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الموسوم:

(Experimental Study of the Effect of Vertical Oscillation on Forced Convection Heat Transfer Coefficient of Vertical Channel)

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Experimental Study of the Effect of Vertical Oscillation on Forced Convection Heat Transfer Coefficient of Vertical Channel

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Abstract

The effect of vertical harmonic oscillation on forced convection heat transfer from vertical channel has been experimentally studied. The base of channel was imposed to heat flux generated by electric input power in the range (8-65 W). The range of airflow velocity was between (0.6-2.3 m/s). Experiments have been carried out for frequencies ranging from (6-12 Hz) at constant amplitude of (5 mm). The results show that the vibration has high influence at low airflow velocities and high power levels, while the effect of vibration disappears as airflow velocity becomes high. Also, the results show that when power increases, vibration effect will be active for wider range of air flow velocity.

Keywords: vertical oscillating, forced convection, vertical channel

Introduction

The effect of oscillation upon both natural and forced convective heat transfer has investigated for flat plates, cylinders and fin arrays; for varied orientation of the vibration vector relative to these surfaces; for different ranges of vibration parameters (the amplitude and frequency) and for different heated conditions. The results of these investigations vary from significant effect to small effect on heat transfer rate. On the other hand, more than one method is used for achieving these results experimentally, numerically and analytically.

A problem of natural and forced convection on heated surfaces of channel is important and widely considered in the design of devices such as dissipated fins in heat exchangers and fin arrays of heat sinks of electronic components in a computer and other applications. In a practical situation the devices in the system are always under dynamic situation due to the operating of the system, which results in the device being unavoidably subject to vibration motion. It is almost impossible to completely avoid the vibration of the heat transfer devices. Therefore a comprehensive knowledge in the vicinity of heat transfer induced by vibrating mechanisms seems to be crucial due to high speed development of technologies.

The effect of vibration on natural convection heat transfer from vertical rectangular fin arrays was investigated by Nag and Bhattacharya [1]. The test section was a vertical fin array consisting of three identical fins protruding from a base plate. Fins and base were made from aluminum plates. Nine sets of fin arrays were made with different heights, fin lengths, fin spacing, fin thicknesses and the width of the fin array. It was seen that up to a certain threshold value of product of amplitude and frequency (15 mm/s), the imparting of vibration did not have any significant effect on heat transfer from the fin array. Beyond this value, however, the heat transfer rate increased considerably with increase in the intensity of vibration, the maximum increase obtained being 250%.

Mahfouz and Badr [2] investigated numerically the effect of rotational oscillation of cylinder about its own axis on heat transfer convection from heated cylinder placed in a uniform stream. The results show that the heat transfer coefficient increase in the lock on frequency range while the effect of oscillation on heat convection in the unlock regime is insignificant.

Wu-Shung Fu and Bao Hong-Tong [3] studied through numerical simulation flow structures and heat transfer characteristics of heated transversely oscillating cylinder in a cross flow. The effect of Reynolds number, oscillating amplitude, oscillating speed on the flow structures and heat transfer characteristics were examined. The results showed remarkably enhancement in heat transfer when oscillating frequency approaches the natural shedding frequency and there is apparently increasing in heat transfer when the oscillating velocity of the cylinder and the Reynolds number are increased.

Zhang *et al.* [4] carried out a numerical study about laminar natural convection on a periodically oscillating vertical flat plate heated at a uniform temperature. The results showed that the heat transfer performance of an oscillation plate depends significantly on the ratio between the oscillation velocity and the flow velocity at the boundary layer of a stationary plate, the larger this ratio, the higher heat transfer. But the heat transfer decreases as Grashof number increase.

Tait Sherman and Mory Gharib [5] investigated experimentally the effects of transverse oscillation on the heat transfer from a circular cylinder in cross flow. The cylinder's heat transfer coefficient was measured for a wide range of oscillation frequencies and amplitudes. The cylinder had heater as a coil of nickel chromium wire and embedded thermocouple at the center of heated length. The cylinder was placed in water tunnel against flow velocity of (64 mm/s). Heating power provided to the cylinder was (63.8 W). One of results of this investigation was that the heat transfer enhancement was found to be depending on synchronization with harmonics of the natural shedding frequency.

A numerically and experimentally study was carried out by Cheng *et al.* [6] on the effect of flow induced vibration on heat transfer in heat exchangers. Experimental model consisted of four circular copper tubes with different radius of curvature designed in a way that can freely vibrate. The hot fluid supposed to flow inside these tubes was replaced by wire heater. Three sets of that model placed in circular vertical tank one is fixed against vibration and others in the bottom and top of tank respectively. Water has specific temperature which allows flowing upward in tank. Heat power source can be controlled by adjusting the voltage input to the heater. It is found that the vibration induced by the pulsation flow at the low flow velocity can significantly increase the convective heat transfer coefficient by two times comparing with non-vibrated tubes.

