ENE310
ENGINEERING LABORATORY I

CONVECTIVE HEAT TRANSFER

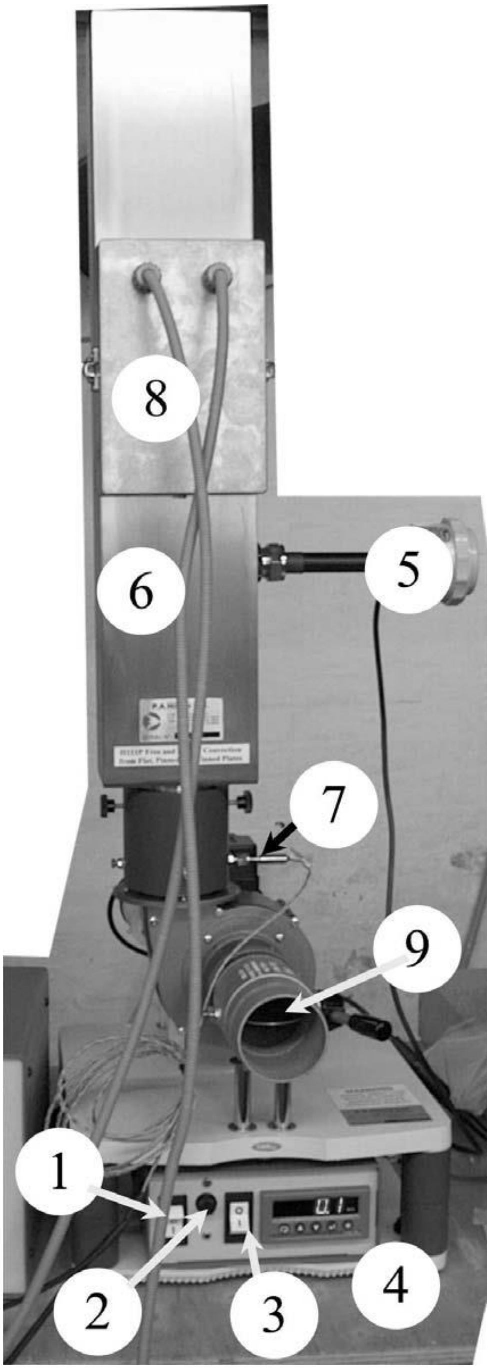
MANUAL

AIM OF THE EXPERIMENT

Free and Forced convection from Flat, Finned and Pinned Plates experiments enables students to investigate convective heat transfer from various surfaces in free and forced convection. In this experiment, convective heat transfer from a pinned plate will be demonstrated.

