KUFA JOURNAL
OF ENGINEERING
ISSN 2071-5528
PRINTED IN IRAQ

Volume 3, Number 2 pp.31-45, 2012

Experimental Study For Effect of Aspect Ratio on Forced Convection Heat Transfer Inside a Rectangular Cross- Sectional Duct

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(Received:13/1/2011 ;Accepted :11/10/2011)

Abstract

The effect of aspect ratio on the forced convection heat transfer is studied experimentally by construction a device formed mainly from an air duct with sliding surfaces to up or down directions and from a copper tube represents a heat generation source placed inside the air duct. The aspect ratio considered the ratio of the distance between the upper and lower surfaces of the air duct to diameter of the copper tube.

The experimental results which obtained from this study show that the Nusselt number decreases with increase of the aspect ratio for Reynolds number range equals to ($500 < Re < 3000$). From the experimental results, a correlation for Nusselt number calculation is presented that depending on the effect of Reynolds number, Prandtl number, and aspect ratio with an accuracy of ±8%.

Key words: Forced convection, Aspect ratio, duct, experimental approach.

دراسة عملية لبيان تأثير النسبة الباعية على انتقال الحرارة بالحمل القسري داخل مجرى مستطيل المقطع

الخلاصة

تم دراسة تأثير النسبة الباعية على انتقال الحرارة بالحمل ألقسري عمليا من خلال إنشاء جهاز يتكون بصورة رئيسية من مجرى للهواء ذو سطحين علوي وسفلي قابلين للحركة باتجاه الأعلى أو الأسفل ومن أنبوب نحاسي كمصدر للحرارة المتولدة موقعه داخل مجرى الهواء. تم اعتماد النسبة الباعية على إنها النسبة بين المسافة بين السطحين العلوي والسفلي لمجرى الهواء إلى قطر الأنبوب الساخن.

إن النتائج العملية التي تم الحصول عليها من هذه الدراسة بينت بأن رقم نسلت يقل بزيادة النسبة الباعية لمدى من رقم رينولدز مساو لـــ ($500 < Re < 3000$). من النتائج العملية تم استخراج علاقة لحساب رقم نسلت بالاعتماد على رقم رينولدز ورقم براندل والنسبة الباعية بنسبة خطأ ±8%.

Nomenclature

Symbol	Definition	Unit
AR	***aspect ratio***	
d	***hot tube diameter***	***m***
h	***heat transfer coefficient***	***W/m²·k***
I	***electrical current***	***Amp.***
k	***thermal conductivity***	***W/m.k***
L	***hot tube length***	***m***
Nu	***Nusselt number***	
q_m	***heat generated by heater per unit length***	***W/m***
$q_{conv.}$	***convection heat transfer***	***W***
Pr	***Prandtl number***	
Re	***Reynolds number***	
s	***distance between the parallel plates of the duct***	***m***
T_a	***temperature of air inside the duct***	***^oC***
T_{av}	***average temperature***	***^oC***
T_s	***hot tube surface temperature***	***^oC***
V	***electrical voltage***	***Volt***

1-Introduction

Heat transfer is an important aspect of thermodynamics and energy. It is fundamental to many engineering applications. There is a heat or energy transfer whenever there is a temperature difference. Engineers are often required to calculate the heat transfer rate for the application of process technology [1].

Convection heat transfer done by external or internal flow, where in present work the flow type is an internal flow. The internal flow is a flow configuration where the flowing material is surrounded by solid walls. Streams that flow through ducts are primary examples of internal flows [2]. There are two types of convection heat transfer, forced convection and free convection.

Forced convection heat transfer inside duct or channel was studied by several researches such as Hongxing et al., [3], presented direct numerical simulation of forced heat convection at a bulk Reynolds number of 10000 inside a straight square duct by using finite difference method. The results of this study showed that the novel numerical scheme solutions satisfy with the straight square duct flow with passive scalar transport under an isoflux condition and the predicted mean Nusselt number was excellently consistent with the value based on the published correlations. Hooman et al., [4], studied heat transfer by forced convection inside the rectangular cross-section duct analytically by used Darcy-Brinkman flow model. The conclusion of this study explained it possible to compare and evaluate alternative rectangular duct design options in terms of heat transfer. Erdogan and Imrak, [5], studied the duct shape effect on the Nusselt number. This studied four types of duct shapes considered rectangular, semicircular, circular, and between two parallel plates. The results showed that the Nusselt number depend on duct shape and wall friction. Chang and Mills, [6], studied experimentally the aspect ratio effect on forced convection heat transfer from cylinders. The aspect ratio was the ratio between length to diameter of the cylinder and equals to 12, 10.8, 8.5, and 6 for Reynolds number range of 6300 to 50960. The results showed that the Nusselt number increased with decreasing aspect ratio. Khan et al., [7], have been carried out a ribbed study on forced convection heat transfer in developing region through a smooth and ribbed square duct with a symmetric heating in order to compare the heat transfer characteristics. The results showed that the performance of heat transfer in ribbed surface duct was much better than that of the smooth surface duct where the Nusselt number in duct with ribbed surface increased 6.24 percent over the duct with smooth surface. Wang and Chen, [8], analyzed forced convection heat transfer inside sinusoidally curved converging-diverging channel using a simple coordinate transformation method and the spline alternating- direction implicit method. This study showed that the amplitudes of the Nusselt number increased with an increase in the Reynolds number and the amplitude wavelength ratio. Zhong et al., [9], studied the forced convection heat transfer in parallel plates channel with streamwise periodic rod disturbances numerically by finite difference schemes with Reynolds number range (50-700) and Prandtl number of 0.71. The results showed that the different flow pattern can occured with different deployments of the disturbances. With appropriate configuration of the disturbances, the Nusselt number can reached a value four times greater than in smooth channel at the same condition. Hwang et al., [10], studied forced convection heat transfer inside a square duct numerically by using concept of pressure deviation and the vorticity velocity method. In this study the Prandtl number and Nusselt number effect was discussed. Lin et al., [11], analyzed numerically the convective instability of heat transfer for forced convection in the entrance region of horizontal rectangular channels. Part of this study results showed that the convective instability was affected by changes of relative humidity and wall temperature for fixed aspect ratio. Yasuo and Isao, [12], studied forced convection heat transfer inside horizontal rectangular duct numerically to show effectiveness of secondary flow on heat transfer rate. This study showed that the heat transfer rate increased with increase of the secondary flow.

2-Experimental Device

As shown in figure (1), the experimental device consists of the main following parts :-

2-1 Wooden structure

This structure is manufactured locally from wood plates with 7 mm thickness. The dimensions of the structure are (40, 50, 80) cm, one end of the structure extended to adjust the electrical fan with diameter of 25 cm. The structure has two symmetrical (50*50) cm wood plates, which represents an air duct, with 1 cm thickness covered with 2 mm aluminum sheet. The two plates slide vertically up or down to increase or decrease the aspect ratio which represents the ratio of the distance between the two plates to the heating element diameter.

