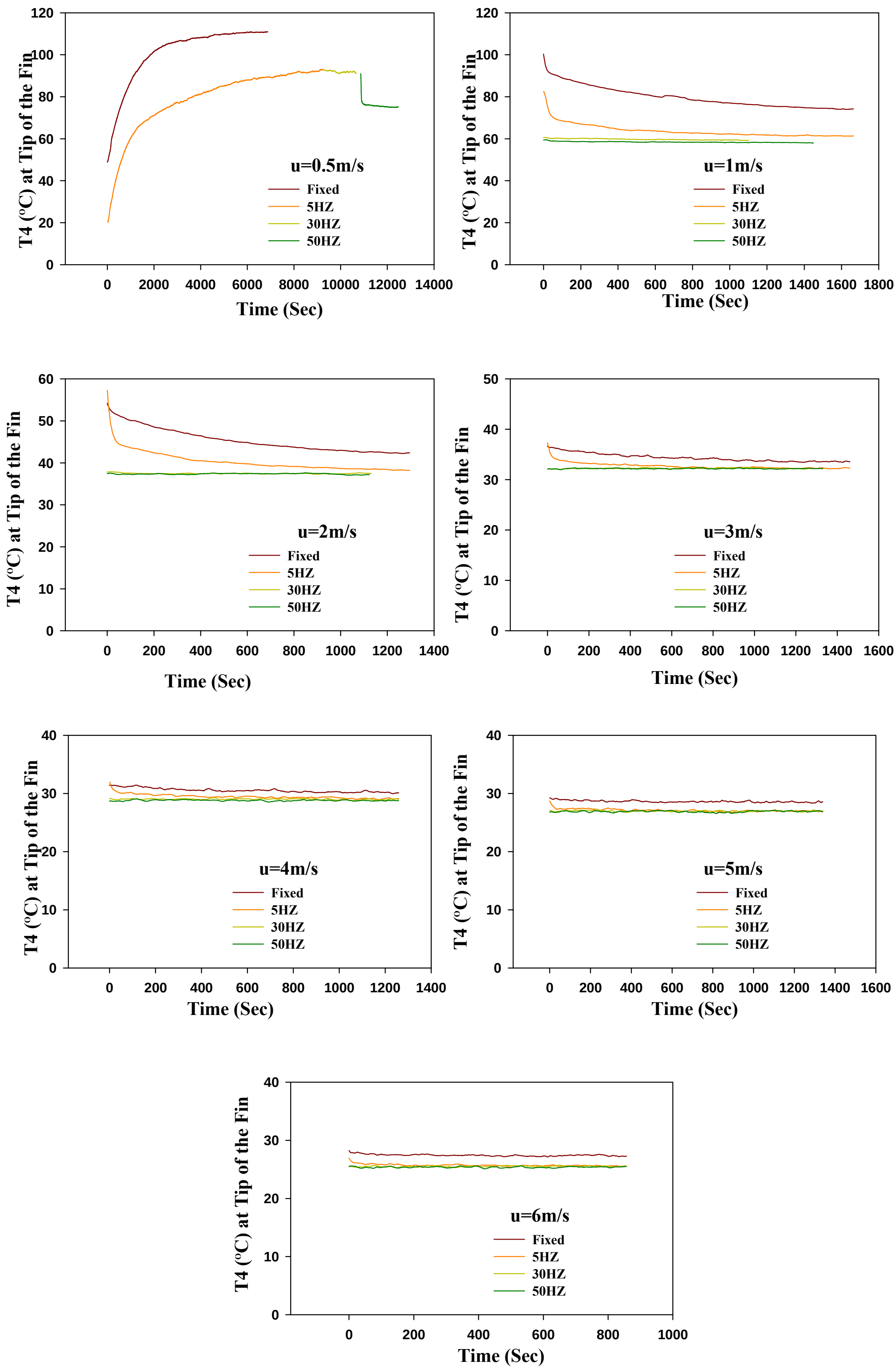


Fig. (6): Variations of the Temperature at the Tip of the Middle Fin with Time for Various Frequency and Inlet Velocity. Triple Fins Of (H=50mm and dis. =3mm), I.P=50Watt.