EXPERIMENTAL SET-UP

Schematic Diagram H112P

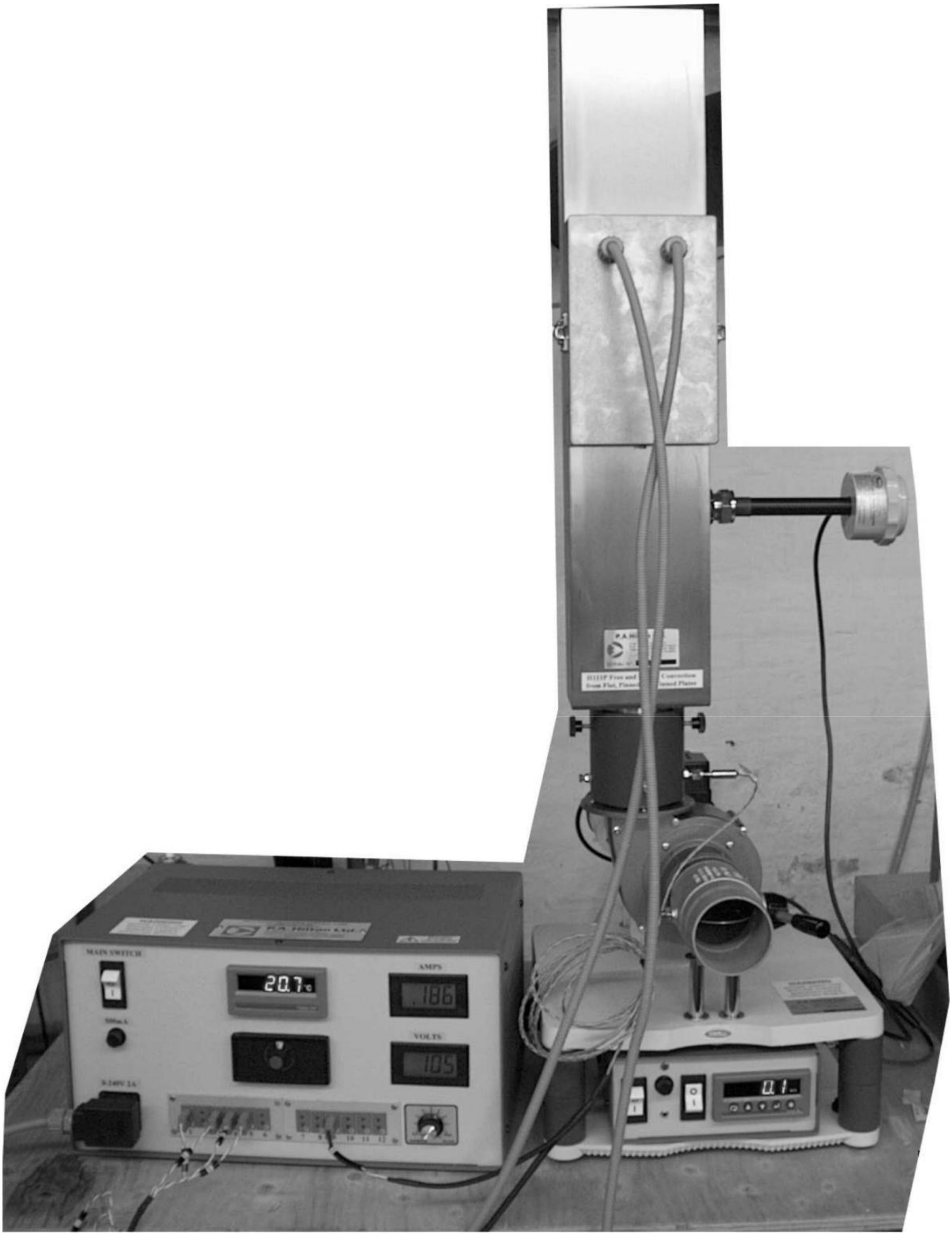


Key

1. Main Switch
2. Instrument Fuse
3. Fan Switch
4. Air Velocity Display (m/s)
5. Air Velocity Sensor (Hot Wire Anemometer)
6. Duct
7. T5 Air Temperature
8. Heated Plate
9. Air Throttle

Typical Installation

H112P Shown connected to H112 (Console)



SYMBOLS AND UNITS

Symbol	Quantity	Fundamental Unit
A	Area	m^2
h	Surface Heat Transfer Coefficient	$W\ m^{-1}\ K^{-1}$
I	Heater Current	Amps
k	Thermal Conductivity	$W\ m^{-1}\ K^{-1}$
P	Pressure	$N\ m^{-2}$
Q	Heat Transfer Rate	Watts
R	Heater Element Resistance	Ohms
t	Temperature (Customary)	ºC
T	Temperature (Absolute)	K
U	Velocity	$m\ s^{-1}$
V	Heater Voltage	Volts

TEMPERATURE CHANNELS LOCATION

T1	Element surface t_s
T2	Pin 10mm from heater
T3	Pin 30mm from heater
T4	Pin 50mm from heater ON PINNED PLATE. 46mm from heater on FINNED PLATE
T5	Air Temperature t_a

Suffixes

a	Refers to the air or bulk fluid
s	Refers to surface conditions

Description of the Experimental Set-up

The H112P Free and Forced convection from Flat Finned and Pinned Plates enables students to investigate heat transfer from various surfaces in free and forced convection. The range of heated plates demonstrates the effect of extended surfaces (fins and pins) on the rate of heat transfer. The H112P is designed to be used with, and to be installed alongside, the Heat Transfer Service Unit H112.

The accessory comprises a rectangular duct (6) mounted on the discharge of a base mounted centrifugal fan. In the middle of the duct is an air velocity sensor (5) that allows the air velocity within the duct to be measured and displayed (metres/second) on the air velocity display (4) below the base. At the centre of the duct is an aperture that allows any of the three heated plates (8) supplied to be installed.

A flat plate, pinned plate, or finned plate heat exchanger may be installed in the duct and secured by two toggle clamps. Each exchanger incorporates an electric heater mat rated at 100W at 240V. Each of the heated plates incorporates thermostatic protection against overheating.

The heater surface temperature (T1) is continuously monitored and displayed by the temperature indicator when plugged in to the console. The Pinned plate is fitted with three extra thermocouples (T2, 3 and 4) to measure the temperature of extended surfaces. T5 is furthest from the heater. The Finned plate is fitted with three extra thermocouples (T2, 3 and 4) to measure the temperature of extended surfaces. T8 is furthest from the heater. Note that the T4 distance is 50mm from the heater on the Pinned Plate and 46mm from the heater on the Finned Plate. The T5 air temperature (7) sensor is located at the base of the duct and records the temperature of the air flowing over the heated plate. Thermocouple attachment points on the heat exchangers are protected by a covering of adhesive.

The air velocity passing the heated plates can be varied from zero to more than 8m/s depending upon the local mains voltage and supply frequency. The air velocity sensor (5) is permanently mounted in the duct and connects to the console below using a line plug and socket.

