LABORATORY MANUAL

ME49601 Thermofluids Laboratory II – Heat Transfer Laboratory

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CONTENTS

Experiment No. 1 Forced Convection Heat Transfer

Objectives

Determination of average Nusselt number for forced convection in a heated circular pipe at various Reynolds numbers, and correlation for Nusselt number.

Apparatus

Test pipe section of circular cross-section, blower, nichrome wire heater wound on test pipe, 6 chromel alumel thermocouples (one at entrance of test section, one at exit of test section and four embedded in the wall of the test section), orifice-meter, U-tube water manometer, dimmerstat, ammeter, voltmeter, digital temperature indicator, selector switches for thermocouples

Experimental Setup

The setup consists of a blower unit fitted with the test pipe of circular cross-section. The test section, which is 50 cm long, is heated by means of a Nichrome wire heater that is wound on the test section. The air temperature at the entrance of the test section (T_1) is measured by means of a thermocouple placed 5 cm upstream of the test section. Four thermocouples are embedded in the test section. These thermocouples measure the wall temperatures (T_2, T_3, T_4 and T_5) at 4 locations equally spaced in the axial direction. The air temperature at the exit of the test section (T_6) is measured by a thermocouple placed 5 cm downstream of the test section. The 6 thermocouples are placed 10 cm apart in the axial direction. The test pipe is connected to the delivery side of the blower. The flow rate of air through the pipe is measured with the help of an orifice-meter. The pressure drop across the orifice is measured using a U-tube water manometer. The input to the heater is given through a dimmerstat.

Draw a schematic of the experimental setup. Symbols used in your observation table and sample calculations should be indicated on your sketch. The range and precision of instruments should also be indicated (e.g. dimmerstat 0-2A, 0-260 V a.c., voltmeter 0-200V, ammeter 0-2A, rating of motor for blower 1/2 h.p.). Indicate the position of the thermocouples on your schematic.

Procedure

1) Record the room temperature.
2) Start the blower and adjust the valve so that the deflection of the manometer connected to the orifice-meter is the maximum (to get the maximum flow rate through the pipe).
3) Start heating the test section with the help of the dimmerstat. Adjust the power input with the help of the Voltmeter and ammeter to a value between 50 W and 100 W.
4) Note the readings of the 6 thermocouples, manometer deflection, voltage and current to the heater at suitable time intervals (e.g. 10 minutes), until steady state is reached. **Note: Keep the flow rate and power input fixed; otherwise, steady state will not be reached.**
5) Repeat the above procedure for two more flow rates, keeping the power input fixed at the same value.
6) Repeat the above procedure for another power input (below 150 W), keeping the flow rate fixed at the last value.

Precautions

Keep the dimmerstat at zero position before switching on power supply.
Do not exceed 150 Watts.
Do not stop the blower while the heater is on.
Handle the change-over switch of temperature indicator gently when changing from one position to another.

Observations

Type of thermocouple used: Chromel Alumel
Manometer fluid: Water
Fluid flowing through pipe: Air
Outside diameter of pipe, D_o = 32 mm
Inside diameter of pipe, D_i = 28 mm
Orifice diameter, d = 14 mm
Length of heated test section, L = 50 cm
Distance between thermocouples,l = 10 cm
Coefficient of discharge, c_d (for large Re) = 0.64
Room temperature, T_0 =
Least count of scale attached to manometer =

Run No. : 1 (Volume flow rate = $(Q_{flow})_1$, Heater power = P_1)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power P (W)	Manometer reading Left (mm)	Right (mm)	H (mm)	T_1 (^0C)	T_2 (^0C)	T_3 (^0C)	T_4 (^0C)	T_5 (^0C)	T_6 (^0C)
1													
2													
. . .													
Steady state													

Run No. : 2 (Volume flow rate = $(Q_{flow})_2$, Heater power = P_1)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power P (W)	Manometer reading Left (mm)	Right (mm)	H (mm)	T_1 (^0C)	T_2 (^0C)	T_3 (^0C)	T_4 (^0C)	T_5 (^0C)	T_6 (^0C)
1													
2													
. . .													
Steady state													