A numerical study was carried out by Subhrajit Dey and Debapriya Chakrborty [7] to enhance heat transfer from 3D fin using oscillation to disturb thermal boundary layer. The test model consists of a heat source placed below substrate of dimension (1 x 1 in) with a single vertical fin of dimensions (0.5 x 1 x 0.01 in). A (20 W) power input was uniformly distributed below substrate and held constant. The test placed in air flow stream of Reynolds number range between (100 – 1000). Another parameters were taken in consideration which are the ratio of fin height to the tip vibration amplitude and the range of frequency of vibration. It has been found that such oscillations lead to tip-leakage vortices from the fins. A local up wash accompanies this on the fin lateral surface, hence increasing the overall heat transfer.

Fadi Ryadh Shamoon [8] performed an experimental study for the effect of forced vertical vibrations on forced convection heat transfer coefficient by using circumferential finned cylinder. The test model is finned cylinder made of aluminum. The cylinder heated using constant heat flux supplied to the core of cylinder. The test section placed in wind tunnel and subjected to a range of Reynolds numbers. Other parameters have been involved in this study which were vibration amplitude, heat flux and vibration frequency. It was found that the relation between the heat transfer coefficient and amplitude of vibration is incremental for all inclination angles, and an increment of inclination angle reduces the values of forced convection heat transfer coefficient.

Saad Mohammed Jalil [9] studied experimentally the influence of vertical oscillation on the natural heat transfer from a vertical channel. The test model was made from aluminum. Results of this work show that for same Rayleigh number, the convective heat at vibrating case is more than the convective heat at stationary case. Also, the increase in Nusselt number changes with vibrational Reynolds number depending on Rayleigh number.

Dheya *et al.* [10] described in his work numerical and experimental investigation of forced convection heat transfer characteristics of a plate fin which has built-in piezoelectric actuator. Two types of test models were investigated one has single fin and other has triple fins fixed in square base plate made from copper plate, also the tested fins are made from copper plate and two height models of (35 and 50 mm). The test model placed in wind tunnel was subjected to different inlet velocities, different frequency levels and input power of many values to the base plate. For the case of triple fins, the distance between fins has been taken into consideration. The results show that heat transfer increases with the increase of frequency and Reynolds number.

Based on the above literature survey, the effect of vibration on forced convection heat transfer was carried out just for few cases. The objective of this work is to investigate the effect of vibration on forced convection from vertically oscillating channel against upward airflow stream of various velocity values. The channel has been loaded by constant heat flux of specified range. The channel's oscillatory movement has also, a range of frequencies.

Experimental setup

The experimental setup was designed to deliver vertical oscillation to a channel that its base is heated by electrical wire resistance and placed in uniform upward airflow stream.
The test model made of an aluminum block which was milled to have dimensions of (65 x 20 x 100 mm). A channel of (10 mm) wide was made using milling machine at the center of the block along its length of (100 mm) at depth of (57 mm) to have the final shape which consists of base and two walls as illustrated in **Figure (1)**. Aluminum was selected as channel material because of its high thermal conductivity, low emissivity, structural strength and durability.

Heating element was made by using sheet of mica wound by nickel chrome wire and placed between two other mica sheets (upper and lower sheets), then folded with copper sheets as shown in **Figure (2)**. Finally the dimensions of heating element became (100 x 20 x 4 mm). The heating element was supplied by AC voltage through a stabilizer which maintains a constant voltage during the data reading. The output from the stabilizer was fed to a variable transformer (Variac) so that the necessary heating level could be selected. A digital voltmeter was used to measure electrical voltage delivered to heater. A digital ammeter was used to measure electrical current passing through the heater. The power input was measured by multiplying current value times voltage applied.

