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Thermo-Fluid Performance of a Vapor- Chamber Finned Heat Sink

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ABSTRACT

Finned heat sinks have long been used for cooling purposes in many engineering systems. Flat plate type sinks have been commonly used for the cooling of computer components such as microprocessors, motherboards, power supplies, etc. In this paper, a flat plate type heat sink provided with fins was examined experimentally. A vapor chamber was located between the heat source (load) and the sink itself. Several cases were considered: fins of various geometries and heights, in absence and presence of the vapor chamber, and Reynolds number levels. Comparisons were held and correlations were derived. The main conclusion is that using a vapor chamber in addition to fins improves the cooling system performance significantly.

1. Introduction

The thermal performance of heat sinks as cooling tools of certain engineering systems has attracted the attention of many researchers. Heat sinks are found in various geometries. Heat pipes may be the most common among these geometries. However, finned flat- plate type of heat sinks find their suitable application in certain engineering systems such as computer hardware components (microprocessors, motherboards, power supplies and so on). Published literature indicates obvious interest in examining the performance of heat sinks as cooling devices.

Wang et Vafai 8(2000) investigated experimentally the thermal performance of a vapor chamber. They found that the temperature distribution on the surface of the wall in the condenser section was uniform. The porous wick in the evaporator section provided most of the thermal resistance and a higher temperature drop than the other layers in the chamber.

Go 2(2005) presented experimental results that elucidated the effects of heating power and tilt angle on the thermal resistance of a vapor chamber, and found that the vapor chamber works effectively under high-power conditions.

Koito et al 5(2006) studied experimentally and numerically the effect of the size of the heat source on the heat transfer of a vapor chamber. The total thermal resistance of the vapor chamber was almost equal to that of the evaporator section. The thermal resistance increased as the size of the heat source decreased.

Hsieh et al 3(2008) examined the spreading thermal resistance of centrally- positioned heat

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sources and the thermal performance of a flat vapor chamber. The effect of the relevant parameters on the cooling performance was presented and discussed. The used vapor chamber heat spreader showed a heat sources and the thermal performance of a flat vapor chamber. The effect of the relevant parameters on the cooling performance was presented and discussed. The used vapor chamber heat spreader showed a heat removal capacity of 220 W/cm2 with a thermal spreading resistance of 0.2 oC/W.

Davis et Garimella 1(2008) measured the evaporative thermal resistance across thin layers of sintered copper wicks of varying porosity experimentally under saturated conditions.
Singh et al 7(2009) studied the effect of wick properties on the heat transfer characteristics of miniature loop heat pipes. It was experimentally observed that copper wicks were able to provide superior thermal performance than nickel wicks.

Sait et Ma 6(2009), constructed a unique experimental system to investigate the effect of heat flux on the film thickness in the evaporating thin-film region. Experimental results showed that as the input power increased the film thickness near the interline region decreased, a result in agreement with prediction

Hung-Yi et al 4(2010) studied experimentally the thermal performance of plate-fin vapor chamber heat sinks using infra-red thermography.. They concluded that generated heat was transferred more uniformly to the base plate by a vapor chamber heat sink than by a similar aluminum heat sink.

In the present paper, results of some experimental work in the area of vapor-chamber finned heat sink performance are presented and discussed. Possible comparison with published work is held and correlations are derived

2. The Physical Model

Fig.(1) shows a schematic of the finned heat sink tested in the present work and Fig.(2) shows the sink mounted on the vapor chamber. Each of these two models was mounted inside the test rig described in the next section.

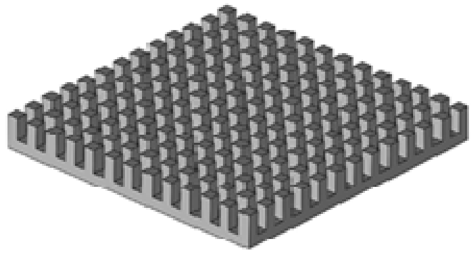


Fig.(1) : Finned Heat Sink

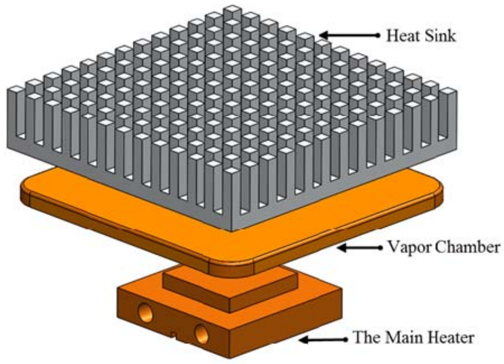


Fig.(2) Heat Sink on a Vapor Chamber

3. Experimental Work

3.1 Test rig

Fig.(3) shows a schematic of the test rig that was built specifically for the present work, consisting of: air source, air duct, working section, discharge section . The tested model was mounted in the working section and fitted with an electric heater as the heat source. The tested model was one time without a vapor chamber and a second time mounted on a vapor chamber located between the sink and the heater. The rig was provided with measuring instruments (Micro Manometer, Pitot-tube, Digital Thermometer, and Digital Wattmeter). Air flow was controlled by means of a valve at exit from the air source (fan). Fig.(4) shows schematic of tested model.

1	Air source	9	Flow straightner (honeycomb)
2	Butterfly valve	10	Contraction
3	Rubber connection	11	Micromanometer
4	Orifice plate	12	Working section
5	Convergent nozzle	13	Heat sink arrangement
6	Rubber conection	14	Electric Power Source
7	Wire gauze screens	15	Discharge duct
8	Diffuser		

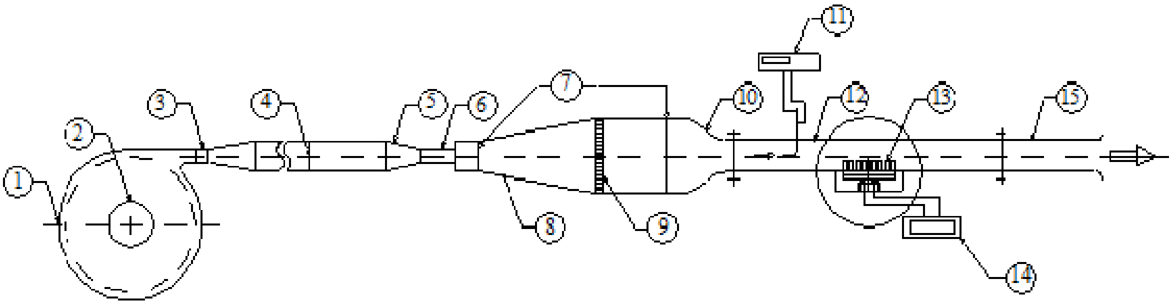
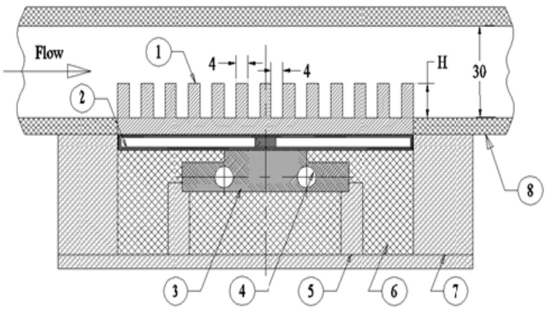


Fig.(3) Schematic Layout of Test Rig



1	Heat sink
2	Vapor chamber
3	Copper heating block
4	Heater element
5	Wood frame
6	Glass wool (insulation)
7	Wood frame
8	Plexiglass wall

Fig.(4) Vapor-Chamber/Heat-Sink Model

3.2 Experiments

Table (1) gives a summary of tests planned in the present work, covering various fin geometries and heights, fin arrangements, Reynolds numbers, all with and without vapor chamber

Base Dimension, L x B mm	Fin Height H, mm	Fin Spacing S, mm	Fin Arrangement	Fin Type
100 x 100	5	4	-	Plate
100 x 100	10	4	-	Plate
100 x 100	15	4	-	Plate
100 x 100	5	4x4	Aligned	Pin
100 x 100	10	4x4	Aligned	Pin
100 x 100	15	4x4	Aligned	Pin
100 x 100	5	4x8	Aligned	Pin
100 x 100	10	4x8	Aligned	Pin
100 x 100	15	4x8	Aligned	Pin

4.Results and Discussions

4.1 Pressure distribution

Figs.(5) (6) show samples of pressure distributions taken along centerline of the test section.. As the flow passes the heat sink obstruction it drops to a lower level downstream. Immediately downstream the pressure drops markedly due to presence of a recirculation zone.

