Mansoura Engineering Journal, (MEJ), Vol. 26, No. 2, June 2001.

AUGMENTATION OF NATURAL CONVECTION HEAT TRANSFER IN VERTICAL CYLINDRICAL ANNULUS

تحسين انتقال الحرارة بالحمل الحر في فراغ حلقي أسطواني رأسي

AHMED A. SULTAN and Y. Z. HASSAN
Mech. Power Eng. Dept., Faculty of Engineering,
Mansoura University, PO 35516, El-Mansoura, Egypt.

خلاصة:

في هذا البحث تم عمليا دراسة انتقال الحرارة بالحمل الحر خلال فراغ حلقي اسطواني رأسي ، النسبة الباعية له تساوى 50 ونسبة الأقطار تساوى 1.5 . الاسطوانة الداخلية مسخنة بفيض حراري منتظم بينما تتعرض الاسطوانة الخارجية للهواء الجوى. الفراغ الحلقي مملوء بالهواء عند الضغط الجوى والفيض الحرا ي يسمح بتغير رقم رايلي من 80 إلى 1500 . استخدمت أسلاك من النحاس بأقطار مختلفة(من 45 ^ إلى 1.35 مم) ، تم لفها على شكل حلزون بأقطار لف مختلفة (من 5.2 إلى 9.6 مم) . تم لف هذا الحلزون على الاسطوانة الداخلية على شكل حلقات منفصلة. تم تغيير عدد الحلزونات في الحلقة (من 60 إلى 160 لفة) و عدد الحلقات على طول الاسطوانة (من 20 إلى 63 حلقة) مما أعطى قيم مختلفة لخطوة الحلزون (من 0.9 إلى 2.39 مم) و خطوة الحلقات (من 7.54 إلى 23.75 مم).
أوضحت الدراسة زيادة انتقال الحرارة بزيادة كل من قطر السلك ، قطر اللف و نقصان خطوة الحلقات بينما تتغير الحرارة المنقولة مع خطوة الحلزون بحيث يكون لهل قيمة عظمى عند نسبة خطوة الى سمكك الفراغ الحلقي تساوي 0.125 تقريبا. أوضحت النتائج أن الحرارة لا تنتقل خلال الفراغ الحلقي فقط بالحمل ولكن أيضا بالإشعاع و التوصيل . بمقارنة النتائج العملية مع الفراغ الحلقي بدون حلقاب اتضح زيادة الحرارة المنقولة بمعامل يربو على 8.25 . صيغت النتائج في صورة معادلة تجريبية لا بعدية لإمكانية الاستفادة منها في تصميم هذا النوع من المبادلات الحرارية.

ABSTRACT

In the present work, the natural convection heat transfer through vertical cylindrical annular tubes was experimentally investigated. The inner cylinder is heated electrically with constant heat flux, while the outer one is subjected to ambient air. Rayleigh number was varied between 80 and 1500 throughout this investigation. Aspect ratio of 50 and radius ratio of 1.5 were used. The annular gap was provided with helical-wire-coil rings wound around the outer surface of the inner cylinder as augmentation devices. The effects of coil pitch, ring pitch, coil diameter and wire diameter were investigated. From the results of the present investigation it is concluded that the heat transfer rate increases with increase of coil diameter and wire diameter and decrease of ring pitch, while it has a peak value at coil pitch to gap thickness nearly equal 0.125. It is concluded from the experimental results that the heat transferred through the annular gap is not only by convection but also by radiation and conduction. The helical-wire-coil rings are found to enhance heat transfer by a factor of 8.25. A general correlation is presented in order to help in the design of such devices

NOMENCLATURE

A	aspect ratio, L/δ
As	surface area, π DL, m^2
d	diameter referring to helical-wire-coils, mm
D	diameter referring to tube, mm
g	gravity acceleration, m/s^2
Gr	Grashof number
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	annular tube effective length, mm
Nu	Nusselt number

Accepted April 14, 2001

P	pitch, mm
Pr	Prandtl number
Q	heat flux, W
R	radius ratio, D_{io}/D_{oi}
Ra	Rayleigh number
Ta	air temperature, K
Tw	wall temperature, K

Greek symbols

β	coefficient of volumetric thermal expansion
δ	annular gap thickness, mm
ΔT	temperature difference, K
ν	kinematic viscosity, m^2/s

Subscripts

c	coil
f	ring
i	inner or inside
io	outside of the inner
1-7	positions of thermocouples on tube surface
L	based on effective length
m	mean
oo	outer or outside
oi	inside of the outer
oo	outside of the outer
w	coil wire
δ	based on gape thickness

INTRODUCTION

Spent nuclear fuel is usually stored in casks that have inner and outer metallic shells, which are sealed in the top and bottom. The radioactivity of the spent nuclear fuel in the inner cylinder causes heating of the inner surface of the cask. The maximum amount of spent fuel, that can be stored in the cask, depends on the effectiveness of heat removal from the inner surface, the design and properties of the cask material itself. The dominant mode of heat removal from the inner surface to the outer surface is natural convection of air in the cask Using helical wire coil rings on the inner surface considerably enhances heat transfer. Therefor, for efficient design of these casks with helical-wire-coil rings, determination of the heat transfer coefficient is necessary.

In general, the literature for finned enclosures deals with the square cavities, and not cylindrical annuli Guglielmini et al [1] theoretically and experimentally investigated free convection heat transfer from staggered vertical fins They studied the effects of fin height, fin length, emissivity of fin material and transverse spacing across a channel on the average heat transfer coefficient It was concluded that, for the staggered vertical fins taken into account the convective and radiant components yields a more efficient heat transfer than that obtained from fins made up of U-shaped vertical channels for the same bulk volume Single-phase natural convection heat transfer data had been obtained by Heindel-et al [2] for an array of highly finned, discrete heat sources The fins were mounted to one wall of a cavity filled with dielectric liquid for both horizontal and vertical cavity orientations. The finned surfaces were found to enhance heat transfer by a factor of 24 Rammohan Rao and venkateshan [3] experimentally investigated the interaction of free convection and radiation in a horizontal fin array Their results were performed to show the effect of various parameters such as emissivity of fin surface, fin spacing, fin height and fin base temperature The main conclusion of this study was that radiation-convection interaction invalidate additive approaches in which convection and radiation contributions are independently calculated assuming all surfaces to be isothermal and then adding radiation and convection effects to obtain the total heat transfer through the fin array