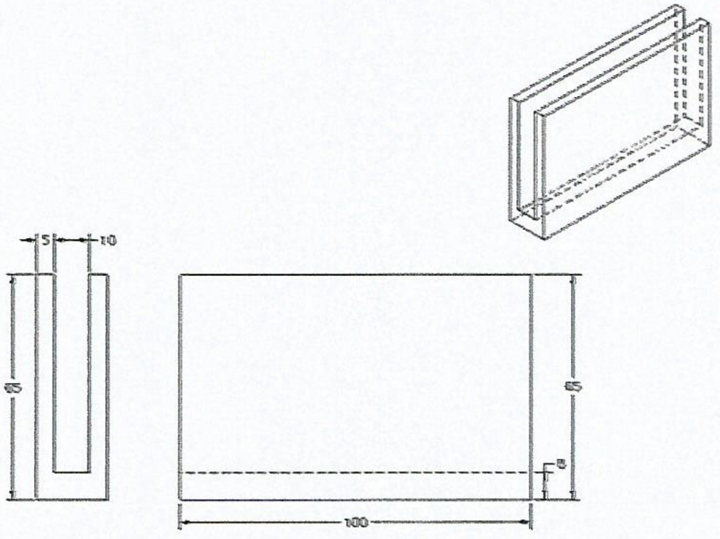
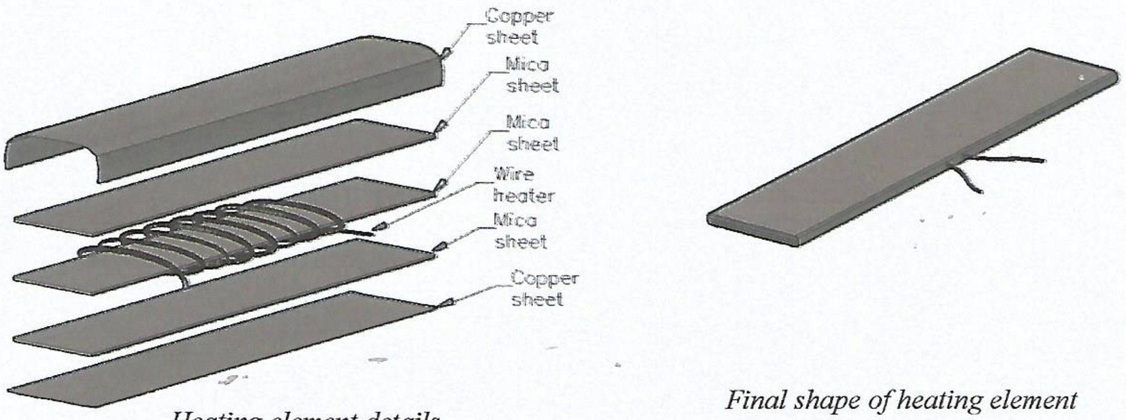


Figure .1 Test model



Heating element details

Final shape of heating element

Figure .2 Heating element

The holder of the test model consists of suspension bar (made of steel) and two symmetric wooden blocks each has half groove engaged with each other by means of two bolts and nuts forming a groove of (20 mm) wide, (12 mm) deep and (100 mm) long. Two types of insulations were placed in wood groove. The first one is sheet of asbestos which was placed on base of groove; second one, over the asbestos, a layer of fiberglass. Test model and heater were placed in groove over insulations then tight bolts and nuts to hold the test model. **Figure (3)** illustrates the holder.

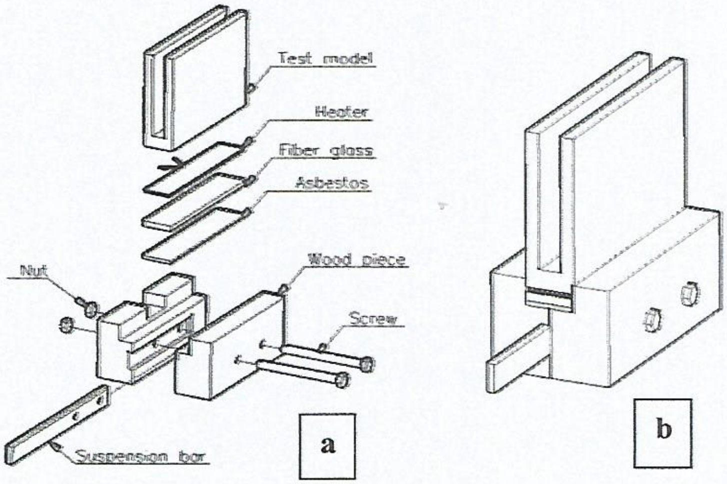


Figure .3 Test model holder and insulations

The temperature of base channel was measured by five pre-calibrated k-type thermocouples embedded at (0.5-0.75 mm) beneath the base surface at equal distance locations, same number of thermocouples distributed along fin height to collect the temperature values along wall. All thermocouples were connected to a selector switch and the output of selector switch was supplied to a k-type digital thermometer. The electric wiring of whole system was illustrated in **Figure (4).**

Test model was suspended vertically inside wooden air passage by oscillating arm which receives its oscillatory motion from exciter. The pins of slide bar engaged to two slots which had been fixed at side walls of air passage working as guides to keep the movement of test model assembly vertically. See **Figure (5a).**