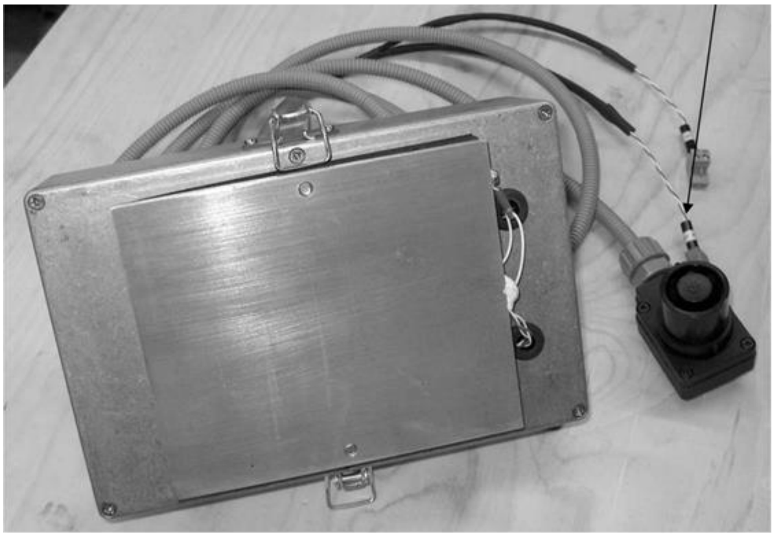
The air velocity is controlled by the use of an intake air throttle (9). For natural convection experiments, the fan may be switched off using the fan switch (3) on the H112P console.

All thermocouples terminated with a miniature plug (identified T1, and T2 to T4) for insertion into the control console sockets.

Component Identification

1) Flat Plate Heat Exchanger

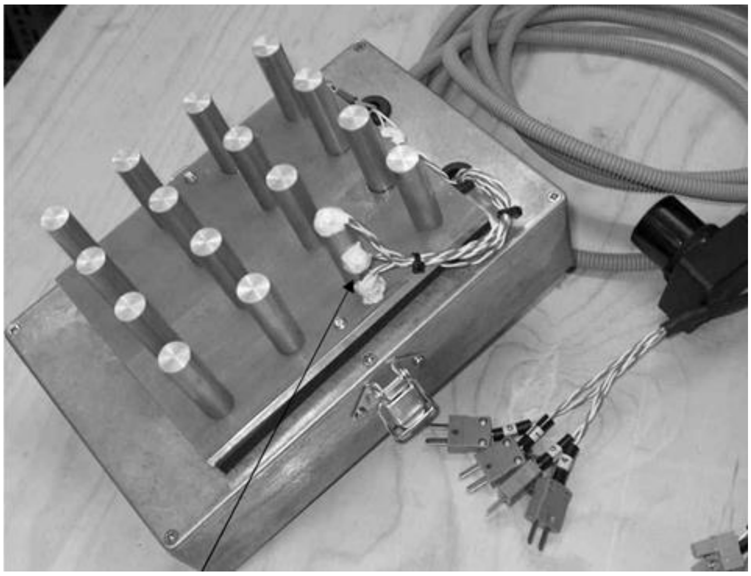
This is the Flat Plate heat exchanger. Note that the surface thermocouple T1 recording the plate temperature is connected to the control console through the plug shown at the bottom of the picture.



There are no extra surface thermocouples on the flat plate that require connection unless the unit is being used with the optional Data Acquisition Upgrade HC351A and this is dealt with in a separate manual. The flat plate is located in the open section of the tunnel and secured with the two toggle clamps. Ensure that the heater is located in the tunnel with the power connection at the top as shown on page 1

2) Pinned Plate Heat Exchanger

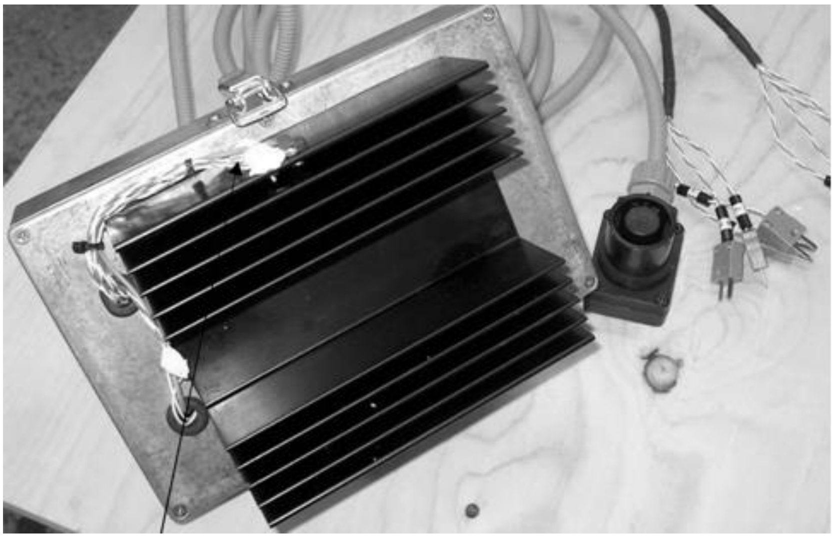
This is the Pinned Plate heat exchanger. Note that the surface thermocouple T1 recording the plate temperature is connected to the control console through one of the four connecting plug shown at the bottom of the picture.



