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Evaluation of Convective Heat Transfer Coefficient of Air Flowing Through an Inclined Circular Duct

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***Abstract*— Circular duct has various applications- pipelines, HVAC, and refrigeration- as it can withstand more pressure drop than non-circular duct. Generally, fluids are forced through the pipes for various purposes. So, Pipes are generally required to be installed at various positions in order to minimize or maximize heat loss, regulate the flow and for the proper utilization of space to meet the design considerations. When fluids are forced through pipes, Heat transfer follows forced convection and the convective heat transfer coefficient plays pivotal role in the design considerations. Hence, it is must to understand the influence of factors such as inclination of pipe, velocity of fluid, and temperature gradient on convective heat transfer coefficient. Literature survey showed little research on effect of those factors in convective heat transfer coefficient. The main purpose of this work is to find out the nature of convective heat transfer coefficient when the air is forced through the copper pipe at different inclination and velocity at constant heat input. Different temperature at various points and the manometer reading were noted and were used to calculate Reynolds number, Prandtl number, and Nusselts number to find out convective heat transfer coefficient. The result obtained was plotted to observe the nature of heat transfer coefficient. The graph showed that heat transfer coefficient rises to its peak at 90^0 inclination of the duct for velocity of 12 m/s and falls to minimum value at 30^0 inclination of the duct for velocity of 8.38 m/s. It is also found that heat transfer coefficient is linearly dependent on velocity and is also influenced by inclination of the duct.**

Keywords - Fluids, convection, Convective heat transfer coefficient, Reynolds number, Prandtl number, Nusselts number.

1. INTRODUCTION

1.1. Heat Transfer:

Heat transfer may be defined as the transmission of energy from one region to another as a result of temperature gradient and it takes place by three modes

a) Conduction
b) Radiation
c) Convection

a) Conduction:
Conduction is heat transfer phenomena from one part of the substance to same substance or from one part of substance to another without appreciable displacement of molecules forming the substance.

b) Radiation:
Radiation is the process of heat transfer in which transfer of energy takes place in absence of medium. It occurs place in vacuum.

c) Convection:
The heat transfer by the energy exchange between the molecules of fluid due to the temperature difference is known as convection.
It can be classified as follows:

I) Free Convection
Free convection occurs due to the buoyancy effect that is by the difference in density of fluid molecules. The heavy molecules travel down to the bottom surface and light molecules travels up there by exchange of heat occurs. The heat transfer coefficient varies with geometry of the system.

II) Forced Convection
The convection process where the fluid motion in a pipe is regulated by external media that is blower or pump is called forced convection. Here, the heat transfer takes place between the adjacent molecules. Forced convection augments the convection process.

1.2. Mechanism of Forced Convection:

Convection heat transfer occurs due to fluid motion and heat conduction there by it is a complicated phenomenon. When fluid is forced, the convection rate is augmented as compared to that of natural convection. The heat transfer process follows Newton's laws of cooling and can be expressed mathematically as follows:

$$Q_{Conv} = hA(T_S-T_a) \qquad \text{Equation (1)}$$

Where, Q= rate of heat transfer in watts
h= heat transfer coefficient in w/m^{2}c^o
T_S= Surface Temperature in c^o.
T_a=ambient temperature in c^o.

The convection heat transfer coefficient depends on boundary cross-sectional area of pipe through which fluid flows, the temperature difference across test specimen and fluid properties.

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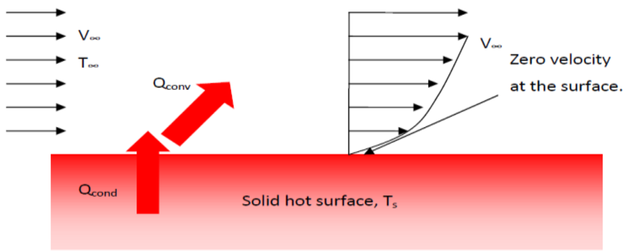

Fig. 1.1: Forced convection.