Heat transfer results indicated that the fin thickness could not be neglected in optimizing the total array heat transfer, as it influences both the efficiency of individual fin and the number of fins (Bar-Cohen [4], Tanaka et al [5], Hahne and Zhu [6], and Facas and Brown [7]) In this group of researches, Hahne and zhu involved a horizontal heated cylinder with a conducting transverse circular fin array While Facas and Brown studied horizontal heated cylinder with multiple longitudinal baffles of low conductivity

Karki and Patankar [8] did a numerical study of laminar natural convection in a vertical shrouded fin array, in which the flow is induced from surroundings, by the chimney effect. Scozia and Frederick [9] obtained numerical solutions for a differentially heated slender cavity with transverse conduction fins on the cold wall Prakash and Renzoni [10] numerically analyzed laminar fully developed flow in an internally finned vertical concentric annular duct. The fins were radial and fixed on the outside of the inner tube. The outer wall was insulated, while a uniform heat flux was applied at the inner tube. Accounting for the buoyancy effect, a finned passage appeared to be an effective heat exchange device.

Many studies have been done for different types of fin arrays, but to the knowledge of the present authors no experimental or theoretical investigations had been made to determine the effect of helical-wire-coil rings on the natural convection heat transfer in a vertical annulus or cavity In fact, Sultan [11&12] in order to enhance free convection heat transfer from horizontal cylinders used helical-wire-coils The cylinders in the two studies were heated electrically under constant heat flux In the first study [11], the helical-wire-coils were formed in the shape of rings around the cylinder circumference In the second study [12], the helical-wire-coils were in contact with the cylinder surface in longitudinal direction The experimental results of the two investigations showed that the maximum increase in heat transfer due to the presence of the coils were about 56-63% with respect to the bare cylinder.

The current paper focuses on the annular space enclosed between two coaxial vertical circular cylinders with helical-wire-coil rings on the outer surface of the inner cylinder and horizontal plates at the top and bottom The effects of the following parameters will be investigated: Rayleigh-number (Ra_δ), coil pitch (P_c), ring longitudinal pitch (P_l), coil outer diameter (d_c) and coil wire diameter (d_w).

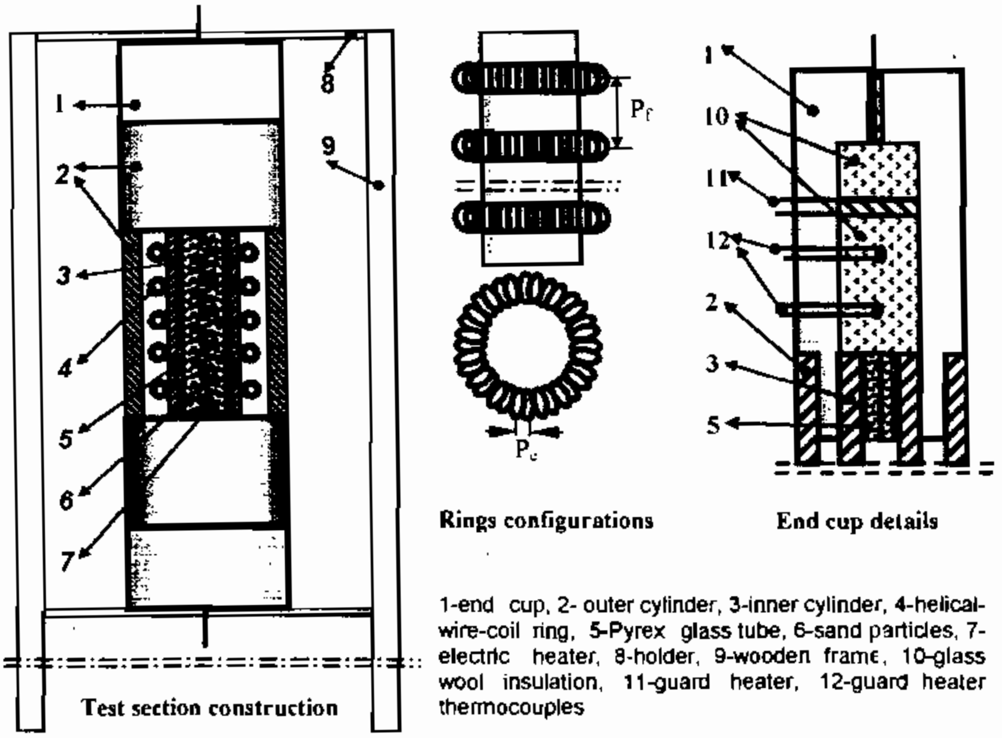
EXPERIMENTAL APPARATUS

The main part of the apparatus used in the present experimental investigation is the inner cylinder, which generates the heat for natural convection, end cups, heater and power supply with associated control and instrumentation. Fig (1) shows a schematic diagram of the experimental apparatus The inner cylinder (3) is made of brass bar, 38 mm in diameter, which is machined to have a central hole of diameter 10 5 mm where the electric heater (7) can be inserted The heater is a nickel chrome wire of 0 8 mm diameter. This inner cylinder is heated by passing an electric current through the nickel chrome wire which is wounded inside a central pyrex glass tube (5) of diameter 10 mm with an effective length of 475 mm and is designed to provide uniform electric power dissipation per unit length. Both ends of the inner cylinder are covered with a layer of glass wool insulation (10) of about 30 mm thickness, inside the glass wool insulation a guard heater (11) is fixed, in order to minimize the axial end losses These guard heaters are put in place and pressed against the inner cylinder by two wooden end cups (1) Two pairs of thermocouples (12) (guard heater thermocouples) are inserted in the glass wool along the axis of the inner tube with 20 mm distance between them The power input to the guard heater is adjusted using a voltage regulator so that, at steady state, the reading of the two thermocouples of each pair becomes equal. All the input to the main heater is then flowing to the air inside the annulus. The voltage drop over the test section of the inner cylinder is measured by a voltmeter An ammeter and wattmeter measure the current and the electric power respectively

To measure the surface temperature of the inner cylinder, eight thermocouples are used and seven rectangular grooves are cut over on the outer surface of the inner cylinder with peripheral angle of 51° between each other Seven thermocouples are placed one in each groove with distances 47, 85, 124, 200, 275, 350 and 430 mm started from the beginning of the lower end of the effective length of the cylinder In order to check the uniformity of temperature around the circumference, one thermocouple is placed in the opposite direction of the first one In all runs the readings of the surface thermocouple and opposite additional one were more or less the same.