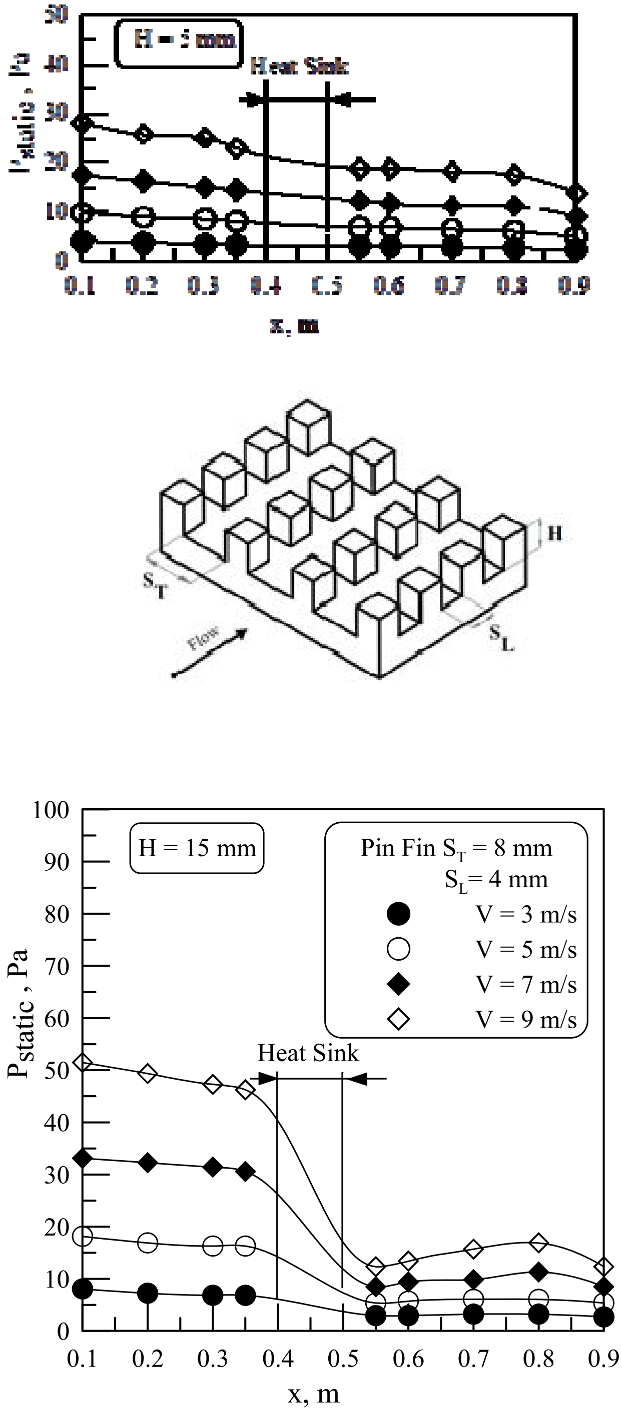


Fig.(5) Pressure Distribution along Channel Center Line for Pin-Finned Heat Sink

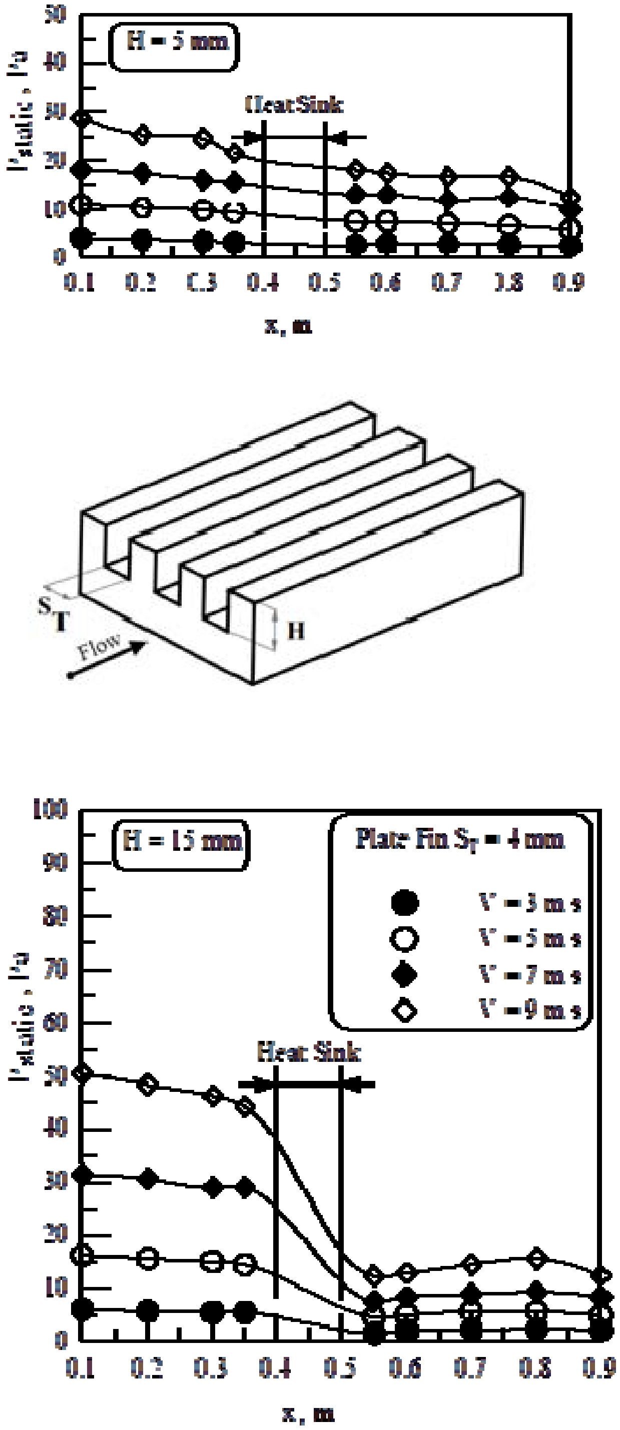


Fig.(6) Pressure Distribution along Channel Center Line for Plate-Finned Heat Sink

4.2 Pressure Drop.

Fig.(7) shows the pressure drop across the heat sink for various Reynolds numbers, being relatively small at Re = 9000. The figure shows also that pressure drop is highest for a pin-finned heat sink of spacing 4x8, ST = 4mm and lowest for a pin-finned heat sink of spacing 4x8, ST = 8 mm.

Fig.(8) displays the effect of heat sink height on pressure drop for various Reynolds numbers. The pressure drop increases with heat sink height by effect of increased blockage area in this case.