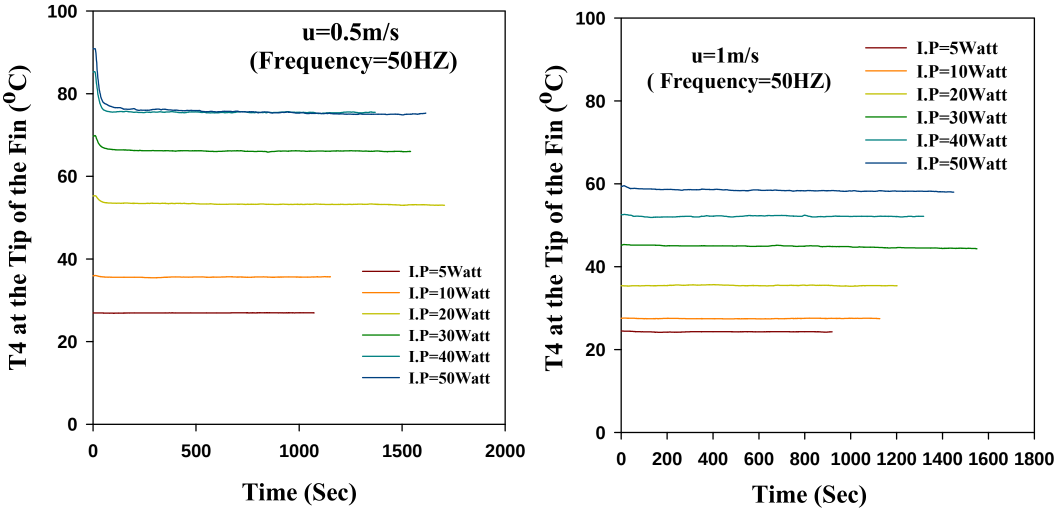


Fig.(7): Variation of the Temperature at the Tip of the Middle Fin with Time for Various Input Power and Inlet Velocity, Triple Fins of (H=50mm and dis.=3mm)

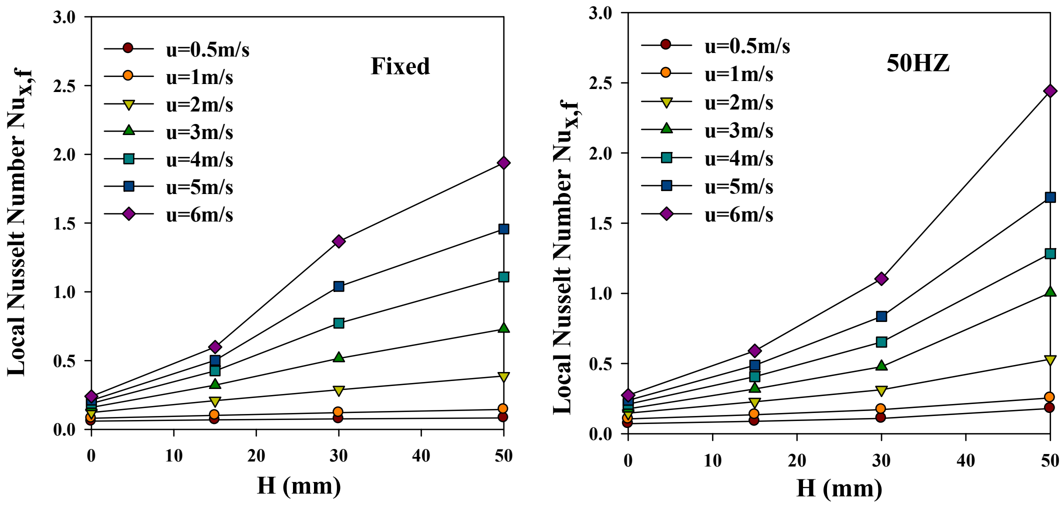


Fig. (8): Variation of the Local Nusselt Number along the Height of the Middle Fin For Different Inlet Velocity. Triple Fins of (H=50mm and dis. =3mm), I.P=50Watt.