The outer cylinder of the test annulus (2) has an inner diameter of 57.2 mm and a thickness of 3.2 mm, and the effective length of both cylinders is 475 mm. The wall temperatures of the outer cylinder are measured by nine thermocouples distributed in the same way as in the inner one. Owing to the high thermal conductivity of the brass, the inside and outside surface temperatures of the outer cylinder are very close to that monitored with the thermocouples (temperature difference of less than 0.02 °C) All thermocouples are copper-constantan impeded inside the grooves to their places, kept in contact with the cylinder surface using glue and then thoroughly polished

The annular tube assembly is fixed inside a vertical square cross section frame (9), using two holders (8). The frame has a sufficient dimensions and wrapped with plastic sheet, in order to avoid the effect of room air current.



Test section construction

Rings configurations

End cup details

1-end cup, 2- outer cylinder, 3-inner cylinder, 4-helical-wire-coil ring, 5-Pyrex glass tube, 6-sand particles, 7-electric heater, 8-holder, 9-wooden frame, 10-glass wool insulation, 11-guard heater, 12-guard heater thermocouples

Fig 1 Experimental apparatus

The readings of all thermocouples are taken by means of a digital temperature recorder, capable of reading 0.1, °C via a multi switch. The ambient temperature is measured by a calibrated mercury-in-glass thermometer capable of reading 0.1 °C. Each experimental run was about two hours for air to reach steady state

The helical-wire-coil rings used as augmentation devices in this experimental investigation are made of copper wires of 0.45, 0.7, 0.9 and 1.35 mm diameters . The wire is coiled around rods of different diameters in order to have helical-coils of 5.2, 7.5, and 9.6 mm outside diameters. The helical-wire-coils are then turned around the inner cylinder of the annulus in the form of separate rings as shown in Fig. 1 The distance between the centers of two adjacent rings (pitch) is nearly equal to 7.54, 8.64, 9.6, 11.88, 18.53 and 23.75 mm along the axial direction of the annulus. The characteristic parameters, which define the helical-wire-coil rings configurations, are given in Table 1.

Table 1 Characteristic dimensions of helical-wire-coil rings used in the present work

Tube No.	Number of coils per ring	Number of rings	Coil pitch, (p_c) mm	Ring pitch (p_r) mm	Coil diameter (d_c), mm	Wire diameter (d_w), mm	Rings surface area (As_r), m^2	Area ratio As_r/As_i
1	160	63	0.90	7.54	7.5	0.70	0.4736	8.309
2	140	63	1.03	7.54	7.5	0.70	0.4144	7.270
3	130	63	1.10	7.54	7.5	0.70	0.3848	6.751
4	120	63	1.20	7.54	7.5	0.70	0.3552	6.232
5	100	63	1.44	7.54	7.5	0.70	0.2960	5.193
6	80	63	1.79	7.54	7.5	0.70	0.2368	4.154
7	60	63	2.39	7.54	7.5	0.70	0.1776	3.116
8	160	55	0.90	8.64	7.5	0.70	0.4134	7.253
9	160	50	0.90	9.60	7.5	0.70	0.3758	6.593
10	160	40	0.90	11.88	7.5	0.70	0.3007	5.275
11	160	30	0.90	15.83	7.5	0.70	0.2255	3.956
12	160	20	0.90	23.75	7.5	0.70	0.1503	2.637
13	84	50	1.62	9.60	5.2	0.70	0.1306	2.291
14	88	50	1.63	9.60	7.5	0.70	0.2067	3.627
15	92	50	1.63	9.60	9.6	0.70	0.2828	4.962
16	92	50	1.63	9.60	9.6	1.35	0.5056	8.870
17	92	50	1.63	9.60	9.6	0.90	0.3555	6.237
18	92	50	1.63	9.60	9.6	0.45	0.1869	3.279

Data reduction

The surface area of the inner cylinder of the annulus (As_{io}) is used to facilitate comparisons with data for annulus without augmentation devices in a similar geometric arrangement [13] The average heat transfer coefficients from the inner and outer cylinders of the annulus, h_i, and h_o, can be defined by equations 1&2 respectively as follows

$$h_i = \{Q/ As_{io} [(Tw_i)_m - (Tw_o)_m]\}, \text{ and} \tag{1}$$

$$h_o = \{Q/ [As_{oo} [(Tw_o)_m - Ta)]\} \tag{2}$$

Where Ta is the ambient air temperature, As_{io} and As_{oo} are the outer surface area of the inner cylinder and the outer surface area of the outer one respectively, defined by equation (3)

$$As_{io} = \pi D_{io} L, \quad \text{and} \quad As_{oo} = \pi D_{oo} L \tag{3}$$

And $((Tw_i)_m$ and $(Tw_o)_m$ are the mean surface temperatures of the inner and outer cylinders defined by equations (4 & 5) respectively.

$$(Tw_i)_m = (Tw_{i1}+Tw_{i2}+Tw_{i3}+Tw_{i4}+Tw_{i5}+Tw_{i6}+Tw_{i7})/7, \text{ and} \tag{4}$$

$$(Tw_o)_m = (Tw_{o1}+Tw_{o2}+Tw_{o3}+Tw_{o4}+Tw_{o5}+Tw_{o6}+Tw_{o7})/7 \tag{5}$$

Where, $(Tw_{i1} \rightarrow Tw_{i7})$ and $(Tw_{o1} \rightarrow Tw_{o7})$ are local surface temperatures of the inner and outer cylinders of the annulus respectively

The mean Nusselt numbers for the inner and outer surfaces of the annulus can be calculated respectively as follows:

$$Nu_\delta = h_i\, \delta \;/ k_i, \text{ and} \qquad Nu_L = h_o L \;/ k_o \tag{6}$$

Where, δ is the annular gap thickness, equal $(D_{oi} - D_{io})/2$ and L is the effective length of the annular tube.

