

**AN EXPERIMENTAL STUDY OF MIXED CONVECTION
HEAT TRANSFER IN AN INCLINED RECTANGULAR DUCT EXPOSED TO UNIFORM
HEAT FLUX FROM UPPER SURFACE**

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Abstract

Combined free and forced convection heat transfer to a thermally developing air flow in a rectangular duct has been studied experimentally. Experimental part deals with the laminar flow. The study was presented to steady and two dimensions flow. The heated surface was subjected to a constant heat flux while the duct short sides were kept unheated, for upper side heated only with constant heat flux and for three-duct angles of inclination -30° , -45° and -60° . In the experimental study, the heat flux applied to the heated surfaces varied from 40 to 500 W/m². This provides a modified Grashof number varied from 2.38×10^6 to 2.8×10^8 respectively, while the Reynolds number varied from 455 to 2000.

Nomenclature

Gr_{Dq} = Grashof number based on D_e and heat flux,
($\beta g D^4 q$) / ($k \cdot \nu^2$)

Gr_L = Average Grashof number, $\beta g L^3 \Delta T_L / \nu^2$

Gr_D = Grashof number based on D_e , $\beta g D^3 (\Delta T_x) / \nu^2$

Nu_L = Average Nusselt number, ($h_L \cdot L / k$)

Nu_D = Nusselt number based on D , ($h_L \cdot D / k$)

Pr = Prandtl number, (ν / α)

Ra_L = Average Rayleigh number, ($Gr_L \cdot Pr$)

Re_D = Local Reynolds number based on D , ($u_i \cdot D / \nu$)

ΔT = Temperature difference, °C

α = Duct angle of inclination (-30° , -45° and -60°)

D_e = Equivalent duct diameter, m

T_B = Bulk temperature, °C

T_{SL} = Lower surface temperature, °C

T_{Su} = Upper surface temperature, °C

U_i = Inlet velocity, m/s

Introduction

An investigation of fully developed mixed convection in an inclined rectangular duct is presented. Mixed convection flows arise in many transport processes in natural and engineering devices. Atmospheric boundary layer flow, heat exchangers, solar collectors, nuclear reactors, and electronic equipments are some examples. Such a process occurs when the effect of the buoyancy force in forced convection or the effect of forced flow in free convection becomes significant. In the study of internal flows of mixed convection heat transfer, the interactions of thermal and hydrodynamic development become fairly complicated. For inclined ducts, the gravity force acts in the vertical direction, and as will as the buoyancy force is in the main flow direction and induces secondary flows in the cross plane. Many works have been investigated on mixed heat transfer in laminar or turbulent flows in inclined rectangular ducts. Yan [1] has studied numerically on the transport phenomena of mixed convection heat and mass transfer in an inclined rectangular duct. He

found that the buoyancy forces distort *the velocity*, temperature and concentration distributions. Huang and Lin [2] investigated the transient mixed convection air flow in a bottom heated inclined rectangular duct. Attention was particularly paid to delineate the effects of the duct inclination on the flow transition with heat transfer only. W. L. Pu, P. Cheng and T. S. Zhao (1999) [3] carried out in the range of $2 < Pe < 2200$ and $700 < Ra < 1500$. The measured temperature distribution indicates the existence of a secondary convective cell inside the vertical packed channel in the mixed convection regime. A correlation equation for Nusselt number in terms of Peclet number Pe and Rayleigh number Ra was obtained from experimental data. A plot of $Nu/Pe^{1/2}$ vs Ra/Pe exhibits the transition of heat transfer results from the natural convection limit to the forced convection limit. It is found that the following three convection regimes exist: natural convection regime: $105 < Ra/Pe$, mixed convection regime: $1 < Ra/Pe < 105$, and forced convection regime: $Ra/Pe < 1$.

Paulo and Genesio (2004) [2], studied the mixed convection heat transfer in an inclined rectangular channel. Three heat sources with finite lengths are flush mounted on the bottom surface of a channel. The Reynolds number, Grashof number and inclination angle are ranged as follows: $1 \leq Re \leq 1000$, $103 \leq Gr \leq 105$ and $00 \leq \gamma \leq 900$. Three comparisons between experimental and numerical results were performed. It is observed that the inclination angle has a stronger influence on the flow and heat transfer for Reynolds number equals to 1000, especially when it is between 00 and 450. The cases which present the lowest temperature distributions on the modules are those where the inclination angles are 450 and 900 with little difference between them. The case where $Gr = 105$ and $Re = 1000$, is an exception where γ equals 00 is the best channel inclination.