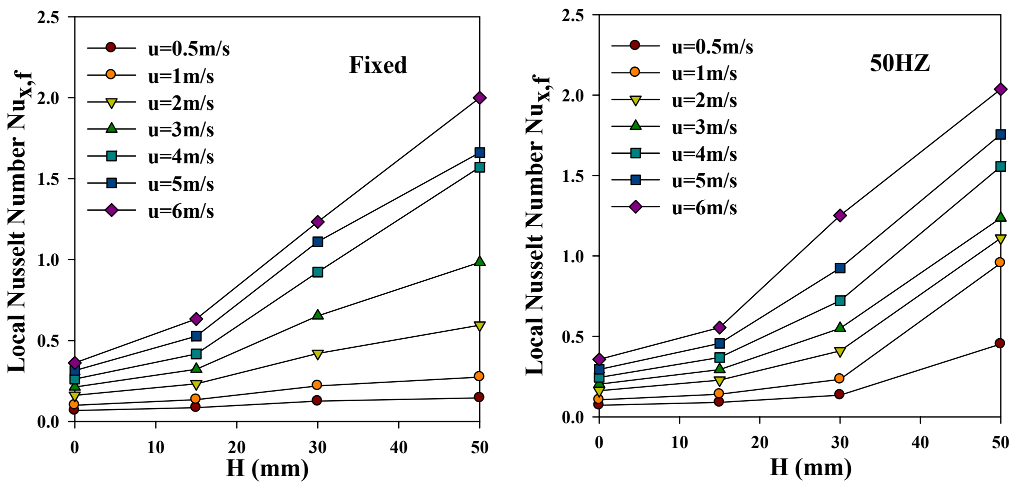


Fig. (9): Variation of the Local Nusselt Number along the Height of the Fin for Different Inlet Velocity. Single Fin (H=50mm), I.P=50Watt.

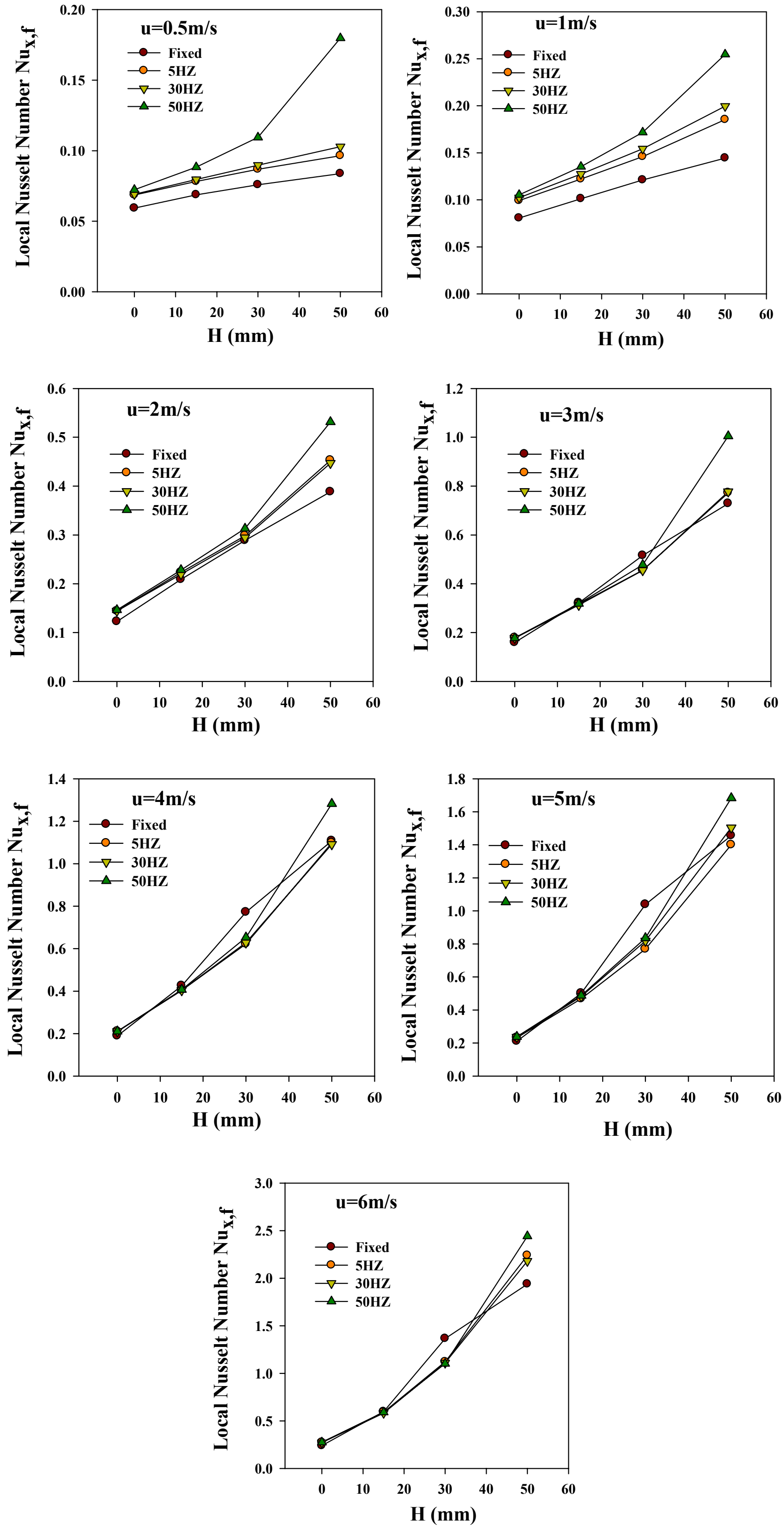


Fig. (10): Variation of the Local Nusselt Number along the Middle Fin with Height for Different Frequency. Triple Fin (H=50mm and dis. =3mm), I.P=50Watt.