The other dimensionless parameters which were used in the formulation of the experimental results were inside and outside Grashof number Gr_δ and Gr_L, inside and outside Rayleigh numbers Ra_δ and Ra_L defined according to the following equations

$$Gr_\delta = g\, \beta_i\, \{(Tw_i)_m - (Tw_o)_m\}\, \delta^3 / \nu_i^2, \text{ and} \quad Gr_L = g\, \beta_o\, \{(Tw_o)_m - Ta\}\, L^3 / \nu_o^2 \tag{7}$$

$$Ra_\delta = Gr_\delta\, Pr_i, \text{ and} \qquad Ra_L = Gr_L\, Pr_o \tag{8}$$

Where $(k_i \;\&\; k_o)$, $(\nu_i \;\&\; \nu_o)$, $(\beta_i \;\&\; \beta_o)$ and $(Pr_i \;\&\; Pr_o)$ are the inside and outside thermal conductivity, kinematic viscosity, coefficient of volumetric thermal expansion and Prandtl number respectively. These parameters were taken from the appendix of Reference [14] at the inside and outside arithmetic mean temperature of air, defined as follows:

$$(Ta_i)_m = \{(Tw_i)_m + (Tw_o)_m\}/2, \text{ and} \qquad (Ta_o)_m = \{(Tw_o)_m + Ta\}/2 \tag{9}$$

RESULTS AND DISCUSSION

Natural convection of air is studied experimentally in a vertical annulus with helical-wire-coil rings on the inner cylinder. The inner wall is subjected to constant heat flux, and the outer wall is subjected to ambient air. The effects of P_c, P_r, d_c, d_w and Ra_δ on the heat transfer results are discussed in this section. Results obtained in this work include temperature distribution on the outer surface of the inner cylinder, mean temperature difference between inner and outer surfaces of the annulus and heat transfer coefficients for free convection. In this work the radius ratio is equal to 1.5, aspect ratio is equal to 50 and Rayleigh number ranges between 80 to 1500. This range of Rayleigh number spans the conduction regime of convection as defined in the study of Thomas and de Vahl Davis [15]. In all cases a correction for thermal radiation in the annulus is applied in the calculation of the coefficient of free convection. This correction includes the effect of surface emissivity and radiative view factor for the empty annulus (annulus without augmentation) The effect of radiation from the augmentation devices is not calculated in this study

Validation of experimental results

Before reporting on the main results of the research, mention will be made of relevant auxiliary experiments. To demonstrate the validity of the experimental apparatus, heat transfer experiments were performed with an empty vertical annulus, in order to enable comparison with heat transfer results in the literature. The relation between Nusselt number and Rayleigh number are presented in Fig. 2 as well as the results of other investigators A mixed boundary condition, as in the present study, results in Nusselt numbers as much as 35 percent higher than those of an isothermal one (Thomas and de Vahl Davis [15]). This difference was also reported by Kehani et al [16] (A=27 6 and R=4 33) and Bushan et al [17] (A=52.82 and R=2 77) It is seen from Fig. 2 that the calculated Nusselt number results lay between those given by the recent heat transfer correlations of References [16] and [17]

As a second verification of the experimental set-up, natural convection from the outer cylinder to the surrounding atmosphere is checked considering the whole annulus as a single vertical cylinder. The collected data are presented in Fig.3 as a relation between the average Nusselt number Nu_l and Rayleigh number Ra_l, both based on the effective length of the outer cylinder. A straight line representing the correlation of McAdams [18] is also presented in the figure with a deviation of about +7 %. It is concluded from Figs.2&3 that the present experimental results are in fair agreement with the literature.

Temperature distribution

A sample of the experimental temperature distributions on the inner wall of the augmented annulus is summarized in Figures 4-7, for heat flux ranged from 2 to 58.5 W The temperature distribution exhibits an almost smooth variation at low power, but at higher power a comparatively high variation is observed

Despite the variation of temperature in the axial direction, the deviation of mean values ranges from 0 2 to 3 percent. The data of small heat flux exhibits somewhat smooth variation along the axial direction with a deviation of ±0 2 to ±0 5 percent.
Relation between the mean temperature differences and the heat flux on the inner cylinder of the annulus is shown in Fig. 8. The figure shows that the existence of coil rings reduces the mean temperature difference across the annulus with respect to that of empty annulus at the same heat flux. This means that, an increase in the heat transfer coefficient of the augmented annular tubes over that of the empty annulus is prevail at the same value of heat flux

HEAT TRANSFER RESULTS

Attention will now be turned to the heat transfer results of the augmented annular tubes. In this connection, the sequence in which the experiments are performed is chosen in order to facilitate the presentation of results. For specified value of three parameters, successive experiments were carried out in which the forth parameter was changed to cover its specified range. Therefor, four groups of experiments were performed, presented and discussed in the following sections

Effect of coil pitch

The effect of coil pitch on the heat transfer rate is given in Figures 9 and 10. In Fig. 9 the relation between Nusselt number and Rayleigh number for different coil pitch to annular gap thickness ratios (p_c/δ) is presented. The other configuration parameters are kept constant, namely (p_r/δ) =0.785 , (d_c/δ)=0.781 and (d_w/δ) =0.073. From the plots of this figure the data can be correlated in the form $Nu_\delta = C\ Ra_\delta^n$ where the mean value of exponent n is equal to 0.114. In order to show the effect of (p_c/δ), elimination of Rayleigh number had been done and the relation between the complex ($Nu_\delta/Ra_\delta^{0.114}$) and ($p_c/\delta$) is presented in Fig.10. The observation from this figure may be summarized as follows: when (p_c/δ) is decreased (i.e. the number of coils in the ring is increased) further enhancement of heat transfer is achieved up to a maximum value at (p_c/δ) nearly equal 0.125. Further decrease in (p_c/δ) decreases the heat tranfer rate. One may observe that the decrease of (p_c/δ) increases the surface area of the helical-wire-coil rings, at constant other parameters and this consequently increases the heat transfer rate. The decrease of (p_c/δ) also increases the degree and domain of turbulence caused by the existence of the rings. At (p_c/δ) less than 0.125 the coils of the rings can be brought closer, due to the small distances between them and this in turn, affect the degree and domain of turbulence. So the heat transfer rate will increase or decrease depending on (p_c/δ)

Effect of ring pitch

This group of results concerns the effect of ring pitch to gap thickness ratio (p_r/δ) on the heat transfer rate. In this group, the other parameters discussed in this work are kept constant at the following values (p_c/δ)=0.094, (d_w/δ)= 0.073 and (d_c/δ) = 0.781. Figure 11 represents the relation between Nusselt number and Rayleigh number at different values of (p_r/δ). The relation between (p_r/δ) and the complex ($Nu_\delta/Ra_\delta^{0.114}$) are presented in Fig.12, in order to eliminate the effect of Rayleigh number. As ring pitch to gap thickness ratio (p_r/δ) is decreased (the number of rings is increased), the heat transfer rate increases. The reason may be given as follow: as (p_r/δ) is decreased, for the same Ra_δ, the porosity of the system decreases and consequently the effective thermal conductivity of the system increases. This increases the conduction heat transfer through the annulus. Also as (p_r/δ) is decreased the surface area of the rings increases, this in turn increases the radiation heat transfer through the annulus. Finally, as (p_r/δ) is decreased the degree and domain of turbulence, caused by rings configurations, increase and as a result the convective heat transfer rate increases.