It is noted that the study of developing mixed convection flow in inclined rectangular ducts is useful in practical sense, but it has not received enough attention and the studies of

developing mixed convection flow in inclined ducts. The aim of this study is to investigate the effects of inclination duct on the developing mixed convection flow in inclined rectangular ducts. The design of industrial heat exchangers in chemical. Food processing industries where problems may be encountered involving combined convection in horizontal channels. Cooling of electrical equipment. The design of certain types of solar energy collectors (flat plate heater). The estimating of energy time scale required in the case of piping failure in the nuclear power plant.

II. ANALYSIS

1. Problem Statement

The geometry of this problem as schematically shown in Fig. 1 is a rectangular duct with inclination angle α , width w , and height h . The velocity components in x , y , and z directions are denoted as u , v , and w , respectively. A uniform axial velocity w_0 and a uniform temperature T_0 are imposed at the inlet $z = 0$. Although practical flows are often

turbulent, the entering upward flow is assumed to be steady and laminar. The temperature of the injected or suctioned fluid is the same as that of the duct wall. The walls are imposed uniform heat flux.

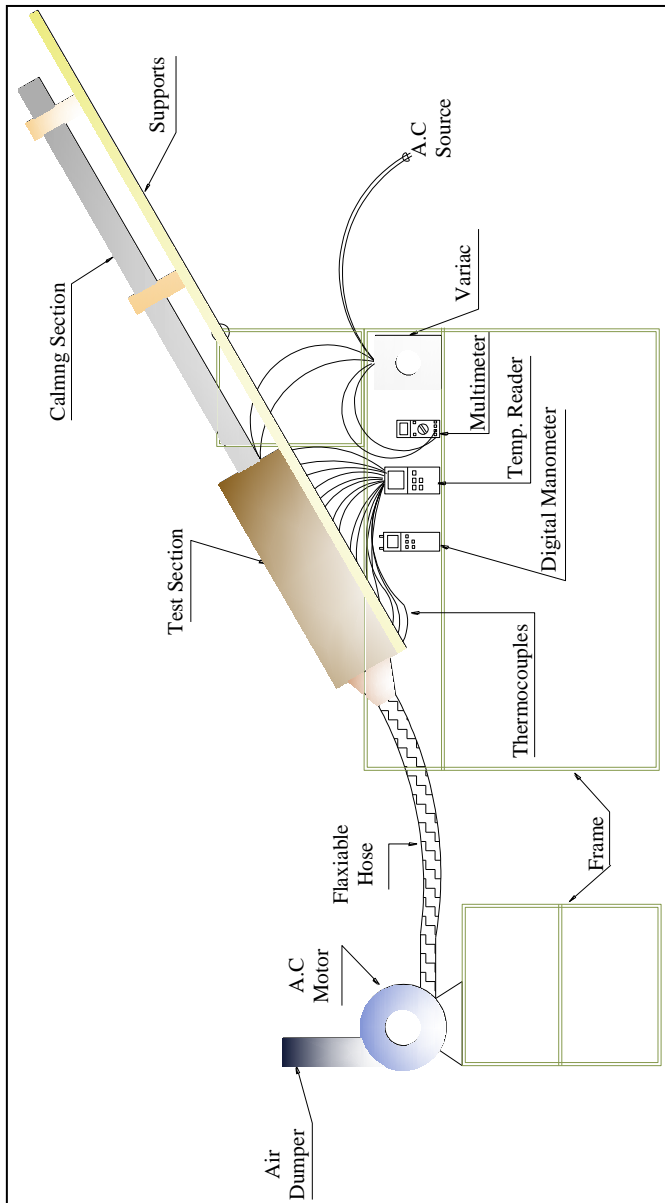


Fig. 1 Schematically sketch for the rig.