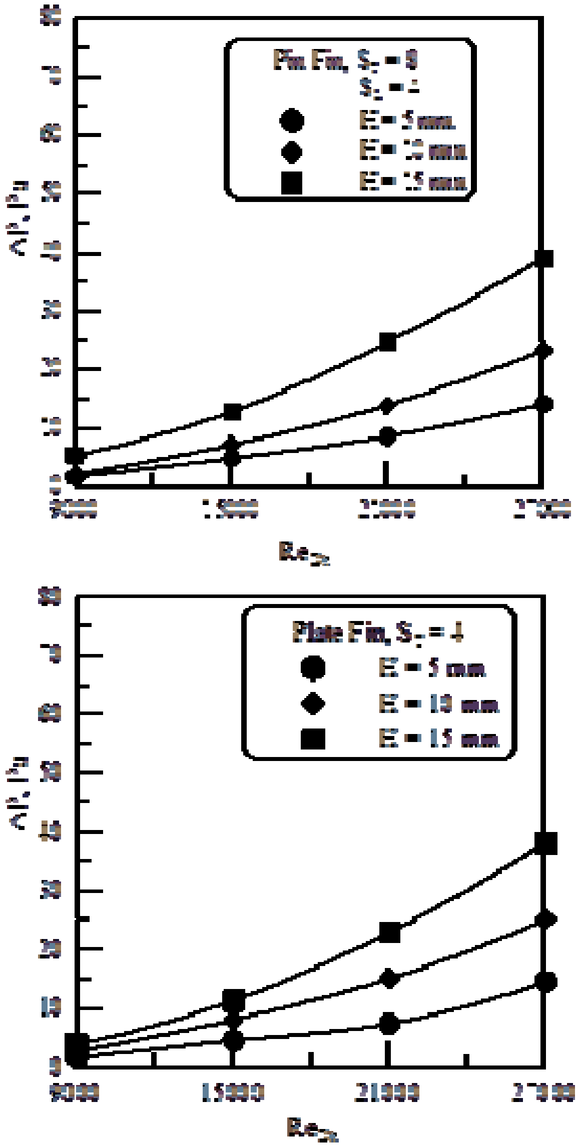


Fig.(7) Effect of Reynolds number on Pressure Drop.

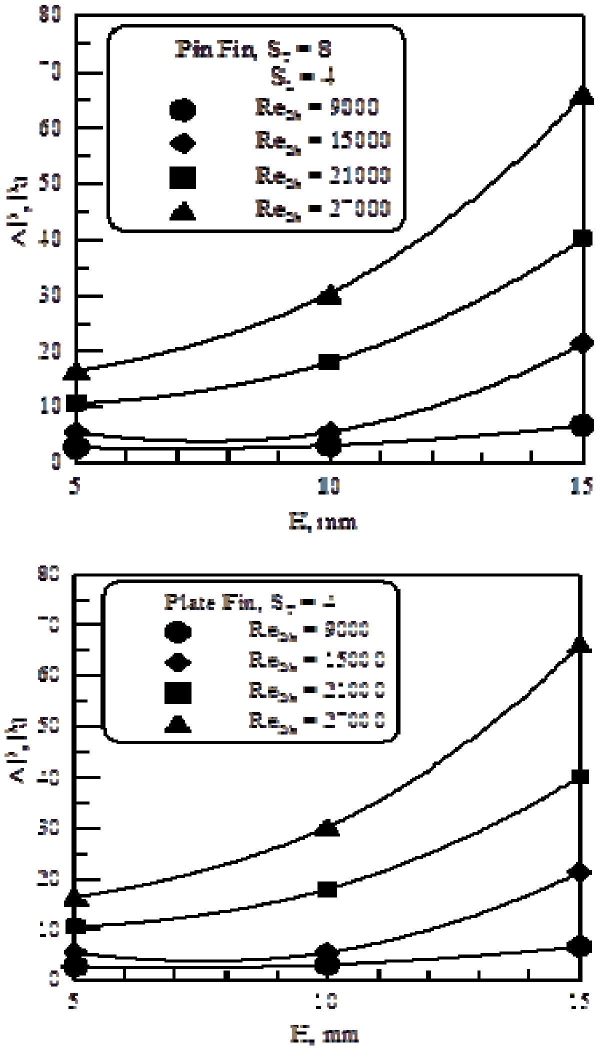


Fig.(8) Effect of Heat Sink Height on Pressure Drop.

4.3 Thermal performance

4.3.1 Pin-finned Heat Sink without Vapor Chamber

(i) Temperature Distribution

Fig.(9) shows temperature distribution for pin-finned heat sink base along its center line with spacing= 4x4 mm, and for H = 5, 10, and 15 mm. It may be observed that the temperature distribution follows a bell shape with maximum temperature values at x=50 mm for all air velocities (Reynolds number). Regions of high temperature are observed in the heating element zone, indicating that the heat generated by the heating element is not conducted uniformly to the base plate.

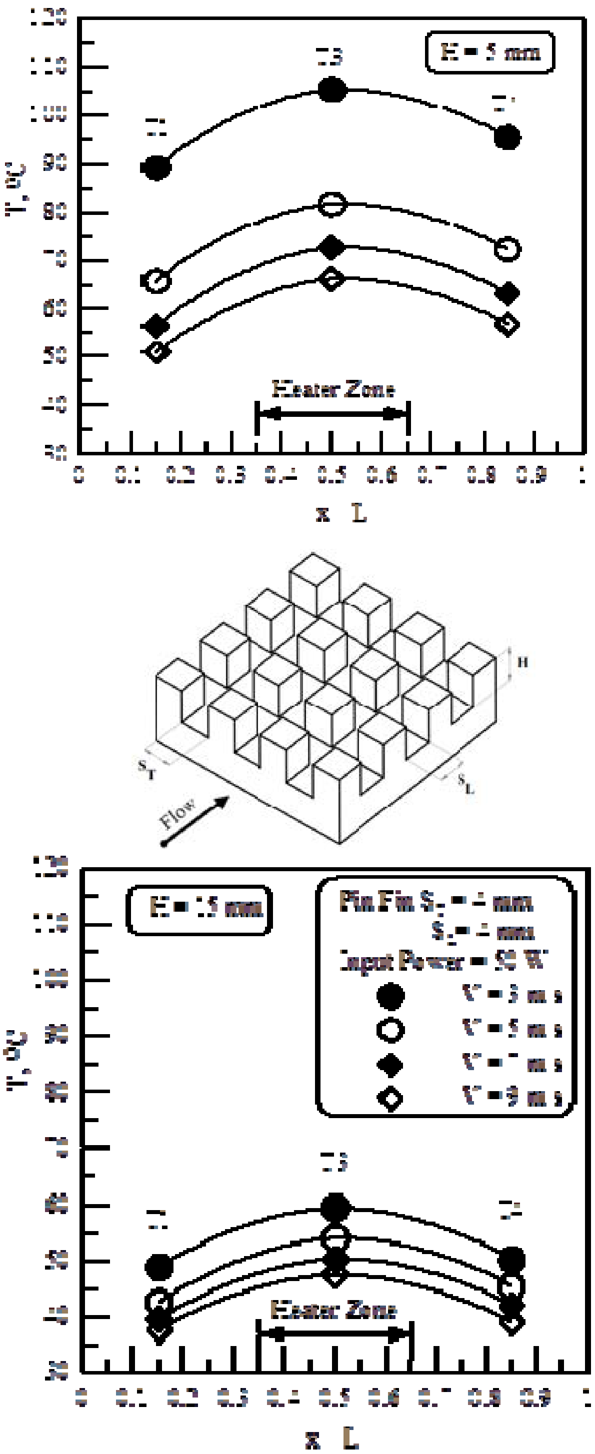


Fig.(9) Temperature Distribution for
a Pin-Finned Heat Sink (no Vapor Chamber)

(ii)Thermal Resistance

Fig.(10) displays the effect of fin height on the thermal resistance of a pin-finned heat sink base (spacing= 4x4 mm, for H = 5, 10, and 15 mm), versus various Reynolds numbers. The figure indicates that the spreading thermal resistance (R_S) of the heat sink is constant over all Reynolds numbers. Also, a heat sink of different heights has the same spreading thermal resistance at all Reynolds numbers (i. e. no height effect).