The velocity of fluid at the boundary of solid surface is nearly zero and is known as no slip condition whereas the velocity of fluid at the centre of the pipe is maximum. The heat transfer rate at the boundary surface of pipe is conduction as there is no motion of fluid molecules. Therefore,

$$\left.\begin{array}{l} \dot{q}_{conv} = \dot{q}_{cond} = -k_{fluid} \left.\dfrac{\partial T}{\partial y}\right|_{y=0} \\ \dot{q}_{conv} = h(T_s - T_\infty) \end{array}\right\} \rightarrow h = \frac{-k_{fluid} \left.\dfrac{\partial T}{\partial y}\right|_{y=0}}{T_s - T_\infty} \quad (W/m^2.K)$$

2. EXPERIMENTAL WORK

2.1. Experimental Setup of Circular Duct

The experimental setup which comprises of test specimen is made up of copper having Circular cross section of dimensions 36x38x500mm, which is connected to a blower through a GI pipe and bellows. Mounting of the five thermocouples takes place on test section at equal distance. The equipment is mounted on 2ft X 3 ft rectangular board which is made up of mild stainless sheets. The panel board consists of voltmeter, ammeter, temperature indicator, and manometer. The difference in height is observed manually whereas other readings are digitally displayed. The Nichrome wire surrounds the test specimen through which specimen is heated. Also, insulation is provided by wool or rope so that heat is not dissipated to surrounding.

2.2. Experimental Setup of Circular Duct at 0^0

Fig. 2.2 Experimental Setup of Circular Duct at 0^0

2.3 Experimental Setup of Circular Duct at 30^0

Fig. 2.3 Experimental Setup of Circular Duct at 30^0

2.4 Experimental Setup of Circular Duct at 60^0

Fig. 2.4 Experimental Setup of Circular Duct at 60^0

2.5 Experimental Setup of Circular Duct at 90^0

Fig. 2.5 Experimental Setup of Circular Duct at 90^0

2.6 Experimental Setup of Circular Duct at 120^0

Fig. 2.6 Experimental Setup of Circular Duct at 120^0

2.7 Experimental Setup of Circular Duct at 150^0

Fig. 2.7 Experimental Setup of Circular Duct at 150^0

3. THERMOCOUPLES

Thermocouples measure the temperature of specimen at different positions. Different types of thermocouple available are listed below.

TYPE E

Type E thermocouple is known as Chromel-Constantan thermocouple. Having more stability in comparison to type K they are used where higher accuracy is needed.

TYPE J

In oxidizing atmosphere above 550°C, Type J thermocouple degrades very rapidly. Around 750ºC they can be operated continuously while 1000°C is the maximum temperature they can withstand for short term. They are generally not used below ambient temperature due to condensation forming on the wires which leads to rusting of the iron when used below ambient temperature.

TYPE K

Due to their wide range and low cost, Type K is the most widely used thermocouples in the Oil & Gas, and refining industries. They are occasionally referred to as Chromel-Alumel thermocouples. Above about 750°C oxidation leads to drift and the need for recalibration.

TYPE N

In the range of 300 to 500°C Type N thermocouples can handle higher temperatures than type K, and also offer better repeatability. They provides far more advantages in comparison to Type R & S over at a tenth of the cost, therefore prove to be popular alternatives.

TYPE R

Type R thermocouples have similar applications as Type S but provides improved stability and a marginal increase in range. Also, Type R tend to be used in preference to Type S.

TYPE S

Type S thermocouples have capability to continually withstand temperatures up to 1450°C while they can be used at the temperature up to 1650°C for short period of time. Emf generated gets reduced if they are not protected from high temperature atmosphere which ingress metallic vapor at the tip.

TYPE T

Type T thermocouples are highly used in the laboratory application and have very rare application in industrial sector.

TYPE B

This type of thermocouple gives negligible output up to 50^{0}C. It has low electrical output below 600^{0}C, therefore not used below that temperature, and it can be used in the temperature range of 1600°C - 1800°C.