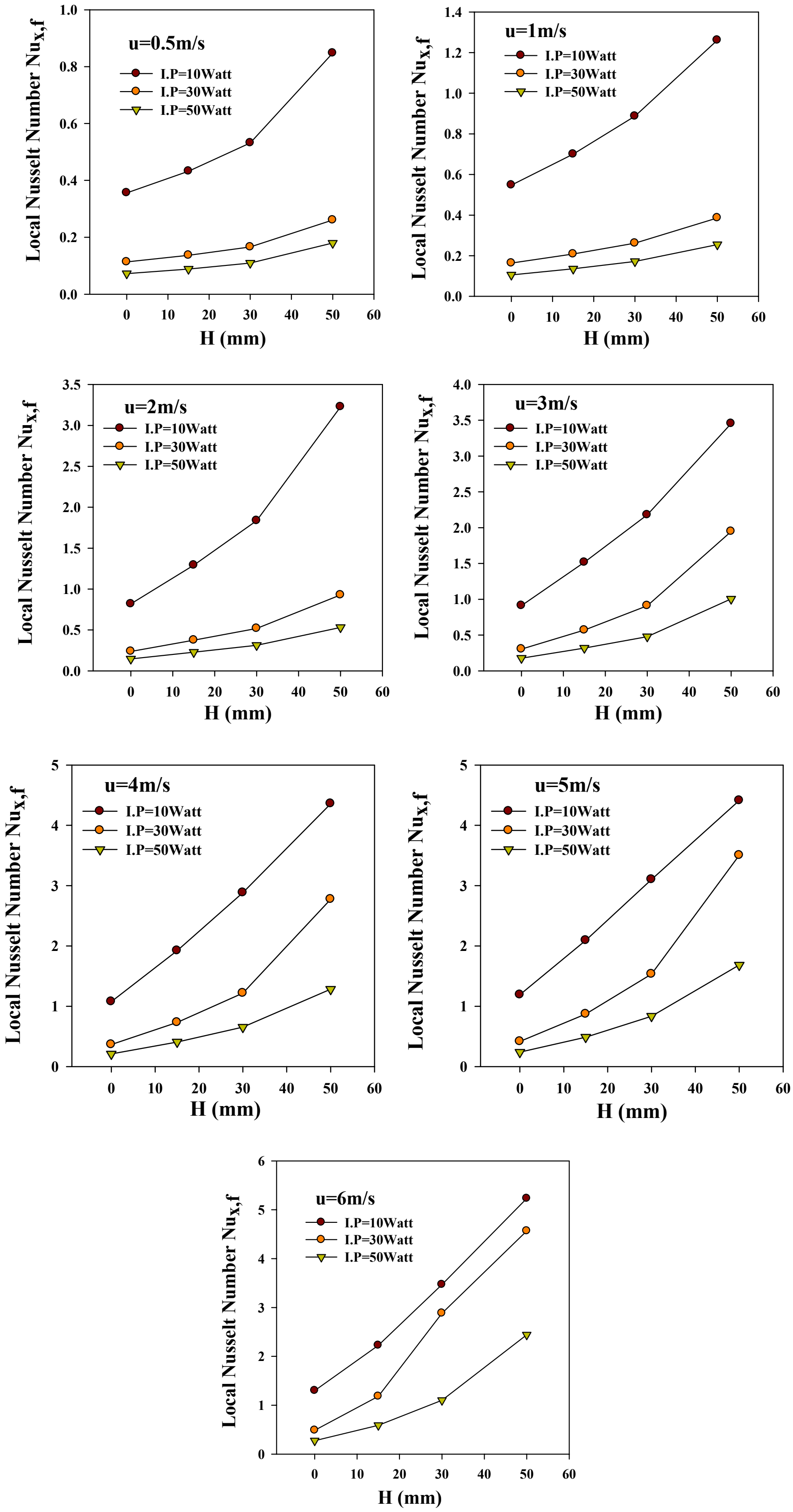


Fig. (11): Variation of the Local Nusselt Number along the Middle Fin with Height for Different Input Power. Triple Fin (H=50mm and dis.=3mm), Frequency=50HZ.