Effect of coil diameter

The data collected in this group of experiments are presented in Figures 13 and 14. Different coil diameter to gap thickness ratios (d_c/δ) are used while the other configuration parameters are kept constant, as (p_c/δ)=0.17, (p_r/δ) =1.0 and (d_w/δ) =0.073 in this group of experiments. Figure 13 represents the relation between Nusselt number and Rayleigh number, and Fig.14 indicates the effect of (d_c/δ) on Nusselt number after eliminating the effect of Rayleigh number. The observation from these figures may be summarized as follows: an increase in (d_c/δ), with other configuration parameters are kept constant, increases the heat transfer across the annulus. This is mainly because a greater surface area is available for heat transfer from the rings, and an increase in the domain of turbulence is existed. The value of (d_c/δ) for maximum heat transfer in this group of results is equal to unity at which the rings contact both the inner surface of the outer cylinder and the outer surface of the inner one. This explains the sharp increase in the heat transfer rate in this case, due to the high thermal conductivity of ring material This portion of heat transfer by conduction may be high compared to the convective and radiative portions of heat transfer, caused by the existence of the coil-rings

Effect of wire diameter

This group of experiments discuses the effect of variation of wire diameter on the heat transfer rate. In this case $p_c/\delta = 0.17$, $p_r/\delta = 1.0$ and $d_c/\delta = 1.0$ are kept constant while d_w/δ is changed from 0.047 to 0.141. From the value of (d_c/δ) one can observe that the helical-wire-coil rings, in this group of experiments, are kept in contact with the inner and outer cylinders of the annulus. The results of this group are presented in Figures 15 and 16. The relation between Nu_δ and Ra_δ is shown in Fig. 15, from which it is seen that Nu_δ increases with Ra_δ for the same value of (d_w/δ), while Fig. 16 shows the relation between (d_w/δ) and Nu_δ divided by Ra_δ to the power 0.114. The figure shows that, the heat transfer rate represented by the complex $(Nu_\delta/Ra_\delta^{0.114})$ increases with d_c/δ Increasing wires diameter increases the effective thermal conductivity of the annular gap, (porosity decreases by about 14%). This in turn increases the heat transfer rate by conduction through the annular gape In the same time, increasing d_w increases the surface area of the rings and consequently increases the heat transfer rate by radiation. (surface area is increased by about 270 %) Also, increasing (d_w/δ) increases the cross section of the wire and consequently increases the conduction heat transfer rate through the indirect contact between inner and outer surfaces of the annulus via coil material

Constant surface area data

To show the effect of helical-wire-coil rings in disturbing air boundary layer in the annular gap (convection effect), some experiments are presented in Fig 17. The data presented here concerns helical wire-coil rings having the following constant parameters. Surface area (to eliminate the effect of radiation heat transfer), wire diameter, coil diameter and total number of coils (to eliminate the effect of conduction heat transfer due to effective thermal conductivity), while coil pitch and ring pitch are varied The figure shows a variation of about 6 % between tube 2 and tube 8 and a variation of about 25% between tube 14 and tube 11(See Table I) From Table I one can see that, the variation in p_c and p_r in case of tube 2 and tube 8 is comparatively small (-14% and + 14% respectively), while the variation in p_c and p_r in case of tube 14 and tube 11 is high (- 82 % and + 67%) This proves the effect of helical-wire-coil rings configurations on the convective portion of heat transfer caused by their existence in the annular gap

In order to indicate the effect of conduction heat transfer caused by the existence of helical-wire-coil rings, two sets of experiments are performed and demonstrated in Fig. 18 In these sets of results, the total surface area and wire length of the helical-wire-coil rings are kept nearly constant (4.6 % change), in order to eliminate the effect of radiation heat transfer While the changes in coil pitch and ring pitch are equal to 14% and 28% respectively, which means a small effect on the heat transfer as discussed above (See Fig.17). In the first set of these results (tube 15) the coil diameter allows contact between the rings and both the inner and outer cylinders of the annulus ($d_c = \delta$), while in the second set (tube 5) $d_c < \delta$, which means that the rings contact only the inner cylinder of the annulus. Figure 18 shows that, the heat transfer rate of tube 15 is 84% higher than that of tube 5. This is because of the indirect contact between the inner and outer cylinders of the annulus via the helical-wire-coil rings.

Correlations

The data obtained in this study are correlated by the use of statistical analysis [19], to estimate the heat transfer rates from values of parameters that influence the process of heat transfer augmentation through the annulus, as follows:

$$Nu_\delta = 15.4924\, Ra_\delta^{0.114} (p_r/\delta)^{0.1409} (d_w/\delta)^{0.3516} f(p_c/\delta)\, f(d_c/\delta) \qquad (10)$$

Where

$$f(p_c/\delta)=1+2.7629(p_c/\delta)-10.6768(p_c/\delta)^2 \text{, and} \qquad (11)$$

$$f(d_c/\delta)=1-3.0369\,(d_c/\delta)+2.7654\,(d_c/\delta)^2 \qquad (12)$$

Correlation (10) is valid in the following ranges of the operating parameters:

$80 \le Ra_\delta \le 1500$, $0.094 \le p_c/\delta \le 0.249$, $0.785 < p_r/\delta \le 2.474$,
$0.047 \le d_w/\delta \le 0.141$ and $0.542 \le d_c/\delta \le 1.0$

Figure 19 shows a plot of the observed data against the predicted values from equation 10. The predicted values are within ±10% of the observed one as shown from the figure

CONCLUSIONS

Experimental results are reported for vertical annular tubes of radius ratio 1.5 and aspect ratio 50. The inner wall of the annulus is heated electrically Using air as a test fluid, the Rayleigh number is ranged from 80 to 1500. In order to augment free convection heat transfer through annular tubes, helical-wire-coil rings having the following configurations are covered. coil pitch to gape thickness ratio range $0.094 \le (p_c/\delta) \le 0.249$, ring pitch to gape thickness ratio range $0.785 \le (p_r/\delta) \le 2.474$, coil diameter to gape thickness ratio range $0.542 \le (d_c/\delta) \le 0.1$ and wire diameter to gape thickness ratio range $0.047 \le (d_w/\delta) \le 0.141$ The temperature fields and the heat transfer rates obtained in this study lead to the following conclusions