3.1. Layout of experimental set up

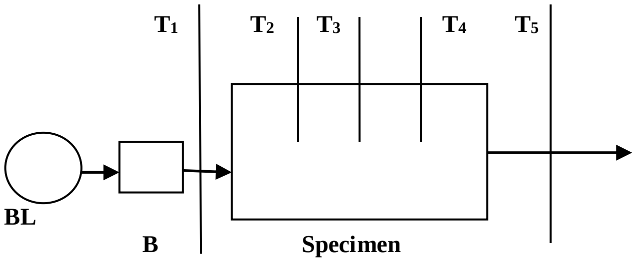

Fig.3.1 Layout of experiment setup

Where BL = Blower
B = Bellows
T_1 = Inlet temperature of air
T_5 = Outlet temperatue of air
T_2, T_3, T_4 ,= Specimen surface temperature

The above figure shows the layout of experimental setup when the pipe is at 0 ^{0}. The angle of inclinations can be varied to different angle by adjusting the positionof the pipe and obseving at the angular protacter attached to panel board. The different angles varied for this work was 0^0, 30^0, 60^0, 90^0, 120^0, 150^0. Temperature at inlet and outlet of duct is measured by temperature sensor at T_1 and T_5 respectively. The surface temperature is measured by the different thermocouples provided at equal distances on test-specimen by T_2 , T_3, T_4 respectively. Thermocouples used here is K-type because of it's easy availibilty and wide range of operating temperature. The heat input is varied by operating variac knob and the reading of voltmeter and ammeter can be digitally observed. Bellows used in this set up is for the purpose of facilitating the connecting between the blower and the copper duct. The blower valve positions can be varied at different valve position

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to vary the velocity and the manometer reading can be noted as well from manometer tube atttached to the panel.

4. METHODOLOGY

The methodology consists of detailed operating procedure of experimental set up and procedure to take the various readings such as temperature, heads, voltmeter, and ammeter reading.

4.1 Description of the Apparatus

The apparatus consists of a blower for forced circulation. The air from the blower passes through a flow passage, heater and then to the test section. Air flow is measured by the height difference of water in manometer tube. A heater placed around the tube heats the air, heat input is controlled by a dimmer stat. Temperature of the air at inlet and at outlet are measured using thermocouples. The surface temperature of the tube is measured at different sections using thermocouples embedded on the Circular duct. Test section is enclosed with wool and rope, where the circulation of rope avoids the heat loss tosurrounding.

4.2 Operating Procedure

1. The valve position is kept at desired level then the blower is turned ON.
2. Switch ON the heater unit and set the voltage to required level by operating voltage knob and wait until the voltmeter shows stable reading of desired voltage value.
3. Note down all the temperatures from T_1 to T_5, voltmeter, ammeter, and manometer head readings.
4. Repeat the procedure for the different angle of inclination of pipes and for different valve positions.

4.3 Precautions to be taken

Do's:

1. The variac knob should be at zero positions before switching ON an apparatus..
2. Operate thermocouple selector switch gently.
3. Operate the experimental set up at least once in two weeks.
4. Increase the voltage very slowly by using variec knob.

Don'ts:

1. Heating test-specimen above 200V is prohibited.
2. Do not perform operations when the line voltage is below 200V.

4.4 Specifications

Specimen : Copper Circular duct, 36 mm x 38 mm x 500 mm long.
Heater : Nichrome wire, Externally heated, Band Heater 500W.
Ammeter : Digital type,0-20amps, AC.
Voltmeter : Digital type, 0-300volts, AC.

Dimmer stat for heating Coil : 0-230v, 2amps.
Thermocouple Used : 5 no. k-type, range: 0 to 400^0c.
Centrifugal Blower : Single Phase 230v, 50 Hz, 13000rpm.
Outer duct : Aluminum.
Insulation : Wool rope

4.5. Procedure For Calculation

1) All the parameters like voltage, current, manometer head, inclination of duct and all temperatures should be noted down precisely and accurately.

2) Calculate the surface temperature, ambient temperatures and film temperature by using the following formulae

$$T_s = (T_2+T_3+T_4)/3$$
$$Ta = (T1+T5)/2$$
$$T_{film} = (Ts+Ta)/2$$

3) Find the properties of air like kinematic viscosity (ν), Prandtl number (Pr), thermal conductivity (K) at obtained film temperature.