There are three extra thermocouples on the pins (T2, T3, T4) that require connection to the control console extra sockets. These are fitted with thermocouple plugs (shown above) that match the sockets on the console. The pinned plate is located in the open section of the tunnel and secured with the two toggle clamps. Ensure that the heater is located in the tunnel with the power connection at the top as shown on page 1

3) Finned Plate Heat Exchanger

This is the Finned Plate heat exchanger. Note that the surface thermocouple T1 recording the plate temperature is connected to the control console through one of the four connecting plug shown at the right of the picture.



There are three extra thermocouples on the fins (T2, T3, T4) that require connection to the control console extra sockets. These are fitted with thermocouple plugs that match the sockets on the console. Note that duplex thermocouples are no longer supplied as thermocouples connect through the digital temperature indicator to the Hilton Data logger The pinned plate is located in the open section of the tunnel and secured with the two toggle clamps. Ensure that the heater is located in the tunnel with the power connection at the top as shown on page 1

SPECIFICATION H112P

Duct and Blower	Rectangular duct with aperture to accept any one of 3 plate heat exchangers. Forced air supply is from a centrifugal blower with damper control on the inlet to control air velocity. Air velocity is measured by a sensor mounted in the duct and a digital display located under the fan.
Flat plate Heat Exchanger	Carrier plate fits into the duct aperture and incorporates a 100W heater mat and flat aluminium plate with surface thermocouple. A power plug and thermocouple plug connects to the Heat transfer Service Unit H112
Pinned Plate Heat Exchanger	Carrier plate fits into the duct aperture and incorporates a 100W heater mat and flat aluminium plate with 16 pins of 12.7mm diameter. Thermocouples are attached to the heater surface and at three points on the extended surface of the pins. A power plug and thermocouple plugs connect to the Heat transfer Service Unit H112
Finned Plate Heat Exchanger	Carrier plate fits into the duct aperture and incorporates a 100W heater mat and finned aluminium plate. Thermocouples are attached to the heater surface and at three points on the extended surface of the fins. Plugs connect to the 70V power source and temperature measurement console.

Useful Data

All heat exchangers have a plain heated area (not considering the fins or pins) of 125mm x 150mm the same as the flat plate heat exchanger. This allows students to make direct comparisons between the performance of the flat plate and the two extended surfaces.

Flat Plate Dimensions

Height (m)	0.15
Width (m)	0.13

Pinned Plate Thermocouple Locations,

Thermocouple	T2	T3	T4
Effective distance(mm) from heater surface	10	30	50

Finned Plate Thermocouple Locations,

Thermocouple	T2	T3	T4
Effective distance(mm) from heater surface	10	30	46

Duct Cross Sectional Area $A_d = 0.01278\ m^2$

Duct Length $L = 0.45\ m$

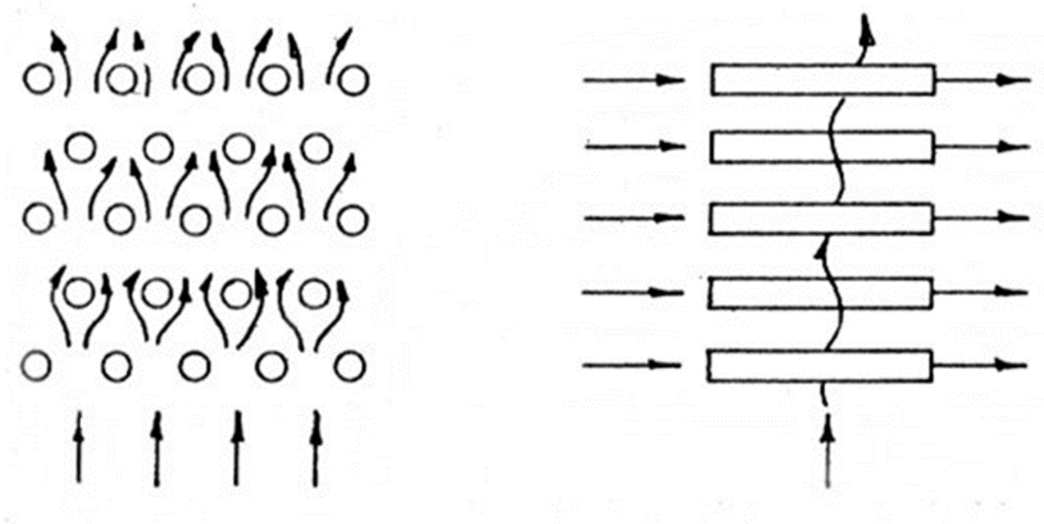
THEORY OF THE EXPERIMENT

Introduction

If a flat surface is heated to a temperature above that of its surroundings heat will be transferred from it by means of convection and radiation. The amount of heat apportioned to each method of heat loss will depend upon the temperature of the surface and its emissivity.

Assuming the surface is not at elevated temperatures the majority of heat will be lost due to convection caused by a local increase in buoyancy adjacent to the surface causing an upward flow. For a simple flat plate the amount of heat lost will be small due to the low heat transfer coefficient.

In order to increase the rate of heat transfer one method is to extend the surface by the addition of conducting fins or pins.