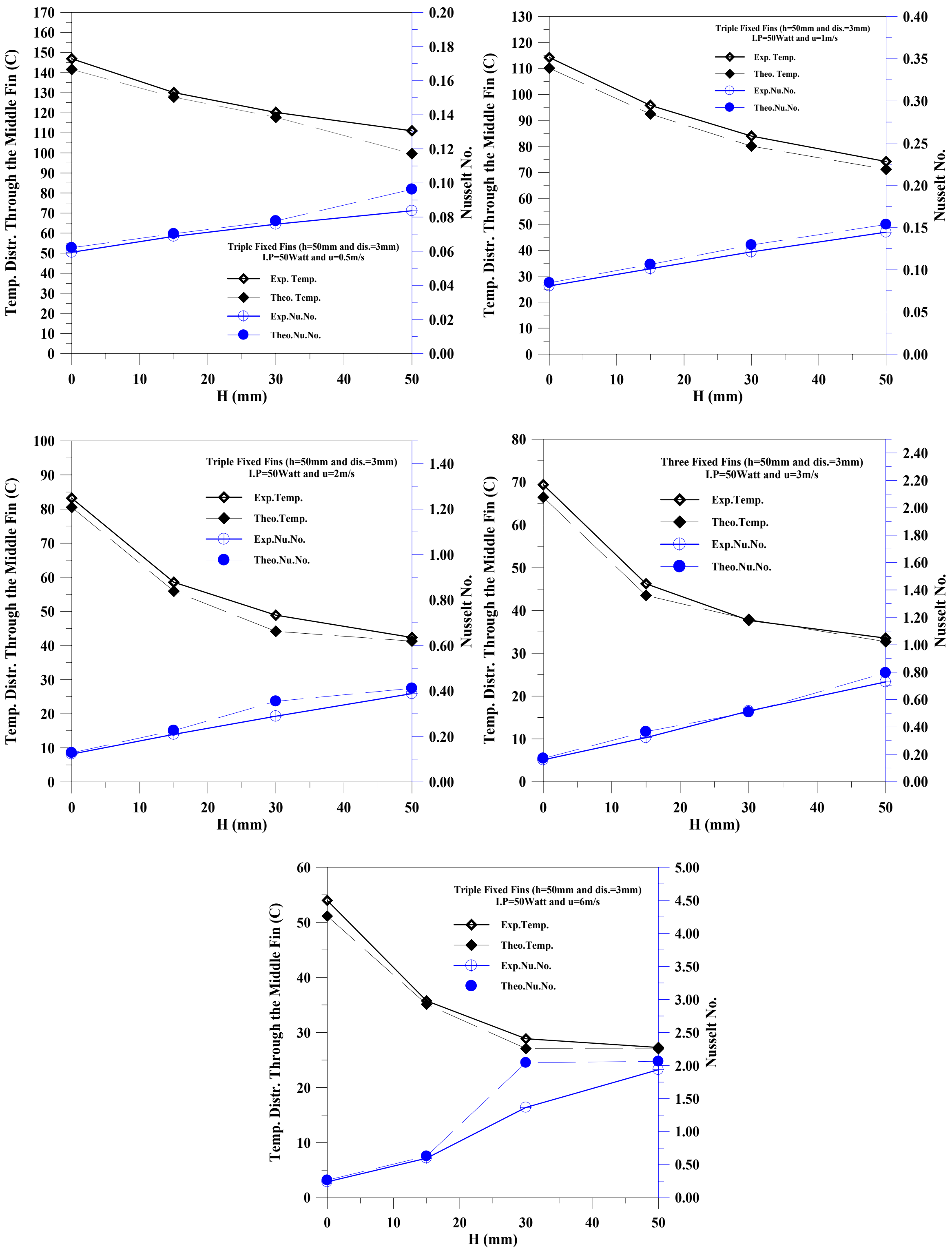


Fig. (12): Comparison between Experimental and Theoretical Temperature Distribution and Local Nusselt No. through the Height of the Middle Fin. (Triple Fixed Fins)