4) Calculate the Reynolds number (Re) using formula.

$$Re= (V\ Dh)/\nu$$

5) Based on the on Reynolds number calculated above, find out Hilpert's constants: C and m.

6) Use parameters like Pr, C, m, Re to calculate Nusselts number. It's formula is given by

$$Nu = C \times Re^m \times pr^{0.333}$$

7) Find out convective heat transfer coefficient by using the formula

$$Nu= (hxDh) / K$$
$$\text{Hence, } h=(KxNu) / Dh$$

8) Repeat the calculation part for following different conditions.

a) Keeping the heat input as constant. Vary the velocities by adjusting the nozzle position at $(1/4)^{th}$ open, $(1/2)^{th}$ open, $(3/4)^{th}$ open, and full open, and for various angle of inclinations like 0^0, 30^0,60^0, 90^0 , 120^0, and 150^0.

9) Tabulate all the calculations for separate angle of inclinations.

5. RESULTS AND DISCUSSIONS

The readings are noted for constant heat input and the calculations were made. The following table shows the value of Reynolds number, Nusselts number and Heat transfer coefficient for different valve position and angle of inclinations. The following table presents only results.

Sl. No.	Θ deg	Open Valve Pos^n	Velocity (m/s)	Re	Nu	h (kW/m^2 ^{0}k)
		1/4th	11.097	21369	81.02	64.98
		1/2	12.578	25132.5	89.6	70.92
		3/4th	12.58	24736.01	88.77	70.04
01	0	Full	12.24	23966.08	86.19	68.24
		1/4th	8.386	16052.12	68.05	54.53
		1/2	12.58	24729.28	88.73	70.24
		3/4th	12.58	24926.84	89.18	70.4
02	30	Full	11.86	23680.18	86.4	67.97
		1/4th	9.375	17835.88	72.45	58.31
		1/2	16.245	31869.22	103.6	81.99
		3/4th	16.245	32268.65	104.6	82.49
03	60	Full	16.245	32191.64	104.5	82.45
		1/4th	9.375	18026.91	72.92	120.9
		1/2	20.54	40866.74	120.9	95.38
		3/4th	22.966	46128.92	131	102.7
04	90	Full	23.72	47907.58	135.1	105.6
		1/4th	13.26	25766.61	90.98	72.51
		1/2	21.787	43276.04	124.9	98.48
		3/4th	23.345	46297.83	131.1	103.6
05	120	Full	23.34	46990.67	132.9	104.3
		1/4th	12.57	21042.95	81.36	70.12
		1/2	19.66	39401.96	117.4	92.26
		3/4th	24.08	48753.44	136.9	108.4
06	150	Full	23.34	46549.82	130.9	103.9

5.1 Graphs

i. Comparison between velocity and heat transfer co efficient for 0^0 inclination

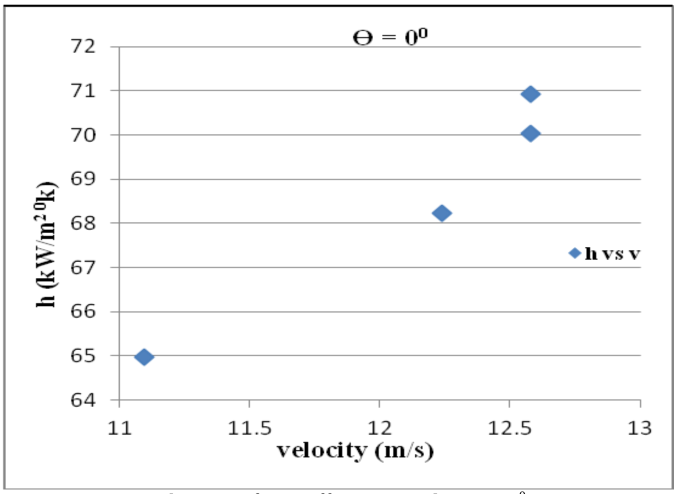

Fig.5.1. heat transfer co-efficient Vs velocity at 0^0

The above graph shows that the heat transfer coefficient, h, varies linearly with respect to the velocity. The maximum value of h observed is 70.92 (kW/m^2 ^{0}k) at the velocity of 12.58 m/s and minimum value of h is 64.98 (kW/m^2 ^{0}k) at the velocity of 11.09 m/s. The increases in velocity has overall resulted the increase in value of h for zero-degree inclination.

ii. Comparison between velocity and heat transfer coefficient for 30^0 inclinations.