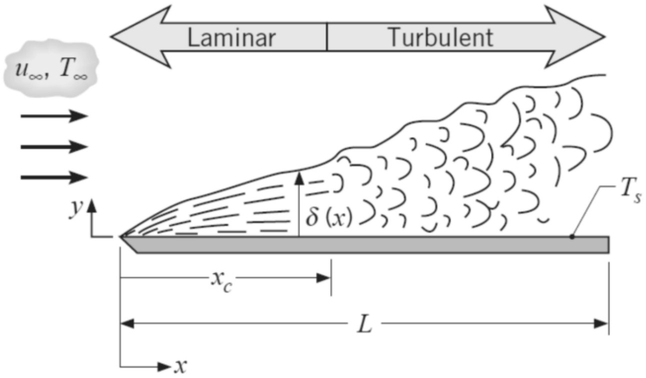
Various tube and fin layouts have been devised in order to improve the efficiency heat exchangers and thereby reduce the physical size for a given heat transfer rate. However, the objective of all of the arrangements is to promote turbulence in the fluid flowing across the extended surfaces.

This turbulence may be increased by raising the stream velocity by means of a fan or pump. Alternatively, the tube layout may be changed in order to maximise turbulence. This is achieved by ensuring that each row of tubes is positioned such that turbulence induced by the preceding row is incident upon the next row. Hence a cascade effect is produced such that the degree of turbulence increases with the depth of the tube bundle.

Alternatively, the surface may be increased by the use of fins rather than pins. These can result in lower aerodynamic drag and enhanced heat transfer rates. An area where this may be important for example is in an aero engine.

Calculations

In this experiment we will calculate rate of convective heat transfer from a flat plate in a parallel flow, see the figure.



The heat lost due to forced convection can be determined from

$$Q = hA_s(T_s - T_a)$$

where h: Overall heat transfer coefficient due to forced convection. And for a vertical plate it can be expressed with a non-dimensional relationship as the following:

$$h = \frac{k\,\overline{Nu_L}}{L}$$

where k = Thermal conductivity (W/mK)
L = Length of the flat plate (m)
Nu_L: Nusselt number for the configuration

Convective heat loss from a flat plate can be calculated analytically if the flow regime stays in the laminar region. And if the flow turns turbulent, then there are many non-dimensional equations of various complexity for the calculation of h. These are the result of extensive tests on flat plates various heights at various operating conditions of air velocity and surface temperature. The resulting heat transfer coefficients are analysed non-dimensionally to develop a general equation for the geometric configuration.

Average Nusselt number for a flat plate in parallel flow can be estimated using following formulations for laminar and turbulent flow regimes

$$\overline{Nu_L} = 0.664 Re_L^{1/2}\, Pr^{1/3}$$ → laminar

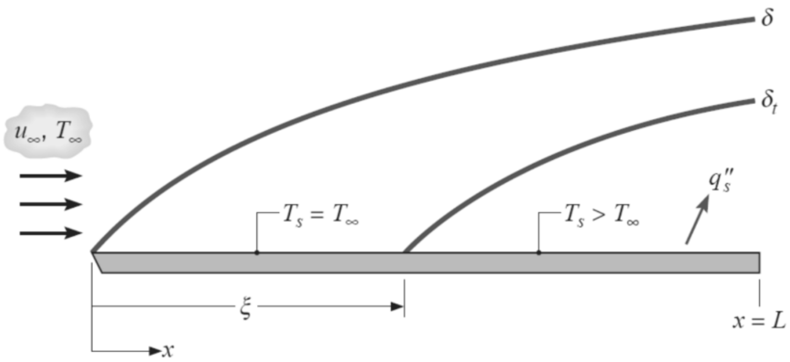
$$\overline{Nu_L} = 0.037 Re_L^{4/5}\, Pr^{1/3}$$ → laminar + turbulent

$$Re_L = \frac{uL}{\upsilon}$$

where Re_L: Reynolds Number for a flat plate based upon the plate height L
u : Air Velocity
υ : Kinematic Viscosity
Pr : Prandl Number

Transition from laminar to turbulent occurs in the critical Reynold number of $5*10^{-5}$.

Our experimental set-up involves an unheated starting length upstream of a heated section as shown in the Figure.



Velocity boundary layer growth begins at x = 0, while thermal boundary layer development begins at x = ξ. Hence there is no heat transfer for $0 < x < \xi$. Therefore, we apply a correction to Nu number.

First, we calculate Nusselt Number for the whole length of the region (duct + flat plate length) as if the whole region is heated using above Nu equations. In our experiment, that length will be duct length till the end of the flat plate instrument. Then we apply the following expression to find corrected Nusselt number for the flat plate only;

$$\overline{\mathrm{Nu}_{\mathrm{L,corrected}}} = \overline{\mathrm{Nu}_{\mathrm{l}}} = \overline{\mathrm{Nu}_{\mathrm{L}}}\left(\frac{\mathrm{L}}{\mathrm{L}-\mathrm{l}}\right)\left[1-\left(\frac{\mathrm{l}}{\mathrm{L}}\right)^{(\mathrm{p}+1)/(\mathrm{p}+2)}\right]^{\mathrm{p}/(\mathrm{p}+1)}$$

where L is the whole length including duct height, and l is the length of the flat plate. p = 2 for laminar flow and p = 8 for turbulent flow, $\overline{\mathrm{Nu}_{\mathrm{L}}}$ and the value of p are determined using whole length L.