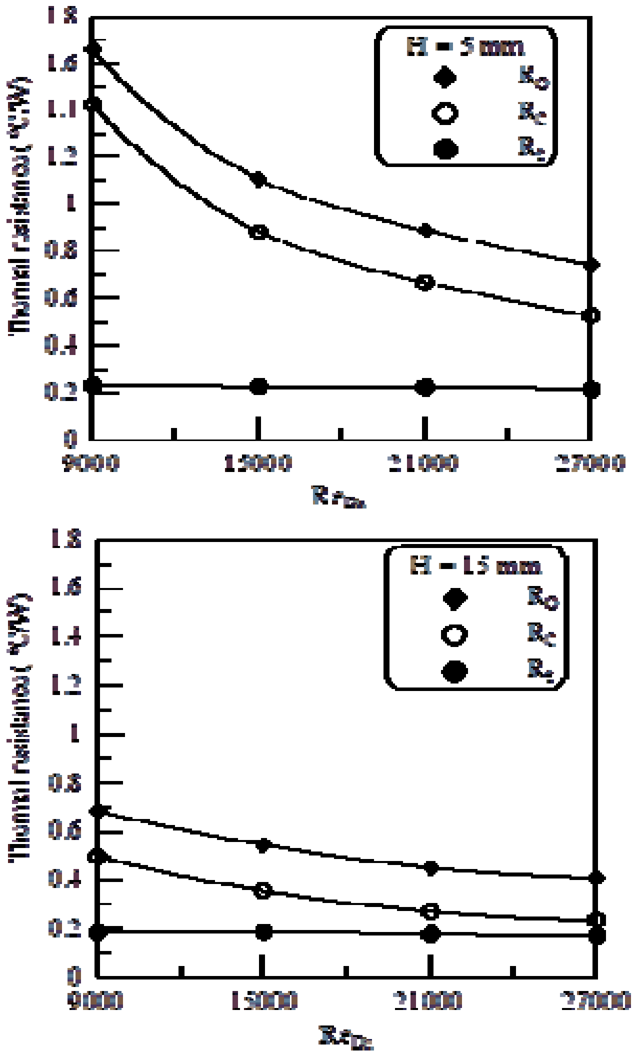


Fig.(10) Thermal resistance vs Reynolds number for
a pin-finned heat sink (no vapor chamber)

Notably, the drop in the convective thermal resistance upon increasing the fin height from 5 mm to 10 mm exceeds that resulting drop when increasing the fin height from 10 mm to 15 mm. The decrease in the convective thermal resistance gets smaller as the fin height continues to increase. Additionally, the effect of the Reynolds number on the convective thermal resistance is larger for a heat sink with lower fins.

4.3.2 Pin-finned Heat Sink with Vapor Chamber

(i) Temperature Distribution

Fig.(11) shows temperature distribution for a pin-finned heat sink base along center line of fin base, spacing= 4x4 mm, S_T = 4 mm for H = 5, 10, and 15 mm, with vapor chamber. The temperature appears more or less uniform. This uniformity of the temperature is most probably the effect of vapor chamber presence.

(ii)Thermal Resistance

Fig.(12) displays the effect of fin height on the thermal resistance of a pin-finned heat sink base (spacing= 4x4 mm, for H = 5, 10, and 15 mm) with vapor chamber, versus various Reynolds numbers. It is shown that the thermal resistance decreases as Reynolds numbers increases.

From Figs.(11) and Figs.(12) indicate clearly the effect of vapor chamber presence. The figures indicate that the spreading thermal resistance (R_S) of the heat sink with vapor chamber is lower than that of heat sink without vapor chamber. Also, a heat sink of different heights has the same spreading thermal resistance at all Reynolds numbers (i. e. no height effect). We can see that the overall thermal resistance (R_O) of the heat sink with vapor chamber is less than that without vapor chamber, being more effective as a cooling device.

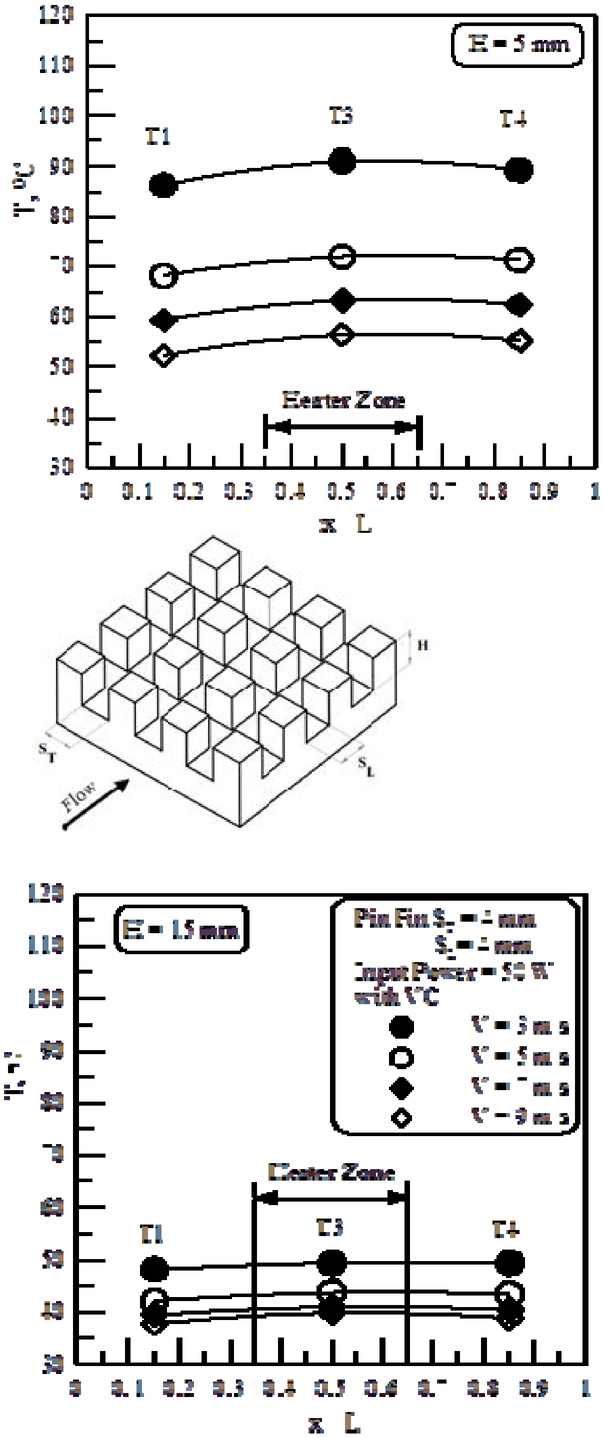


Fig.(11) Temperature Distribution for
a Pin-Finned Heat Sink (with Vapor Chamber)