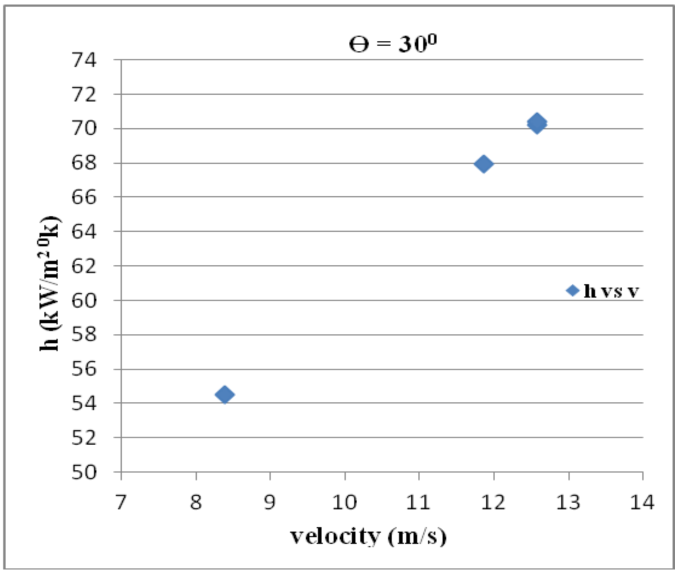

Fig.5.2. heat transfer co-efficient Vs velocity at 30^0

The above graph shows that the heat transfer coefficient, h, varies linearly with respect to the velocity. The maximum value of **h** observed is 70.4 (kW/m^2 ^{0}k) at the velocity of 12.58 m/s and minimum value of **h** is 54.53 (kW/m^2 ^{0}k) at the velocity of 8.38 m/s. The increases in velocity has overall resulted the increase in value of **h** for thirty-degree inclination.

iii. Comparison between velocity and heat transfer co efficient for 60^0 inclination

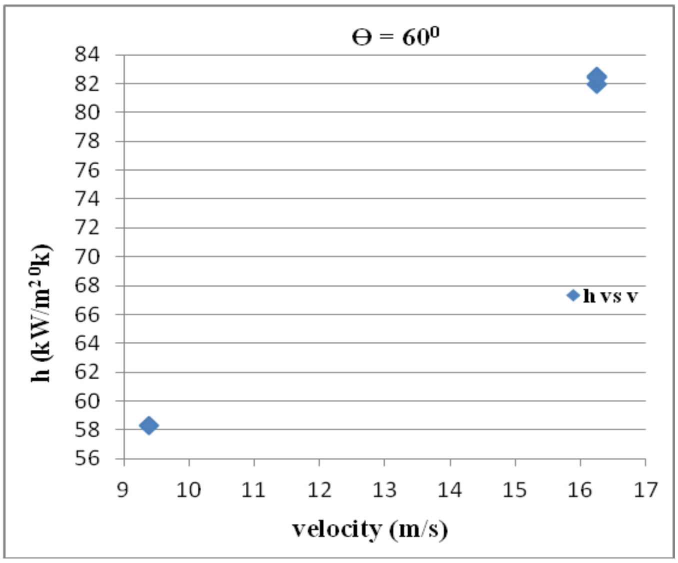

Fig.5.3. heat transfer co-efficient Vs velocity at 60^0

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The above graph shows that the heat transfer coefficient, h, varies linearly with respect to the velocity. The maximum value of **h** observed is 82.49 (kW/m^2 ^{0}k) at the velocity of 16.25 m/s and minimum value of **h** is 58.31 (kW/m^2 ^{0}k) at the velocity of 9.37 m/s. The increases in velocity has overall resulted the increase in value of **h** for zero-degree inclination.

iv. Comparison between velocity and heat transfer co efficient for 90^0 inclinations.