Also note that thermophysical properties of air are taken at film temperature, which can be calculated as

$$\mathrm{T}_{\mathrm{film}} = \frac{\mathrm{T_a} + \mathrm{T_s}}{2}$$

The values of these temperature dependent properties can be found in the table provided in the following page.

Inclusion of fins on a surface is expected to boost the convective heat transfer due to increased area exposed to the flow. But, fins also introduce a conductive resistance to the system since heat has to travel across the fin material to the surface, and that might actually slow down the heat transfer rate. So, there is an optimal point when the fins are concerned. These calculations are outside of the scope of this experiment. The experimental configuration satisfies this optimal limit and we expect to see a reduction in the plate surface temperature given the same heat input and air velocity.

TABLE A.4 Thermophysical Properties of Gases at Atmospheric Pressure[a]

T (K)	ρ (kg/m^3)	c_p (kJ/kg·K)	$\mu \cdot 10^7$ (N·s/m^2)	$\nu \cdot 10^6$ (m^2/s)	$k \cdot 10^3$ (W/m·K)	$\alpha \cdot 10^6$ (m^2/s)	Pr
Air, $\mathcal{M}$ = 28.97 kg/kmol							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709
850	0.4097	1.110	384.3	93.80	59.6	131	0.716
900	0.3868	1.121	398.1	102.9	62.0	143	0.720
950	0.3666	1.131	411.3	112.2	64.3	155	0.723
1000	0.3482	1.141	424.4	121.9	66.7	168	0.726
1100	0.3166	1.159	449.0	141.8	71.5	195	0.728
1200	0.2902	1.175	473.0	162.9	76.3	224	0.728
1300	0.2679	1.189	496.0	185.1	82	257	0.719
1400	0.2488	1.207	530	213	91	303	0.703
1500	0.2322	1.230	557	240	100	350	0.685
1600	0.2177	1.248	584	268	106	390	0.688
1700	0.2049	1.267	611	298	113	435	0.685
1800	0.1935	1.286	637	329	120	482	0.683
1900	0.1833	1.307	663	362	128	534	0.677
2000	0.1741	1.337	689	396	137	589	0.672
2100	0.1658	1.372	715	431	147	646	0.667
2200	0.1582	1.417	740	468	160	714	0.655
2300	0.1513	1.478	766	506	175	783	0.647
2400	0.1448	1.558	792	547	196	869	0.630
2500	0.1389	1.665	818	589	222	960	0.613
3000	0.1135	2.726	955	841	486	1570	0.536

EXPERIMENTAL PROCEDURE

Experiment 1: Determination of the Total Rate of Heat Transfer from a Flat Plate in Different Flow Velocities.

Procedure

The following procedure may be undertaken either in natural convection conditions (fan not operating) or in forced convection conditions. However, the time taken to achieve stable temperatures when investigating natural convection can be considerable. Therefore, a forced convection experiment will be performed and the procedure is described as follows.

(i) Ensure the instrument console main switch is sin the off position. Ensure the fan is switched off
(ii) If the flat plate is not in position, open the toggle clamps retaining the plate in the tunnel and removes the existing plate from the tunnel. Replace with the flat plate and close the toggle clamps. Note that with the plate heat exchangers the power leads exit from the top of the plates.
(iii) Ensure that the air temperature thermocouple T5, surface temperature thermocouple T1 is connected to the instrument console.
(iv) Switch on the main switch and set the air velocity to a low value by closing the air throttle (9). Increase the heater power to a suitable level such that ts (T1) does not exceed 100°C.
(v) Allow the temperatures to stabilise and then record the surface temperature ts (T1), air stream temperature ta (T9), the heater supply voltage V and current I, and the air velocity reading U.
(vi) Maintain the heater voltage at the same condition and then increase the air velocity by opening the air throttle (9) slightly. Once again allow the temperatures to stabilise and repeat the readings. Repeat the procedure at increasing air velocities.

Typical data for the flat plate is shown on the following pages.

Sample Data

Heater Used:- Flat Plate

Atmospheric Pressure =1 .013 x 105 kNm^{-2}

Sample No.	**1**	**2**	**3**	**4**
Heater Volts V	98			
Heater Current I (Amps)	0.162			
Heater Power V × R Watts	61.40			
Ambient ta (T5)/°C	25			
Flat Plate ts (T1)/ °C	50.2			
Difference (ts – ta) / K	25.2			
Duct Air Velocity U m/s	2.04			

Calculations

For the Flat Plate plate (Sample No.2) the following data was collected.