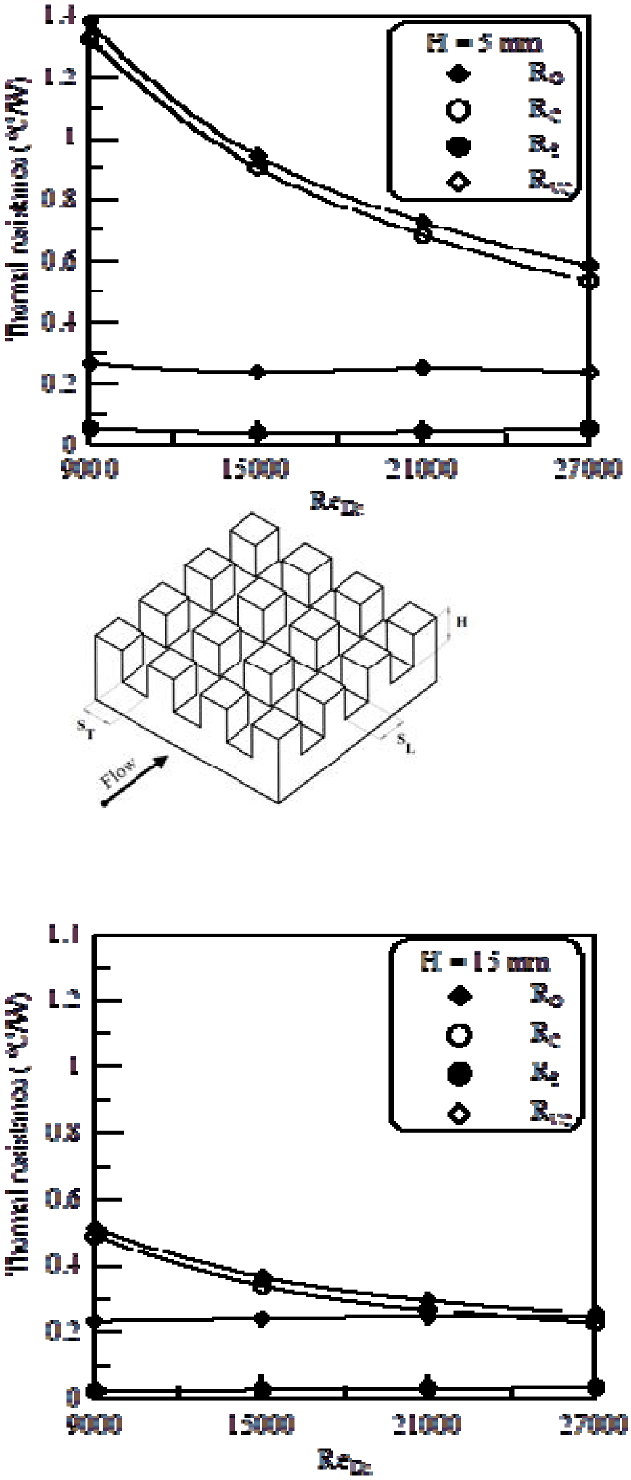


Fig.(12) Thermal resistance vs Reynolds number for a pin-finned heat Sink (with vapor chamber)

4.3.3 Plate-finned heat sink without vapor chamber

(i) Temperature distribution

Fig. (13) shows temperature distribution for plate-finned heat sink base along its center line with S_T = 4 mm, and for H = 5, 10, and 15 mm. It may be observed that the temperature distribution follows a bell shape with maximum temperature values at x=50 mm for all air velocities (Reynolds number). Regions of high temperature are observed in the heating element zone, indicating that the heat generated by the heating element is not conducted uniformly to the base plate.

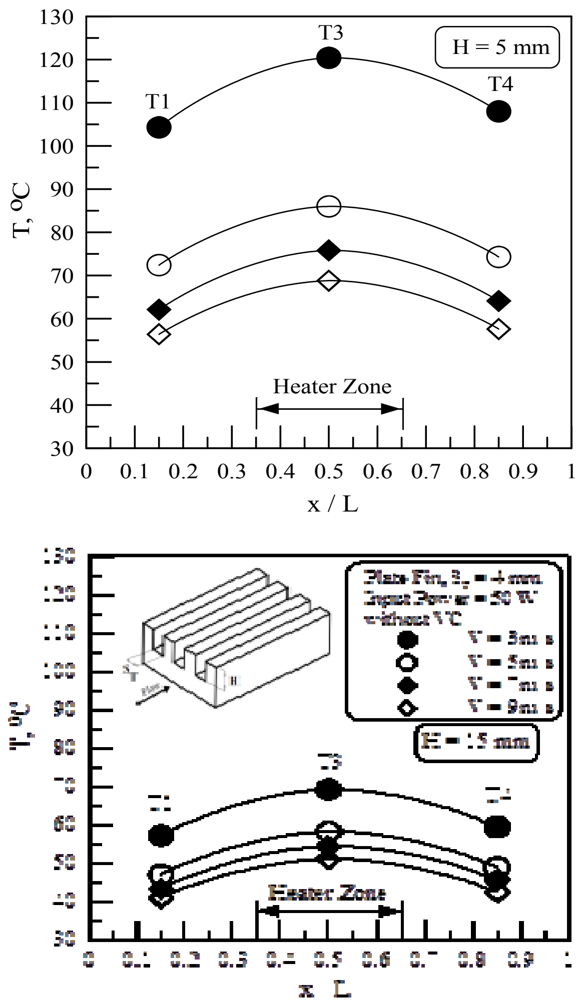


Fig.(13) Temperature distribution for a plate-finned Heat Sink Base (no vapor chamber)

(ii)Thermal Resistance

Fig.(14) displays the effect of fin height on the thermal resistance of a plate-finned heat sink versus various Reynolds numbers. The figure indicates that the spreading thermal resistance (R_S) of the heat sink is constant over all Reynolds numbers. Also, a heat sink of different heights has the same spreading thermal resistance at all Reynolds numbers (i. e. no height effect). The heat sink with higher fins provides a better thermal performance at any Reynolds number. The effects of the fin height on the overall thermal resistance are greater at lower Reynolds numbers.

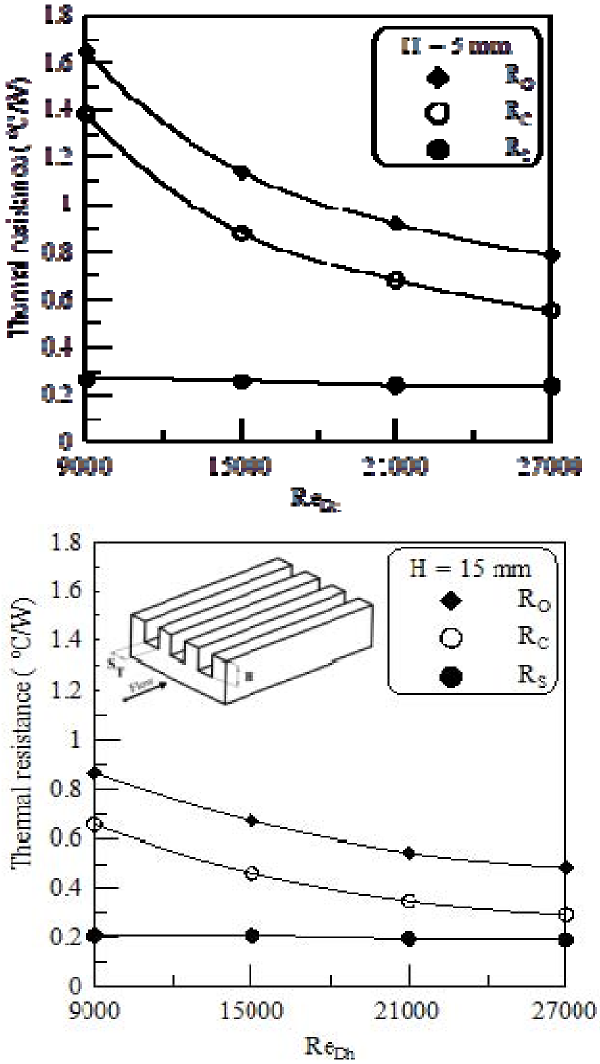


Fig.(14) l Thermal resistance vs Reynolds number for a pin-finned heat sink (no vapor chamber)

4.3.4 Plate-finned Heat Sink with Vapor Chamber

(i) Temperature Distribution

Fig. (15) shows a temperature distribution at plate-finned heat sink base along center line of fin base with vapor chamber. The temperature appears more or less uniform. This uniformity of the temperature is most probably the effect of vapor chamber presence. The generation of heat is spread more uniformly to the base plate and the fins in the vapor chamber heat sink. Heat is then effectively transferred to the air by convection. Therefore, the surface temperature distribution is more uniform.