1- Temperature fields are influenced by the variation of wire diameter, coil diameter, coil pitch, ring pitch and heat flux. This results in an enhancement of heat transfer rate.
2- The heat transfer rate increases with the increase of both coil diameter and wire diameter and the decrease of ring pitch. While it has a peak value through the variation of coil pitch
3- Relative to the annulus without augmentation, the use of helical-wire-coil rings experienced heat transfer enhancement by as much as 8.25 times.
4- The heat transfer coefficients are correlated as a function of (p_c/δ), (p_r/δ), (d_c/δ), (d_w/δ) and Rayleigh numbers

REFERENCES

1- Guglielmini, G., Nannei E., and Tanda G. Natural convection and radiation heat transfer from staggered vertical fins, Int. J Heat Mass Trans., Vol 30, No 9, pp 1941-1948, 1987
2- Heindel T. J., Incropera F P., and Ramadhyani, S., Enhancement of natural convection heat transfer from an array of discrete heat sources, Int J. Heat Mass Trans., Vol. 39, No 3, pp 479-490, 1996

3- Rammohan Rao, V., and Venkateshan, S. P., Experimental study of free convection and radiation in horizontal fin arrays, Int. J. Heat Mass Trans., Vol 39, No 4, pp 779-789, 1996.

4- Bar-Chen, A., Fin thickness for an optimized natural convection array of rectangular fins, ASME Journal of Heat Transfer, Vol. 101, pp. 564-566, 1979.

5- Tanaka, S., Yoshida, T., and Kunitomo, T., Optimization and heat transfer for a vertical fin array on isothermal and non-isothermal plane surfaces with combined natural convection and radiation, Heat Transfer-Japanese Research, Vol. 16, pp. 91-112, 1987

6- Hahne, E., and Zhu, D., Natural convection heat transfer on finned tubes in air, Int. J. Heat Mass Trans., Vol. 37, No. 1, pp. 59-63 , 1994.

7- Faeas, G. N., and Brown, H. L., Natural convection from a cylinder with multiple, Low conductivity, longitudinal baffles, Int. J Heat Mass Trans., Vol 39, No 10, pp 2077-2086, 1996

8- Karki, K. C., and Patankar, S. V., Cooling of vertical shrouded fin array by natural convection; a numerical study, ASME Journal of Heat Transfer, Vol 109, pp 671-676, 1987

9- Scozia, R., and Frederich, R. L., Natural convection in slender cavities with multiple fins attached to an active wall, Numerical Heat transfer, Part A, Vol 20, pp 127-158, 1991

10- Prakash C. and Renzoni P., Effect of buoyancy on laminar fully developed flow in vertical annular passage with radial internal fins, Int. J. of Heat Mass Trans., Vol. 28, No 5, pp. 995-1003, 1985

11- Ahmed A. Sultan, Natural convection heat transfer from horizontal circular cylinder with transverse wire-coil fins, Al-Azhar Eng. Fifth inter. Conferenee, Cairo, Egypt, Vol. 8, pp 278-289, 1993.

12- Ahmed A. Sultan, Augmentation of natural convection heat transfer from horizontal cylinder using longitudinal helical-wire-coils, Third Int Eng., Research, Port-Said, Egypt, pp.157-168, 1999

13- Heindel T. J., A numerical and experimental study of three dimensional natural convection in a discretely heated cavity, Ph. D., Thesis , Purdu University, West Lafayette, IN, 1994

14- Karlekar, B. V., and Desmond, R. M., Engineering heat transfer, West Publishing Company, USA, 1977

15- Thomas W., and de Vahl Davis E., Natural convection in annular and rectangular cavities, A numerical study, Proc. Forth Int Heat Transfer Conf., Paris, Vol. 4, Paper NC2.4, Elsevier, Amsterdam, 1970

16- Keyhane, M., Kulaki, F., and Christensen, R., Free convection in vertical annulus with constant heat flux on the inner wall, ASME Journal of Heat Transfer, Vol. 105, pp.454-459, 1983

17- Bhushan R., Keyhani M., Christensen R. M., and Kulacki F. A., Correlation for convective heat transfer in vertical annular gap layers with constant heat flux on the inner wall, ASME Journal, Vol. 105, pp 910-912, 1983

18- McAdams, W. H., Heat transmission, Mc Graw-Hill Book Company, Third Edition, New-York, 1954

19- Bajpai A. C., Claus I. M. and Fairley J. A., "Numerical Method for Engineering and Scientests", John Wiely& Sons Ltd., 1977

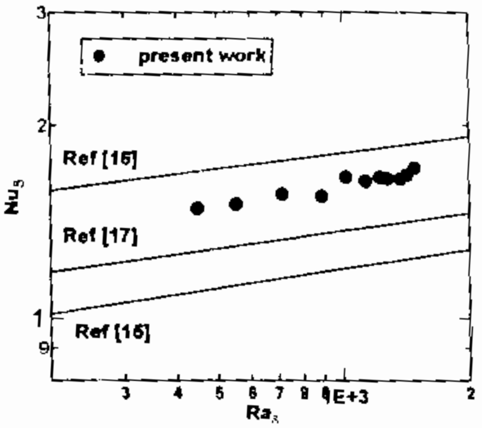


Fig. (2) Relation between Nusselt number and Rayleigh number for empty annular tube.

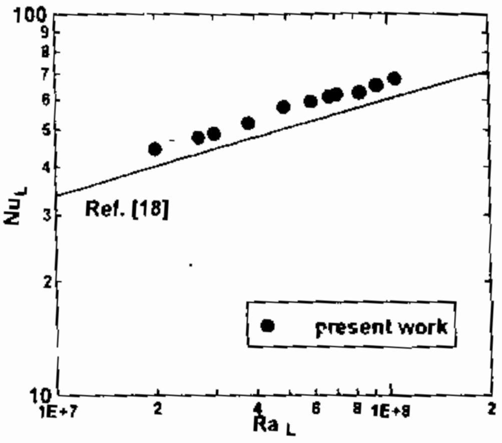


Fig. (3) Relation between Nusselt number and Rayleigh number for smooth vertical cylinder.