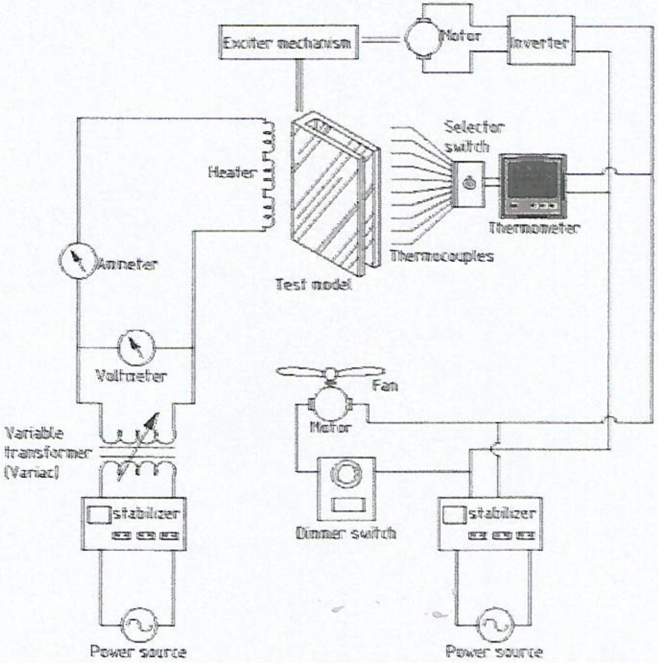


Figure .4 Wiring diagram of system

Next, the air passage with all tools and mechanisms were installed at a frame which was made using right angle structural steel as in **Figure (5b)**. The frame has been provided with horizontally fixed fan to deliver vertical upward air stream, air passes in pipe (**Figure 5b**) through straightener which was made manually using many small pipes of (12mm dia. x 50mm length) glued to each other and placed horizontally inside pipe to have uniform air stream. See **Figure (5a).**

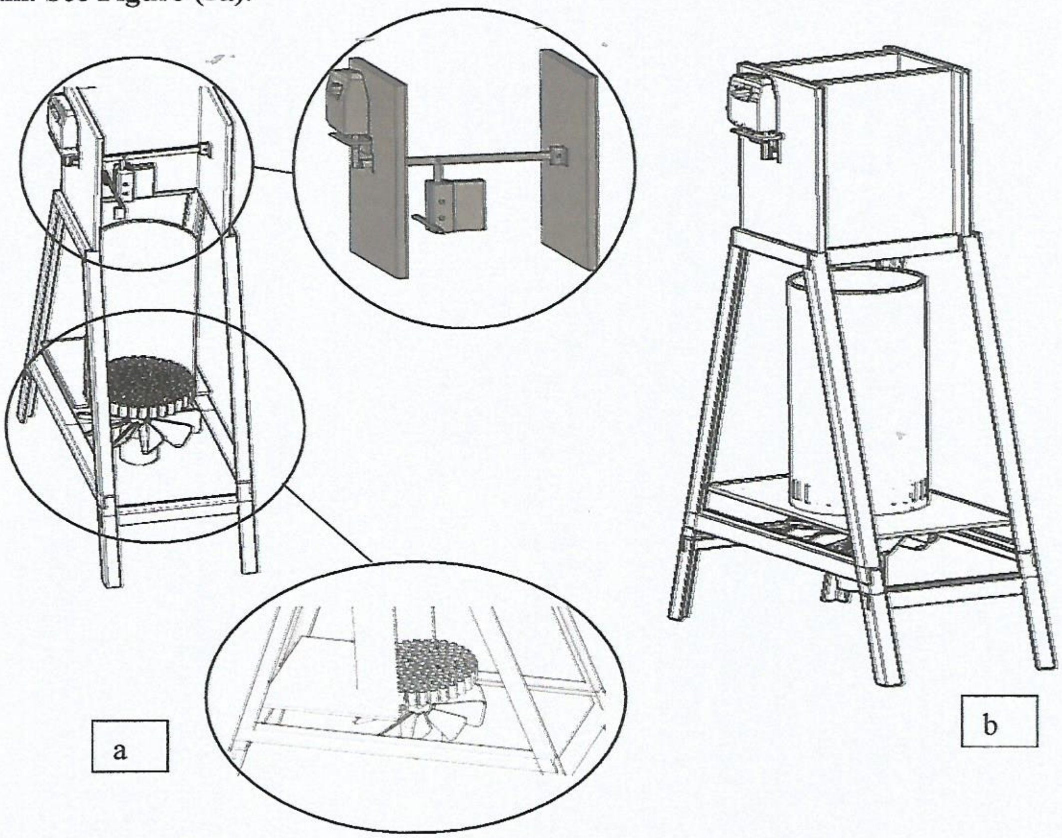


Figure .5 (a) Sectional views showing air passage, pipe and straightener.
(b) Final assembly of system

Processing experimental data

The heat generated by electric current using nickel-chrome wire is transferred to the test model by conduction and then dissipated to the surroundings by convection and radiation in addition of few losses through insulations. Using energy balance [11], this leads to:

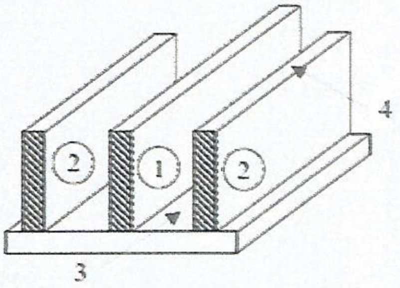


Figure .6 Cavity

$$Q_{gen} = Q_{con} + Q_{rad} + Q_{los} \qquad (1)$$

Heat generated in heating element is calculated as follows:

$$Q_{gen} = R * I^2 \qquad (2)$$

Heat dissipated by radiation from test model is estimated after determining the equivalent cavity emissivity [12] (refer to **Figure 6**):

$$\varepsilon_{cavity} = \frac{\dfrac{\varepsilon_s A_3 (A_1 + A_2 + A_3)}{A_3 + \varepsilon_s (A_1 + A_2)} + \varepsilon_s A_4}{A_3 + A_4} \qquad (3)$$