2-2 Heat source

An electrical heating element consists of an electrical wire fitted inside copper tube with 1.875 cm diameter to provide variable heat by using variable AC power supply. This element represents the heating source inside the air duct.

2-3 Electrical fan

An axial fan with 25 cm diameter is placed at the end of the structure to draw the air through the duct with varying velocity by using variable DC power supply.

2-4 measurement instruments

Six k-type thermocouples, calibrated with standard thermometer between 0 ^oC and 110 ^oC, distributed inside the duct and at the surface of the heating element, as shown in figure (2), to measure temperature of the air inside the duct and the heater surface temperature which displayed by digital displayer with 1% sensitivity.

A digital anemometer, model (DA40), placed at the duct entrance to measure the air speed which drawn by the fan. This anemometer is connected with digital displayer with 1.5% sensitivity.

An analog standard voltmeter and ammeter used to measure the voltage and current which drawn by the heating element to calculate the power of it.

3-Governing equations

In this study the aspect ratio equals to :

$$AR = \frac{s}{d} \qquad \text{.....................(1)}$$

The heat generated by the heat source can be calculated as [13]:

$$q = I\,.V \qquad \text{..................(2)}$$

The rate of heat transfer from the surface by convection is given by [14]:

$$q_{conv.} = h\ A\ (T_s - T_a) \qquad \text{...................(3)}$$

Where $q_{conv.} = q$ and (A) is the hot tube surface area and equal to : $A = \pi\, d\, L$..................(4)

Then the equation (3) can be written as :

$$q = h\, \pi\, d\, L\, (T_s - T_a) \qquad (5)$$

When equation (5) is dividing on (L), yields to :

$$h = \frac{q_m}{\pi\, d\, (T_s - T_a)} \qquad (6)$$

Where (q_m) is the heat generation per unit length.

Nusselt number is calculated as follows [14] :

$$Nu = \frac{h\, d}{k} = \frac{\dfrac{q_m}{\pi\, d\, (T_s - T_a)}\, d}{k} = \frac{q_m}{\pi\, k\, (T_s - T_a)} \qquad (7)$$

The air characteristics are limited according to average temperature of the hot tube surface temperature and air which flows inside the duct temperature as [13] :

$$T_{av} = \frac{T_s + T_a}{2} \qquad (8)$$

The aspect ratio which chosen in the present work are 4,8, and 12 and at each value of the aspect ratio the heat generation in the heat source are (28,72,128,200,and 288) W/m and the velocity of the air inside the duct are (0.6, 1, 1.5, and 2) m/sec.

4-Results and Discussion

According to the experimental results of above cases, the figures (3-6) show the relations between Nusselt number with aspect ratio at constant Reynolds number and different values of Prandtl number for each relation, (i.e the variation of Nusselt number with aspect ratio at same velocity of air flows inside the duct and different values of the heat generation in the heat source). It can be seen from these figures that the same trends of Nusselt number behavior with change of aspect ratio for all values of Prandtl number at any value of Reynolds number. The range of Reynolds number which chosen in this study is ($500 < Re < 3000$). These figures show that Nusselt number equals to range of (18.17 to 94.63). The maximum value of Nusselt number calculates at AR=4, Re=2203.46, and Pr=0.07179, as shown in figure (6), (i.e at 2 m/sec of air flow velocity and 288 W/m of the heat generation). The minimum value of Nusselt number calculates at AR=12, Re=642.77, and Pr=0.7247, as shown in figure (3), (i.e at 0.6 m/sec of air flow velocity and 28

W/m of the heat generation). These figures show that when the aspect ratio increases, this tend to decrease in Nusselt number. This behavior of Nusselt number because of decreasing in the heat transfer rate. When the aspect ratio increases will tend to addition more layers of the air which flows around the heat source (i.e increasing of the air thickness) and this additions are tend to rise the air particles resistance against the heat transfer which passes throw it.

The relation between Nusselt number and aspect ratio in present study is agreement with results of Erdogan and Imrak, [5], and Chang and Mills, [6], where, in these studies the Nusselt number increased with decreasing aspect ratio. The aspect ratio in study of Erdogan and Imrak, [5], is the ratio between long side to the short side of the rectangular duct and the relation between Nusselt number and aspect ratio is shown in figure (7).

To estimate a correlation for Nusselt number calculation, this requires to plot a relations between Nusselt number with Reynolds number and between Nusselt number with Prandtl number, this shown in figures (8-10) and (11-13) respectively. The figures (8-10) show the relations between Nusselt number with Reynolds number at constant aspect ratio and different values of Prandtl number for each relation, it can be seen from these figures that the same trends of Nusselt number behavior for all values of Reynolds number. The increasing in Reynolds number leads to increase in Nusselt number, this because the increasing in velocity of the air flow inside the duct which leads to increase in heat transfer rate. The figures (11-13) show the relations between Nusselt number with Prandtl number at constant aspect ratio and different values of Reynolds number for each relation, It can be seen from these figures that the same trends of Nusselt number behavior for all values of Prandtl number. The increasing in Prandtl number leads to decrease in Nusselt number. This because Prandtl number limits from air characteristics table according to average temperature (T_{av}) of air and heat source temperatures. When the heat generation in the heat source increases (i.e Nusselt number increases) the average temperature will increase and this leads to decrease in Prandtl number.

With mathematical processing for the all experimental relations, a correlation for Nusselt number calculation estimated with an accuracy of ±8%. Where, this correlation can be applied to calculate Nusselt number of the forced convection heat transfer inside rectangular cross- section duct. This correlation can be written as :

$$\mathrm{Nu} = 2.416 * 10^{-9}\,(\mathrm{Re})^{0.79}\,(\mathrm{AR})^{-0.169}\,(\mathrm{Pr})^{-56.07} \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

5-Conclosions

The findings in the present study indicated that:

1- The forced convection heat transfer rate inside rectangular cross-section duct decreases with increasing of the aspect ratio value, with decreasing of Reynolds number , and with increasing of Prandtl number.

2- There is a relation can be used to calculate Nusselt number of the forced convection heat transfer inside rectangular cross- section duct with an accuracy of ±8% which is :