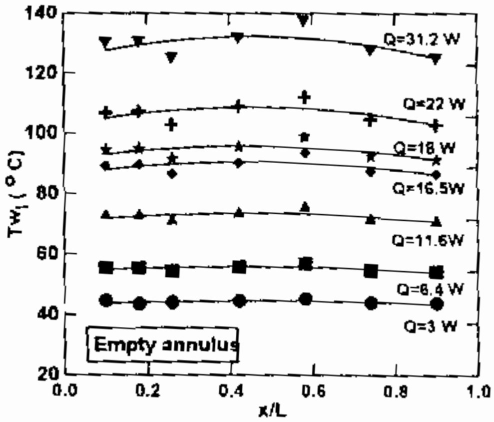


Fig. (4) Temperature distribution on the outer surface of the inner cylinder

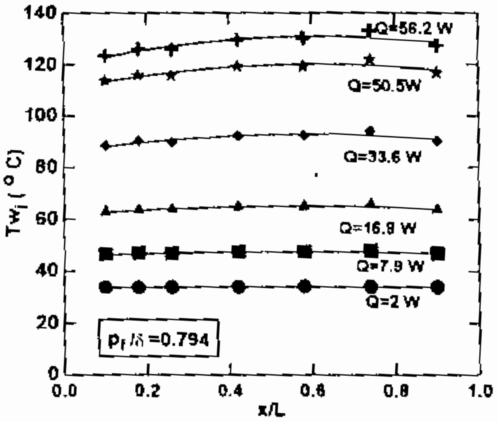


Fig. (5) Temperature distribution on the outer surface of the inner cylinder

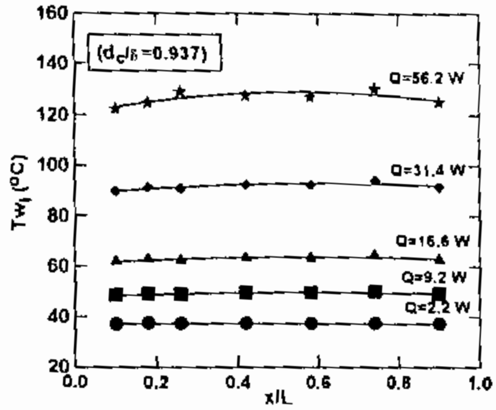


Fig. (6) Temperature distribution on the outer surface of the inner cylinder

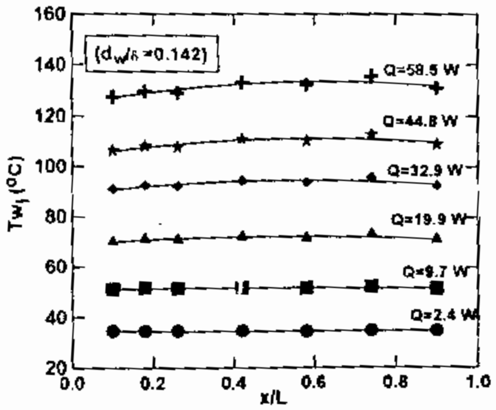


Fig. (7) Temperature distribution on the outer surface of the inner cylinder

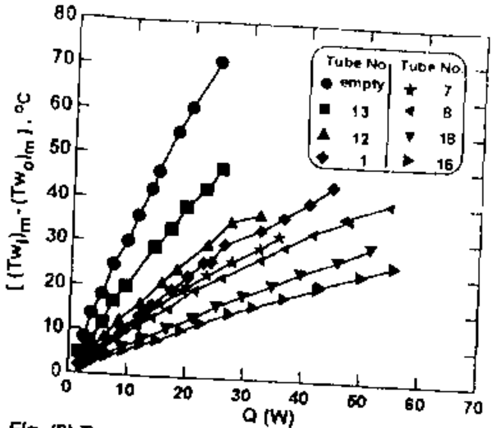


Fig. (8) Temperature difference across the annulus as a function of heat flux on the inner cylinder.

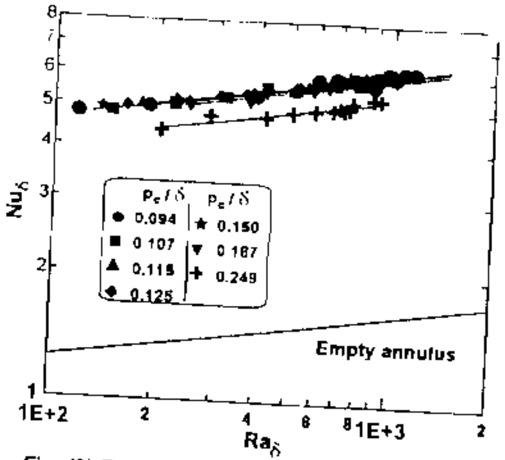


Fig. (9) Relation between Nusselt number and Rayleigh number at different coil pitches.

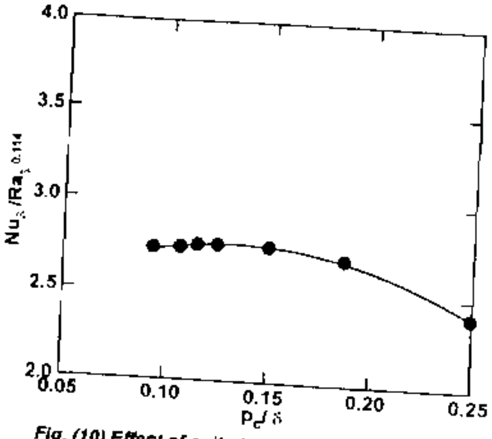


Fig. (10) Effect of coil pitch (p_c/δ) on Nusselt number

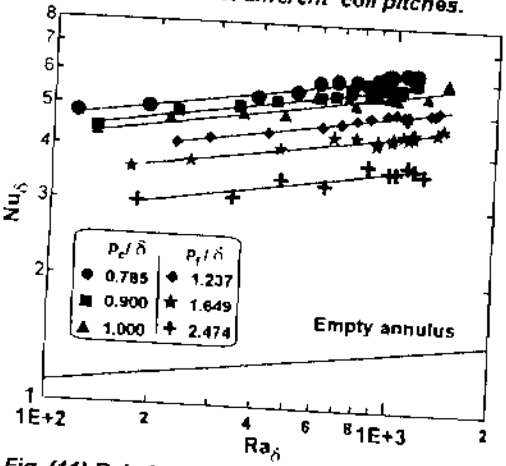


Fig. (11) Relation between Nusselt number and Raylegh number at different ring pitches.