Run No. : 3 (Volume flow rate = $(Q_{flow})_3$, Heater power = P_1)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power P (W)	Manometer reading Left (mm)	Right (mm)	H (mm)	T_1 (^0C)	T_2 (^0C)	T_3 (^0C)	T_4 (^0C)	T_5 (^0C)	T_6 (^0C)
1													
2													
. . .													
Steady state													

Run No. : 4 (Volume flow rate = $(Q_{flow})_3$, Heater power = P_2)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power P (W)	Manometer reading Left (mm)	Right (mm)	H (mm)	T_1 (^0C)	T_2 (^0C)	T_3 (^0C)	T_4 (^0C)	T_5 (^0C)	T_6 (^0C)
1													
2													
. . .													
Steady state													

Results and discussion

The following should be presented:

1) A sample calculation. (Each student should select a different set of readings).
2) A table summarizing the calculations (e.g. with Nu and Re for each run.)
3) A plot of log(Nu) vs log(Re) obtained from your calculated values & plot of Dittus-Boelter correlation ($Nu = 0.023\, Re^{0.8}\, Pr^{0.4}$) on the same set of axes.
4) Determination of correlation for Nusselt number.
5) Uncertainty analysis for Nusselt and Reynolds numbers.
6) A plot of the wall temperature distribution.
7) Comparison of your correlation with Dittus-Boelter correlation.
8) Discussion of results and sources of errors.

Sample calculation

Density of water,

$$\rho_w = 1000 \text{ kg/m}^3$$

Gravitational acceleration,

$$g = 9.81 \text{ m/s}^2$$

Average surface temperature

$$T_s = (T_2 + T_3 + T_4 + T_5) / 4$$

Average temperature of air

$$T_a = (T_1 + T_6) / 2$$

Density of air at temperature T_a and atmospheric pressure ($p_{atm} = 1.01325 \times 10^5$ N/m^2)

$$\rho_{air} = p_{atm} / (R\, T_a),\ T_a \text{ in Kelvin, } R = 287 \text{ J / (kg K)}$$

Volume flow rate of air through orifice

$$Q_{flow} = c_d\ (\pi\, d^2 / 4)\ [2\, g\, H\, (\rho_w / \rho_{air} - 1)]^{1/2}$$

Mass flow rate of air through pipe

$$m = \rho_{air}\, Q_{flow}$$

Rate of heat transfer to the air

$$Q_a = m\, c_p\, (T_6 - T_1)$$

Power input to heater

$$P = V\, I$$

Is P greater than, equal to or less than Q_a ?

Surface area of heated section

$$A = \pi\, D_i\, L$$

Average heat flux

$$q_a = Q_a / A$$

$$q_i = P / A$$

Is q_a greater than, equal to or less than q_i ?

Average heat transfer coefficient

$$h_a = q_a / (T_s - T_a)$$

Average Nusselt number

$$Nu = h_a\, D_i / k,\ k = \text{thermal conductivity of air at } T_a$$

Average velocity

$$V = Q / (\pi\, D_i^2 / 4)$$

Reynolds number

$$Re = V\, D_i / \nu,\ \nu = \text{kinematic viscosity of air at } T_a$$

Experiment No. 2 Natural Convection Heat Transfer

Objectives

Determination of local heat transfer coefficients and average Nusselt numbers for free convection from a heated vertical cylinder at various Rayleigh numbers, and correlation for Nusselt number.

Apparatus

Vertical brass tube in a rectangular duct open at the top and bottom with perspex on one side, electrical heating element, 7 chromel alumel thermocouples to measure the surface temperature of the cylinder at several axial locations, 1 chromel-alumel thermocouple for measuring the temperature of the air inside the enclosure, ammeter, voltmeter and dimmerstat, digital temperature indicator, selector switches for thermocouples

Experimental Setup

The apparatus consists of a brass tube fitted vertically in a rectangular duct. The duct is open at the top and bottom and forms an enclosure. One side of the duct is made of perspex, for visualization. An electric heating element is kept in the vertical tube to heat the tube surface. The tube surface is polished to minimize radiation losses. The temperature of the cylindrical tube is measured at seven axial locations using chromel alumel thermocouples. Another thermocouple is used to measure the temperature of the air inside the enclosure.