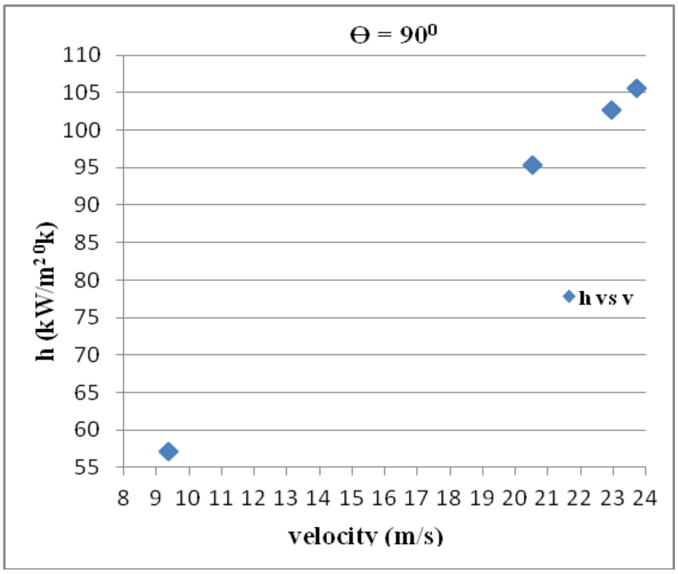

Fig.5.4. heat transfer co-efficient Vs velocity at 90^0

The graph shows that the value of heat transfer coefficient is maximum i.e. 105.6 (kW/m^2 ^{0}k) at the velocity of 23.72 m/s. The minimum value of **h** is 57.17(kW/m^2 ^{0}k) at the velocity of 9.375 m/s. This shows that the value of **h** varies linearly with respect to velocity for 90-degree.

v. Comparison between velocity and heat transfer co efficient for 120^0 inclination.

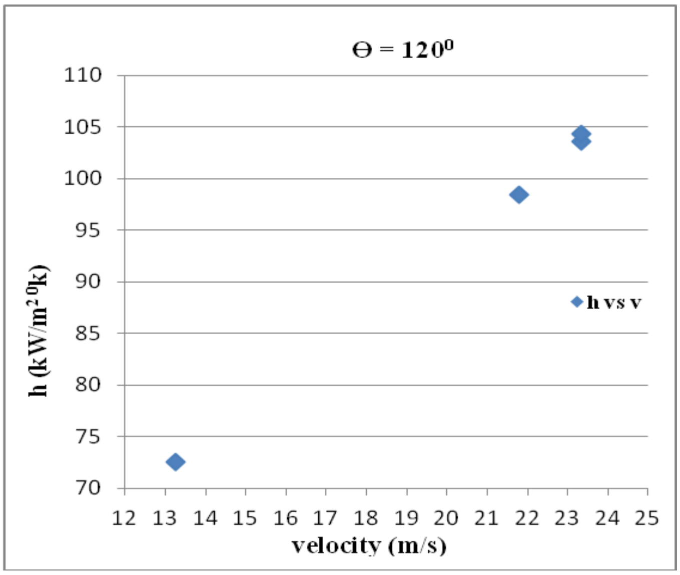

Fig 5.5. heat transfer co-efficient Vs velocity at 120^0

In the above plot it can be seen that the heat transfer coefficient increases linearly with respect to velocity. The minimum value of **h** is 72.51 (kW/m^2 ^{0}k) at lowest velocity 13.26 m/s and starts increasing to the maximum value of 104.3(kW/m^2 ^{0}k) at the velocity 23.34 m/s. This indicates the heat transfer coefficient varies linearly in this inclination.

vi. Comparison between velocity and heat transfer co efficient for 150^0 inclination.