Hence, radiation heat transfer is:

$$Q_{rad} = \sigma A_3 \varepsilon_{cavity}\left(T_{bv}^4 - T_\infty^4\right) + 2\sigma A_4 \varepsilon_s \left(T_{tip}^4 - T_\infty^4\right) + 2\sigma A_2 \varepsilon_s \left(T_{finv}^4 - T_\infty^4\right) \qquad (4)$$

Since the arrangement of insulations is layer by layer, then the heat flow through any layer is the same. The heat lost through insulation has been calculated by using two thermocouples located on each surface of wooden layer (holder). Hence, heat lost through insulations [9] is:

$$Q_{los} = k_{ins} * A_{ins} * \frac{\Delta T_{ins}}{L} \qquad (5)$$

It is found that all lost energy by radiation and conduction do not exceed 3% from the electric power supplied to system.

The convective heat is:

$$Q_{con} = Q_{gen} - Q_{rad} - Q_{los} \qquad (6)$$

Determination of heat transfer coefficient

Based on above classifications, the heat transfer coefficient by convection is illustrated as follows [11]:

$$h = \frac{Q_{con}}{A_T * \left(T_b - T_\infty\right)} \qquad (7)$$

Where T_b represents the average of temperatures which were recorded by thermocouples which were placed at the base of channel.

Area which dissipates heat to environment could be estimated as:

$$A_T = LM\left[\left(WM - NM.t_{fin}\right) + \eta_{fin} NM\left(2H_{fin} + t_{fin}\right)\right] \qquad (8)$$

The fin efficiency η_{fin} can be expressed as:

$$\eta_{fin} = \frac{\tanh(mH_{finE})}{mH_{finE}} \qquad (9)$$

where

$$m = \sqrt{\frac{hp}{k_{fin} A_c}} \qquad (10)$$

and $$H_{finE} = H_{fin} + \frac{t_{fin}}{2} \qquad (11)$$

Rearranging the equations and solving for *h*. Simple iteration method has been used to evaluate *h*.

To accomplish calculation of other parameters, it is necessary to find the thermophysical properties of fluid involved in this work which is air. The properties were evaluated at film temperature (T_{film}) which is equal to (T_b+T_∞)/2.

Dimensionless parameters

The effect of vibrations on heat transfer could be expressed as a function of dimensionless parameters which are listed below taking the width of channel as characteristic length:

Nusselt number

$$Nu = \frac{h.S}{k_l} \qquad (12)$$

Reynolds number

$$\mathrm{Re} = \frac{U.S}{\nu} \qquad (13)$$

Vibrational Reynolds number [13]

$$\mathrm{Re}_\upsilon = \frac{2.\pi.a_o.f.S}{\nu} \qquad (14)$$

Results and discussion

An experimental study has been carried out using air as a working fluid to show the effect of forced vertical vibration on the heat transfer coefficient of vertical channel.

The range of power input was between (8-65 W) with vibration range between (6-12 Hz) and maximum amplitude of (5 mm). The flow velocity has a range between (0.6 – 2.3 m/s). The product of maximum amplitude times frequency (a_o*f) was used to express the vibration intensity.

The effect of vibration on Nu

Figures (9 – 14) exhibit the effect of vibration intensity on Nu for all power levels for air flow velocities between (0.6 – 2.3 m/s).

It could be recognized that at low power levels and low air flow velocity, the effect of low level vibration intensities on Nu is less than effect of high level vibration intensities, but at low power levels and high air flow velocity it could be seen that there is no effect of vibration on Nu. At high power levels and low air flow velocities, it could be noted that increasing the vibration intensity causes increasing in Nu, but at high power levels and high air flow velocities, approximately, there is no effect of vibration on Nu except at high vibration intensity levels.

The ratio of maximum vibration velocity to maximum fluid flow velocity plays an important role in heat transfer performance and Nu value.

The smallest value of this ratio at which the effect of vibration begins to appear and takes place is (0.1) [4].

The air flow velocity which is considered as the maximum flow velocity at outer surface of test model and the maximum velocity between channel walls (considered as parallel plate channel) is one and a half of air flow velocity [14].

As an example to illustrate this point, the Nu was represented against vibration intensity in **Figure (15a)** and its corresponding variation in velocity ratio is plotted in **Figures (15b and 15c)** for power input of (52 W).