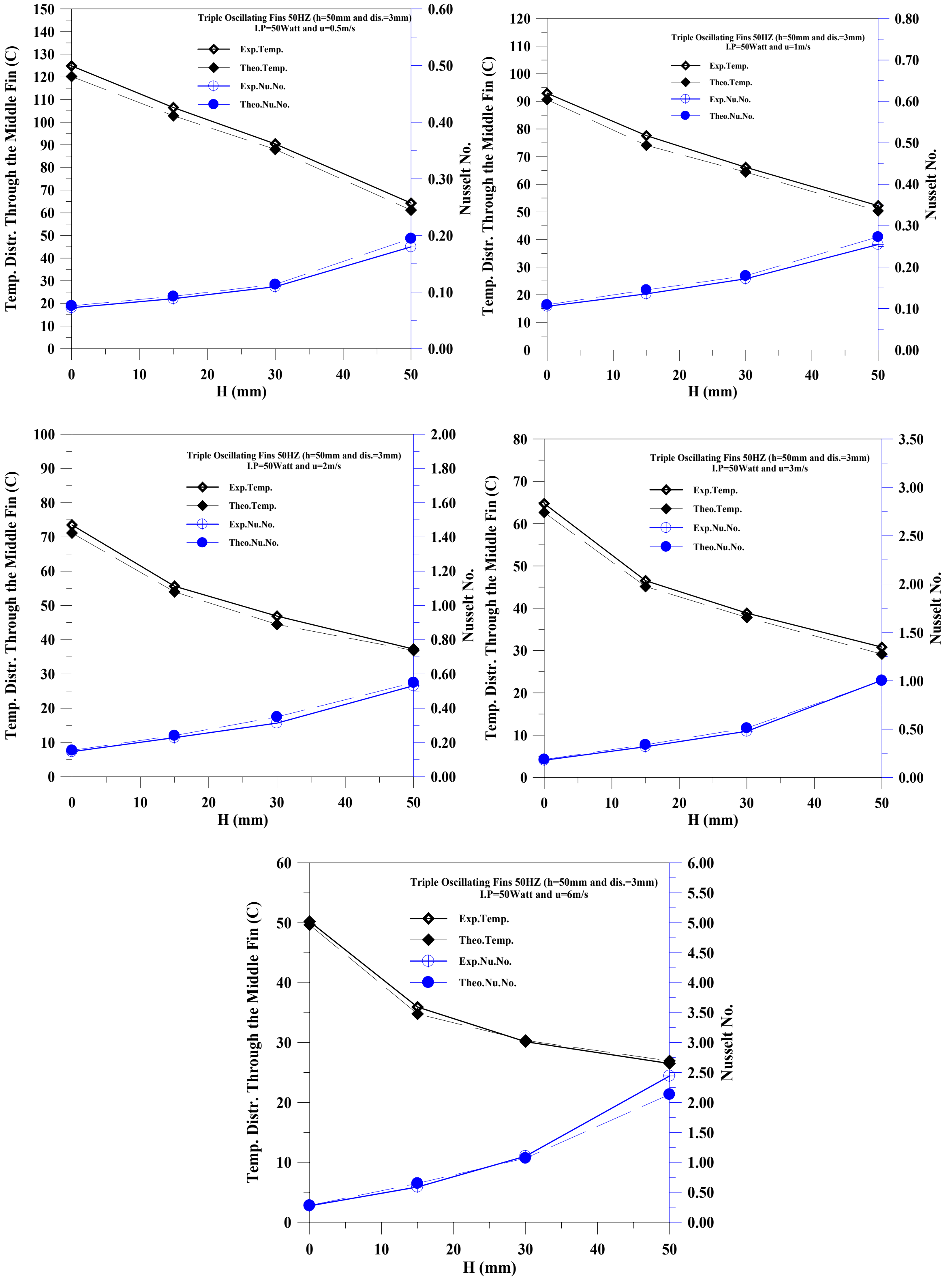


Fig. (13): Comparison between Experimental and Theoretical Temperature Distribution and Local Nusselt No. through the Height of the Middle Fin. (Triple Oscillating Fins)