2. Test Section.

The most important of the open air circuit is the test section where most of the measurements were made. The two vertical walls (shorter sides of rectangular duct) the left and right wall consist of the following, three layers arranged from the duct inside to the duct outside, a 20mm thick of asbestos sheet, a 20mm thick of glass wool sheet and a 50mm thick of a solid compressed wood, respectively. The upper and lower walls of test section were designed to be the duct side heated with a constant heat flux so the situation of upper side heated or lower side heated or both side heated can be achieved by powering the side requires. The details of these walls are shown in fig. (2). The heated surface was constructed from three layers glued together to form a composite heater. The composite heater consists of a heating element as nickrom 1mm diameter wounded uniformly flat on a 1mm mica sheet. The heating element then covered from both sides by 1mm mica sheet. The heat element with covers fixed on 0.5mm stainless steel plate to force a composite layer heating element.

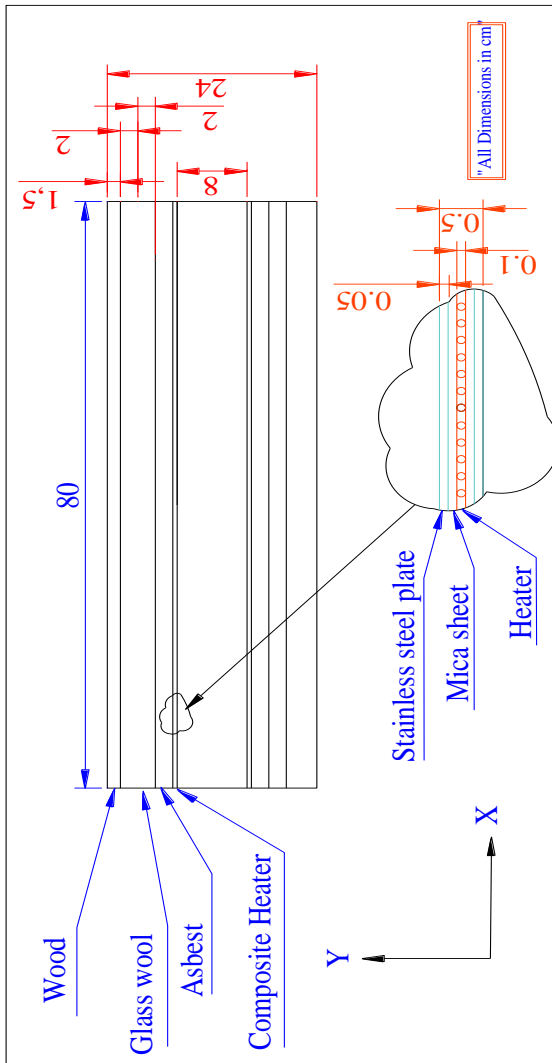


Fig. (2) Test section duct composition

All thermocouples penetrate the mica layer to be fixed on the stainless steel plate. Thermocouples' locations are mentioned in fig. (3) starting from test section entrance.

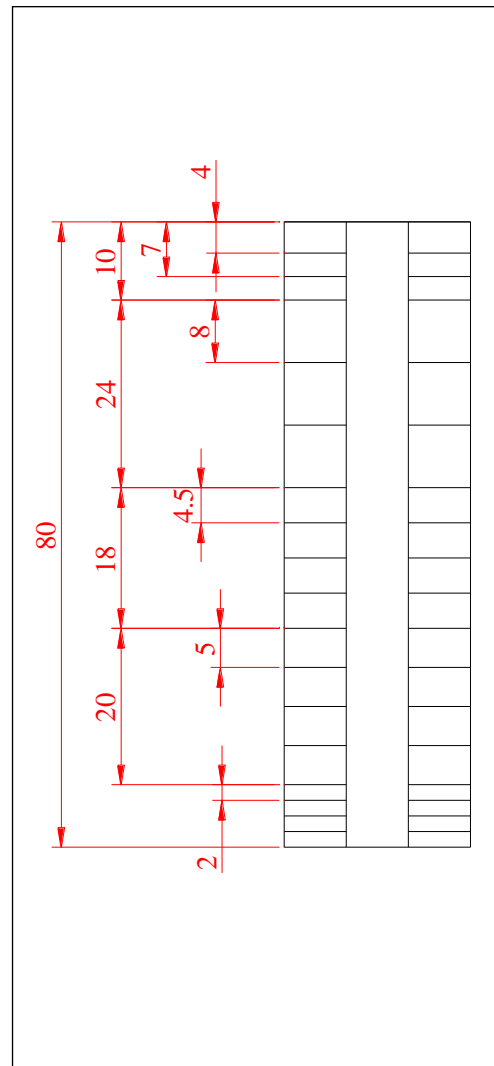


Fig (3) Distributed locations of thermocouples on the heaters plates

III. RESULTS AND DISCUSSION

1. Velocity distribution study:

Three velocity profile tests have been carried out for inclined duct opposing flow situations comprising combinations of