$$Nu = 2.416 * 10^{-9} (Re)^{0.79} (AR)^{-0.169} (Pr)^{-56.07}$$

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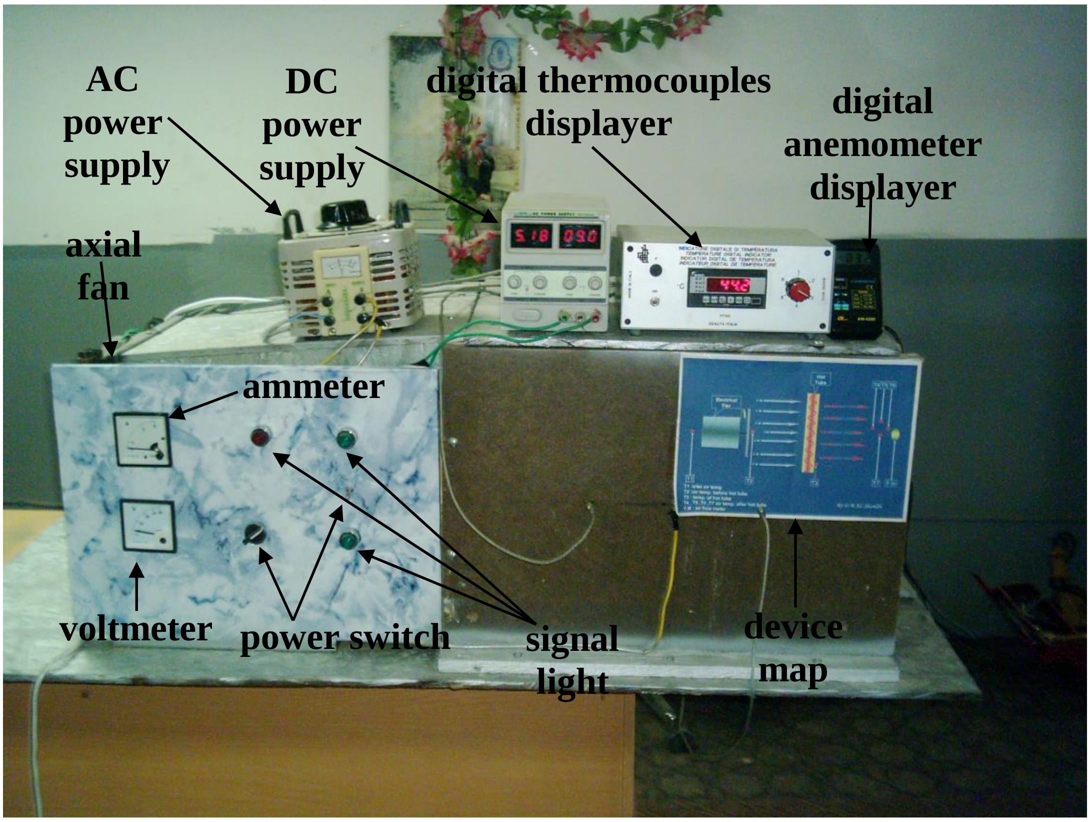
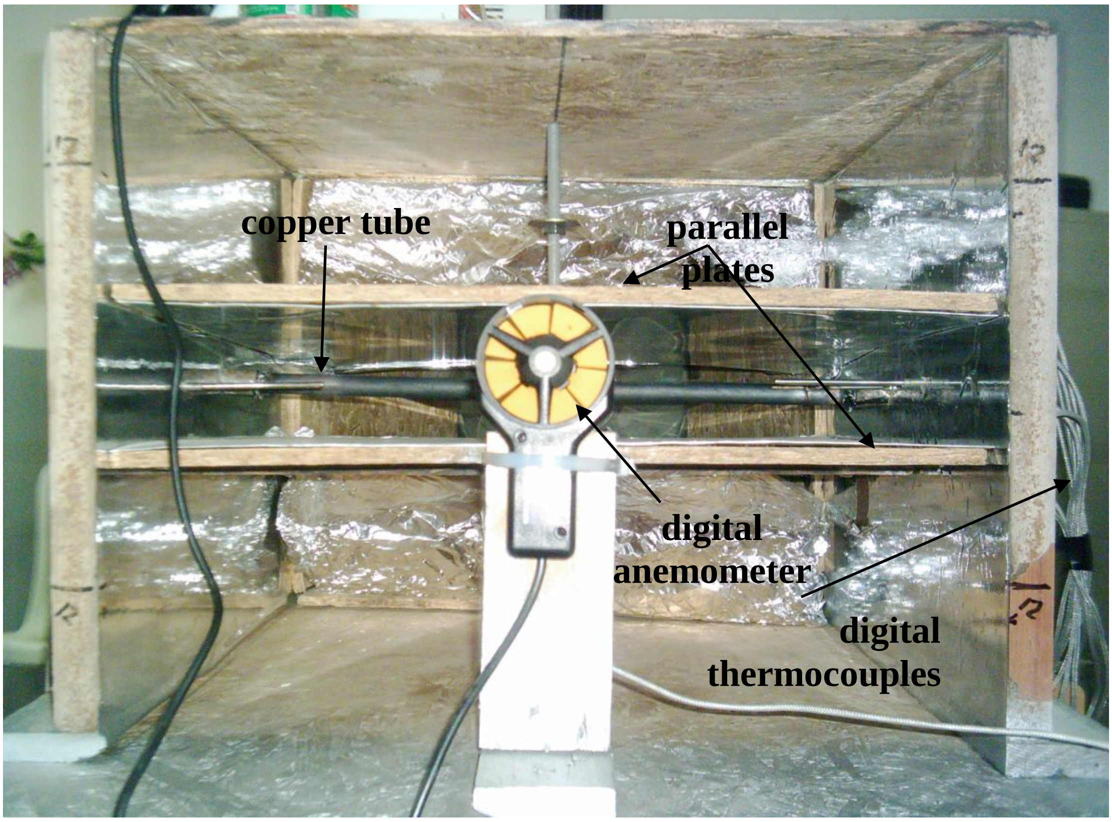


(front view)



(side view)

Fig. (1): Experimental device.