Draw a schematic of the experimental setup. Symbols used in your observation table and sample calculations should be indicated on your sketch. The range and precision of instruments should also be indicated (e.g. dimmerstat 0-2A, 0-230 V a.c., voltmeter 0-200V, ammeter 0-2A, temperature indicator 0-300^{0}C). Indicate the position of the thermocouples on your schematic.

Procedure

1) Record the room temperature.
2) Start heating the cylinder with the help of the dimmerstat. Adjust the power input with the help of the Voltmeter and ammeter to a value between 40 W and 70 W.
3) Note the readings of the 8 thermocouples, voltage and current to the heater at suitable time intervals (e.g. 10 minutes), until steady state is reached**. Note: Keep the power input fixed; otherwise, steady state will not be reached.**
4) Repeat the above procedure for another power input.

Precautions

Keep the dimmerstat at zero position before switching on power supply.
Do not exceed 80 Watts.
Handle the change-over switch of temperature indicator gently when changing from one position to another.

Observations

Thermocouple type: Chromel Alumel

Diameter of cylinder, d	= 38 mm
Length of cylinder, L	= 50 cm
Vertical distance between thermocouples 1 and 2	= 5 cm
Vertical distance between thermocouples 2 and 3	= 5 cm
Vertical distance between thermocouples 3 and 4	= 10 cm
Vertical distance between thermocouples 4 and 5	= 10 cm
Vertical distance between thermocouples 5 and 6	= 10 cm
Vertical distance between thermocouples 6 and 7	= 10 cm
Room temperature, T_0	=

Run No. : 1 (Heater power = P_1)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power (W)	T_1 (^0C)	T_2 (^0C)	T_3 (^0C)	T_4 (^0C)	T_5 (^0C)	T_6 (^0C)	T_7 (^0C)	$T_8 = T_a$ (^0C)
1												
2												
. . .												
Steady state												

Run No. : 2 (Heater power = P_2)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power (W)	T_1 (^0C)	T_2 (^0C)	T_3 (^0C)	T_4 (^0C)	T_5 (^0C)	T_6 (^0C)	T_7 (^0C)	$T_8 = T_a$ (^0C)
1												
2												
. . .												
Steady state												

Run No. : 3 (Heater power = P_3)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power (W)	T_1 (^0C)	T_2 (^0C)	T_3 (^0C)	T_4 (^0C)	T_5 (^0C)	T_6 (^0C)	T_7 (^0C)	$T_8 = T_a$ (^0C)
1												
2												
. . .												
Steady state												

Results and discussion

The following should be presented:

1) A sample calculation. (Each student should select a different set of readings).
2) A table summarizing the calculations (e.g. with Nu_{av} and Ra for each run.)
3) A plot of log(Nu_{av}) vs log(Ra) obtained from your calculated values & plot of standard empirical correlation on the same set of axes.
4) Determination of correlation for average Nusselt number.
5) Uncertainty analysis for Nusselt and Rayleigh numbers.
6) A plot of the local heat transfer coefficient with axial distance along the surface of cylinder.
7) Discussion of results and sources of errors.

Sample calculation

Heat Transfer Rate

$$Q = V\, I$$

Heat Transfer Area

$$A_s = \pi\, D\, L$$

Heat flux

$$q = Q / A_s$$

Average surface temperature

$$T_s = (T_1+T_2 + T_3 + T_4 + T_5 + T_6+T_7) / 7$$

Ambient temperature of air in enclosure

$$T_a = T_8$$

Film temperature

$$T_f = (T_s + T_a) / 2$$

Local heat transfer coefficient at 7 axial locations

$h_j = q / (T_j - T_a)$, $j = 1, 2, \ldots, 7$

Average heat transfer Coefficient

$h_{av} = q / (T_s - T_a)$

Average Nusselt number

$Nu_{av} = h_{av} L / k$, k = thermal conductivity of air at T_f

Gravitational acceleration

$g = 9.81$ m/s^2

Coefficient of thermal expansion

$\beta = 1 / T_f$, T_f in Kelvin

Grashof number

$Gr = g \beta (T_s - T_a) L^3 / \nu^2$, ν = kinematic viscosity of air at T_f

Rayleigh number

$Ra = Gr\, Pr$, Pr = Prandtl number of air at T_f

Standard empirical correlation for natural convection (for comparison)

$$Nu = \begin{cases} 0.56\, Ra^{1/4}, & 10^4 < Ra < 10^9 \\ 0.13\, Ra^{1/3}, & 10^9 < Ra < 10^{12} \end{cases}$$