three angles of inclination -30° , -45° and -60° ,

The results for the upper side heated only situation at -30° , -45° and -60° are shown in Figs. (4), (5) and (6). The velocity profile for $\alpha = -30^\circ$, is shown in Fig. (4), reveals a conspicuous skewing of these profiles toward the upper plate especially at the duct center and 4-cm off-center positions. The shift of the velocity profile is increased toward the upper plate as (α) increases to -45° and -60° as shown in Figs. (5) and (6). The deformation in the upper plate boundary layer with (α) shows a clear merging of transverse profiles.

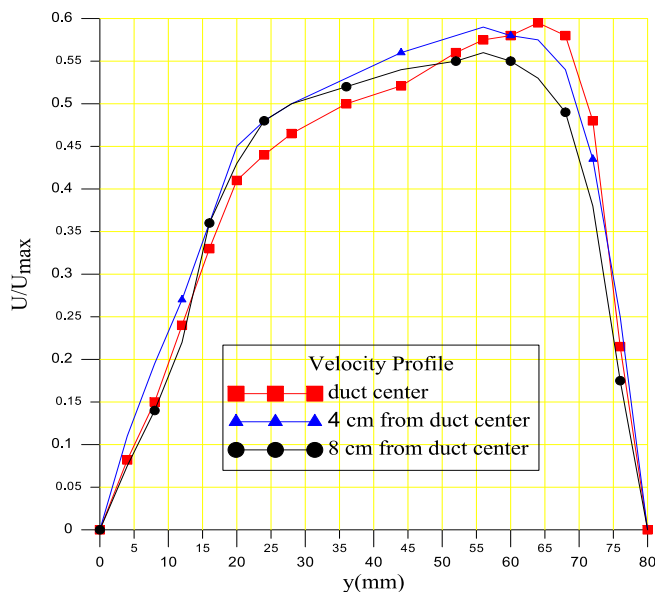


Fig. (4) Velocity profile. $Re_{De}=2060$, $x_{meas.}=0.6$

m , $Gr_{De}=2.648 \times 10^7$, $U_i=0.388$ m/s, $T_B=20^\circ C$,
 $T_{Su}=71.7^\circ C$, $T_{SL}=32.2^\circ C$. Inclined duct, $\alpha = -30^\circ$,
 upper side heated, opposing flows.

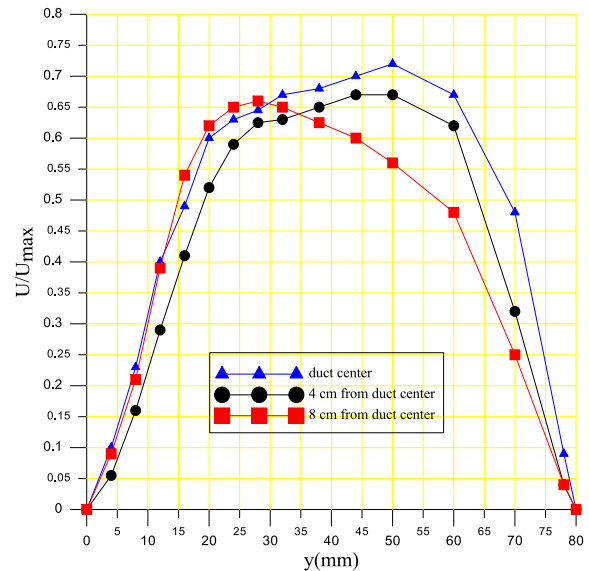


Fig. (5) Velocity profile. $Re_{De}=2064$, $x_{meas.}=0.6$
 m , $Gr_{De}=2.58 \times 10^7$, $U_i=0.389$ m/s, $T_B=17^\circ C$,
 $T_{Su}=74^\circ C$, $T_{SL}=34.6^\circ C$. Inclined duct, $\alpha = -45^\circ$,
 upper side heated, opposing flows