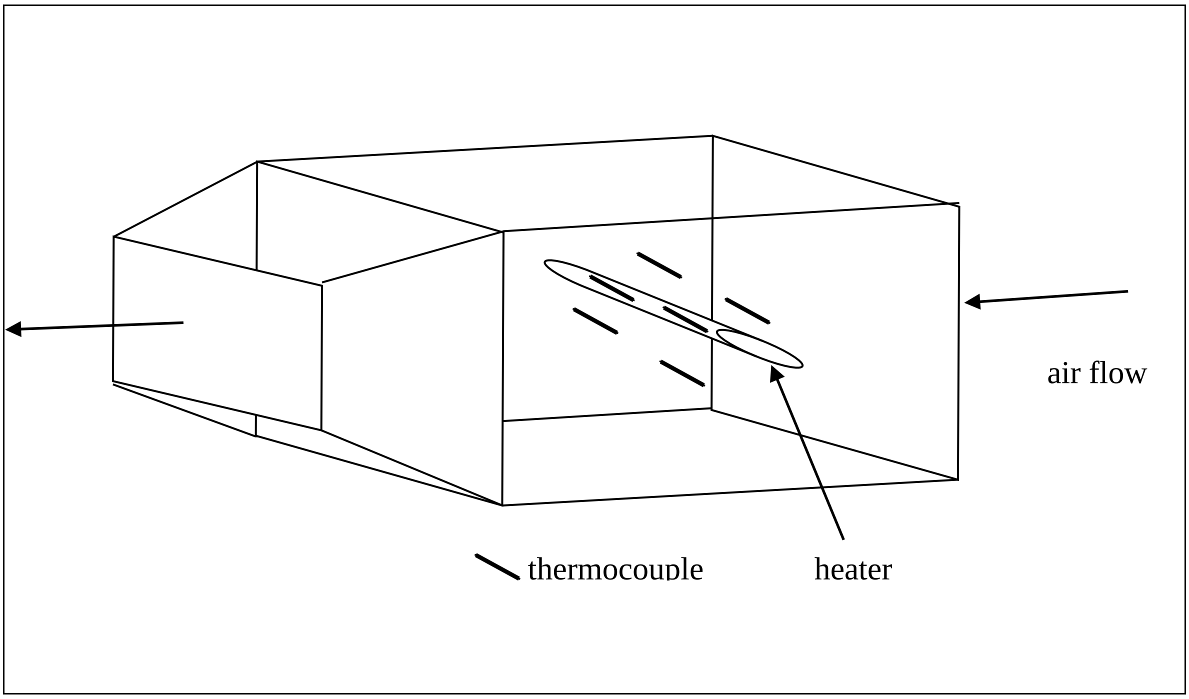


Fig. (2) Distribution of thermocouples

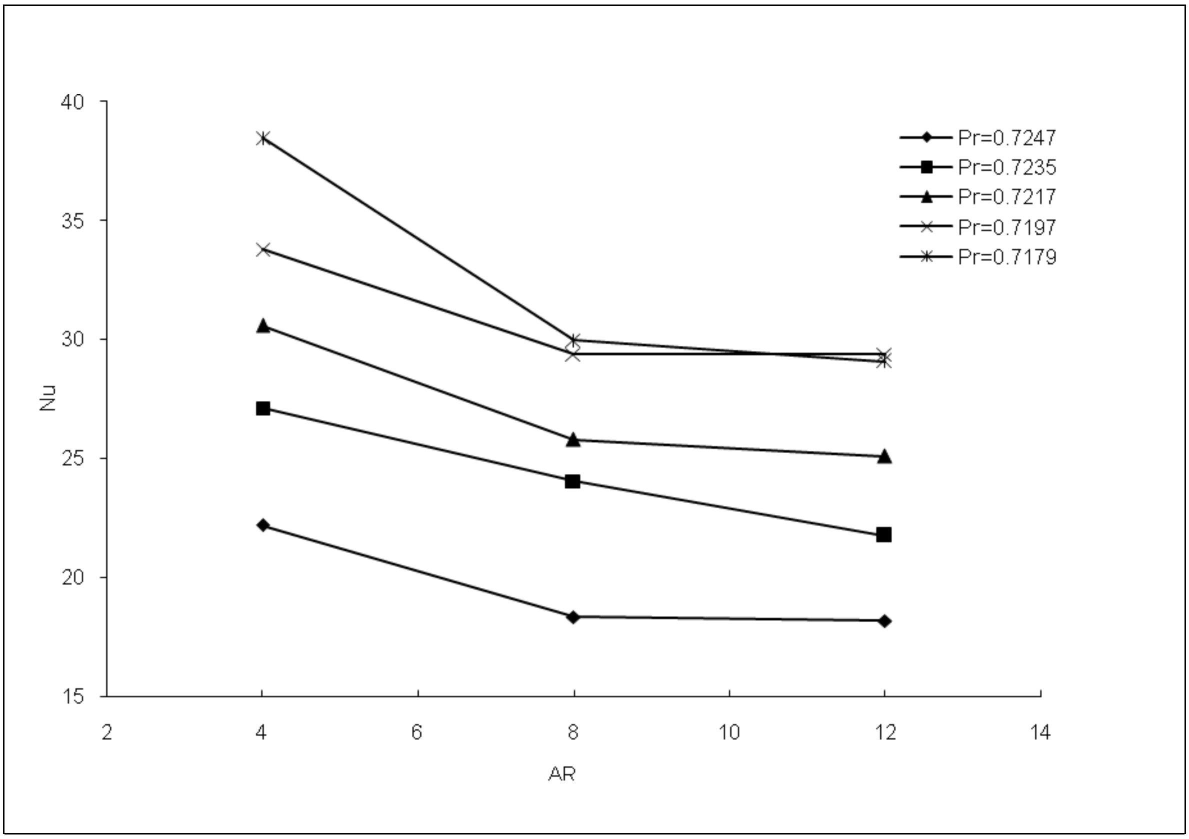


Fig. (3) Relation between Nuseelt number and aspect ratio at Re=642.77

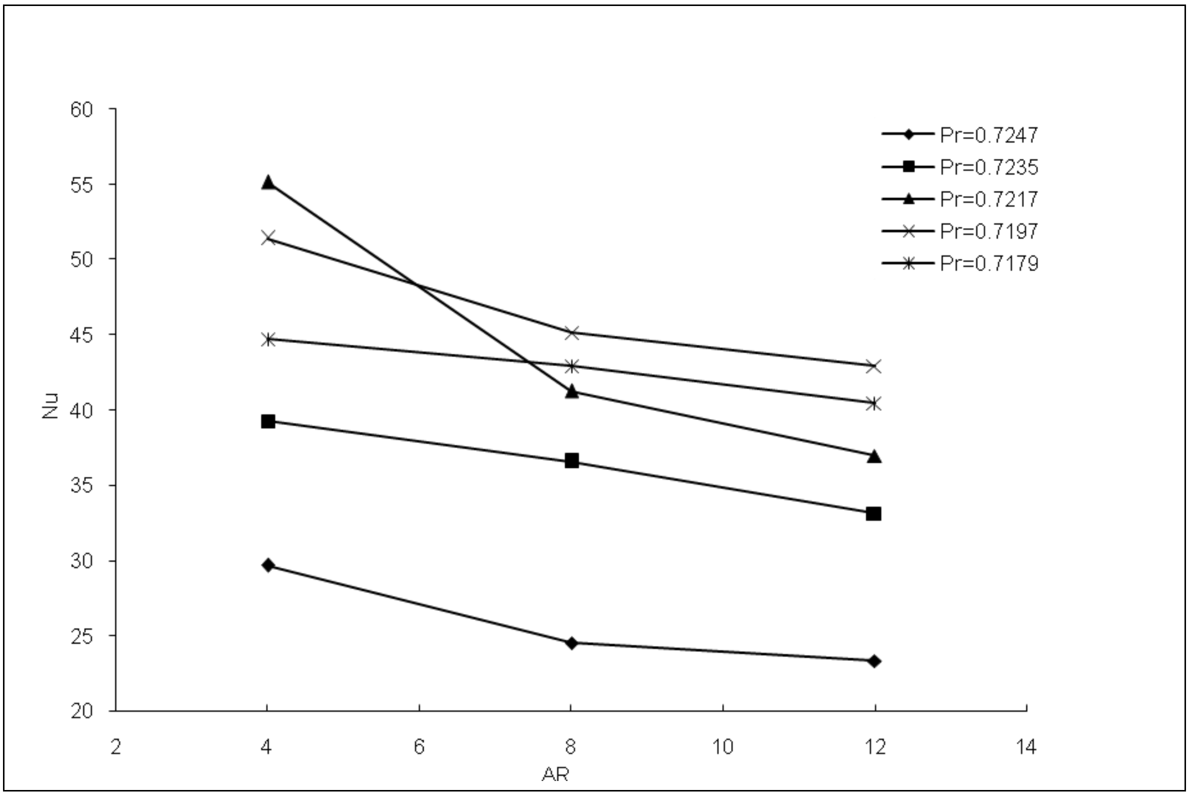


Fig. (4) Relation between Nuseelt number and aspect ratio at Re=1086.14

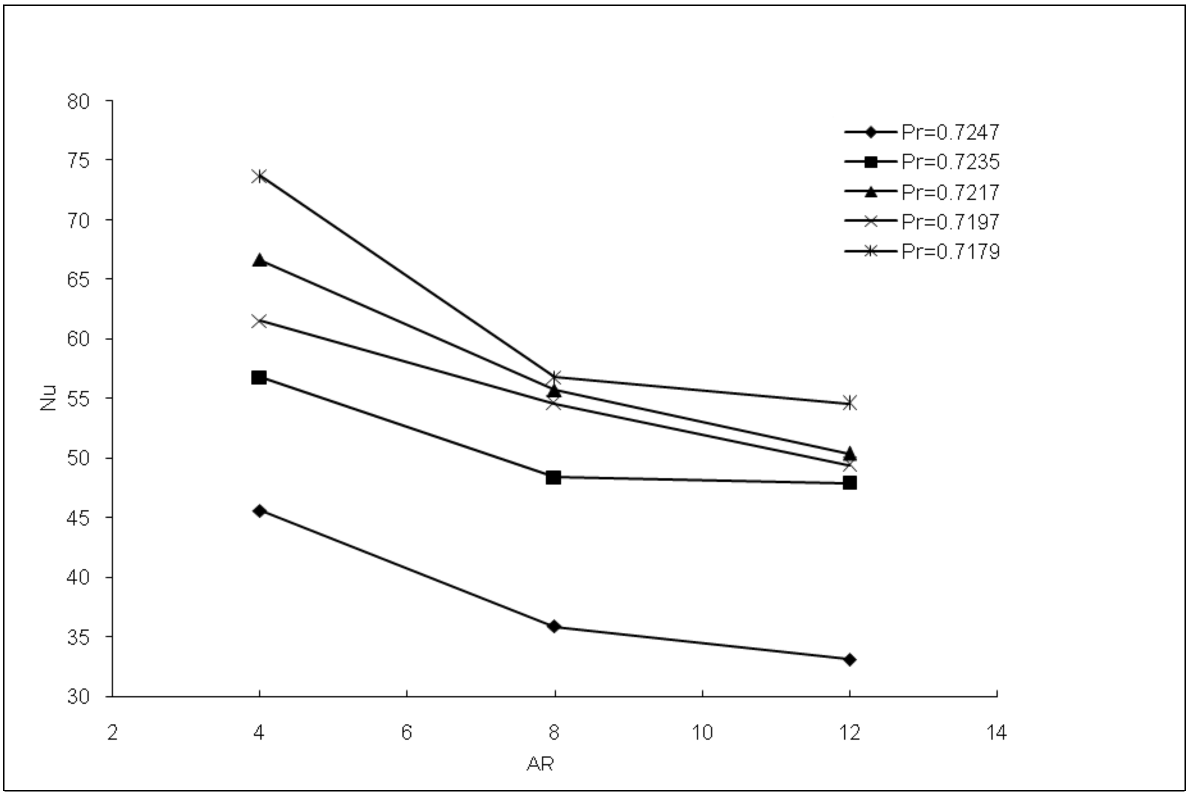