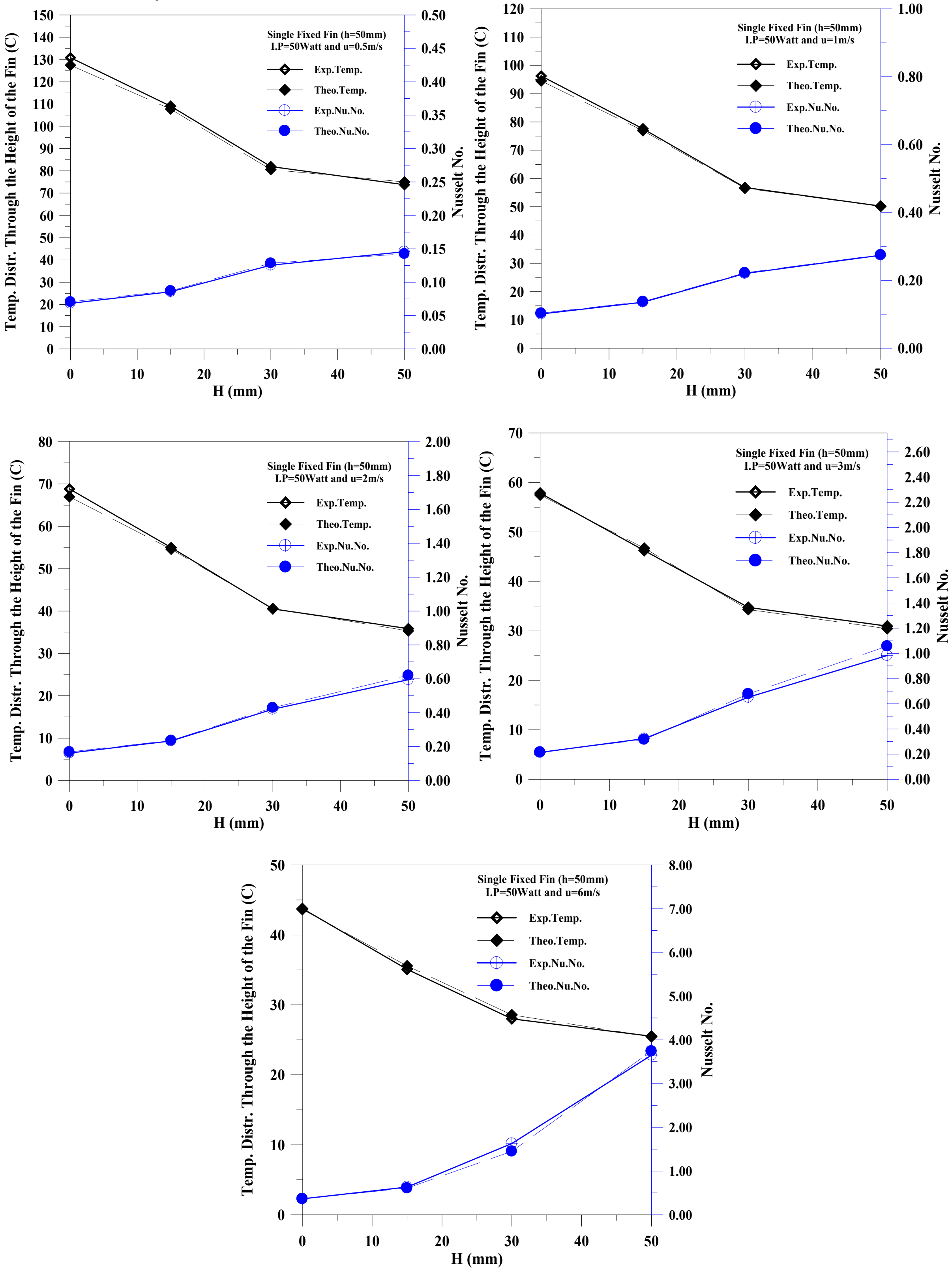


Fig. (14): Comparison between Experimental and Theoretical Temperature Distribution and Local Nusselt No. through the Height of the Middle Fin. (Single Fixed Fin)