The figure reveals that the Nu keep going rise as long as the velocity ratio is greater than (0.1) and close to non vibration value when the velocity ratio is less than (0.1)

Another ratio could have an important influence on convective heat transfer which is the ratio of amplitude to the maximum thickness of boundary layer where Nu increases as this ratio increase and Nu decrease as this ratio decrease, hence Nu enhance when the boundary layer thickness approaches to maximum vibration amplitude. On contrary, Nu decreases when the boundary layer thickness is greater than maximum amplitude of vibration [4].

At forced convection part, the value of boundary layer thickness at low velocity is greater than its value at high velocities on outer surfaces of test model. At inner region (channel between walls), the flow is fully developed at low velocities and each wall has its own boundary layer at high velocities.

In case of high flow velocities range, although thin boundary layer exists at outer and inner surfaces where Nu is expected to be high, but low value of velocity ratio (less than 0.1) leads to Nu which has no any better value over its stationary value.

In case of low flow velocities range, the outer surfaces of test model has thick boundary layer which leads to expect no increase in Nu, but velocity ratio has high value (greater than 0.1) causes increase Nu at outer surfaces. Also, low flow velocities causes fully developed flow between channel walls where the effect of vibration is generating flow circulation because vibration creates an oscillating relative velocity vector between a heated surface and fluid [13]. Additionally, vibration intensity helps Nu to shift to a higher value because of the modification of the flow field which is adding a value of circulation to flow [15].

Conclusions

An investigation was carried out for forced convection from vertical channel undergoing vertical vibration movement placed in upward uniform airflow. It was found that heat transfer coefficient was influenced by vibration intensity, flow velocity and power input.

The experiments led to conclude that Nu increases with increase of flow velocity either at stationary state or at vibrated state. At slow airflow, the vibration causes an increasing in Nu compared with stationary state. At high air flow velocities, the effect of vibration decays and eventually disappears. The effect of vibration on forced convection at high power levels is more than its effect at low power levels. The effect of vibration could be noticed at wider range of air flow velocity when power input increased.

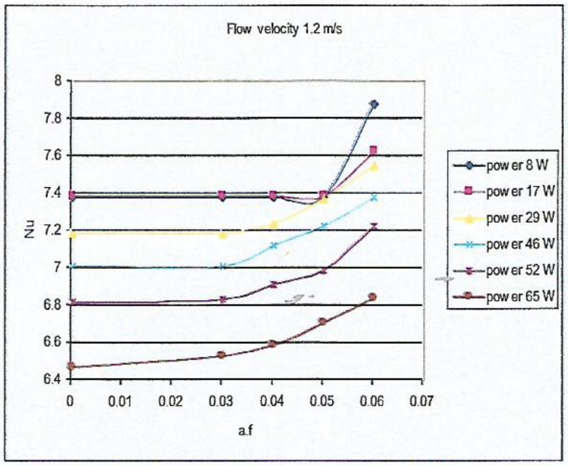


Figure .11 Effect of vibration on Nu against flow of 1.2 m/s at different power levels

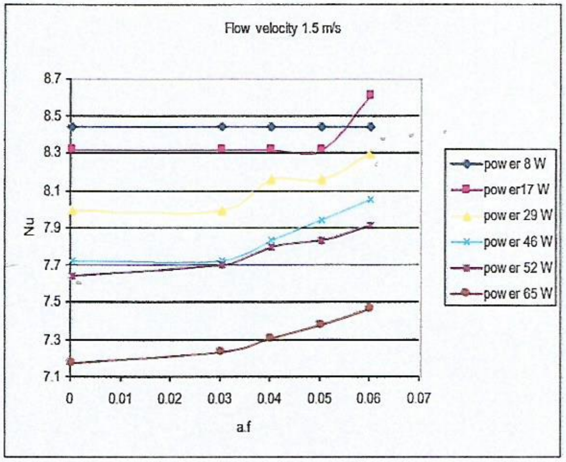


Figure .12 Effect of vibration on Nu against flow of 1.5 m/s at different power levels

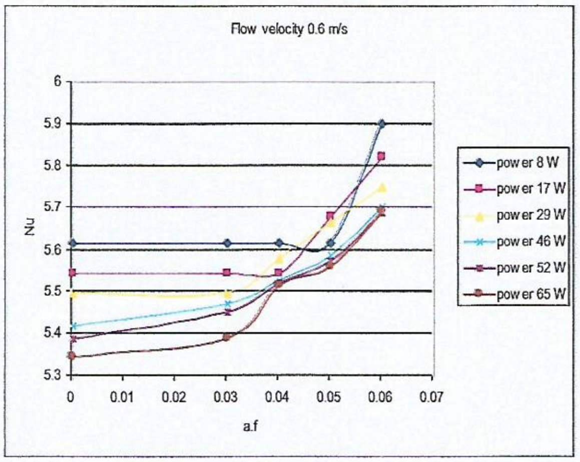


Figure .9 Effect of vibration on Nu against flow of 0.6 m/s at different power levels