Fig. (5) Relation between Nuseelt number and aspect ratio at Re=1642.09

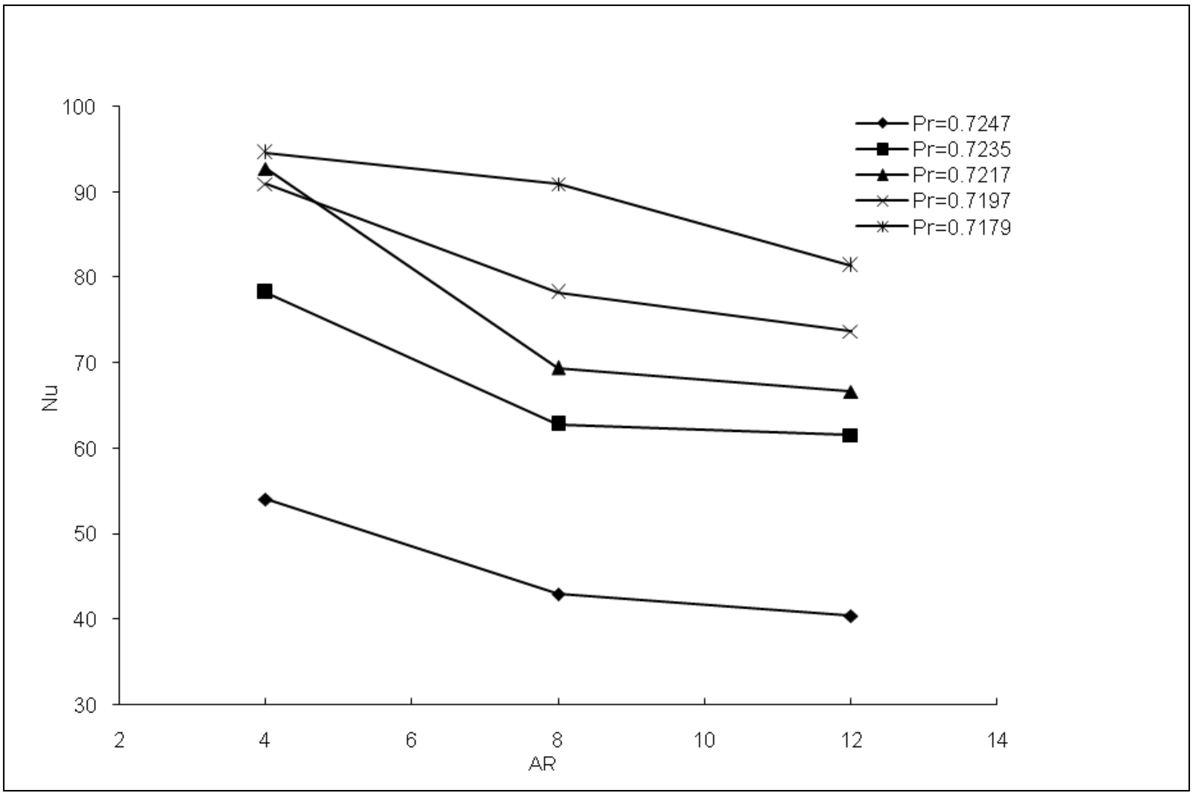


Fig. (6) Relation between Nuseelt number and aspect ratio at Re=2203.46

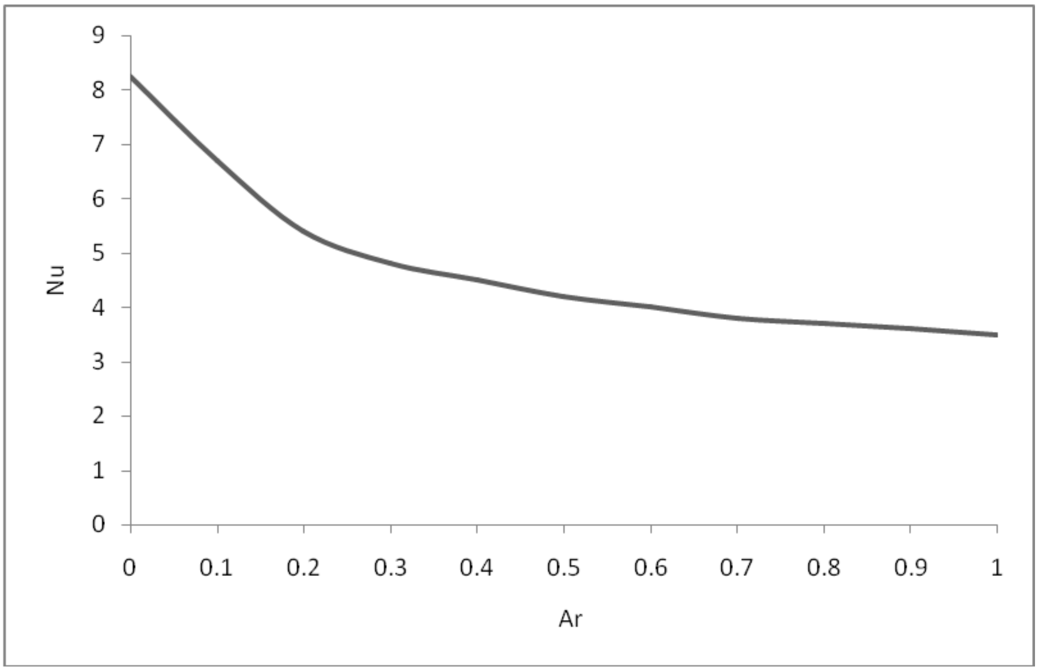


Fig. (7) Relation between Nuseelt number and aspect ratio in study of Erdogan and Imrak, [5]