Experiment No. 3 Measurement of Emissivity

Objectives

Determination of emissivity

Apparatus

A circular aluminium test plate, a circular plate of identical size blackened by a layer of lamp black, 2 Nichrome heating strips wound on mica sheet and sandwiched between two mica strips, 2 asbestos cement sheets, enclosure, ammeter, voltmeter, 2 dimmerstats, 2 double pole double throw switches, 3 thermocouples, digital temperature indicator, selector switches for thermocouples

Experimental Setup

The setup consists of two circular aluminium plates identical in size and provided with heating coils. The plates are mounted vertically on an asbestos cement sheet and are kept in an enclosure so as to provided undisturbed natural convection surroundings. The enclosure has one side of perspex and a bottom fitting on the cement sheet.

Plate 2 is blackened by a thick layer of lamp black to form the idealized black surface. Plate 1 is the test plate whose emissivity is to be measured. The temperatures of the test plate (T_1) and black plate (T_2) are measured by two thermocouples. Separate wires are connected to diametrically opposite points to get the average surface temperature of the plates. Another thermocouple is kept in the enclosure to estimate the ambient temperature (T_3) inside the enclosure.

The power input to the heaters is varied by separate dimmerstats and is measured by using an ammeter and voltmeter with the help of double pole double throw switches. The power inputs to the two plates are transferred from the plates to the surroundings by conduction, convection and radiation. The experimental setup is designed in such a way that under *steady state* conditions, the heat transferred to the surroundings by conduction and convection is same for both the plates *when the surface temperatures of the two plates are the same* (i.e. if $T_1 = T_2 = T_{ss}$ at steady state). Under these conditions, the difference in the power input to the black plate (W_2) and the power input to the test plate (W_1) is because of the difference in radiation characteristics due to their different emissivities. The difference in the power inputs to the two heaters can be used to estimate the emissivity of the test plate.

Draw a schematic of the experimental setup. Symbols used in your observation table and sample calculations should be indicated on your sketch. The range and precision of instruments should also be indicated (e.g. dimmerstat 0-2A, 0-260 V a.c., voltmeter 0-100/200V, ammeter 0-2A, temperature indicator 0-300^{0}C).

Theory

At steady state, the power input to each plate is equal to the heat transferred from the plate to the surroundings by conduction (q_{cond}), convection (q_{conv}) and radiation (q_{rad}). Thus,

$$W_1 = (q_{cond})_1 + (q_{conv})_1 + (q_{rad})_1$$
$$W_2 = (q_{cond})_2 + (q_{conv})_2 + (q_{rad})_2,$$

where the subscripts 1 and 2 refer to plates 1 and 2 respectively. If the surface temperatures of the two plates are the same at steady state i.e. if $T_1 = T_2 = T_{ss}$, the heat transferred to the surroundings by conduction and convection is the same for each plate, that is, $(q_{cond})_2 = (q_{cond})_1$ and $(q_{conv})_2 = (q_{conv})_1$. Under these conditions,

$$W_2 - W_1 = (q_{rad})_2 - (q_{rad})_1.$$

The view factor for radiative heat exchange between the two plates is zero. Assuming that the emissivity of the "black" plate is 1, $(q_{rad})_2$ is given by

$$(q_{rad})_2 = \sigma A (T_{ss}^4 - T_3^4),$$

where T_3 is the surrounding temperature inside the enclosure, A is the area of the black plate and σ is the Stefan-Boltzmann constant, while $(q_{rad})_1$ is given by

$$(q_{rad})_1 = \varepsilon\sigma A (T_{ss}^4 - T_3^4),$$

where ε is the emissivity of the test plate whose area is the same as that of the black plate. Thus,

$$W_2 - W_1 = \sigma A (T_{ss}^4 - T_3^4) (1 - \varepsilon) .$$

This relation may be used to estimate ε using the values of W_1, W_2, T_{ss} and T_3.