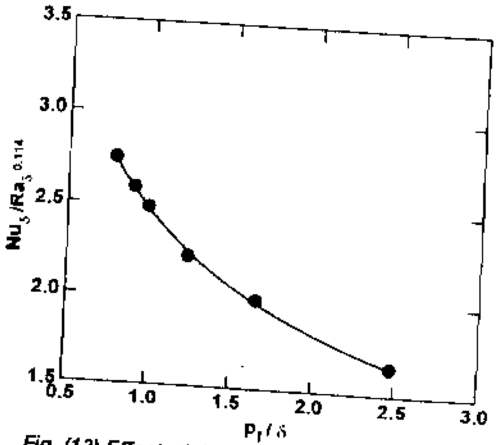


Fig. (12) Effect of ring pitch (p_r/δ) on Nusselt number

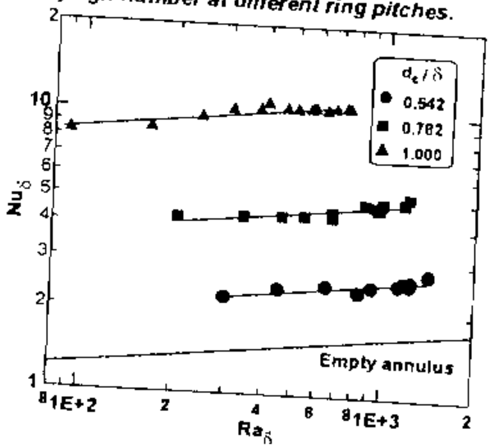


Fig. (13) Relation between Nusselt number and Rayleigh number at different coil diameteres.

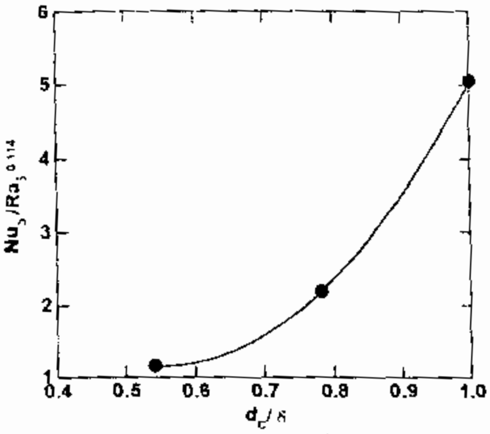


Fig. (14) Effect of coil diameter (d_c/δ) on Nusselt number

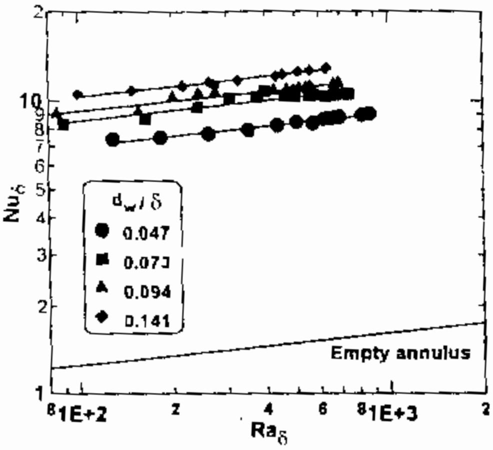


Fig. (15) Relation between Nusselt number and Raylegh number at different wire diameteres.

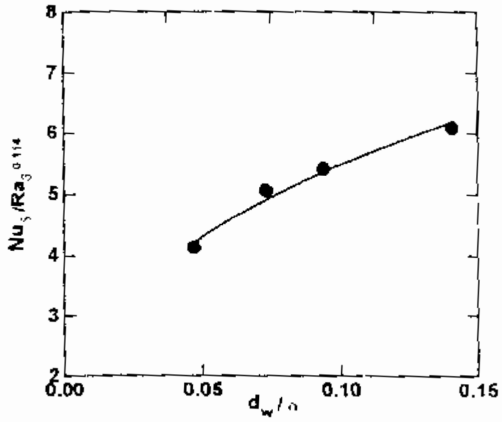


Fig. (16) Effect of wire diameter (d_w/δ) on Nusselt number

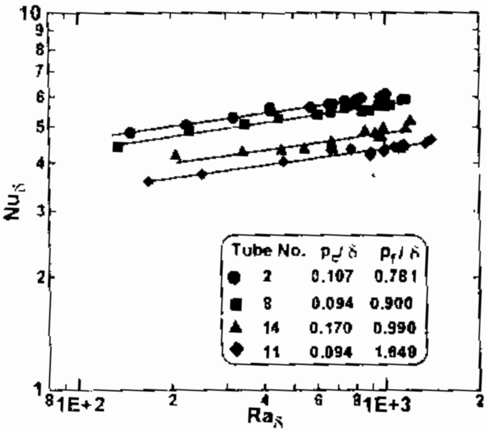


Fig. (17) Effect of configuration parameters on Nusselt number at constant surface area and constant total number of coils

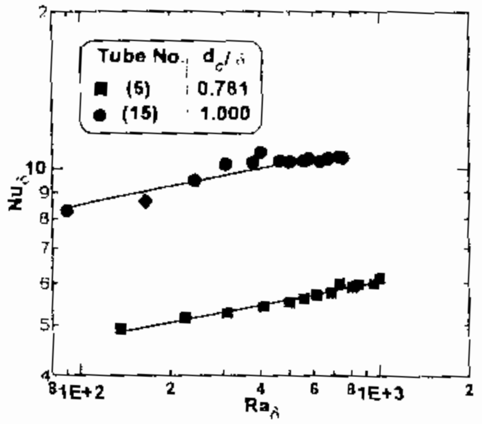


Fig.(18) Effect of conduction on Nusselt number at constant surface area of the rings

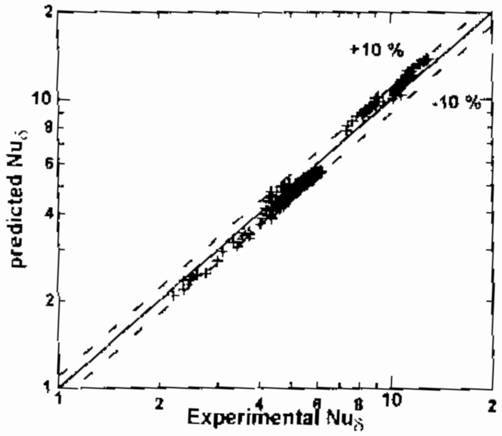


Fig. (19) Experimental versus predicted Nusselt numbers for all augmented annular tubes.