Air Velocity	= 2.04 m/s
ts (T1)	= 50.2°C
ta (T5)	= 25°C
V	= 98 V
I	= 0.162 A

Film temperature: $T_{film} = \frac{T_a + T_s}{2}$

$= \frac{25+50.2}{2} + 273.15$

$= 310.75$ K

Thermophysical properties of air at film temperature from the table can be listed as

k	$= 26.4 \cdot 10^{-3}$ W/mK
υ	$= 16.794 \cdot 10^{-6}$ m^2/s
Pr	= 0.7261

Reynolds Number Re_L $= \frac{uL}{\upsilon}$

$= \frac{2.04 * 0.45}{16.794 * 10^{-6}}$

$= 0.5466 \cdot 10^5$ → laminar flow

And Nusselt Number $\overline{Nu_L}$ $= 0.664\, Re_L^{1/2}\, Pr^{1/3}$

$= 0.664 * (0.5466 \cdot * 10^5)^{1/2} * 0.7261^{1/3}$

= 139.53

Now we apply the correction to Nusselt Number with p=2 since the flow is in laminar regime

$$\overline{Nu_l} = \overline{Nu_L}\left(\frac{L}{L-l}\right)\left[1-\left(\frac{l}{L}\right)^{(p+1)/(p+2)}\right]^{p/(p+1)}$$

$$= 139.53\left(\frac{1}{0.45-0.15}\right)\left[1-\left(\frac{0.15}{0.45}\right)^{(2+1)/(2+2)}\right]^{2/(2+1)}$$

= 142.42

Now we can calculate convective heat transfer coefficient h

h $= \frac{k\,\overline{Nu_l}}{L}$

$= \frac{142.41}{0.45} 26.4 \cdot 10^{-3}$

$= 8.368$ W/m^2

And total rate of convective heat transfer becomes

Q $= hA_s(T_s - T_a)$

$= 8.368 \cdot 0.15 \cdot 0.13 \cdot (25)$

= 4.112W

Comparing with the heat input the plate by the heater

Q = V ×I

= 98×0.162

= 15.87 Watts

They are not very close values. One of the reasons for this error might be the disruption of the flow regime by the duck walls. The above formulation is for a semi-infinite plane.

EXPERIMENTAL PROCEDURE

Experiment 2: Determination of the Temperature Difference Along an Extended Surface (Pinned Plate) and Comparison with the Flat Plate

Procedure

The following procedure may be undertaken either in natural convection conditions (fan not operating) or in forced convection conditions. In both cases the use of extended surfaces does increase the rate of heat transfer. However, the time taken to achieve stable temperatures when investigating natural convection can be considerable. Therefore, a forced convection experiment will be performed and the procedure is described as follows.

(i) Ensure the instrument console main switch is sin the off position. Ensure the fan is switched off
(ii) If the pinned plate is not in position, open the toggle clamps retaining the plate in the tunnel and removes the existing plate from the tunnel. Replace with the pinned plate and close the toggle clamps. Note that with the plate heat exchangers the power leads exit from the top of the plates.
(iii) Ensure that the air temperature thermocouple T5, surface temperature thermocouple T1 and additional thermocouples fitted to the pinned (T2, T3, T4) plates are connected to the instrument console.
(iv) Switch on the main switch and set the air velocity to a low value by closing the air throttle (9). Increase the heater power to a suitable level such that ts (T1) does not exceed 100°C.
(v) Allow the temperatures to stabilise and then record the surface temperature ts (T1), air stream temperature ta (T9), the heater supply voltage V and current I, the air velocity reading U and the thermocouples on the extended surface (T2, T3, T4)

Typical data for the pinned plate is shown on the following pages.

Sample Data

Heater Used:- Pinned Plate

Atmospheric Pressure =1 .013 x 105 kNm^{-2}

Sample No.	1	2	3	4
Heater Volts V	200			
Heater Current I (Amps)	0.307			
Heater Power V × R Watts	61.4			
Ambient ta (T5)/°C	19.0			
Pinned Plate ts (T1/°C)	42.4			
Pinned Plate T2/°C	42.3			
Pinned Plate T3/°C	38.5			
Pinned Plate T4/°C	37.8			
Difference (ts – ta) / K				
Duct Air Velocity U m/s	9.8			

Calculations

For the Pinned plate (Sample No.2) the following data was collected.

Air Velocity	=9.8 m/s
ts (T1)	= 42.4°C
ta (T5)	=19.0°C
V	= 200V
I	= 0.307 A

Hence the heat input

$$Q = V \times I$$
$$= 200 \times 0.307$$
$$= 61.4 \text{ Watts}$$

Similar experiments and calculations may be undertaken for different velocities and for the remaining extended surface plate. If the temperatures recorded are plotted against the location of the thermocouples along the extended surface the effect of the fins or pins may be seen. Refer to Useful Data for the thermocouple locations. Note that due to the physical limitations of locating the tip thermocouples the location of these on the fin and pin heat exchangers are at different distances from the heater surface. However due to the high thermal conductivity of aluminium this has little effect.

Test data for the finned heat exchanger is plotted on the following page. It may be seen from the plotted data that the temperature along the fin reduces rapidly from the surface temperature t_s adjacent to the heater. The difference between the temperatures along the fin is very small.