Procedure

1) Record the room temperature.
2) Select the proper range of voltage on voltmeter/ammeter.
3) Gradually increase the power input (W_2) to the heater to plate 2 (black plate) and adjust it to some value, say, 20 W. Adjust the power input (W_1) to plate 1 (the test plate) to a value slightly below W_1, say, 17 W.
4) Monitor the temperature of the two plates and adjust the power input to the test plate (plate 1) using the dimmerstat so that *steady state is reached with* $T_1 = T_2$. Note that this requires some trial and error, and one may need to wait for a sufficiently long interval of time (of the order of 1 hour). Maintain a record of the temperatures and power inputs at suitable time intervals.
5) Repeat the experiment with increased values of W_2 (viz. 30 W, 40 W, 50 W etc.) and W_1 (initial values less than 25 W, 35 W, 45 W etc.)

Precautions

Keep the dimmerstats at zero position before switching on power supply.
Use the proper range on the voltmeter and ammeter.
The power input to the heaters should be increased gradually.
Handle the change-over switch of temperature indicator gently when changing from one position to another.

Observations

Size of enclosure	= 50 cm x 30 cm x 30 cm
Diameter of test plate, D	= 160 mm
Diameter of black plate, D	= 160 mm
Area of each plate, A	$= 2\ \pi D^2/4 =$
Stefan Boltzmann constant, σ	$= 5.67 \times 10^{-8}$ W / (m^2 K^4)
Room temperature, T_0	=

Run No. : 1

Sl. No.	Time (min)	Ambient temperature T_3 ^0C	Test plate (Plate 1) Temperature T_1 ^0C	Voltage V_1 (V)	Current I_1 (A)	Power W_1 (W)	Black plate (Plate 2) Temperature T_2 ^0C	Voltage V_2 (V)	Current I_2 (A)	Power W_2 (W)
1										
2										
3										
. . .										
Steady state										

Run No. : 2

Sl. No.	Time (min)	Ambient temperature T_3 ^0C	Test plate (Plate 1) Temperature T_1 ^0C	Voltage V_1 (V)	Current I_1 (A)	Power W_1 (W)	Black plate (Plate 2) Temperature T_2 ^0C	Voltage V_2 (V)	Current I_2 (A)	Power W_2 (W)
1										
2										
3										
. . .										
Steady state										

Run No. : 3

Sl. No.	Time (min)	Ambient temperature T_3 ^0C	Test plate (Plate 1) Temperature T_1 ^0C	Voltage V_1 (V)	Current I_1 (A)	Power W_1 (W)	Black plate (Plate 2) Temperature T_2 ^0C	Voltage V_2 (V)	Current I_2 (A)	Power W_2 (W)
1										
2										
3										
. . .										
Steady state										

Results and discussion

The following should be presented:

1) A sample calculation. (Each student should select a different set of readings).
2) A plot of ε vs T_{ss}
3) Discussion of results and sources of errors.

Sample calculation

Stefan Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
Power input to plate 1, $W_1 = V_1 I_1$
Power input to plate 2, $W_2 = V_2 I_2$
Plate area $A = 2\, \pi D^2/4$
Emissivity of test plate $\varepsilon = 1 - (W_2 - W_{1)}\, / \, \sigma A\, (T_{ss}{}^4 - T_3^4)$

Experiment No. 4 Heat Transfer from Pin Fin

Objectives

Determination of temperature distribution along pin fin in natural and forced convection and estimation of the rate of heat transfer from the fin

Apparatus

A brass fin of circular cross section in a long rectangular duct, blower, orificemeter, U-tube water manometer, dimmerstat, ammeter, voltmeter, digital temperature indicator, selector switches for thermocouples, 6 iron constantan thermocouples

Experimental Setup

The setup consists of a brass fin of circular cross section fitted across a long rectangular duct. One end of the duct is connected to the suction side of a blower. The flow rate of air inside the duct is measured by an orificemeter fitted on the delivery side of the blower. The pressure drop across the orifice is measured by a U-tube manometer using water as the manometer fluid. When the blower is switched on, air flows past the fin perpendicular to its axis. One end of the fin projects outside the duct and is heated electrically by a heater. The input to the heater is given through a dimmerstat. The voltage across the heating coil is measured by a voltmeter; the current through the coil is measured by an ammeter. The temperatures (T_1, T_2, T_3, T_4 and T_5) at 5 equally spaced points along the length of the fin are measured by iron constantan thermocouples. Another thermocouple measures the temperature (T_6) of air inside the rectangular duct.