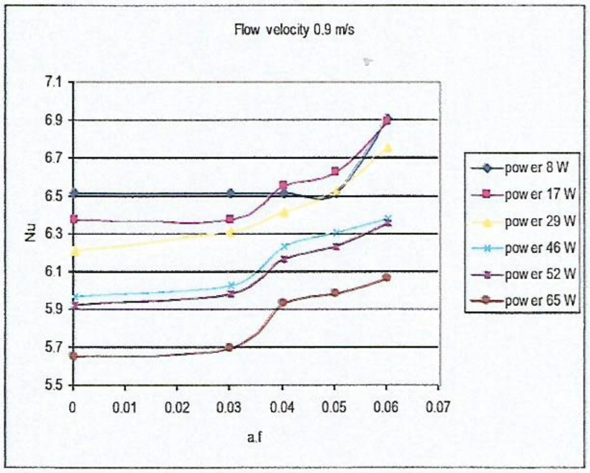


Figure .10 Effect of vibration on Nu against flow of 0.9 m/s at different power levels

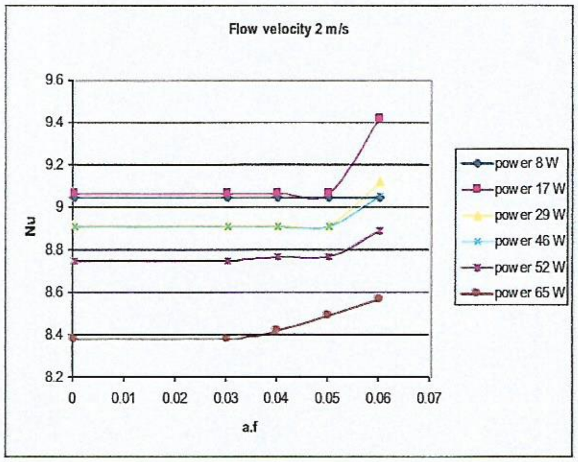


Figure .13 Effect of vibration on Nu against flow of 2 m/s at different power levels

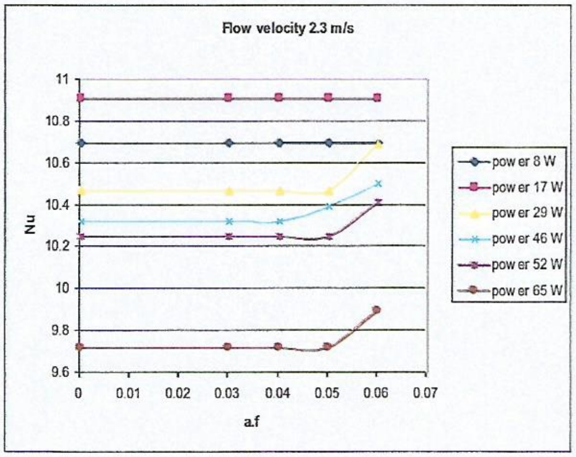
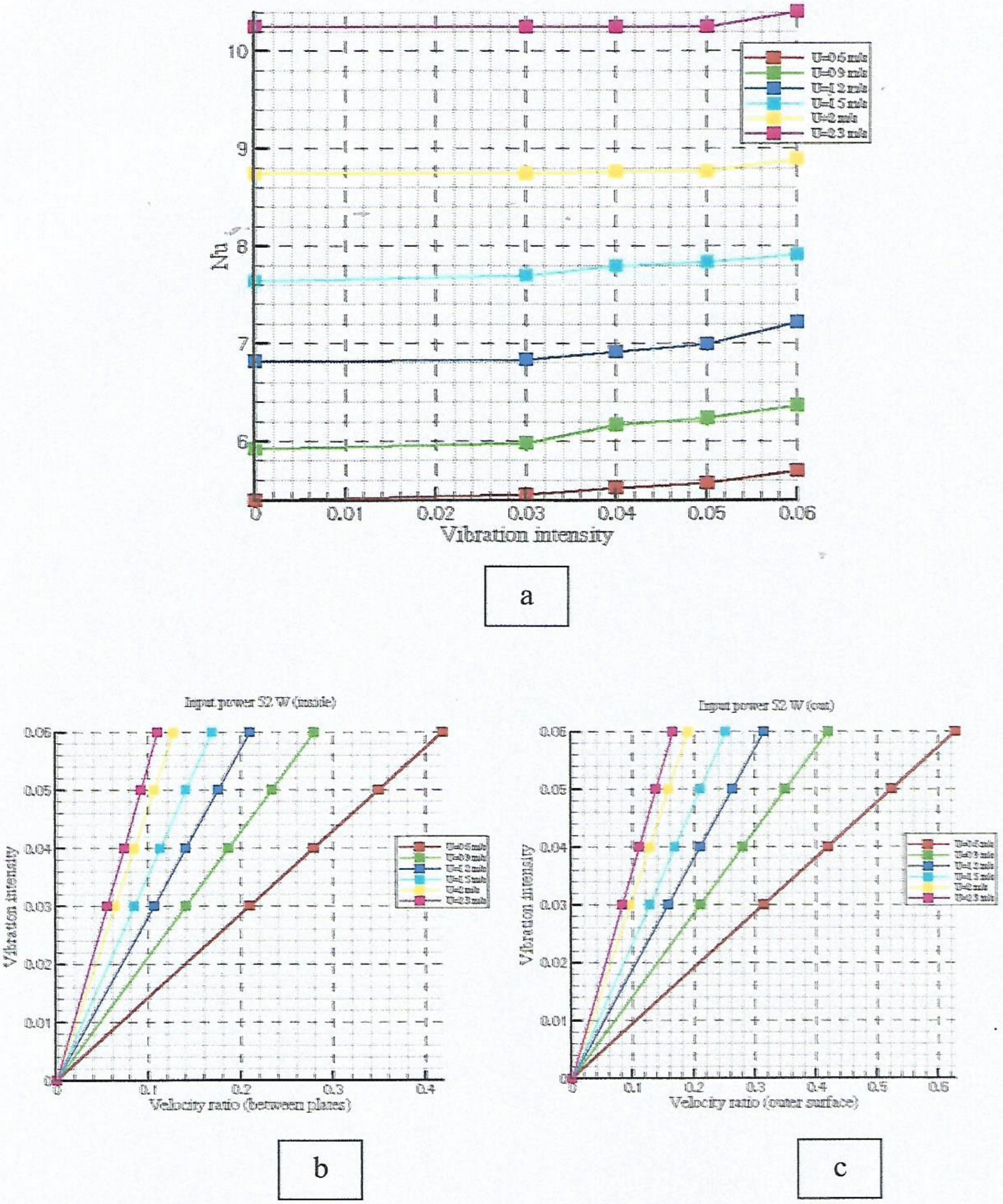