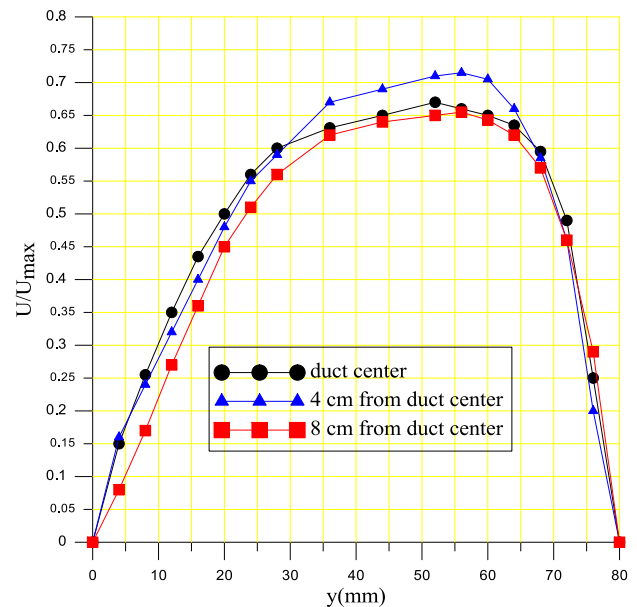


Fig. (6) Velocity profile. $Re_{De}=2020$, $x_{meas.}=0.6$ m, $Gr_{De}=2.58 \times 10^7$, $U_i=0.377$ m/s, $T_B=15^\circ\text{C}$, $T_{Su}=69^\circ\text{C}$, $T_{SL}=34.6^\circ\text{C}$. Inclined duct, $\alpha = -60^\circ$, upper side heated, opposing flows.

2. Surface temperature :

For the upper plate heated only case. The surface temperature distribution along the plate shown in fig. (7) for $\alpha=-30^\circ$ indicates a reduction in surface temperature. This reduction is the result of the upper plate inclined (with the flow free to be carried away downstream) which is dominated by the natural convection. Surface temperatures reduce further as the duct orientation moves to $\alpha = -45^\circ$ as shown in Fig. (8) but the reduction in the range between -30° to -45° is lower than that obtained -30° .

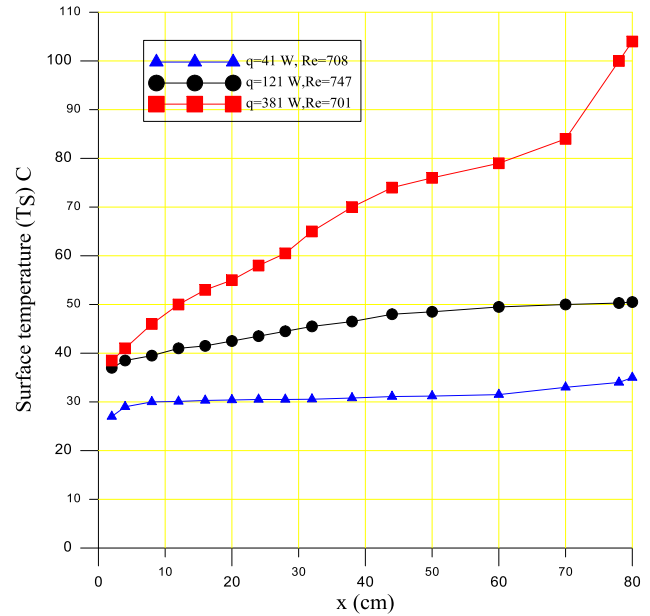


Fig. (7) Axial variation of heated surface temperature, Inclined duct, $\alpha = -30^\circ$, upper side heated only.