Draw a schematic of the experimental setup. Symbols used in your observation table and sample calculations should be indicated on your sketch. The range and precision of instruments should also be indicated (e.g. dimmerstat 0-2A, 0-230 V a.c., voltmeter 0-200V, ammeter 0-2A, rating of motor for blower 1/2 h.p.). Indicate the position of the thermocouples on your schematic.

Procedure

1) Record the room temperature.
2) Start heating the fin by switching on the heater element. Adjust the voltage to 80 V using the dimmerstat.
3) Note the readings of the 6 thermocouples, voltage and current to the heater at suitable time intervals (e.g. 5 minutes or 10 minutes), until steady state is reached**. Note: Keep the power input fixed; otherwise, steady state will not be reached.**
4) Start the blower and adjust the valve so that the deflection of the manometer connected to the orifice-meter is the maximum (to get the maximum flow rate through the duct). Note the readings of the 6 thermocouples, manometer deflection, voltage and current to the heater at suitable time intervals (e.g. 5 minutes or 10 minutes), until steady state is reached**. Note: Keep the flow rate and power input fixed; otherwise, steady state will not be reached.**
5) Repeat the above procedure for two more flow rates, keeping the power input fixed at the same value.

Precautions

Keep the dimmerstat at zero position before switching on power supply.
Handle the change-over switch of temperature indicator gently when changing from one position to another.

Observations

Type of thermocouple used: Iron Constantan
Manometer fluid: Water

Duct Size : 100 mm x 150 mm
Diameter of fin, D = 12.5 mm
Length of fin, L = 150 mm
Inside diameter of delivery pipe, D_i = 25 mm
Orifice diameter, d = 12.5 mm
Thermal conductivity of fin material (brass), k = 110 W / (m K)
Coefficient of discharge, c_d (for large Re) = 0.64
Room temperature, T_0 =
Least count of scale attached to manometer =

Run No. : 1 (Natural Convection Mode)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power (W)	T_1 (^{0}C)	T_2 (^{0}C)	T_3 (^{0}C)	T_4 (^{0}C)	T_5 (^{0}C)	T_6 (^{0}C)
1										
2										
. . .										
Steady state										

Run No. : 2 (Forced Convection Mode)

Sl. No.	Time (min)	Voltage V (V)	Current I (A)	Power P (W)	Manometer reading Left (mm)	Right (mm)	H (mm)	T_1 (^{0}C)	T_2 (^{0}C)	T_3 (^{0}C)	T_4 (^{0}C)	T_5 (^{0}C)	T_6 (^{0}C)
1													
2													
. . .													
Steady state													

Results and discussion

The following should be presented:

1) A sample calculation.
2) A plot of the temperature distribution along the fin in natural and forced convection.

Sample calculation

Density of water,

$\rho_w = 1000 \text{ kg/m}^3$

Gravitational acceleration,

$g = 9.81 \text{ m/s}^2$

Power input to heater

$P = V I$

Average fin temperature

$T_m = (T_1 + T_2 + T_3 + T_4 + T_5) / 5$

Base temperature of fin

$T_{base} = T_1$

Duct fluid temperature

$T_f = T_6$

Mean film temperature (for evaluation of fluid properties)

$T_{mf} = (T_m + T_f) / 2$

Density of air at temperature T_f and atmospheric pressure ($p_{atm} = 1.01325 \times 10^5 \text{ N/m}^2$)

$\rho_{air} = p_{atm} / (R\, T_f)$, T_f in Kelvin, $R = 287 \text{ J / (kg K)}$

Volume flow rate of air through orifice

$Q_{flow} = c_d\ (\pi\, d^2 / 4)\ [2\, g\, H\, (\rho_w / \rho_{air} - 1)]^{1/2}$

Area of duct

$$A_{duct} = 100 \times 150 \times 10^{-4}\,\text{m}^2$$

Velocity of air at duct fluid temperature (T_f)

$$V_f = \frac{Q_{flow}}{A_{duct}}$$

Ratio of densities of air at T_f and T_{mf}

$$\frac{\rho_{air}}{\rho} = \frac{T_{mf} + 273.15}{T_f + 273.15}$$

Velocity of air at duct mean film temperature (T_{mf})

$$V = \frac{\rho_{air}}{\rho} V_f$$

Reynolds number

$$\text{Re} = \frac{\rho V D}{\mu}$$

Coefficient of thermal expansion

$$\beta = \frac{1}{T_{mf} + 273.15}$$

Characteristic temperature difference

$$\Delta T = T_m - T_f$$

Grashof mumber

$$Gr = \frac{g\beta \Delta T D^3}{\upsilon^2}$$

Prandtl number

$$\Pr = \frac{\mu c_p}{k_{air}}$$, k_{air} = thermal conductivity of air at T_{mf}