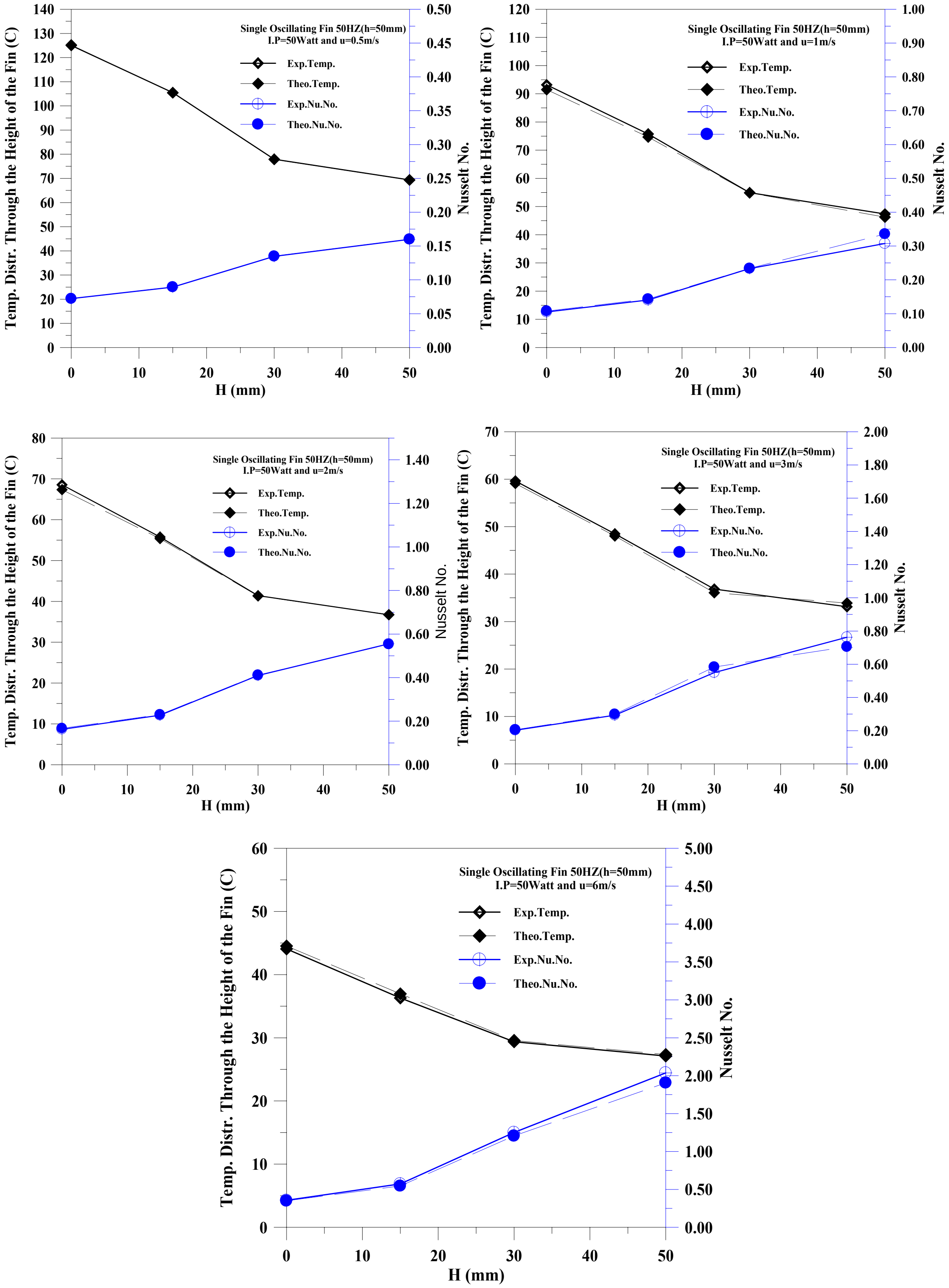


Fig. (15): Comparison between Experimental and Theoretical Temperature Distribution and Local Nusselt No. through the Height of the Middle Fin. (Single Oscillating Fin)

CONCLUDING REMARKS

It was concluded that:

1- Triple fins (h=50mm and dis.=3mm) is the best case for enhancing heat transfer and the triple fins (h=35mm and dis.=3mm) gives minimum heat transfer with respect to the other height.

2- The maximum enhancement of heat transfer occurs at the tip of the fins.

3- With low velocity and high input power, The temperature at the tip of the middle fin is decrease by (45 %) by using oscillating frequency of 50HZ for the case (h=50mm and dis.=3mm) w.r.t. case with fixed fins. While 10% for the case (h=50mm and dis.=6mm) and 7% for single fin.

4- The optimal height for the fins is 35mm. so the better cooling with triple fixed fins for the case (h=35mm and dis.=3mm or dis.=6mm). While this height is not effective with oscillating.

5- The enhancement of heat transfer with oscillating well with low velocity from 0.5m/s to 2m/s and high input power.

6- The high velocity effect reduce the effect of oscillation because the air work as damping to the oscillating.

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NOMENCLATURE

CPU	Central Processing Unit
dis.	Distance Between the Fin (mm)
D_h	Hydraulic Diameter (mm)
h	Local Heat Transfer Coefficient ($W/m^2.^oC$)
H	Height of the Duct (mm)
I.P.	Input Power (Watt)
K	Thermal Conductivity ($W/m.^oC$)
Lc	Characteristic Length of the Fin
L	Length of the Duct (mm)
N	Number of Fins
$Nu_{x,f}$	Local Nusselt Number = h Lc/Ka
PID	Proportional Integral and Derivative
Re	Reynolds Number $= \rho V D_h / \mu$
t	Thickness of the Fin (mm)
T	Temperature (^oC)
T1	Temperature at the Root of the Fin (^oC)
T4	Temperature at the Tip of the Fin (^oC)
u	Inlet Velocity (m/s)
u	x-Direction Velocity (m/s)
UDF	User Defined Function
v	y-Direction Velocity (m/s)
w	Z-Direction Velocity (m/s)
W	Width of the Duct (mm)
X, Y, Z	Rectangular Coordinates