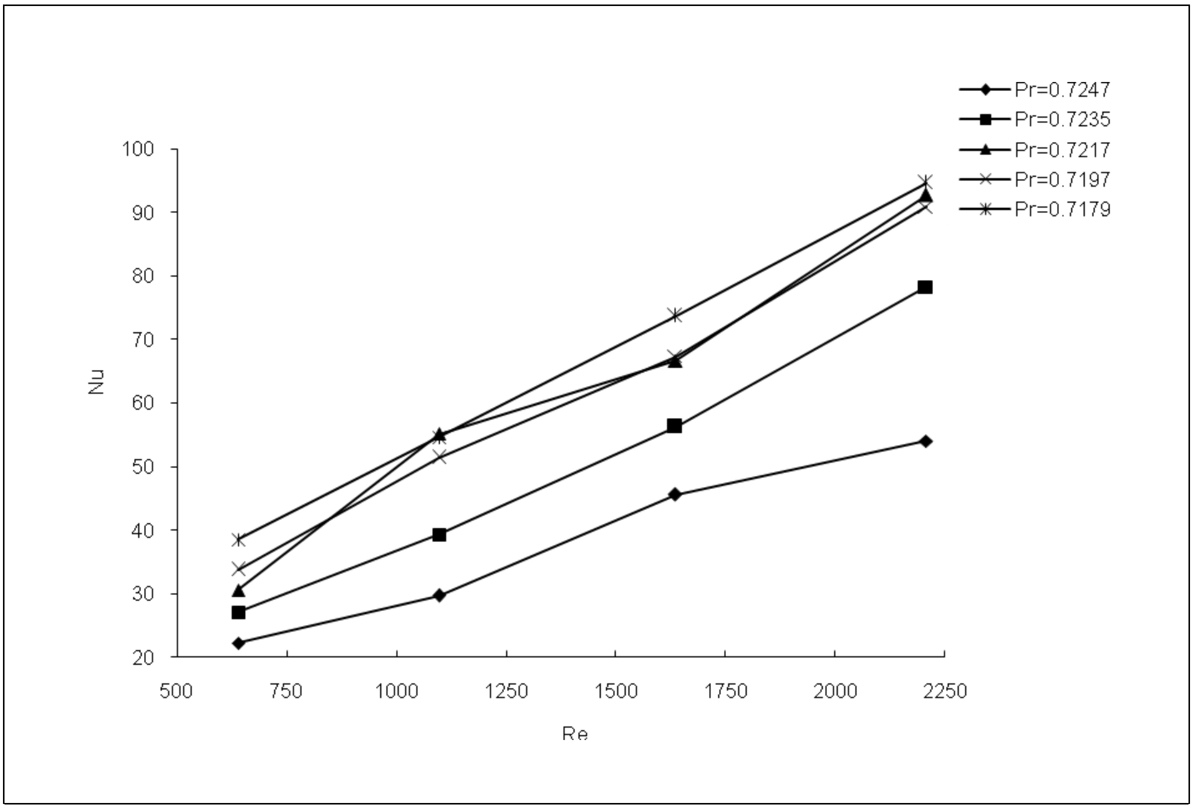


Fig. (8) Relation between Nuseelt number and Reynolds number at AR=4

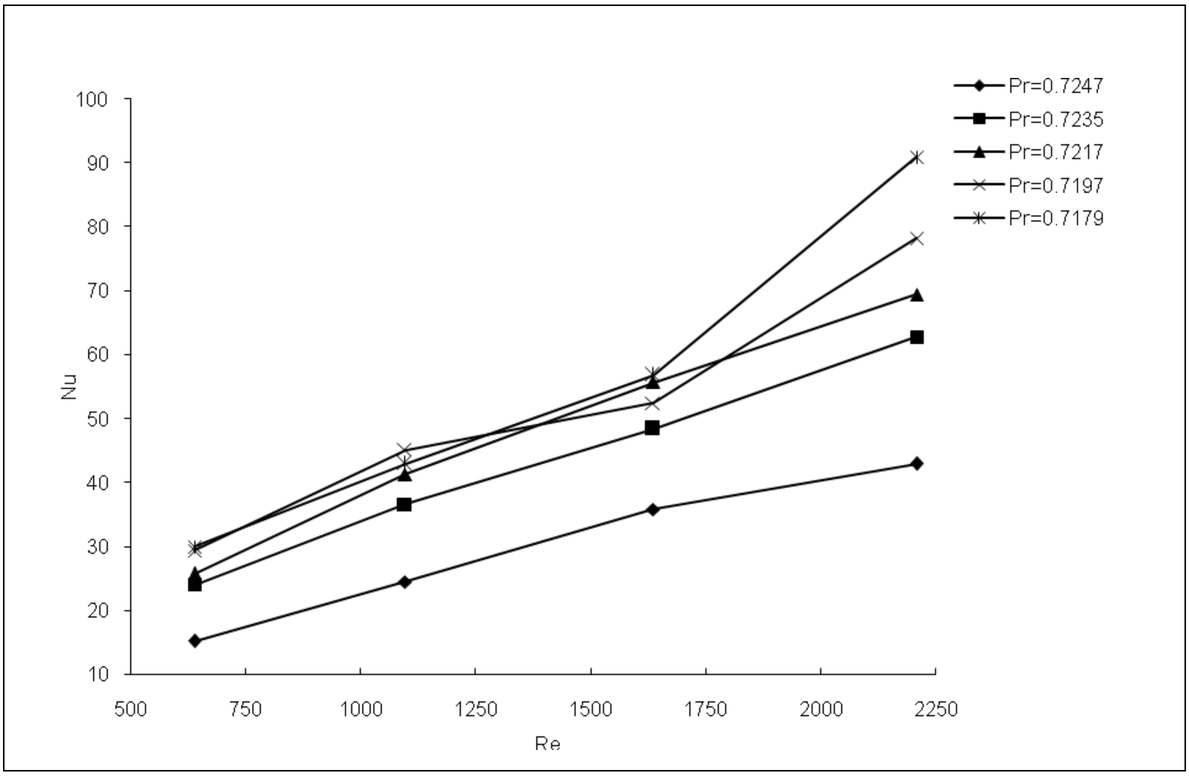


Fig. (9) Relation between Nuseelt number and Reynolds number at AR=8