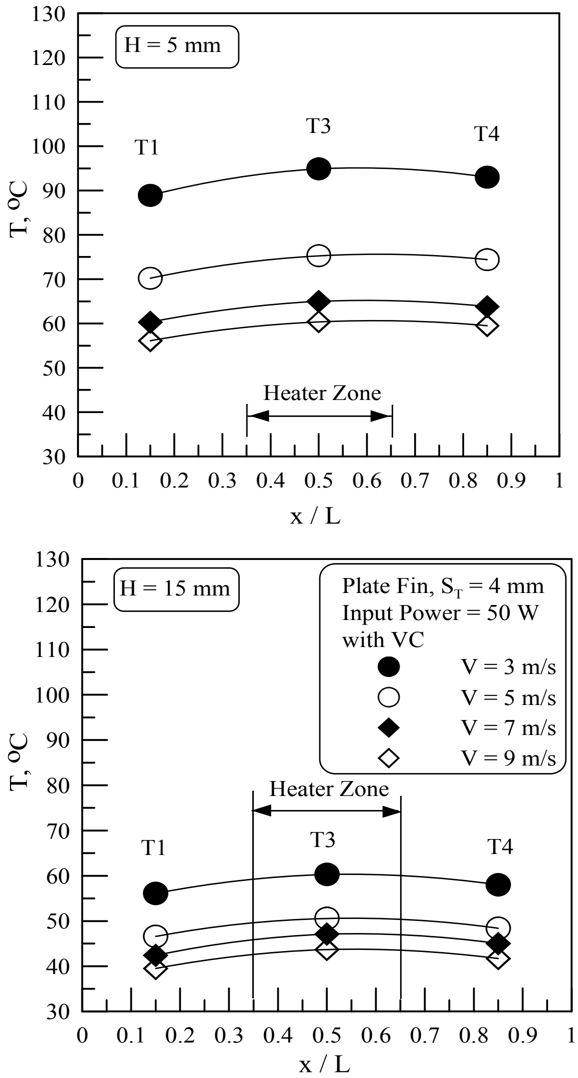


Fig.(14) Temperature distribution for a plate-finned heat sink (with Vapor Chamber).

(ii)Thermal Resistance

Fig.(16) displays the effect of fin height on the thermal resistance of a plate-finned heat sink base with vapor chamber, versus various Reynolds numbers. It is shown that the thermal resistance decreases as Reynolds numbers increases.

From Figs.(14) and Figs.(16) indicate clearly the effect of vapor chamber presence. The figures indicate that the spreading thermal resistance (R_S) of the heat sink with vapor chamber is lower than that of heat sink without vapor chamber. Also, a heat sink of different heights has the same spreading thermal resistance at all Reynolds numbers (i. e. no height effect). We can see that the overall thermal resistance (R_O) of the heat sink with vapor chamber is less than that without vapor chamber, which more effective cooling of the device.

4.4 Nusselt number

Effect of Height on Nusselt Number (Nu_{Dh})

Figs.(17) and Fig(18) show the effect of Height on Nusselt number Nu_{Dh} of Heat Sink) without VC at various Reynolds Numbers. Nusselt number is increases with Reynolds number

Figs.(19) and Fig(20) show the effect of Height on Nusselt number Nu_{Dh} of Heat Sink with VC at various Reynolds Numbers. It is clear from the figure that Nusselt number increases with Reynolds number.

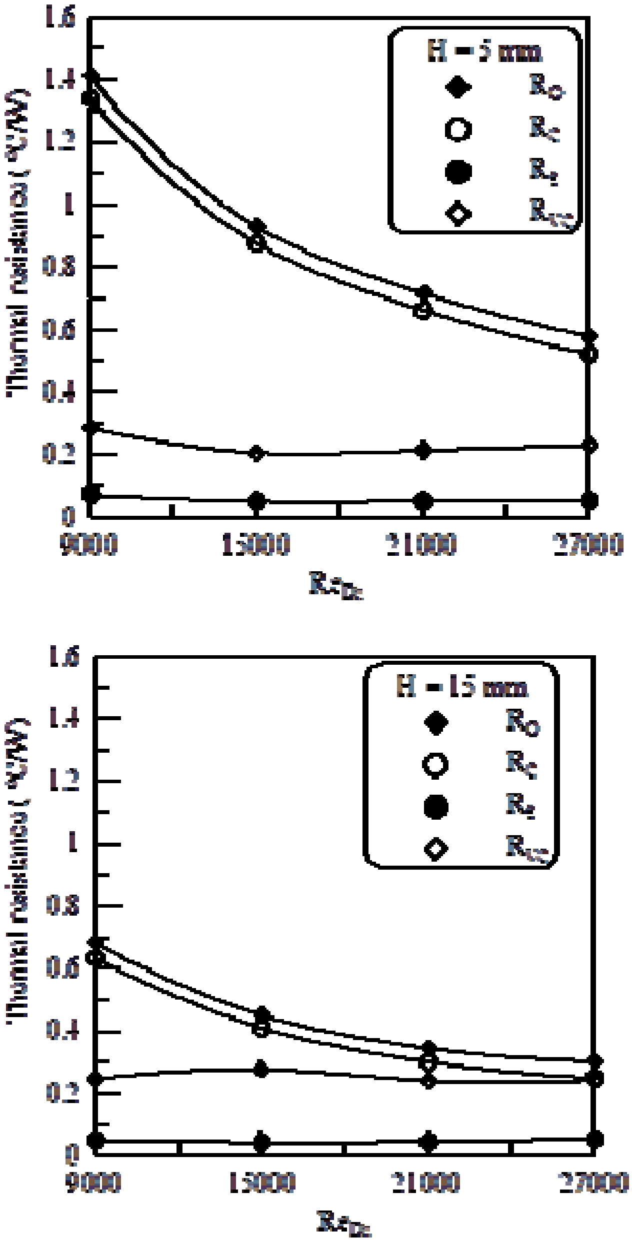


Fig.(16) Thermal Resistance vs Reynolds Number for a Plate-Finned Heat Sink (with Vapor Chamber)