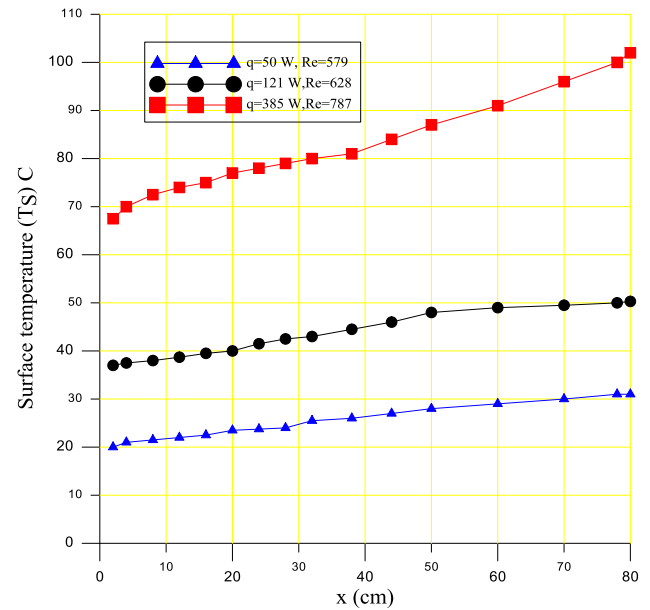


Fig. (8) Axial variation of heated surface temperature, Inclined duct, $\alpha = -45^\circ$, upper side heated only.

The surface temperature distribution for $\alpha = -60^\circ$ in Fig. (9) show the same trends as

for $\alpha = -30^\circ$ and -45° with a small reduction in surface temperature in comparison with $\alpha = -45^\circ$. Therefore, duct angle of inclination changes at -30° , manifests a large improvement in the local and average heat transfer coefficients.

-45° and -60° . At the same time, the rate of improvement of $Nu_{L,t}$ low Re_D range is higher than that for high Re_D . This behavior can be attributed to natural convection behavior and its contribution to the upper plate heat transfer process.

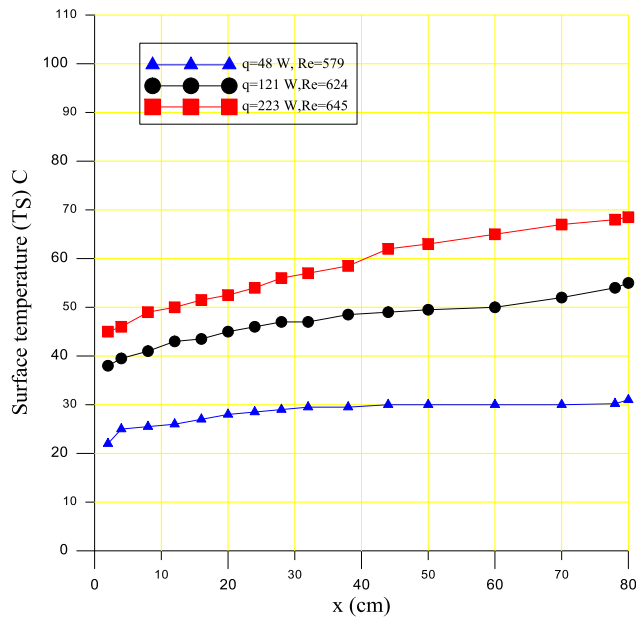


Fig. (9) Axial variation of heated surface temperature, Inclined duct, $\alpha = -60^\circ$, upper side heated only.

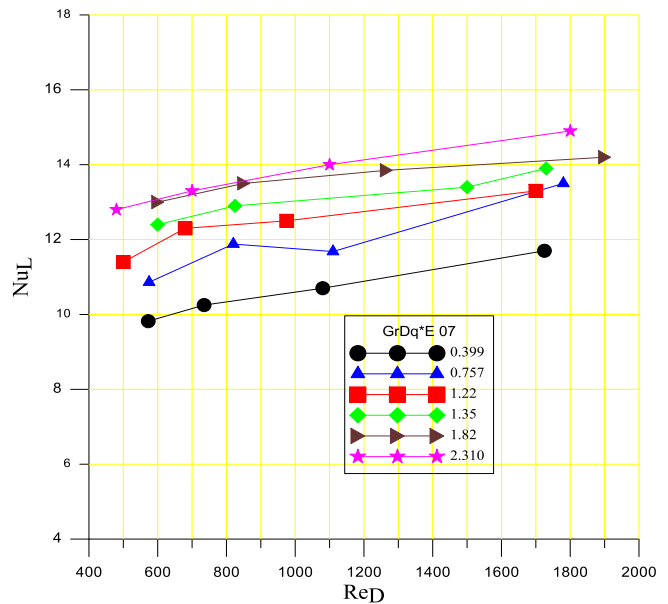


Fig. (10) Variation of Nu_L with Re_D , inclined duct, $\alpha = -30^\circ$, Upper side heated.