Rayleigh number

Ra = Gr Pr

Nusselt number

For natural convection,

$Nu = 1.1\ Ra^{1/6}$, $10^{-1} < Ra < 10^4$

$Nu = 0.53\ Ra^{1/4}$, $10^4 < Ra < 10^9$

$Nu = 0.13\ Ra^{1/3}$, $10^9 < Ra < 10^{12}$

For forced convection,

$Nu = 0.615\ Re^{0.466}$, $40 < Re < 4000$

$Nu = 0.174\ Re^{0.618}$, $4000 < Re < 40000$

Heat transfer coefficient

$$h = Nu\frac{k_{air}}{D}$$

Cross sectional area of fin

$A = \pi D^2 / 4$

Circumference of fin

$C = \pi D$

Fin efficiency-

Ratio of rate of actual heat transfer from fin to the rate of ideal heat transfer from an identical fin of infinite thermal conductivity, with the entire surface at the fin base temperature (assuming the heat transfer coefficient to be the same)

For a fin with negligible heat transfer from the tip,

$$\eta = \frac{\tanh\left(mL\right)}{mL},$$

where

$$m = \sqrt{\frac{hC}{kA}}$$

Rate of heat transfer from a fin with negligible heat transfer from the tip

$$Q = \sqrt{hCkA}\left(T_{base} - T_f\right)\tanh\left(mL\right)$$

Fin effectiveness-

Ratio of the rate of heat transfer from the fin of base area A to the rate of heat transfer without fin, from surface of area A (assuming the heat transfer coefficient to be the same)

$$\varepsilon = \frac{A_{fin}}{A}\eta$$

$$A_{fin} = CL$$

Appendix- Properties of dry air at atmospheric pressure
(Ref.: Instruction Manual, Raste Enterprises, Sangli)

T ^{0}C	ρ kg/m^3	c_p kJ/(kg K)	μ x 10^6 N s /m^2	K W/(m K)	υ x 10^6 m^2/s	Pr
0	1.293	1.005	17.2	0.0244	13.28	0.707
10	1.247	1.005	17.7	0.0251	14.16	0.705
20	1.205	1.005	18.1	0.0259	15.06	0.703
30	1.165	1.005	18.6	0.2670	16.00	0.701
40	1.128	1.005	19.1	0.0276	16.96	0.699
50	1.093	1.005	19.6	0.0281	17.95	0.698
60	1.060	1.005	20.1	0.0290	18.97	0.696
70	1.029	1.009	20.6	0.0297	20.02	0.694
80	1.000	1.009	21.1	0.0305	21.09	0.692
90	0.972	1.009	21.5	0.0313	22.10	0.690
100	0.946	1.009	21.9	0.0321	23.13	0.688
120	0.898	1.009	22.9	0.0334	28.45	0.686
140	0.854	1.013	23.7	0.0349	27.80	0.684
160	0.815	1.017	24.5	0.0364	30.09	0.682
180	0.779	1.022	25.3	0.0378	32.49	0.681
200	0.746	1.026	26.0	0.0393	34.85	0.680
250	0.674	1.038	27.4	0.0427	40.61	0.677
300	0.615	1.047	29.7	0.0461	48.33	0.674
350	0.566	1.059	31.4	0.0491	55.46	0.676
400	0.524	1.255	33.0	0.0521	63.09	0.678
500	0.456	1.093	36.2	0.0575	79.38	0.687
600	0.404	1.114	39.1	0.0622	96.89	0.699
700	0.362	1.135	41.8	0.0671	115.4	0.706
800	0.329	1.156	44.3	0.0718	134.8	0.713
900	0.301	1.172	46.7	0.0763	155.1	0.717
1000	0.277	1.185	49.0	0.0807	177.1	0.719