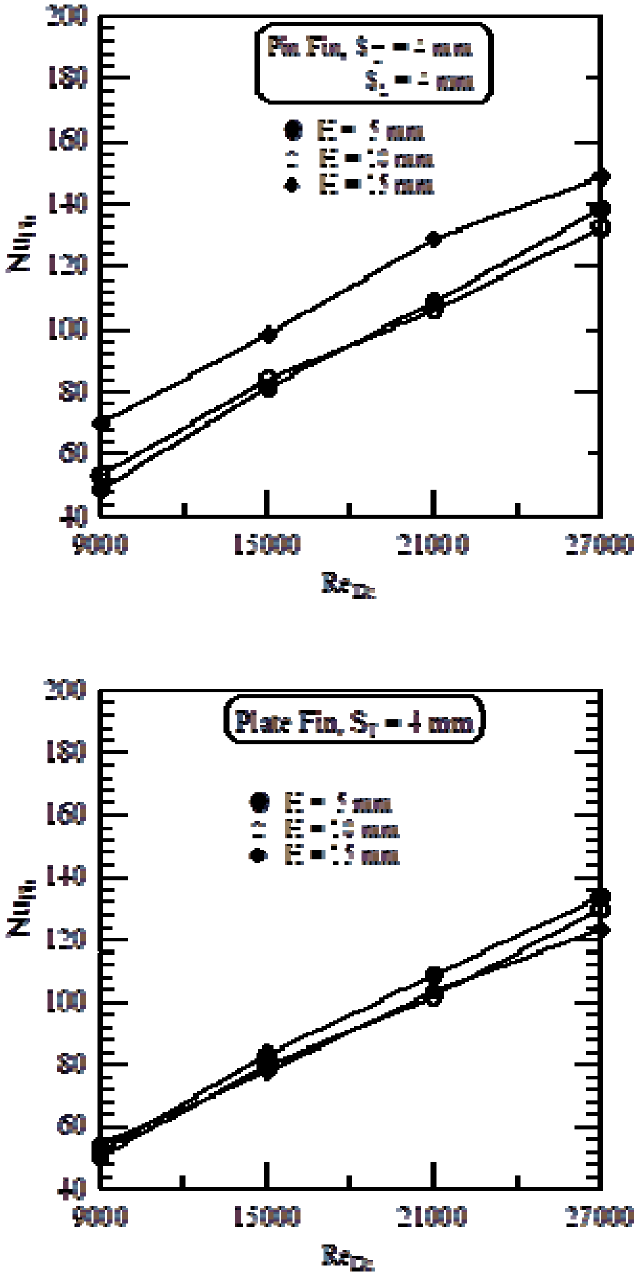


Fig.(17) Effect of Height on Nusselt number of Heat Sink (no Vapor Chamber).
(Nu_{Dh} based on Actual Surface Area of Heat Sink, At).

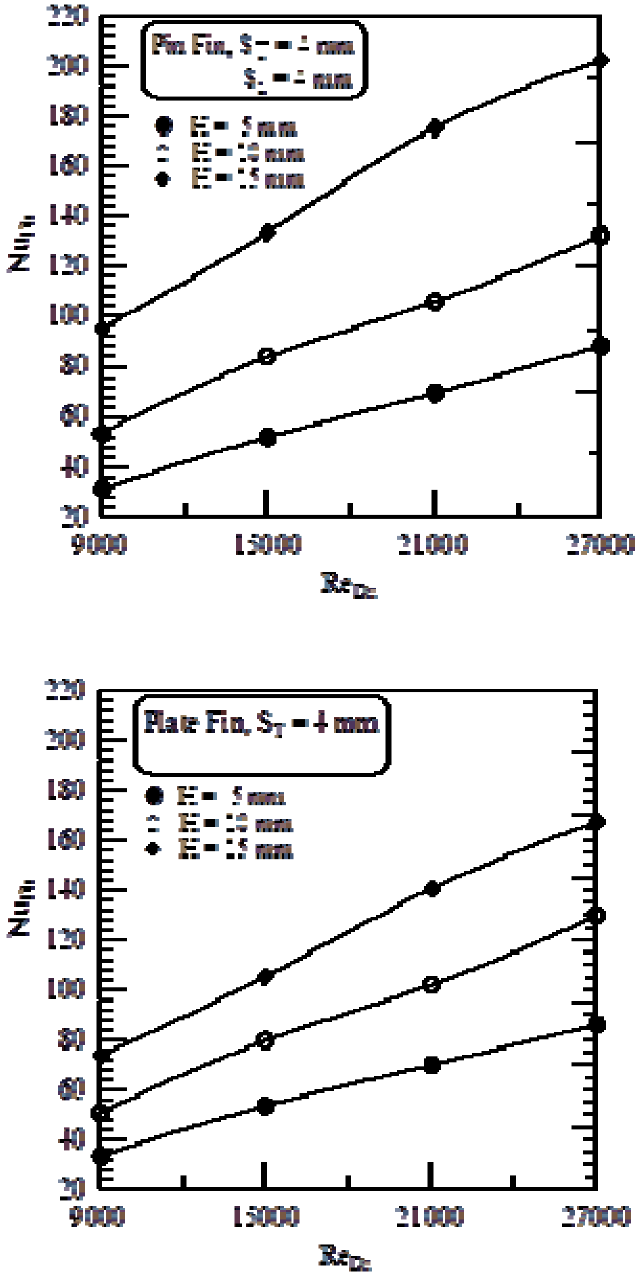


Fig.(18) Effect of Height on Nusselt number of Heat Sink (no vapor chamber)
(Nu_{Dh} based on Assuming that heat sinks with different Height have a constant area).

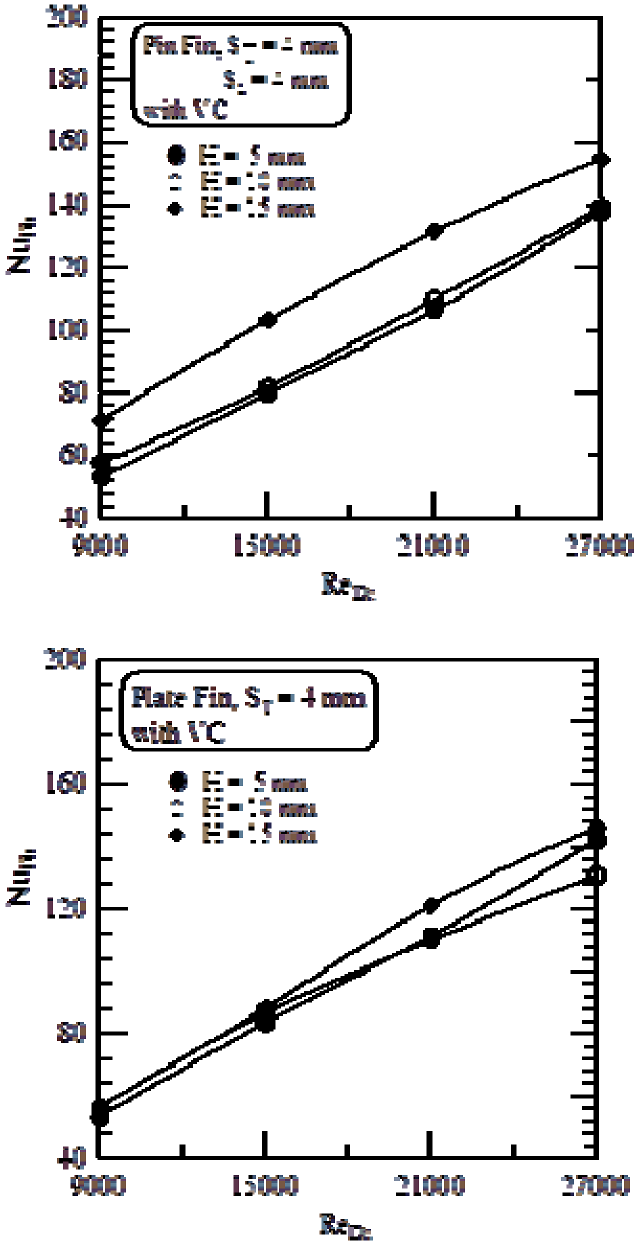


Fig.(19) Effect of Height on Nusselt Number of Heat Sink (with Vapor Chamber).
(Nu_{Dh} based on Actual Surface Area of Heat Sink, At).