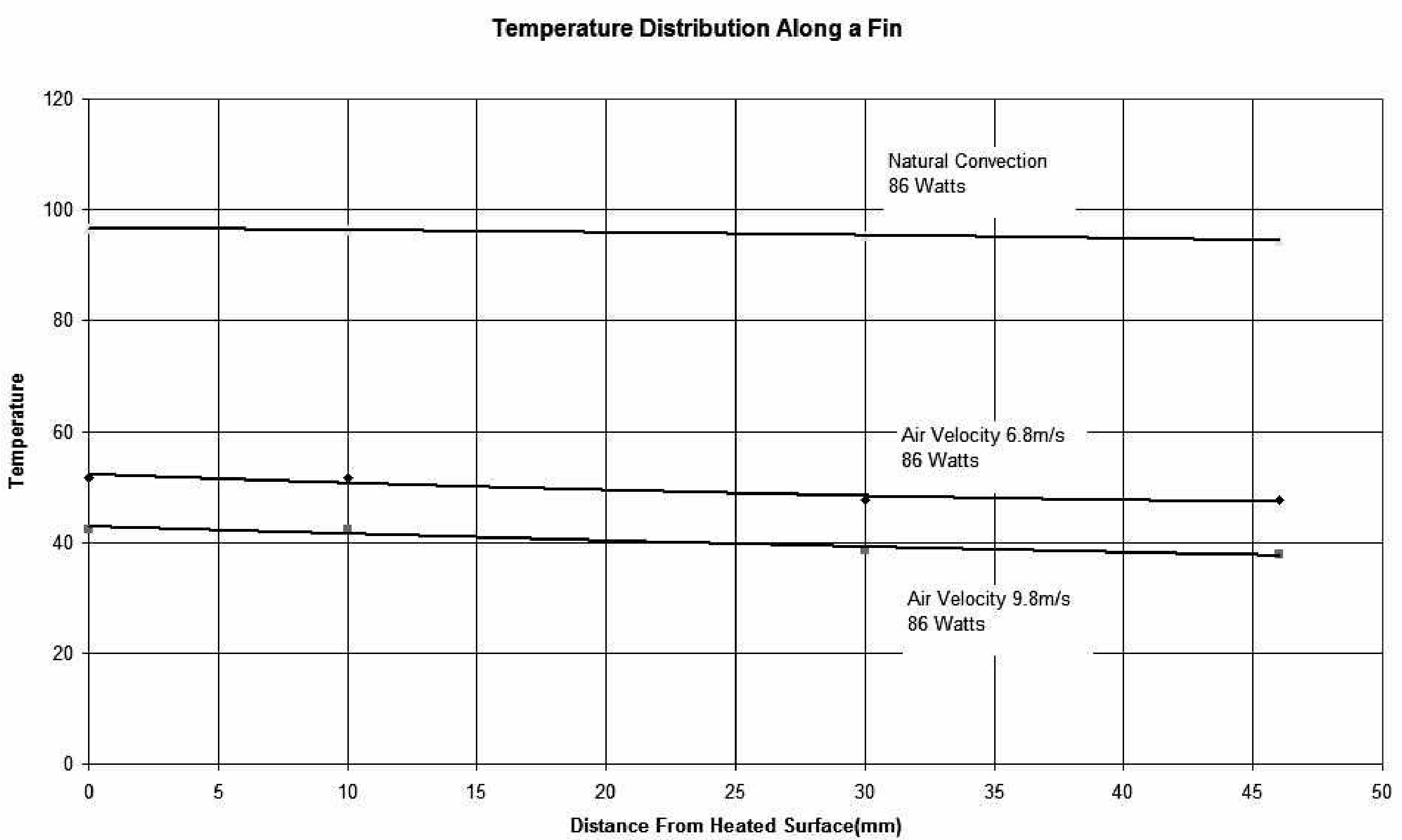
At the base of the fin the temperature is close to that of the heater and this causes heating of the fin due to conduction. However due to the fin area and the air stream the heat is conveyed rapidly to the air.

This establishes a temperature gradient along the fin. The effectiveness of the fins depends not only upon the fin surface area but also its thickness and conductivity. The material used for all of the plates is aluminium, which has a thermal conductivity of approximately 230 W/m K.

If the material were cast iron for example (as used on many early air-cooled engines) the thermal conductivity of this material is approximately 55 W/mK. Hence the “resistance” to heat conduction along the fins would be approximately four times as great and the slope of the temperature gradient would be expected to be higher.

It can be seen that at the higher air velocity the temperatures are slightly lower but the gradients remain the same along the fin.

Sample data for the same plate operating under natural convection conditions is also shown in the graph. Here it can be seen that in order to dissipate a lower heat input (90Watts) the temperatures are higher both at the base t_s and along the fin. Also, the gradient along the fin is slightly higher than in the forced convection situation.


Temperature Distribution Along a Fin
Temperature
Distance From Heated Surface(mm)
Natural Convection
86 Watts
Air Velocity 6.8m/s
86 Watts
Air Velocity 9.8m/s
86 Watts
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
45
50