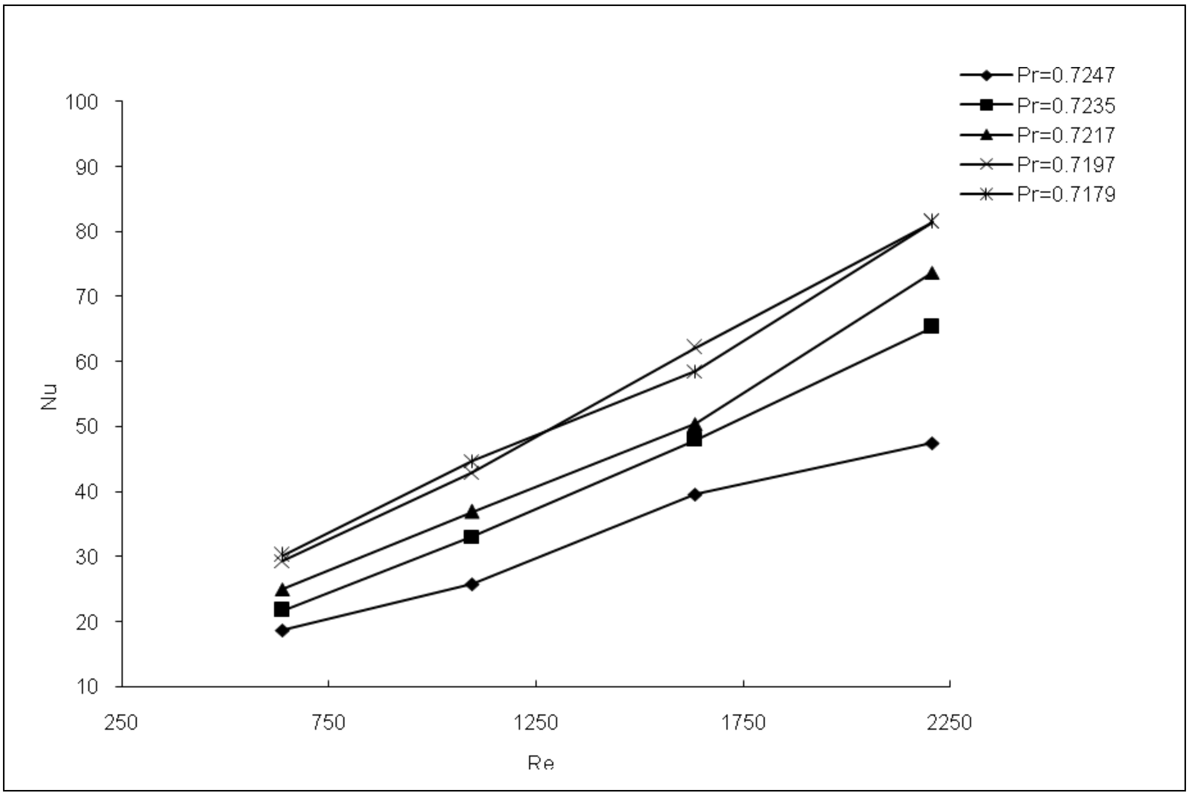


Fig. (10) Relation between Nuseelt number and Reynolds number at AR=12

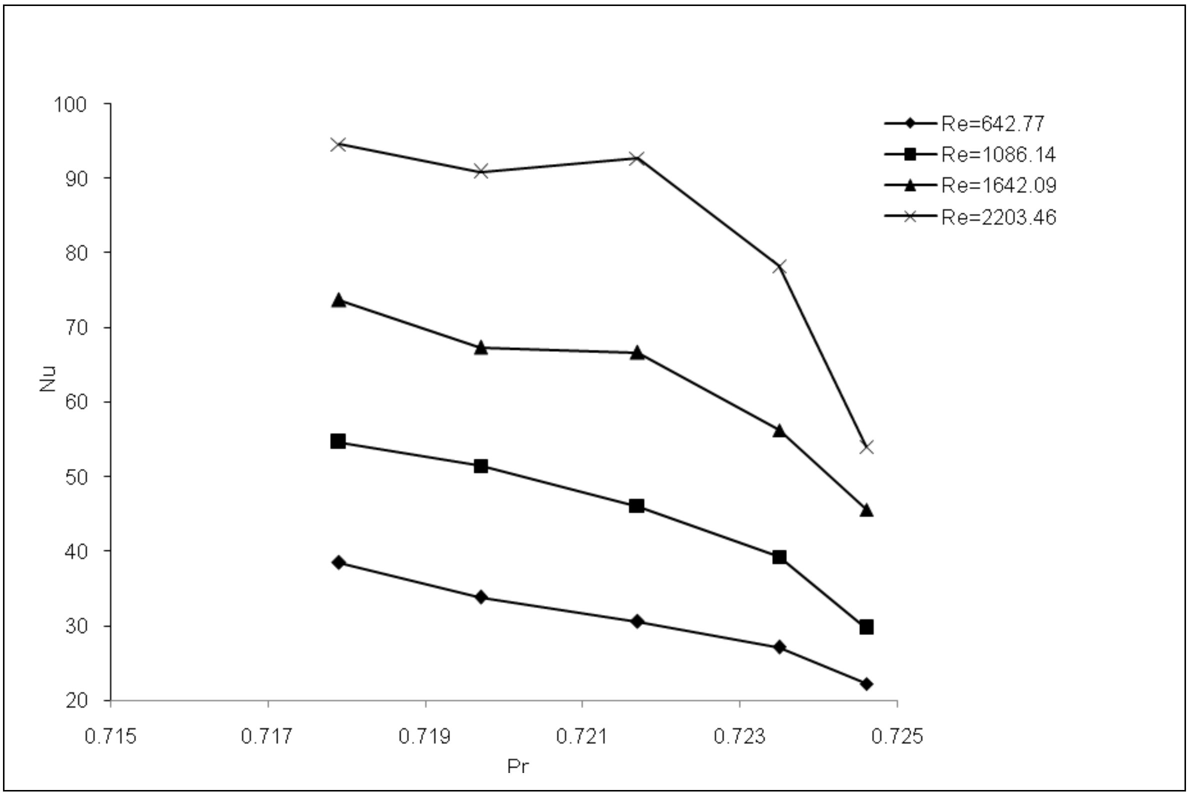


Fig. (11) Relation between Nuseelt number and Prandtl number at AR=4