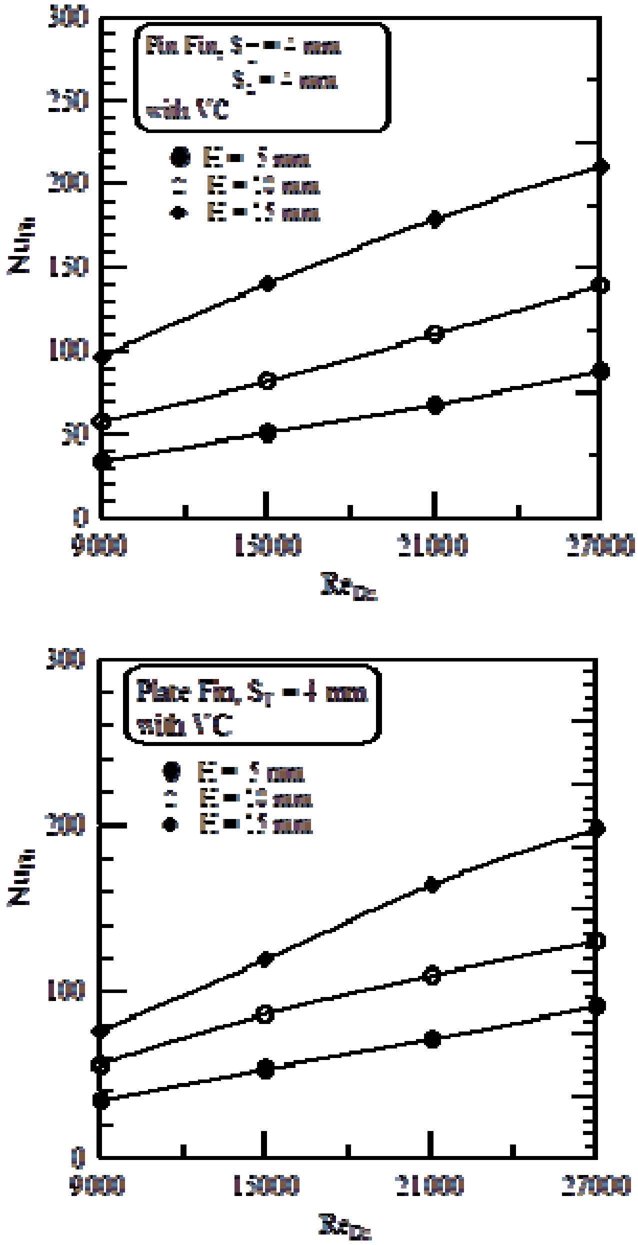


Fig.(20) Effect of Height on Nusselt Number Nu_{Dh} of Heat (with Vapor Chamber).
(Nu_{Dh} based on Assuming that heat sinks with different Height have a constant area).

5. Comparison and Correlations

Fig.(21) shows a comparison with some published work (Hung-Yi et al [4](2010))

The agreement appears good, taking into consideration the difference in the working conditions.

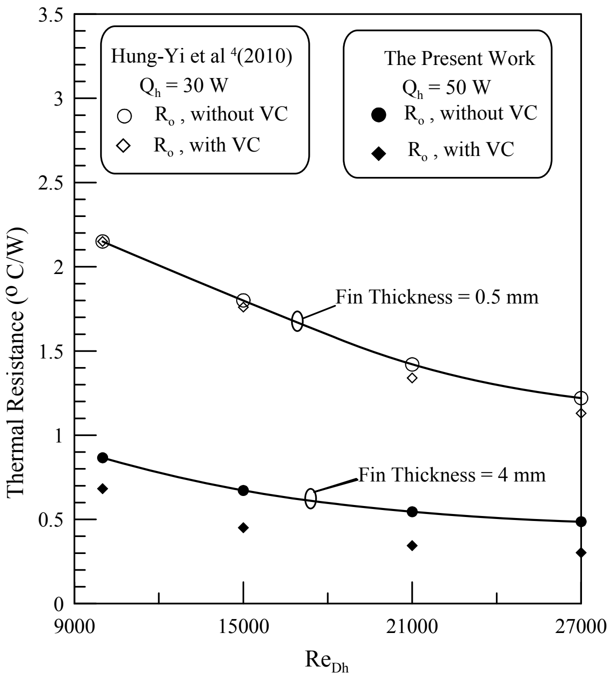


Fig.(21) Comparison with published work

From the work described here the following correlation was derived.

6.1 Heat Sink without Vapor Chamber

$$Nu_{Dh} = 0.0337.(\mathrm{Re}_{Dh})^{0.913} + 0.00673.\left(\frac{H}{CH}\right)^{-0.0129}.\left(\frac{S_T}{CH}\right)^{-0.115}.\mathrm{Re}_{Dh}$$

The correlations are valid within the ranges given in Table (2).

6.2 Heat Sink with Vapor Chamber.

$$Nu_{Dh} = 0.0378(\mathrm{Re}_{Dh})^{0.92} - 0.0809.\left(\frac{H}{CH}\right)^{-0.0784}.\left(\frac{S_T}{CH}\right)^{-0.113}.\mathrm{Re}_{Dh}$$

These correlations are valid within the ranges given in Table (2).

Table (2) Limits within which the correlation is valid.

Minimum	Variable	Maximum
9000	Re_{Dh}	27000
0.1667	H/CH	0.5
0.133	S_T/CH	0.267

7. Conclusions

***Hydrodynamic Performance:**

(i) Increasing fin height increases the heat sink pressure drop for the same flow rate.

(ii) The pressure drop is highest for pin-finned heat sink of spacing 4x8, S_T = 4mm whereas it is lowest in case of pin-finned heat sink of spacing 4x8, S_T = 8 mm.

***Thermal Performance:**

(i) The vapor chamber heat sink can transfer heat uniformly to the base plate and prevent the formation of local concentrations of high temperature.

(ii) The effect of the heat sink height on the overall thermal resistance declines as the Reynolds number increases. The effect is stronger for the vapor chamber heat sink than the aluminum heat sink.

(iii) At a high Reynolds number (Re=27000), the overall thermal resistance declines with fin height.

Nomenclature

(i) Symbols

Alphabetical Symbols	**Definition**	**Units (SI)**
A_t	Total convection heat transfer area of a heat sink	m^2
B	Heat sink foot print width	m
CB	working section width	m
CH	working section height	m
D_h	hydraulic diameter of working section	m
H	fin height	m
h	convection heat transfer coefficient	$W/m^2.K$
k	thermal conductivity of a heat sink material	W/m.K
k_f	thermal conductivity of cooling fluid (air)	W/m.K
L	Heat sink length	m
Nu_{Dh}	Nusselt number	-
P	Pressure	Pa
Q_h	heater electric power input	W
Q_{conv}	heat transfer by convection	W
Q_{loss}	heat loss	W
R_C	convective thermal resistance of heat sink	K/W
R_O	overall thermal resistance of a heat sink	K/W
R_S	spreading thermal resistance of heat sink	K/W
R_{vc}	thermal resistance of a vapor chamber	K/W
Re_{Dh}	Reynolds number, $\rho V D_h/\mu$	-
S	fin spacing	m
S_L	longitudinal pitch	m
S_T	transverse pitch	m
T_{air-in}	air temperature at working section inlet	K
T_{b-avg}	base plate average temperature	K
T_C	temperature of base plate of heat sink at center	K
T_h	temperature of vapor chamber bottom	K
T_m	mean air temperature	K
T_{ref}	reference temperature = 298.15 K	K
t	fin thickness	m
t_b	heat sink base thickness	m
V	air velocity at inlet of working section	m/s
x	Axial Coordinate	m
y	The normal distance to the wall	m

Greek Symbols	**Definition**	**Units (SI)**
μ	Dynamic viscosity of air	Pa.s
ν	Kinematic viscosity of air	m^2/sec
ρ	Density of air	kg/m^3
ΔP	Pressure drop across heat sink	Pa
Δh	Pressure head through Pitot tube	mm H_2o
ΔT	Temperature difference	K
w	uncertainty	-

(ii) Subscripts:

b-avg	base plate average
D_h	Hydraulic Diameter
VC	Vapor chamber
w	Wall , or Water
X	Component in x-direction.
Y	Component in y-direction.
Z	Component in z-direction.
conv	For convection
air-in	Air at inlet
ins-up	Insulation up
ins-dn	Insulation down
loss	For loss
ref	reference

(iii) Superscripts:

(iv) Abbreviations:

2D	Two dimension.
3D	Three dimension.

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