Figure .14 Effect of vibration on Nu against flow of 2.3 m/s at different power levels



a

b

c

Figure .15 (a) effect of vibration intensity on Nu for forced convection (b) relation between velocity ratio and vibration intensity inside channel (c) relation between velocity ratio and vibration intensity on outer surface

Nomenclature	
A : Area	m^2
A_T : total surface area of test model	m^2
A_c : fin cross section area	m^2
a_o : vibration amplitude	m
f : frequency	s^{-1}
H_{fin} : fin hight	m
H_{finE} :equivalent fin hight	m
h : heat transfer coefficient	$W/m^2\ K^o$
I : electric current	Amp.
k : thermal conductivity	W/mK^o
L : thickness of wood insulation	m
LM : model length	m
m : parameter	
Nu : Nusselt number	
NM : number of fins	
P : electric power	W
p : fin perimeter	m
Q : Heat energy	W
R : electric resistance	ohm
Re : Reynold number	
Re_v : vibration Reynolds number	
S : channel width	m
T : temperature	K^o
T_{bv} : average base temperature	K^o
T_{finv} : average fin temperature	K^o
t_{fin} : fin thickness	m
WM : test model width	m

Greek symbols

β : volumetric expansion factor

ε : emmisivity

η : efficiency

ν : kinematic viscosity

σ : Steven poltzman constant

Subscripts

b : base plate

cavity : space of channel

con : convection

fin : fin

gen : generation

ins : insulation

l : fluid

los : losses

rad : radiation

s : surface

tip : fin tip

∞ : bulk

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دراسة عملية لبيان تأثير الاهتزازات العمودية على معامل انتقال الحرارة بالحمل القسري لمجرى عمودي

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جامعة الانبار

خلاصة:

تم اجراء دراسة عملية لبيان تأثير الاهتزازات القسرية العمودية على معامل التبادل الحراري بالحمل الحر و القسري لمجرى عمودي. تم تسليط فيض حراري على قاعدة المجرى بواسطة قدرة كهربائية حرارية تتراوح بين (8–65 واط) وضع المجرى بشكل عمودي بمواجهة تيار هوائي من الاسفل الى الاعلى بسرع تتراوح بين (0،6–3،2 م/ثا). اجريت التجارب ضمن مدى اهتزازات بين (6–12 هرتز) بازاحة قصوى ثابتة مقدارها (5 ملم). أظهرت النتائج ان الاهتزاز يكون مؤثرا في السرعات البطيئة ومستويات الطاقة العليا، في حين ان تأثير الاهتزاز يختفي في السرعات العالية. كما أظهرت النتائج ان ازدياد مقدار الطاقة المسلطة يؤدي الى زيادة مدى سرعات الجريان التي يظهر فيها تأثير الاهتزاز.

كلمات رئيسية: اهتزاز قسري عمودي، حمل قسري، مجرى عمودي