3. Nusselt number

Average Nusselt number variation with Reynolds number for $\alpha = -30^\circ$, -45° and -60° are given in Figs. (10) to (12). The improvement in $Nu_{L,t}$ continued, for the same Grashof number $Gr_{D,q}$ and Reynolds number, as the duct orientation changes to

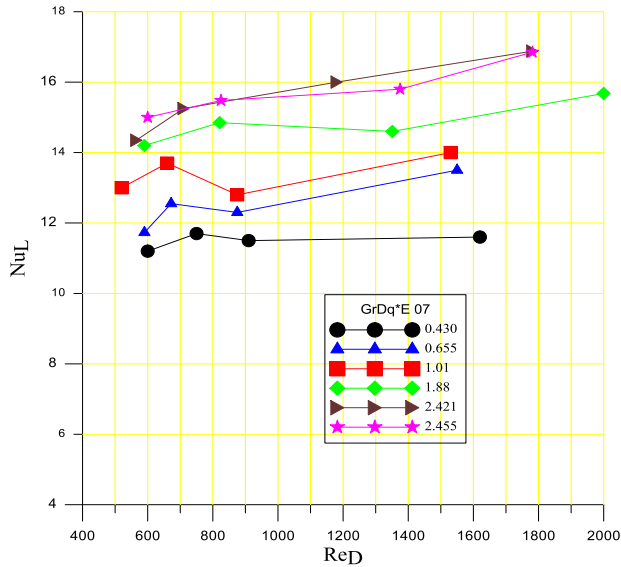


Fig. (11) Variation of Nu_L with Re_D , inclined duct, $\alpha = -60^\circ$, Upper side heated.

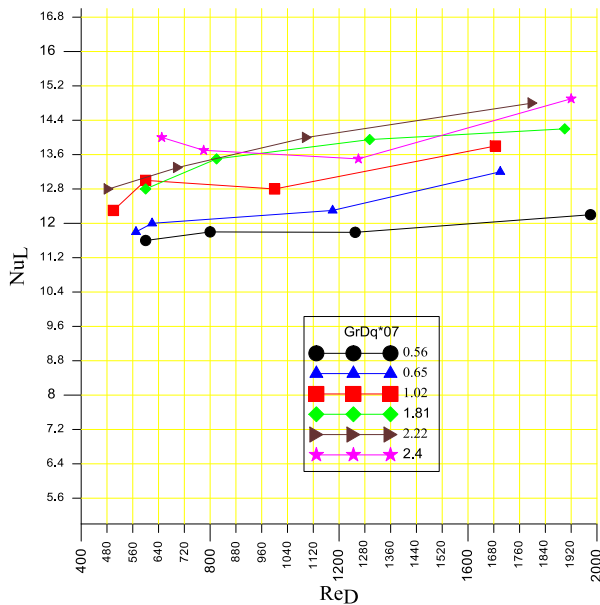


Fig. (12) Variation of Nu_L with Re_D , inclined duct, $\alpha = -45^\circ$ upper side heated

IV. CONCLUSION

Experimental studies have been performed to determine the effects of the secondary flow created by natural convection on a fully opposed developed air flow in a rectangular duct. The duct boundary conditions have been combined for inclined duct.

The inclined duct results reveal the following conclusions:-

1. The biasing of the velocity profile towards the heated surface as α moves to upward.
2. As inclination angle increases, the buoyancy effect increases as well which causes an unstable secondary flow resulting the fluctuation in the distribution of Nu.
3. The upper plate Nu_L is considerably improved as $\alpha = -30^\circ$ and this improvement is lower for $\alpha = -45^\circ$ and -60° .
4. In the uniform heat flux case, Nu is increased with increasing modified Raleigh number throughout duct.

5. Nu is increased with increasing mixed convection parameter throughout the duct in the uniform heat fluxcase.

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