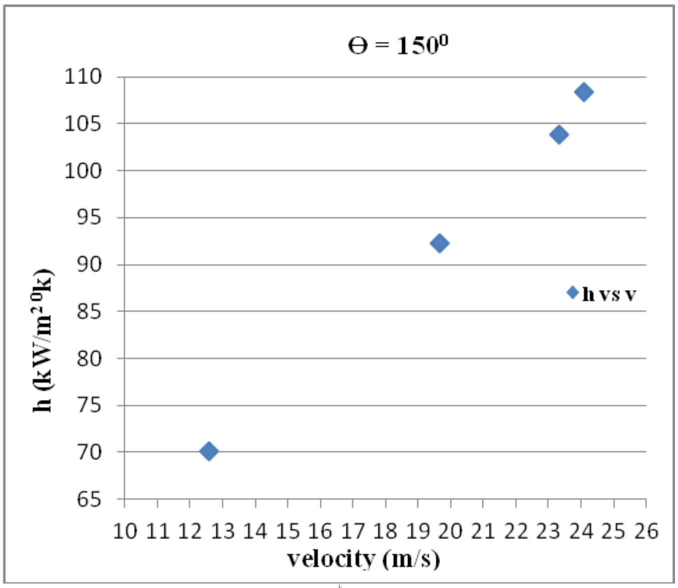

Fig.5.6. heat transfer co-efficient Vs velocity at 150^0

It is clear from the above graph that **h** is linearly dependent on velocity. The value of convective heat transfer coefficient increases as velocity increases. The highest value of **h is** 108.4(kW/m^2 ^{0}k) at the velocity of 24.08 m/s whereas the minimum value is 70.12(kW/m^2 ^{0}k) at the velocity of 12.57 m/s.

vii. Comparison between Reynolds number and Nusselts number

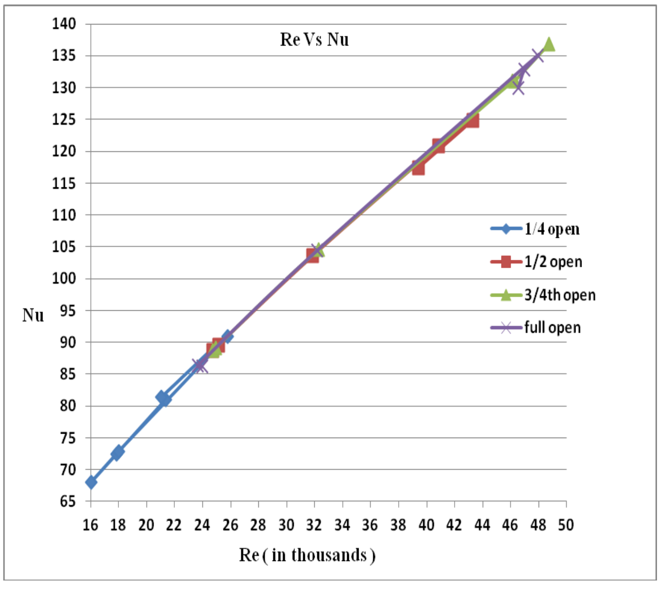

Fig.5.7.Reynolds number v/s Nusselts number

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The above graph shows the variation of Reynolds number Vs Nusselts number. It is evident that the increase in Reynolds number increases Nusselts number in each of the different openings. The lowest value of Reynolds number has resulted lowest value of Nusselts number for one-fourth of opening of the valve. Similarly, highest value of Nusselts number is obtained at highest Reynolds number at three-fourth opening of the valve.

viii. Comparison between inclination of Circular duct and heat transfer co efficient for different angles and different valve positions.