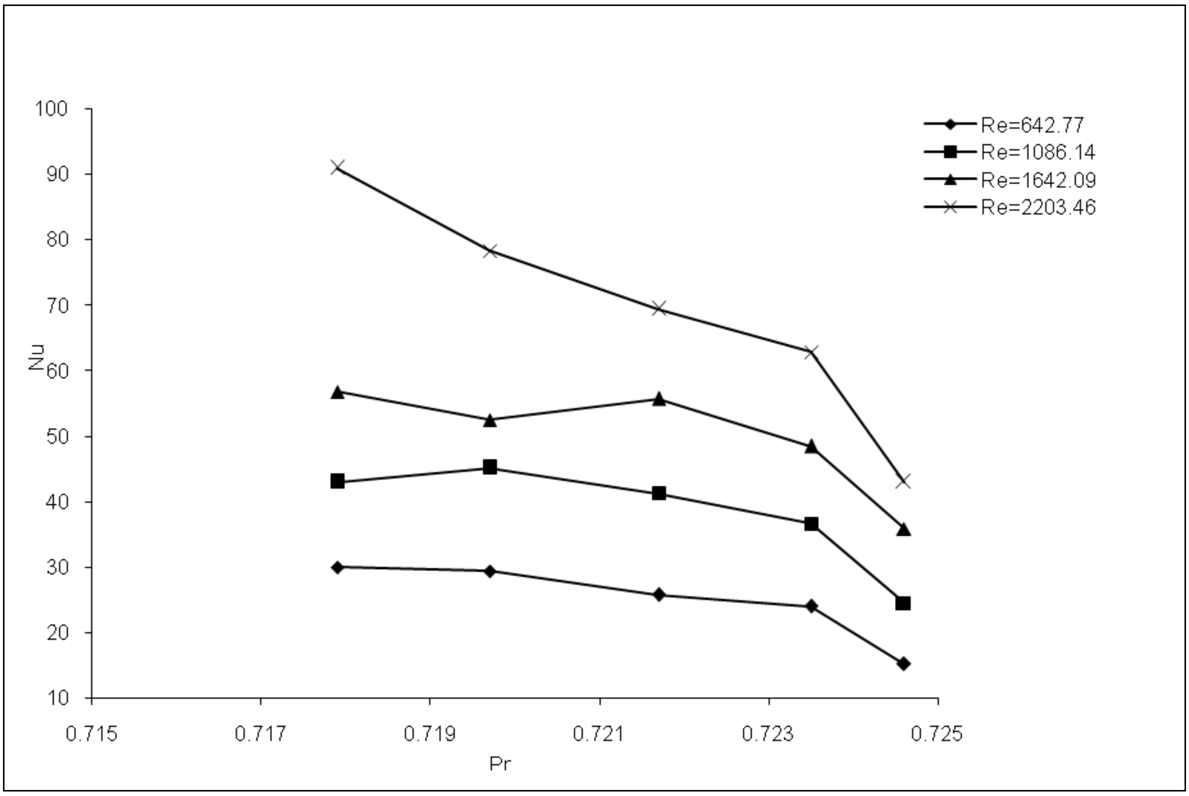


Fig. (12) Relation between Nuseelt number and Prandtl number at AR=8

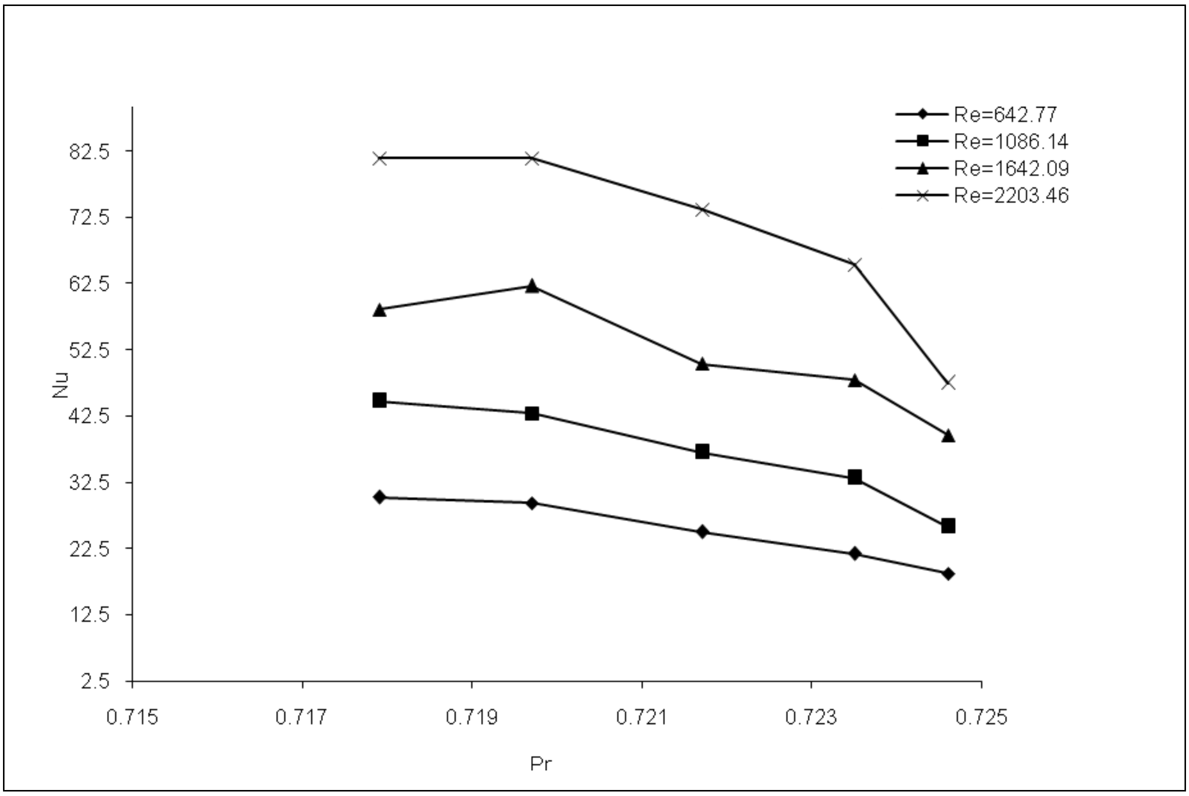


Fig. (13) Relation between Nuseelt number and Prandtl number at AR=12