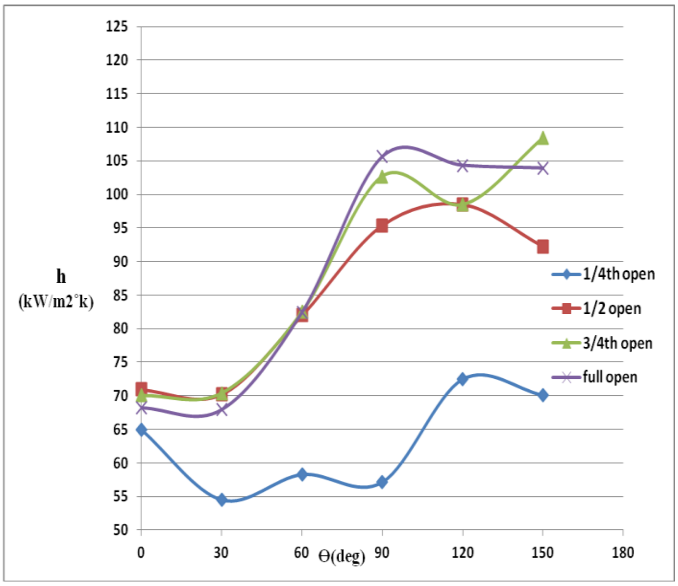

Fig.5.1.Inclination v/s heat transfer coefficient for all velocities

a) When the valve is one-fourth open, the heat transfer coefficient has decreased at 30^0 inclination compared to that of 0^0 inclination and increases at 60^0 then again it decreases at 90^0 then the value of convective heat transfer increases somewhat abruptly than previous degrees at 120^0 and falls slightly at 150^0 inclination of duct.

b) When the valve was half open, the heat transfer coefficient slightly decreased at 30^0 compared to 0^0 then increased at 60^0 , 90^0 , and 120^0 respectively and again decreased at 150^0 .

c) When the valve is three-fourth open, the heat transfer coefficient slightly decreased at 30^0 compared to 0^0 then increased at 60^0 , 90^0 , and decreased slightly at 120^0 and reaches maximum value at 150^0 inclination of the pipe.

d) The heat transfer coefficient plot shows same nature for full opening of the valve at angles 30^0, 60^0, 90^0, 120^0 as that of plot of three-fourth opening at same angles respectively but shows nearly constant value for 150^0 as that of 120^0.

e) The variation of velocity is established by operating the valve. The higher value of heat transfer coefficient for zero degree inclination is recorded for half open. The near constant value was obtained for half-open, three-fourth open, and full open at 60- degree which was highest at that angle but the lowest value was observed for one-fourth angle for the same angle of inclination of pipe. The value of heat transfer coefficient was decreasing in the order for full open, three-fourth open, half open and one-fourth open valve position respectively and was maximum for full opening and lowest for one-fourth opening at 90^0 inclination of the duct. Highest value of heat transfer coefficient is obtained for full opening, same value for half and three-fourth open but is slightly lesser than that of full open and then lowest value is recorded for one-fourth opening at an angle of 120^0. For 150^0 inclination of duct the value of heat transfer coefficient was in the decreasing order for the three-fourth, full, half, one-fourth opening of the valve respectively.

f) The highest value of convective heat transfer coefficient is recorded for three-fourth opening of the valve at 150^0 inclination of the duct where as the lowest value is obtained for one-fourth opening of the valve at 30^0 inclination of the duct.

6. CONCLUSIONS

1. This work has indicated that the use of correlations for horizontal pipe in correlations for inclined pipe produces erroneous result. Therefore, formulation of correlations for convective heat transfer coefficient for inclined duct is necessary.
2. It is also observed that angle of inclination of the duct influences heat transfer coefficient.
3. The heat transfer coefficient varies linearly with respect to the velocity.
4. From our work it can be concluded that the maximum value of heat transfer coefficient (h_{max} = 108.4 kW/m^2 ^{0}k) is obtained at the inclination of 150^0 for three-fourth opening of the valve.
5. The lowest value of heat transfer coefficient (h_{min} = 54.53 kW/m^2 ^{0}k) is obtained at the inclination of 30^0 for one-fourth opening of the valve.

7. SCOPE FOR FUTURE WORK

1. This research work can be carried out for different fluids. Work can be done at various heat input values so that the natures for various parameters can be compared.
2. Work can be done for the different geometrical cross-sections.
3. Heat transfer rate can also be determined by boundary layer analysis to compare with the values obtained experimentally.
4. The accurate measurement by computerized control can be done to increase the accuracy of the method.
5. Fins can be attached and its effect can be observed on convective heat transfer coefficients.

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